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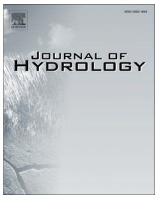

Vertical leakage in sharp-interface seawater intrusion models of layered coastal aquifers

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SUMMARY

Previous sharp-interface studies of seawater intrusion (SWI) adopt various approaches to the treatment of vertical fluxes in regions where alternating saltwater and freshwater are found in overlying aquifers. In this study, we compare dispersive modeling and sand-tank experiments to the results of sharp-interface models to evaluate assumptions regarding vertical fluxes in coastal multi-aquifer systems. The sand-tank experiments (one transient and two steady-state cases) consist of two coarse sand layers separated by a lower-permeability layer of fine sand. Vertical freshwater leakage in sharp-interface models is treated in one of three ways. Case 1: upward freshwater leakage flows only into freshwater in the aquifer above, bypassing any overlying saltwater; Case 2: no upward freshwater leakage occurs if there is overlying saltwater; Case 3: freshwater leaks into any overlying saltwater without modifying the saltwater salinity. Sharp-interface models over-predicted the toe position of the saltwater wedge in both the experiments and numerical models (regardless of the vertical leakage assumption), in agreement with previous studies. Nonetheless, Case 1 produced improved prediction of the sand-tank results relative to Cases 2 and 3. Freshwater leakage fluxes in areas where the interface was absent were reasonably well represented by all three sharp-interface leakage assumptions, compared to those of the dispersive model. In regions where saltwater overlies freshwater, the upward freshwater fluxes predicted by dispersive modeling were found to be consistently closest to the upward freshwater flux of Case 1, compared to Cases 2 and 3. Saltwater-to-saltwater leakages from the dispersive models were poorly represented by the sharp-interface models. Vertical flux assumptions were then evaluated for idealized field-scale situations, and Case 1 again best matched the dispersive modeling results. Streamlines from dispersive modeling show that upward freshwater leakage tends to flow around and bypass overlying saltwater. This matches optimally the assumption of Case 1. We conclude that Case 1 is the ideal approach to the treatment of upward freshwater fluxes in sharp-interface models of multiple-aquifer systems, whereas Cases 2 and 3 may create unrealistic SWI predictions, especially for situations where overlying aquifers are separated by a layer of low conductance.

1. Introduction

Population growth and the scarcity of coastal freshwater resources have increased the stresses on many coastal aquifers, leading to aquifer storage decline and seawater intrusion (SWI) (Bear et al., 1999; Feseker, 2007; Werner et al., 2013). Most coastal aquifers comprise overlying sequences of geological strata, resulting in SWI characteristics that may differ significantly to those of homogeneous cases (e.g. Collins, 1971; Paniconi et al., 2001). Layered coastal aquifers have received significantly less attention than the more simplified single-layer case, despite that stratified aquifers are widespread (Lu et al., 2013).

The investigation of coastal aquifers routinely involves the application of SWI models, which can be divided into two categories, namely sharp-interface and dispersive-interface approaches. Sharp-interface approaches are computationally more efficient, and allow for the application of analytical solutions, predominantly assuming steady-state conditions and considering both single-layer aquifers (e.g. Mantoglou, 2003; Werner et al., 2012) and layered systems (e.g. Mualem and Bear, 1974; Dagan and Zeitoun, 1998). This approach is more practical for problems requiring reduced computational effort, such as large-scale problems applied to automated

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calibration procedures, or where the transition zone is thin relative to the depth of aquifer (Bear, 1979). Dispersive-modeling approaches are more numerically challenging, but allow for freshwater–saltwater mixing and the estimation of the dynamics of a wider range of salinities (e.g. Werner and Gallagher, 2006).

In the application of sharp-interface methods to layered aquifers, there is no mixing between freshwater and saltwater, and therefore it is necessary to make simplifying assumptions about vertical fluxes between overlying aquifers, in particular in areas where saltwater overlies freshwater. For example, Essaid (1990) applied a finite-difference sharp-interface approach to simulate SWI in the Soquel-Aptos Basin, USA. She assumed horizontal flow in the aquifer and vertical flow in the aquitard. Where freshwater and saltwater are juxtaposed across the aquitard, the head value of one fluid type is converted to an equivalent head of the other fluid type (depending on the direction of leakage), and leakage fluxes are presumed to enter the receiving water body (e.g. freshwater flows into saltwater) without modifying its salinity. Huyakorn et al. (1996) developed a sharp-interface numerical model of SWI in multi-layer aquifers based on Essaid's (1990) methodology, except with modified assumptions regarding vertical leakage. They implemented three different conditions for areas of overlying freshwater and saltwater: (1) downward freshwater leakage is prohibited where freshwater is underlain by saltwater; (2) saltwater cannot leak upward where it is overlain by freshwater; (3) the upward leakage of freshwater that is overlain by an aquifer containing both freshwater and saltwater (separated by a freshwater–saltwater interface) bypasses the saltwater in the upper aquifer to flow into the overlying freshwater. In the sharp-interface SWI package for MODFLOW (Bakker et al., 2013), vertical leakage occurs only between water bodies of the same type, despite that saltwater may separate the freshwater bodies. Hence, freshwater may bypass saltwater in leaking upwards, in a similar manner to the third condition of Huyakorn et al. (1996). The upward vertical leakage of freshwater into an aquifer containing only saltwater is converted to saltwater (without modifying the saltwater salinity). The SWI package has been assessed for stratified aquifer conditions by comparing to SEAWAT results (Dausman et al., 2010; Bakker et al., 2013; Fitts et al., 2014), but the implications of the different assumptions to vertical flow have not been assessed previously. In particular, the effect of vertical leakage on the distribution of the freshwater–saltwater interface in multi-layer aquifers, when the sharp-interface approach is applied, has not been examined.

