REPRESENTING HYDRODYNAMIC DISPERSION IN SALTWATER INTRUSION MODELS THAT DIFFER IN TEMPORAL RESOLUTION

Alyssa Dausman[1] and Christian Langevin[1]

ABSTRACT: Variable-density groundwater flow models are often used to understand the complex nature of coastal groundwater systems. Hydrodynamic dispersion is a difficult process to represent with a model because of spatially varying hydraulic conductivity and temporally varying hydrologic boundary conditions. Temporal variations in water levels, for example, that occur in the field are often averaged into boundary conditions in a model. Three cross-sectional models were developed to test the response of a simulated saltwater interface to different methods for treating the temporally variability in the ocean boundary condition. Results indicate that if temporal tidal variations in model are averaged, simulated concentrations within the interface can be quite different than for the same model that includes the tidal variations. This observation indicates that for certain aquifers, it may not be appropriate to calibrate a variable-density model at one temporal scale and apply the model to a different temporal scale.

KEY TERMS: Hydrodynamic dispersion, saltwater intrusion, saltwater interface

INTRODUCTION

As a contamination plume moves through an aquifer, it mixes with the ambient groundwater causing the plume to increase in size and decrease in concentration. This mixing process is referred to as hydrodynamic dispersion and is caused primarily by spatial variations in groundwater flow velocity and to a lesser degree by molecular diffusion. The mixing due to the spatial variations in groundwater flow velocity is called mechanical dispersion. The simulation of mechanical dispersion as a solute-transport process is complicated because one can never include enough detail in a model to represent all of the spatial variations in groundwater flow velocity. Recognizing this limitation, most modelers rely on a Fickian model for mechanical dispersion to account for some of the mixing that cannot be represented by spatial variations in groundwater flow velocity. Therefore, even if the groundwater flow velocity and direction are the same at all locations in the model, the mixing process can be represented with the Fickian model, which will cause the plume to spread. With this approach, the degree to which the plume will spread depends on the concentration gradient, the magnitude of the groundwater flow velocity, and the dispersivity value. Appropriate dispersivity values for a particular problem are often estimated through model calibration and tend to increase with the scale of the problem.

The cause of the spatial variations in flow velocity is normally attributed to spatial variations in hydraulic conductivity. Molz et al. (1987) have suggested that it may be better to try and incorporate the spatial variations in hydraulic conductivity rather than try to represent the mixing with mechanical dispersion. Goode and Konikow (1990) demonstrated, however, that spatial variations in hydraulic conductivity are not the only cause of spatial variations in groundwater flow velocity. They concluded that dispersion also could be caused by temporal variations in flow velocity. Thus, if one does not include temporal variations in a model, the appropriate dispersivity value may have to be larger than the dispersivity value for the same system without the temporal variations. Goode and Konikow (1990) refer to this larger dispersivity value as "apparent dispervity." Ackerer and Kinzelbach (1985) present a formula for calculating apparent dispersivity, as do Goode and Konikow (1990). Rehfelt (1988) also shows how an apparent dispersivity value can be calculated using the temporal and spatial variability in flow velocity.

A coastal setting is one environment where the presence of temporal fluctuations in groundwater flow velocity and direction can be important. Near the ocean, tides can significantly affect groundwater flow rates and directions. During low tide,

[1] Hydrologist, U.S. Geological Survey-Water Resources Division, Miami Subdistrict, 9100 NW 36th St, Miami, Florida 33178, phone: (305) 717-5872, fax: (305) 717-5801, e-mail: adausman@usgs.gov, langevin@usgs.gov

groundwater discharges into the ocean, but during high tide, flow can change directions and ocean water is forced into the aquifer. In the subsurface, tidal fluctuations cause a pressure wave to propagate through the aquifer material at a rate dependent upon the aquifer properties. At some depth and distance from the coast, this tidal signal is completely damped. Because of this propagation, flow velocities at one point in the aquifer may be out of phase or partially out of phase with velocities at another point in the aquifer. This spatial variation in flow velocity caused by hydraulic transients results in more mixing than for a similar case in which tides are absent.

To accurately represent dispersion, a model should include all factors that cause spatial variations in fluid velocity, including those caused by a fluctuating boundary condition. In the development of numerical models of coastal groundwater flow, tidal fluctuations are often ignored because of the time, effort, and computer resources required to include them in the simulation. Instead, an average value of ocean stage typically is assigned to the ocean boundary in the model. This paper examines the type of problems that can arise from the temporal averaging of tides, a procedure commonly used in the development of a variable-density groundwater flow model. The problems with temporal averaging are highlighted by comparing the results from three numerical simulations, each with a different representation of the tidal ocean boundary.

