EFFECTS OF PUMPAGE REDUCTIONS IN THE SAVANNAH, GEORGIA–HILTON HEAD ISLAND, SOUTH CAROLINA, AREA ON SALTWATER INTRUSION NEAR HILTON HEAD ISLAND

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Abstract. Numerical simulations were used to test the effects of variable pumpage reductions on the movement of chloride plumes in the Upper Floridan aquifer at the northern end of Hilton Head Island, at Pinckney Island, and near the Colleton River, South Carolina. Several combinations of pumpage reductions in the Savannah, Georgia, and Hilton Head Island, South Carolina, areas were simulated using a previously published, variable-density, solute-transport model of the Savannah–Hilton Head Island area. Simulation results indicate that the Colleton River plume responds more to pumpage reductions in the Savannah area than does the northern Hilton Head Island plume, and that the northern Hilton Head Island plume responds more to local pumpage reductions in the Hilton Head Island area than does the Colleton River plume. The Pinckney Island plume responds to pumpage reductions at both Savannah and Hilton Head Island areas. Substantial reductions, more than 75 percent, in the Savannah and Hilton Head Island areas may be required to prevent the expansion and salinity increase of the plumes. Finally, if all pumping is eliminated, the chloride plumes may persist for the foreseeable future.

INTRODUCTION

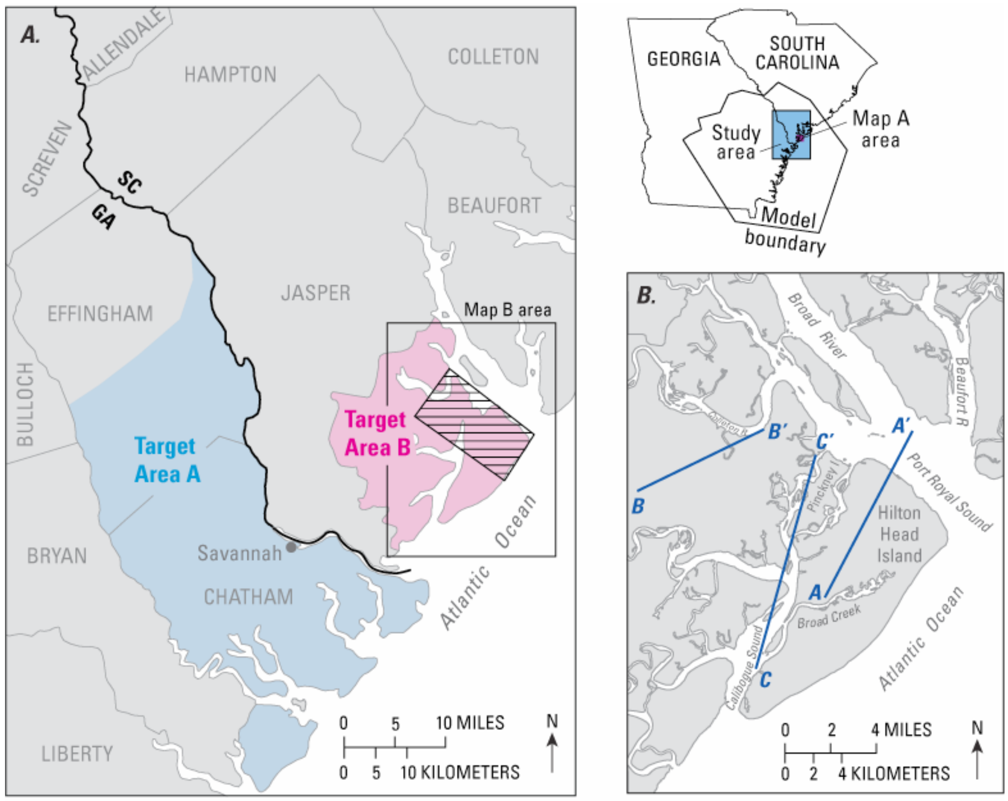
Pumping from the Upper Floridan aquifer, the principal source of water in the coastal Georgia and adjacent South Carolina area, has resulted in substantial water-level decline near Savannah, Georgia, and contributed to saltwater intrusion in the Hilton Head Island, South Carolina, area (Fig. 1). Specific-conductance monitoring of ground water from the Upper Floridan aquifer in the Hilton Head Island area indicates the presence of chloride plumes at the northern end of Hilton Head Island, at Pinckney Island, and near the Colleton River in Beaufort County (Childress and Ransom, 2005). This saltwater contamination has constrained further development of the Upper Floridan aquifer in the coastal area, which has created competing demands for the limited water supply. Projected increase in coastal population during the next several decades is expected to result in increased competition for ground water.

