

Contaminant Transport in Aquifers Influenced by Tide

B Ataie-Ashtiani, BE, MEngSc, PhD
Department of Civil Engineering,
Sharif University of Technology, Tehran, Iran

RE Volker, BE, MEngSc, PhD, FIEAust, CPEng
Department of Civil Engineering
University of Queensland

DA Lockington, BSc, PhD
Department of Civil Engineering,
University of Queensland

SUMMARY: For an unconfined coastal aquifer, an improved understanding of the effects of tidal fluctuations on contaminant movement allows better strategies to be implemented to control or mitigate the effects of contaminants on coastal wetlands, coastal aquifers, and the adjacent marine environment. These effects are investigated using a two-dimensional groundwater flow and contaminant transport numerical model. Density differences have not been included because of the marked increase in complexity and computational cost entailed. The results are useful nevertheless, since they are relevant to saline groundwater carrying contaminants to the sea. In addition, when freshwater discharge is large the seawater wedge formed due to the higher seawater density will be short and the velocity patterns, and hence the contaminant discharge at the shore, will still be dominated by outflow at the top of the aquifer as in the present analyses.

It is shown that tidal fluctuations have a significant effect on the spatial distribution of contaminant in the aquifer near the shore line. The concentration profile along the sloping face between sea and aquifer is influenced significantly by tidal fluctuations. A practical implication of this phenomenon, in the context of environmental management, is a better understanding of the effects of land based pollutants on the near shore marine biology.

1 INTRODUCTION

A substantial amount of work can be found in the literature regarding groundwater flow dynamics in response to tides. However, no studies were located, except Yim and Mohsen,¹ that investigate the effects of tidal fluctuations on the temporal and spatial distributions of contaminant plumes in aquifers.

Yim and Mohsen¹ use the simple one-dimensional heat-conduction equation² to predict the response of groundwater levels to a sinusoidal variation in water level in an estuary. They then apply a numerical solution of a one-dimensional, advection-dispersion

equation for contaminant transport in the flow domain. They conclude that tidal fluctuations cause the concentration level close to the periodic boundary condition to be significantly diluted by the water infiltrating inland during the high tide cycles. Also, they suggest that tides affect the migration process only over a short distance from the tidal boundary condition.

As was shown by Ataie-Ashtiani et al.³ the response of the groundwater flow to the tidal fluctuations in unconfined coastal aquifers cannot be fully described by the simple one-dimensional heat-conduction equation. Yim and Mohsen¹ were forced to make a number of other simplifications. They did not include the unsaturated zone, they assumed that an unconfined aquifer responded like a confined one, and they simply superimposed the regional hydrau-

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lic gradient on that due to tidal oscillation. These limitations have all been overcome in the present study. Moreover, in many cases the two-dimensional distribution of a contaminant plume is very important for example when the profile of discharged contaminant to the sea at the exit face is of interest for the ecological management of the adjacent marine environment. Therefore, a more detailed investigation of the effects of tidal fluctuation on contaminant transport in coastal aquifers is necessary.

The objectives of this work are to investigate the effects of tidal fluctuation on migration of contaminant in a coastal aquifer using a two-dimensional groundwater flow and contaminant transport numerical model which is able to handle the complexities of the problem. An improved understanding of the interactions between the tidal fluctuations and a contaminant plume allows for better strategies to be implemented to control or mitigate the effects of contaminants on coastal wetlands, coastal aquifers, and the adjacent marine environment.

2 SIMULATION MODEL

The variably saturated flow problem is solved using a modified version of the SUTRA model.⁴ The model which is based on a hybrid finite element and finite difference (HFEFD) scheme, has the following advantages:

1. Celia et al.⁵ observed that lumping the mass storage matrix prevents oscillations in the finite-element solution of the variably saturated flow problem. Spatial approximation of the variably saturated flow equation using the HFEFD method is naturally mass lumped, in contrast to common formulations of the finite-element method.
2. The HFEFD method has all the advantages of finite element methods in accommodating irregular geometries and complex boundary conditions.

The governing equation describing the SUTRA fluid mass balance, was written in pressure-based form as:⁴

$$\frac{\partial}{\partial x_i} \left[\frac{k_{ij} k_r \rho}{\mu} \left(\frac{\partial p}{\partial x_j} - \rho g e_j \right) \right] = (S_w \rho S_{op} + \varepsilon \rho) \frac{dS_w}{dp} \frac{\partial p}{\partial t} + \varepsilon S_w \frac{\partial \rho}{\partial c} \frac{\partial c}{\partial t} - Q_p \quad (1)$$

where p is pressure; c is solute concentration of fluid as a mass fraction; k_{ij} is the permeability tensor; k_r is the relative permeability with respect to the water phase; x_i ($i=1,2$) are Cartesian coordinates; t is time; e_j is the unit gravitational vector in the direction of x_2 (where x_2 is vertically upward); Q_p is fluid mass source; S_w is degree of saturation; S_{op} is the specific pressure storativity; ρ is fluid density; μ is fluid vis-

cosity; ε is porosity; and g is gravitational acceleration.