MODEL DESIGN

To evaluate the effects of averaging temporal hydrogeologic stresses, a two-dimensional cross-sectional model (Figure 1) was developed using generalized hydrogeologic conditions in southeastern Florida. The horizontal axis is aligned perpendicular to the coast along a groundwater flow line. Therefore, flow can be evaluated in the horizontal and vertical directions. The active cells in the model were assigned properties similar to the Biscayne aquifer in Broward County, Florida (Table 1). The SEAWAT code (Guo and Langevin, 2002), which is a combined version of MODFLOW and MT3DMS, is used to simulate the variable-density flow patterns.

The model grid contains 1 row, 152 columns, and 14 layers, and each cell is 150 by 150 by 7.5 m (meters). The active cells represent the Biscayne aquifer, and the inactive cells represent low-permeability units beneath the Biscayne and the part of the ocean that was not necessary to include. The constant head cells along the right boundary represent the bottom of the ocean, and in two of the simulations the heads in these cells vary with time. These ocean cells also are constant concentration cells with a salinity value of 35 parts per thousand (ppt), the concentration of pure saltwater. General head boundary (GHB) cells are placed along the left boundary to represent connection to the Everglades. The head in the GHB cells is held constant at 2.12 m; the conductance is 8625 m^2/day; and the concentration is specified as zero. Recharge is added to the active model cells at 0.254 m/year with a concentration of zero.

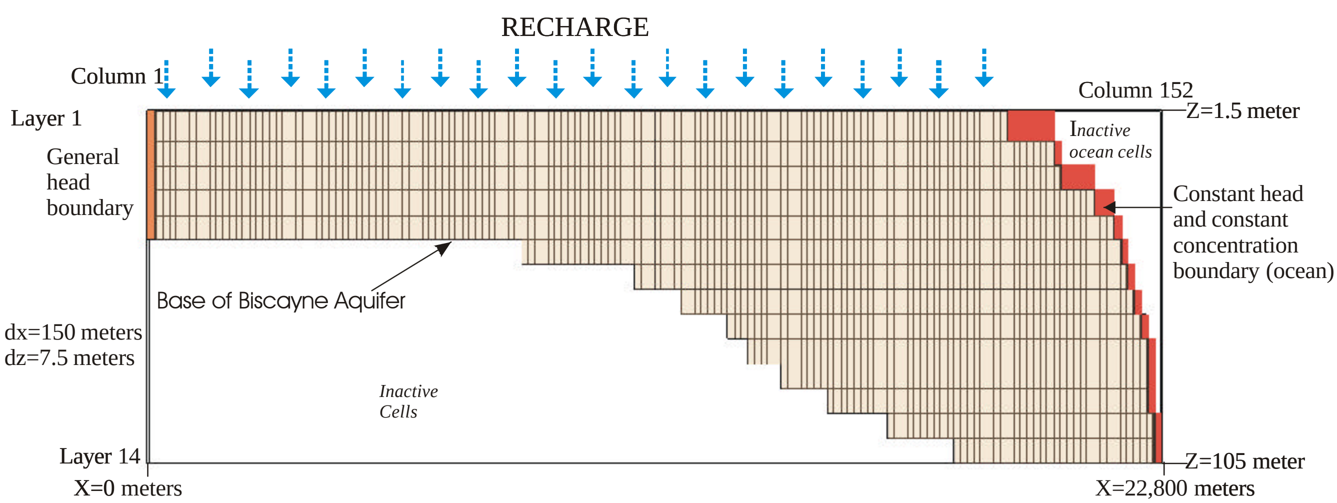

Figure 1. Boundary conditions and finite difference model grid

Table 1. Aquifer parameters and boundary stresses used in the variable-density cross-sectional models. [K_H, horizontal hydraulic conductivity; K_v, vertical hydraulic conductivity; α_L, longitudinal dispersivity; α_T, transverse dispersivity; R, recharge; S_y, Specific Yield; S, storage; n, porosity]

Parameter/Stress (units)	**Value**
K_H, in meters per day	1150
K_H, in meters per day	150
K_v, in meters per day	150
α_L, in meters	3.0
α_T, in meters	0.3
R, in centimeters per year	25.4
Ocean Stage (constant head value), in meters	
Base Case	0.308
Case 1, observed data	
mean	0.308
min	-0.18
max	0.78
Case 2, amplified SIN wave	
mean	0.308
min	-1.69
max	2.31
S_y (dimensionless)	0.1
S (dimensionless)	1×10^{-5}
n (dimensionless)	0.1

