Improvements to SEAWAT and Applications of the Variable-Density Modeling Program in Southern Florida

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ABSTRACT

By coupling two commonly used computer programs, MODFLOW (McDonald and Harbaugh, 1988) and MT3Dms (Zheng and Wang, 1998), the SEAWAT program was developed to simulate variable-density, transient ground-water flow in three dimensions. Freshwater head and salt concentration are used as the two principal dependent variables. Major improvements from the previous version of SEAWAT include (1) reformulation of the flow equation based on the conservation of mass, (2) modification of stress packages to allow variable-density sources and sinks, and (3) incorporation of an implicit coupling procedure between the flow and solute-transport equations. These improvements produce more accurate simulation results and extend the applicability of the code to a wider range of hydrogeologic problems.

The SEAWAT program has been widely used in southern Florida by the U.S. Geological Survey and CDM-Missimer International to investigate coastal ground-water flow processes. Seven applications have been completed or are in progress and pertain to the following types of hydrogeologic problems: availability of brackish ground water, saltwater intrusion, surface water and ground-water interactions, submarine ground-water discharge, and effectiveness of salinity barriers. For each application, the SEAWAT program was successfully used to investigate the effects of fluid density variations on ground-water flow rates and patterns.

INTRODUCTION

The SEAWAT program has been substantially improved since it was first published by Guo and Bennett (1998). Major improvements from the previous version of SEAWAT include (1) reformulation of the flow equation based on the conservation of mass, (2) modification of stress packages to allow variable-density sources and sinks, and (3) incorporation of an implicit coupling procedure between the flow and solute-transport equations. These improvements produce more accurate simulation results and extend the applicability of the code to a wider range of hydrogeologic problems (Langevin and Guo, 1999). The SEAWAT code has been verified with a number of benchmark problems that are commonly used to test variable-density ground-water flow codes. The results of these tests indicate that SEAWAT is capable of accurately simulating variable-density ground-water flow (Langevin and Guo, 1999).

The SEAWAT program is being applied by the U.S. Geological Survey and CDM-Missimer International in southern Florida to investigate coastal ground-water flow processes and other water-supply related projects. This paper briefly summarizes the major improvements to the SEAWAT code and illustrates the application of SEAWAT to three completed and four ongoing studies in southern Florida.

MAJOR IMPROVEMENTS TO SEAWAT

Reformulation of Ground-Water Flow Equation

The SEAWAT code was improved by using a more general form of the ground-water flow equation than was used in previous versions of the code. Under isothermal conditions, the ground-water flow equation based on the conservation of mass is:

$$-\nabla\cdot(r\vec{q})+\bar{r}q_s = rS_P\frac{\partial P}{\partial t}+q\frac{\partial r}{\partial C}\frac{dC}{dt}, \quad (1)$$

where r is fluid density [ML^{-3}], $\vec{q}$ is specific discharge [LT^{-1}], $\bar{r}$ is density of water entering from a source or leaving through a sink [ML^{-3}], q_s is rate of flow from a source or to a sink [T^{-1}], S_p is storage coefficient in terms of pressure [$ML^{-1}T^{-2}$]$^{-1}$, P is fluid pressure [$ML^{-1}T^{-2}$], t is time [T], q is effective porosity [dimensionless], and C is solute concentration [ML^{-3}]. The last term on the right-hand side of equation 1 is the rate of fluid mass accumulation due to the change in solute concentration.

The relation between fluid pressure and equivalent freshwater head (h_f [L]) is:

$$P = r_f g(h_f - Z), \quad (2)$$

where r_f is density of freshwater [ML^{-3}], g is acceleration due to gravity [LT^{-2}], and Z is elevation [L]. Guo and Bennett (1998) show that Darcy's law for variable-density ground-water flow in the α direction (parallel to bedding) can be approximated with the following equation if it is assumed that solute concentration does not affect fluid viscosity:

$$q_a = -K_{fa}\left[\frac{\partial h_f}{\partial a}+\frac{(r-r_f)}{r_f}\frac{\partial Z}{\partial a}\right], \quad (3)$$

where K_{fa} is the freshwater equivalent hydraulic conductivity [LT^{-1}] in the α direction. By substituting Darcy's Law, equation 1 is rewritten as:

