Numerical Simulation of Saltwater Intrusion in Response to Sea-Level Rise

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Abstract

A two-dimensional numerical model of variable-density groundwater flow and dispersive solute transport was used to predict the extent, rate, and lag time of saltwater intrusion in response to various sea-level rise scenarios. Three simulations were performed with varying rates of sea-level rise. For the first simulation, sea-level rise was specified at a rate of 0.9 mm/yr, which is the slowest rate of sea-level rise estimated by the Intergovernmental Panel on Climate Change (IPCC). After 100 years, the 250 mg/L chloride isochlor moved inland by about 40 m, and required an additional 8 years for the system to reach equilibrium. For the next simulation, sea-level rise was specified at 4.8 mm/yr, which is the central value of the IPCC estimate. For this moderate rate of sea-level rise, the 250 mg/L isochlor moved inland by about 740 m after 100 years, and required an additional 10 years for the system to reach equilibrium. For the fastest rate of sea-level rise estimated by IPCC (8.8 mm/yr), the 250 mg/L isochlor moved inland by about 1800 m after 100 years, and required more than 50 years to reach equilibrium.

Introduction

In response to global climate change, sea level is expected to rise between 9 and 88 centimeters (cm) by the year 2100 (IPCC, 2001). A central value of 48 cm is widely considered to be the most likely increase in sea-level over the next 100 years. Concerns are growing regarding the impact sea-level rise will have on coastal areas. Beach erosion, increased flooding, and increases in estuary salinity are all likely outcomes of sea-level rise (Wanless, 1989). Saltwater intrusion into coastal aquifers is another potential concern. The interface between fresh and saline groundwater will probably move inland in response to an increase in sea level. A complicating factor is that movement of the interface is not instantaneous, and many years or decades may be required before the interface will reach equilibrium with the current sea level.

This paper presents the results of a simple two-dimensional numerical model used to evaluate interface movement in response to sea-level rise. The model developed here is based on generalized characteristics of the highly permeable Biscayne aquifer of Broward County, Florida (Figure 1). Southern Florida has experienced significant saltwater intrusion (e.g. Parker et al., 1955; Andersen et al., 1988; Merritt, 1996); however, intrusion has been attributed to lowering of the water table, either by draining for urban and agricultural development or from groundwater withdrawals at municipal well fields. To date, there are no reported quantitative evaluations of saltwater intrusion in southern Florida in response to sea-level rise.

