REPRESENTING THE SALTWATER-FRESHWATER INTERFACE IN REGIONAL GROUNDWATER FLOW MODELS

L. H. MOTZ

Water Resources Research Center
Department of Civil and Coastal Engineering
University of Florida
Gainesville, Florida 32611 U.S.A.
E-mail: lmotz@ce.ufl.edu

Abstract

Numerical experiments were performed to investigate how the saltwater-freshwater interface should be approximated in a groundwater flow model to yield accurate values for hydraulic heads in the freshwater part of a coastal aquifer. These experiments consisted of obtaining solutions for a vertical cross-section using the groundwater flow code MODFLOW and comparing the results to a solution for equivalent freshwater heads obtained using the variable-density flow and transport code SEAWAT, which was considered to be the accurate solution to the problem. The MODFLOW solution that best matched the SEAWAT solution for hydraulic heads in the freshwater part of the aquifer was the solution in which equivalent freshwater heads were specified at the coastal boundary over the full thickness of the aquifer at the seacoast.

Keywords: coastal aquifers, hydraulic heads, numerical experiments, numerical modeling, saltwater-freshwater interface.

Introduction

In regional groundwater flow models that border the seacoast, the saltwater-freshwater interface at the seacoast is represented by various approximations. In many models, for example, it is assumed that the saltwater-freshwater interface is stable and flowing freshwater occurs above the interface and static saltwater exists beneath the interface. In these models, inactive cells are used to represent the saltwater part of the aquifer and a no-flow boundary along the interface. In other applications, the coastal boundary is represented as a specified head boundary condition, and values for the specified heads are equal to the seawater potential ($h_{sw} = 0$) or to equivalent freshwater heads. Of course, sharp-interface models and variable-density groundwater flow and transport models also are used to simulate saltwater and freshwater in coastal aquifers. The objective of the investigation described in this paper was to determine how the saltwater-freshwater interface could best be represented in groundwater flow models using groundwater flow codes such as MODFLOW (McDonald and Harbaugh, 1988). Numerical experiments were performed to investigate how the saltwater-freshwater interface should be approximated in a groundwater flow model to yield accurate values for hydraulic heads in the freshwater part of a coastal aquifer.

Selection of variable density code

SEAWAT (Guo and Langevin, 2002; Langevin, 2001), which simulates three-dimensional, variable-density groundwater flow following a modular structure similar to MODFLOW, was used to represent the saltwater-freshwater interface. In SEAWAT, the dependent variable is the equivalent freshwater head:

$$h_{fw} = \frac{P_N}{\rho_f g} + Z_N \tag{1}$$

where h_{fw} is equivalent freshwater head; P_N is pressure at point N; ρ_f is density of freshwater; g is acceleration due to gravity; and Z_N is the elevation of point N above a datum. The equivalent freshwater head and the head in a saline aquifer are related by:

$$h_{fw} = \frac{\rho}{\rho_f} h - \frac{\rho - \rho_f}{\rho_f} Z \tag{2}$$

where h is hydraulic head; and ρ is density of saline groundwater at point N.

Design of numerical experiments

The numerical experiments consisted of obtaining solutions with different approximations and boundary conditions using MODFLOW and comparing the results to a solution obtained using SEAWAT. A two-dimensional vertical cross-section was used to represent a coastal aquifer (see Figure 1). The cross-section was discretized into one row, 50 columns, and 40 layers. The columns were equally spaced with Δx = 250 m for a total length of 12,500 m, and the layers were equally spaced with Δz = 5 m for a total depth of 200 m. The width of the row perpendicular to the direction of flow in the cross-section was set arbitrarily to Δy = 250 m. The upstream boundary condition was a specified flux boundary condition with a flux of 2.0 m^2/day, and the coastal boundary condition was a specified head boundary condition. The concentration at the coastal boundary was specified as constant and equal to 35 kg/m^3, representing the total dissolved solids (TDS) concentration of seawater. In the SEAWAT solution, equivalent freshwater heads at the coastal boundary were calculated over the vertical using Equation 2 with h = 0, ρ = 1025 kg/m^3, and ρ_f = 1000 kg/m^3. The horizontal and vertical dimensions of the cross-section, the boundary conditions at the seacoast, the hydraulic conductivities, dispersivities, and other aquifer parameters were chosen so that the cross-section was representative of a field-scale coastal aquifer such as the Floridan aquifer system in the southeastern U.S.A. (see Table 1).

