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3-D Modeling of Coastal Aquifers

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Introduction:

AnAqSim (Analytic Aquifer Simulator) was developed by Dr. Fitts to provide an analytic element approach to modeling groundwater flow. One of the program's applications is the 3-D modeling of coastal aquifers, which involves the added complexity of the moving interface between fresh and salt water in the subsurface.

AnAqSim fresh/saltwater assumptions:

- saltwater is hydrostatic (no vertical head gradient)
- freshwater is hydrostatic within a layer
- sharp interface between fresh and saltwater (no mixing)

The USGS program SEAWAT also simulates coastal systems. Unlike the assumptions employed in AnAqSim, SEAWAT solutions account for fresh and saltwater mixing and density variations due to salinity. However, the aquifer must be discretized to a fine degree, and steady-state simulations must be done using long-term transient simulations. This results in complicated input procedures and very large run times, making the approach impractical for most applications.

AnAqSim has the benefit of fewer and quicker computations and the assumptions generally hold true for simulations on a regional scale (see Figure 1), but result in small-scale inaccuracies. The purpose of this project was to assess the accuracy of the 3-D multi-layer approach employed by AnAqSim.

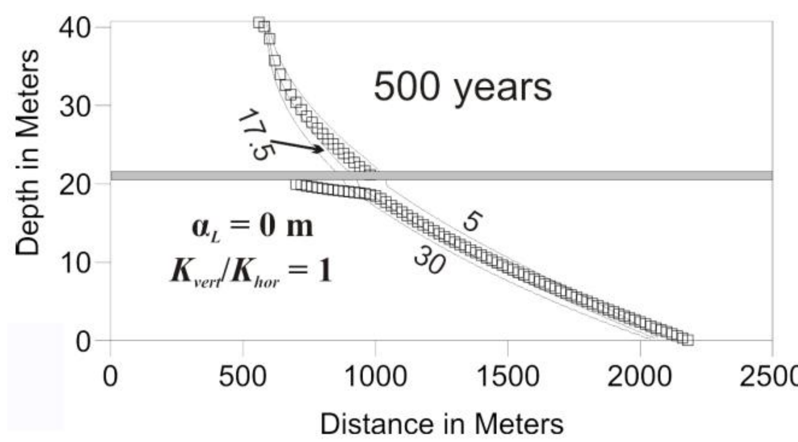

Figure 1: Simulated sharp interface (black squares) and the SEAWAT-simulated transition zone contoured at total dissolved solid intervals of 5, 17.5, and 30 g/L TDS at 500 years (Dausman, Langevin, Bakker, & Schaars, 2010).

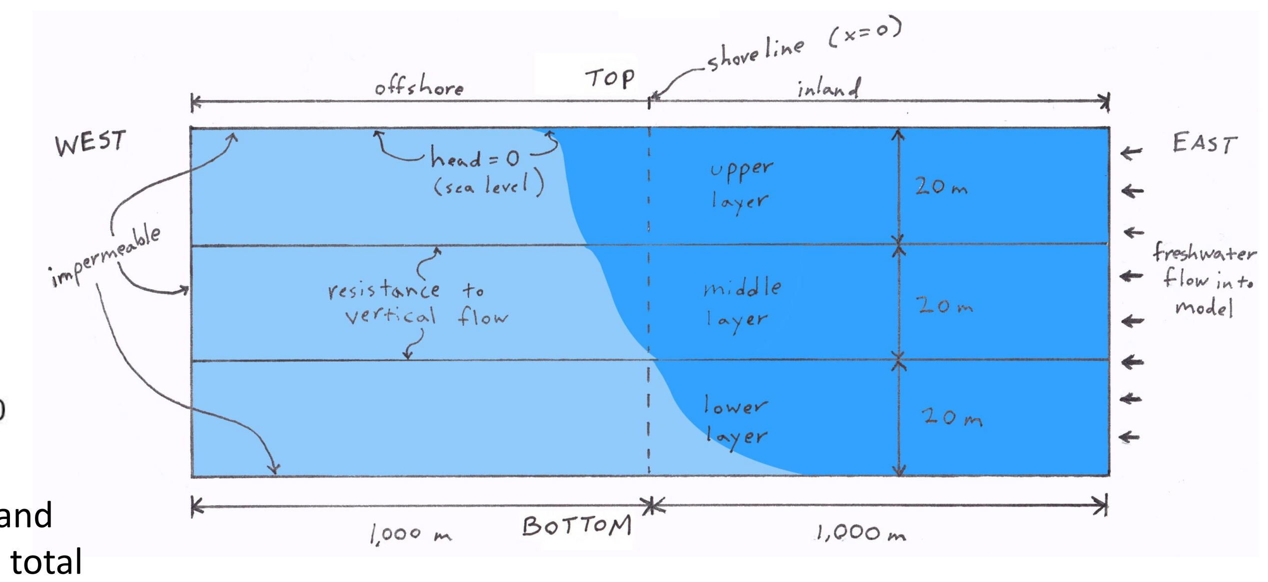

Figure 2: Representation of 3-D AnAqSim approach three-layer model.