Three different model scenarios were performed. The Base Case, which has temporally averaged boundary conditions for the ocean, was run until concentrations reached steady state. Then, two transient simulations were performed, Cases 1 and 2, each with 2976 fifteen-minute stress periods, totaling one month. Case 1 has a temporally varying ocean boundary using observed data from a coastal monitoring station in Broward County. Case 2 is similar to Case 1 but the head value for the ocean boundary is varied using an amplified SIN wave (Figure 2). In each case the models were run numerous times with heads and concentrations from the previous run until concentrations reached "dynamic equilibrium".

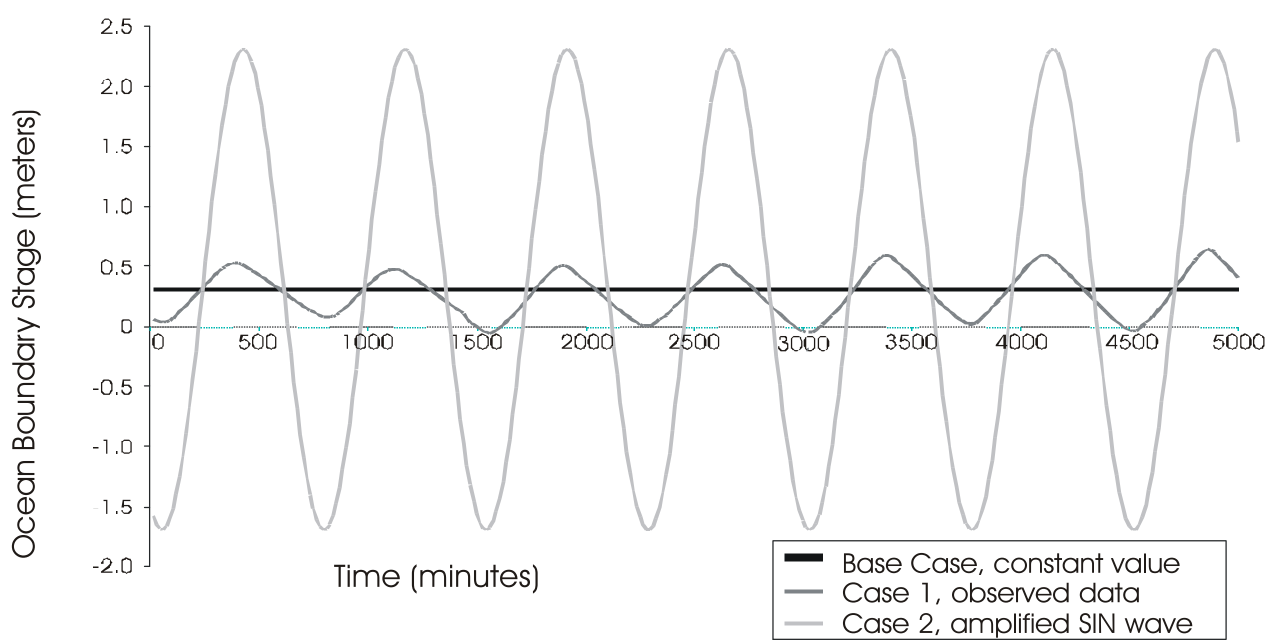

Figure 2. Graph showing the first 3.5 days of data used to represent the stage in the ocean cells

MODEL RESULTS

In general, the flow patterns for each of the three models are from left to right with water discharging into the constant head cells that represent the ocean. For the Base Case, contours of salinity illustrate the disperse interface between freshwater and saltwater (Figure 3). The highest concentration gradients within the interface are near the coast. The saltwater interface is approximately 4100-m thick. The toe of the saltwater interface, which is the inland extent of the interface at the base of the aquifer, is located 13,400 m from the left side of the model.

