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# MODSharp: Regional-scale numerical model for quantifying groundwater flux and contaminant discharge into the coastal zone

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## Abstract

In this paper the development of a quasi-three-dimensional numerical model that can be used for quantifying groundwater inputs and associated contaminant discharged from coastal aquifers into the coastal zone at a regional scale is presented. The present model is called MOD-Sharp. In order to handle problems at a regional scale, the sharp interface approach which is used for conceptualising seawater intrusion, is applied to this model. This model can be used for the simulation of groundwater flow and contaminant transport in layered coastal aquifers at a regional scale. The method of characteristics is used to solve the advection-dispersion equation, which governs contaminant transport in coastal aquifers. In this study, MODSharp is used to investigate the influence of Sea Water Intrusion Interface (SWII) on the temporal and spatial variations of contaminant flux from coastal aquifers into the sea. Thus, a large number of simulations for different scenarios are performed. For the case that the land-ward boundary condition is constant head, it is shown that simplification and neglecting the effects of SWII causes an erroneous estimate of the speed of the contaminant plume movement towards sea. The value of hydraulic conductivity is shown to have a significant effect on the amount of discharged contaminant. Finally, it is concluded that over-simplification of the sea-ward boundary condition in numerical simulations, causes an incorrect estimate of temporal and spatial variations of the discharged contaminant into coastal water.

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*Keywords:* Coastal aquifers; Ocean-land interface; Saltwater intrusion; Numerical simulation; Contaminant discharge; Coastal zone

## 1. Introduction

In coastal areas that are densely populated or have been industrialized, often, serious environmental problems occur. Contaminants and nutrients which are carried by groundwater flow and discharged into coastal waters, have a considerable influence on environmental management of coastal zones. Common problems include salt-water intrusion due to over-pumping of groundwater and brine discharges from desalination plants, as well as coastal water pollution by plume leachate from contaminated coastal aquifers (e.g., Bear et al., 1999; Purnalna et al., 2003; Ataie-Ashtiani et al., 2002; Mao et al., 2006).

Coastal aquifers are complex zones due to mixing of seawater, inland groundwater and the possible subsurface

contaminants discharging into the sea. As groundwater flow approaches to the sea in a coastal aquifer, due to seawater intrusion through the coastal aquifer the flow pattern and contaminant path lines become very complicated. For a successful integrated coastal zone management, it is necessary to have a proper estimate of groundwater inputs to coastal waters. The groundwater flux to coastal water can be a major component of the water balance in coastal zones. In some cases it is as high as 40% of river-water flux into coastal water (Moore, 1996).

Until recently, the principal concern associated with the hydrological connection between groundwater and the ocean has been the saline water intrusion into coastal water supplies. Increasingly, however, there is concern that submarine and marginal marine discharges of nutrient- and contaminant-rich groundwater may have a more significant impact on material fluxes than that implied by the relative magnitudes of groundwater and surface water discharges. Submarine

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groundwater discharge (SGWD) has been recognized as an important factor influencing the near-shore environmental ecology for over a decade (Simmons, 1992; Moore, 1996). Quantitative measurements by Simmons (1992) showed the importance of seawater intrusion role on the contaminant transport in coastal areas.

In many settings seep zones appear to be associated with unique and important marginal marine and inter-tidal biological communities of high productivity. Therefore, these discharges may also play an important role in local biodiversity, in ecosystem function, and potentially in contaminant transfer up the marine and terrestrial food chains (Uchiyama et al., 2000; Ullmana et al., 2003).

Since the beginning of the twentieth century, exclusive studies about saltwater intrusion have been performed and different mathematical models have been used to investigate this phenomenon quantitatively. Bear et al. (1999) reviewed recent progress on saltwater intrusion in coastal aquifers, including field studies, theoretical basis, analytical solutions and numerical analyses of real cases. The salt-water intrusion phenomenon in groundwater systems has been conceptualized by two general approaches: the sharp interface approach and the dispersed interface approach. In the former it is assumed that the salt-water and freshwater are immiscible fluids separated by a sharp interface. In the latter a transition zone of mixed salt and fresh water is considered to be present at the interface. In this approach, the diffusion and hydrodynamic dispersion effects, density dependent fluid flow and solute transport are incorporated. An historical perspective of salt-water intrusion is presented by Reilly and Goodman (1985). The models of Volker (1980), who employed the finite element method for the saltwater intrusion problems in coastal confined and unconfined aquifers, Volker and Rushton (1982), Taigbenu et al. (1984) who applied the boundary integral method, and the models of Mercer et al. (1980), Polo and Ramis (1983), Ledoux et al. (1990), who used the finite difference method are based on the first approach. Also the recent model of Masciopinto (2006) is based on the sharp interface approach.

