MODELING COASTAL AQUIFERS WITH THE SEA WATER INTRUSION (SWI) PACKAGE FOR MODFLOW2000

M. BAKKER[1,✉], F. SCHAARS[2] and D. BORDEN[3]

[1] Department of Bio and Ag Engineering, University of Georgia, Athens, GA, USA, E-mail: mbakker@engr.uga.edu.
[2] Artesia Water Research, Schoonhoven, The Netherlands, E-mail: f.schaars@artesia-water.nl.
[3] Department of Bio and Ag Engineering, University of Georgia, Athens, GA, USA, E-mail: dborden@engr.uga.edu.

Abstract

The Sea Water Intrusion (SWI) package was developed for the modeling of regional seawater intrusion with MODFLOW2000. The SWI package may be applied to simulate the evolution of the three-dimensional salinity distribution through time; 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. Sea water intrusion may be simulated in an existing MODFLOW2000 model through the addition of one input file, as detailed in the SWI manual. In this paper we present an example of seawater intrusion in an island aquifer system consisting of three aquifers. First, seawater intrusion is modeled as interface flow and the steady-state position of the interface before pumping is computed. Next a pumping well is started in aquifer 2 and the interface upconing in aquifer 3 is computed. Finally, the interface in aquifer 3 is replaced by a brackish zone and the upconing of the brackish zone is compared to the upconing of the interface.

Introduction

The SWI package was developed for the modeling of regional three-dimensional seawater intrusion modeling. The main advantage of the SWI package is that one aquifer can be modeled with just one model-layer of cells. The 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 from www.engr.uga.edu/~mbakker/swi.html.

✉ Corresponding author

Representation of the density distribution

The basic idea behind the SWI package is that the groundwater in each aquifer is discretized vertically into a number of zones bounded by curved two-dimensional surfaces. A schematic vertical cross-section of an aquifer is shown in Figure 1a; the thick lines represent the surfaces. The elevation of each surface is a unique function of the horizontal coordinates. The SWI package has two options. For the stratified flow option, water has a constant density (salinity) between surfaces and the surfaces represent interfaces; the density is discontinuous across a surface (Figure 1b). For the variable density flow option, the surfaces represent iso-surfaces of the density; the density varies linearly in the vertical direction between surfaces and is continuous across a surface (Figure 1c). During a transient simulation, the movement of these surfaces is tracked. A simple tip/toe tracking algorithm is applied to simulate the horizontal movement of the tip and toe of the surfaces.

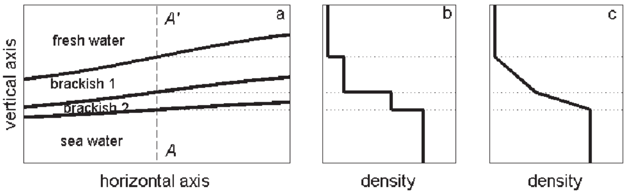

Figure 1. (a) Conceptual model with three surfaces, (b) density distribution of stratified flow, (c) density distribution of variable density flow

The SWI package is implemented in MODFLOW2000. Only one additional input file is needed to simulate seawater intrusion in an existing MODFLOW2000 model. The input file consists of the initial elevations of the surfaces in each aquifer, the density between the surfaces, whether flow should be treated as stratified or variable density, and some tip/toe tracking parameters. MODFLOW2000/SWI may then be used to compute the positions of the surfaces at the requested times. Details of the SWI input file requirements may be found in the SWI manual (Bakker and Schaars, 2004).

One of the major benefits of the SWI package is that it can simulate interface flow, stratified flow, and variable density flow efficiently, even in the same model. Especially when little data is available, it is useful to determine the steady-state position of the interface. This position may already be sufficient to solve the posed problem, or may be used as a starting point for additional transient simulations. When a significant brackish zone is present, the interface may be replaced by one or more brackish zones, either of constant density or variable density. One aquifer may have an interface, while another may have a brackish zone, as will be demonstrated in the following example.

Seawater upconing below an island with three aquifers

Consider seawater intrusion below a hypothetical square island. The aquifer system consists of three sandy aquifers and two leaky layers of lower permeability. The water level in the top, sandy aquifer is fixed by ditches and drains. A schematic cross-section of the aquifer system is shown in Figure 2. The porosity of all aquifers is 0.2. The island is 3750 m by 3750 m and is discretized into cells of 50 meters by 50 meters; the grid is extended at least 750 m into the sea in all directions. Besides the discretization (DIS) file, the MODFLOW2000 model makes use of three packages for this model: the basic (BAS) package, the block-centered flow (BCF) package, and (later on in the paper) the well (WEL) package. It is noted that use could have been made of the layer-property flow (LPF) package, but that it is, in general, not necessary to track interfaces or surfaces through leaky layers, and thus use is made of the BCF package. Input instructions for all these packages are presented in Harbaugh *et al.* (2000). In addition, the SWI package is used to model seawater intrusion.

