Prepared in cooperation with the Brunswick-Glynn County Joint Water and Sewer Commission and the Georgia Environmental Protection Division

Simulation of Groundwater Flow in the Brunswick Area, Georgia, for 2004 and 2015, and Selected Groundwater-Management Scenarios

Scientific Investigations Report 2019–5035

U.S. Department of the Interior
U.S. Geological Survey

Cover photograph: South end of Jekyll Island, Glynn County, Georgia. Photograph by Alan M. Cressler, U.S. Geological Survey.

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By Gregory S. Cherry

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DAVID BERNHARDT, Secretary

U.S. Geological Survey
James F. Reilly II, Director

U.S. Geological Survey, Reston, Virginia: 2019

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Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
million gallons (Mgal)	3,785	cubic meter (m^3)
	Flow rate	
inch per year (in/yr)	2.54	centimeters per year (cm/yr)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
cubic foot per day (ft^3/d)	0.02832	cubic meter per day (m^3/d)
foot per day (ft/d)	0.3048	meter per day (m/d)
foot per year (ft/yr)	0.3048	meter per year (m/yr)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day (m/d)
	Transmissivity*	
foot squared per day (ft^2/d)	0.0929	meter squared per day (m^2/d)
	Potentiometric gradient	
foot per mile (ft/mi)	0.1894	meter per kilometer (m/km)

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as
°C = (°F – 32) / 1.8.

Datum

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29) or the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to North American Datum of 1983 (NAD 83).

Altitude, as used in this report, refers to distance above the vertical datum.

Supplemental Information

*Transmissivity: The standard unit for transmissivity is cubic foot per day per square foot times foot of aquifer thickness [(ft^3/d)/ft^2]ft. In this report, the mathematically reduced form, foot squared per day (ft^2/d), is used for convenience.

Concentrations of chemical constituents in water are given in milligrams per liter (mg/L).

Georgia Well-Identification System

Wells described in this report are assigned a well identifier according to a system based on the index of U.S. Geological Survey (USGS) 7.5-minute topographic maps of Georgia. Quadrangles shown on the map of Georgia have been assigned a two- to three-digit number and letter designation (for example, 07H) beginning at the southwestern corner of the State. Numbers increase sequentially eastward, and letters advance alphabetically northward. Quadrangles in the northern part of the State are designated by double letters: AA follows Z, and so forth. The letters "I," "O," "II," and "OO" are not used. Wells inventoried in each quadrangle are numbered consecutively, beginning with 001. Thus, the fourth well inventoried in the 34H quadrangle is designated 34H004. In the USGS National Water Information System (NWIS) database, this information is found in the "Site Name" field.

Abbreviations

BGJWSC	Brunswick-Glynn County Joint Water and Sewer Commission
FLETC	Federal Law Enforcement Training Center
GaEPD	Georgia Environmental Protection Division
LFA	Lower Floridan aquifer
LWBZ	lower water-bearing zone
NWIS	National Water Information System
RMSE	root-mean-square error
UFA	Upper Floridan aquifer
USGS	U.S. Geological Survey
UWBZ	upper water-bearing zone
WRMAC	Water Resources Management Advisory Committee

Acknowledgments

The authors thank Billy Simmons of the Brunswick-Glynn County Joint Water and Sewer Commission and James Kennedy, State Geologist, Georgia Environmental Protection Division, for support of ongoing water-resources investigations in the Glynn County area. During early stages of model development, members of the Glynn County Water Resources Management Advisory Committee (WRMAC) provided technical guidance, including development of water-management scenarios for evaluation by the revised model. Appreciation goes to WRMAC members Bobby Palmer, Chair, private citizen; Glenn Hoffman, Vice Chair, Hercules Inc.; Dan McFee, City of Brunswick; Keith Morgan, Brunswick-Glynn County Joint Water and Sewer Commission; John Day, Jekyll Island Authority; Kenneth Hase, Brunswick Cellulose Inc.; Jim Benson, private citizen; William Francis, private citizen; Dick Johnston, private citizen; Hal Hart, private citizen; David Kyler, private citizen; and Milton Peterman, private citizen.

Groundwater-use data were updated to 2015 thanks to the assistance of Julie Dickens, Brunswick Cellulose Inc., and Maurice Gray, Pinova Inc. Thanks are extended to Bradford Price, Brunswick Cellulose Inc., who provided coordinates and well information on the new Brunswick Cellulose production well.

Thanks are also extended to Michael Peck, Michael Hamrick, and Gary Holloway, U.S. Geological Survey (USGS), who collected water-level data during the October 2015 synoptic survey, and to Jaime Painter, USGS, who provided assistance in the development of model input and display of model results using geographic information system techniques.

