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Numerical Study of Saltwater Freshwater Interface and Dispersion

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Abstract

In this study we numerically examined the dynamics of the saltwater-freshwater interface. We compared the results of the numerical simulator with those of the laboratory experiments and obtained good agreement, with both producing sharp saltwater-freshwater fronts. Using similar parameters as those observed at Biscane Bay we could not numerically reproduce the extensive mixing zone observed there (Cooper et al., 1964). Under static or periodic tidal boundary conditions mixing does not seem to occur even with significant heterogeneity, which questions the physical representativeness of the Henry problem. We conclude that the wide transition zone is most likely caused by the seasonal fluctuation (low frequency) of freshwater head rather than tidal effects (high frequency) and is a transient phenomenon.

1 Introduction

Understanding the dynamics of seawater and fresh water interaction is critical for protection of water resources and other environmental challenges including nuclear waste storage and geologic sequestration of CO2. In recent years, the predicted sea level rise due to the global warming has made it even more important. Some countries are contemplating storing high-level nuclear wastes in coastal areas. Accurate characterization and reliable long term prediction of groundwater flow and transport around a potential repository are crucial to the safe operation of the repository.

Many works have been published regarding seawater-freshwater interactions involving analytical and numerical works. Bear et al (1999) compiled numerous works on the investigation of sea water intrusion in coastal aquifers. In their seminal report "Sea

Water in Coastal Aquifers", Cooper et al (1964) concluded that sea water in coastal formations is not stagnant but is in constant cyclic motion where a significant amount of intruding salt water is carried back to the sea by dispersive mixing due to the tidal motion and seasonal rainfall. They concluded that the dispersion causes the saltwater wedge to be blunt in shape and that a wide transition zone exists, limiting the landward intrusion of seawater, as opposed to the sharp interface predicted by the Ghyben-Herzberg line. The same report presented a semi-analytical solution to the density coupled flow equations that allow mixing of saltwater and freshwater by assuming a large dispersion coefficient, which later became known as the Henry problem. Over the years many works were published (ex. Voss and Sousa, 1987; Croucher and O'Sullivan, 1995; Oldenburg and Pruess, 1995; to name a few), where the Henry problem was used as a benchmark for numerical simulators. None of them seem to match exactly to each other's results or the Henry solution itself. Gotovac et al (2003) proposed an improved collocation method that has less numerical stability problem to solve the Henry problem. In the Henry problem it is the freshwater outflow portion of the sea side boundary that poses numerical challenges, which is that of Dirichlet maintained at the concentration of sea water. They also solved a modified Henry problem by introducing a buffer zone between the well-mixed sea and the porous media. Simpson and Clement (2004) proposed a modified Henry Problem, with a sharper front, for benchmarking numerical models. Held et al (2005) numerically examined the Henry problem in heterogeneous formations, producing wide mixing front. Servan-Camas and Tsai (2010) successfully used the lattice Boltzmann method to suppress numerical errors to study the Henry problem in an anisotropic heterogeneous conductivity and velocity-dependent hydrodynamic dispersion filed. Herckenrath et al (2011) showed that the null-space Monte Carlo method is effective for quantifying uncertainty of a saltwater intrusion model with a mildly heterogeneous parameter field.

Strack (1976) introduced a sharp-interface (immiscible flow) solution using a single potential function to study the saltwater intrusion problem. Volker and Rushton (1982) compared the sharp-interface solution solved by a boundary element method with a miscible-interface solution obtained by a finite difference model. Huyakorn et al (1996) presented a sharp-interface numerical model for a multi-layered system. Sakar (1999) conducted a numerical study on the applicability of the sharp-interface approach and concluded that the sharp-interface solution can be used in some cases with caution.

Through a numerical study, Ataie-Ashtiani et al (1999) concluded that tidal effects are significant in unconfined aquifers, producing wide transition zones between saltwater and freshwater. Dausman and Langevin (2004) predicted future movement of the saltwater-freshwater interface in Broward County, Florida using field observations and numerical modeling and concluded that the upstream canal stage controls the movement and location of the saltwater interface. Cheng et al (2004) numerically investigated the effects of tidal loading in China and concluded that the length of the aquifer roof extending under the sea corresponds with certain aquifer parameters in the extrapolation zone. Shibuo et al (2006) conducted a numerical study to examine the effect of bathymetry in the Aral Sea and showed that the regional topography and bathymetry largely influence submarine groundwater discharge and seawater intrusion transients as the Aral Sea shrinks. Brovelii et al (2007) numerically examined the tidal effects on contaminant transport in the coastal area and concluded that it is important to consider the effects of tides. Lu et al (2009) and Lu and Luo (2010) postulated using numerical simulations that kinematic mass transfer between mobile and immobile domains may explain wide mixing zones.

As opposed to the abundance of analytical and numerical works, limited publications are available on laboratory and field measurements. Barlow (2003) presented a comprehensive analysis on the saltwater-freshwater environments of the Atlantic Coast based on a massive amount of field data. Kim et al (2006) used various geophysical techniques to observe seawater-freshwater interactions on a volcanic island. They observed sharp interfaces in most boreholes. Taniguchi et al (2006) studied the relationship between submarine groundwater discharge (SGD) and the freshwater saltwater interface by measuring SGD rates, conductivity and temperature of SGD, and resistivity measurements across a coastal aquifer and found that the processes of SGD differ between the offshore and near shore environments. Goswami and Clement (2007) presented laboratory results of steady-state and transient data to be used for benchmarking numerical models. Maekawa et al. (2007) also presented results from their laboratory experiments. In addition to a homogeneous case, Maekawa et al. examined a two-layer heterogeneous case. Abarca and Clement (2009) proposed a colorimetric method that employs the reaction between alkaline freshwater and acidic saltwater to visualize the mixing zone.