Since conventional pressure-based formulations of the variably saturated flow equation exhibit poor mass-balance behaviour,⁵ in this work SUTRA has been modified to solve the mixed form of the flow equation

$$\frac{\partial}{\partial x_i} \left[\frac{k_{ij} k_r \rho}{\mu} \left(\frac{\partial p}{\partial x_j} - \rho g e_j \right) \right] = S_w \rho S_{op} \frac{\partial p}{\partial t} + \varepsilon \rho \frac{dS_w}{dt} + \varepsilon S_w \frac{\partial \rho}{\partial c} \frac{\partial c}{\partial t} - Q_p \quad (2)$$

The modified Picard iterative procedure for the mixed form of the variably saturated flow equation is fully mass conserving in the unsaturated zone.

The van Genuchten⁶ soil water equations are used for unsaturated soil hydraulic properties

$$S_w = \left[\frac{1}{1 + [\alpha |h|]^n} \right]^m \quad (3a)$$

$$k_r(S_w) = S_w^{(1/2)} \left[1 - (1 - S_w^{1/m})^m \right]^2 \quad (3b)$$

in which h is pressure head and α , n , and m are fitting parameters, with m related to n by $m=1-1/n$.

Degree of saturation is defined as $\frac{\theta - \theta_r}{\theta_s - \theta_r}$

where θ is water content and θ_r and θ_s are residual and saturated water contents.

The general expressions for flow boundary conditions are given by

$$p(x_i, t) = p_{BC} \quad \text{on } B_1 \quad (4a)$$

$$Q_p = Q_{BC} \quad \text{on } B_2 \quad (4b)$$

where B_1 and B_2 designate the relevant portions of the flow boundary where p and Q_{BC} respectively are prescribed.

In the present work, the model has also been modified to handle a seepage face boundary condition. A seepage face is an external boundary of the saturated zone where flux is directed outward and pressure is atmospheric. Negative pressures exist above the seepage-face. Therefore, all the nodes along the seepage-face are treated as Dirichlet nodes with the prescribed pressure, $p=0$. Nodes above the seepage face are specified as no-flow nodes. The position of the seepage-face is initially unknown and must be determined using an iterative process. Cooley⁷ modified Neuman's⁸ iterative procedure to determine the seepage-face length. The same procedure is used in this work.

Moreover, to improve the ability of the model to handle the non linearity of the unsaturated zone equation, an automatic under-relaxation method has been applied for adjustment of pressure after each iteration.⁷

Solute transport is simulated through numerical solution of a solute mass balance equation including advective and dispersive spreading mechanisms. This is described mathematically by:

$$\varepsilon \rho \frac{\partial c}{\partial t} + \varepsilon \rho v_i \frac{\partial c}{\partial x_i} - \frac{\partial}{\partial x_j} [\varepsilon \rho (D_m \delta_{ij} + D_{ij}) \cdot \frac{\partial c}{\partial x_i}] = Q_p (c^* - c) \quad (5)$$

where v_i is fluid velocity, D_{ij} is the mechanical dispersion tensor, D_m is the molecular diffusion coefficient of the solute in pure fluid including aquifer material tortuosity effects, c^* is concentration of solute as a mass fraction in the source fluid, and δ_{ij} is equal to 1 if $i=j$, otherwise it is zero.

Darcy's law gives the mass average fluid velocity at any point in a cross section as

$$v_i = \frac{k_{ij} k_r}{\varepsilon \mu} \left(\frac{\partial p}{\partial x_j} - \rho g e_j \right) \quad (6)$$

The dispersion tensor, \underline{D} , is expressed for a two dimensional system as:

$$\underline{D} = \begin{bmatrix} D_{11} & D_{12} \\ D_{21} & D_{22} \end{bmatrix} \quad (7)$$

where \underline{D} is symmetric and the diagonal elements are:

$$D_{11} = \left(\frac{1}{v^2} \right) (d_L v_1^2 + d_T v_2^2) \quad (8)$$

$$D_{22} = \left(\frac{1}{v^2} \right) (d_T v_1^2 + d_L v_2^2) \quad (9)$$

and the off-diagonal elements are:

$$D_{12} = D_{21} = \left(\frac{1}{v^2} \right) (d_L - d_T) (v_1 v_2) \quad (10)$$

The terms d_L and d_T are called the longitudinal and transverse dispersion coefficients, respectively.

