Tidal Effects on Transient Dispersion of Simulated Contaminant Concentrations in Coastal Aquifers

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ABSTRACT
Variable-density flow and transport models require extensive computational resources often resulting in lengthy runtimes, particularly for simulations that represent saltwater intrusion and tidal fluctuations. The majority of saltwater intrusion models do not explicitly represent tidal variations; instead, an average tidal level is assigned to the ocean boundary. By neglecting tidal fluctuations, errors may be introduced if a contaminant included in the simulation reaches the seawater/freshwater interface, and then discharges into the ocean. This paper presents multiple variable-density flow and transport simulations of a coastal aquifer. Each model is conceptually similar; however, tides are either neglected or explicitly included in the ocean boundary. An analysis was performed to determine if the effects of tides could be approximated in simulations with a constant ocean boundary by using apparent dispersivities. The apparent dispersivity value was calculated for each model cell using the velocity variations from the tidal simulation. The transport and discharge patterns of a contaminant plume were used to examine the accuracy of this approach. Use of apparent dispersivity in models with a constant ocean boundary seems to provide a reasonable approach for approximating tidal effects in simulations where explicit representation of tidal fluctuations is not feasible.

INTRODUCTION
Simulating variable-density flow and contaminant transport in coastal aquifers is intrinsically complex and computationally expensive when the effect of tides is included. Tidal variations necessitate the use of a short time step, resulting in substantial computational effort (Volker et al. 1998). The purpose of this paper is to investigate the influence of transient dispersion on the concentration distribution in a variable-density flow and transport model. Simulations with steady-state conditions are compared with simulations of transient flow that include tidal fluctuations in the ocean boundary. The simulations are simple two-dimensional cross-sectional models that explicitly represent coastal groundwater flow within the freshwater and saltwater transition zone. The work in this paper follows previous work from La Licata et al. (2007).

SIMULATIONS AND RESULTS
To analyze the influence of tidal fluctuations on contaminant transport, simulations that neglected (*No Tide*) and included (*Tide*) a tidally fluctuating ocean boundary were compared. *Tide* represents a 2-year simulation period using 3-hour stress periods (8 stress periods per tidal cycle). Longitudinal and transverse dispersivities were constant over the entire section (longitudinal dispersivity [α_L] = 10 m, transverse dispersivity [α_T] = 0.1 m). A contamination source, releasing a hypothetical pollutant, was located 75 m from the western border of the model domain. The constant-concentration cell representing the contaminant source was assigned an arbitrary concentration value of 100 kg/m^3. The contaminant was simulated as being conservative. Contaminant concentrations were compared for *Tide* and *No Tide* simulations to analyze the influence of tidal variations on the contaminant and salinity distributions. Differences are evident in the contaminant and salinity concentrations between *No Tide* and *Tide* (Figure 1). The tidally driven hydraulic transients in *Tide* increase the overall mixing resulting in a relatively broader saltwater/freshwater transition zone. The increased mixing in *Tide* also

caused contaminant concentrations near the ocean to be lower than for the *No Tide* simulation (Figure 1). Differences in contaminant concentrations between the two simulations were as high as 15% within the freshwater/saltwater transition zone (Figure 2a).

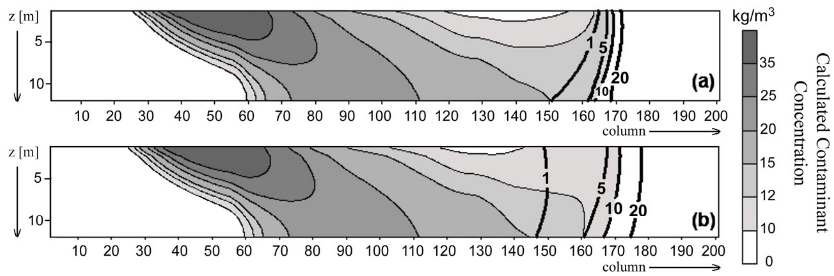

Figure 1. Overlap of calculated contaminant concentration on freshwater/saltwater interface in simulation: (a) without tides, *NO TIDE*, and (b) with tidal variations, *TIDE*. Dark black contours represent salinity isosurfaces in kg/m^3.

Simulations with spatially varying dispersivity values were performed with the *No Tide* model to determine if the mixing due to tidally driven hydraulic transients could be approximated with an increase in dispersivity. Additional details on this test are provided in La Licata et al. (2007). The dispersivity was increased in the area around the freshwater/saltwater transition zone where the hydraulic transients were greatest. With this change in the dispersivity value the difference in simulated contaminant concentration between cases with and without tides decreases to about 8% (Figure 2b). Results suggest that it may be possible to approximate tidal effects in a simulation without tides by spatially altering the dispersivity value. The error that occurs in the estimation of contaminant concentration near the ocean is a function of dispersivity corresponding to the location of the freshwater/saltwater transition zone.

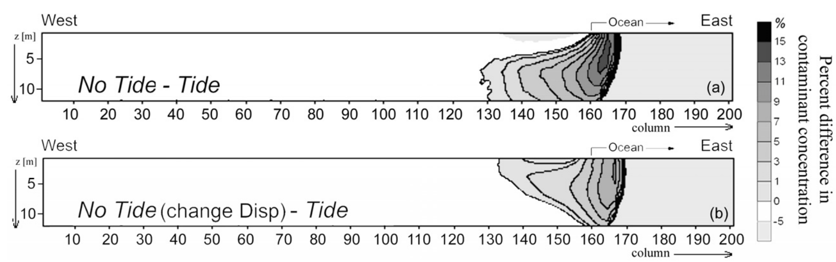

Figure 2. Percent difference in contaminant concentration (a) without and (b) with spatially varying dispersivity.