To develop a strategy to address declining water levels and saltwater intrusion in coastal aquifers and manage projected future coastal water-resource needs, the Georgia Environmental Protection Division (GaEPD) has implemented the Georgia Coastal Sound Science Initiative (CSSI), a series of scientific and feasibility investigations designed to assess ground-water resources in the coastal area and address issues of saltwater intrusion and resource sustainability. As part of this initiative, the U.S. Geological Survey (USGS) developed a ground-water flow and solute-transport model of the Savannah–Hilton Head Island area to simulate the development of the inferred chloride plumes in the Upper Floridan aquifer and to simulate the effects of hypothetical variations in the pumping distribution on the location and movement of the chloride plumes (Provost and others, 2006; Payne and others, 2006). These simulations were designed to assist in the development of a ground-water permitting strategy for the coastal area.

This paper describes results of numerical simulations using the Savannah–Hilton Head Island solute-transport model to evaluate the effects of hypothetical ground-water withdrawal reductions on the existing chloride distribution in the Upper Floridan aquifer. Specifically, several questions are addressed by the simulations: (1) what happens to the chloride plumes if pumping is completely eliminated in some areas?; (2) how much combined pumpage reduction is required to prevent expansion of the existing plumes?; and (3) how do the extent and concentration of chloride plumes respond to separate pumpage reductions in the Savannah, Ga., and Hilton Head Island, S.C., areas?

CONCEPTUAL MODEL

Seismic data indicate that the Upper Floridan aquifer confining unit is thin in the Hilton Head Island area and is breached offshore of Hilton Head Island, in Calibogue Sound, at the Colleton River, and in the Beaufort and Broad Rivers, where seawater and brackish water overlie the aquifer (Foyle and others, 2001). Local pumping from the Upper Floridan aquifer on Hilton Head Island and regional pumping centered at Savannah have lowered the potentiometric surface of the Upper Floridan aquifer in the study area. This has resulted in downward flow from the water table and the ocean-seafloor interface, and lateral flow along the hydraulic gradient toward pumping centers at Hilton Head Island on a local scale, and toward Savannah on a regional scale. If not diluted when it enters the Upper Floridan aquifer, denser, more saline water may accumulate at the bottom of the aquifer.



Base from U.S. Geological Survey
1:100,000 and 1:250,000-scale data

Base modifed from U.S. Census Bureau
ArcInfo Tiger files, 1:100,000, 1991

Figure 1. Location of (*A*) Savannah–Hilton Head Island study area, area of inferred plumes, and pumping target areas for the scenario simulations; and (*B*) line of sections for which simulation results are shown.

EXPLANATION

Area of inferred plumes

A—*A′* **Line of section**—Cross section shown in figure 3

APPROACH

Pumpage-reduction scenarios were simulated using a three-dimensional, variable-density, solute-transport model that was previously developed to simulate saltwater intrusion in the Savannah–Hilton Head Island area (Provost and others, 2006). The Savannah–Hilton Head Island area model was preliminarily calibrated to September 1998 water levels in Beaufort, Colleton, Hampton, and Jasper Counties, S.C., and then refined to match generally the distribution of chloride concentrations in the Upper Floridan aquifer during 2000, as estimated from measured specific conductance. The pumping history was then updated to estimated 2004 pumping conditions, and resulting simulated chloride concentrations were compared to available estimated maximum chloride concentrations in the Upper Floridan aquifer in the area during 2004. Refinements to the physical properties of the model were not made because the extension of the pumping history did not result in a poorer match to measured chloride concentrations.

Pumpage modifications were applied in (1) Target Area A, which consists of Chatham and southern Effingham Counties, Ga.; (2) Target Area B, which consists of that part of Beaufort County, S.C., southwest of Port Royal Sound; and (3) the remaining model area (Fig. 1). During 2004, estimated pumpage in Target Area A was 75.3 million gallons per day (Mgal/d), and in Target Area B was 13.5 Mgal/d. Simulated pumpage reductions were in percentage increments of 2004 pumpage (Table 1).