Numerical models based on the dispersed interface approach have been used extensively to investigate different aspects of sea-water intrusion by including the density difference between sea-water and fresh groundwater (Segol et al., 1975; Volker and Rushton, 1982; Frind, 1982; Voss and Souza, 1987; Konikow and Arevalo, 1993). Ataie-Ashtiani et al. (1999a) studied the effect of tidal oscillations on seawater intrusion in coastal aquifers based on the dispersed interface approach. It was noted that the effect can be significant on near-shore groundwater hydrodynamics and salt-water intrusion, especially for a low relief beach. Custodio (1988) mentions that in many real situations, such as sluggish freshwater flow, stresses caused by tidal oscillations and recharge events, and enhanced dispersivity by macroscopic heterogeneities, the sharp interface approach is a crude one. The sharp interface approach is computationally less demanding in comparison to dispersed interface approach.

Ataie-Ashtiani et al. (1999a,b) presented a numerical model for simulation of groundwater flow in coastal aquifers that could handle tidal fluctuations and the seepage-face condition at the seaward boundary. In their model the seawater intrusion into the coastal aquifer was simulated using dispersed interface approach. However, the model can be used either for simulation of contaminant transport or the seawater intrusion. Besides, solving density-dependent flow for dispersed interface approach is computationally demanding and therefore it imposes severe limitations on the scale of aquifer considered for simulation. Also, Ataie-Ashtiani et al. (2001, 2002) studied the influence of tidal fluctuation effects on groundwater dynamics and contaminant transport in unconfined coastal aquifers. In their studies the Sea-Water Intrusion Interface (SWII) into the coastal aquifers was not considered. Also their studies were limited to the part of aquifer close to coast.

Numerical models can be utilized to simulate the groundwater flow and contaminant transport in coastal aquifers. However, there are serious limitations in the available efficient numerical models for application at a regional scale. The objective of this study is to develop a quasi-three-dimensional numerical model that can be used for quantifying groundwater inputs and associated contaminant discharged from coastal aquifers into the coastal zone at a regional scale. Although few models such as SEAWAT (Langevin et al., 2003), are capable of handling the seawater intrusion and contaminant transport simultaneously, the model developed in this study uses the sharp interface approach and is much more efficient for application at a regional scale. This model is used to investigate the influences of the up-stream (land-ward) boundary condition of a coastal aquifer on the seawater intrusion and the migration of contaminant in a coastal aquifer.

The mathematical formulation and numerical methods are presented in Section 2. The application of the model to study the influence of Sea Water Intrusion Interface (SWII) on the temporal and spatial variations of contaminant flux from coastal aquifer into the sea is presented in Section 3.

## 2. Mathematical and numerical model

In this study the SHARP Model (Essaid, 1987) has been improved and modified for modelling groundwater flow and contaminant transport in coastal aquifers. SHARP is a quasi-three-dimensional, finite difference model that simulates fresh water and salt water flow separated by a sharp interface in layered coastal aquifer systems. Vertically integrated fresh water and salt water flow equations, incorporating the interface boundary condition and leakage terms calculated by Darcy's law, are solved within each aquifer. The governing equations describing the SHARP fluid mass balance are (Essaid, 1987):

$$S_f B_f \frac{\partial \Phi_f}{\partial t} + n\alpha \frac{\partial \Phi_f}{\partial t} + \left[ n\alpha \frac{\partial \Phi_f}{\partial t} - n(1 + \delta) \frac{\partial \Phi_s}{\partial t} \right] \\ = \frac{\partial}{\partial x} \left( B_f K_{fx} \frac{\partial \Phi_f}{\partial x} \right) + \frac{\partial}{\partial y} \left( B_f K_{fy} \frac{\partial \Phi_f}{\partial y} \right) + q_f + q_{lf} \quad (1)$$

and,

$$S_s B_s \frac{\partial \Phi_s}{\partial t} + \left[ n(1 + \delta) \frac{\partial \Phi_s}{\partial t} - n\delta \frac{\partial \Phi_f}{\partial t} \right] \\ = \frac{\partial}{\partial x} \left( B_s K_{sx} \frac{\partial \Phi_s}{\partial x} \right) + \frac{\partial}{\partial y} \left( B_s K_{sy} \frac{\partial \Phi_s}{\partial y} \right) + q_s + q_{ls} \quad (2)$$

Where  $x$  and  $y$  are areal coordinates [L],  $t$  is time [T],  $\Phi_f$  and  $\Phi_s$  are fresh and salt water hydraulic heads [L],  $S_f$  and  $S_s$  are fresh and salt water specific storages [ $L^{-1}$ ],  $K_{fx}$  and  $K_{sx}$  are fresh and salt water hydraulic conductivities in  $x$ -direction [ $LT^{-1}$ ],  $K_{fy}$  and  $K_{sy}$  are fresh and salt water hydraulic conductivities in  $y$ -direction [ $LT^{-1}$ ],  $B_f$  and  $B_s$  are fresh and salt water saturated thickness [L],  $q_f$  and  $q_s$  are fresh and salt water source/sink terms [ $LT^{-1}$ ],  $q_{lf}$  and  $q_{ls}$  are fresh and salt water leakage terms [ $LT^{-1}$ ],  $\gamma_f$  and  $\gamma_s$  are fresh and salt water specific weights [ $ML^{-2}T^{-2}$ ],  $n$  is the effective porosity of the aquifer [–], and  $\delta = \gamma_f / (\gamma_s - \gamma_f)$ .  $\alpha$  is 1 for an unconfined aquifer and 0 for a confined aquifer.