Goode and Konikow (1990) define apparent dispersivities as "those values that yield the best match or calibration of the solute transport model under steady state flow conditions to a plume that developed under transient flow conditions". The concept of transient dispersion is used here to test the hypothesis that the effects of tidal mixing can be included in a *No Tide* model by calculating and using apparent dispersivities. Apparent dispersivities for the longitudinal and transverse directions were calculated using the equations presented by Ackerer and Kinzelbach (1986). The distribution of apparent transverse dispersivity is shown in Figure 3; the distribution of apparent longitudinal dispersivity is not shown. The equations required the transient velocity variations at each model cell, which were taken from the *Tide* simulation. The following calculations were applied to each cell of the domain to calculate apparent longitudinal and transverse dispersivity values that characterize the velocity variation in that cell during one tidal cycle (8 stress periods). In the equations below, V is velocity, θ is the angle relative to the horizontal, and α is dispersivity. With the exception of the large apparent dispersivities near the upper right corner of the model (which are due to boundary effects), the largest apparent dispersivities are located within the interface between freshwater and saltwater (Figure 3). This is an area where the velocity variations are the largest.

$$V_i = \left(V_{xi}^2 + V_{zi}^2\right)^{1/2} \quad i = 1 \ldots 8 \quad \textit{Stress Period}$$

$$\overline{V} = \frac{\Sigma V_i}{8}$$

$$\theta_i = \begin{cases} arctg(V_z / V_x) & Vx > 0 \\ arctg(V_z / V_x) + 180^\circ & Vx < 0 \end{cases}$$

$$\overline{\theta} = \frac{\Sigma \theta_i}{8}$$

$$\overline{\theta}_V = \theta_i - \overline{\theta}$$

$$V_{Li} = V_i \cos(\theta_V)$$

$$\overline{V_L} = \frac{\Sigma V_{Li}}{8}$$

$$\overline{V}_L^2 = \frac{\Sigma V_{Li}^2}{8}$$

$$V_{Ti} = V_i \, sin|\theta_{Vi}|$$

$$\overline{V}_T^2 = \frac{\Sigma V_{Ti}^2}{8}$$

$$\alpha_{La} = \frac{\alpha_L}{\overline{V}} \frac{\overline{V}_L^2}{\overline{V_L}} + \frac{\alpha_T}{\overline{V}} \frac{\overline{V}_T^2}{\overline{V_L}}$$

$$\alpha_{Ta} = \frac{\alpha_T}{\overline{V}} \frac{\overline{V}_L^2}{\overline{V_L}} + \frac{\alpha_L}{\overline{V}} \frac{\overline{V}_T^2}{\overline{V_L}}$$

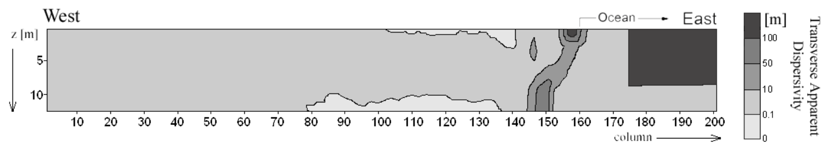

Figure 34. Calculated apparent dispersivity.

The contaminant concentration plume simulated under transient conditions is compared to the plume simulated with steady-state conditions using the apparent dispersivity distribution in Figure 3. The use of apparent dispersivities seems to provide a reasonable approximation of tidal effects. The maximum difference in simulated concentrations is still 15%, but for this simulation, the large differences are confined to areas where contaminant concentrations are relatively low (Figure 4).

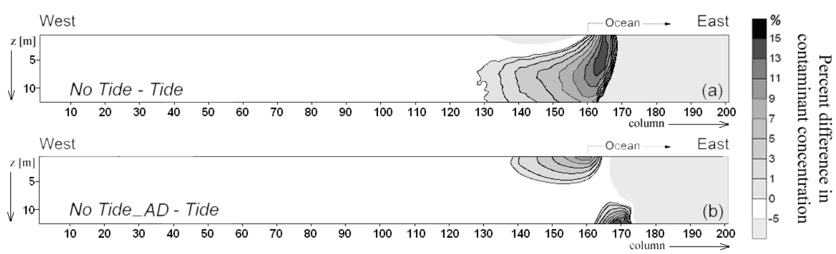

Figure 4. Percent difference in contaminant concentration with (a) constant dispersivity and (b) apparent dispersivity.

CONCLUSION

Simulations reveal that the mixing from tides results in a contaminant and salinity concentration distribution that is more mixed than the distribution for an equivalent steady-state model without tidal effects. These results could have critical implications for model calibration where erroneous adjustments to parameters may be required to match concentrations in a steady-state model because tides are not explicitly represented. Results also indicate that the mixing effects of tides can be represented in a steady-state model by arbitrarily increasing the dispersivity value in the area around the interface. A more rigorous approach based on the calculation and use of apparent dispersivity values provides a better method for including the effects of tidal mixing in a steady-state model. The apparent dispersivity distribution created and assigned to the steady-state model using the velocities from a transient model result in similar contaminant and salinity distributions between the two models. The calculated apparent dispersivity correction, therefore, appears to be a practical way to replace tidal effects when calibrating a model. Using the concept of apparent dispersivity could save time and money in model development and calibration because the steady-state model does not require multiple stress periods; therefore, the model simulations require less time to run.

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