

## Effects of aquifer heterogeneity on the intrusion of sea water

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### ABSTRACT

In this study we examined the effects of geologic heterogeneity upon the seawater intrusion in coastal aquifers. Subsurface formations display spatial variability of the permeability such that it changes in an irregular manner in space over scales much larger than the pore scale. We describe hydraulic conductivity as random and characterize it statistically. The study domain is hypothetical aquifer with the properties similar to the actual case study of the Nitzanim aquifer in Israel. 100 realizations of the heterogeneous aquifer are generated and seawater intrusion problem using numerical code SUTRA [Voss, 1984] is solved. The results are statistically analyzed and compared to the common deterministic solution with homogeneous domain and macrodispersion coefficient. We examined the shape of the transition zone, intrusion length and salt concentration uncertainty as a result of aquifer heterogeneity. The results indicate that aquifer heterogeneity does affect the shape of the transition zone and shifts the zone inland compared to the deterministic solution with macrodispersion. The concentration uncertainty is more pronounced in the front of the transition zone and increases with depth.

### INTRODUCTION

Seawater intrusion problems are becoming very important water management issues in coastal regions. As salt water intrudes the coastal aquifer, the groundwater abstraction, especially close to the coastline, becomes saline and remediation measures have to be taken. Since the saline and brackish water cannot be used directly for water supply and agriculture, often desalinization or artificial recharge is attempted to resolve the situation. These actions, particularly desalinization, are very expensive measures directly related to the salinity level in the pumped groundwater. When designing the exploitation of fresh groundwater in coastal aquifers it is important to predict the possible salt concentration level for different pumping scenarios. The salt concentration in the abstracted water will depend, besides system dynamics and considered processes, also on the aquifer geologic heterogeneity through which all physical processes are taking place.

The recent advances in solute transport in aquifers are not directly applicable in saltwater intrusion cases because of coupled flow and transport problem. The saltwater intrusion problems are commonly treated either using the sharp interface models often employing analytical tools or applying transition zone models using numerical modeling. Subsurface geologic variability and dual density between fresh water and salt water in reality creates the transition zone between seawater and fresh inland water. In coastal regions, within that transition zone most groundwater management is usually taking

place. Heterogeneity aspect on saltwater intrusion is not yet fully analyzed and remains one important topic for future studies. In this article we will examine some aspects of spatial variability and their effect on saltwater intrusion prediction. We describe hydraulic conductivity field as a random field and generate 100 aquifer realizations in vertical plane. For each realization, the saltwater intrusion case is solved and results are analyzed statistically. In this study we focus on following issues; (1) comparison between stochastic solution based on Monte Carlo method of 100 aquifer realizations and homogeneous aquifer with macrodispersion coefficient (deterministic solution), (2) distribution of water fluxes (fresh water and salt water) on vertical cross sections within the transition zone and (3) uncertainty in the transition zone position and salt concentration uncertainty within the transition zone.