Although numerous works have been published on the Henry problem and comparisons between the sharp-interface and miscible-interface models, most of them have been focused on numerical solution techniques or benchmarking between codes. Comparisons have been made between the sharp-interface solution and the dispersive interface approach with an a priori assumption that the latter is more realistic. However, to our knowledge the question of whether there is substantial mixing at the freshwater−saltwater interface, which warrants the large dispersion coefficient commonly used in the benchmarking and comparisons, has not been adequately addressed. Nor has the mechanism of mixing has been satisfactorily studied to explain the physical cause of the mixing. In the present paper, we examine if there is indeed a strong mixing at the saltwater-freshwater interface. We do so by first making some laboratory observations and then conducting numerical experiments using the TOUGH2 simulator (Pruess et al, 1999), a non-isothermal multi-component, multi-phase simulator capable of simulating miscible density flow.

2 Experiments vs. numerical simulation

Maekawa et al (2007) constructed an apparatus and conducted laboratory experiments to visually observe the saltwater-freshwater interactions. Figure 1 shows the apparatus. Shown in the center is the sandbox with a transparent face plate to allow visual observation. Glass beads were used in place of natural sand. The dimension of the sandbox is 25 cm × 50 cm × 10 cm. On the left hand side is the saltwater reservoir with a circulation mechanism to maintain a constant concentration of saltwater and on the right is the freshwater reservoir. Each reservoir is attached to a tank with adjustable elevation to regulate the levels of the saltwater and freshwater columns.

First the system is filled with freshwater with a designated difference in the fluid levels between the two sides. When the system comes to a steady state with freshwater flowing from right to left, the reservoir on the left is swiftly filled with colored salt water of a predetermined concentration. A higher water level is maintained on the freshwater side so that fresh water keeps flowing to the saltwater side. If the water level difference is

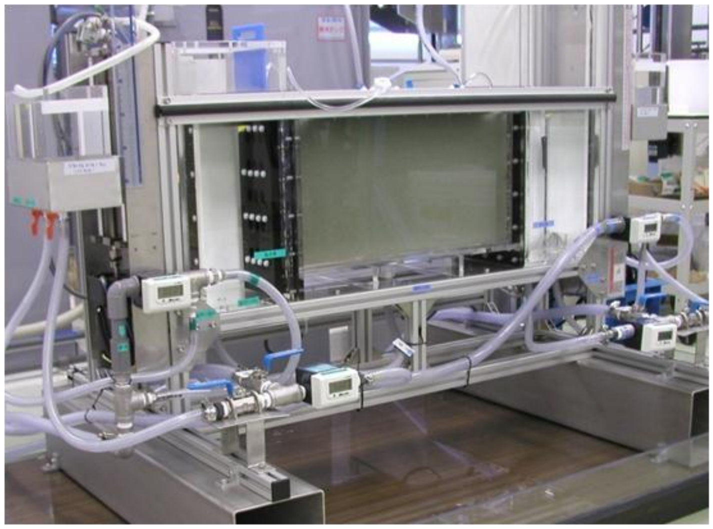

Figure 1. Experimental setup for the saltwater intrusion experiment

low enough to be overcome by the density difference, a saltwater wedge begins to encroach into the sand box. Depending on the density of saltwater and the difference in water levels, the encroachment speed and distance vary. Using glass beads of different sizes, sand layers of different permeability are created. A description of the apparatus and the results from the experiments with varying parameters are discussed in Maekawa et al (2007). The use of an optical measurement to accurately measure the interface geometry using the same apparatus is discussed in Oda et al (2011).

We compare the results of the experiment to numerical simulations using the numerical simulator TOUGH2 (Pruess et al., 1999). Detailed results and analysis of the various laboratory experiments are outside the scope of the present paper and only selected comparisons are presented here. Figure 2 shows a comparison between the experiment and the simulation for a homogeneous case with the freshwater level maintained 7.5 mm higher than the level of the salt water of 4% concentration. Glass beads of 1 mm diameter with a measured average hydraulic conductivity of 1.2×10^{-2} m/s are used. The simulation uses a molecular diffusion coefficient of 1×10^{-9} m^2/s for both