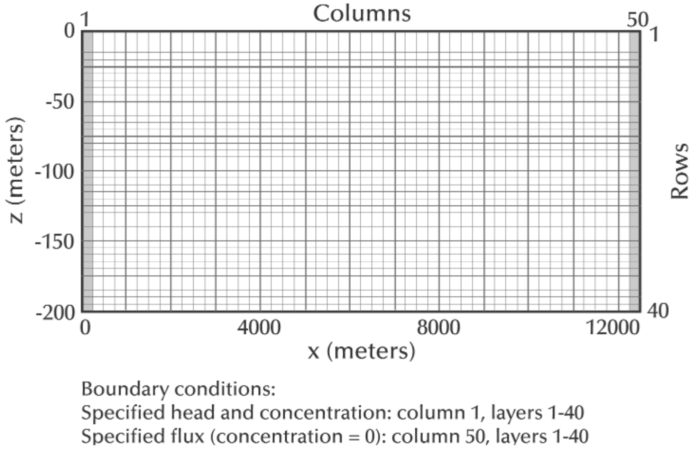

Figure 1. Finite-difference grid used for numerical experiments.

Table 1. Aquifer parameters and boundary inflow used in numerical experiments

Parameter	Value
Horizontal hydraulic conductivity (K_H)	50 m/day
Vertical hydraulic conductivity (K_V)	0.5 m/day
Longitudinal dispersivity (α_H)	125 m
Transverse dispersivity (α_T)	12.5
Vertical dispersivity (α_V)	1.25 m
Porosity (η)	0.30
Flow per unit width (Q/W)	2.0 m^2/day

Results of numerical experiments

Five solutions were calculated. For solution one, TDS concentrations and equivalent freshwater heads were calculated using SEAWAT, which was considered to be the accurate solution to the problem (see figures 2 and 3). Hydraulic heads also were calculated using MODFLOW to obtain four additional solutions (see figures 4-7):

- solution two: head at the coastal boundary was specified equal to the seawater potential ($h_{sw} = 0$) (Figure 4);
- solution three: head at the coastal boundary was specified equal to the equivalent freshwater head (h_{fw}), which increased with depth based on Equation 2 (Figure 5);
- solution four: inactive cells were used to represent the saltwater-freshwater interface (based on solution one), and head at the coastal boundary was specified equal to the seawater potential ($h_{sw} = 0$) (Figure 6); and

- solution five: inactive cells were used to represent the saltwater-freshwater interface (based on solution one), and head at the coastal boundary was specified equal to the equivalent freshwater head (h_{fw}), which increased with depth based on Equation 2 (Figure 2).

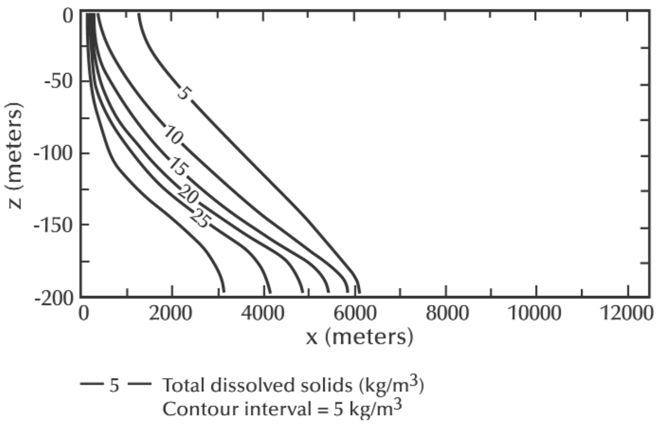

Figure 2. TDS concentrations calculated using SEWAT for solution one.

