Effect of tidal fluctuations on contaminant transfer to the ocean

IVANA LA LICATA[1], CHRISTIAN D. LANGEVIN[2] & ALYSSA M. DAUSMAN[2]

1 *Dipartimento di Ingegneria Idraulica Ambientale e del Rilevamento (D.I.I.A.R.), Politecnico di Milano, I-20133 Milan, Italy*
ivana.lalicata@polimi.it

2 *US Geological Survey, Florida Integrated Science Center, Fort Lauderdale, Florida 33315, USA*

Abstract Variable-density groundwater flow was simulated to examine the effects that tide has on the coastward migration of a contaminant through a freshwater/saltwater interface and toward a coastal ocean boundary. Simulated ocean tides did not significantly affect the total contaminant mass input to the ocean; however, the difference in tidal and non-tidal simulated concentrations could be as much as 15%. It may be possible to numerically approximate the tidal-driven hydraulic transients in transport models that do not explicitly include tides by locally increasing dispersivity.

Key words tidal variation; contaminant transport; density

INTRODUCTION

Simulation of contaminant transport in coastal aquifers is intrinsically complex and computationally expensive because of the complex flow patterns that develop when freshwater mixes with saline groundwater. Because of its density, seawater intrudes landward below freshwater and a diffuse transition zone occurs between these two different fluids (Henry, 1959). The extent of saltwater intrusion is affected by a large number of physical and hydraulic parameters, such as recharge and aquifer dispersivity. The location and shape of the transition zone influences groundwater flow direction and its velocity. Furthermore, contaminant migration in groundwater is also affected by the characteristics of the transition zone between freshwater and saltwater. An additional complication in simulating contaminant transport in coastal aquifers is the confounding effect of tides which necessitates the use of a short time step, resulting in substantial computational effort (Volker *et al.*, 1998). Several studies have been completed on these topics: Schincariol & Schwartz (1990) and Oostrom *et al.* (1992a,b) studied the behaviour of dense plumes in a horizontal and uniform flow field in porous media; Knoch & Zhang (1992) considered also the effects of contaminant density on its movement in a steady horizontal flow field. Li *et al.* (1999) showed, by a theoretical model, an important contribution of local tide variations on groundwater discharge into the ocean. In order to investigate the consequence of simplifying the seaward boundary condition by neglecting the seawater density and tidal variations in numerical prediction of contaminant transport, Zhang *et al.* (2001) presented a comparison of numerical prediction with experimental results. The comparison indicates that neglecting seawater intrusion and tidal variations does not markedly affect the migration rate of the plume before it reaches the saltwater interface.

Shoemaker (2004) demonstrated that the dispersivity parameter is necessary to reproduce an exact distribution of hydraulic head, salinity and flow in the transition zone between freshwater and saltwater in a coastal aquifer system. Recently, Robinson *et al.* (2006) showed that tidal variations significantly affect the transport pathway of contaminants discharging to coastal waters in a study that examined mixing mechanisms in the subterranean estuary driven by tidal forcing.

The purpose of this paper is to investigate the influence of tidal variation on solute transport where contaminants reach the freshwater–saltwater transition zone and discharge into the ocean. This is accomplished using simulations based on a simple two-dimensional cross-sectional model that explicitly represents coastal groundwater flow within the freshwater and saltwater transition zone. Simulations that neglected (*No Tide*) and included (*Tide*) a tidally fluctuating ocean boundary were compared with the aim to analyse the influence of tidal variation on contaminant behaviour and mass flux toward the sea. Similar simulations were conducted using three different dispersivity values. These simulations also considered the effects of a pumping well on capturing a contaminant moving toward the sea. Simulations with spatially varying dispersivity values were also run to determine if the mechanical dispersion attributed to hydraulic transients could be approximated in a steady-flow model with increases in dispersivity.

Coastal groundwater flow problems require careful representation of fluid density and its effect on groundwater flow. For this reason, the SEAWAT computer program (Langevin *et al.*, 2003; Langevin & Guo, 2006) was used for the analyses. SEAWAT is a combination of MODFLOW (McDonald & Harbaugh, 1996) and MT3DMS (Zheng, 1990), designed to simulate variable-density groundwater flow coupled with solute transport. SEAWAT has been tested with many of the commonly used benchmark problems (Guo & Langevin, 2002; Langevin *et al.*, 2003; Bakker *et al.*, 2004; Langevin & Guo, 2006). The program has been applied to issues related to submarine groundwater discharge (Langevin, 2001, 2003), saltwater intrusion (Shoemaker & Edwards, 2003; Rao *et al.*, 2004; Shoemaker, 2004; Masterson, 2004; Dausman & Langevin, 2005), coastal wetland hydrology (Langevin *et al.*, 2004, 2005), and island hydrology (Schneider & Kruse, 2003).