This system of coupled, non-linear partial differential equations is discretized using an implicit finite difference scheme that is centred in space and backward in time. The locations of the interface tip and toe, within grid blocks, are tracked by linearly extrapolating the position of the interface based on the known grid point elevations. The discretized system of equations is solved using the strongly implicit procedure (SIP) for three-dimensional, two-phase flow.

In the present work the equation of two-dimensional areal contaminant transport is included in the SHARP Model. The equation may be written as (Konikow and Bredehoeft, 1978):

$$\frac{\partial(CB)}{\partial t} = \frac{\partial}{\partial x_i} \left( BD_{ij} \frac{\partial C}{\partial x_j} \right) - \frac{\partial}{\partial x_i} (BCV_i) - \frac{C'Q}{n} \quad i, j = 1, 2 \quad (3)$$

where  $C$  is the concentration of the dissolved chemical species [ $ML^{-3}$ ],  $V_i$  is the seepage velocity in the direction of  $x_i$  [ $LT^{-1}$ ],  $D_{ij}$  is the coefficient of hydrodynamic dispersion [ $L^2T^{-1}$ ],  $B$  is the saturated thickness of the aquifer [L],  $Q$  is the volume flux per unit area [ $LT^{-1}$ ], and  $C'$  is the concentration of dissolved chemical in a source or sink fluid [ $ML^{-3}$ ]. The seepage velocity is determined from Darcy's law:

$$V_i = -\frac{K}{n} \frac{\partial \Phi}{\partial x_i} \quad (4)$$

The method of characteristics (MOC) is used in MODSharp model to solve the solute-transport equation. The method has been successfully applied to a variety of field problems of flow (Konikow and Bredehoeft, 1978). The approach taken by MOC is not to solve Eq. (3) directly, but rather to solve an equivalent system of ordinary differential equations.

The first step in the MOC involves placing a number of traceable particles in each cell of the finite difference grid to form a set of points that are distributed in a geometrically uniform pattern throughout the area of interest. It was found that placing four to nine points per cell provided satisfactory results for most two-dimensional problems. The initial

concentration assigned to each point is the initial concentration associated with the node of the cell containing the point (Konikow and Bredehoeft, 1978).

For each time step every point is moved a distance proportional to the product of the time increment and the velocity at the location of the point. After all points have been moved, the concentration at each node is temporarily assigned as the average of concentrations of points that are located within the area of that cell. The moving points simulate convective transport because the concentration at each node of the grid will change in each time step as different points with different concentrations enter and leave the area of that cell. Changes in concentration caused by hydrodynamic dispersion, fluid sources, divergence of velocity, and changes in saturated thickness are calculated using an explicit finite-difference approximation.

The accuracy of numerical solution of the solute transport equation that has been added to the SHARP model can be evaluated by analysing relatively simple problems for which analytical solutions are available and then comparing the numerical results with the results obtained from analytical solution. A series of these types of tests has been performed to verify the MODSharp model (Ataie-Ashtiani, 2003). The results of the three cases are presented in this section.

### 2.1. Contaminant transport from a continuous source

According to van Genuchten and Alves (1982), the analytical solution of the case of one-dimensional contaminant transport from a continuous source into a homogeneous aquifer is given by Eq. (5),

$$C(x, t) = \frac{C_0}{2} \left( \exp\left(\frac{vx}{2D}\right) \operatorname{erfc}\left(\frac{x-vt}{2(Dt)^{\frac{1}{2}}}\right) \right. \\ \left. + \exp\left(\frac{vx}{2D}\right) \operatorname{erfc}\left(\frac{x+vt}{2(Dt)^{\frac{1}{2}}}\right) \right) \quad (5)$$

for the initial and boundary conditions:

$$C = 0 \quad t = 0 \quad x > 0 \\ C = C_0 \quad t > 0 \quad x = 0 \\ C = 0 \quad t > 0 \quad x \rightarrow \infty$$

Average linear velocity  $v$ , longitudinal dispersion  $D$ , and concentration at the boundary  $C_0$  are all assumed to be constant in Eq. (5).

In a domain 320 m long and 100 m wide with the porosity of 0.35, there is a uniform flow in  $x$  direction and  $v$  equals 42 m/day. A tracer with concentration of 10 g/l is supplied at the boundary. The hydraulic conductivity is 50 m/day.

This problem is solved using the MODSharp model with a grid of 32 by 10 cells in  $x$  and  $y$  directions, respectively, and with a time step of 3600 s. 16 particles are initially inserted in each cell for solving the solute transport equation

by MOC. Three cases with  $\alpha_1$  of 0.1, 5 and 10 m ( $D_x$  of 4.2, 21, and 42 m<sup>2</sup>/day) are considered.

Fig. 1 shows the simulated contaminant concentration obtained from the numerical model of MODSharp and the analytical solution results. As seen there is an excellent agreement between analytical and numerical results.