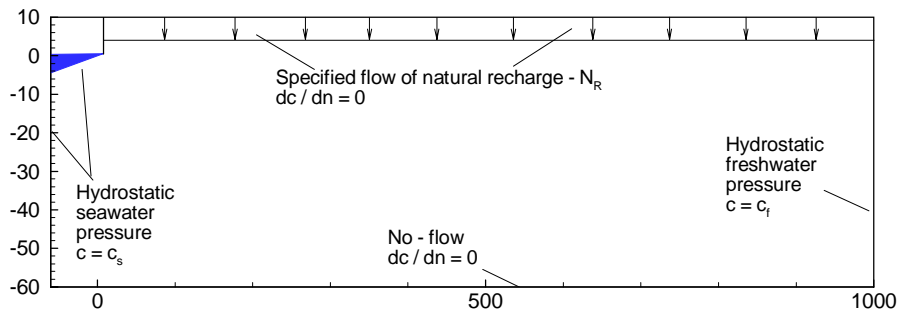
## STATEMENT OF THE PROBLEM

The presented domain is a vertical cross section perpendicular to the coastline extending 1064m in length and 64m in depth. Seawater concentration is considered in total dissolved solids (TDS) and spatial discretization is selected with  $\Delta x = 8m$  and  $\Delta z = 4m$ . All other parameters are actual data from the Nitzanim coastal aquifer in Israel [Berglund et al., 2000]. We also consider a uniform amount of natural recharge of 0.20m/year that represents 40% of precipitation in that region. Table 1 summarizes necessary input data for the numerical simulation. The initial and boundary conditions are presented in Fig. 1. The choice of dispersivity is a lower bound based on grid Peclet number requirement.

Parameter	Value
Seawater concentration	35 000 ppm TDS
Freshwater concentration	100 ppm TDS
Seawater density, $\rho_s$	1025.0 kg/m <sup>3</sup>
Freshwater density, $\rho_f$	1000 kg/m <sup>3</sup>
Density change $d\rho / dC$	700 kg <sup>2</sup> /(kg TDS m <sup>3</sup> )
Geometric mean hydraulic conductivity, $K^G$	$1.75 \times 10^{-4}$ m/s
Longitudinal dispersivity, $\alpha_L$	4.0 (16.0) m
Transverse dispersivity, $\alpha_T$	0.5 (1.60) m
Molecular diffusivity of solute in water, $D_m$	$1 \times 10^{-9}$ m <sup>2</sup> /s
Specific yield	0.36
Natural recharge, $N_R$	0.20 m/year

**Table 1.** Input parameters

For the stochastic simulation we generated hydraulic conductivity field on the selected grid resolution using Hydro\_gen [Bellin and Rubin, 1996] with estimated (based on actual data) ln-K statistics with geometric mean of  $1.75 \cdot 10^{-4} m / s$ , variance  $\sigma_Y^2 = 0.5$  and anisotropic integral scales of 32m and 16m in horizontal and vertical direction, respectively.



**Figure 1.** Domain and boundary conditions

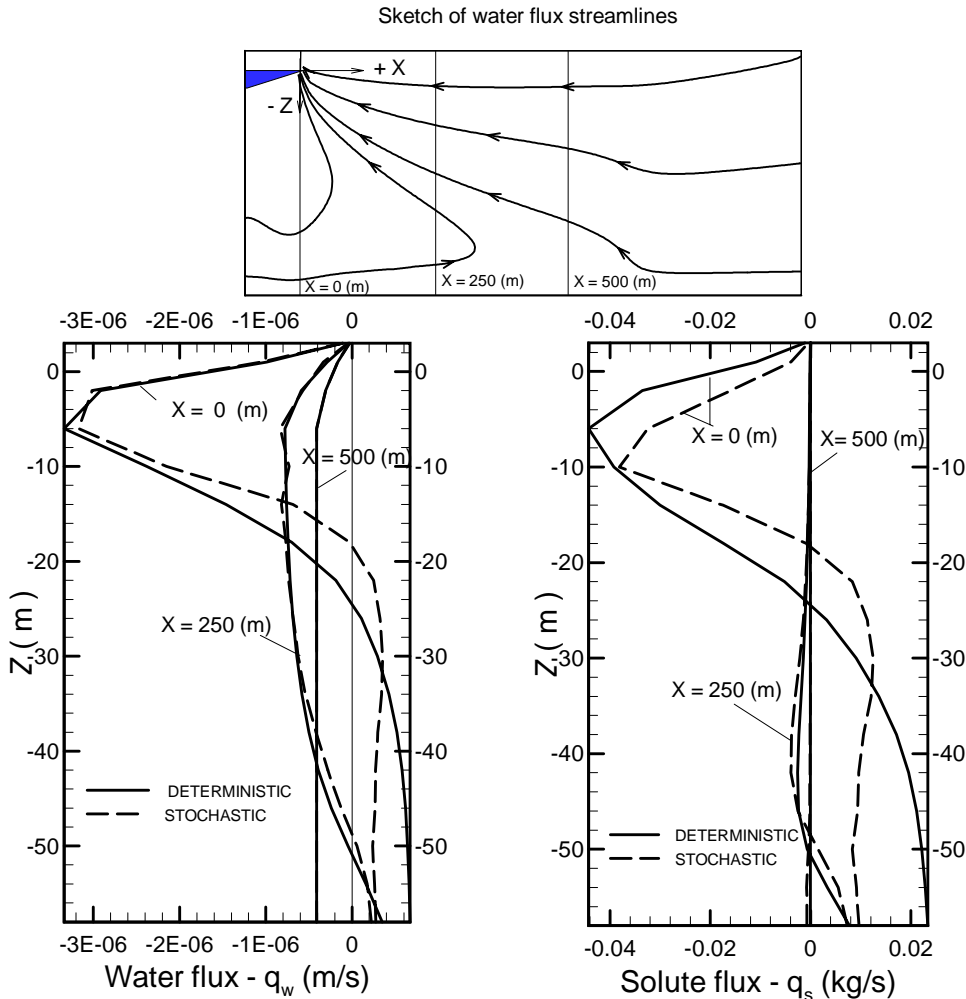
The coupled flow and transport problem is solved in each of 100 realizations of the  $K$ -field using numerical code SUTRA [Voss, 1984]. The output results are processed to evaluate the uncertainty in transition zone displacement and salt concentration.