PROBLEM DESCRIPTION

Groundwater flow and transport simulations were run using a two-dimensional cross-section model (Fig. 1) in which active cells were assigned properties similar to those of a coastal aquifer located near a coastal refinery in eastern Italy. The parameters assigned to the model are shown in Table 1 and are based on general knowledge, field data and results from prior studies (Alberti *et al.*, 2006).

A constant head equal to 1.25 m was assigned on the western boundary. Constant heads and salinities were assigned to the eastern sea boundary. In the simulation without tides (*No Tide*) the constant-head boundary representing the sea was set to mean sea level (0 m) and salinity to 35 kg/m^3. For *Tide*, the sea boundary was assigned temporally fluctuating heads to represent tides (Fig. 2). A diurnal tidal cycle is simulated in accordance with the relation $h_T = A\sin(\varpi t)$, where h_T is the time-varying

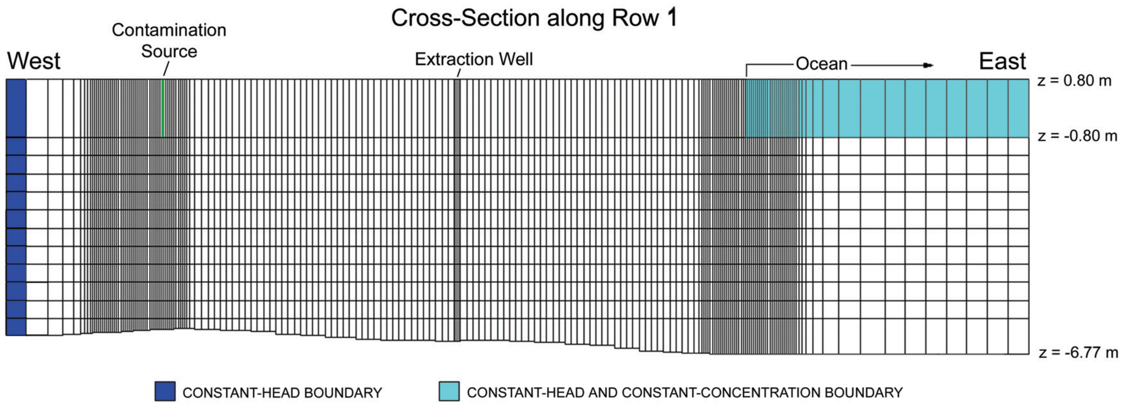

Fig. 1 Cross-section showing model grid and boundary conditions.

Table 1 Parameters assigned to the model.

Height (m)	7.5	Number of layers	12
Length (m)	500	Hydraulic conductivity (m/s)	5×10^{-3}; 1×10^{-5}
Number of rows	1	Recharge (m/d)	4.8×10^{-3}
Number of columns	201	Porosity	0.25

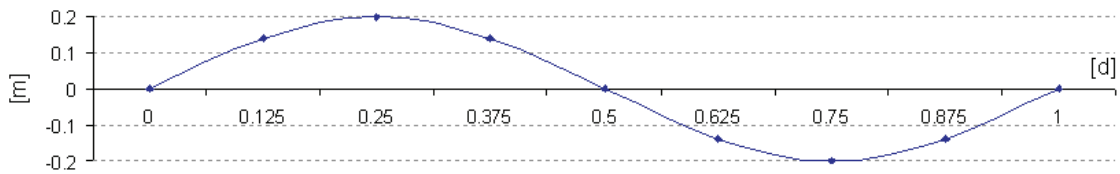

Fig. 2 Head variations in one tidal cycle.

head (relative to the level 0 m), A is the tidal amplitude, and ϖ the tidal frequency (6.283 d^{-1}; period = 1 day). The resulting tidal signal roughly approximates the tidal signal observed in the northern Adriatic Sea. *Tide* represents a 2-year period using 3-hour stress periods (a total of 5760 stress periods).

Simulations were performed using a variety of dispersivity values. For several simulations, a heterogeneous dispersivity distribution was used. For all representations, the ratio of longitudinal to transverse to vertical transverse dispersivity was held constant at 1:0.1:0.01 (Table 2). A contamination source, releasing a pollutant similar to MTBE, was located at a distance of 75 m from the western border of the model domain. The constant-concentration cell representing the source was assigned an arbitrary concentration value of 100 kg/m^3. The contaminant is simulated as being conservative.