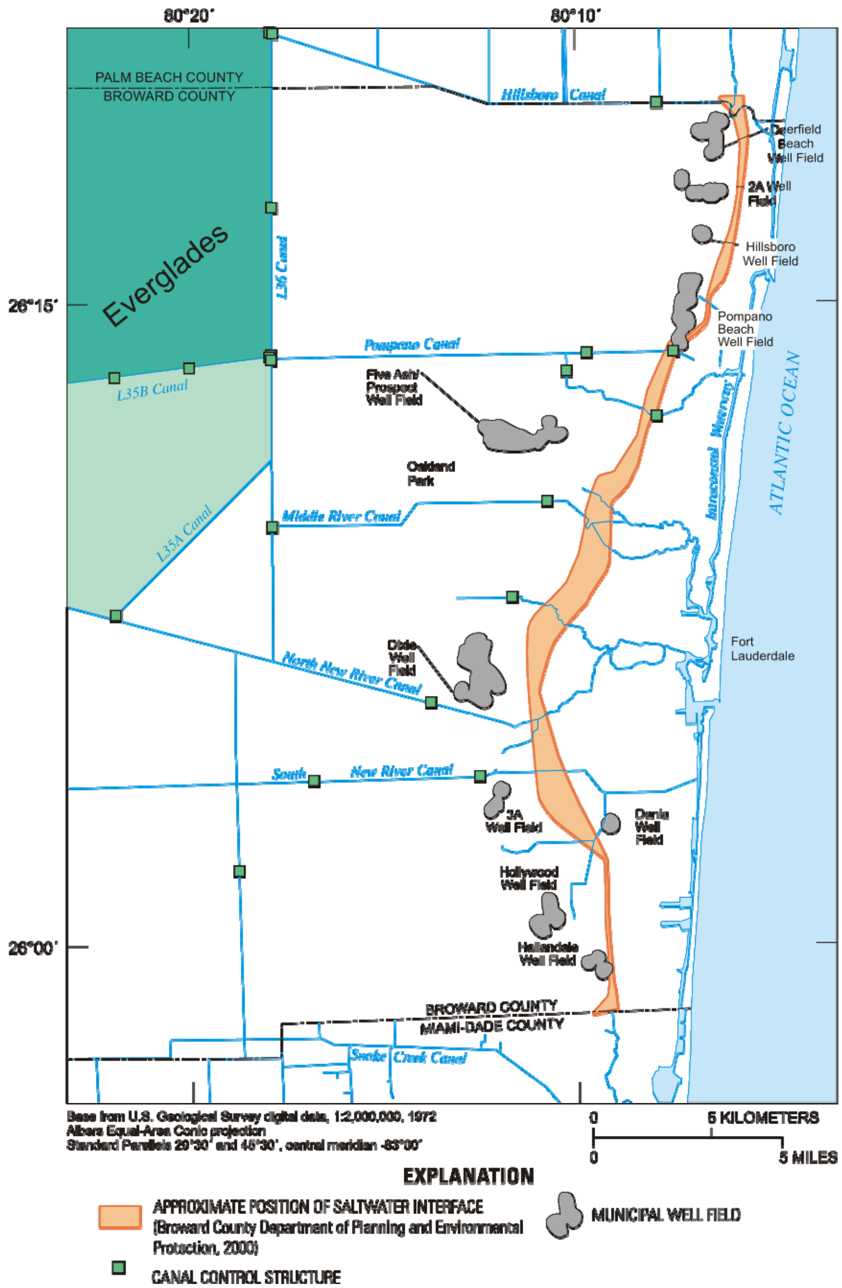

Figure 1. Map of eastern Broward County, Florida, showing municipal well fields and position of the saltwater interface.

Model Design and Analysis

To evaluate the effects sea-level rise on saltwater intrusion, a two-dimensional cross-section model was developed using average hydrologic conditions for 1998 and generalized hydrogeologic characteristics of Broward County, Florida (Figure 1). The horizontal axis of the model was aligned perpendicular to the coast along a groundwater flow line, allowing the evaluation to be performed in a two-dimensional vertical cross section. Based on the geometry of the canal network, west to east flow paths are generally expected to occur through the middle of surface-water basins bound on the north and south by east-west canals. The model grid contains 1 row, 152 columns, and 14 layers, and each cell is 150 by 7.5 m (Figure 2). Representative properties of the Biscayne aquifer in Broward County (Table 1) were assigned to active model cells. Only the highly permeable Biscayne aquifer, which thickens to the east to a depth of around 110 m, is represented in the model. Constant-head cells were assigned along the bottom of the ocean; all other ocean cells were inactive. A salinity value of 35 g/L was assigned to inflow from the constant-head cells; a zero value was assigned to all other boundary concentrations. General-head boundaries (GHBs) were placed along the left face of the model to represent hydraulic connection to the Everglades. The head in the GHB cells was held constant at 1.48 m, and the GHB conductance was calculated using the horizontal hydraulic conductivity of the Biscayne aquifer and model cell dimensions. Net recharge was assigned to active cells in the top layer of the model at a rate of 23 cm/yr, which is about 15% of the annual rainfall for 1998. Additional details on the model design are given in Dausman and Langevin (2002; 2005).