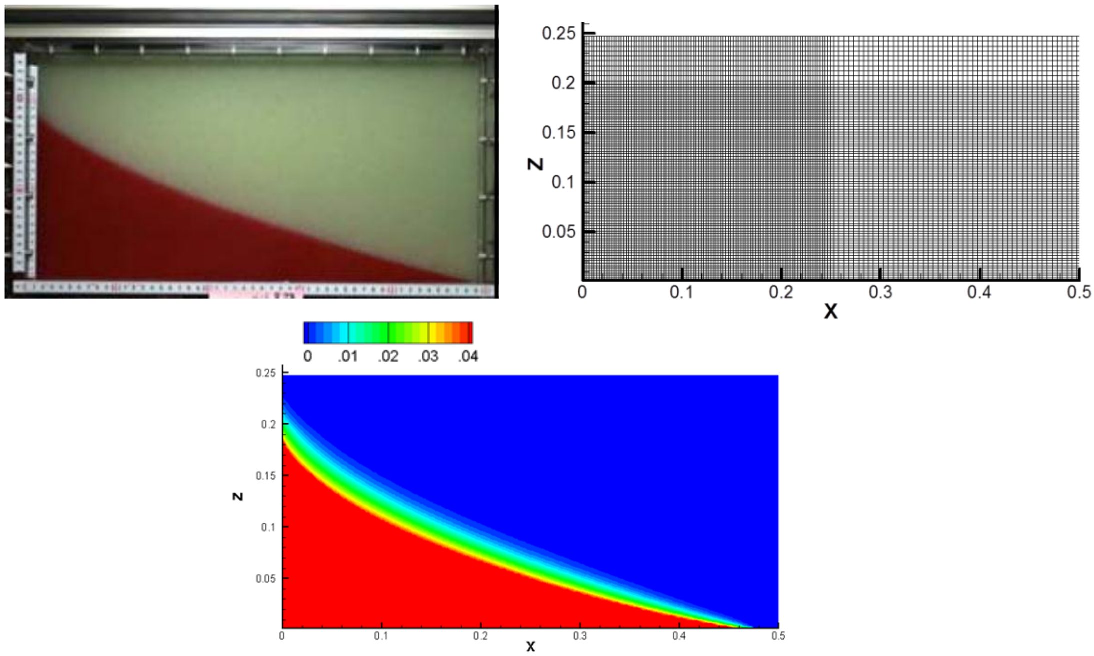

Figure 2. Comparison between the experiment (top left) and simulation (bottom) for a homogeneous steady state case. The color bar shows the salt concentration with red being 4%. The top right figure shows the mesh density.

saltwater and freshwater. The picture (left) is taken when the saltwater wedge came to rest. The plot on the right is the steady-state simulation result. The red color represents the original concentration of the saltwater and the blue is freshwater. As can be seen from the figure, the simulation closely matches the experiment except that in the simulation the saltwater−freshwater interface is blurred because of numerical dispersion, which we tried to minimize by a fine mesh discretization as shown in the figure. In contrast, the experiment shows very little dispersion at the interface, where saltwater and freshwater are flowing in opposite directions. The effect of molecular diffusion is insignificant. Similar observations were made by Goswami et al (2007) in their experiment.

The next comparison is the heterogeneous two-layer case with a layer of 1mm diameter glass beads on top of the layer with 0.4mm diameter glass beads (Figure 3). The average measured hydraulic conductivity of the latter is 1×10^{-3} m/s, which makes the permeability contrast about one order of magnitude. The fresh water level is maintained 7.5mm higher than the saltwater. The saltwater wedge in the top layer advances faster than that in the bottom layer and the red saltwater from the top layer is seen to leak down to the layer below at 24 minutes. The wedge in the bottom layer eventually catches up with the top layer to form an almost single wedge at large time.

Blue colored water is released from the bottom part of the right side to observe the flow of freshwater from the right side. It is interesting to note that a thin layer of uncolored water is visible between the blue streak and the red wedge at 48 and 72 minutes. That is the water flowing from the bottom layer over and along the wedge in the top layer. At 225 minutes, the blue water that flows through the bottom layer finally fills the space. The moving front of the saltwater wedges does not disperse noticeably in either layer.