$$\frac{\partial}{\partial a}\left[rK_{fa}\left(\frac{\partial h_f}{\partial a}+\frac{(r-r_f)}{r_f}\frac{\partial Z}{\partial a}\right)\right]+\frac{\partial}{\partial b}\left[rK_{fb}\left(\frac{\partial h_f}{\partial b}+\frac{(r-r_f)}{r_f}\frac{\partial Z}{\partial b}\right)\right]$$
$$+\frac{\partial}{\partial g}\left[rK_{fg}\left(\frac{\partial h_f}{\partial g}+\frac{(r-r_f)}{r_f}\frac{\partial Z}{\partial g}\right)\right]= rS_f\frac{\partial h_f}{\partial t}+q\frac{\partial r}{\partial C}\frac{\partial C}{\partial t}-\bar{r}q_s, \quad (4)$$

where b and g are coordinate directions parallel and normal to bedding. Fluid density is treated as constant during iterations of the flow equation for a single time step; therefore, equation 4 can be written in a form identical to that solved by MODFLOW.

Incorporation of Variable-Density Stress Packages

The applicability of SEAWAT was extended by incorporating options for variable-density sinks and sources. These options were implemented by (1) converting volumetric fluxes to mass fluxes with the appropriate fluid density before being added to the right-hand-side (*RHS*) and h-coefficient (*HCOF*) accumulators, (2) using a variable-density form of Darcy's law for head-dependent boundaries, and (3) converting equivalent freshwater head to head for boundaries involving the elevation of the water table. Appropriate modifications were made to the revised SEAWAT code for each of the following stress packages implemented in the 1988 version of MODFLOW (McDonald and Harbaugh, 1988): Well, Drain, General Head, Recharge, Evapotranspiration, and River.

Implementation of Implicit Coupling for Flow and Transport

Implicit coupling between the flow and solute-transport equations was added as an option. With this option, the flow and solute-transport equations are solved repeatedly for each time step until the maximum difference in calculated fluid density from one iteration to the next is less than a user-defined convergence value (Figure 1). The implicit-coupling procedure provides a more accurate solution for problems in which solute concentrations are changing rapidly compared to the length of the time step, and can improve computational efficiency.

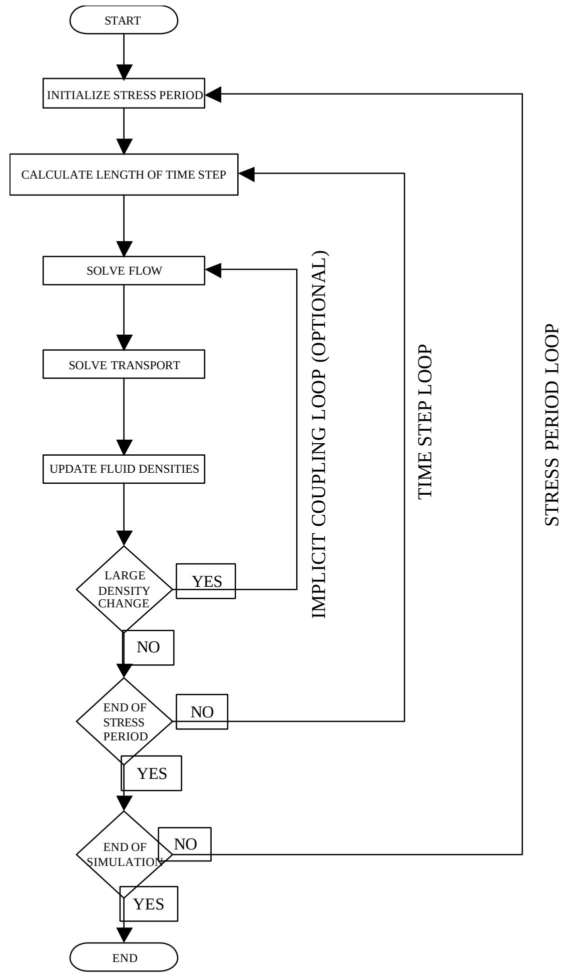

Figure 1. Flow chart showing the implicit coupling procedure.

APPLICATIONS OF SEAWAT IN SOUTHERN FLORIDA

Water-resource management has become an important issue in southern Florida because of rapid population increase and concerns with Everglades ecosystem restoration. Problems with water supply in coastal areas are often caused by saltwater intrusion into shallow aquifers, which are commonly used as a source of potable water. In some cases, the simulation of variable-density ground-water flow is required to adequately address issues of saltwater intrusion, water supply and ecosystem restoration. The SEAWAT program has been successfully applied to three such cases, and four additional case studies are currently (May 2001) in progress.

