A comparison between SWI and SEAWAT – the importance of dispersion, inversion and vertical anisotropy

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ABSTRACT

SWI and SEAWAT are both computer codes designed to model variable-density systems. One of the options in SWI is to model Dupuit interface flow, where freshwater and seawater are separated by an interface. In this paper we compare seawater intrusion model results of SWI to model results of SEAWAT, which simulates full variable-density flow and transport. Results indicate that SWI is valid for many variable-density systems. For the case considered in this paper, SWI results are accurate when the simulated width of the transition zone between seawater to freshwater is 15% or less of the scale of the problem, density inversion (saltwater over freshwater) occurs over only a small part of the model domain, and the ratio of vertical to horizontal hydraulic conductivity is larger than 0.01. Results also show that the simulated interface moves further inland using SWI than for the same conditions using SEAWAT. SWI is preferable to be used in systems where run times for a fully-coupled variable-density flow and transport model would be prohibitive; for the case considered here, SWI run times were a few seconds and SEWAT run times were almost three hours.

INTRODUCTION

The Sea Water Intrusion (SWI) Package was developed by Bakker and Schaars (2005) to simulate regional seawater intrusion problems with MODFLOW-2000. The package is based on the Dupuit approximation, which allows an aquifer to be represented with only a single model layer (Bakker, 2003). Flow may be simulated with one or multiple sharp interfaces with constant density or as variable-density flow with continuously varying density. This design is computationally efficient when simulating seawater intrusion at a regional scale. There are some limitations to the approach: (1) dispersive or diffusive mixing between freshwater and seawater are not represented, (2) inversion of seawater overlying freshwater cannot be accurately simulated, and (3) vertical movement of the interface within a single layer is based solely on continuity where resistance to vertical flow is neglected. Conversely, SEAWAT (Langevin *et al.* 2008) simulates fully coupled variable-density groundwater flow and solute transport, including mixing, inversion, and vertical resistance to flow. For SEAWAT to simulate variable-density flow and transport accurately, however, aquifers have to be discretized more finely, particularly in the vertical direction. The increased discretization is often required to minimize numerical dispersion near the saltwater-freshwater interface as well as to represent convective flow patterns. This may result in excessive model run times, which may be prohibitive for development of regional-scale saltwater intrusion models.

Results from previous investigations of the two programs indicated they produce similar results, provided that the SEAWAT grid was finely discretized and numerical dispersion was minimized

(Bakker *et al.* 2004). Because of the computational efficiency of SWI, the program may be preferred when dispersive fluxes have no significant effect on the outcome of a model. The purpose of this investigation is to evaluate when simulations using SWI are appropriate, considering the effects on saltwater transport of density inversion, dispersion, and vertical anisotropy.

METHODS

SWI and SEAWAT simulation results are compared for conditions of (1) density inversion, (2) varying degrees of dispersion, and (3) varying degrees of vertical resistance to flow. Results from a single SWI simulation (test problem 3 of the SWI manual, Bakker and Schaars 2005) are compared against multiple SEAWAT simulation results. The conceptual model is a 2-dimensional representation of a two-aquifer system (Fig. 1).

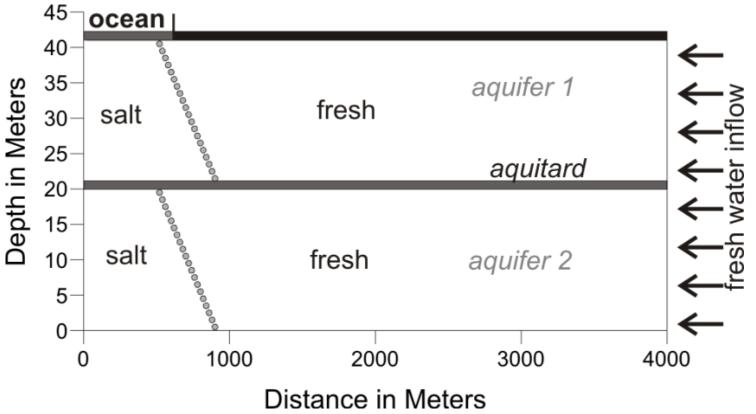

Figure 1: Conceptual model. The initial location of the interface is the dotted line between the salt and fresh parts of the aquifer.

