Effects of climate change on saltwater intrusion at Hilton Head Island, SC. U.S.A.

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ABSTRACT

Sea-level rise and changes in precipitation patterns may contribute to the occurrence and affect the rate of saltwater contamination in the Hilton Head Island, South Carolina area. To address the effects of climate change on saltwater intrusion, a three-dimensional, finite-element, variable-density, solute-transport model was developed to simulate different rates of sea-level rise and variation in onshore freshwater recharge. Model simulation showed that the greatest effect on the existing saltwater plume occurred from reducing recharge, suggesting recharge may be a more important consideration in saltwater intrusion management than estimated rates of sea-level rise. Saltwater intrusion management would benefit from improved constraints on recharge rates by using model-independent, local precipitation and evapotranspiration data, and improving estimates of confining unit hydraulic properties.

INTRODUCTION

Saltwater intrusion of the Upper Floridan aquifer has been observed in the Hilton Head Island, South Carolina area since the late 1970s. Seawater or brackish water is believed to be leaking downward through the Upper Floridan confining unit in areas where the confining unit is thin or eroded, offshore of Hilton Head Island and within local creeks and rivers (Foyle and others, 2001). Although groundwater pumping is a major driving force for saltwater intrusion, the effects of climate change may contribute to the occurrence and affect the rate of saltwater contamination of aquifers in coastal areas. Sea-level rise is one effect of climate change, and has been the focus of a previous study on saltwater intrusion in the Hilton Head Island area (Payne, 2010). Sea-level rise creates an increased driving force of seawater into areas prone to downward leakage of saltwater. Rising sea level also may result in a larger land area inundated by saltwater, which then may migrate downward into units that presently contain freshwater. Changes in precipitation patterns may also contribute to saltwater intrusion. An increase in local precipitation may result in higher onshore freshwater recharge rates, effectively mitigating the driving force of seawater intrusion. Alternatively, prevailing drought conditions may result in a decrease of onshore freshwater recharge, providing less resistance to the landward movement of a saltwater interface.

To examine the possible effects of climate change on saltwater intrusion in the Upper Floridan aquifer in the Hilton Head Island area, the U.S. Geological Survey (USGS) developed a groundwater flow and solute-transport model to test the effects of different potential rates of sea-level rise and the pumping elimination on saltwater intrusion (Payne 2010). The purpose of this paper is to show simulation results from changes in recharge to the Upper Floridan aquifer as a result of changes in precipitation patterns, and to compare the relative importance of sea-level rise with changes in precipitation on saltwater intrusion in the Hilton Head Island area.

METHODS

The model was developed using the USGS three-dimensional, finite-element, variable-density, solute-transport simulator SUTRA 2.1 (Voss and Provost, 2008), modified from a previous model (Provost and others, 2006) to account for the time-dependent boundary conditions (pumping and sea-level rise history from 1885 to 2004) in the Hilton Head Island area. This model represents the hydrogeologic system from the surficial aquifer to the base of the Floridan aquifer system. It is calibrated to 2004 conditions, and indicates a three-lobed saltwater plume occurs beneath the northern end of Hilton Head Island, and beneath and west of Pinckney Island. Details of model construction, calibration and testing are provided in Payne (2010).
The model was originally used to test the effects of different rates of sea-level rise on saltwater intrusion. The sea-level rise scenarios represent: (1) continuation of the estimated sea-level rise rate of 1 ft/century from 1885–2004; (2) doubling the current rate of the sea-level rise to 2 ft/century; and (3) a cessation of sea-level rise (rate decreases to 0 ft/century). For this analysis, two additional scenarios were conducted representing (4) an increase in onshore freshwater recharge; and (5) a decrease in onshore freshwater recharge, both maintaining the current rate of sea-level rise, as in Scenario 1. These latter two scenarios were implemented by increasing and decreasing, respectively, the water table altitude as a proxy for the change in recharge, which controls the onshore, freshwater boundary pressure. For all scenarios, simulated initial conditions and pumping rates remained at 2004 values and the duration of each scenario is 100 years.

For the calibrated model, a Cauchy boundary condition was used to represent recharge to the water table aquifer as a head-dependent flux. Water table altitude was set as a linear function of land surface altitude, regressed from available water-table altitude data over the entire model area. To simulate increased recharge, the water table was set to land surface altitude, the highest possible altitude. The relation between water-table and land surface altitudes diverges from linear at altitudes below about 30 ft, closest to the coast. So, to simulate decreased recharge, the water table was set as a 2nd order function of land surface altitude, regressed from a representative subset of water table values at sites for which land surface altitude was below 30 ft, as described in Payne (2010).