The size of the dispersion coefficients in an isotropic flow system depend upon the absolute magnitude of the average velocity in a flowing system:⁹

$$d_L = \alpha_L v \quad (11a)$$

$$d_T = \alpha_T v \quad (11b)$$

where α_L and α_T are the longitudinal and transverse dispersivities, respectively.

For the transport equation, the boundary conditions take the form

$$c(x_i, t) = c_{BC} \quad \text{on } B'_1 \quad (12a)$$

$$\frac{\partial c}{\partial l} = 0 \quad (12b)$$

$$Q_P (c^* - c) = Q_{BC} (c^*_{BC} - c) \quad \text{on } B'_3 \quad (12c)$$

where B'_1 is the portion of the boundary where concentration is prescribed, B'_2 is that where the convective flux in the direction normal to the boundary is the same on both sides of the boundary, l is the outward normal at the boundary, and B'_3 is the portion of the boundary where a known flux at a known concentration enters the system. The details of the modifications and validation of the new model are presented in Ataie-Ashtiani et al.¹⁰

3 PROBLEM DESCRIPTION

A schematic representation of the basic problem is presented in figure 1. The coastal aquifer, $L=155$ m long and $H=8.5$ m deep with a 1:10 beach slope, has no-flow boundaries on the base and on the top of the flow domain. The aquifer medium is assumed to be homogeneous and anisotropic. Values of the parameters used are: horizontal and vertical saturated hydraulic conductivity, $K_h=25$ m.day⁻¹, and $K_v=8.4$ m.day⁻¹ respectively; porosity, $\varepsilon=0.3$; residual water content, $\theta_r=0.01$, and specific storage, $S_s=10^{-6}$ m⁻¹. The values of the Van Genuchten⁶ parameters for the soil are: $\alpha=3.3$ m⁻¹, $n=4.1$, which represent a fine sand of reasonably regular grain-size distribution.

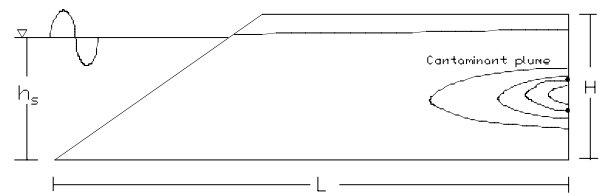


Figure 1: Schematic of the flow domain used in the simulations

A constant flux per unit width of 1.86 m²day⁻¹, equivalent to about 0.01 regional hydraulic gradient, is imposed at the landward boundary. The seaward boundary is described by a mean sea water level of 7m, on which is superimposed a sinusoidal semidiurnal tide with 0.5 m amplitude and 12 hr period.

It should be noted that the surface water body influenced by the tide is assumed to be 'fresh' in this study with the same density and concentration as the uncontaminated groundwater. To include a density different from that of groundwater introduces density coupling of the flow and transport equations with major computational cost consequences. It also would require programming to cater for multi-species transport if the contaminant is not the same as seawater since the model is currently single species. Consideration of a single density system is a valuable exercise, however, since many coastal zones have saline groundwater flows with density close to that of seawater and hence can be treated effectively as having uniform density. Moreover, it will be seen that the seaward discharge of groundwater is concentrated around the top of the saturated part of the sloping outflow face even for no density difference. While the detailed flow pattern will change with different density fluids, this focus of outflow toward the seepage face will be enhanced, not counteracted, by the presence of a higher density seawater wedge at the base of the aquifer. This seawater wedge will be shorter for larger groundwater discharges and hence the effect of density differences on the flow pattern and, therefore, on the contaminant plume will be restricted to a smaller zone than for lower groundwater discharges. The study of contaminant transport patterns in the single density system is useful, therefore, from a number of perspectives.

Two sources of contamination, one at elevation 3m and one at 4m from the base of the aquifer and each with unit concentration are assumed at the landward boundary. In this problem the longitudinal and transverse dispersivities are assumed to be 2m and 0.1m respectively.

Two variations of this problem, with and without tidal fluctuations, are simulated. The steady-state non-tidal flow condition is calculated and is then applied as the initial flow condition for the contaminant transport simulation in the aquifer, neglecting tidal fluctuation. For the case including tidal fluctuation, first the periodic steady-state flow condition is calculated and is then used as the initial condition for the contaminant transport simulation. The aquifer is initially assumed to be free of contamination.

The finite element mesh that is applied for simulation is illustrated in figure 2. The element dimensions vary from 0.25m in the unsaturated part to 1m in saturated parts of the aquifer. A smaller element size is used near the seaward and landward boundaries to model, respectively, the seepage face and water level more accurately. The numbers of nodes and elements are 1665 and 1471 respectively. The time step, Δt is 0.5 hr in the simulations which represent a 6 month period.