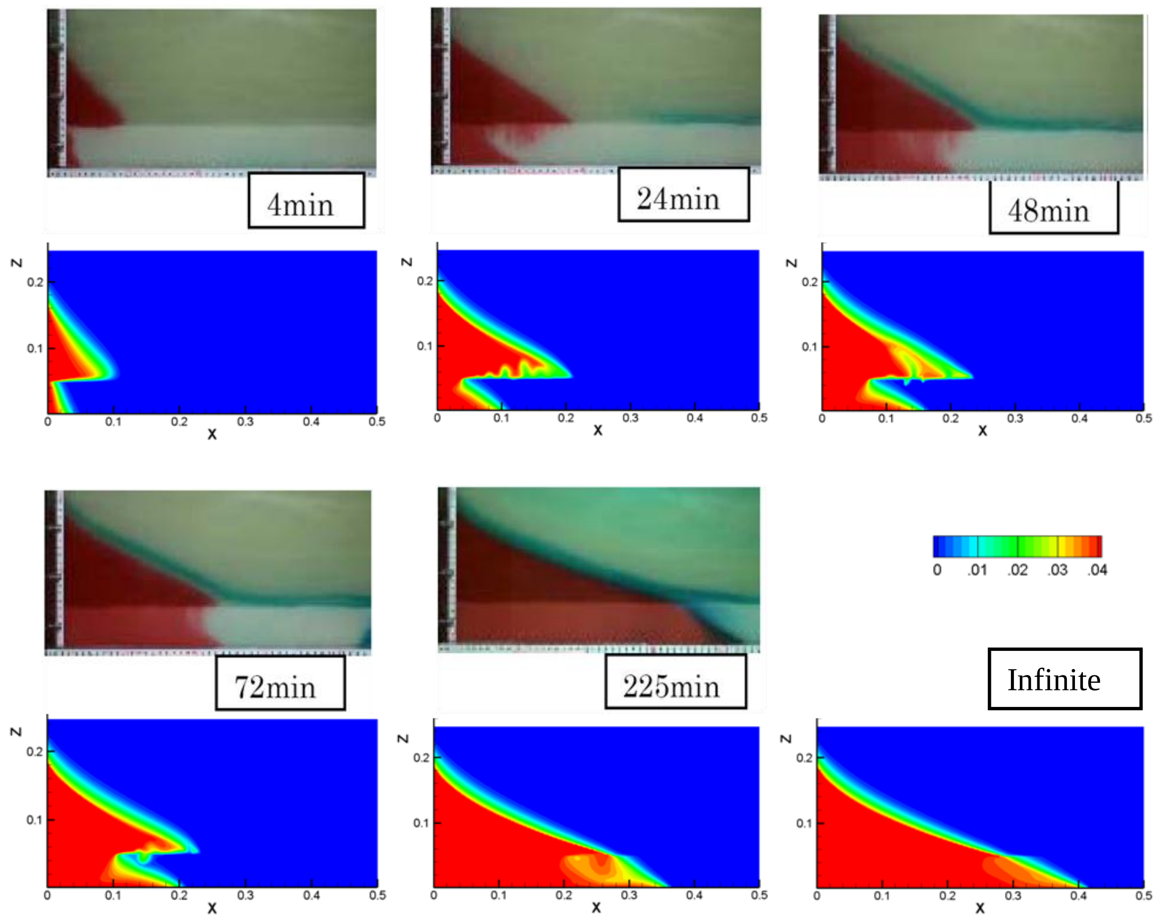

Figure 3. Comparison between the experiment (top) and simulation (bottom) for the two layer case.

As can be seen in Figure 3, the simulation matches reasonably well with the movement of the wedges. It even reproduces the saltwater leakage from the top layer to the layer below. Initial simulations failed to produce any leakage, which was accomplished by assigning a slightly rough boundary between the two layers to induce instability. This is reasonable because the layers of glass beads with two different diameters are not expected to be packed perfectly with a smooth boundary. The discrepancies between the experiment and simulation such as the wedge lengths and speed may be attributable to subtle variations in the experiment as well as numerical difficulties in re-creating the exact experimental conditions. For example, although a great care was taken in the preparation, the measured permeability of the glass beads varied from as much as by 25% and the porosity varied by 10% between each measurement. This is probably caused by subtle differences in the filling and subsequent settling of glass beads. Another difficulty is the delicateness of the experiment: a few mm difference in the water level significantly affects the wedge position.

Based on the two examples shown, we can reasonably assume that the simulation is correctly capturing the saltwater-freshwater interaction for the cases studied.

3 Mixing mechanism

Deducing from the observations made at Biscayne Bay, which show a wide transition zone between sal and fresh water, Cooper et al (1964) theorized that there is strong dispersion at the freshwater-saltwater interface that retards landward advancement of saltwater, whereby much of saltwater is carried back to the sea mixed with freshwater. They reasoned that the seawater wedge is in constant to-and-fro motion due to the tides and that the upward flow of freshwater approaching the sea enhances the mixing. In the accompanying paper Henry (Cooper et al., 1964) presented the solution to the Henry problem, where a large dispersion coefficient (1.88×10^{-5} m^2/s) is assumed. Works that followed also used similarly large dispersion coefficient or a dispersivity of 0.075m combined with a molecular diffusion coefficient of 5×10^{-7} m^2/s (Held et al, 2005). A large dispersion coefficient no doubt causes a wide mixing zone. However, none questioned the rationale of using such a large dispersion coefficient. In this section we conduct numerical experiments to see if a wide mixing zone is indeed produced by the conditions likely to exist in coastal aquifers without assuming a large dispersion coefficient a priori. We model layered and random heterogeneities and assign sinusoidal boundary conditions that resemble those encountered such as tides and seasonal fluctuations in coastal aquifers.

We use the same numerical model used in Section 2 with a horizontal dimension of 0.5m and a grid size of 5mm or 1/100th of the horizontal dimension. A model with 500m length and 5m grid spacing was also examined and it was found that the results are essentially linearly scalable.

3.1 Tidal Motion

To examine if cyclic saltwater level changes mimicking the tidal motion can cause mixing, we assigned a sinusoidal boundary condition on the saltwater side (the left side) with an amplitude of 1 mm (equivalent of 1m amplitude for a 500m long model) with a 12 hour cycle. The result of the simulation (no figures shown) was that the saltwater wedge moved smoothly back and forth without showing any sign of additional mixing, much like the experiments in Section 2. It is found that the tidal motion alone does not enhance mixing under the given conditions.

The parameters used in the simulation (Table 1) are based on the dimensions of the sandbox and the properties of the glass beads in the original laboratory experiment. However, the parameters are not very different from those observed by Cooper et al (1964) in the Biscayne Bay area except the hydraulic gradient, which is not explicitly mentioned in their paper. It should be noted that in the Henry problem, a specific freshwater discharge is prescribed on the freshwater side boundary. On the other hand, in the experiment and in the model, the difference in water levels are specified, i.e., it is a Dirichlet boundary condition.

