Axisymmetric simulation of aquifer storage and recovery with SEAWAT and the Sea Water Intrusion (SWI) Package for MODFLOW

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ABSTRACT

SEAWAT and the Sea Water Intrusion (SWI) Package for MODFLOW were used to simulate hypothetical aquifer storage and recovery (ASR) scenarios under constant- and variable-density conditions. To test the codes, both models were used to represent two-dimensional axisymmetric groundwater flow near an ASR well. The models were “tricked” into representing axisymmetric flow by multiplying the input values for horizontal and vertical hydraulic conductivity, specific storage, and porosity by $2\pi r$, where r is the radial distance from the well to the cell center. Additionally, the logarithmic transmissivity weighting option was used, instead of the harmonic weighting option, to ensure that the calculated horizontal conductances were consistent with axisymmetric flow. Results from constant-density simulations were in good agreement with the Theis solution and the equation for an expanding cylinder. For variable-density conditions, SEAWAT and SWI results also were similar, provided that a large vertical hydraulic conductivity value was used for the SEAWAT simulation. Results from a sensitivity analysis with SEAWAT indicated that recovery efficiency is highly dependent on vertical grid resolution, vertical hydraulic conductivity, native aquifer salinity, storage time, and hydrodynamic dispersion.

INTRODUCTION

An increasing number of water-resource plans rely on the success of aquifer storage and recovery (ASR). With some coastal ASR applications, freshwater is injected into brackish or saline aquifers for recovery at a later date. Due to the effects of buoyancy, injected freshwater may rise and spread beneath the base of a confining unit. Numerical modeling plays an important role in the effective management of ASR; however, complexity and computational burden often have restricted the viability of using flow and transport models to help predict and manage ASR operation. The purpose of this paper is to show how SEAWAT (Langevin et al. 2003) and the Sea Water Intrusion (SWI) package for MODFLOW (Bakker and Schaars 2003) can be used to simulate ASR operations in saline aquifers. The two codes are based on fundamental differences; SEAWAT simulates variable-density flow and dispersive solute transport, whereas SWI simulates variable-density flow and movement of interfaces between different fluid types. To minimize computational burden, a simple approach is presented for simulating axisymmetric (also referred to as radial or cylindrical) flow and transport. The utility of the modeling approach is demonstrated by examining the effects of grid resolution, vertical resistance to flow, native aquifer salinity, length of storage period, and hydrodynamic dispersion for a simple ASR application.

APPROACH FOR SIMULATING AXISYMMETRIC FLOW AND TRANSPORT

Although MODFLOW is designed to work with rectangular finite-difference model grids, the program can be “tricked” into simulating radial groundwater flow near a well. With this type of configuration, known as an axisymmetric profile, the well is located at a radius (r) of zero. Radial flow can be simulated in MODFLOW, MT3DMS, SEAWAT, and SWI by making adjustments to hydraulic conductivity, specific storage, and porosity.

MODFLOW uses the following formulation for hydraulic conductance along a row:

$$CR_j = \frac{2 \cdot DELC \cdot T_{j+1/2}}{DELR_j + DELR_{j+1}}, \tag{1}$$

where $DELC$ is the width of the row, and would normally be set to a value of 1 for standard cross section or axisymmetric profile models; and $DELR_j$ is the width of column j. Depending on the assumed spatial distribution for hydraulic conductivity, interblock transmissivity (T) can be weighted in MODFLOW2000

	Parameter	Value	Units
Aquifer Parameters	K_h	100	m/d
	K_v	100,000	m/d
	b	20	m
	S_s	0.0001	m^{-1}
	n	0.20	-
Injection Parameters	$Q_{injection}$	3600	m^3/d
	$Q_{storage}$	0	m^3/d
	$Q_{recovery}$	-3600	m^3/d
	$t_{injection}$	4	d
	$t_{storage}$	4	d
	$t_{recovery}$	4	d
Grid Parameters	NCOL	100	
	NLAY		
	SEAWAT	20	
	SWI	1	
	$DELC_{(j)}$		
	j=1,75	0.5	m
	j=76,100	$DELC_{(j-1)}$×1.5	m
	DZ		
	SEAWAT	1	m
	SWI	20	m

Table 1. Parameter values used for constant-density comparison simulation.

using either a harmonic or logarithmic option. If the logarithmic option is selected, the interblock transmissivity is calculated as:

$$T_{j+1/2} = \frac{T_{j+1} - T_j}{\ln\left(\dfrac{T_{j+1}}{T_j}\right)}. \qquad (2)$$

