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Applicability of a sharp-interface model for estimating steady-state salinity at pumping wells—validation against sand tank experiments

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ABSTRACT

A numerical sharp-interface model of saltwater and freshwater behavior was validated against experiments conducted in two small scale sand tanks. A simple algorithm was proposed to determine saltwater and freshwater withdrawal rates at a pumping well at which a total pumping rate was specified. Model estimates were compared with transient salinity breakthroughs and steady-state salinities of water extracted from pumping wells in the sand tanks. Experimental scenarios included various combinations of freshwater pumping and injection and saltwater pumping. The corresponding Nash–Sutcliffe model efficiency was 0.95, which showed that the agreement between observations and computed results was satisfactory.

1. Introduction

Salinity and saltwater intrusion are challenges for coastal groundwater protection and management. Although considerable attention has been focused on understanding and modeling freshwater and saltwater flows in aquifers, research on the salinity of pumped water is limited. Moreover, the identification of sustainable management schemes for groundwater in coastal areas may require numerical modeling to assess responses of groundwater system to anthropogenic and natural disturbances. A density-dependent flow and advective and dispersive solute transport approach (Diersch, 2002; Guo and Langevin, 2002; Kim, 2005; Kipp, 1987; Sanford and Konikow, 1985; Voss, 1984; Zheng and Wang, 1999) is the most rigorous method for simulating groundwater flow phenomena subject to saltwater intrusion.

Alternatively, a sharp-interface approach may be used for problems in which transition zones can be neglected. Bear (1979) reviewed two-dimensional analytical solutions based on the hodograph method and conformal mapping. Strack (1976) derived an analytical solution for groundwater flow and a freshwater–saltwater sharp interface subject to ambient flow and a pumping well. Cheng et al. (2000) extended Strack's solution for multiple wells. Kacimov et al. (2006) developed an analytical solution for arid regions where evaporation of freshwater may significantly impact groundwater flow. Park et al. (2009) developed design curves for maximum pumping or minimum injection rates using the analytical solution derived by Cheng et al. (2000). Numerical sharp-interface models have also been developed. Sa da Costa and Wilson (1979) developed a Galerkin finite-element model for freshwater and saltwater flows in a single-aquifer layer. Essaid (1990) and Huyakorn et al. (1996) developed numerical models for layered aquifer systems. The sharp-interface approach is especially useful for large-scale problems, but simulating the salinities of pumped water with it is cumbersome.

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Most modeling studies have dealt with temporal and spatial distributions of salinity, but only a limited number of studies have addressed the salinity of water extracted from pumping wells. For example, Paster and Dagan (2008) derived an approximate analytical solution using the boundary-layer approximation and estimated the salinity of pumped water from a confined aquifer by integrating the saltwater entrainment in the well capture zone. However, their solution was limited to a fully penetrating well in homogeneous, constant-thickness confined aquifers of semi-infinite areal extent. Therefore, its application is limited to ideal situations. Diersch and Nillert (1990), Merritt (1997), and Reilly and Goodman (1987) simulated the salt concentrations of pumped water using dispersion models and compared simulated results with observed data from field sites. Merritt (1997) was able to calibrate a few model parameters, including dispersivities, and closely matched simulated results to measured data. Comparisons made by others resulted in larger errors ranging from a few percent to nearly 20%. In their sharp-interface models, Essaid (1990) and Huyakorn et al. (1996) implemented algorithms to estimate the saltwater content in a pumping well. Huyakorn et al. (1996) used a simple analytical solution for well flow, while Essaid (1990) distributed the total pumping rate to freshwater and saltwater equations based on thicknesses at the well location. In both models, the interface position and the screen length were the main variables affecting the salinity of the pumped water. To date, the accuracy of salinity predictions using sharp-interface models has not been investigated.