2.2. Contaminant transport from a pulse source

If a pulse of contaminant is injected over the full thickness of a two-dimensional homogeneous aquifer, it will move in the direction of flow and spread out with time. If a tracer with concentration  $C_0$  is injected over an area  $A$  at a point  $(x_0, y_0)$ , the concentration at any point  $(x, y)$  at time  $t$  after the injection is given by Eq. (6) (De Josselin De Jong, 1958).

$$C(x, y, t) = \frac{C_0 A}{4\pi.t(D_x D_y)^{\frac{1}{2}}} \exp\left\{ -\frac{((x-x_0) - V_x t)^2}{4D_x t} - \frac{(y-y_0)^2}{4D_y t} \right\} \tag{6}$$

Average linear velocity  $V_x$ , longitudinal dispersion  $D_x$ , and transverse dispersion  $D_y$  are all assumed to be constant in this equation.

In a domain 320 m long and 100 m wide with the porosity of 0.2, there is a uniform flow in  $x$  direction and  $V_x$  equals 5.27 m/day. A tracer with concentration of 1 g/l is injected at  $x_0 = 50$  m and  $y_0 = 55$  m over an area of  $10 \times 10$  m. The hydraulic conductivity is 50 m/day.  $D_x$  and  $D_y$  are 26 m<sup>2</sup>/day and 2.6 m<sup>2</sup>/day, respectively.

This problem is solved using the MODSharp model within a grid of 32 by 10 cells in  $x$  and  $y$  directions, respectively, and with a time step of 3600 s. 16 particles are inserted initially in each cell for solving the solute transport equation by MOC. Fig. 2 shows the comparison between analytical solution results and the numerical results obtained from MODSharp for the distributions of tracer 30 days after injection. As seen there is a good agreement between analytical and numerical results for plume movement and distribution.

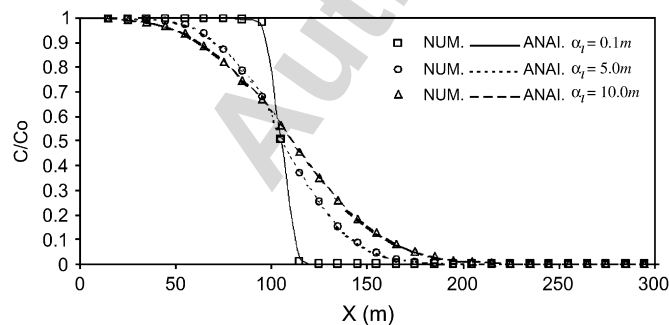


Fig. 1. Analytical solution and numerical results from MODSHARP for the case of one-dimensional contaminant transport from a continuous source into a homogeneous aquifer.

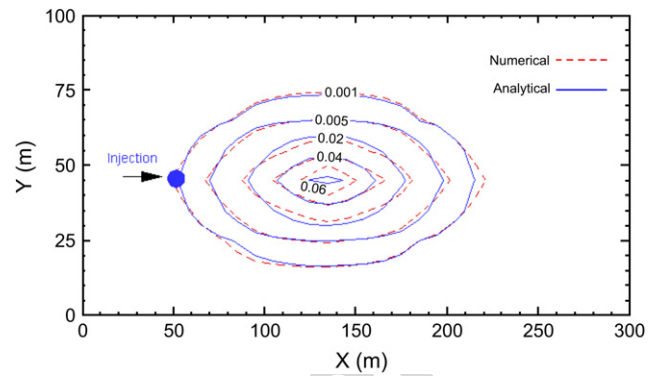


Fig. 2. Analytical solution and numerical results of MODSHARP for the distributions of tracer 30 days after injection.

2.3. Contaminant transport in an aquifer with injection and discharge wells

A coastal aquifer of length 20 km, width 10 km and thickness 204 m is considered. Fig. 3 shows the schematic of this coastal aquifer. The horizontal and vertical hydraulic conductivities are 1000 m/day and 100 m/day, respectively, the porosity is 0.4, and the fresh and saltwater specific storages

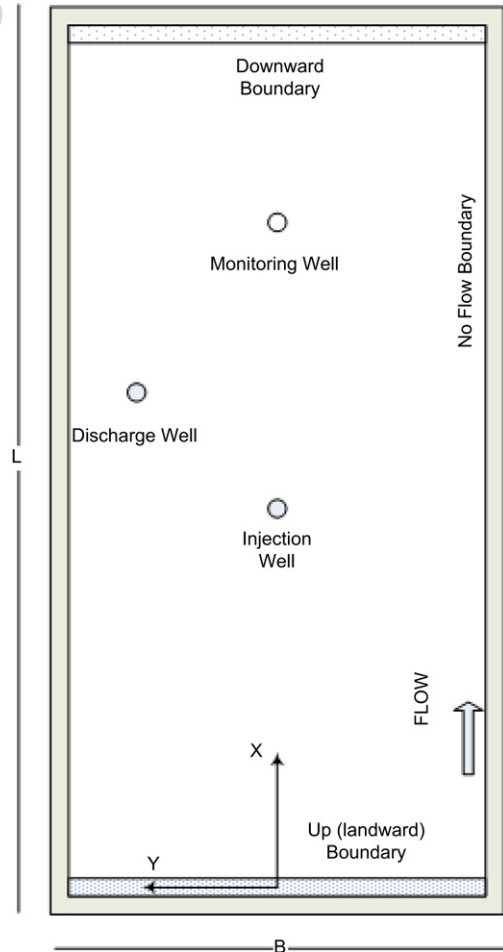


Fig. 3. Schematic of considered coastal aquifer.