In this study, we consider SWI in layered aquifers where upward freshwater leakage occurs. Steady-state and transient predictions using both sharp-interface and dispersive models are evaluated, and compared to the results of sand-tank experiments. Sand-tank experiments have been used previously to study SWI mechanisms, although mostly for homogeneous settings (e.g. Zhang et al., 2002; Goswami and Clement, 2007; Werner et al., 2009; Luyun et al., 2009; Shi et al., 2011). Experiments of stratified aquifers are rare. Lu et al. (2013) used sand tanks and dispersive modeling to investigate the effects of aquifer stratification on the thickness of steady-state mixing zones. Various aquifer-aquitard hydraulic conductivities, layer thicknesses, head gradients and dispersivities were simulated in three-layered aquifer arrangements. The dependency of the mixing zone on these parameters was assessed. Lu et al. (2013) showed that the interface position is seaward in comparison to the homogeneous case when a low hydraulic conductivity (*K*; L/T) layer is embedded between two high-*K* layers. Sensitivity analyses of large-scale layered aquifers indicated significant effects of aquifer stratification on flow paths and the flow rate near the coastal boundary. The mixing zone profile was dependent on the *K* contrast rather than the magnitude of *K*. Sand-tank experiments and steady-state analytical solutions have also been applied by Liu et al. (2013) for stratified aquifers where a high-*K* layer occurs between two lower *K* layers. They found a reduced SWI extent with the introduction of the high-*K* interlayer. Their attempts to apply the sharp-interface analytical solution of Pistiner and Shapiro (1993) for layered aquifers produced discrepancies that Liu et al. (2013) attributed to vertical leakage effects that are ignored in the solution. Their results highlight the importance of both geological stratification and vertical flow effects in controlling the wedge configuration.

2. Methodology

The vertical leakage assumptions of sharp-interface SWI models of layered aquifers were assessed in this study using three approaches. Firstly, laboratory sand-tank experiments were used to develop a physical basis for assessing interface characteristics in a coastal system comprised of two coarse-sand aquifers separated by a fine-sand layer. Laboratory experiments allowed for a representation of SWI in a layered system that was independent of the assumptions inherent in mathematical models. Secondly, dispersive, density-dependent flow and transport modeling was used to assess the laboratory results, in particular to provide quantification of vertical fluxes within the sand-tank experiments since measuring the vertical leakage across the lower-permeability middle layer was not possible in our experiments. Thirdly, sharp-interface models in which vertical leakage was modified to test different leakage approaches were developed. Dispersive and sharp-interface models were compared for hypothetical stratified aquifers at the field scale to assess vertical leakage assumptions under more realistic conditions.

2.1. Laboratory experiments

Experiments were conducted in a sand tank with internal dimensions 1170 mm length, 600 mm height and 52 mm width. The front and back of the tank were constructed with transparent plate glass of 10 mm thickness, supported by rectangular steel framing. Twelve inflow/outflow taps were installed at 50 mm intervals along the sides. A schematic diagram of the experimental set up is shown in Fig. 1.

Boundaries were controlled using constant head reservoirs (i.e. freshwater and saltwater interconnected Mariotte bottles). Freshwater entered the tank via L2–L11 taps, while saltwater inflow occurred via R2–R7 taps (Fig. 1). Mixed water discharged from the system via R9–R11 taps. Three manometers were attached to taps L1, R1 and R8 to measure the heads at the boundaries. All head-control devices were placed at known elevations, with both water and air interconnected in the same manner as adopted by Klute and Dirksen (1986).

The stratified aquifer consisted of three horizontal layers. Coarse sand (i.e. '16–30' grade sand, Sloan Sands P/L, Dry Creek, South Australia) was used for the top and bottom layers, with layer thicknesses of 25 cm and 20 cm, respectively. The middle layer was 10 or 15 cm thick (see Table 1) and comprised fine sand (i.e. 'N-30' grade sand, Sloan Sands P/L). A wet-packing method similar to that described by Ataie-Ashtiani (1998) was used to minimize entrapped air and non-uniform compaction.

Saltwater solution was produced by dissolving 35 g of calcium chloride dehydrate ($CaCl_2{\cdot}2H_2O$) in 1 L of tap water. The salinity and density of tap water were tested. The electrical conductivity was 480 (±20) μs/cm at 16 (±1) °C, and the total dissolved ion concentration was 280 mg/L. Rhodamine WT (fluorescent FWT Red dye, ENVCO, Australia) with concentration of 500 mg/L was used for visual monitoring of the saltwater wedge. The rhodamine tracer has been used successfully in previous studies (e.g. Schincariol and Schwartz, 1990; Simmons et al., 2002; Werner et al., 2009; Shi et al., 2011). Slight adsorption of rhodamine was found in our