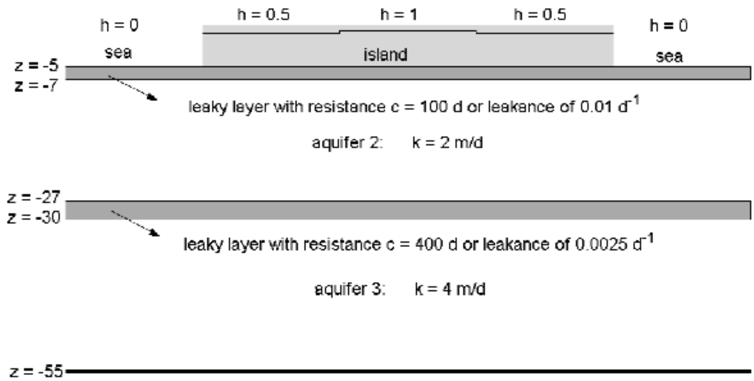

Figure 2. Schematic cross-section of the island aquifer system

As a first step in the modeling process, flow is treated as interface flow. The saltwater has a density of 1025 kg/m^3. Several tip/toe tracking parameters need to be specified. Guidelines for the choice of these parameters are given in the SWI manual (Bakker and Schaars, 2004). One of the parameters is the maximum slope of the interface, which is used to decide when an interface moves horizontally into an adjacent cell; the value used here is 0.03, and the other two tip/toe tracking parameters are computed with equation 16 in the SWI manual. The steady-state position of the interface is obtained through a transient simulation, starting from a rough first guess; no interface is tracked in the first aquifer where heads are fixed. The SWI package computes freshwater heads at the top of each aquifer. The freshwater heads are computed assuming consecutive steady-state conditions, as the heads will react much quicker than the position of the interface; heads can be treated as transient as well, but modeling them as consecutive steady-states has little influence on the results and allows for the specification of much larger time steps. Contours of the fixed heads in aquifer 1 are shown in Figure 3. Contours of the steady interface

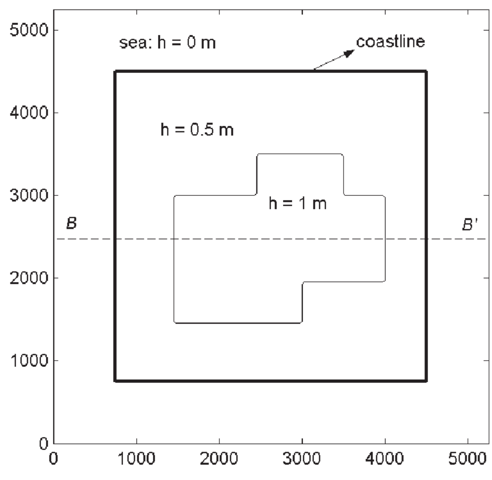

Figure 3. Fixed heads in aquifer 1

elevation in aquifers 2 and 3 are shown in figures 4a and b, respectively. The thickness of the freshwater zone reaches a maximum thickness of about 10 m in aquifer 3. A cross-section along the line *B–B'* is shown in Figure 5.

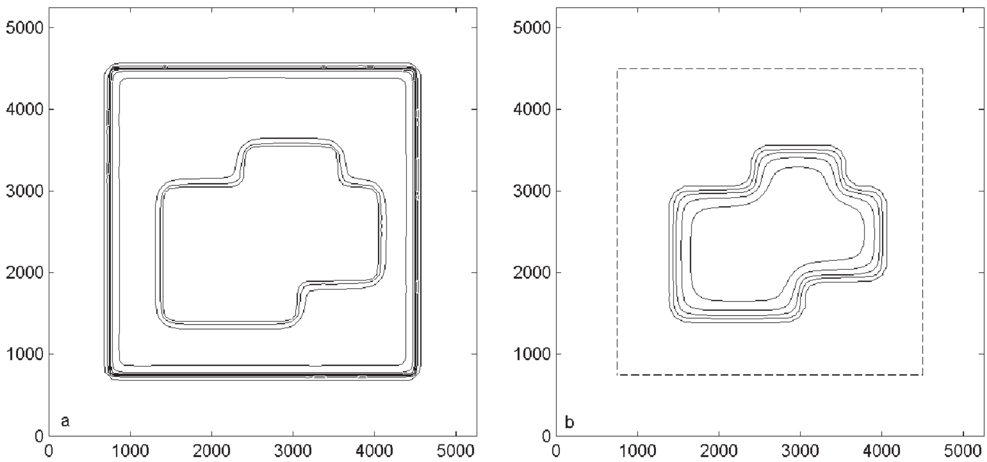

Figure 4. Contours of the elevation of the steady interface position in (a) aquifer 2, and (b) aquifer 3