Transmissivity is the product of horizontal hydraulic conductivity and layer thickness. Thus, the transmissivity value calculated by MODFLOW for cell *j* is:

$$T_j = K_{h,j}\Delta z\,. \qquad (3)$$

To “trick” MODFLOW2000 into representing axisymmetric radial flow, the horizontal hydraulic conductivity value of the aquifer (K_h) is entered as input to the model as a function of radial distance:

$$K^*_{h,j} = r_j\theta K_h\,, \qquad (4)$$

where $r_j\theta$ is the arc length passing through the center of cell *j*. By substituting equations 2, 3, and 4 into equation 1, and setting θ to 2π, the resulting conductance value along a row is:

$$CR_j = \frac{2\pi K_h \Delta z}{\ln\left(\dfrac{r_{j+1}}{r_j}\right)}. \qquad (5)$$

Equation 5 is identical to the conductance equation presented by Reilly and Harbaugh (1993), and can be derived from the Thiem equation or from the limit of many radial conductances in series (Bennett et al. 1990). It is important to note here that the more commonly used harmonic averaging for interblock transmissivity does not give equation 5. The harmonic averaging option does not represent the gradual increase in conductance within a single finite-difference cell, and thus, should not be used for axisymmetric models.

Similar adjustments also are required for vertical hydraulic conductivity, specific storage, and in the case of transport, for porosity. MODFLOW calculates the area of cell *j* as: $A_j = DELR_j \cdot DELC$. However, because this area does not correspond to the true area in the axisymmetric representation, adjustments are made for all input values used in equations that contain an area or volume. For example, specific storage must be entered into MODFLOW as:

$$Ss^*_j = Ss_j \frac{A_j}{DELR_j} = Ss_j\theta r_j\,. \qquad (6)$$

Likewise, vertical hydraulic conductivity and porosity are entered as:

$$K^*_{v,j} = K_{v,j}\theta r_j \qquad (7)$$

and

$$n^*_j = n_j\theta r_j\,. \qquad (8)$$

To test the accuracy of the radial simulation approach previously described, constant-density simulations were performed with both SEAWAT and SWI for a hypothetical injection scenario. The parameters used for the simulations are listed in Table 1. Water with a concentration of zero was injected at a rate of 3600 m^3/d for 4 days into a 20-m-thick aquifer with a relative concentration of 1.0. For the SEAWAT simulation, a fully penetrating injection well was simulated by equally apportioning the injection volume among the 20

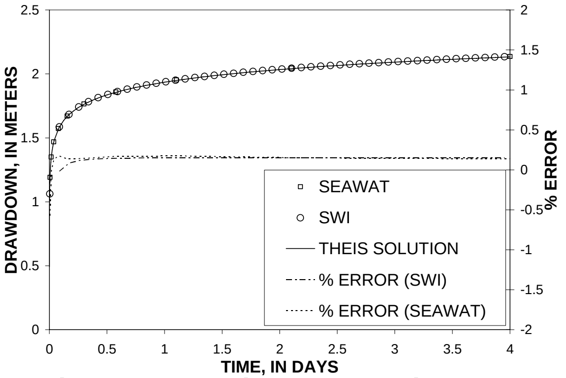

Figure 1. Drawdown versus time at a distance of 1.75 m from injection well.

layers. A fully penetrating well was used in SEAWAT to create horizontal one-dimensional flow that would allow for a direct comparison with SWI results and with the Theis analytical solution. An important consideration here is that a large vertical hydraulic conductivity value (100,000 m/d) was assigned to the multilayer SEAWAT model to minimize the vertical resistance to flow, as SWI is formulated based on an assumption of no vertical resistance.

Simulated drawdowns (a positive value indicates a rise in the water level) and drawdowns calculated using the Theis analytical solution are shown in Figure 1 for a distance of 1.75 m (the distance from the injection well to the center of column 4). The close match between the simulated results and the Theis solution is evidence that the approach provides a reasonable representation of axisymmetric flow. A distance-drawdown analysis (not shown) also was performed by comparing simulated drawdowns with drawdowns from the Theis solution, and a close match also was observed. As expected, a better match was observed when the logarithmic weighting option (as opposed to the harmonic option) was used to calculate internodal conductances.

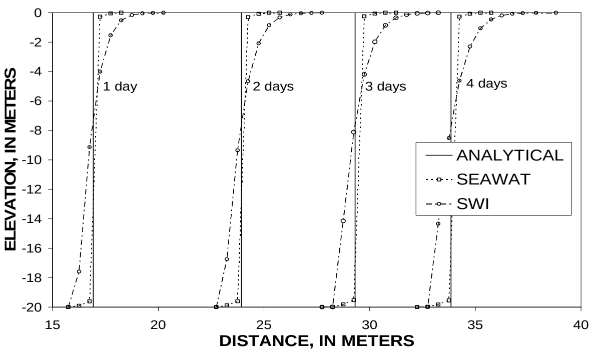

Figure 2. Comparison of interface positions at selected times.