Table 1. Pumpage reductions in percentage relative to 2004 rates and total pumpage applied in million gallons per day (Mgal/d) in each area for each scenario in the Savannah, Georgia–Hilton Head Island, South Carolina, solute-transport ground-water flow model area.

[Mgal/d, million gallons per day]

Scenario number	Target Area A		Target Area B		Rest of model area	
	Percent reduction	Applied in Mgal/d	Percent reduction	Applied in Mgal/d	Percent reduction	Applied in Mgal/d
NP	100	0.0	100	0.0	100	0.0
0	100	0.0	100	0.0	0	667.4
1	0	75.3	0	13.5	0	667.4
2	100	0.0	0	13.5	0	667.4
3	0	75.3	100	0.0	0	667.4
4	50	37.6	50	6.8	0	667.4
5	75	18.8	75	3.4	0	667.4
6	50	37.6	0	13.5	0	667.4
7	0	75.3	50	6.8	0	667.4

SIMULATION RESULTS

Results are presented as maps showing simulated chloride distribution for the middle of the Upper Floridan aquifer, in response to various pumpage reductions. Most results are shown for the year 2104, and are compared with the simulated conditions in 2004, herein called the Base Case. Vertical profiles showing the distribution of simulated head and chloride concentrations for the middle of the Upper Floridan aquifer are shown along three cross sections through simulated chloride plumes at the northern end of Hilton Head Island, Pinckney Island, and near the Colleton River.

Elimination of Pumpage

The elimination of pumpage in both target areas (Scenario 0) represents the greatest possible reduction in pumpage in those areas and would have the greatest possible effect on the simulated plumes through pumpage reductions in those areas. For Scenario 0 during 2104, the extent of the plumes (as represented by the 250-milligrams-per-liter [mg/L] isochlor) shifts slightly to the northeast, and the areas of highest chloride concentration (greater than 10,000 mg/L) at Hilton Head Island and the Colleton River decrease moderately (Fig. 2*A*), relative to the chloride distribution during 2004. Between 2104 and 2200, the northern extent of the plumes shifts farther to the northeast, and the southern extent of the plume and the areas of highest chloride concentration remain relatively unchanged. The elimination of pumpage in the entire model area would represent the return to predevelopment stress conditions and allow the greatest possible recovery of water levels and mitigation of the chloride plumes (scenario NP). Simulated changes in plume extent for Scenario NP are similar to those for Scenario 0 (Fig. 2*B*). This indicates that the elimination of pumpage outside of the target areas has minimal additional effect on reducing plume extent and concentration. One explanation is that once saline water has accumulated in the aquifer, the naturally low hydraulic gradient in the area may result in low flow rates and slow dilution, and the density of the saltwater causes it to move more sluggishly than freshwater. Additionally, when pumping is eliminated, saltwater may continue to enter the aquifer well into the future because the vertical hydraulic gradients are naturally low in the area and density differences between seawater and fresh ground water may continue to drive saltwater downward. An example of this situation is shown along cross section A–A' at about 6 miles (mi) from Broad Creek, where chloride concentration for scenario 0 during 2104 is essentially as high as for scenario 1 (Fig. 3*A*). Results from previous modeling studies indicate that saltwater may enter the system in this area even under predevelopment conditions (Provost and others, 2006).

Equivalent Fractional Pumpage Reductions in Target Areas A and B

Fractional reductions of 2004 pumpage rates were applied equivalently in Target Areas A and B and simulated. Results of Scenario 1 indicate that if pumping is maintained at 2004 rates until 2104 (0 percent reductions in Target Areas A and B), saltwater will continue to enter the Upper Floridan aquifer, the plume will continue to migrate toward the pumping centers, and areas of highest chloride concentration will expand (Fig. 4*A*). If equivalent pumpage reductions of 50 and 75 percent are applied to Target Areas A and B (scenarios 4 and 5, respectively), the resulting plumes migrate toward the pumping centers relative to the plume extent during 2004, though the extent of the plumes during 2104 are not as great as for Scenario 1. Even with pumpage reductions of 75 percent in both target areas, in some areas the simulated plume during 2104 may migrate from about 0.5 to 1.0 miles beyond its extent during 2004.