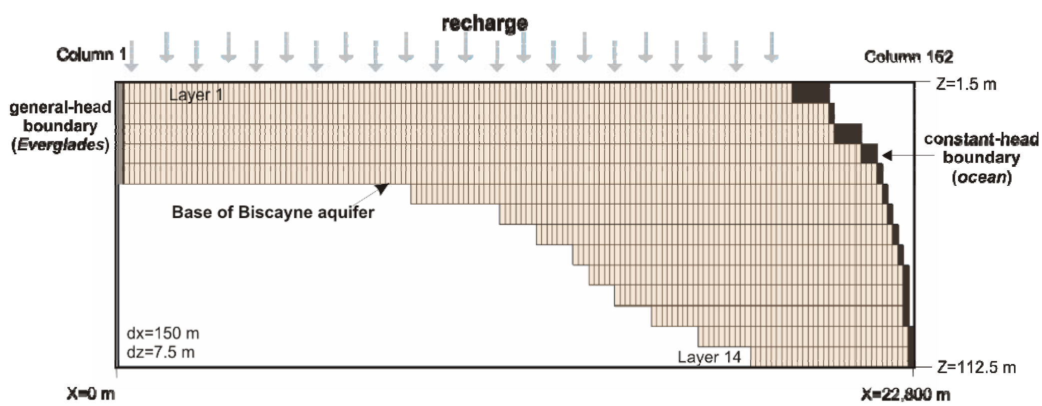

Figure 2. Model grid and boundary conditions for two-dimensional cross-section model.

The extent, rate, and lag time of saltwater intrusion were evaluated using SEAWAT-2000 (Langevin et al., 2003), an updated version of the SEAWAT computer program (Guo and Bennett, 1998; Guo and Langevin, 2002). For the sea-level rise scenarios evaluated here, initial conditions (heads and salinities) were specified using the results from a long-term simulation in which the model had reached steady-state flow and transport conditions. This long-term simulation was performed using the present-day sea level of 0.19 m NGVD (National Geodetic Vertical Datum of 1929). For the sea-level rise simulations, heads at the ocean boundary were linearly increased from present day values using the lower, middle, and upper bounds of the sea-level rise estimates presented by the IPCC (2001). The first simulation used a sea-level rise rate of 9 cm over 100 years, the second used a rate of 48 cm over 100 years, and the third used the upper bound of 88 cm over 100 years. For each of the three simulations, a linear rise was specified for the first 100 years. Sea level was held constant for the remaining 50 years of the 150-year simulation to determine the length of time (or lag time) required for the interface to reach equilibrium.

Table 1. Aquifer properties and boundary stresses used in the cross-section model. [K_H, horizontal hydraulic conductivity; K_v, vertical hydraulic conductivity; α_L, longitudinal dispersivity; α_T, transverse dispersivity; R, recharge; S_y specific yield; S, storage; n, porosity]

Parameter/Stress [units]	Value
K_H, [m/d]	1150
K_v, [m/d]	150
α_L, [m]	3.0
α_T, [m]	0.3
R, [cm/yr]	23
S_y [dimensionless]	0.1
S [dimensionless]	1×10^{-5}
n [dimensionless]	0.1
Sea level	
Equilibrium simulation (constant-head value) [m]	0.19
Sea-level rise simulations (constant-head increase) [mm/yr]	
Slow increase	0.9
Moderate increase	4.8
Fast increase	8.8

Results from the dispersive flow and transport model were processed by calculating the position of the 250 mg/L chloride isochlor (which corresponds with a salinity value of 0.46 g/L) at the base of the aquifer as a function of time. The chloride value of 250 mg/L represents the Environmental Protection Agency's (EPA's) maximum drinking water standard. This procedure required simple linear interpolation between adjacent model cells to locate the exact isochlor position. Simpson and Clement (2004) used a similar method to describe isochlor movement in their analysis of the Henry problem.

Results

Results from the three numerical simulations indicate varying degrees of saltwater intrusion (Figure 3). For the slowest rate of sea-level rise, the 250 mg/L isochlor moves inland only about 40 m over the 100-year period. This represents an average intrusion rate of about 0.4 m/yr. For the moderate rate of sea-level rise (4.8 mm/yr), the 250 mg/L isochlor moves inland by about 740 m after 100 years, which represents an average intrusion rate of about 7.4 m/yr. Lastly, for the simulation with the relatively fast rate of sea-level rise, the 250 mg/L isochlor moves inland about 1800 m after 100 years, giving an intrusion rate of about 18 m/yr.