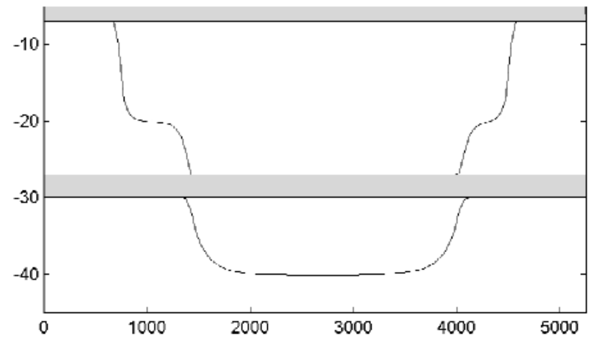

Figure 5. Steady position of the interface along cross-section *B–B'*

The steady-state position is used as a starting point for further modeling. A well is started in the second aquifer and has a discharge of 200 m^3/d. The position of the interface is computed after 20 years of pumping; this position is shown in cross-section *B–B'* (through the well) in Figure 6. The well has little effect on the position of the interface in aquifer 2, but there is a significant upconing below the well in the bottom aquifer.

As it is crucial for the saltwater to remain in the bottom aquifer and not reach the leaky layer below the well, modeling is continued by replacing the steady interface in the lower aquifer with a brackish zone, initially extending 2 m above the steady-state position of the interface. The brackish water has a constant density of 1012.5 kg/m^3. The position of the brackish zone after 20 years of pumping is shown in cross-section *B–B′* in Figure 7. The brackish zone almost reaches the leaky layer. This result puts into question the sustainability of the pumping rate of 200 m^3/d. If the brackish zone is a reasonable representation of reality, the brackish water will reach the bottom of the leaky layer and eventually will flow into the well.

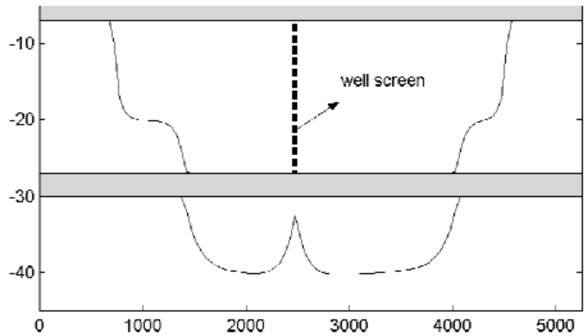

Figure 6. Position of the interface after 20 years of pumping along cross-section *B–B′*

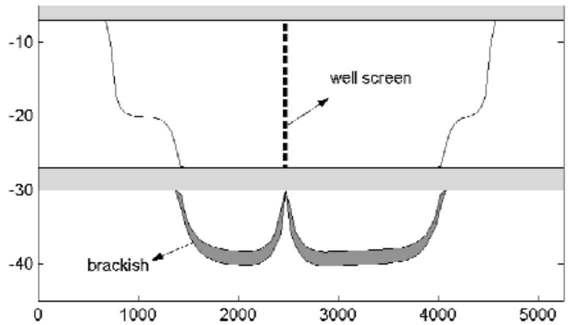

Figure 7. Position of an initially 2 m thick brackish zone after 20 years of pumping along cross-section *B–B*í

Conclusions and future plans

The presented example illustrates the capabilities of the SWI package to model three-dimensional sea water intrusion with MODFLOW2000. Application of the SWI package has three main advantages. First, aquifers may be modeled with a single layer of cells. The presented example consisted of three aquifers and thus only three model layers. Second, the salinity distribution may be represented by interface flow, stratified flow, or continuously variable density flow simultaneously in the same model. In the final part of the presented model, interface flow was simulated in aquifer 2 and stratified flow in aquifer 3. And third, the SWI package is implemented in MODFLOW2000, so that existing MODFLOW2000 models of coastal aquifers may be adapted to simulate seawater intrusion with the SWI package.

Version 1.1 of the SWI package was released recently (September, 2004). This new version allows for the specification of different water types for sources and sinks in the model. This makes it possible to pump salt water from below the fresh water zone in the same aquifer, while still representing the aquifer with just one layer of cells. Future plans for development of the SWI package include a new option for a continuous interface through multiple layers (this is especially useful for aquifers consisting of several layers of different hydraulic conductivity), implementation in MODPATH, and inclusion of dispersion. The SWI package is available for free from www.engr.uga.edu/~mbakker/swi.html.

Acknowledgements

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