How to become a Jedi master in modeling seawater intrusion with MODFLOW-SWI

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ABSTRACT

Regional seawater intrusion in coastal aquifers may be modeled with the Sea Water Intrusion (SWI) package for MODFLOW. The importance of including a coastal boundary condition in regional seawater intrusion models is discussed. Guidance is given for how far a model needs to be extended below the ocean bottom and an example is given of what will go wrong when the model is not extended far enough below the ocean bottom. Finally, the movement of a mount of salt water over a sloped aquifer base is presented as an example of a correct box model without a coastal boundary condition.

INTRODUCTION

The Sea Water Intrusion (SWI) package for MODFLOW has proven to be an efficient tool for modeling regional seawater intrusion. It has a number of powerful features (and some limitations) that are unlike many of the other tools for modeling seawater intrusion, such as Seawat, Mocdens3D, and Sutra (SMS). The key feature of the SWI package is that one aquifer may be represented by one model layer. This is in sharp contrast to the SMS models, which require discretization of the model domain in regular or irregular lego blocks each with their own salinity color. As a result, SWI models run much faster and can readily be used for regional models on Macs or PCs.

Experience with the SWI package has shown that correct specification of initial and boundary conditions is crucial and not always entirely obvious. Unexpected results may be the direct consequence of the chosen boundary conditions or may be the result of the (unnecessary) division of one aquifer layer into multiple model layers. The objective of this paper is to discuss the importance of the inclusion of a saltwater boundary, and what can go wrong when the saltwater boundary is too short. As an example of a correct box model, a simulation is presented of the movement of a mount of saltwater along a sloped aquifer base.

It is pointed out that this paper is only a first step in becoming a Jedi Master in modeling with SWI. A Jedi Master is the highest rank in the Jedi order after Grand Master. Proper understanding of initial and boundary conditions in SWI models, as described in this paper, will likely elevate the reader to a Jedi Initiate in modeling with SWI; no grasp of meta-physical powers (i.e., the force) are required to produce SWI models (although that may help).

THE SWI PACKAGE

The Sea Water Intrusion (SWI) Package was developed by Bakker and Schaars (2005) to simulate regional seawater intrusion problems with MODFLOW. The package is based on the Dupuit approximation, which allows an aquifer to be represented with only a single model layer (Bakker, 2003). Flow may be simulated with one or with multiple interfaces (stratified flow), or as variable-density flow with continuously varying density. This paper focuses on the modeling with one interface. The movement of the interface is determined from continuity of flow. Resistance to vertical flow, as well as inversions and dispersion are neglected. Dausman *et al*. (2010) shows that SWI gives accurate results when compared to a detailed SEAWAT model that incorporates the effects of vertical anisotropy, inversion, and dispersion.

COASTAL BOUNDARY CONDITION

Consider interface flow in a vertical cross-section as shown in Fig. 1. Flow is from right to left. The hydraulic conductivity of the aquifer is k = 10 m/d, and the effective porosity is 0.2. The impermeable bottom of the aquifer is H = 40 m below sealevel. The aquifer is unconfined; variations in the transmissivity of the aquifer are not taken into account, but that is not a limitation of SWI. Inflow into the model on the right side is specified as 0.2 m^3/d per meter width of cross-section, corresponding to a gradient of G = 0.0005. On the left side, the aquifer is bounded by the ocean on top. The connection between the ocean and the aquifer is modeled as a resistance layer with resistance c = 100 days and zero thickness; the left boundary of the model is impermeable. The density of seawater is ρ_s = 1025 kg/m^3. For steady flow, the length L of the outflow face below the ocean bottom and the distance D from the coast to the toe of the interface may be computed with the formulas presented in Bakker (2006).

$$L = \sqrt{kHc}(18\mu)^{1/3}$$

$$D = \sqrt{kHc}[1 - (3\mu^2/2)^{2/3}]/(2\mu)$$

$$\mu = G\rho_f\sqrt{kHc}/[H(\rho_s - \rho_f)]$$

which gives L = 243 m, and D = 939 m for this case.

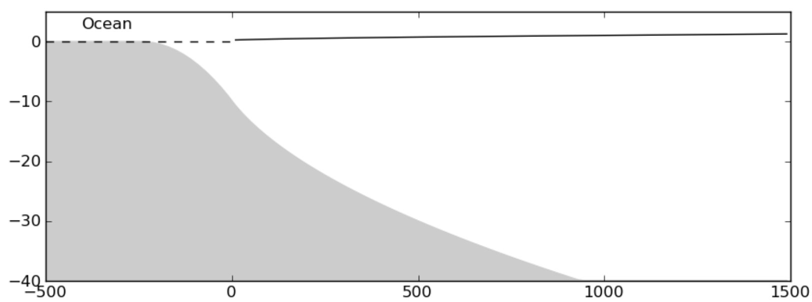

Figure 1. Steady Dupuit interface flow in a vertical cross-section. Flow is from left to right. The grey area is salt water. The ocean floor starts at x = 0 and is modeled with GHB cells.

A SWI model is created with one layer and 100 cells, each of length 20 m. The model is extended several times the distance D = 243 m below the ocean bottom, as the length of the outflow face may vary during transient simulations. The ocean bottom is represented by 25 cells (500 m). It will be shown that this may not be sufficient depending on the initial position of the interface.

