MODELING THE FRESHWATER LENS BELOW BARRIER ISLANDS WITH THE SEA WATER INTRUSION (SWI) PACKAGE

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REFERENCE: Proceedings of the 2005 Georgia Water Resources Conference, held April 25-27, 2005, at the University of Georgia, Athens, Georgia, Kathryn J. Hatcher, Editor, Institute of Ecology, The University of Georgia, Athens, Georgia.

Abstract. The Sea Water Intrusion (SWI) package was developed for the modeling of regional seawater intrusion with MODFLOW2000. To demonstrate the capabilities of the SWI package, a hypothetical example is presented concerning the modeling of the steady freshwater lens below a barrier island that is similar in size and properties to the islands along the Georgia coast. The model results in an asymmetric shape of the freshwater lens, which is caused in this model by the low permeability of the marshland bordering the island on one side; a significant zone of freshwater outflow exists below the marsh.

INTRODUCTION

The SWI package was developed for the modeling of three-dimensional seawater intrusion with the specific characteristic that one aquifer can be modeled with just one model layer of cells. The mathematical formulation is based on vertically integrated fluxes; the Dupuit approximation is applied within each aquifer layer, and dispersion and diffusion are not taken into account. The mathematical formulation of the SWI package is presented in Bakker (2003). A comparison with the results of MOCDENS3D and SEAWAT for the case of three rotating immiscible fluids is presented in Bakker et al. (2004). The SWI package is free and open-source software; an executable, detailed manual, and the source code are available over the internet.

The objective of this paper is to demonstrate that the modeling of seawater intrusion with the SWI package is relatively straightforward, provided that the modeler is familiar with MODFLOW2000. MODFLOW2000, developed by Harbaugh et al. (2000), is a commonly used USGS computer program for the modeling of groundwater flow based on the finite-difference method. The SWI package may be applied to simulate the evolution of the three-dimensional salinity distribution in the aquifers along the Georgia coast; effects of variations in density on the flow are taken into account explicitly. The SWI package is significantly different from most existing computer programs used for seawater intrusion modeling, as it can simulate interface flow, stratified flow, and continuously-varying density flow, even simultaneously in the same model. Aquifers do not have to be discretized vertically, such that sea water intrusion can be simulated on a regional scale with a manageable number of cells. Starting from an existing MODFLOW2000 model, only one additional input file is needed to simulate seawater intrusion. Details of the SWI input file requirements may be found in the SWI manual (Bakker and Schaars, 2004). As an example, the modeling of the freshwater lens below a hypothetical barrier island is presented here. The size and hydrogeological parameters of the island are chosen to be representative of sizes and values found along the Georgia coast.

A HYPOTHETICAL BARRIER ISLAND

Consider the hypothetical case of a barrier island that is approximately 12 km long and has a width that varies between 1.5 and 2.5 km (Figure 1). For simplicity, all hydrogeological parameters are approximated as homogeneous (specification of variable properties is, of course, fairly straightforward in MODFLOW2000). Seawater intrusion is modeled in the sandy top aquifer of the island. The hydraulic conductivity is chosen as 5 m/d, the horizontal impermeable base is at –50 m, and the transmissivity is approximated as constant and equal to 250 m^2/d. Net recharge to the groundwater on the island is 0.15 m/year. Two different boundary conditions are specified at the edge of the island. Along the eastern edge, the hydraulic head is specified to 0 m along the coastline. The island is bounded on the western side by marshland (grey area in Figure 1) that is hypothesized to consist of a layer of lower vertical hydraulic conductivity than the sand of the aquifer. Outflow q_z into the marsh is approximated as $q_z = C(h-h^*)$, where q_z is the discharge per unit area into the marsh, C is the vertical leakance of the marsh, h is the hydraulic head in the aquifer, and h^* is the fixed hydraulic head in the marsh. The head in the marsh is specified as $h^* = 0$, and the vertical leakance as

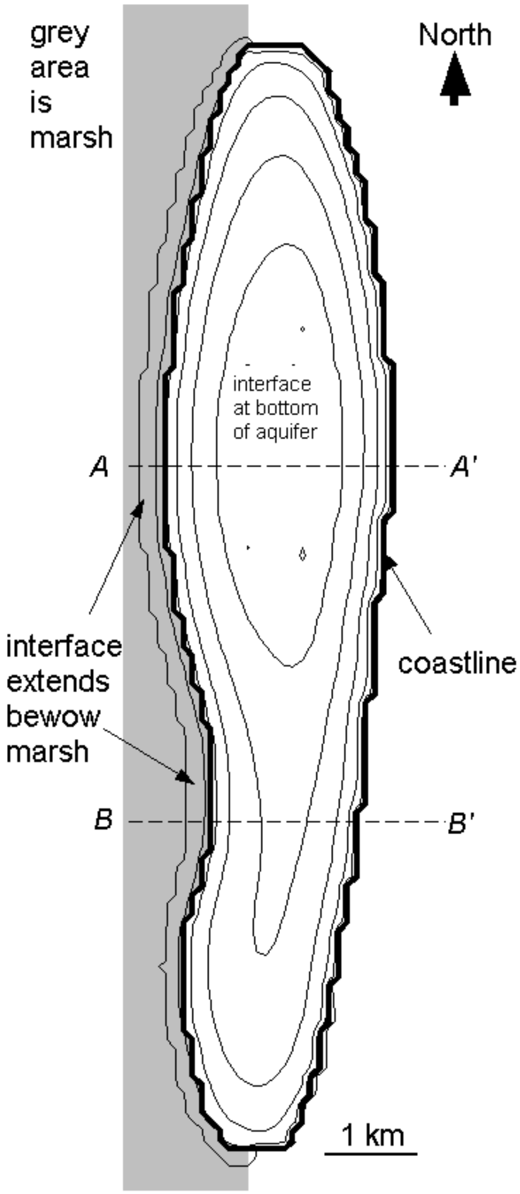

Figure 1. Contours of the interface below a hypothetical barrier island. Coastline is bold. Contour interval is 10 m

C = 0.025 d^{-1}, equivalent to a layer 40 cm thick with a vertical hydraulic conductivity of 1 cm/d.