## RESULTS

### TOTAL FLUX BUDGET

Distribution of water and solute fluxes on vertical cross sections near the coastline presents important discharge characteristics. Along the vertical cross section near the seepage face the fluxes are distributed commonly as outlined on the sketch on Fig. 3. Fresh groundwater is discharging mixed with the saline water flux that has originally intruded the aquifer and then is returning towards the sea. Both fluxes are out flowing the aquifer through the seepage face whose size will depend on system dynamic and heterogeneity level of the aquifer.

We have analyzed three vertical cross sections at  $x=0, 250, 500$  m. At the vertical plane closest to the coastline ( $x=0$ ), the water flux has a significant negative component (direction towards sea) that results in the seepage face at the sea bottom. Total freshwater discharge by outflow at the sea bottom is roughly equal to the groundwater flux imposed by hydraulic gradient (including recharge if any) plus water flux as a density driven flow at the aquifer bottom. The result is an increase of the volume of saline water and a decrease of the volume of fresh groundwater in the aquifer.

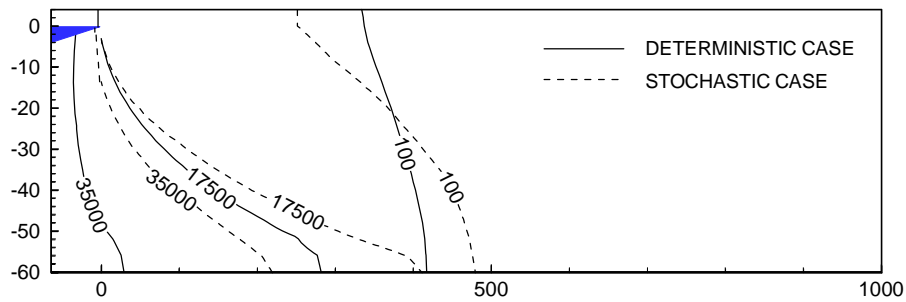


**Figure 3.** Distribution of water and solute flux along the depth for three defined vertical cross - sections.

The comparison between deterministic and stochastic component indicates that stochastic solution has shorter vertical span of the negative flux and in magnitude smaller positive flux in the rest of the vertical cross section. Other two vertical planes, further inland, equilibrate water fluxes and at  $x=500\text{m}$  both solutions show constant flux along the vertical that is equal to the groundwater flux due to the imposed hydraulic gradient. The solute flux at the vertical cross section on the coastline shows a positive component that intrudes the aquifer, get mixed with fresh water and discharges back reduced level of saline water through the seepage face. Stochastic solution behaves similarly as with water fluxes and quickly inland equilibrates at zero solute flux.