The aquifer and simulation parameters are listed in Table 1. For the SEAWAT simulation, transport was solved using the finite-difference method with upstream weighting. The general-head boundary cells representing the ocean have a salinity value of 35 g/L total-dissolved solids (TDS). For all three comparisons, the initial conditions represent a density inversion, as shown by saltwater in aquifer 1 overlying freshwater in aquifer 2 over a portion of the simulation domain. In the first test of density inversion, the SEAWAT model has dispersivities set to zero and the ratio of vertical to horizontal hydraulic conductivity set to one. For the second test, the results from SEAWAT simulations with increasing values of longitudinal dispersivity (and with transverse dispersivity set to one tenth of the longitudinal value) are compared with the SWI simulation results. For the third test, SEAWAT simulation results using decreasing values of vertical hydraulic conductivity are compared to the SWI simulation results.

Table 1 Parameters	SWI	SEAWAT
Row	1	1
Columns	200	800
Layers (total)	2	82
# layers in aquifer 1	1	40
# layers in aquifer 2	1	40
# layers for aquitard	N/A	2
Horizontal Hydraulic Cond. Aq. 1 (m/d)	2	2
Horizontal Hydraulic Cond. Aq. 2 (m/d)	4	4
VCONT Aquitard (day^{-1})	0.01	0.01
Freshwater Inflow aquifer 1 (m^2/day)	0.005	0.005
Freshwater Inflow aquifer 2 (m^2/day)	0.01	0.01
Porosity	0.2	0.2
Longitudinal Dispersivity, α_L (m) Range	N/A	0-100
Anisotropy ratio (K_{vert}/K_{hor}) Range	N/A	0.001-1
Total time period modeled (years)	500	500
Approximate model run time	2 seconds	3 hours

RESULTS AND DISCUSSION

Density Inversion

At 100 years, the models match well except in the area of the density inversion (Fig. 2). With SWI, the vertically migrating seawater from aquifer 1 is added to the bottom of aquifer 2 (for more detailed explanation, see Bakker and Schaars, 2005). The final location of the interface (Fig. 2) at 500 years shows that the two model results are almost identical. However, the toe of the interface for the SEAWAT model is slightly seaward of the SWI surface. It should be noted that, as dispersivity is set to zero in the SEAWAT model, theoretically there should be no transition zone from saltwater to freshwater. As seen in Figure 2 there is a thin transition zone as a result of numerical dispersion.

Dispersion

Model results reveal that as dispersivity increases, the location of the toe moves seaward (Fig. 3). Results indicate that if the simulated width of the transition zone from freshwater to seawater (1 g/L to 34 g/L) is less than 15% of the horizontal scale of the problem, SWI would likely produce valid results (Fig. 3). These results indicate if dispersivity is estimated to be greater than a few meters (Fig. 3), a fully-coupled variable-density flow and transport model might be necessary for more accurate results. Calibrated values of the dispersivity for seawater intrusion models in the literature are generally less than a couple of meters (e.g. Oude Essink, 2001); therefore, SWI would likely be appropriate in most saltwater intrusion models. It is also important to note that the SWI-simulated interface surface is landward of SEAWAT-simulated transition zone.

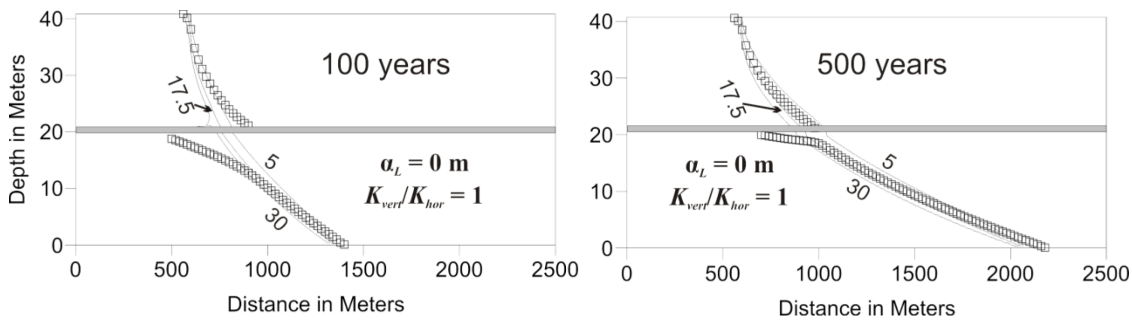

Figure 2: The SWI-simulated sharp interface (black squares) and the SEAWAT-simulated transition zone contoured at 5, 17.5, and 30 g/L TDS at 100 and 500 years for the density inversion test.