Model results for the last 50 years of the simulations also provide insight into the lag time response of saltwater movement following sea-level rise (Figure 3). For the slow sea-level rise simulation, the 250 mg/L isochlor continues to migrate inland (albeit at very slow speeds) for another 8 years. For the moderate sea-level rise simulation, the lag time appears to be about 10 years, but for the fast sea-level rise simulation, the lag time appears to be greater than 50 years. Moreover, the 250 mg/L isochlor moved an additional 700 m for the fast sea-level rise scenario, even after the specified sea-level rise had ceased.

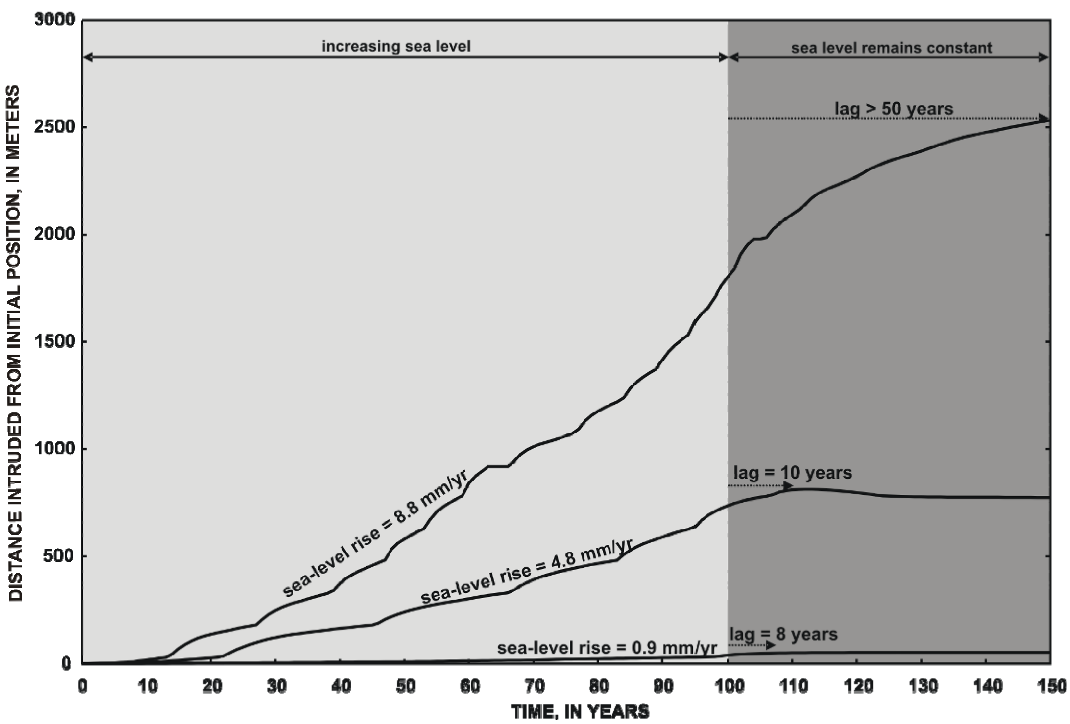

Figure 3. Simulated movement of the 250 mg/L chloride isochlor in response to sea-level rise.

Discussion

The results from this analysis suggest that the threat of saltwater intrusion is related to the actual sea-level rise that southern Florida is expected to experience over the next 100 years. As shown in Figure 1, the municipal well fields, which supply nearly all of the potable water in the area, are within about 5 km of the present-day saltwater interface. Model results suggest that many of these well fields may become threatened by an advancing saltwater front if sea-level rise is near the upper bounds of the predictions. Saltwater intrusion in response to sea-level rise will probably not be a problem if sea-level rise is near the lower bound of the predictions.

