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Effects of Sea-water Intrusion Interface on the Flux of Contaminant from Coastal Aquifers into the Coastal Water: Results of seven years of continuous work on modeling of ground water discharge into the coastal zone

B. Ataie-Ashtiani and M.A. Seyedabbasi

Dept. of Civil Eng.,
Sharif University of Technology,
Tehran, Iran
P.O. Box 11365-9313
ataie@sharif.edu

ABSTRACT

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Recently, a regional-scale numerical model for simulation of groundwater flow and contaminant transport in coastal aquifers has been developed by Ataie-Ashtiani (2004). In this paper, this numerical model is employed 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. For this study a large number of simulations for different scenarios are performed. For the cases that the land-ward boundary condition are 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 toward sea. The value of hydraulic conductivity has a significant effect on the amount of discharged contaminant. It is concluded that the over-simplification of sea-ward boundary condition in numerical simulations causes an incorrect estimate of temporal and special variations of the discharged contaminant into coastal water.

ADDITIONAL INDEX WORDS: *Coastal aquifers, ocean-land interface, saltwater intrusion, numerical simulation.*

INTRODUCTION

The seaward boundary of coastal aquifers has significant influence of the groundwater flow and the amount of contaminant discharged from coastal aquifers into the costal waters. Prediction of the fate of contaminant plume in coastal aquifers 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. As groundwater flow approaches to the sea in a coastal aquifer the flow pattern and contaminant path lines become so complicated due to seawater intrusion through the coastal aquifer.

Exclusive studies about saltwater intrusion have been performed since the beginning of twentieth century and different mathematical models have been suggested to investigate this phenomenon quantitatively. Limitations in hydrogeologic statistics and indeterminate boundary conditions for most of natural problems make the results of these mathematical models acceptable just for their case studies. Therefore, a more detailed investigation of the effects of seawater intrusion on contaminant transport in coastal aquifers is necessary. A great amount of work may be found in the literature regarding simple geometries or uniform flow patterns in the coastal aquifer. Primary researchers who investigated the freshwater discharge into the sea were KOHOUT (1964) and KOHOUT and KOLIPINSKI (1973). Quantitative measurements by SIMMONS (1992) showed the importance of seawater intrusion role on the contaminant transport in coastal areas.

The discharge of groundwater and associated nutrients and contaminants, however, is not a simple advective process. While fluid advection is certainly important, the dispersive mixing of groundwater with seawater, driven in part by tidal pumping and waveswash (ATAIE-ASHTIANI *et al*., 2001; BAIRD and HORN, 1996), and the chemical transformations that occur during mixing in the beachface zone may contribute significantly to the impact of groundwater to the seep-associated ecosystem (UCHIYAMA *et al*., 2000). Intertidal and subtidal sediments in estuaries are biogeochemically dynamic, and a range of chemical transformations and exchanges between the sedimentary material and interstitial groundwater should be expected as water passes through these reactive sediments and the adjacent beachface. ATAIE-ASHTIANI *et al*. (2001 and 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 were not considered. Also those studies were limited to the part of aquifer close to coast.

Recently, a regional-scale numerical model has been developed by ATAIE-ASHTIANI (2004). This model can simulate the groundwater flow and contaminant flux from coastal aquifers into the coastal zone.

The objective of this study is to investigate the effects of seawater intrusion on migration of contaminant in a coastal aquifer using a two-dimensional groundwater flow and contaminant transport model that is capable to handle the seawater intrusion and contaminant transport simultaneously.

METHODS

We have used MODSharp model in order to investigate the effect of seawater intrusion on the contaminant transport process in coastal aquifers and determine the amount of contaminant discharge into the sea (ATAIE-ASHTIANI, 2004). MODSharp program has the capability to solve salt water and fresh water flow equations simultaneously by using a continuous pressure boundary condition at the interface. Sharp interface approach for conceptualization of seawater intrusion is applied in this model in order to be able to handle problems in regional-scale. Method of characteristics is used to solve advection-dispersion equation, governing to contaminant transport in the coastal aquifer. The model can be used for simulation of groundwater flow and contaminant transport in layered coastal aquifer at regional-scale. The present regional-scale numerical model can be used to develop a better understanding of the interactions between water bodies in coastal zone.