Figure 2: Finite element mesh for numerical simulation

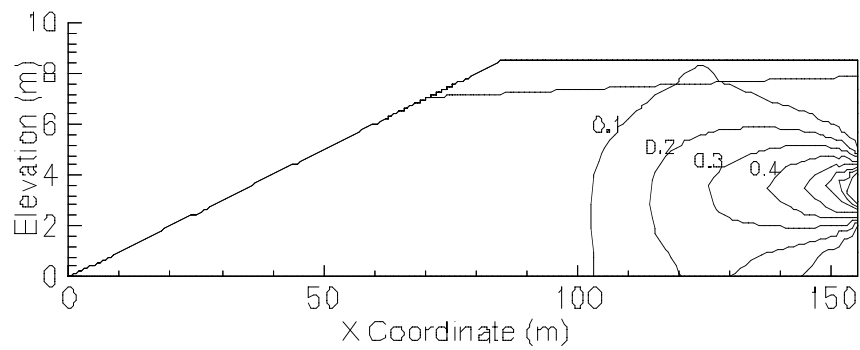
4 RESULTS

Figures 3 and 4 present the variation of the plume concentrations simulated without and with tidal fluctuations respectively at times equal to 2, 4, and 6 months. The spatial distribution of concentration at the upstream is almost the same for both cases. However, near the shore line and especially around the exit point the contaminant concentration in the case with tidal fluctuations is different from that for the no tide case.

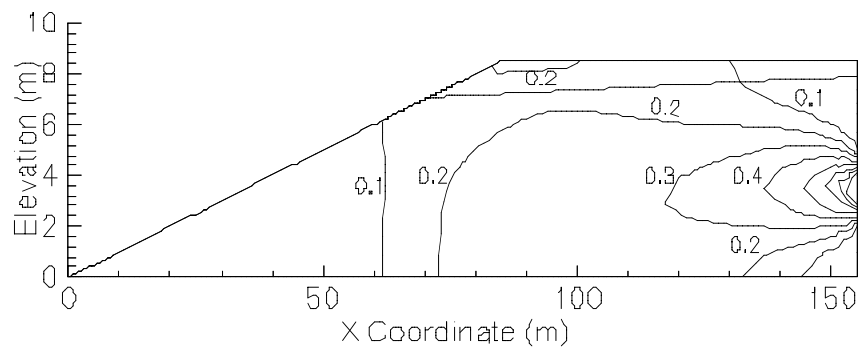
The positions of the water table at high and low tide are presented in figure 5. The velocity fields for the simulated cases after 6 months without and with tidal fluctuations are shown in figures 6 and 7, respectively. Comparing the figures shows that the velocity field near the exit point has been greatly influenced by the tide. This influence, with lessening intensity, extends inland to about $X=100$ m for this problem. The effect of velocity field change on contaminant distribution is evident by comparing the 0.2 and 0.25 contours in figure 3c with corresponding contours in figure 4c.

Figure 8 shows the concentration profile at three horizontal sections with 5, 6, and 7 m elevations respectively from the bottom of aquifer, at a time equal to 6 months. This figure clearly shows that the tidal fluctuation mainly affects the contaminant concentration near the shore line. As seen, near the exit point in the horizontal plane at 7m elevation the contaminant concentration for the case without tide is significantly higher than that simulated with tidal fluctuation. Yim and Mohsen¹ suggested this behaviour for all elevations using their one-dimensional model. However, figure 8a shows that at the 5m elevation, the concentration at the exit point and for a very short distance inland is higher for the case with tide than for the case without tide. Further inland a reversal in relative magnitudes occurs.

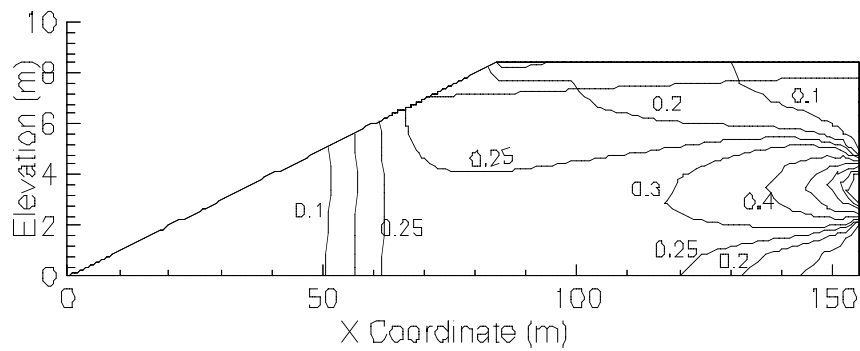
The concentration profile on the sloping face of the aquifer is shown in figure 9. The figure shows that the tidal fluctuation has an important effect on the distribution of contaminant over the sloping face of aquifer. A practical implication of this phenomenon, in the context of environmental management, is a better understanding of the effects of inland pollutants on the near shore marine biology. For example, in the case of resort islands near coral reefs, the near shore environment has a significant impact on tour-