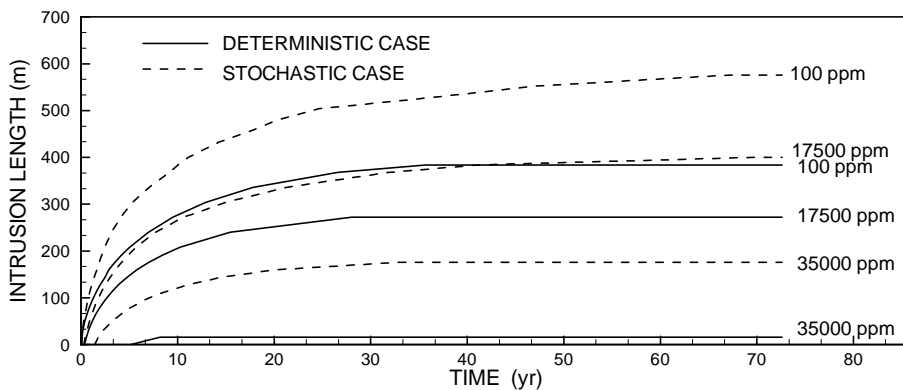
## TRANSITION ZONE DISPLACEMENT STATISTICS

The transition zone is formed as a result of mixing of the solute flux intruding the aquifer bottom and the fresh water flux discharging through the seepage face at the sea bottom. The shape of transition zone and its extent is described with three characteristic contours representing the seawater concentration (35000 ppm), half the seawater concentration (17500 ppm) and fresh water background concentration (100 ppm). Fig. 3 shows the set of contours describing the transition zone in the steady state for deterministic and stochastic case (mean displacement). On the average the stochastic case (based on 100 heterogeneous aquifer realizations) displays larger intrusion at the bottom of the aquifer but with a narrower transition zone. The key difference is in the position of the seawater contour (35000 ppm) that has migrated inland 200 m more in the stochastic case. We contribute this finding to the difference between the deterministic solution with macrodispersion coefficient that applies immediately contrary to the stochastic solution that experience dispersion through the velocity variations slowly as the transition zone develops through time.



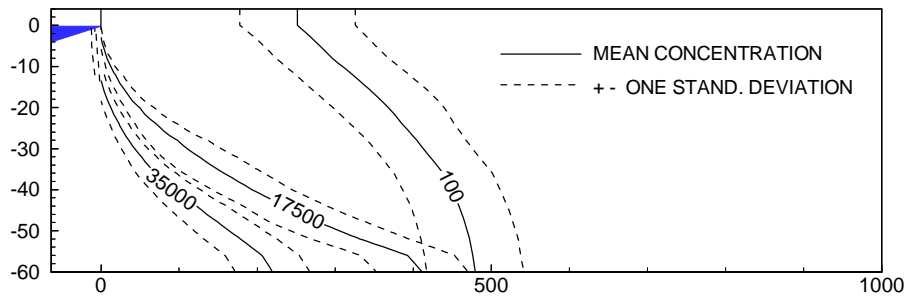
**Figure 3.** Steady state transition zone for deterministic and stochastic solution

Fig. 4 displays the intrusion length at the bottom of aquifer as a transient process. The stochastic solution needs longer time to reach the steady state, which is more pronounced in the front of the transition zone.