Table 1. Comparison of the parameters between the Biscayne Bay and the model.

	K (m/s)	*Porosity*	*Δh/L*	*Specific freshwater discharge (m/s)*
Biscayne Bay	3.5×10^{-2}	*0.35*	*0.001**	*NA*
Henry Problem	1×10^{-2}	*0.35*	*NA*	6.6×10^{-5}
Experiment, Model	1.2×10^{-2}	*0.38*	*0.015*	9.6×10^{-5}**

***:** Estimated; **:Model calculation at steady state, no measurements in the experiment.

3.2 Heterogeneity

In the homogeneous case and two-layer case discussed above, we are unable to create any noticeable dispersion that induces a wide transition zone, even with a sinusoidal boundary condition. This is somewhat expected because so far we have dealt with a homogeneous system and a system with just two layers. In reality, even seemingly homogeneous sand formations can have many sub-layers with varying properties.

We now model a formation with alternating layers with a permeability contrast of one order of magnitude (Figure 4-a) that is subjected to a sinusoidal boundary condition with an amplitude of 1mm and a period of 12 hours. Figure 4(b) and Figure 4(c) show a snapshot of the wedge at low tide and high-tide, respectively. Repeated cycling by the sinusoidal boundary condition does not induce noticeable mixing. A case (not shown) with one order of magnitude lower permeabilities for each layer gave similar results without retarded front. Cooper heuristically argued that the saltwater in the lower permeability layers will be swept up by the vertical flow and mixing will ensue, which does not seem to take place with the parameters tested here. Furthermore, we find that Cooper's calculation of the amplitude of tide-produced motion is in error, predicting one order of magnitude lager amplitude of 12.5 feet at the distance of zero from the shore. In our calculation we obtain 1.2 feet instead for the same parameters.

Next we construct models with a random permeability field to examine if random heterogeneity enhances mixing and thus creates a wide transition zone. The first case is an isotropic random field for log-permeability with the correlation length λ of 0.025m or 1/20 of the width and an exponential covariance function with variance $\sigma^2 = 0.5$ (Figure 5(a)). We use Hydro-Gen (Bellin and Rubin, 1995) to generate the random fields. The second case is a random field with an anisotropic correlation length with $\lambda_x=10\cdot\lambda_y=0.025$m and the same variance (Figure 5(d)).

A sinusoidal boundary condition is applied on the saltwater side to simulate the tidal motion with an amplitude of 1.25mm. Figure 5(b) and (f) show snapshot of the advancing wedge in the isotropic and anisotropic random model, respectively, when the saltwater level is rising, and Figure 5(c) and (g) show the retreating wedge in the same respective model. As can be seen from the figures, although the saltwater front is somewhat dispersed due to the heterogeneity, the transition zone is not very wide and the advancement does not appear retarded or the shape of the wedge stubbed-toed. The transition zone becomes wider when the wedge is retreating, leaving some unswept spots behind, which disappear at the lowest tide. The transition zone is compressed when the wedge is advancing. Figure 5 (d) and (h) show the wedge at steady state without cyclic tidal boundary condition for isotropic and anisotropic random model, respectively. As can be seen from the figures, a combination of heterogeneity and tidal motion does not enhance mixing significantly at the interface.

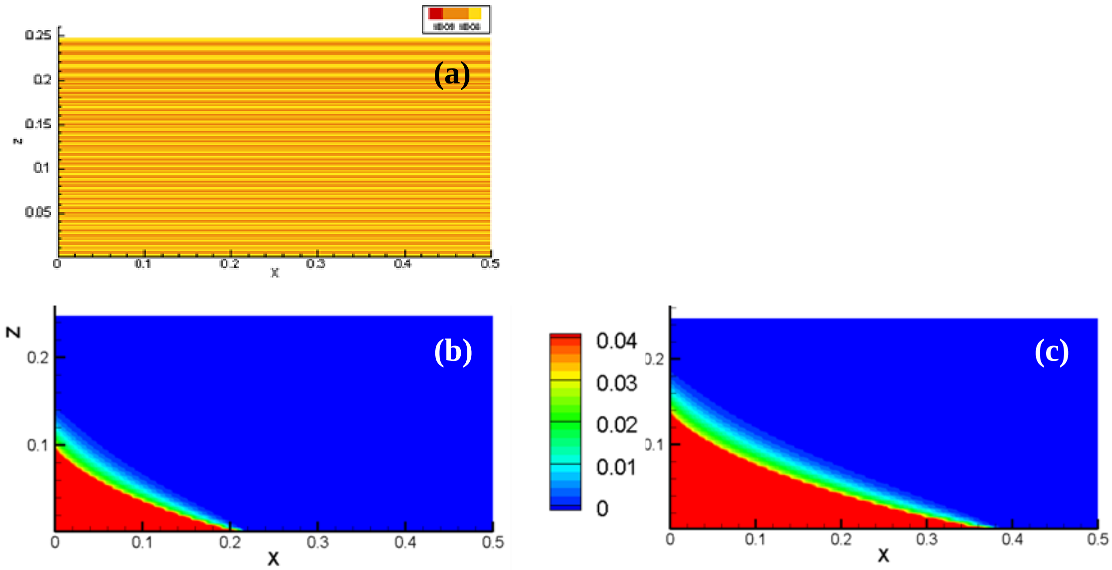

Figure 4. (a) Alternating layer model with the yellow color representing the permeability of 10^{-8} m^2 and the brown, 10^{-9} m^2. (b) Saltwater wedge at low tide when a sinusoidal boundary condition is applied on the right edge, and (c) at high tide.