SIMULATION RESULTS

The development of the three-lobed plume for Scenarios 2 through 5 are compared with that for Scenario 1, which represents a continuation of the current rate of sea-level rise, and no change in the top boundary condition from the calibrated model.

Effects of sea-level rise

Comparison of results for Scenarios 1, 2, and 3 indicates that the rate of sea-level change has little effect on overall plume development, except in the Pinckney Island area (Figure 1). With an increase in sea-level rise rate, the highest concentration area of the plume increases in extent near Pinckney Island (Figure 1A), whereas with a decrease in sea-level rise rate, the highest concentration area of the plume decreases in extent (Figure 1B). Pinckney Island is particularly prone to increased saltwater intrusion with change in sea level because it is a relatively large area of low land-surface altitude and confining unit thickness (Foyle and others, 2001).

Effects of changes in precipitation

Comparison of Scenarios 1 and 4 (Figure 2A) indicates that an increase in onshore freshwater recharge diminished the overall extent of the plume only slightly in the Pinckney Island area. For this implementation of the onshore top boundary condition, the maximum driving force for freshwater recharge is for the water table set to land surface altitude, i.e. the surficial aquifer is fully saturated. At low land surface altitude, the difference between the water table altitudes for Scenarios 5 and 1 is so small, on the order of a fraction of a foot, that it does not provide a substantially large enough driving force to decrease the resulting plume extent and concentration. Conversely, a comparison of Scenarios 1 and 5 (Figure 2B) indicates that a decrease in onshore freshwater recharge increases the overall extent of the plumes in several areas. The lower water table altitude in Scenario 5 is substantially lower than the water table altitude in Scenario 1, by up to 5 ft. It is also lower over a large enough area to reduce the driving force for freshwater recharge and enable a more landward migration of the saltwater plume.

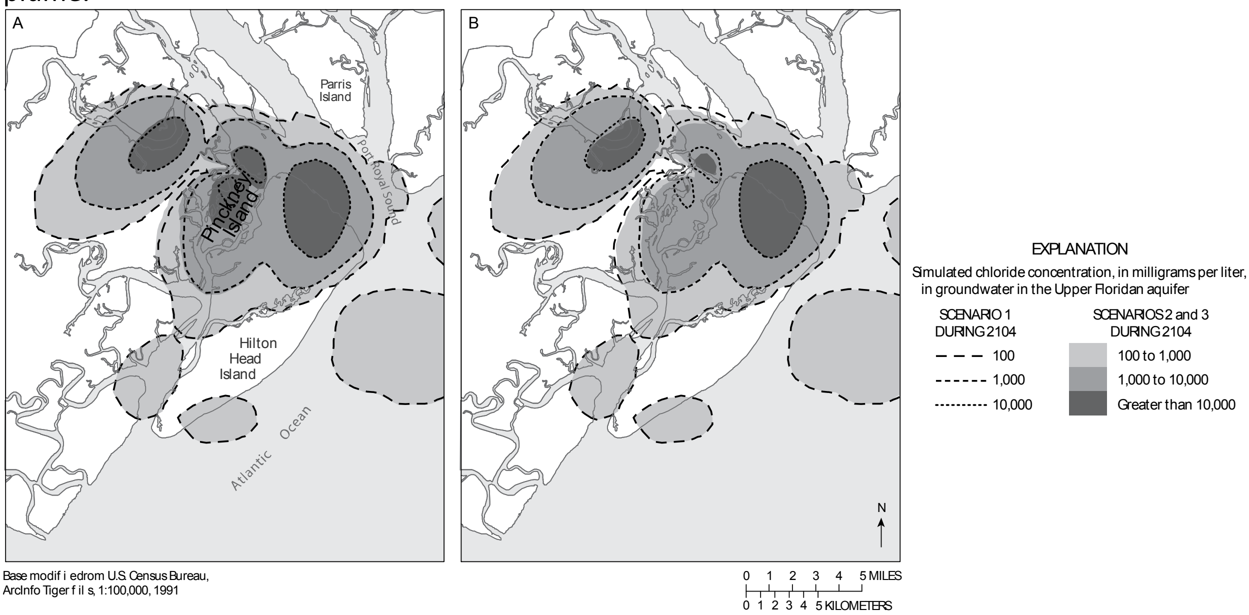

Figure 1. Simulated chloride concentration in groundwater for (A) Scenarios 1 and 2 and (B) Scenarios 1 and 3 during 2104 in the Hilton Head Island area, South Carolina.