Submarine Ground-Water Discharge to Biscayne Bay

The U.S. Geological Survey initiated a project in 1996 in cooperation with the Army Corps of Engineers to quantify the rates and patterns of submarine ground-water discharge to Biscayne Bay, Florida. Rates of submarine ground-water discharge for the period from January 1989 to September 1998 were evaluated through the development of a regional-scale, three-dimensional, variable-density ground-water flow model (C. Langevin, U.S. Geological Survey, written commun.). Hydrologic stresses and boundaries in the 10-layer model include recharge, evapotranspiration, ground-water withdrawals from municipal well fields, interactions with surface-water (canals and standing water in the Everglades), boundary flows, and submarine ground-water discharge to Biscayne Bay. The model was calibrated by matching ground-water levels in monitoring wells, canal base flow, and position of the 1996 saltwater intrusion line.

Rates of submarine ground-water discharge were converted to equivalent freshwater rates using the simulated salinity of the discharged water and the salinity of seawater. Results from the model suggest that fresh submarine ground-water discharge to Biscayne Bay exceeded surface-water discharge during the 1989, 1990, and 1991 dry seasons. For the entire simulation period, however, the average ground-water discharge rate was about 10 percent ($1.3x10^{6}$ ft^{3}/day) of the surface-water discharge to the bay. Results from the model also suggest that the combined freshwater discharge to tidal portions of the Miami, Coral Gables, and Snapper Creek canals was also about 10 percent of the surface-water discharge. These tidal canals penetrate the freshwater portion of the aquifer and intercept fresh ground water that might have discharged directly to Biscayne Bay. The result is relatively low rates of submarine ground-water discharge near the mouths of canals compared to rates of ground-water discharge further from canal mouths.

Evaluation of Ground-Water Supply at the City of Clearwater

The City of Clearwater, Florida, is currently conducting a study of the feasibility of expanding the existing well field in the City of Clearwater and developing brackish ground water as a source of water supply within the Pinellas Park area. A three-dimensional ground-water flow and solute-transport model was developed using SEAWAT (CDM/Missimer International, 2001). The model consists of 6 layers, which represent the surficial aquifer, the confining bed between the surficial aquifer and the underlying aquifers, the Upper Zone A aquifer, the Lower Zone A aquifer, the semi-confining formation between Zone A and Zone B, and the Zone B aquifer. The model was calibrated to average hydrological conditions for 1996 and to chloride concentrations measured at the City of Clearwater well field from 1995 to 2000. Figure 2 shows the close agreement between calculated and measured chloride concentrations at Reservoir 2. Reservoir 2 is a group of production wells located at the south end of the well field. Water budget analysis indicated that most of the pumped water is actually derived from the surficial aquifer. Model results show relatively minor changes in chloride concentration at the well field for the next 10 years, likely due to downward leakage of relatively fresh water from the surficial aquifer. This prediction may need to be updated as boundary conditions and hydrologic stresses change in the future. A water-quality monitoring plan also was recommended.

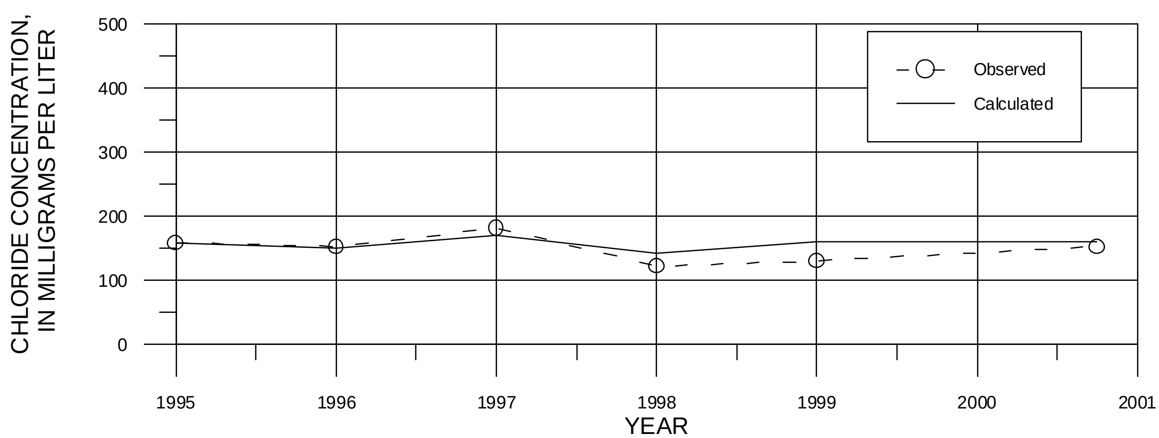

Figure 2: Calibration of chloride at the City of Clearwater well field. Solid line represents model calculated chloride concentration. Dashed line and open circle represent observed chloride concentration at Reservoir 2 from 1995 to 2000.