3.3 Field Scale Model

So far the model dimensions have been those of the laboratory experiment, i.e., 25cm high and 50cm long. Although the scalability has been examined using a 250m by 500m model, the effects of the dynamic boundary condition and heterogeneous permeability fields have not been examined at a realistic field scale. We construct a 720m long model aquifer with a thickness of 30m, which approximates the Biscayne Bay aquifer. We subject the model to sinusoidal boundary conditions both on the saltwater side and freshwater side. The seawater side is the tidal boundary condition with an amplitude of 0.35m and a period of 12 hours. The boundary condition on the freshwater side is also sinusoidal but with a 250 day cycle and an amplitude of 0.3m that simulates the seasonal fluctuation of freshwater head. It was found that the tidal boundary condition alone has no discernable effects on the saltwater wedge movement. However, the seasonal fluctuation even with lower amplitude than the tide has a large effect on the wedge position as can be seen in Figure 6, which is the homogeneous case. Although the position moves rather markedly with the fluctuating freshwater head, the advancing freshwater-saltwater boundary is not dispersed more than what is expected by numerical dispersion. The retreating wedge does show a slightly wider transition zone.

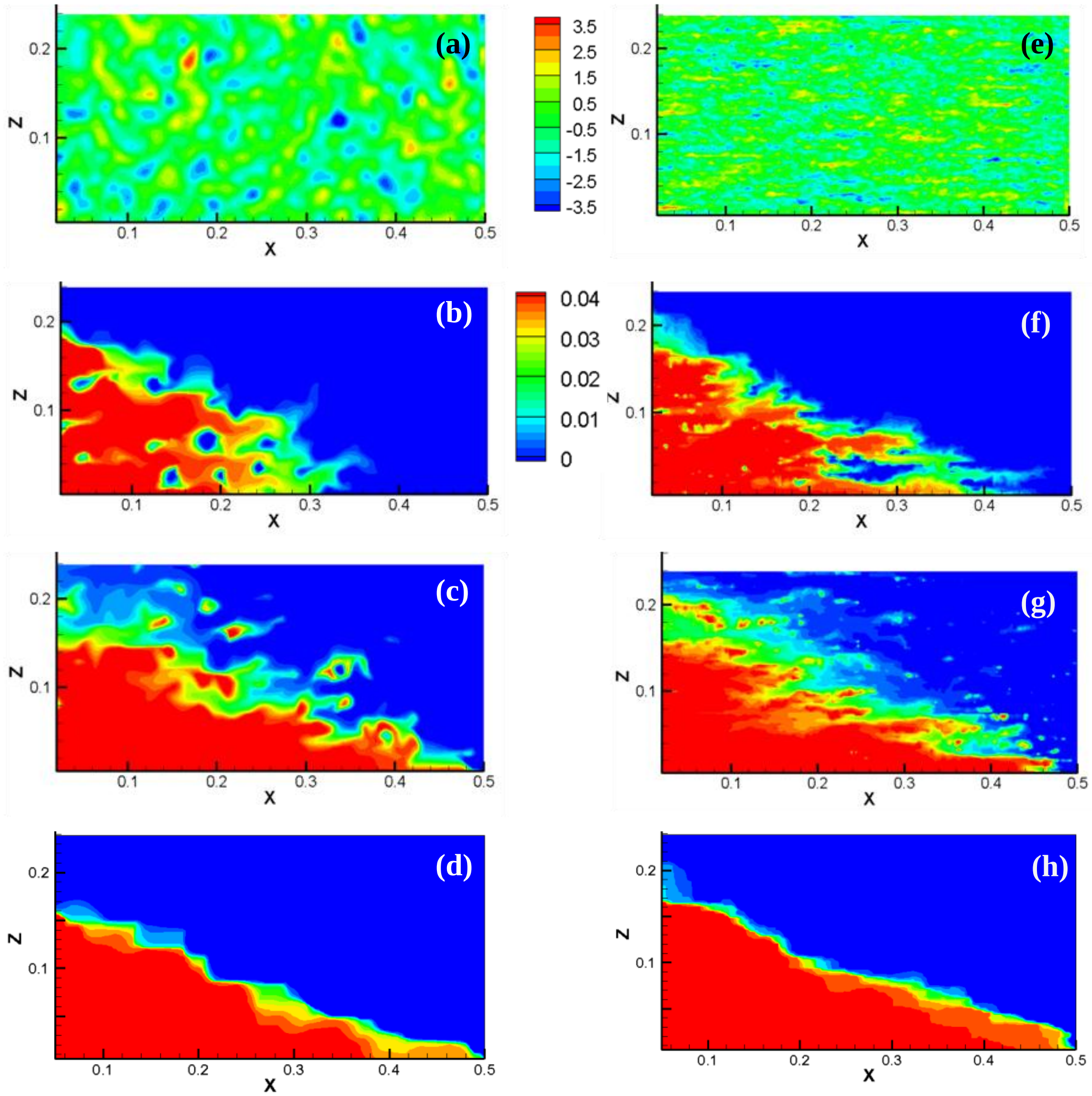

Figure 5. (a) Isotropic random log-permeability field generated with the exponential covariance function with an integral scale of 0.025m and σ^2=0.5. Colors show logarithmic deviation of permeability from the mean. (b) advancing saltwater wedge with the sinusoidal boundary condition, (c) retreating saltwater wedge, (d) wedge at steady state. (e) Anisotropic random permeability field with an integral scale of 0.025m in x, with x:z anisotropy ratio of 10:1, (f) advancing wedge, (g) retreating wedge, and (h) wedge at steady state. Colors for (a) and (b) indicate log permeability ratio, and (b)~(d) and (f) ~ (h) indicate the salt concentration.

Figure 7 shows the case where the permeability of the aquifer is a random field with the horizontal anisotropy ratio of 10:1 with the exponential covariance function and the variance σ^2=0.5. The seasonal freshwater level fluctuation with a long period of 250 days has a large effect on the wedge movement. The retreating wedge during the wet period (high freshwater level) has relatively wide transition zone. However, it is a transient phenomena and the advancement of the wedge does not appear to be held back by dispersion compared to Figure 6.

Based on these results, we conclude that the apparent wide mixing zone in Copper et al (1964) and elsewhere is likely to be a transient phenomenon caused by long period (lower frequency) changes such as the seasonal fluctuations of the freshwater level than diurnal tidal motions with a 0.5 day period.

Mapping the geometry of the interface and its movement in the field is very tenuous. Monitoring wells are typically used for this purpose. However, it is difficult to measure the evolving salt concentration accurately as a function of time and space because there is inherent mixing within the monitoring intervals that would dilute the salt concentration. It is also a challenge for geophysical methods such as electrical resistivity tomograms to resolve a high contrast interface.