Table 2 Dispersivity values used.

	α_L	α_T	α_V
Case1	16 m	1.6 m	0.16 m
Case2	10 m	1.0 m	0.10 m
Case3	5 m	0.5 m	0.05 m

α_L: longitudinal dispersivity; α_T: transverse dispersivity, α_V: vertical dispersivity.

RESULTS AND DISCUSSION

At the end of the 2-year simulation, the contaminant is at steady state, and the leading edge of the plume has reached the ocean (Fig. 3). As expected, the plume moves toward the freshwater–seawater interface and rises to a shallower part of the section as it reaches the denser water of the transition zone. The contaminant discharges into the ocean through a narrow outflow face near the shoreline.

Cumulative contaminant transfers were compared for simulations that neglected and included a tidally fluctuating ocean boundary to analyse the influence of tidal variation on contaminant transfer from the aquifer to the ocean. These comparisons were performed for three separate cases (Case 1, Case 2, and Case 3) characterized by three different, but homogenous, dispersivity values. Moreover, the concentration distribution was analysed for Case 2 and the differences in calculated concentration for simulations with and without tide were compared. Then, simulations with spatially varying dispersivity values were performed (case2a, case2b, case2c) to determine if the mechanical dispersion attributed to tidally driven hydraulic transients could be approximated in the model without tides by adjusting the dispersivity value near the transition zone (i.e. where the hydraulic transients are the largest).

Analysis 1 – Estimation of tidal effects on contaminant transfer into the ocean

In the first analysis, the results from the three simulations were compared to examine the effect of dispersivity on the contaminant flux to the ocean. A plot of the cumulative mass transfer from the aquifer to the ocean is shown in Fig. 4. This figure shows that tidal variations do not affect the cumulative transfer of the contaminant into the ocean. There essentially is no difference between simulations with and without tidal variations at the end of the 2-year simulation period. Close inspection of Fig. 4 reveals minor differences in the contaminant transfer between the tide and no-tide simulations from about 250 to 550 days. This slight difference is due to slightly higher concentrations reaching the ocean (for the simulation without tides) compared to the tidal simulation where tidally-driven mixing disperses the contaminant as it reaches the ocean. After this analysis, the effects of an extraction well were included in the simulations. The extraction well (representing a line sink in three dimensions), pumping at a rate of 1.44 m^3/d (approximately 60% of recharge), was assigned to column 100. Results from these simulations also show that the difference in contaminant transfer to the ocean is unimportant with and without tides.

The modelling results also demonstrate that the aquifer dispersivity affects the rate and cumulative contaminant transfer to the ocean. More dispersive mixing will result in a higher contaminant flux and higher cumulative contaminant transfer to the ocean. This difference is due to the constant-concentration boundary type used to represent the contaminant source. In fact, because of the constant-concentration boundary, the dispersive flux from the boundary into the aquifer is larger for higher dispersivity values than for lower values. Application of another type of concentration boundary (e.g. constant flux) would probably result in the same cumulative contaminant transfer regardless of dispersivity value.

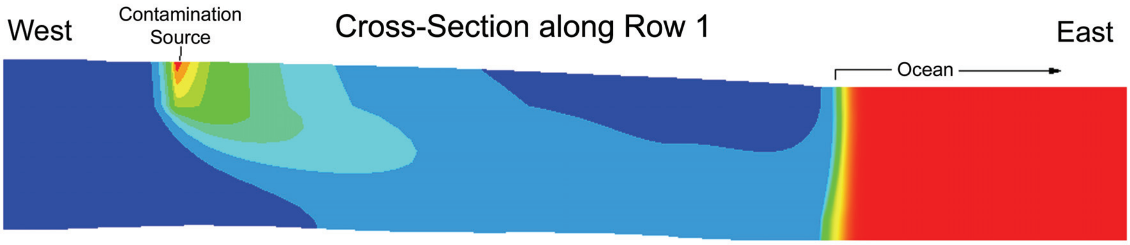

Fig. 3 Simulation of contaminant path toward the ocean.