A coastal aquifer with the length of 35 km, width of 25 km and thickness of 204 m is considered. The horizontal and vertical hydraulic conductivity of aquifer are 100 m/day and 10 m/day, respectively, the porosity is 0.4, and the fresh and

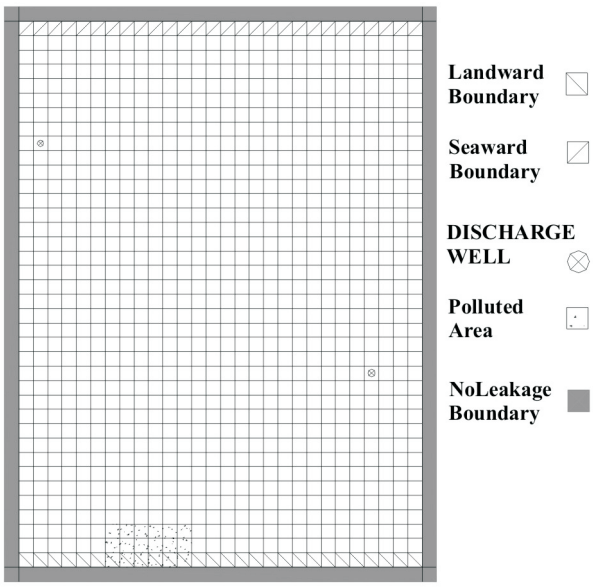


Figure 1. Schematic of considered coastal aquifer.

saltwater specific storages are 10-6 and 1.03x10-6 m-1, respectively. A constant head of 24.1 m at landside and 0.072 m at sea side are considered that cause a constant hydraulic gradient of 0.0012 toward sea. The fresh and saltwater densities are 1000 kg/m3 and 1030 kg/m3. A contamination source with constant concentration of 100 mg/l, C0, in an area of 500x500 m in the middle of land ward boundary is considered. The longitudinal and transverse dispersions of aL=100 m and aT=50 m are assumed. For numerical simulation blocks of 500x500 m are considered. Therefore the number of blocks is 1200 (30x40) and time step is 1 day. Figure.1 shows schematic of considered coastal aquifer.

The concentration contours for both simulated cases (with and without seawater intrusion) after 100 years are shown in Figure 2. As shown, for the case that the influence of SWII is considered the contaminant plume moves slower that the case that SWII is neglected. This difference increases with time. For example after 10 years this difference is 150m and reaches 1200m after 200 years. For practical problems, ignoring seawater intrusion will cause faster contaminant transport which lead to over estimation in spreading and distribution of contaminant plume. Indeed, saltwater intrusion changes the pattern of contaminant transport and distribution before reaching the sea.

RESULTS

Figure.3 illustrates the amount of contaminant discharged to the sea for both cases. Contaminant discharge starts at t=163 yr for the case with SWII while in the other case (without SWII) it happens at t=144 yr. seawater intrusion causes a great delay in contaminant discharge start time. However, the speed and the rate of the discharge for the case of seawater intrusion is so that after 183 years the cumulative amount of contaminant discharge into the sea will become equal.

Hydraulic conductivity is a factor that has a noticeable effect on the seawater intrusion and contaminant transport pattern in the coastal aquifers and also the amount of contaminant discharge into the sea. To investigate the influence of hydraulic conductivity cases with hydraulic conductivity values of 10, 50 and 100 meter per day are considered. A constant flux boundary condition equal to 0.15 m3/sec at landward is assumed. Longitudinal and transverse dispersion are 100 and 50 meters, respectively.

The position of interface has been shown in Figure.4. By increasing the amount of hydraulic conductivity the length of intruded interface increases. This intrusion for the heel of the interface is 120, 360 and 1270 m in the coastal aquifer for the 10, 50 and 100 m/day hydraulic conductivity, respectively.

Due to constant flux boundary condition, the velocity of groundwater flow is constant and changes are just in the shape and length of intruded interface. Figure.4 shows the temporal changes of contaminant concentration in the monitoring well (w1) for both cases.

Monitoring well for the cases of k=10 and 50 m/day is located in the freshwater region and for the case k=100 m/day it is located in the seawater intrusion region. Because of constant velocity in the aquifer the contaminant plume reaches the well at t=115 yr and have the same amount of concentration except the case of seawater intrusion with k=100 m/day that the rate of concentration increase if faster, but finally they meet at t=201 yr.

The amount of contaminant discharged to the sea by using different hydraulic conductivities is shown in Figure.5 and