are  $10^{-6}$  and  $1.03 \times 10^{-6} \text{ m}^{-1}$ , respectively. Constant heads of 22.27 m at landward and 0.07 m at seaward boundaries respectively cause a constant hydraulic gradient of 0.0011 toward the sea. The fresh and saltwater densities are  $1000 \text{ kg/m}^3$  and  $1030 \text{ kg/m}^3$  respectively. The contamination source with constant concentration  $C_0$  of 100 mg/l is in an area of  $500 \times 500 \text{ m}$  in the middle of the landward boundary. Longitudinal and transverse dispersivities of  $\alpha_L = 0.0 \text{ m}$  and  $\alpha_T = 0.0 \text{ m}$  are assumed (where  $D_L = \alpha_L \cdot |V|$  and  $D_T = \alpha_T \cdot |V|$ ). For numerical simulation, blocks of  $500 \times 500 \text{ m}$  are considered. Therefore the number of blocks is 800 ( $20 \times 40$ ) and the time step is 1 day. Injection and discharge wells are located at coordinates (12250, 1750) and (5250, 7750) respectively. A semi analytical solution is (Nelson, 1978):

$$t = \int_0^{S(t)} \frac{ds}{V_s(s)} = -\frac{n}{K} \int_0^{S(t)} \frac{ds}{\partial\Phi/\partial s} \quad (6)$$

$$V_x = V_{0x} - \sum_{j=1}^m \frac{Q_j}{2\pi \cdot n \cdot B} \frac{x - x_j}{r_j^2} \quad (7)$$

$$V_y = V_{0y} - \sum_{j=1}^m \frac{Q_j}{2\pi \cdot n \cdot B} \frac{y - y_j}{r_j^2} \quad (8)$$

where  $V_s$  is velocity on path line,  $\Phi$  is head of flow,  $V_{0x}$  is initial velocity in  $x$  direction;  $V_{0y}$  is initial velocity in  $y$  direction,  $Q_j$  is discharge and injection rate,  $x_j$  and  $y_j$  are the  $x$  and  $y$  components of the position of well  $Q_j$ , and  $r_j$  is distance from well to point where the velocity is calculated.

Concentration contours from the numerical and semi analytical solutions after 900, 1700 and 7300 days are shown in Fig. 4a. The concentration contours for both simulated cases (with and without seawater intrusion) after 20 years are shown in Fig. 4 a. For the case where SWII is considered, the contaminant plume moves slower than for the case where SWII is neglected. This difference increases with time. For example after 900 days the difference is 500 m and reaches 2000 m after 1700 days. No SWII numerical contours are the same as those from the semi analytical solution. Fig. 4b shows streamlines of the Nelson solution.

Further details of the MODSharp formulations and numerical model can be found in Ataie-Ashtiani (2003).

### 3. Effects of sea-water intrusion interface on the flux of contaminant into coastal zone

The MODSharp model is used to investigate the effect of seawater intrusion on the contaminant transport process in coastal aquifers and to determine the amount of contaminant discharged into the sea. This program has the capability to solve salt water and fresh water flow equations simultaneously by using a continuous pressure boundary condition at the interface. The model can be used for the simulation of groundwater flow and contaminant transport in layered coastal aquifers at a regional scale. The present regional-scale numerical model

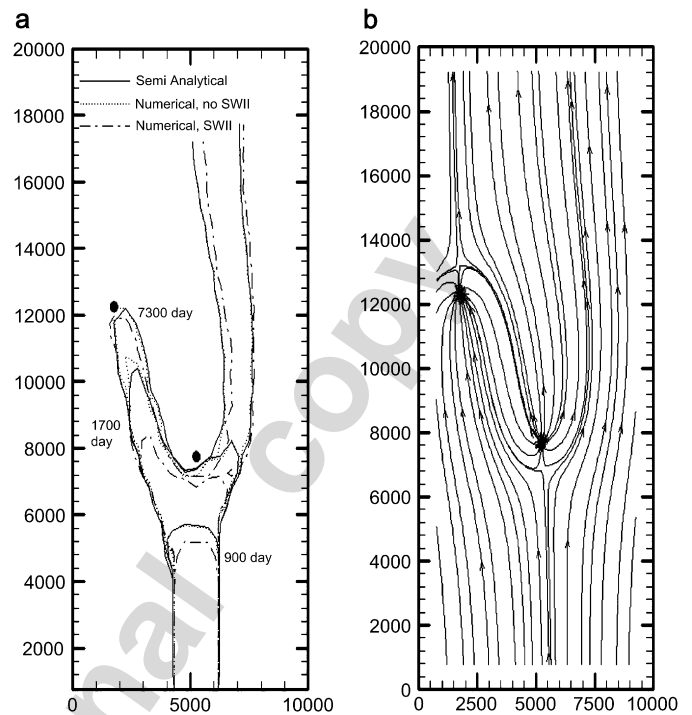


Fig. 4. Concentration contours for the case (a) Numerical and semi Analytical SWII influence after 20 years on contours (b) stream lines.

can be used to develop a better understanding of the interactions between water bodies in the coastal zone.