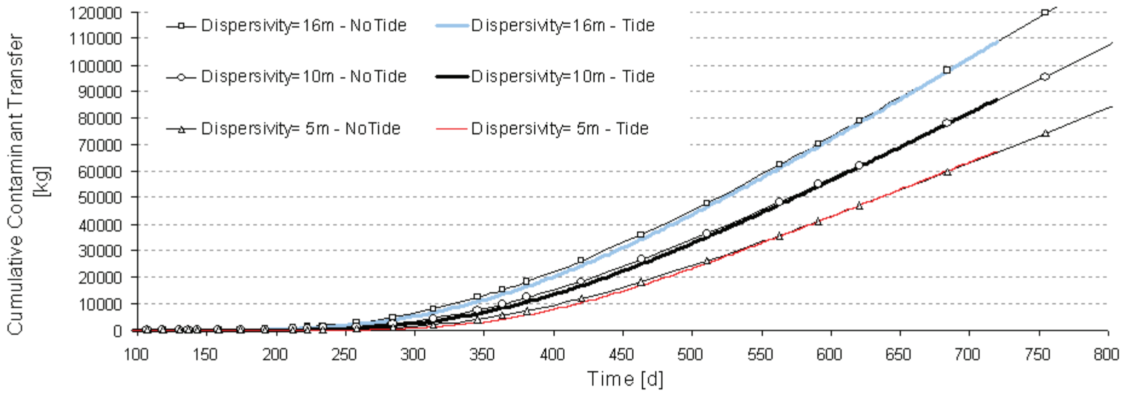

Fig. 4 Cumulative contaminant transfer from the aquifer to the ocean for the 2-year simulation period, without extraction well.

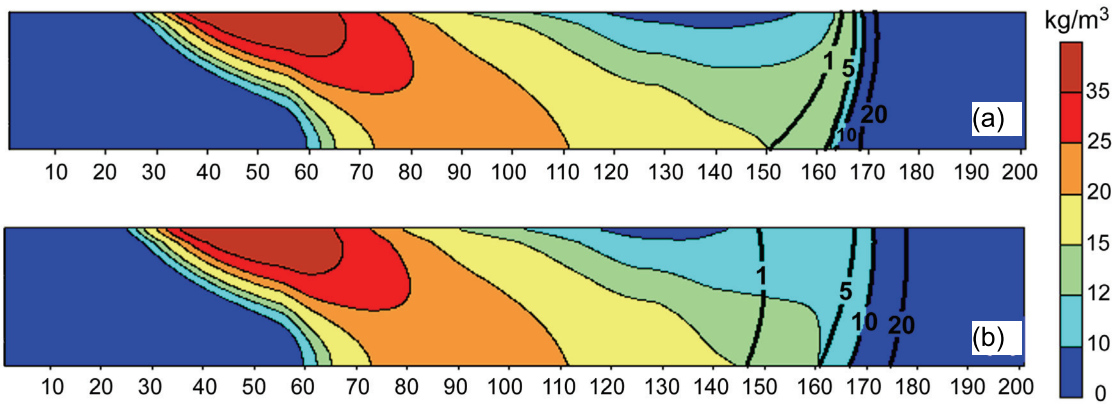

Fig. 5 Overlap of calculated contaminant concentration on freshwater–saltwater interface in simulation without (a) and with (b) tidal variations. Dark black contours represent salinity isosurfaces in kg/m^3.

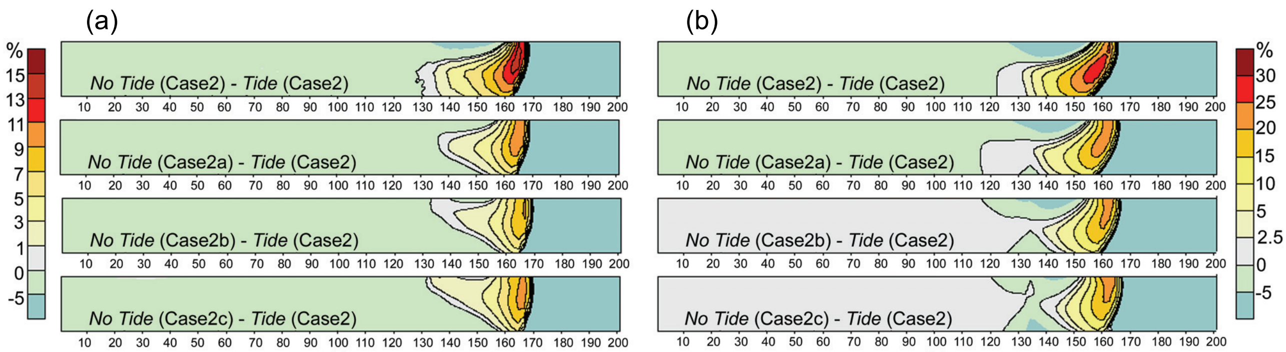

Fig. 6 Percentage difference in contaminant concentration without (a) and with (b) the extraction well.