The numerical model was developed with the simplifying assumption of a two-dimensional system, whereas the actual system is probably dominated by three-dimensional groundwater flow as a result of the extensive canal network. Consequently, the saltwater intrusion rates and distances are probably an underestimate considering that coastal canals allow sea-level heads to extend inland to the easternmost control structures (Figure 1). Future studies that will focus on the development of a fully three-dimensional groundwater model would be able to represent the effects of canals more accurately, and improve estimates of saltwater intrusion in response to sea-level rise.

The results presented here contain numerous uncertainties, in addition to those introduced by the assumption of two-dimensional conditions. As described in Dausman and Langevin (2002, 2005), the properties used in the model are thought to be reasonable estimates for the Biscayne aquifer in Broward County; however, if the assigned aquifer properties are in error, the predicted saltwater intrusion rates may not accurately reflect future interface movement. Another limitation is the assumption that the net recharge and head values used for the simulation will remain constant over the next 100 years. For example, in the simulations, the water table is predicted to rise in the aquifer over the 100-year period in response to the sea-level rise. In low-lying parts of southern Broward County, future canal levels will probably be managed to maintain the current elevation of the water table in order to prevent flooding. Thus, the net recharge to the aquifer would actually decrease through increased runoff, causing saltwater to intrude farther than predicted by the simulation. For these and other simplifying assumptions, model results should be interpreted with caution.

From a saltwater intrusion perspective, southern Florida has already experienced a hydrologic change similar to sea-level rise. In the early 1900's, large parts of the Everglades were drained to increase the land available for urban and agricultural development. In some areas, dredged canals lowered inland water levels by as much as 1.8 m (Parker et al., 1955, p. 584). In the Silver Bluff area, which is located in Miami-Dade County (just south of Broward County), Parker (1945, p. 539) estimated that prior to 1942, saltwater intrusion was occurring in the Biscayne aquifer at rate of about 70 m/yr. During an extreme drought (in 1943 and 1944), Parker (1945, p. 539) and Parker et al. (1955, p. 590) reported a saltwater intrusion rate of about 270 m/yr. One of the most reliable estimates of saltwater intrusion rates in southern Florida can be calculated from chloride graphs at groundwater monitoring wells located along a transect perpendicular to the coastline near the Hallandale well field (Figure 1). Based on the chloride graphs presented in Merritt (1996), the 250 mg/L isochlor moved inland at a rate of about 20 m/yr from 1974 to 1981. A comparison of these observed intrusion rates (20 to 270 m/yr) with the simulated rates (0.4 to 18 m/yr) suggests that sea-level rise will probably result in a slower rate of saltwater intrusion than the intrusion rate caused by extensive Everglades drainage.

Conclusion

A simple two-dimensional numerical model was developed to predict the possible effects of sea-level rise on saltwater intrusion into the permeable carbonate aquifer in southern Florida. The severity of saltwater intrusion is largely related to the expected rate of sea-level rise over the next 100 years. According to the IPCC (2001), sea level is expected to rise between 9 and 88 cm (with a central value of 48 cm) by the year 2100. Slow, moderate, and fast rises in sea level (9, 48, and 88 cm over 100 years) were tested with the numerical model by evaluating the movement of the 250 mg/L chloride isochlor, which is the EPA's maximum drinking water standard. For the relatively slow rate of sea-level rise, the 250 mg/L chloride isochlor moved inland by about 50 m. For the moderate rate of sea-level rise, the 250 mg/L isochlor moved inland by about 740 m; the 250 mg/L isochlor moved inland by about 1800 m for the fast sea-level rise scenario. The model was also used to test the lag (or response time) for the saltwater interface to reach equilibrium with changes in sea-level rise. Estimated lag times ranged from about 8 to greater than 50 years for the three scenarios tested with the model. The saltwater intrusion rates estimated here for Broward County, Florida, may not be indicative of the intrusion rates expected elsewhere. The carbonate Biscayne aquifer is much more permeable than most unconsolidated coastal plain aquifers. Thus, the saltwater intrusion rate as a result of sea-level rise would probably be much slower for other coastal aquifers than the rate estimated here.

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