This investigation focused on how a saltwater-freshwater interface could be approximated in a groundwater flow model to yield accurate values for hydraulic heads in the freshwater part of a coastal aquifer. Accordingly, the MODFLOW solutions were compared to the corresponding SEAWAT solution at the upstream freshwater boundary. The calculated head at the upstream boundary in the SEAWAT solution is 4.95 m (Figure 3), and it is 2.45 m (solution two, Figure 4), 4.95 m (solution three, Figure 5), 3.63 m (solution four, Figure 6), and 4.10 m (solution five, Figure 7) in the MODFLOW solutions. The MODFLOW solution that best matched the calculated hydraulic head at the upstream specified-flux boundary in the SEAWAT solution was considered the best solution. Thus, the MODFLOW solution that best matches the SEAWAT solution using this criterion is solution three, i.e., specifying equivalent freshwater heads (h_{fw}) at the coastal boundary over the full thickness of the aquifer at the seacoast.

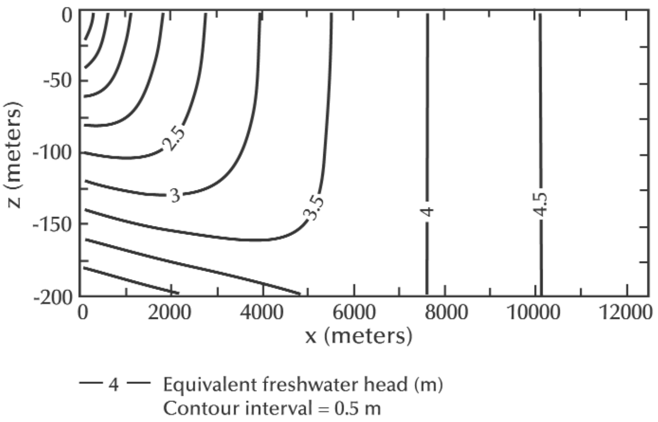

Figure 3. Equivalent freshwater heads calculated using SEAWAT for solution one.

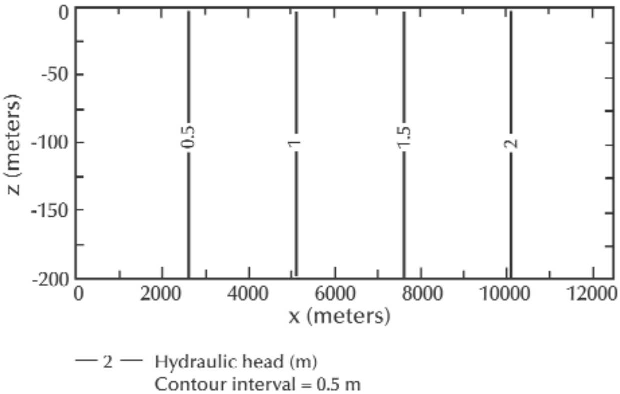

Figure 4. Hydraulic heads calculated using MODFLOW for solution two (h_{sw} = 0 at coastal boundary).

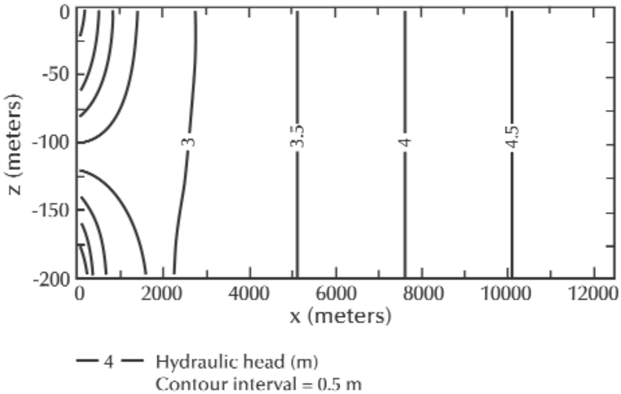

Figure 5. Hydraulic heads calculated using MODFLOW for solution three (equivalent freshwater head h_{fw} at coastal boundary).