To verify the transport component of the radial approach, simulated results were compared with the radius of a cylinder, as calculated from the height of the aquifer, the effective porosity, and the total volume of injected water at different times (Figure 2). In general, the simulation results compare well with the analytical solution. The interface between the injected and native aquifer water was calculated from the SEAWAT results by interpolating the position of the 50-percent water mixture. Due to a small degree of numerical dispersion, the SEAWAT results show slight deviations from the analytical solution at the top and bottom of the aquifer. SWI also shows similar deviations, which likely are the result of the interface tracking algorithm.

Results from this analysis indicated that constant-density axisymmetric flow and transport can be represented with the existing versions of MODFLOW, MT3DMS, SEAWAT, and SWI without any code modifications. In the following sections, SEAWAT and SWI are used to represent variable-density conditions.

COMPARISON BETWEEN SEAWAT AND SWI

Results from SEAWAT and SWI simulations are presented in this section to provide a comparison between the two different methodologies for simulating ASR in a variable density system. The comparison simulation consists of 4 days of freshwater injection into a seawater saturated confined aquifer. Aquifer, injection, and grid parameters are listed in Table 1.

Results from SEAWAT and SWI after 2, 4, 6, 8, 10, and 12 days of injection are shown in Figure 3. In general, the SEAWAT and SWI results are in good agreement. Slight deviations occur at the top and bottom of the aquifer, which presumably are due to a lack of sufficient vertical resolution in the SEAWAT grid. The SWI results also show a lowering of the interface during recovery in the cell adjacent to the pumping well, which is inconsistent with the SEAWAT results. Attempts to eliminate the strange lowering of the interface by decreasing time steps and adjusting interface tracking parameters were unsuccessful, suggesting a potential problem with this version of SWI.

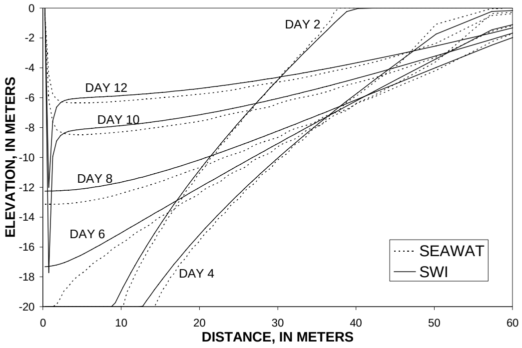

Figure 3. Interface positions at selected times for SWI and 20-layer SEAWAT model.

SENSITIVITY ANALYSIS OF SELECTED SIMULATION PARAMETERS

The analysis here describes sensitivity simulations in which a single model parameter was changed from its initial value. The effects were quantified by comparing the interfaces between injected water and native aquifer water at different times during operation. Recovery efficiency (RE) also was determined from the simulation results by calculating the percentage of the injected water that could be withdrawn without exceeding a chloride concentration of 250 mg/L. Sea water is assumed here to have a chloride concentration of 19,000 mg/L.

The effect of vertical resolution was tested for the SEAWAT simulation. The injected water was assigned a density of 1000 kg/m^3, and the native aquifer water was assigned a fluid density equivalent to that of seawater (1025 kg/m^3). All other parameters are listed in Table 1. Results from three SEAWAT simulations, each with a different level of vertical resolution, are shown in Figure 4. This comparison suggests that a minimum of 20 layers is required to accurately represent changes in aquifer salinity.

In the preceding SEAWAT simulations, vertical resistance to flow was minimized by assigning a large value to the vertical hydraulic conductivity. To determine the effect of vertical resistance, the ASR simulation was performed with SEAWAT using six different values for vertical hydraulic conductivity. Results from the simulations are shown in Figure 5a. Clearly, vertical resistance has a large effect on the amount of water that can be recovered. With a low vertical hydraulic conductivity value, about 43% of the injected water can be recovered before chloride concentrations exceed 250 mg/L, whereas none of the water can be recovered with K_v values greater than 10 m/d.

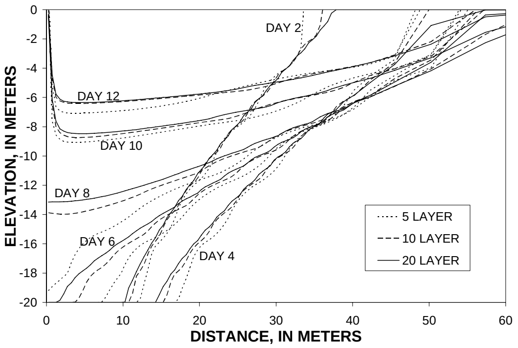

Figure 4. Interface positions for 5, 10, and 20 layer SEAWAT simulations.