A coastal aquifer with a length of 20 km, width of 10 km and thickness of 204 m is considered. The horizontal and vertical hydraulic conductivities of the aquifer are 100 m/day and 10 m/day, respectively, the porosity is 0.4, and the fresh and saltwater specific storages are  $10^{-6}$  and  $1.03 \times 10^{-6} \text{ m}^{-1}$ , respectively. Constant heads of 22.27 m at landward and 0.072 m at seaward boundaries respectively cause a constant hydraulic gradient of 0.0012 toward the sea. The fresh and saltwater densities are  $1000 \text{ kg/m}^3$  and  $1030 \text{ kg/m}^3$ , respectively. A contamination source with constant concentration  $C_0$  of 100 mg/l is supplied over an area of  $500 \times 500 \text{ m}$ , which is located in the middle of the landward boundary. The longitudinal and transverse dispersivities are  $\alpha_L = 100 \text{ m}$  and  $\alpha_T = 50 \text{ m}$  (where  $D_L = \alpha_L \cdot |V|$  and  $D_T = \alpha_T \cdot |V|$ ). For numerical simulation, blocks of  $500 \times 500 \text{ m}$  are considered. Therefore the number of blocks is 800 ( $20 \times 40$ ) and time step is 1 day.

Two cases, one with and one without seawater intrusion are simulated by imposing the proper boundary conditions at the seaward boundary for each case. The contours of the 50 percent concentration for both simulated cases after 60 and 100 years are shown in Fig. 5. For the case where the influence of SWII is considered the contaminant plume moves slower than in the case where SWII is neglected. This difference increases with time. For example after 60 years this difference, for the contours of the 50 percent concentration, is 400 m and reaches 700 m after 100 years. For practical problems, ignoring seawater intrusion will cause faster contaminant transport which leads to over estimation of the spreading and distribution of the contaminant

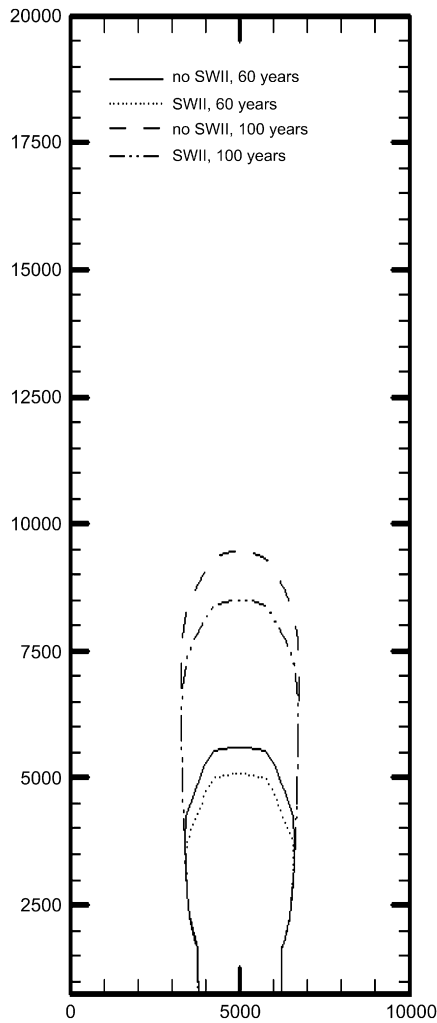


Fig. 5. Concentration contours showing SWII influence on contours after 60 and 100 years.

plume. Indeed, saltwater intrusion changes the pattern of contaminant transport and distribution before the contaminant reaches the sea.

Fig. 6 illustrates the amount of contaminant discharged into the sea for both cases. Contaminant discharge starts at

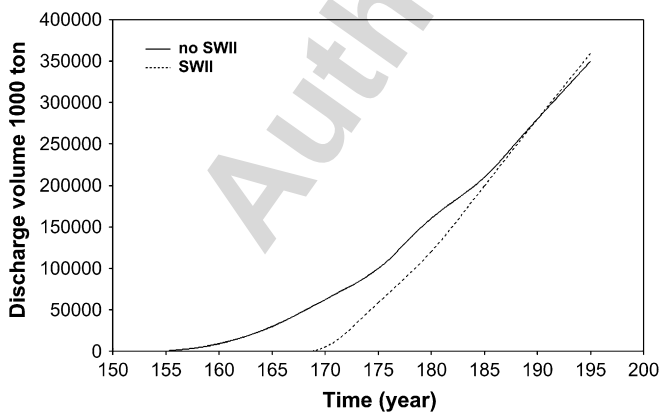


Fig. 6. Contaminant discharged to the sea with constant head at the landward boundary.