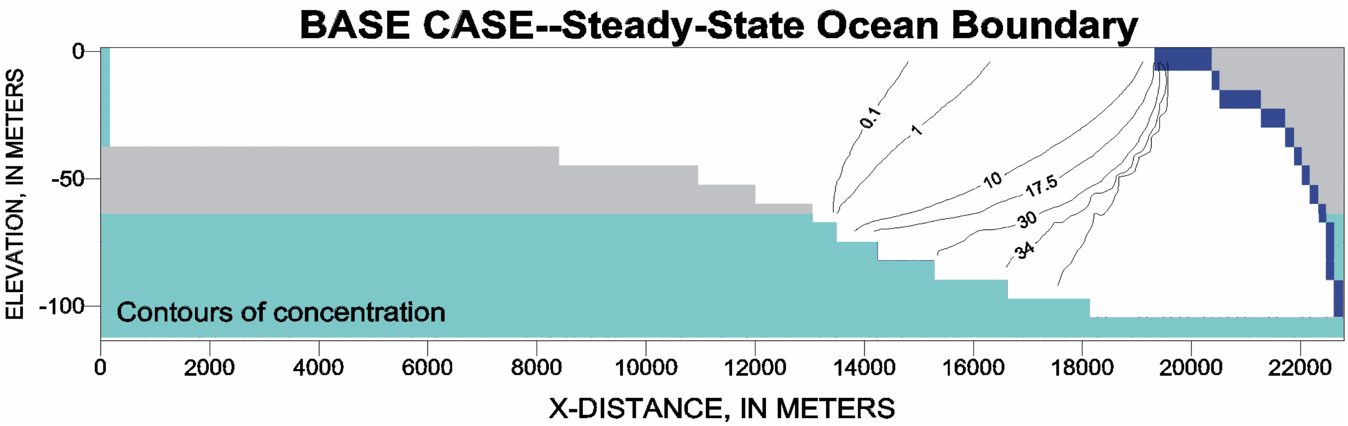

Figure 3. Results from the base case simulation showing salinity concentrations of the saltwater interface.

For Case 1, contours of salinity (Figure 4a) appear to match the contours of salinity for the Base Case (Figure 3). For Case 1, the toe of the interface also is at 13,400 m from the left, but the interface is 4800-m thick. A contour plot of the salinity differences between the Base Case and Case 1 (Figure 4b), however, reveals a zone within the interface where the two models do not match. This zone is mainly observed between concentrations of 17.5 and 30 ppt. Case 1 salinities are less than the Base Case salinities by up to 5 ppt because the temporally varying ocean boundary disperses the interface more than for the Base Case with a constant ocean boundary. Simulated salinities beneath the ocean seem to be slightly higher for Case 1 than for the Base Case.

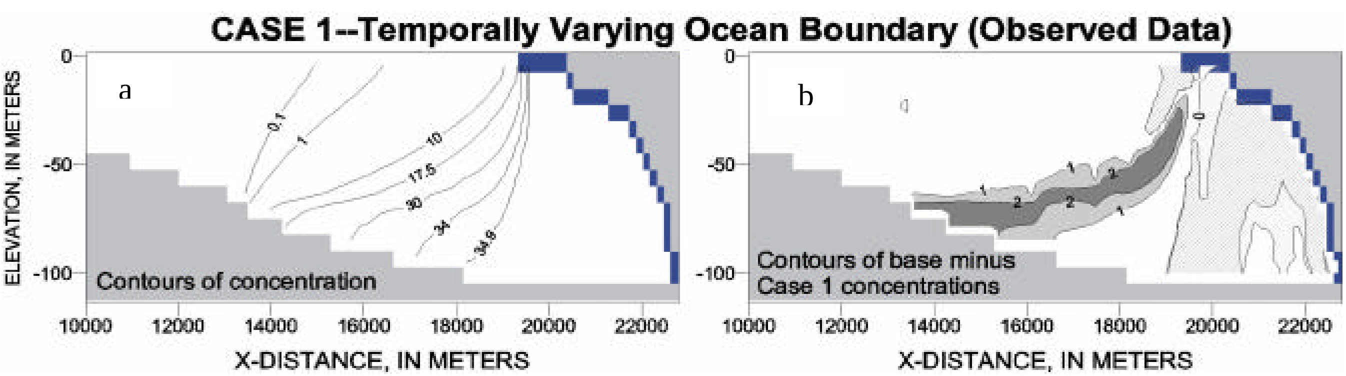

Figure 4. Results from Case 1 simulations: (a) contours of simulated salinity in parts per thousand; and (b) contours of salinity difference between Base Case and Case 1.

For Case 2, which has an increased tidal range, the interface is more dispersed (Figure 5a) than for the Base Case and Case 1. The toe of the interface for Case 2 is 14,000 m from the left and the width of the interface is 5400 m. When subtracting Case 2 salinities from the Base Case, the concentration difference is as much as 17 ppt. The difference in concentrations appears mainly between the contours of 17.5 and 30 ppt.