**Figure 4.** Intrusion length development for three contours through time

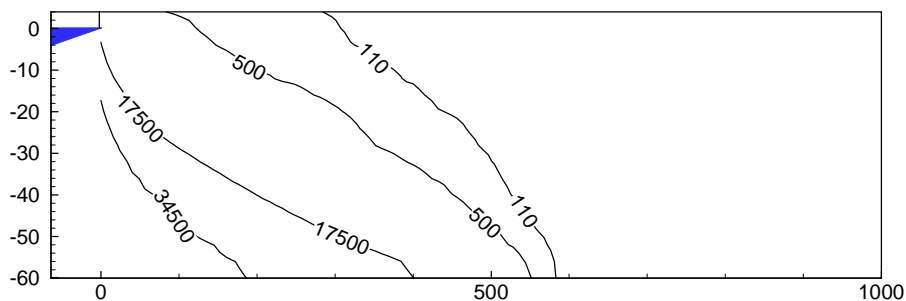
The transition zone displacement uncertainty is shown on Fig. 5. Displacement uncertainty is more pronounced in the front of the transition zone (100 ppm contour) at all depths. The other two concentration levels exhibit the uncertainty increasing from very small at the sea bottom to a similar level at the aquifer bottom. Due to the uncertainty in the seepage face size the uncertainty will never go to zero at the sea bottom unless the sharp interface assumption is adopted [Dagan & Zeitoun, 1999]. This distribution of concentration within the seepage face and its uncertainty in size is very important fresh water discharge characteristic from the marine research point of view usually overlooked when focusing on seawater intrusion in aquifers.



**Figure 5.** Steady state transition zone displacement uncertainty for three characteristic contours  
The uncertainty levels presented in Fig. 5 are given with its mean and plus/minus one standard deviation of the displacement uncertainty.

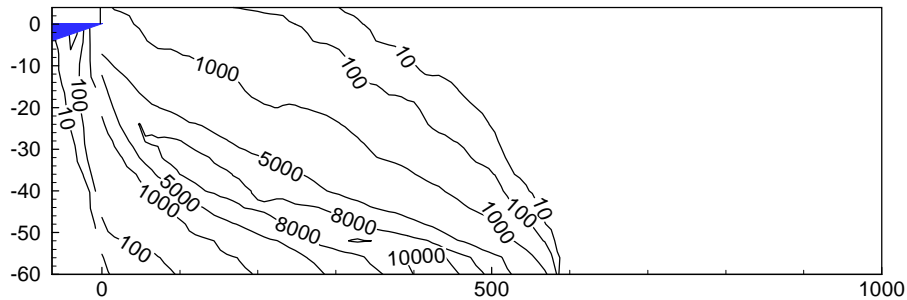
## TRANSITION ZONE CONCENTRATION STATISTICS

The concentration statistics is evaluated by calculating the concentration variability at the fixed location for different times. Fig. 6a displays the mean concentration field and shows the shape of the transition zone created as a result of averaging 100 heterogeneous aquifer realizations. At the bottom of the aquifer the sea level concentration intruded 200m inland and additional 400m is the span of transition zone. Transition zone has very steep mean concentration gradient from the sea-side and it flattens out at the front of the transition zone.



**Figure 6a.** Mean concentration field

Fig. 6b represents the standard deviation of the concentration field. This information is particularly important to provide the confidence bound on the salt concentration level at different locations within the coastal aquifer. The results show that the salt concentration uncertainty is largest in the middle of the transition zone and increases towards bottom where it reaches the highest point close to the intrusion toe. The highest level observed in this example is above 10000 ppm located 450m inland. The high degree of uncertainty at the bottom of coastal aquifer may have important impact on degree of salt in the groundwater abstracted from pumping wells. This phenomenon is called upconing as the interface deforms locally in the shape of cone with its top around the end of the well screen resulting in the gradual increase of the salt content in the pumped water. Since the saline water cannot be used directly for public and agricultural use the actual prediction of salinity level is crucial. The confidence limit of such prediction is important information for selection of remedial actions to be taken in the area.