Results from the remaining three sensitivity analyses are shown in Figure 5b, c, and d. For each of these analyses, a relatively small value (1 m/d) was used for K_v to ensure that some of the injected water would be recovered. Simulation results indicated that recovery efficiency, and thus the viability of this specific ASR operational schedule, is highly dependent on the native aquifer salinity, storage time, and dispersive properties of the aquifer.

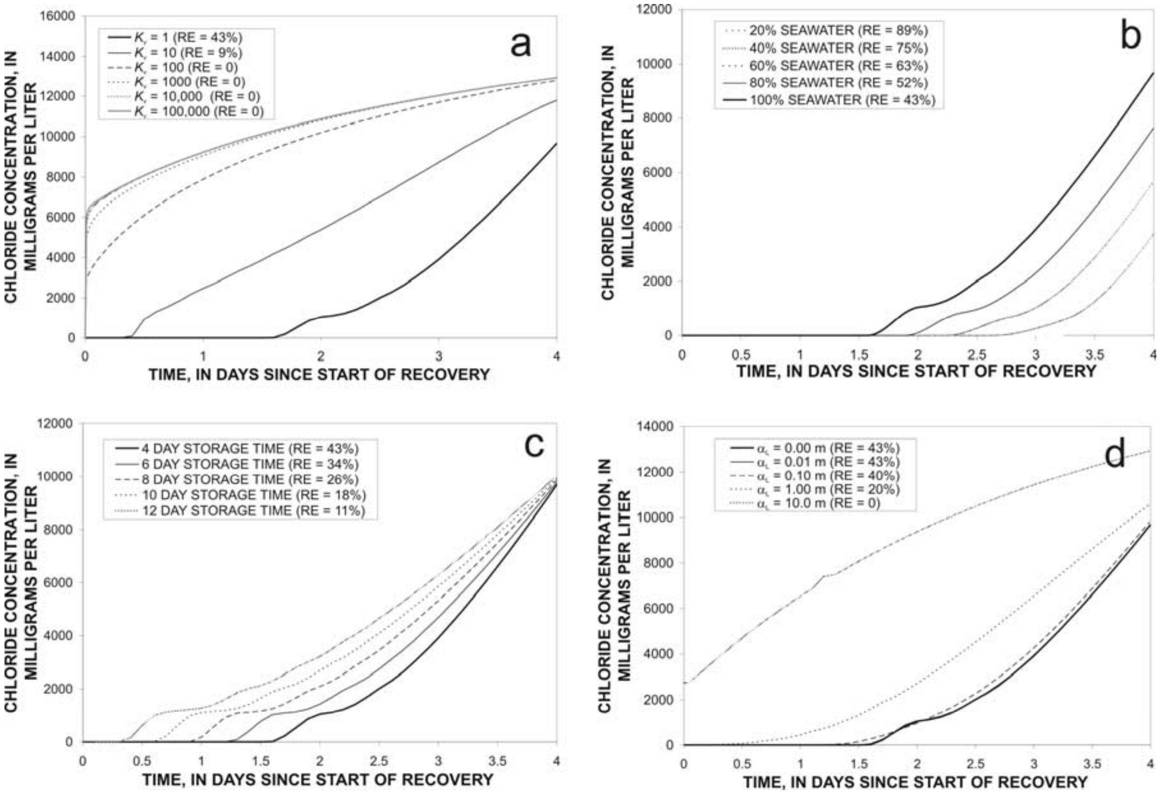

Figure 5. Effect of (a) vertical hydraulic conductivity (K_v), (b) native aquifer salinity, (c) storage time, and (d) longitudinal dispersivity (α_L) on recovery efficiency (RE) and on the chloride concentration of the recovered water as a function of time.

SUMMARY

Existing groundwater flow and transport models, such as SEAWAT and SWI, can be used to simulate axisymmetric flow near an ASR well. If the SEAWAT model has an adequate level of vertical resolution and there is little vertical resistance to flow, the two models will provide similar representations of spatial and temporal changes in aquifer water quality. SWI provides quick and accurate interface solutions with only a single model layer, but is only applicable for ASR simulations if the vertical resistance to flow can be neglected. Because axisymmetric simulations are computationally efficient, sensitivity analyses can be used to quickly evaluate the effects of various parameters, such as vertical hydraulic conductivity, native aquifer salinity, storage time, and hydrodynamic dispersion.

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