SWI SIMULATION OF DIFFERENT INITIAL CONDITIONS

The steady position shown in Fig. 1 was obtained by running the SWI model for 500 years with time steps of 1 year (this takes only 0.2 seconds on a Mac). The initial position of the interface was the straight dotted line in Fig. 2a, upstream of the steady position. After 50 years, the interface has tilted and moved towards the ocean (dashed line in Fig. 2a), after which it slowly moves to the steady position. Note that the tip of the interface (the intersection with the top of the aquifer) never reaches the impermeable model boundary on the left (at x = -500). In Fig. 2b, model results are shown when the initial position of the interface is chosen farther below the ocean bottom. During the simulation, the interface tilts and reaches the impermeable model boundary on the left. Shortly thereafter, the inflow of saltwater from the ocean bottom ceases and the total amount of saltwater in the aquifer remains constant. This is, of course, not what was intended. For this initial position of the interface (which extends too far below the bottom of the ocean), the model needs to be extended below the ocean bottom. When this is done, the tip of the interface does not reach the left model boundary and the interface eventually reaches the steady-state position, as shown in Fig. 2c.

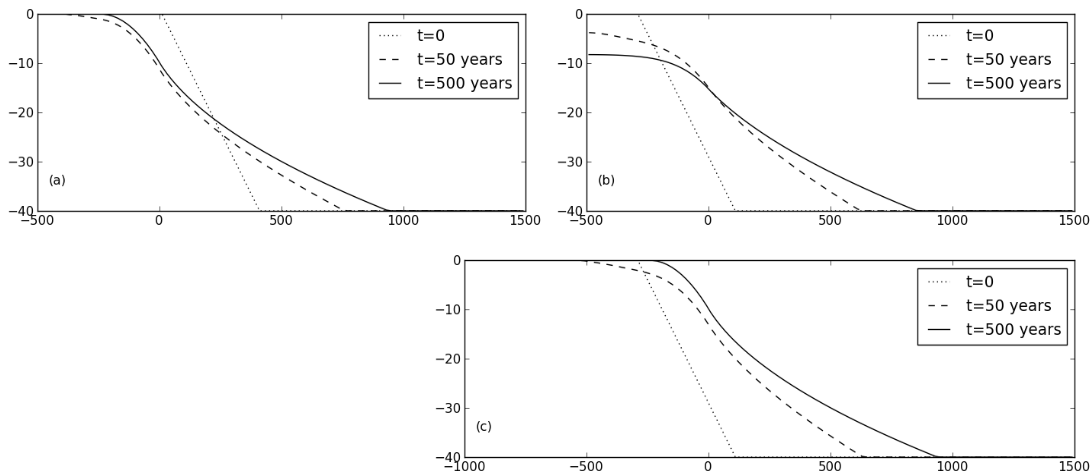

Fig 2. When the initial position of the interface (dotted line) is too far below the ocean bottom, the tip of the interface may reach the left impermeable model boundary (b) unless the model is extended far enough below the ocean bottom (c). The interface reaches the same steady position in (a) and (c).

Three other common errors in specifying the initial position of the interface are:

1) The initial interface is specified as horizontal. In this case there is no source of salt water in the model, and thus the amount of salt water will remain constant during the simulation (in the absence of any sinks in the salt water).
2) The initial interface is almost vertical, where the initial interface is at the top of the aquifer in one cell, and at the bottom in the adjacent cell. In this case the initial interface has no cells where the elevation of the interface is somewhere between the top and bottom of the aquifer. As a result, it will not move during the simulation.
3) The initial interface is highly irregular. When the shape of the initial interface is very irregular, it will start moving towards a smoother shape, which may cause large fluctuations in the position of the interface in the early part of the simulation unless the time step is chosen sufficiently small.

SWI SIMULATION IN A BOX AQUIFER WITH A SLOPING BASE

SWI may also be applied to simulate flow in a box aquifer with four impermeable sides. Several examples are shown in the SWI manual for a rotating interface. For these problems there is no source of salt water, and the total amount of salt water remains constant during the simulation. As a final example in this paper, we show the recession and movement of a salt water mount in an aquifer with a slanted base (Fig. 3). The box aquifer is 2000 m long and the thickness varies from 38 meters on the left to 42 meters on the right; the top of the aquifer is horizontal. All boundaries are impermeable. Initially, a mount of saltwater exists in the middle of the domain (grey area in Fig. 3). The domain is discretized in 100 cells of 20 m width. During the simulation, the mount tends to flatten out and flow down the sloped aquifer bottom. Eventually, all salt water is pooled at the bottom of the aquifer and the interface is horizontal (Fig. 3).

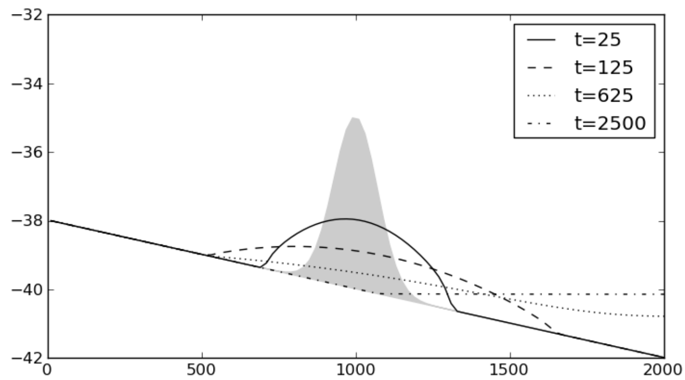

Fig. 3. Movement of a saltwater mount down the sloped bottom of an aquifer. The grey mount is the initial position. All boundaries are impermeable. Horizontal top boundary of the aquifer is at *z* = 0.

CONCLUSIONS

Rules were presented for the appropriate specification of a coastal boundary condition in SWI models, and it was demonstrated what goes wrong when the length of the coastal boundary is too short. As a bonus, the movement of a saltwater blob along a sloped aquifer bottom was shown.

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