Laboratory experiments have been used extensively to investigate saltwater intrusion phenomena in porous media (Boufadel, 2000; Goswami and Clement, 2007; Nakagawa et al., 2005; Simmons et al., 2001; Werner et al., 2009). Many experiments have also been conducted to test or to validate dispersion models (Mao et al., 2006; Oswald and Kinzelbach, 2004; Thorenz et al., 2002; Watson et al., 2002; Zhang et al., 2001). To the best of our knowledge, Hong et al. (2004) and Werner et al. (2009) presented the only laboratory experiments in which the salinities of pumped water were measured. In both works salinities were measured to determine if the wells had been intruded.

Huyakorn et al. (1996) developed a sharp-interface finite-element model for freshwater and saltwater flows in multi-layer aquifer systems. The numerical model was verified against test problems for which analytical or numerical solutions were available, and the comparisons showed good agreement. The objective of this research was to investigate the applicability of the sharp-interface model (Huyakorn et al., 1996) for estimating the salinity of pumped water. Numerical treatment of a well for a multi-layer system involves the additional complication of assigning fluxes across aquifer layers when a well screen spans multiple aquifer layers. For simplicity, we focused on a single-layer numerical model. Numerical results were compared against experimental results conducted in sand tanks. We conducted experiments to examine modeling capabilities for complex field problems that may involve not only excessive pumping from freshwater wells but also saltwater pumping and freshwater injection, which may be used to mitigate saltwater intrusion or for artificial recharge.

2. Sharp–interface groundwater flow model

For a single-aquifer layer, the vertically averaged governing equations for freshwater and saltwater flows can be simplified as follows (Huyakorn et al., 1996):

$$\nabla\cdot(b_f K_f\cdot\nabla h_f) = (b_f S_{sf} + \beta)\frac{\partial h_f}{\partial t} - \theta\frac{\partial \xi}{\partial t} - Q_f \quad (1)$$

$$\nabla\cdot(b_s K_s\cdot\nabla h_s) = (b_s S_{ss} + \beta)\frac{\partial h_s}{\partial t} + \theta\frac{\partial \xi}{\partial t} - Q_s \quad (2)$$

where subscripts f and s refer to freshwater and saltwater, respectively; ∇ is the two-dimensional gradient operator; h is the piezometric head [L]; b is the thickness of each fluid [L]; K is the hydraulic conductivity [LT^{-1}]; S_s [L^{-1}] is the aquifer specific storage; β is the effective porosity (θ) for an unconfined aquifer and is 0 for a confined aquifer; ξ is the elevation of saltwater-freshwater interface [L]; and Q is the flux [LT^{-1}] per unit area due to pumping (or injection). The interface elevation is calculated by equating pressures at the interface and assuming the hydrostatic condition as follows (Bear, 1979):

$$\xi = \frac{\rho_f}{\rho_s - \rho_f}\left(\frac{\rho_s}{\rho_f}h_s - h_f\right) = \frac{\rho_s h_s - \rho_f h_f}{\rho_s - \rho_f} \quad (3)$$

where ρ is the fluid density [ML^{-3}].

At pumping wells, we assumed that the total extraction rate was constant regardless of the proportions of saltwater and freshwater encountered in the well. When both freshwater and saltwater are extracted from a well, the following relationship holds:

$$Q_t = Q_f + Q_s \quad (4)$$

where subscript t denotes the total amount. Pumping rates of extracted freshwater and saltwater are assumed to depend on the interface position within a well screen and on transmissivities. Thus, freshwater and saltwater extraction rates are calculated as follows:

$$Q_f = \frac{K_f l_f}{K_f l_f + K_s l_s} Q_t \quad (5)$$

$$Q_s = \frac{K_s l_s}{K_f l_f + K_s l_s} Q_t \quad (6)$$

where l_f and l_s are thicknesses [L] of freshwater and saltwater, respectively, in the well screen (see Fig. 1). Here l_f and l_s can be determined as follows:

$$l_f = max(min(z_{wt}, z_{at}) - \max(z_{wb}, \xi), 0) \quad (7)$$

$$l_s = l' - l_f \quad (8)$$

$$l' = min(z_{wt}, z_{at}) - max(z_{wb}, z_{ab}) \quad (9)$$

where z_{wt} and z_{wb} are the elevations [L] of the top and bottom of a well screen, respectively; z_{at} is the elevation [L] of the