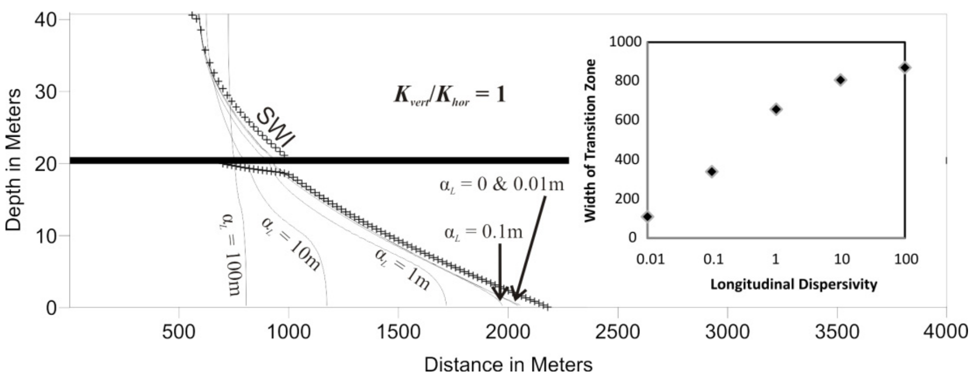

Figure 3: The location of the SWI-simulated interface (black crosses) and the 50% seawater line (17.5 mg/L TDS) from SEAWAT-simulated transition zone (black/grey lines) with a range of dispersivity values. Longitudinal dispersivity is shown (transverse dispersivity=0.1*longitudinal). The graph is the longitudinal dispersivity vs. the width of the transition zone (1 g/L - 34 g/L TDS) from the SEAWAT simulations.

Vertical Resistance to Flow

As vertical resistance to flow is increased for the SEAWAT simulations, the toe of the interface only moves seaward when the anisotropy ratio (K_{vert}/K_{hor}) is smaller than 0.01 (Fig. 4). As with the results from the dispersion test, the SWI-simulated interface is landward of all SEAWAT-simulated 17.5 mg/L TDS contours.

CONCLUSIONS

The approximations in SWI produce reasonable estimates of the location of the saltwater-freshwater interface in the system shown in this paper. SWI results may not be realistic when the dispersion across the interface is large, when the anisotropy ratio is very small, or in some systems where inversion occurs and a significant amount of vertical fingering is observed. For simulations where SWI and SEAWAT results diverge, the SWI-simulated interface tends to be more landward than the SEAWAT-simulated transition zone. In terms of evaluating the risk of saltwater intrusion to freshwater resources, these results could be considered more conservative. Because of the computational savings in SWI with run times of a few seconds, as compared to SEAWAT with run times of a few hours, it is preferred and valid to use in many groundwater models if the run times of full variable-density flow and transport models are prohibitive such as in a regional-scale model.

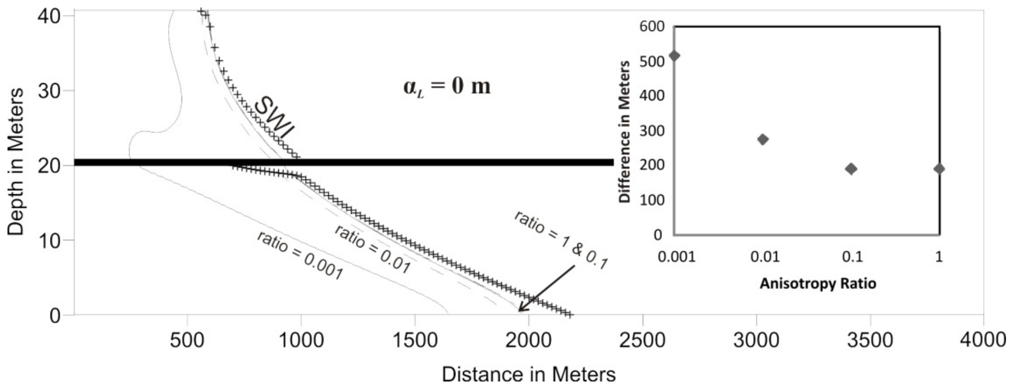

Figure 4: The location of the SWI-simulated interface (black crosses) and the 50% seawater line (17.5 mg/L TDS) from SEAWAT-simulated transition zone (black/grey lines) with different vertical: horizontal hydraulic conductivity anisotropy ratios. The graph shows the anisotropy ratio vs. the difference between the toe of the SWI interface and the toe (50% seawater line or 17.5 mg/L TDS) of the SEAWAT simulations.

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