Methods:

Model simulated a narrow strip of land oriented perpendicular to the coast. A normal flux of 0.2 m^3/day per meter of aquifer thickness was specified in each layer for freshwater flow into the model along the inland boundary. Saltwater density was set at 1.025 times the density of freshwater. A horizontal hydraulic conductivity of 10 m/d was used in all models.

Three simulations were run for each model with different levels of anisotropy introduced. Values of 0.5 m/day, 0.1 m/day and 0.02 m/day were assigned to the vertical hydraulic conductivity.

3-D AnAqSim Approach:

This approach is approximate due to the fact that the model is discretized into just three layers in the vertical, and the resistance to vertical flow is just accounted for in the computation of leakage between layers. This approach was run using two different methods for computing leakage between layers.

Model parameters (see Figure 2):

- extended 1,000 m offshore to West and 1,000 m inland to East
- shoreline set as zero horizontal reference point
- three 20 m thick layers, total aquifer thickness of 60 m
- impermeable West, top, and bottom boundaries
- upper layer west of x=0: leakage boundary condition, leaking upward to a head of zero (representing a shallow sea level boundary condition)
- East, inland, half of the upper layer: no vertical leakage in/out of model
- lower layer: no vertical leakage in/out of the bottom of the model

2-D AnAqSim Approach:

Vertical 2-D profile model of same situation as 3-D AnAqSim three-layer model. Vertical resistance to flow is accounted for perfectly without discretization. Fresh/saltwater interface represented by a no-flow line boundary. The position of this line was adjusted east/west until the pressure on the fresh water side equaled the pressure in static salt water at depths of 10, 20, 30, 40, 50, and 60 meters.