Analysis 2 – Estimation of apparent dispersivity

Although tides do not appear to have a substantial affect on the contaminant transfer into the ocean, results show substantial differences in contaminant and salinity concentrations between *No Tide* and *Tide*. These concentration differences are due to the tidally-driven hydraulic transients in *Tide* that increase mixing. Simulations with tidal effects show a larger transition zone than simulations where the tide is not represented (Fig. 5). Contaminant concentrations near the ocean are generally higher for *No Tide* than for *Tide* (Fig. 5). This difference is due to the fact that the contaminant flux is the same (the contaminant flux from the constant-concentration boundary is identical between the two models); however, the mixing patterns are different. This induces a difference in the concentration distribution. In the following analysis, the results from three simulations were compared to examine the effect of dispersivity on the distribution of contamination concentrations.

Goode & 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 model with a constant ocean stage boundary by increasing the aquifer dispersivity value. In this analysis the dispersivity values for a model without tides are adjusted to try and match the concentrations from the Case 2 simulation with tides. For the model without tides, the dispersivity (apparent) was increased only near the freshwater–seawater interface (from column 135 to column 190). Increasing dispersivity over the whole section creates large differences in calculated concentrations far from the zone influenced by the tide, and causes a larger contaminant flux into the aquifer from the constant-concentration boundary.

Three simulations with spatially varying dispersivity values were run to determine if the mechanical dispersion attributed to hydraulic transients could be approximated in a steady-flow model with increases to dispersivity. In these simulations, a larger dispersivity value was used in the tidal zone. These cases are referred to as cases 2a, 2b, and 2c. The dispersivity values used in the tidal zone are listed in Table 3.

Table 3 Used dispersivity values across the interface in steady-state simulations and percentage difference in contaminant concentration without pumping well.

	α_L	α_T	α_V	%
Case 2	10 m	1.0 m	0.10 m	15
Case 2a	16 m	1.6 m	0.16 m	10
Case 2b	20 m	2.0 m	0.20 m	8
Case 2c	26 m	2.6 m	0.26 m	10

α_L: longitudinal dispersivity; α_T: transverse dispersivity, α_V: vertical dispersivity.

Figure 6 shows the contaminant concentration difference (as a percentage) between Case 2 (with tides) and cases 2a, 2b, and 2c (tides represented by an increase in dispersivity). For Case 2 (without the extraction well) the maximum difference is between 13% and 15% and decreases when the longitudinal dispersivity in the coastal zone increases to 20 m. In this case (Case 2b), the largest difference is at its minimum (equal to 8%). By doubling the dispersivity value, the maximum concentration difference is halved. When the dispersivity is larger than 20 m, the maximum difference increases. This occurs with and without the extraction well so it is not necessary to calibrate the dispersivity value and the extension of the area again when adding the well. These results indicate that, in order to achieve the calibration, it may be possible to approximate tidal effects in a model with a constant ocean boundary by optimizing the dispersivity value near the boundary.

CONCLUSION

Contaminant transport models require extensive computational resources that can result in lengthy runtimes, especially for those simulations that deal with seawater intrusion and tidal fluctuations. Several simulations were performed to investigate the influence of tidal variation on contaminant transport patterns for the situation in which a contaminant migrates through a coastal aquifer through the transition zone and into the ocean. This paper presents a comparison of numerical results between contaminant transport simulations with and without tidal effects. The comparison of simulations indicates that tidal variations do not affect the cumulative flux of a conservative contaminant from the aquifer to the ocean. In general, the cumulative mass transfer to the ocean does not differ between simulations. Model results also show that the aquifer dispersivity affects the rate and cumulative contaminant transfer to the ocean. This difference is due to the boundary type used to represent the contaminant source.

Simulations also show that a difference in the contaminant and salinity concentration distributions occurs when tides are represented. This is because of the larger transition zone that develops when tidal effects are included in the simulation. Thus, even if the contaminant transfer to the ocean is not affected by the ocean boundary conditions, the concentration distribution is different when tide is accounted for because of the different mixing zone. This conclusion has potentially severe implications for model calibration where erroneous adjustments may be required to match concentrations for models that do not explicitly represent tides. Results indicate that the dispersive mixing effects of tides can be represented in a model that does not explicitly represent tides by increasing the dispersivity value near the ocean. Thus, when tidal effects are neglected, the error that occurs in the estimation of concentration near the ocean is a function of the apparent dispersivity in correspondence to the transition zone. Therefore, it may be possible to replace tidal effects with a change in the dispersivity value in this zone when calibrating a model.

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