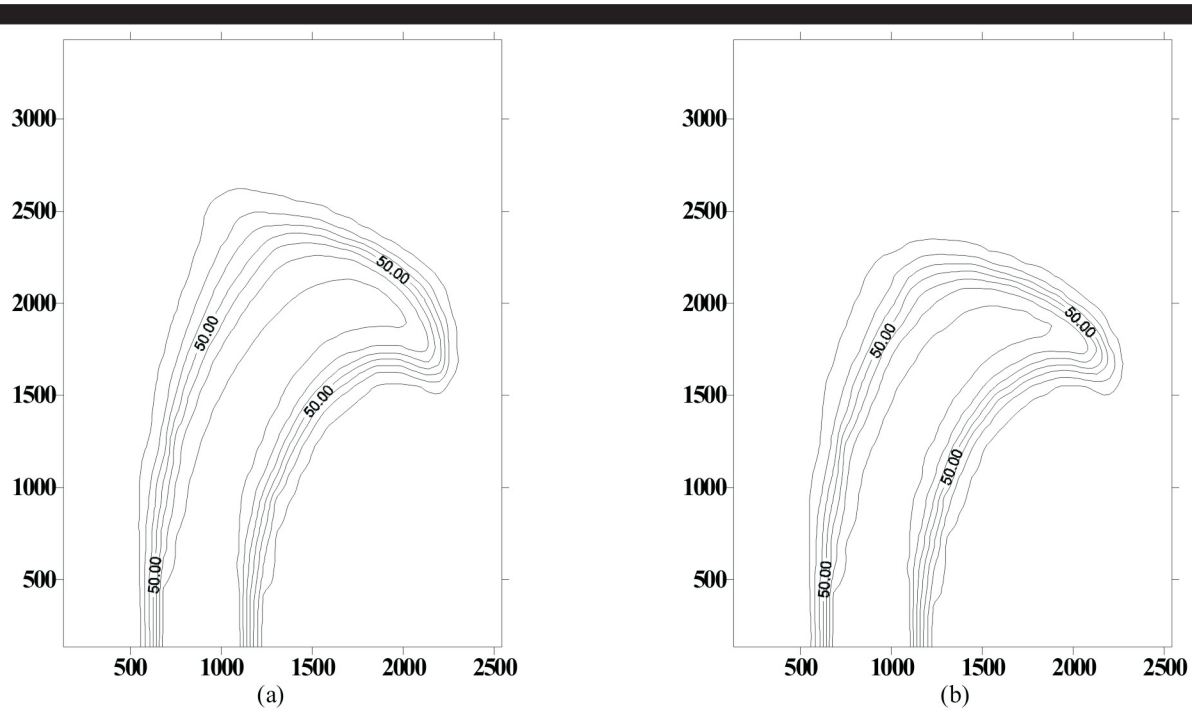


Figure 2. Concentration contours for the case (a) without SWII and (b) with SWII influence after 100 years.

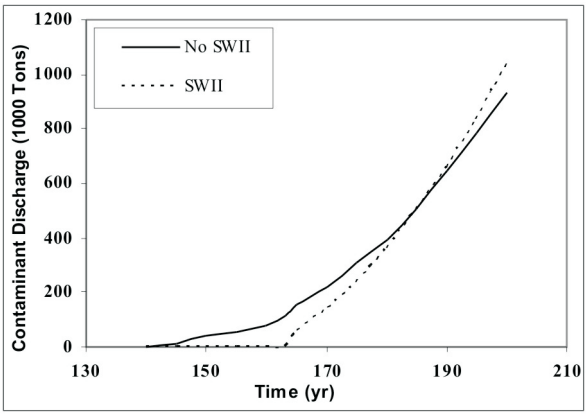


Figure 3. Contaminant discharged to the sea.

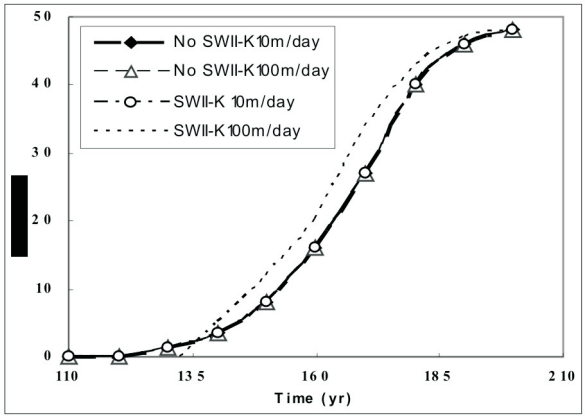


Figure 4. Temporal changes of contaminant concentration in the monitoring well (w1).

Table.1. When we have no seawater intrusion the amount of discharged contaminant is the same for different hydraulic conductivities and occurs at t=140 yr, but for the case of seawater intrusion, saltwater and freshwater interface locates at different depths due to different freshwater heads for different hydraulic conductivities.

Another parameter to consider was specific storage. We have concluded that specific storage does not have a significant influence on the contaminant transport and discharge. It is because specific storage affects on the contaminant concentration just when the subsurface flow regime is unsteady and after reaching the steady state condition 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. For this cases hydraulic conductivity of 100 m/day and a constant flux boundary condition have been used. Figure.6 shows the temporal changes in contaminant concentration of the monitoring well (w1). As dispersion increases, differences between observed concentration in the well and the time of reaching to the well for both cases decrease.