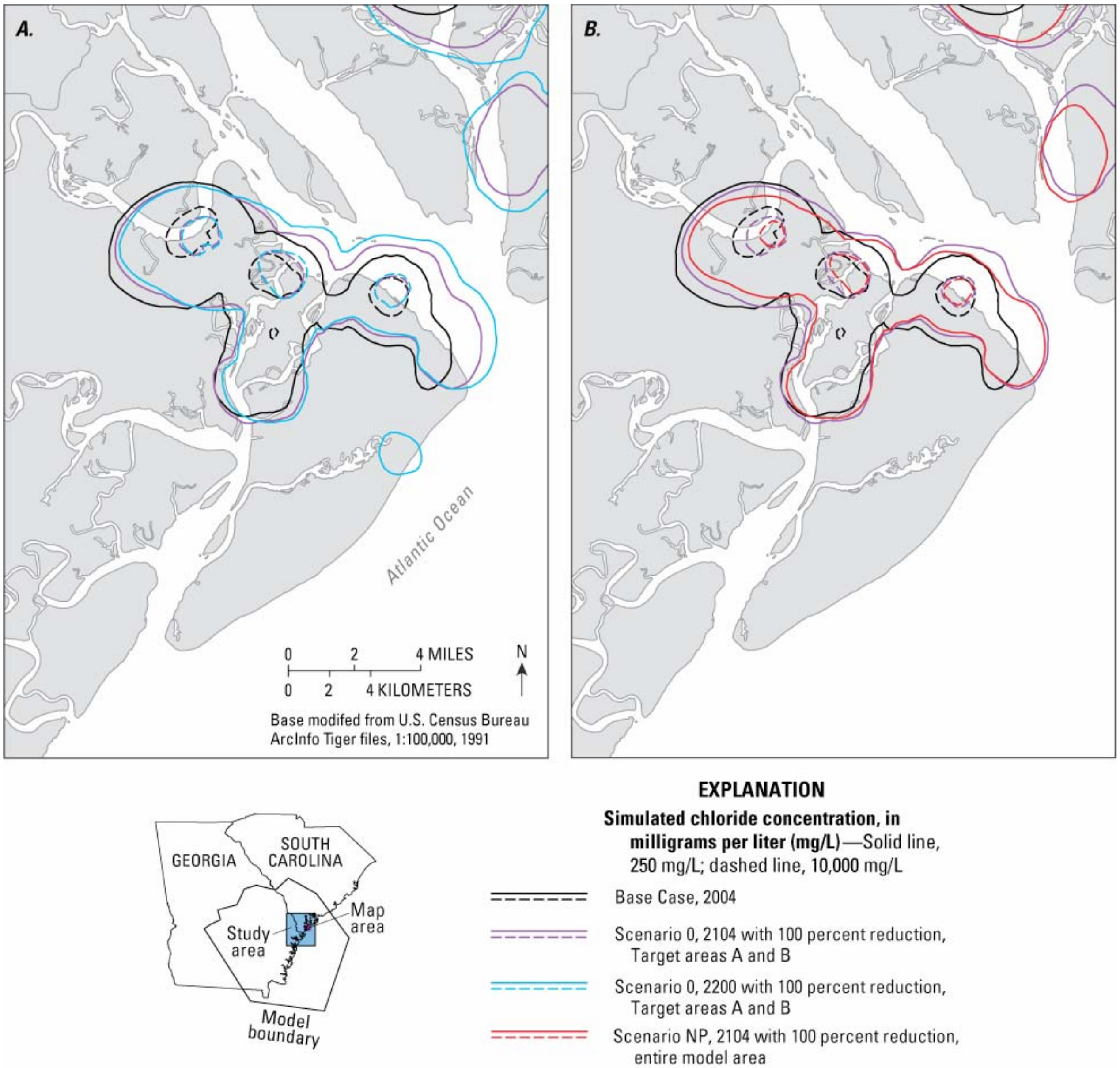


Figure 2. Simulated chloride concentration in the middle of the Upper Floridan aquifer in the Hilton Head Island area, for (*A*) 100 percent pumpage reductions in Target Areas A and B, during 2104 and 2200, relative to the Base Case, and for (*B*) 100 percent pumpage reductions in entire model area during 2104, relative to the Base Case.