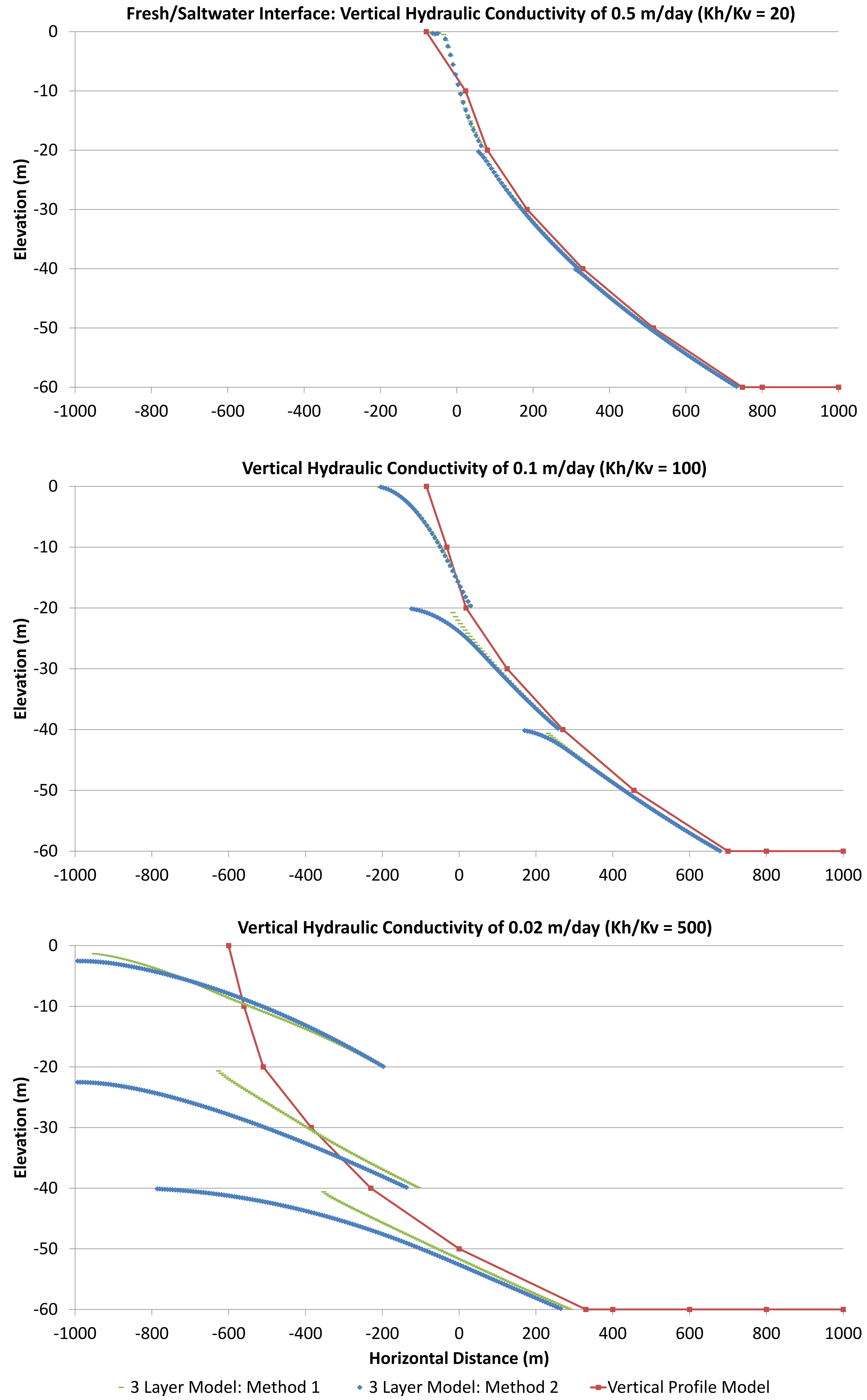

Figure 3: Comparison of simulated fresh/saltwater interfaces in a coastal aquifer based on three-layer AnAqSim modeling versus that of a vertical profile interface defined by calculated fresh/saltwater pressure equilibrium values. The aquifer has a horizontal hydraulic conductivity of 10 m/day and vertical hydraulic conductivity of 0.5 m/day (top), 0.1 m/day (middle), 0.02 m/day (bottom). The shoreline is located at a horizontal distance of zero. Positive horizontal distances represent inland areas; whereas, negative distances are offshore. 3 Layer: Method 2 represents a simulation performed using an updated version of the AnAqSim software.

References:

Dausman, A. M., Langevin, C., Bakker, M., & Schaars, F. (2010, June). *A comparison between SWI and SEAWAT: The importance of dispersion, inversion and vertical anisotropy*. Swim 21: 21st salt water intrusion meeting, Azores, Portugal.

Acknowledgements:

Many thanks to Dr. Fitts for his time and expertise in developing and guiding this project.

Results:

For a vertical hydraulic conductivity of 0.5 m/day, the three-layer model closely matched the interface of the vertical profile model (Figure 3 top). The 0.1 m/day vertical hydraulic conductivity models showed slightly more deviation, but continued to correspond well with the vertical profile model interface (Figure 3 middle). The degree of diversion increased towards the top of each layer in the three-layer models. The degree of diversion became more significant when the vertical hydraulic conductivity was again decreased by a factor of 5, down to 0.02 m/day (Figure 3 bottom). While the three-layer models still followed the general trend of the vertical profile model at 0.02 m/day, there was notable divergence, particularly in the upper layer.

Discussion:

In general, the three-layer approach agreed well with the calculated fresh/saltwater interface vertical profile. Increasing the degree of anisotropy in hydraulic conductivity to a horizontal to vertical ratio of 500 to 1 contributed significantly to the degree of divergence between the two models (Figure 3 bottom). The higher ratio also resulted in pushing the interface seaward. This is due to the relatively low resistance to horizontal flow seaward as opposed to the high resistance to vertical flow, resulting in a higher horizontal component to the net direction of freshwater flow.

For each of the simulation conditions, method 1 of AnAqSim corresponded more closely to the vertical profile model interface than method 2. The difference in methods became more pronounced with increasing anisotropy. This is a result of method 2 assigning a lower head value to the overlying layer than the method 1, causing less upward leakage. Method 2 may be better suited to model flow in cases where vertical resistance is concentrated within an aquitard between less resistant layers, but less appropriate where resistance is distributed uniformly across aquifer layers, as in the 2-D vertical plane models here.

Based on the results of this project, the vertical discretization employed in the 3-D AnAqSim models do not appear to significantly alter the location of the fresh/saltwater interface in a coastal aquifer. The 3-D AnAqSim approach is less accurate with high degrees of anisotropy; however, a finer degree of layering would abate this deficiency. A 2010 study comparing the performance of SEAWAT to the Sea Water Intrusion (SWI) Package developed by Bakker and Schaars for MODFLOW-2000, employing a sharp interface and discretization techniques similar to that of AnAqSim, found comparable results (Dausman et al., 2010). The study found that the assumptions were valid for narrow transition zones relative to the scale of the problem and horizontal to vertical hydraulic conductivity ratios of less than 100 to 1. The study also found that run times of SEAWAT were nearly three hours, compared to only a few seconds for SWI using the same parameters. In light of these findings and those of this project, AnAqSim is likely to be a valuable resource for many instances of coastal aquifer modeling.