Results indicate that contaminant transport is not considerably sensible to the changes in longitudinal dispersivity. At the same time, when dispersion increases, contaminant discharge to the sea occurs sooner, but the rate of contaminant discharge decreases by increasing dispersion amount for both cases, which is more severe for the case of seawater intrusion. Accordingly, the amount of contaminant discharge is greater in this case.

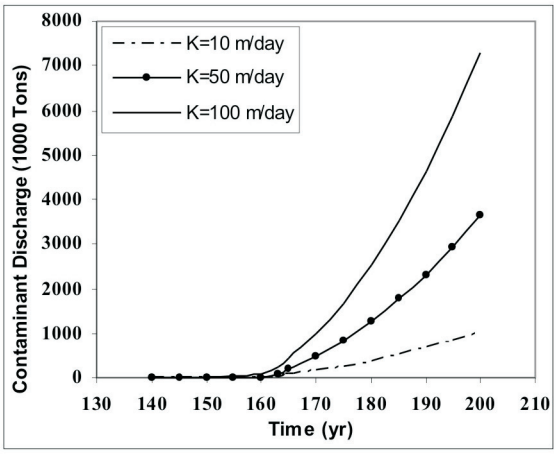
For the cases that the land-ward boundary condition is constant head, it is shown that the simplification and neglecting the effects of SWII causes an erroneous estimate of the speed of the contaminant plume movement toward sea. The existence of SWII decreases the amount of discharged contaminant for a period of time in these cases. However, for the both cases of 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 the cases that the imposed landward boundary condition is constant flux. In this case the amount of contaminant discharge into the sea, for the cases that SWII are considered, is considerably more than this amount for the cases without SWII. The value of hydraulic conductivity has a significant effect on this difference in the amount of discharged. The discharge of contaminant increases, for the cases that SWII exists, with the increases of hydraulic conductivity. However, this amount does not show any difference for the cases without SWII, when hydraulic conductivity changes.

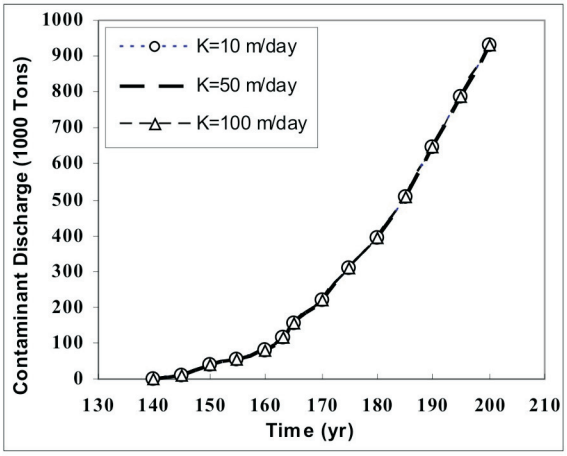
CONCLUSIONS

In order to investigate the effects of seawater intrusion on migration of contaminant in a coastal aquifer a two-dimensional groundwater flow and contaminant transport model (MODSHARP) has been used. The seaward boundary of coastal aquifers has significant influence on the groundwater flow and the amount of contaminant discharged from coastal aquifers into the costal waters.

It is concluded that the over-simplification of seaward boundary condition in numerical simulations causes an



(a)



(b)

Figure 3. An example of the most representative wave and surfer at Brava beach during this work.

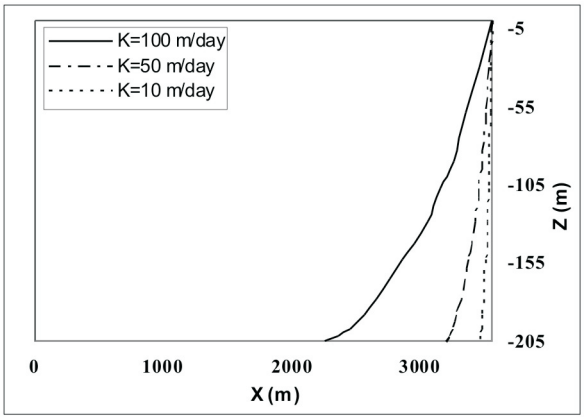


Figure 6. The position of interface for different hydraulic conductivity.

incorrect estimate of discharged contaminant into coastal water. Therefore, it is necessary to properly simulate the SWII in coastal aquifers for a sound environmental management of coastal zone.

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

Table 1. *Amount of Contaminant Discharge (1000 Tons).*

Hydraulic conductivity (m/day)	With SWII	Without SWII
10	1040	947
50	3650	947
100	7340	947

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