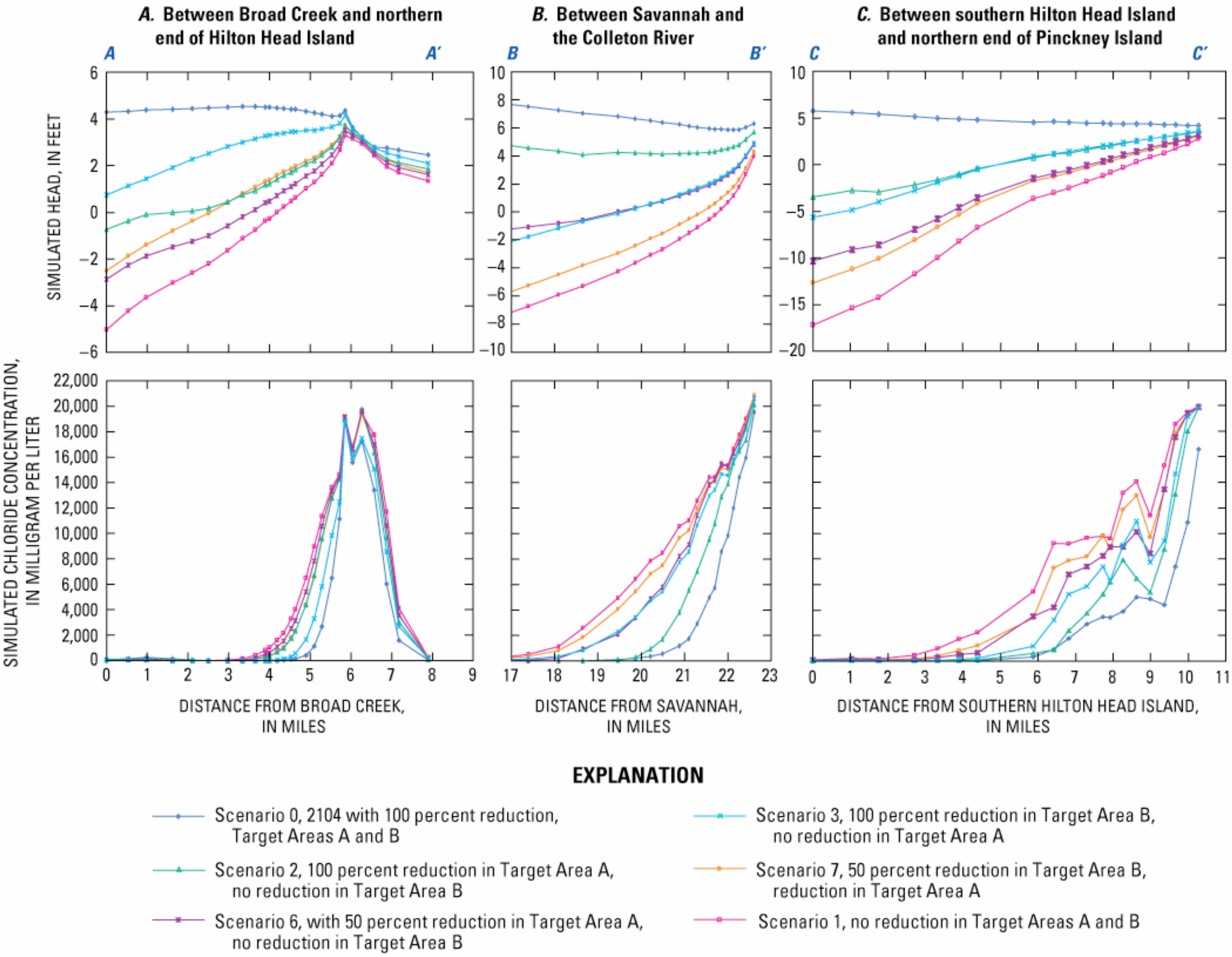


Figure 3. Simulated potentiometric surface and chloride concentration during 2104 for scenarios 0, 1, 2, 3, 6 and 7, for (*A*) cross section A–A', between Broad Creek and the northern end of Hilton Head Island, (*B*) cross section B–B' between Savannah and the Colleton River, and (*C*) cross section C–C', between southern Hilton Head Island and the northern end of Pinckney Island.