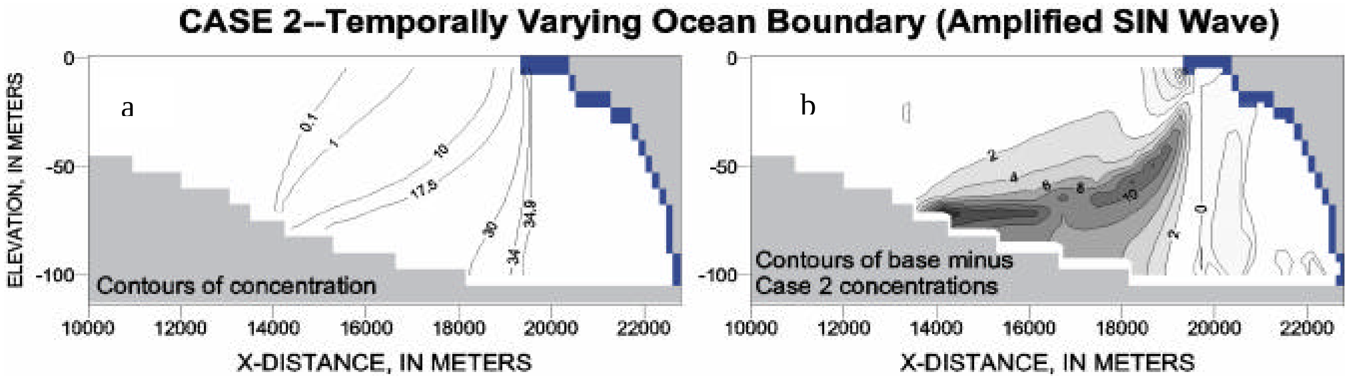

Figure 5. Results from Case 2 simulations: (a) contours of simulated salinity in parts per thousand; and (b) contours of salinity difference between Base Case and Case 2.

DISCUSSION AND CONCLUSIONS

A variable-density groundwater flow model that has an average stage value assigned to the ocean boundary will produce different results of simulated salinity within the interface than an identical model that includes tidal variation in ocean stage. This conclusion has important implications for model calibration and model application. During calibration of a variable-density flow model, one often adjusts the dispersivity values so that simulated values of concentration match observed concentration values. If calibration is performed with a model that does not contain tidal fluctuations (i.e. an average stage value is used for the ocean boundary), the calibrated dispersivity values actually represent apparent dispersivity values. If that model is then modified to include tidal fluctuations, the use of those same apparent dispersivity values could introduce a significant level of error both in terms of simulated concentrations and groundwater flow. The level of error would be a function of the tidal range and of the aquifer properties. For the example problem representative of southeastern Florida, simulated concentrations at a single cell can be different by up to 5 parts per thousand, depending on how the ocean boundary is represented. This difference in simulated concentrations may change for other model geometries, aquifer parameters, and tidal properties.

Although the results for this two-dimensional example problem did not show a significant change in the location of the toe, a three-dimensional scenario with tidal canals or streams could show a larger change in the toe location. The location of the toe could be affected by the tidal fluctuations and concentrations in the canal. This averaging of a tidal boundary has the potential to cause problems when predicting the interface location, saltwater intrusion rates, and supply-well contamination with a model that is calibrated at one temporal scale and then applied to another.

REFERENCES

Ackerer, P., and Kinzelbach, W., Modelization du Transport de Contaminant par la Method de Marche au Hasard: Influend des Variations du Champ D'Ecoulement au Cours de Temps sur la dispersion. The Stochastic Approach to Subsurface Flow, ed. by G. deMarsily, pp. 446-458., 1985.

Goode, D. J., and Konikow. L.F., 1990. Apparent Dispersion in Transient Groundwater Flow. Water Resources Research.

Guo, Weixing, and Langevin, C.D., 2002, User's guide to SEAWAT: A computer program for simulation of three-dimensional variable-density ground-water flow: U.S. Geological Survey Open-File Report 01-434, 79p.

Molz, F.J., Guven, O., Melville, J.G., and Keely, J.F., 1987. Performance and analysis of aquifer tracer tests with implications for contaminant transport modeling-a project summary. GROUNDWATER. Vol. 25, No.3, pp. 337-341.

Rehfeldt, K.R., 1998, Prediction of Macrodispersivity in Heterogeneous Aquifers: Massachusetts Instutute of Technology, Dissertation, 233 p.