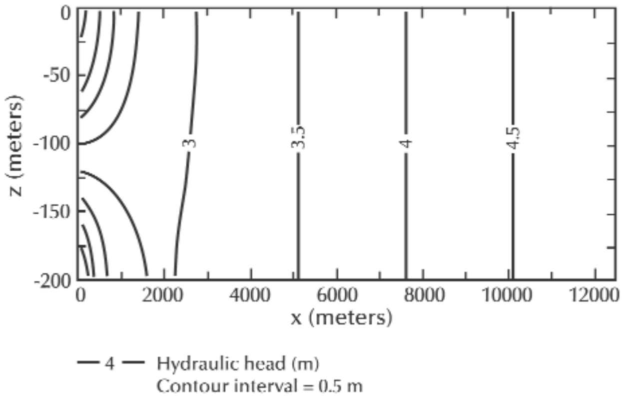

Figure 6. Hydraulic heads calculated using MODFLOW for solution four (inactive cells to represent interface and h_{sw} = 0 at coastal boundary).

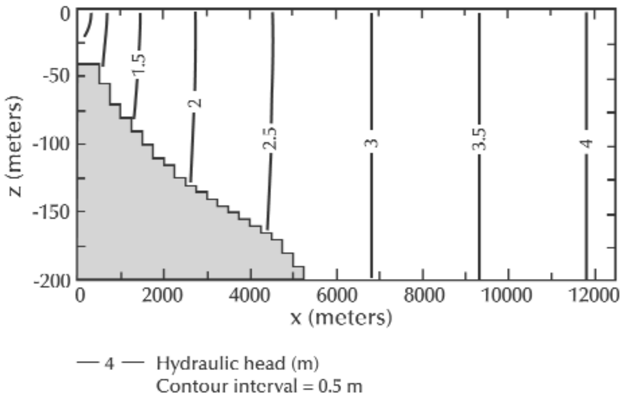

Figure 7. Hydraulic heads calculated using MODFLOW for solution five (inactive cells to represent interface and equivalent freshwater head h_{fw} at coastal boundary).

Discussion

Additional numerical experiments are currently underway to verify these results and to consider whether reducing the transmissivity in an aquifer layer to represent the reduced thickness of the freshwater zone will yield accurate results for heads. Also, the additional experiments will evaluate whether general head boundaries located along the saltwater-freshwater interface can be used to represent the impacts that pumping from the freshwater zone near the saltwater-freshwater interface will have on heads along the interface. The results from this investigation are for a field-scale regional aquifer, which complements and expands results such as those reported by Simpson and Clement (2003, 2004) for the Henry and Elder problems.

Conclusions

Based on the results of a limited number of experiments, it appears that it is possible to represent the effects of the saltwater-freshwater interface in MODFLOW simulations by specifying equivalent freshwater heads at the coastal boundary over the full thickness of the aquifer. These results can be used to evaluate whether existing regional models have represented correctly the effects of the saltwater-freshwater interface, which would affect the accuracy of hydraulic heads predicted in the freshwater part of the aquifer near the interface. Also, these results can be used as a guide during the construction of new regional groundwater flow models to ensure that heads in the freshwater part of the aquifer will be calculated correctly.

Acknowledgments

Financial support for this investigation was provided in part by the St. Johns River Water Management District, Palatka, Florida, and the U.S. Geological Survey State Water Research Institute Program. The

information in this paper represents the opinions and conclusions of the author, and it does not necessarily represent the official position of the St. Johns River Water Management District or the U.S. Geological Survey.

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