The MODFLOW2000 model is constructed as follows. The island is modeled with cells of 100 by 100 m. Besides the Discretization file, four standard MODFLOW2000 packages are used: the Basic package, the Block-Centered flow package, the Recharge package, and the General-Head Boundary (GHB) package (for representation of the marsh).

The interface between freshwater and seawater is modeled with the SWI package (note that SWI can also

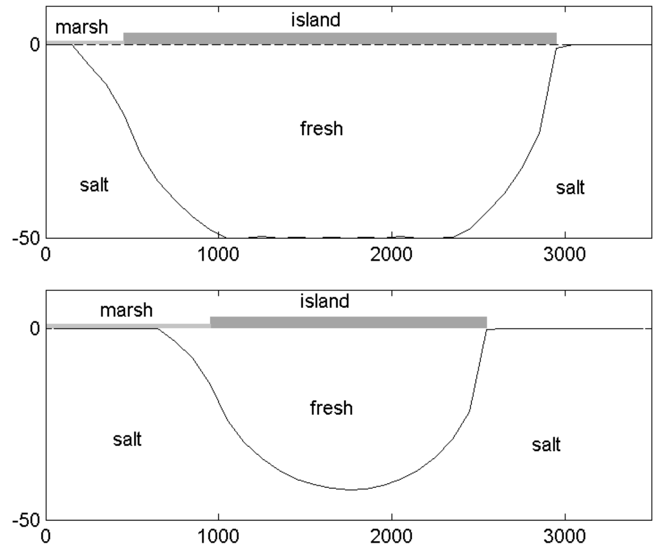

Figure 2. Position of the interface along cross-sections A—A' (top) and B—B' (bottom); vertical scale exaggerated.

simulate stratified and variable density flow). The density of the seawater is specified as 1025 kg/m^3. Other parameters in the SWI package are specified according to the guidelines in the manual. An initial interface is specified 10 meters below sea level on the island, and equal to sealevel off the island. The model is run until the interface reaches a steady-state position. Contours of the steady interface elevation are shown in Figure 1; the contour interval is 10 m. In the center part of the island (in the middle part of cross-section A—A') the interface reaches the bottom of the aquifer (see also Figure 2). The interface extends about 300 meters below the marsh, creating a fairly wide zone of freshwater outflow. This is in contrast to the narrow outflow face along the western side, essentially equal to the width of one finite-difference cell. It is noted that, from a modeling perspective, an outflow face of 100 m wide (one cell width) is equivalent to a general head boundary condition with a leakance of 0.28 d^{-1} (i.e., identical results are obtained when the fixed-head cells in the east are replaced with GHB cells with that leakance value). It may be seen from the vertical cross-sections in Figure 2 that the shape of the freshwater zone is asymmetric. An asymmetric shape of the freshwater zone is often observed on barrier islands. Explanations include a higher average water level on the ocean side, or variations in aquifer properties (Vacher, 1988; Ruppel et al., 2000). Here, the asymmetry is caused by the vertical resistance to outflow on the western side. A significant head gradient is needed across the layer of low hydraulic conductivity at the bottom of the marsh. The resulting higher heads in the aquifer in turn result in a deeper position of the interface and the asymmetry shown in Figure 2.

FURTHER MODELING

The SWI package may be used to perform a number of further modeling studies, starting from the steady position of the interface shown in Figure 1. These include:

1. The transient evolution (upconing) of the interface due to the installation of pumping wells on the island
2. The replacement of the interface by one or more brackish transition zones separating the freshwater from the saltwater.
3. The addition of deeper aquifers that are separated from the surficial aquifer through aquitards, and the simulation of the freshwater interface and/or the brackish zone in these deeper aquifers.

SUMMARY AND DISCUSSION

The SWI package was used to compute the steady position of the interface between freshwater and seawater below a hypothetical barrier island. It was shown that a significant zone of freshwater outflow may exist below marshland that borders the island, provided that the marshland is bounded at the bottom by a layer consisting of lower permeable material. An additional consequence of this resistance to outflow in the marsh is an asymmetric shape of the freshwater zone.

The SWI package has many other options. First of all it may be used for transient simulations, for example to investigate the evolution of the interface upon changes in the system, such as the installation of a pumping well, or the decrease of recharge due to changes in land use. Second, SWI can model variable density flow; for example, the interface may be replaced by a brackish zone of an arbitrary thickness, which will vary through time during a transient simulation. Third, SWI can simulate flow in multi-aquifer systems. This allows for the simulation of seawater intrusion in all aquifers underlying the island. Examples of all these options are given in the SWI manual (Bakker and Schaars, 2004). SWI is currently being applied to simulate seawater intrusion along the coast of the Netherlands (by the Amsterdam Water Supply) and along the coast of Israel (by Tel Aviv University).

ACKNOWLEDGEMENTS

Development of the SWI package was funded in part by a Georgia Coastal Incentive Grant administered by the Georgia Department of Natural Resources, and by support from the Amsterdam Water Supply, The Netherlands. The SWI package is available for free from www.engr.uga.edu/~mbakker/swi.html

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