a) after 2 months

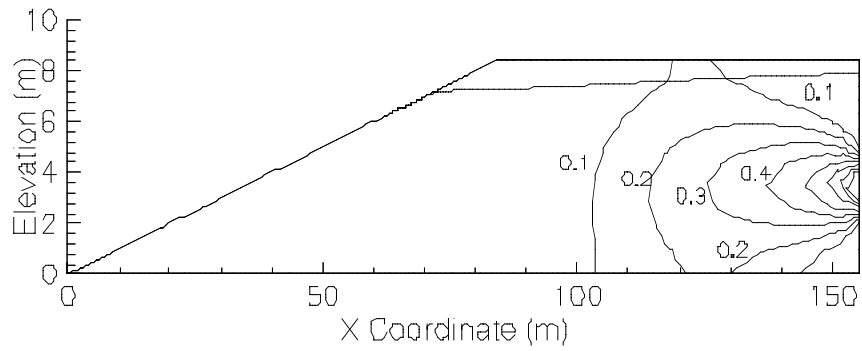


b) after 4 months

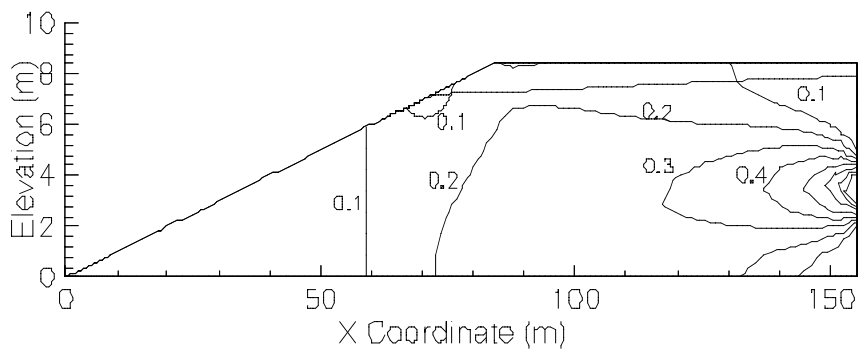


c) after 6 months

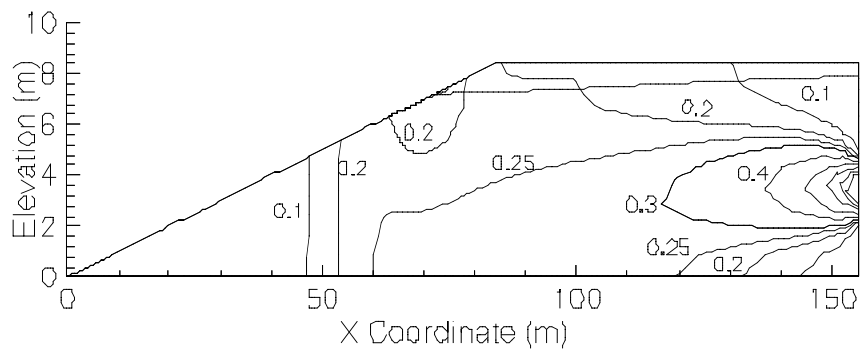
Figure 3: Concentration contours for the case simulated without tidal fluctuation.