Pilot Study of Salinity Barrier for City of Hollywood

The problem of saltwater intrusion along the lower east coast of Florida has been known for many years (Leach, et al., 1972). The intrusion of saltwater into the Biscayne aquifer in Dade and Broward Counties is well documented and results from a combination of increased drainage, decreased recharge, and excessive pumping of ground water for agricultural, industrial, and municipal water supplies. A pilot project by the City of Hollywood was designed to investigate the feasibility of a salinity barrier created by injecting reclaimed water into the Biscayne aquifer. A short-term injection test with potable water was conducted from January 6 to February 10, 2000 at test well IW-1. Injection lasted for 14 days. The average injection rate was approximately 1,130 gallons per minute over the test period with a nearly constant flow rate maintained after the first 24 hours of injection.

A three-dimensional ground-water flow model of the test site was developed by converting an existing ground-water flow and solute-transport model developed for the South Florida Water Management District using SWIFT/486 code (ViroGroup, Inc., 1994) to a SEAWAT model. The model has five layers, representing the surficial aquifer, a semi-confining layer, the shallow production zone of the Biscayne aquifer, the deep production zone of the Biscayne aquifer and a deeper semi-confining layer (CDM/Missimer International, Inc. 2000).

The model was recalibrated based on data collected during the field test. Figure 3 shows the simulated concentrations of chloride near the test injection well. Observed concentrations of chloride are posted for comparison. Figure 4 shows a simulated head profile along an east-west cross-section through the injection well, as shown in Figure 3. The modeling results suggest that an increase in head resulting from the injection of water into the deep production zone of the Biscayne aquifer would form a hydraulic barrier that would prevent further inland movement of the saltwater/freshwater interface.

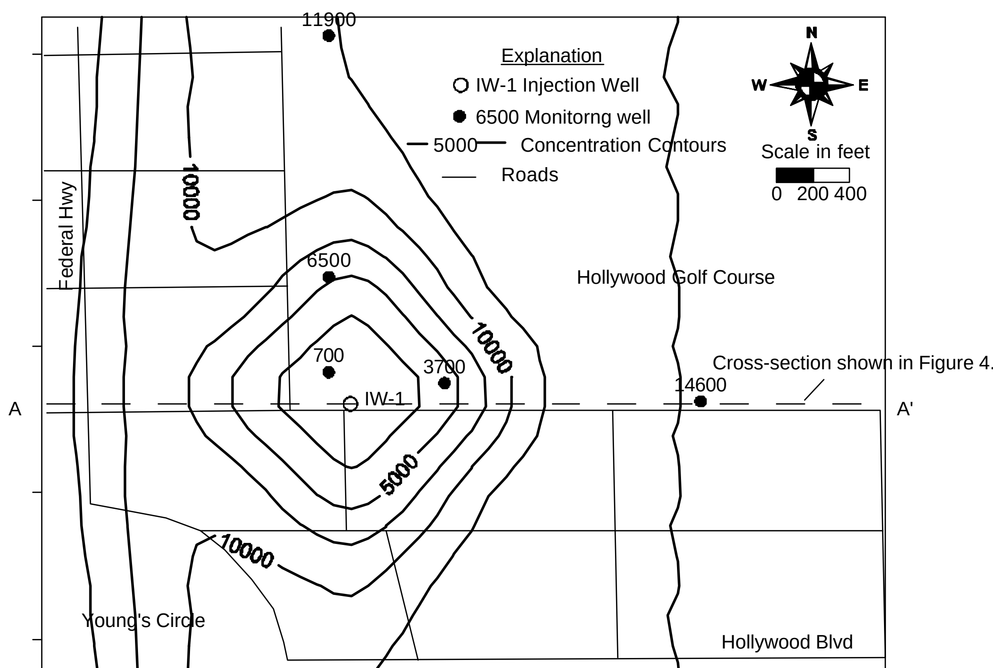

Figure 3: Model-predicted chloride concentration (milligrams per liter) after 7 days of recovery from the 14-day injection test. Measured concentrations are shown for comparison. Contour interval is 2,500 milligrams per liter.