Fractional Pumpage Reductions in Either Target Area A or B

Fractional reductions of 2004 pumpage were applied individually in Target Areas A and B to simulate differential effects of pumping reductions in either area on the extent and concentrations of chloride plumes. Scenarios 1, 6, and 2 represent progressive reductions in Target Area A only (0, 50, and 100 percent, respectively) (Fig. 4*B*). In each scenario, Target Area B pumpage remained at 2004 rates. Simulation results indicate that reduced pumping in Target Area A resulted in reduced plume extent, and reduced extent of the highest concentrations for the Colleton River plume and the western side of the Pinckney Island plume. In contrast, the extent of the northern Hilton Head Island plume, the eastern part of the Pinckney Island plume, and the extent of the highest chloride concentration are little affected by the decrease in pumpage in Target Area A.

Similar reductions in Target Area B (Scenarios 1, 7, and 3) resulted in decreased extent of the plumes and areas of highest concentration for all three plumes (Fig. 4*C*). Comparison of Figure 4*B* and *C* shows that, whereas Target Area A pumpage reductions had little effect on plume extent on the southern side of the northern Hilton Head Island plume and the eastern side of the Pinckney Island plume, Target Area B reductions did affect resultant plume extent in these areas. In contrast, the effect of Target Area B reductions on plume extent near the Colleton River is less than the effect of Target Area A reductions.