a) after 2 months



b) after 4 months



c) after 6 months

Figure 4: Concentration contours for the case simulated with tidal fluctuation

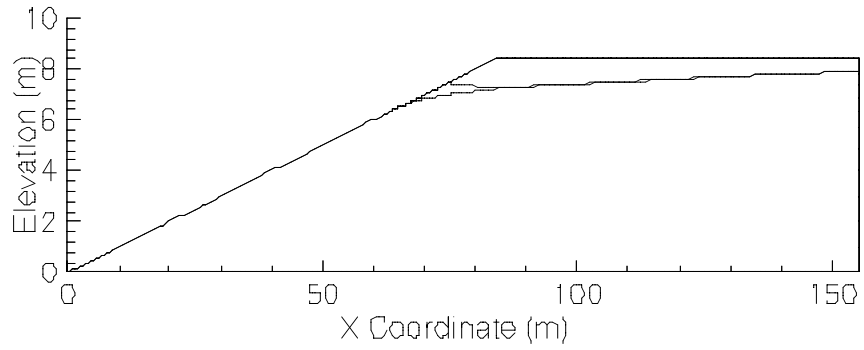


Figure 5: Water level at high and low tide stage

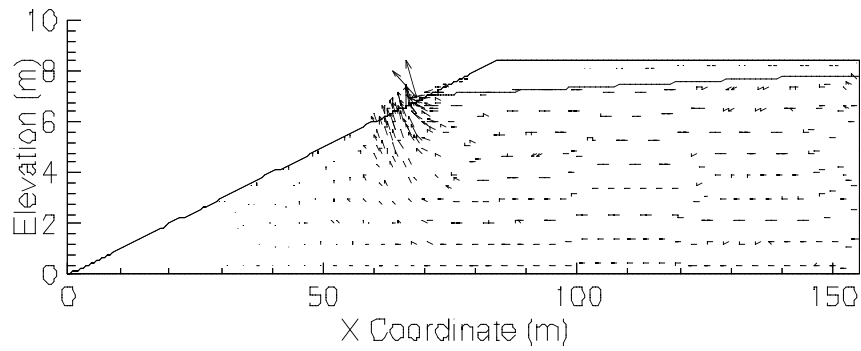
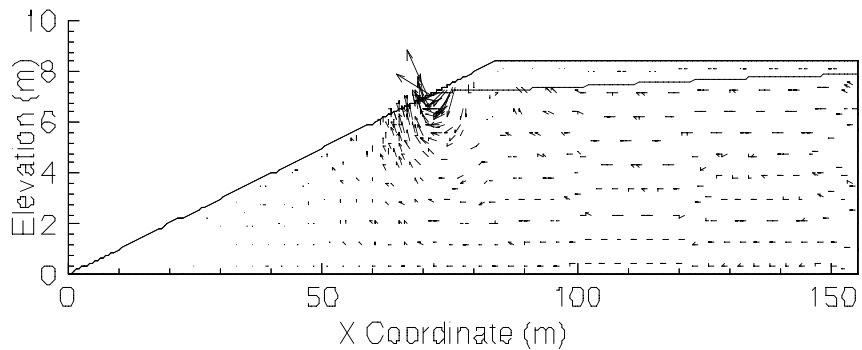
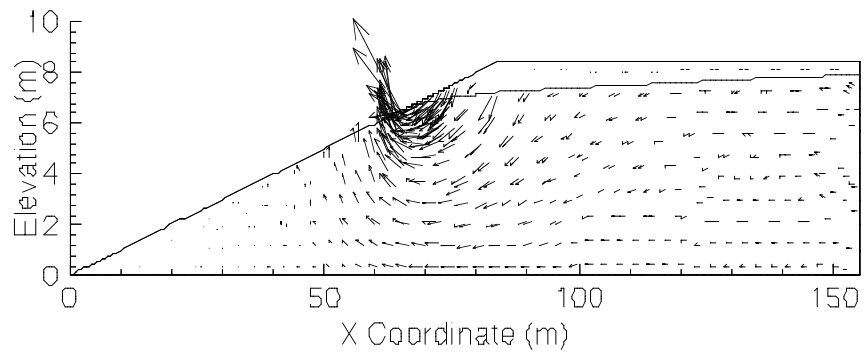


Figure 6: Velocity field for the case simulated without tidal fluctuation

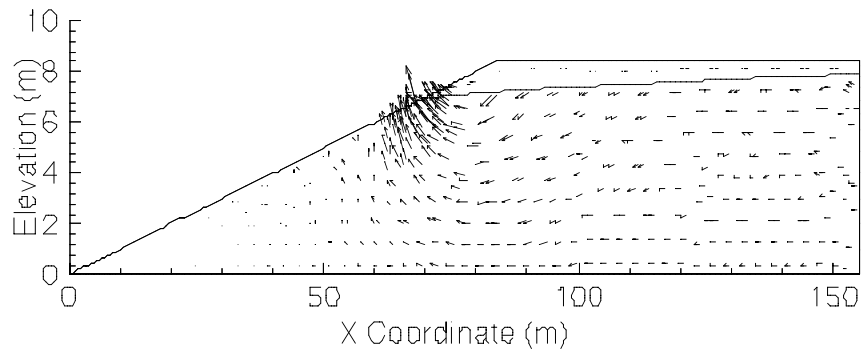


a) falling tide stage

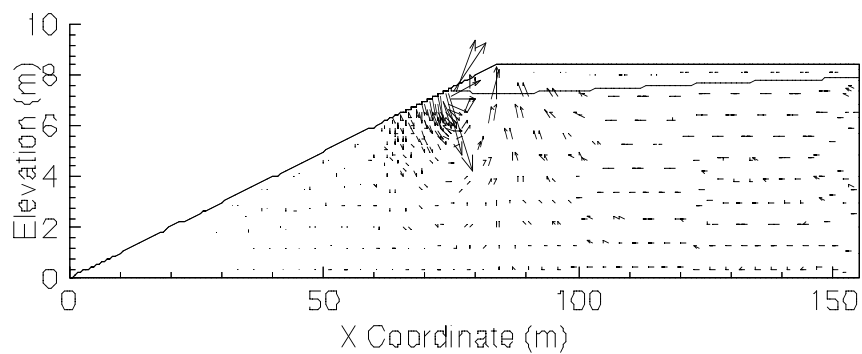
Figure 7: Velocity field for the case simulated with tidal fluctuation



b) low tide stage



c) rising tide stage



d) high tide stage

Figure 7: Velocity field for the case simulated with tidal fluctuation cont.