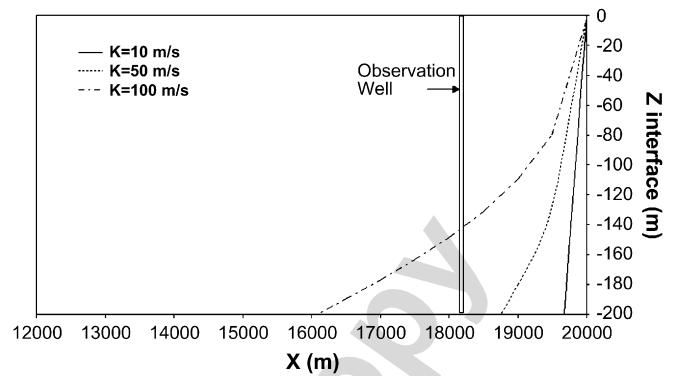


Fig. 7. The position of interface for different hydraulic conductivities.

$t = 170$  yr for the case with SWII while in the other case (without SWII) it starts at  $t = 155$  yr; hence, neglecting seawater intrusion leads to a prediction of the contaminant discharge starting sooner than it really does. However, the speed and the rate of the discharge for the case with seawater intrusion is such that after 190 years the cumulative amount of contaminant discharged into the sea will become equal for both cases.

Hydraulic conductivity is a factor that has a noticeable effect on the seawater intrusion and contaminant transport patterns in coastal aquifers and also on the amount of contaminant discharged into the sea. To investigate the influence of hydraulic conductivity, cases with hydraulic conductivity values of 10, 50 and 100 m/day are considered. A constant flux boundary condition equal to  $0.15 \text{ m}^3/\text{sec}$  is assumed at the landward end. Longitudinal and transverse dispersivities are 100 and 50 m, respectively. The contaminant source is the same as above case. The position of the interface is shown in Fig. 7. By increasing the hydraulic conductivity the length of intruded interface increases. The intrusion from the toe of the interface is 120, 360 and 1270 m in the coastal aquifer for the 10, 50 and 100 m/day hydraulic conductivities, respectively.

Due to the constant flux boundary condition, the velocity of groundwater flow is constant and changes are just in the shape and length of intruded interface. Fig. 8 shows the temporal changes of concentration in the observation well. For the cases of  $k = 10$  and 50 m/day the observation well is located in the freshwater region and for the case  $k = 100$  m/day it is located in the seawater intrusion region. Due to the constant velocity in the aquifer the contaminant plume reaches the well at  $t = 115$  yr. The concentration values in the observation well are the same for all cases with different hydraulic conductivities except in the case where seawater intrusion occurs with  $k = 100$  m/day. In this case the rate of concentration increases, but finally they meet at  $t = 201$  yr.

The amount of contaminant discharged into the sea for different hydraulic conductivities is shown in Fig. 9 and Table 1. When we have no seawater intrusion, the amount of discharged contaminant is the same for different hydraulic conductivities and commences at  $t = 140$  yr, but for the case where seawater intrusion is considered, due to different freshwater heads for different hydraulic conductivities, the interface between saltwater and freshwater is located at different depths.

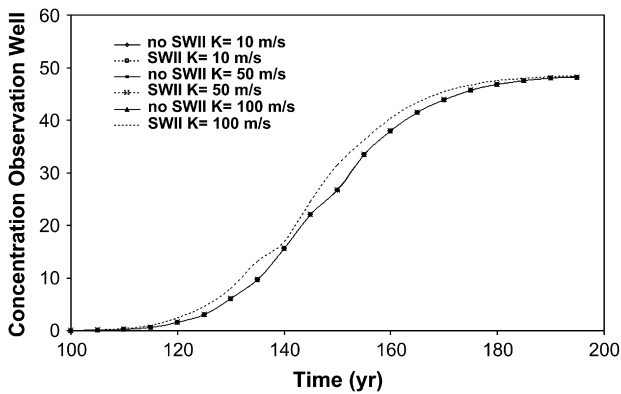


Fig. 8. Temporal changes of contaminant concentration in monitoring well for the cases of with and without seawater intrusion.

Another parameter considered, is specific storage. We have concluded that specific storage does not have a significant influence on the contaminant transport and discharge. This is because specific storage affects the contaminant concentration only when the subsurface flow regime is unsteady and after it reaches steady state conditions the influence of this factor will come to an end.

Hydrodynamic dispersion is another important parameter that can be considered. Longitudinal dispersivity equal to 0 and 100 m and transverse dispersivity equal to 0 and 50 m have been used to investigate the effect of hydrodynamic dispersion. The hydraulic conductivity of 100 m/day and a constant flux boundary condition are used for this study. Fig. 10 shows the temporal changes in contaminant concentration of the monitoring well for different hydrodynamic dispersions. As dispersion increases, differences between observed concentration in the well and the time they reach the well decreases for both cases. Fig. 11 shows the total amount of contaminant discharged to the sea for these cases. As seen, when dispersion increases, contaminant discharge to the sea occurs sooner, but the rate of contaminant discharge decreases when the dispersivity is increased for both cases. The decrease of contaminant discharge is more severe for the case of seawater intrusion.