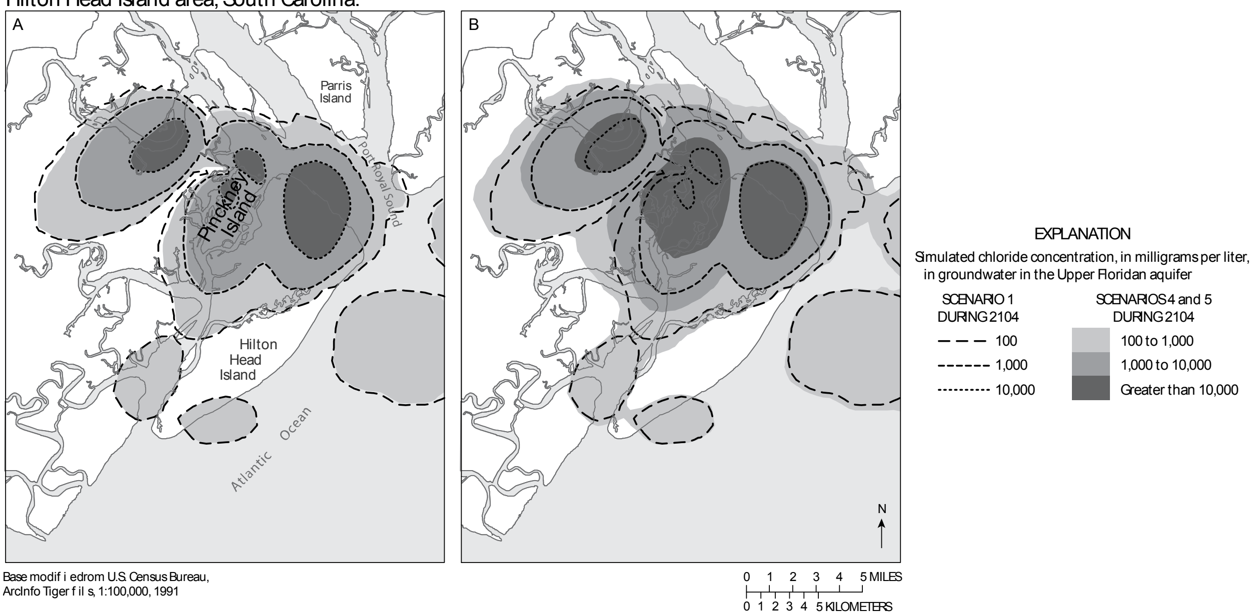

Figure 2. Simulated chloride concentration in groundwater for (A) Scenarios 1 and 4 and (B) Scenarios 1 and 5 during 2104 in the Hilton Head Island area, South Carolina.

DISCUSSION AND CONCLUSIONS

The greatest effect on simulated saltwater intrusion resulted from a reduction in onshore freshwater recharge, which increased overall plume extent. From a resource management perspective, this finding indicates a potential to contaminate more supply wells sooner than for the other conditions tested. As a result, recharge conditions may be a more important consideration in saltwater intrusion management than the rate at which sea level rises. This type of analysis might be useful for resource managers in evaluating remedial actions such as artificial recharge.

Major limitations to this analysis are that (1) recharge rates in the area are poorly understood, and (2) this model is not specifically designed to estimate recharge. The upper boundary condition in onshore areas assumes that freshwater recharge to the confined aquifer system occurs as downward leakage from the water table. The method used to estimate the water-table altitude contributes uncertainty because there are few data with which to constrain it. Furthermore, the permeability and effective porosity of the confining unit are poorly known, yet the predicted rate and extent of saltwater intrusion is very sensitive to these values (Payne, 2010). Although there is uncertainty in freshwater recharge in the area, and the model is not designed to address specifically that component of the budget, the approach used is a reasonable initial approximation. An estimate of 3.2 inches per year (in/yr) recharge during 2004 was made using this model, and it compares reasonably well with regional estimates ranging from 0-3 in/yr since the 1970s. Study area-specific data, for example local precipitation and evapotranspiration rates and water table data, and confining unit hydraulic properties need to be used where available, or collected, to estimate model-independent recharge. The model could then be refined to directly incorporate recharge.

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