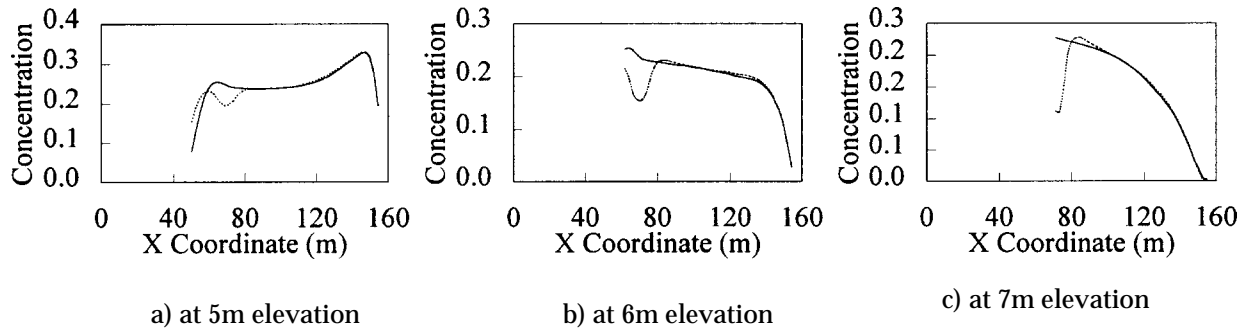


Figure 8: Contaminant concentration profile at horizontal sections for no tide (full line) and with tide (dotted line) cases

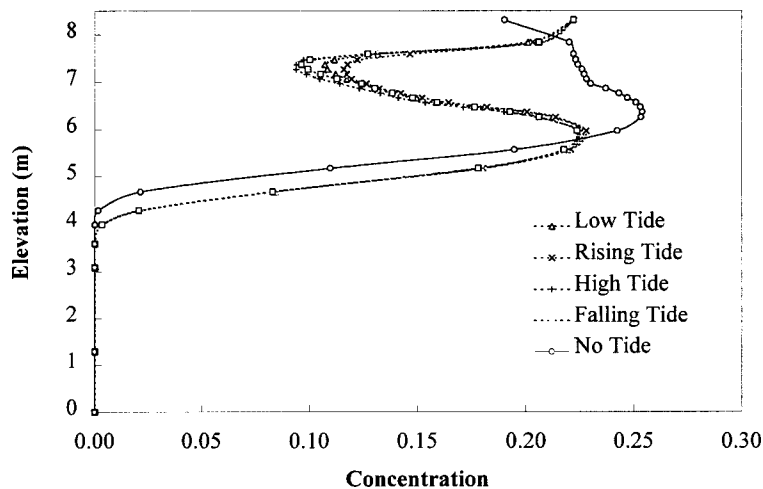


Figure 9: Contaminant concentration profile on the sloping face of the aquifer

ist attraction. As seen, the concentration profiles at different stages of a tidal period are mostly the same and only a little variation is observed near the sea water level.

If comparisons are made of contaminant concentration contours at the low, rising, and high water level stages of tide after 6 months, very little variation is observed. The result for the falling stage was shown in figure 4c. In general, the contaminant distribution even with tidal fluctuations, reaches a quasi steady state situation with only a very small variation near to the exit face as shown in figure 9.

The total amount of contaminant discharged to sea as a function of time is shown in figure 10 for the simulations conducted with and without tidal fluctuations. The figure shows that tidal fluctuations have little effect on the overall contaminant discharge to the sea; for example, after 6 months the contaminant discharged to the sea for the case with tidal fluctuations is about 2 percent less than that for the case without tidal fluctuations. In this problem the effect of tide on the overall contaminant discharge is not significant. To determine whether this result is of general validity would require further simulations

with other sets of parameters.

Figure 11 shows the variation of contaminant discharge to the water body during a tidal cycle after an elapsed time equal to 6 months. As seen, there is significant variation in the contaminant discharge to the sea during a tidal period. As expected the maximum discharge happened when the water level is at the lowest position. The magnitude of velocity vectors in figure 7 confirms this result, as the largest velocity vectors are seen in figure 7b. Figure 11 reveals that there is no contaminant discharge when the water level is about the highest level. This is again confirmed by referring to figure 7d which shows that the velocity vectors are directed toward the aquifer at the high tide stage of tidal fluctuation.