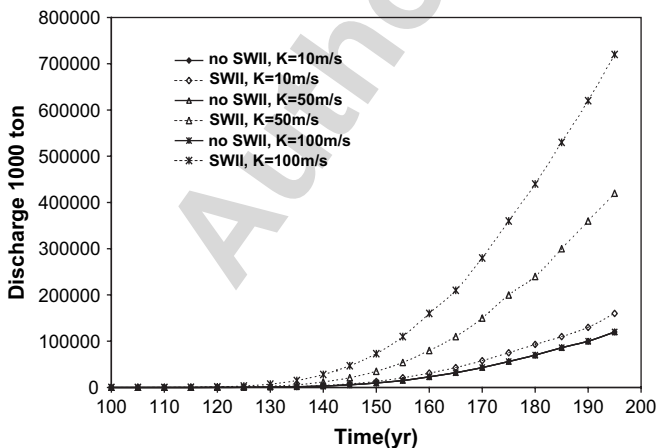


Fig. 9. The amount of contaminant discharged to the sea by using different hydraulic conductivities.

Table 1

Total amount of contaminant discharge during 195 years (million Tons)		
Hydraulic conductivity (m/day)	With SWII	Without SWII
10	160	120
50	420	120
100	720	120

Accordingly, the amount of contaminant discharge is greater in this case.

When the land-ward (up-stream) boundary condition is constant head, it is shown that simplifying and neglecting the effects of SWII causes an erroneous estimate of the speed of the contaminant plume movement toward sea. The existence of SWII decreases the amount of contaminant discharged for a given period of time. However, for both cases, simulations with and without SWII, the discharged amount will reach to the same values after a long period of time.

The results are different for cases where the imposed land-ward boundary condition is constant flux. In this case the amount of contaminant discharged into the sea, when SWII is considered, is considerably more than the corresponding amount for cases where SWII is neglected. The value of hydraulic conductivity also has a significant effect on the amount discharged. For the cases when SWII exists, the discharge of contaminant increases with increases in hydraulic conductivity. However, for cases without SWII, the amount of discharge is not sensitive to changes in hydraulic conductivity.

The model is also available to public by request to author.

#### 4. Conclusions

A regional-scale numerical model (MODSharp) is developed in this work. The present numerical model can be used to develop a better understanding of the interactions between water bodies in the coastal zone. It can also be used to predict the fate of a contaminant plume in coastal aquifers and therefore allow better strategies to be implemented for controlling or mitigating the effects of contaminants on coastal wetlands, coastal aquifers, and adjacent marine environments.

In order to investigate the effects of seawater intrusion on groundwater flow and the amount of contaminant

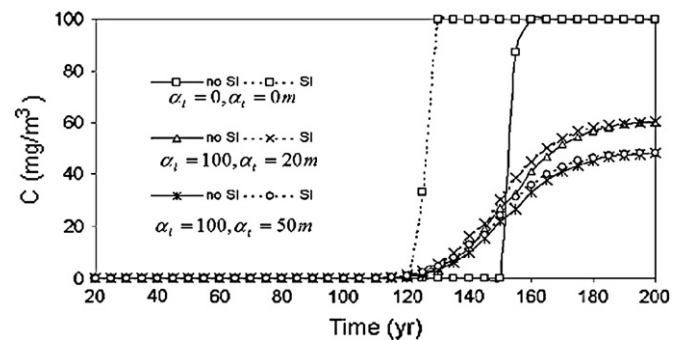


Fig. 10. Temporal changes of contaminant concentration in observation well for different dispersivities in the cases of Seawater Intrusion (SI) and without Seawater Intrusion (no SI).

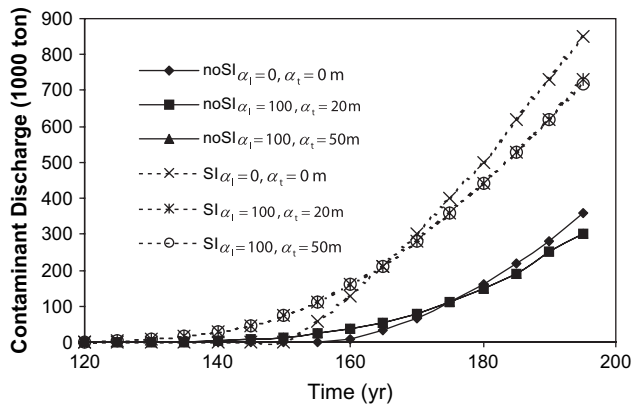


Fig. 11. The amount of contaminant discharged to the sea for different dispersivities in the cases of Seawater Intrusion (SI) and without Seawater Intrusion (no SI).

discharged from coastal aquifers into coastal waters the MODSharp model is employed. The landward and seaward boundary conditions of coastal aquifers have a significant influence on the groundwater flow and the amount of contaminant discharged from aquifers into coastal waters. It is shown that over-simplification of the seaward boundary condition in numerical simulations causes an incorrect estimate of amount of contaminant discharged into coastal waters. Therefore, it is necessary to properly simulate the SWII in coastal aquifers to provide accurate data on which sound environmental management of the coastal zone can be based.

The present numerical model can be used to develop a better understanding of the interactions between water bodies in the coastal zone. It can also be used to predict the fate of a contaminant plume in coastal aquifers and therefore allow better strategies to be implemented for controlling or mitigating the effects of contaminants on coastal wetlands, coastal aquifers, and the adjacent marine environment.

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