**Figure 6b.** Standard deviation of the concentration field

To better grasp the uncertainty distribution within the transition zone, we present on Fig. 7 the horizontal distribution of the concentration coefficient of variation at three depths. The horizontal axis is normalized thickness of the transition zone such that 0 represents the location of 35000ppm contour and 1 is 100ppm contour location at the certain depth. At all depths the largest uncertainty is within 25% of the front of the transition zone. At the depth of 50m, which is close to the bottom of the aquifer, the CV exceeds 2 within the large area (approximately 100m) and shows the large confidence limits around the mean concentration. Moving close to the surface the concentration variability is decreased and at the 10m below the surface, the concentration CV is mostly below one and more evenly spread within the transition zone.

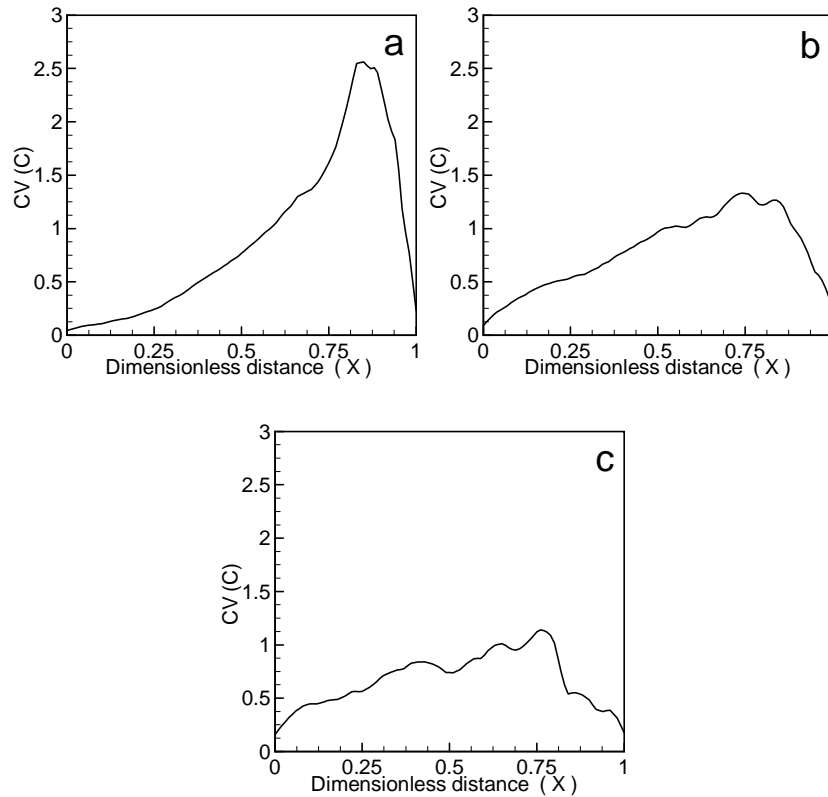


Figure 7. Concentration coefficient of variation  $CV = \sigma / \mu$  at a)  $Z = -50\text{m}$ , b)  $Z = -30\text{m}$  and c)  $Z = -10\text{m}$

### CONCLUDING REMARKS

In this study we analyzed the impact from the geologic heterogeneity upon the development of the transition zone of saltwater intrusion. The results clearly indicate that heterogeneity plays the important role not only in the transition zone displacement but also results in the salt concentration variability particularly in the lower portion of the coastal aquifer. The size of the seepage face and the concentration level of discharging water are also subject to uncertainty and may have impact on the marine research issues. The formation of transition zone and its shape is affected by aquifer heterogeneity and on average the stochastic solution shows larger intrusion of the background sea level concentration than deterministic solution. The concentration variability as presented with its coefficient of variation clearly indicates that the largest uncertainty in the salt concentration level is at the bottom of a coastal aquifer. This uncertainty can have direct impact on groundwater abstractions in the coastal areas and can cause many pumping wells to quickly become saline and have to be abandoned. The effects from heterogeneity upon saltwater intrusion should be accounted for on the site-specific basis since those

effects are dependent on the conceptualization of the domain and physical processes considered.

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