5 CONCLUSIONS

Contaminant transport in a hypothetical coastal aquifer influenced by tidal fluctuations was simulated using the two-dimensional groundwater flow and contaminant transport model. It was shown that tidal fluctuations have a significant effect on the spa-

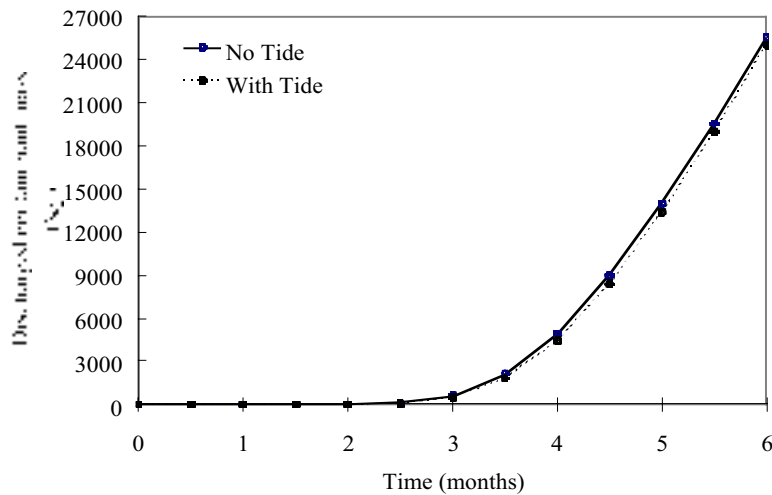


Figure 10: Comparison of the total amount of contaminant discharge

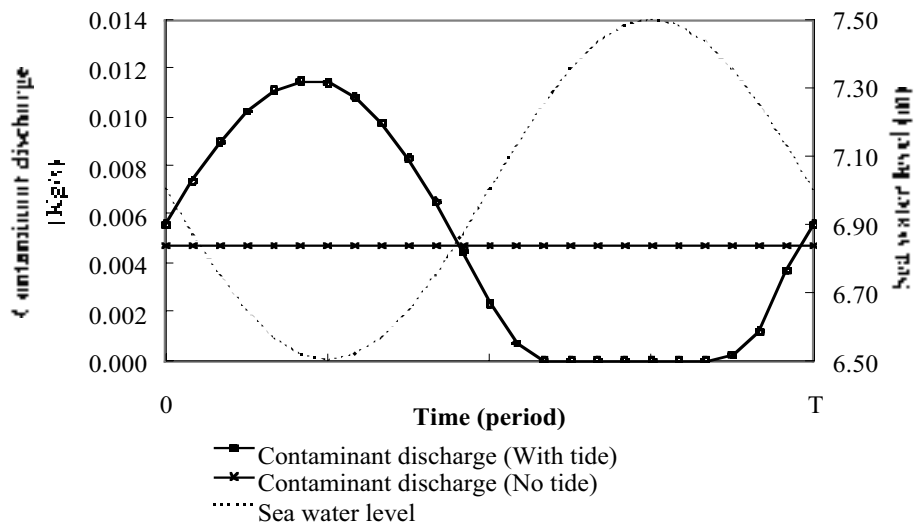


Figure 11: Variation of contaminant discharge to the sea in a tidal period after 6 months simulation

tial distribution of contaminant in the aquifer near the shore line. The concentration profile on the sloping interface between sea and aquifer is influenced significantly by tidal fluctuations. This phenomenon is of interest, especially for environmental management of adjacent marine environment. It was shown that the overall contaminant discharge to the sea is not significantly affected by tidal fluctuation but there is a substantial variation in the contaminant discharge to the sea during a tidal period.

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BEHZAD ATAIE-ASHTIANI

Behzad Ataie-Ashtiani is an assistant professor with Sharif University of Technology, Tehran, Iran where he obtained his BSc (1988) and MEng (1991). He gained his PhD in 1998 from the University of Queensland, Brisbane, Australia. His research interest is in numerical and experimental simulation of water flow and contaminant transport in groundwater and multiphase flow in heterogeneous porous media.



RAY VOLKER

Ray Volker is Professor of Civil Engineering and Head of Department of Civil Engineering at the University of Queensland. His research interests are in groundwater modelling including contaminant transport. He is also interested in wider environmental issues including movement of nutrients and agricultural chemicals in the surface and subsurface zones at a catchment scale. He has taken a particular interest in sea-water intrusion in coastal aquifers and is currently working on several projects based on actual aquifers as well as more fundamental analyses of specific aspects.



DAVID LOCKINGTON

David Lockington is a senior lecturer in the Department of Civil Engineering at the University of Queensland. His research interests primarily lie in the area of modelling transport in porous media, especially partially saturated material. Research applications include soil water dynamics and solute transport, groundwater and contaminant modelling, acid mine drainage, and durability of concrete and other porous building materials.