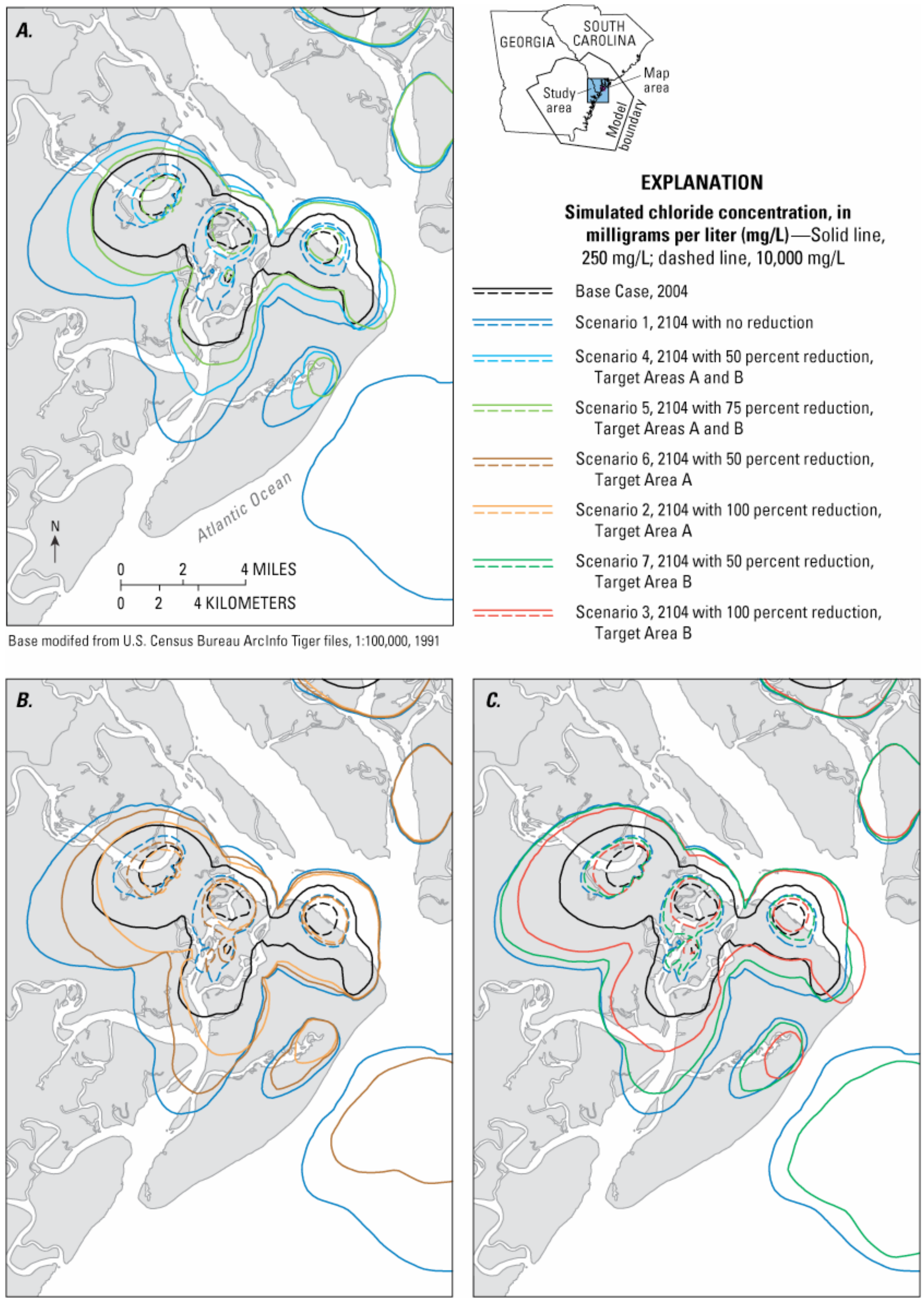


Figure 4. **Simulated chloride concentration in the middle of the Upper Floridan aquifer in the Hilton Head Island area, during 2104 relative to the Base Case for (*A*) equivalent pumpage reductions in Target Areas A and B of 0 percent, 50 percent and 75 percent, (*B*) equivalent pumpage reductions in Target Area A of 0 percent, 50 percent, and 100 percent, and (*C*) equivalent pumpage reductions in Target Area B of 0 percent, 50 percent, and 100 percent.**

Comparison of Simulated Heads and Chloride Concentrations

Cross sections A–A', B–B' and C–C' are used to illustrate the relation between simulated head and chloride concentration during 2104 along transects that are approximately parallel to the direction of solute transport (Fig. 3*A*, *B*, and *C*). For all three cross sections, the highest simulated heads occur for Scenario 0 with 100 percent reductions in pumpage in the target areas, and the lowest simulated heads occur for Scenario 1, with no reductions in pumpage. Simulated chloride concentration is lowest for Scenario 0, and highest for Scenario 1 for all three cross sections. In comparing cross sections, higher simulated concentrations generally occur at lower simulated heads, and lower simulated concentrations generally occur at higher simulated heads. For each simulation, the highest chloride concentration occurs closest to the simulated breach in the confining unit, which is the source of saltwater. Because the breach also acts as a recharge area, there is locally a simulated potentiometric high point for most of the simulations along most of the cross sections.

Along cross section A–A', the next highest simulated heads, and corresponding lowest chloride concentration, relative to the simulated heads for scenario 0, occur with 100 percent pumpage reduction in Target Area B and 0 percent reduction in Target Area A (Scenario 3) (Fig. 3*A*). For about 3 mi south of the source area, simulated heads and chloride concentrations are similar for Scenario 2 (100 percent pumpage reduction in Target Area A and 0 percent reduction in Target Area B) and Scenario 7 (0 percent pumpage reduction in Target Area A and 50 percent reduction in Target Area B). The simulated heads and chloride concentrations indicate that Target Area B pumpage reductions have a greater influence on elevating simulated heads and reducing simulated chloride concentrations than Target Area A pumpage reduction on northern Hilton Head Island. Furthermore, comparison of simulated heads and concentrations for Scenarios 2 and 7 indicates that a 50 percent reduction in pumping in Target Area B (6.8 Mgal/d) has approximately the same effect on simulated heads and concentration as 100 percent reduction in Target Area A (75.3 Mgal/d).

Along cross section B–B’, the next highest simulated heads, and corresponding lowest chloride concentration, relative to the simulated heads for scenario 0, occur with 100 percent pumpage reduction in Target Area A and 0 percent reduction in Target Area B (Scenario 2) (Fig. 3*B*). Simulated heads and chloride concentrations are similar for Scenario 3 (100 percent pumpage reduction in Target Area B and 0 percent reduction in Target Area A) and Scenario 6 (50 percent pumpage reduction in Target Area A and 0 percent reduction in Target Area B). These results indicate that Target Area A pumpage reductions have a greater influence on elevating simulated heads and reducing simulated chloride concentrations than Target Area B pumpage reductions for the Colleton River plume area. A comparison of simulated heads and concentrations for Scenarios 2 and 7 indicates that a 50 percent reduction in pumping in Target Area A (37.6 Mgal/d) has approximately the same effect on simulated heads and concentration as 100 percent reduction in Target Area B (13.5 Mgal/d).