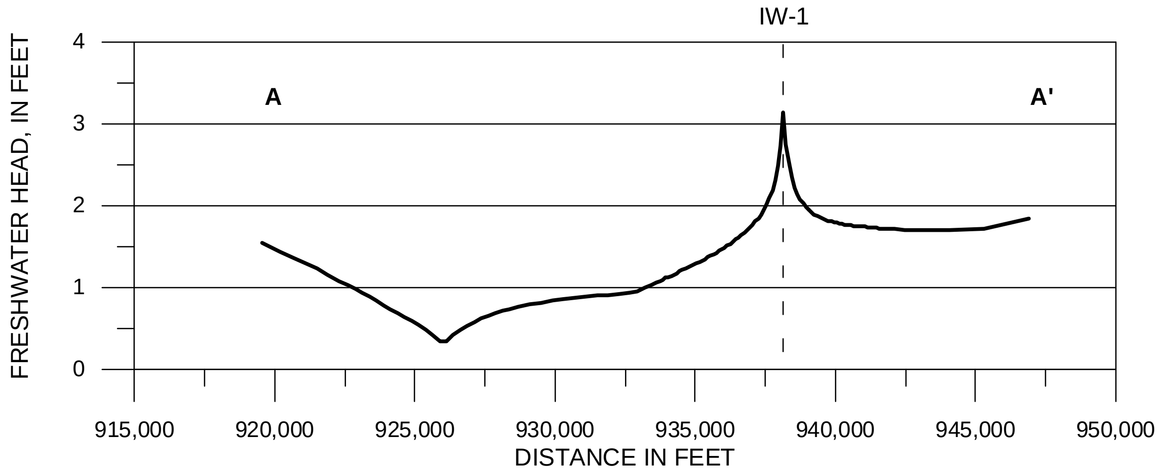

Figure 4: Simulated freshwater heads after 30 days of injection in model layer 4 along an east-west cross-section.

Studies in Progress

Locations of the four ongoing projects that are currently using the SEAWAT code are Bonita Springs, the southeastern portion of the Everglades, Everglades National Park and the Big Cypress Preserve, and Broward and Palm Beach Counties. Near Bonita Springs, saltwater intrusion has been observed over a 20- to 30-square mile area where the potentiometric surface of the Lower Tamiami aquifer is below sea level. The SEAWAT code is being used to study the hydrogeologic effects of this potentiometric low, and model results completed to date suggest that upconing of saline water from deeper aquifers is a greater threat to potable ground-water resources than is lateral saltwater intrusion (W. Shoemaker, U.S. Geological Survey, written commun.). Variable-density ground-water flow models for the southeastern portion of the Everglades (Wolfert and others, 2001) and all of the southern Everglades (Schaffranek and others, 2001) also are being developed. As part of these modeling efforts, the SEAWAT code is being coupled with the dynamic surface-water model SWIFT2D (Leendertse, 1987) to simulate the complex interactions between surface water and ground water. For Broward and Palm Beach Counties, the relationship between water-level fluctuations and saltwater intrusion in the highly permeable Biscayne aquifer is being investigated with field studies and variable-density ground-water flow modeling (A. Dausman, U.S. Geological Survey, written commun.). Preliminary simulations with SEAWAT suggest that daily fluctuations in the water levels in the canals can cause the freshwater/saltwater interface in the aquifer to advance and retreat over a period of days or weeks.

SUMMARY

SEAWAT has been substantially improved since it was first published in 1998. The major improvements include the change from fluid volume conservation to fluid mass conversation, reformulation of stress packages, and addition of an implicit coupling method. This new version of SEAWAT provides more accurate simulation results, and provides users with more options for representing variable-density sources and sinks than were available in previous versions of the code.

In recent years, SEAWAT has been successfully applied to a number of projects in southern Florida by the U.S. Geological Survey and CDM/Missimer International, Inc. Preliminary results from four ongoing projects and results from three completed projects demonstrate the practical capability of SEAWAT to simulate complex problems of variable-density ground-water flow.

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