4 Discrepancy in the dispersion theory

There are some problems in applying the concept of dispersion mechanism at boundaries and as an initial condition. The dispersion is a statistical interpretation of the spreading phenomena and there is no physical driving force involved. But once the framework of Fickian diffusion is assumed to hold for dispersion, concentration gradient becomes the driving force.

For example, let us consider the case where an instantaneous point source of a tracer is introduced at $x = 0$ in a 1-D uniform flow field of velocity U. According to the classical advection/dispersion theory, the tracer spreads due to dispersion as the center of mass travels downstream. The spread is symmetric and the half width of the plume, δ at time t due to dispersion is approximately $\sqrt{4Dt}$. D is the dispersion coefficient which can be written as: $D = D_m + \alpha U$, where D_m is the molecular diffusion coefficient and α is the dispersivity. If we consider the case where kinematic dispersion is much larger than molecular diffusion, i.e., $\alpha U \gg D_m$, then $D \sim \alpha U$. Because kinematic dispersion does not have any physical force to spread tracer upstream beyond the injection point, the half width δ should never be greater than the travel distance, Ut, of the center of the mass. Therefore, we require

$$Ut \geq \sqrt{4\alpha Ut} \tag{1}$$

However, $\alpha, U\ and\ t$ are all independent variables (other than $\alpha U \gg D_m$), there is no guarantee that Equation (1) is satisfied in general. Simplifying we get

$$\alpha \leq {Ut}/{4} \tag{2}$$

When modeling tracer transport using the classical advection/dispersion theory, Equation (2) should be implemented to condition α. A similar argument was made by de Marsily (1986, p 243) questioning the applicability of the classic dispersion theory when the concentration gradient is positive in the flow direction causing the kinematic dispersion to spread a contaminant upstream. However, in our opinion, even when the concentration gradient is negative, dispersion could not be a physical driving force to enhance the propagation of contaminant. In the classical theory dispersion is symmetric and thus Eqaution (2) should also be applied when the concentration gradient is negative.

5 Conclusions

In this study we numerically examined the dynamics of the saltwater and freshwater interface. We compared the results of the numerical simulator with those of the laboratory experiments and obtained good agreement. Some moderate to extreme cases of heterogeneity such as layered models did not produce a wide mixing zone. Using similar parameters as those observed at Biscane Bay we could not numerically reproduce the wide transition zone or significant movement of the interface by the diurnal tidal process. Only when the level changes on the fresh water side is of long periods caused by seasonal fluctuations did we see a significant movement of the interface which produces an apparent wide mixing zone. We conclude that the wide transition zone observed in the literature is most likely caused by the seasonal fluctuation of freshwater head rather than the short period diurnal tidal effects. Under static or tidal boundary conditions mixing does not seem to occur even with significant heterogeneity, which questions the physical representativeness of the Henry problem with the use of large coefficient of dispersion.