Along cross section C–C', simulated heads and corresponding simulated chloride concentrations for Scenarios 2 and 3 are similar (100 percent pumpage reductions in Target Areas A and B, respectively), with generally a slightly higher simulated chloride concentration for Scenario 3 (Fig. 3*C*). Simulated heads and corresponding simulated chloride concentrations for Scenarios 6 and 7 are similar (50 percent pumpage reductions in Target Areas A and B, respectively), with generally a slightly higher simulated chloride concentration for Scenario 7. Simulated heads are higher and simulated chloride concentrations are lower for Scenarios 2 and 3, than for Scenarios 6 and 7. These results show that in the Pinckney Island area, fractional pumpage reduction of similar magnitude in Target Areas A and B have similar effects on simulated head and chloride concentration. Furthermore, Target Area A pumpage may influence chloride concentrations slightly more than Target Area B pumpage in this area, based on percentage reductions.

These results indicate that the chloride plume on the northern end of Hilton Head Island would respond more readily to local pumpage reductions, while the chloride plume near the Colleton River would respond more readily to the pumpage reductions in the Savannah area. The chloride plume at Pinckney Island would respond to both local and Savannah area pumpage reductions. Although the pumping in Target Area B is closer to the locations of the plumes, pumpage in Target Area A is 4.5 times greater than pumpage in Target Area B during 2004. These results indicate that both pumping rate and proximity to source areas will affect plume growth, and that there is a trade-off between these factors. The response of the system is complicated further by the nonlinear nature of variable-density flow, such that the combined effects of pumpage reductions in each area are not equivalent to the effects of combined pumpage reductions in both areas. This makes it difficult to assign to each target area a percentage reduction that would stop further expansion of the existing simulated plumes.

CONCLUSIONS

The local hydrogeology makes the Hilton Head Island area susceptible to saltwater intrusion, even for low pumpage conditions relative to current ground-water demands. Both local (in the Hilton Head Island area) and regional (Savannah area) pumping likely contribute to saltwater intrusion, and there is a trade-off between proximity of pumping to source areas and pumping rate. Because the system geometry is complex and variable-density flow processes are nonlinear, it is difficult to assign to each Target Area a relative percentage reduction that would be required to mitigate saltwater intrusion with any technical defensibility.

Simulation results generally indicate: (1) the northern Hilton Head Island plume responds more to local pumpage reductions than to regional pumpage; (2) the Colleton River plume responds more to regional pumpage reductions than does the northern Hilton Head Island plume; (3) the Pinckney Island plume responds to both regional and local pumpage reductions; (4) substantial pumpage reductions in the Savannah and Hilton Head Island areas may be required to prevent expansion of existing plumes; and (5) chloride plumes in the study area may persist for longer than 100–200 years into the future, even if all pumping is eliminated.

Model results must be interpreted in light of uncertainties and approximations inherent in the formulation of the model and characteristics of the simulated scenarios. The solute-transport model used in this study is a simplified representation of natural processes and properties of the hydrologic system, and is thus subject to limitations as described by Provost and others (2006). These limitations include error and uncertainty in field measurements, uncertainty in the conceptual models and interpretation of hydraulic properties, errors associated with numerical approximation and solution of the mathematical model of the flow system, and the limited conditions for which the model is calibrated. Additionally, the further removed the scenario conditions are from calibration conditions, the more speculative are the model results. Specifically, the measured rate of plume movement is poorly constrained because of limited data, and there is no measure of accuracy of the simulated rate of plume movement. These limitations do not, however, invalidate the model results or interpretation thereof. The model is a rigorous mathematical approach for analyzing three-dimensional, variable-density ground-water flow, and represents the best available data and most current understanding of saltwater intrusion in the study area. Therefore the numerical simulations meet the study objectives of testing the effects of variable pumpage reductions on the possible future movement of chloride plumes.

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