Acknowledgements

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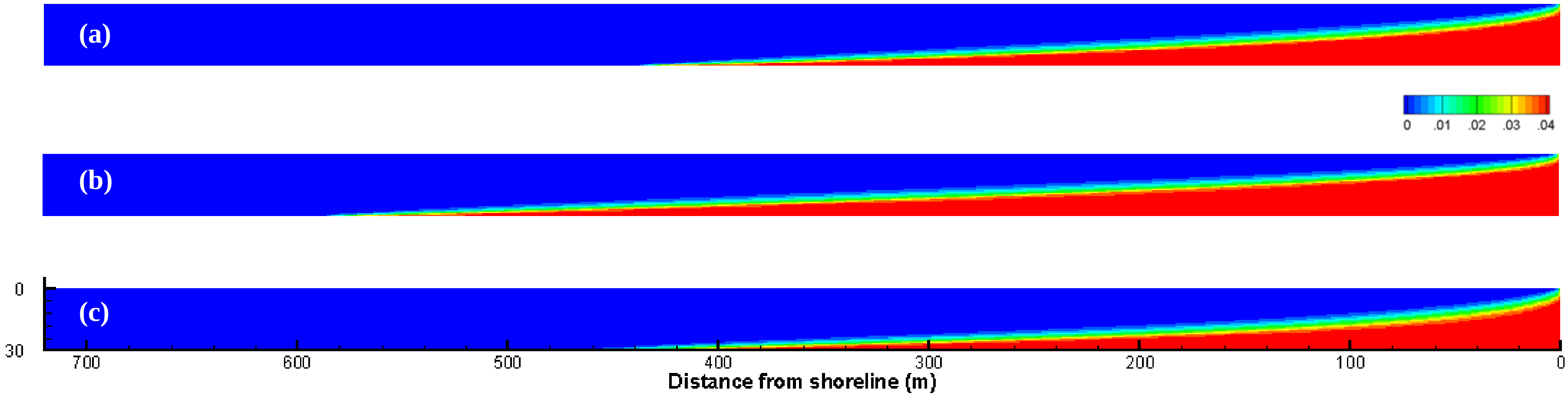

Figure 6. A 720m×30m homogeneous model of the Cutler area of the Biscayne aquifer subjected to tidal and seasonal fluctuations on the right and left boundary, respectively, showing the saltwater wedge position a) at the annual average groundwater level, (b) at the lowest groundwater level (-0.3m), and (c) retreating back to the sea due to increasing groundwater level.

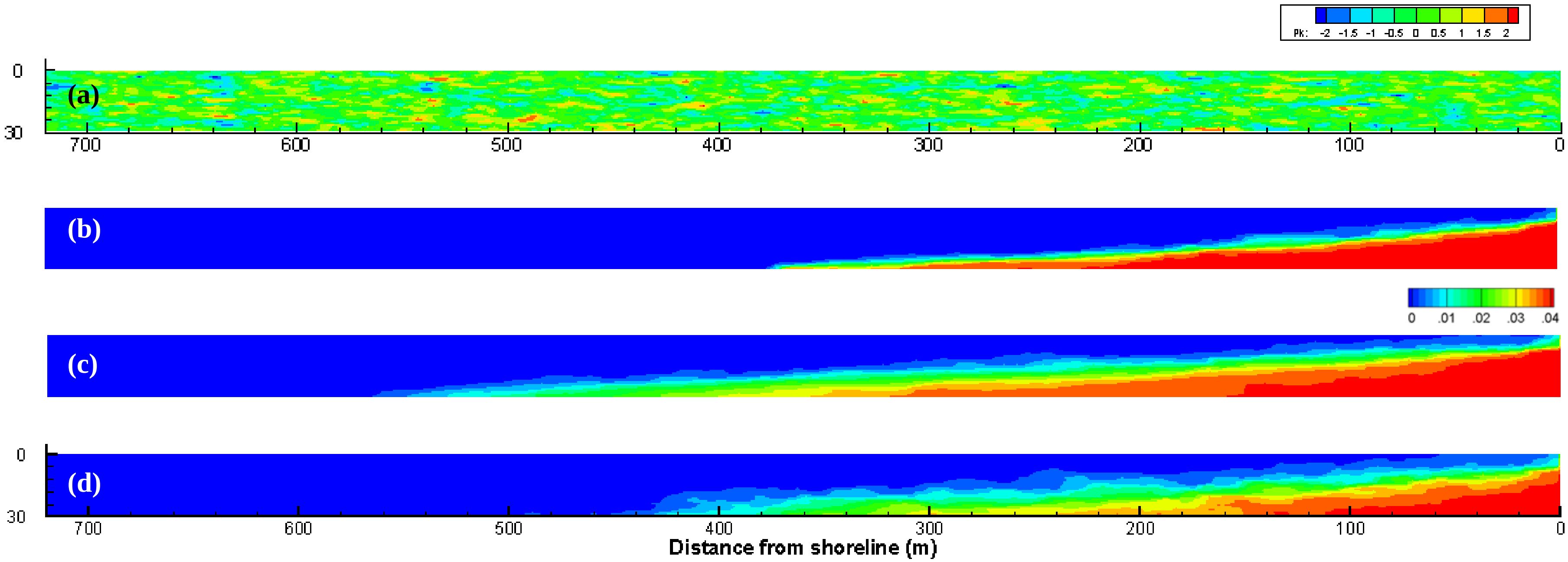

Figure 7. (a) Horizontally anisotropic random model of the Cutler area of the Biscayne aquifer. Color legend shows the deviation of permeability from the log mean. Model is subjected to tidal and seasonal fluctuations on the right and left boundary, respectively. Shown is the saltwater wedge position: (b) at the annual average groundwater level, (c) at the lowest groundwater level (-0.3m), and (d) retreating toward the sea with increasing groundwater level.