Simulation of Groundwater Flow in the Brunswick Area, Georgia, for 2004 and 2015, and Selected Groundwater-Management Scenarios

By Gregory S. Cherry

Abstract

The Upper Floridan aquifer (UFA) is the principal water source for industrial and public supply in Glynn County, Georgia. Wells in active pumping centers that tap the UFA for industries near the city of Brunswick have created an upward hydraulic-head gradient in the Floridan aquifer system, which has allowed high chloride (saline) groundwater from the Fernandina permeable zone of the Lower Floridan aquifer (LFA) to migrate upward into freshwater zones. Chloride concentrations of more than 250 milligrams per liter—the State and Federal secondary drinking-water standard—have been measured in a 2-square-mile area near downtown Brunswick.

An existing regional U.S. Geological Survey modular finite-difference groundwater-flow model (MODFLOW-2000) was modified using greater horizontal and vertical resolution to enable more detailed simulation of the effects of pumping in the vicinity of chloride contamination. Modifications to the regional model consisted of (1) limiting grid size to a maximum of 500 feet (ft) per side in the vicinity of the chloride plume; (2) representing the upper and lower Brunswick aquifers with distinct model layers; (3) similarly, representing upper and lower water-bearing zones of the UFA with distinct model layers in Glynn and Camden Counties, Ga.; and (4) establishing new hydraulic-property geographic zones in the UFA within Glynn County. The revised groundwater-flow model was calibrated to steady-state conditions that were assumed to exist during 2000 and 2004. The calibration and framework of the revised groundwater-flow model were documented in a separate report. For the current study, steady-state conditions were calibrated using October 2015 pumping rates in the Brunswick/Glynn County area as a 2015 Base Case. The 2015 Base Case simulation was used as the basis to evaluate seven groundwater-management scenarios in the Brunswick/Glynn County area.

Seven groundwater management-scenarios were developed on the basis of short- and long-term groundwater-use projections for the UFA in the Brunswick/Glynn County area. Scenarios A and B simulated additional pumping in the upper water-bearing zone (UWBZ) of the UFA at existing public-supply wells located near a chloride plume and planned public-supply wells to be constructed north of downtown Brunswick. Scenario C simulated a shutdown at Brunswick Cellulose Inc. and Pinova Inc. and the resulting deactivation of nine production wells, with a combined total pumping of 31.3 million gallons per day (Mgal/d) for the 2015 Base Case simulation. Scenario D (three scenarios) simulated 12.5, 25, and 50 percent (designated Scenarios D1, D2, and D3) of the total pumping of 31.3 Mgal/d at Brunswick Cellulose and Pinova. The objective of Scenario D was to determine pumping rates that may reverse groundwater-flow directions toward the Brunswick Cellulose well field and potentially allow groundwater with higher chloride concentration to migrate toward nearby public-supply wells. Scenario E simulated an additional pumping of 5 Mgal/d from the UWBZ of the UFA at a recently constructed production well within the Brunswick Cellulose well field.

Backward particle-tracking (MODPATH) analysis in public-supply wells located just outside the chloride plume to the north shows that predominant groundwater-flow directions are from the northeast toward the Brunswick Cellulose well field. The analysis covered 20- and 50-year periods for the 2015 Base Case and Scenario C simulations with 100 percent of backtracked particles remaining in the UWBZ and lower water-bearing zone of the UFA. Groundwater-flow directions are characterized by some vertical movement and dominant horizontal movement away from the chloride plume in the northern Brunswick area. For the 2015 Base Case simulation, the mean rate of particle movement ranged from 268 to 413 feet per year. For the Scenario C simulation, the mean rate of particle movement ranged from 89 to 182 feet per year with 50 percent of particles migrating from the chloride plume area. The rate of particle movement is influenced most by the horizontal hydraulic-head gradient in the UWBZ of the UFA.

The revised groundwater-flow model is subject to the limitations documented in the original model. In addition, the values used for the specified-head boundaries in the Floridan aquifer system for the 2004 calibrated model were based on the sparse data available and were not changed for the 2015 update to the model. These model boundaries control 80 percent of the inflows and about 60 percent of the outflows. Composite-scaled sensitivities of the model parameters indicate the revised model is most sensitive to pumping rates, followed by the horizontal hydraulic conductivity in the UFA for zones along coastal Georgia.

Introduction

In the Brunswick/Glynn County area of Georgia, saltwater intrusion has been contaminating the Upper Floridan aquifer (UFA) for more than 50 years. Currently (2015) within an area covering several square miles in downtown Brunswick, the aquifer yields water that has a chloride concentration greater than 2,000 milligrams per liter (mg/L), well above the 250-mg/L State and Federal secondary drinking-water standard (Georgia Environmental Protection Division, 1997; U.S. Environmental Protection Agency, 2000). Saltwater contamination has constrained further development of the UFA in the Brunswick area, prompting interest in the development of alternative sources of water supply primarily from the shallower surficial and Brunswick aquifer systems. In the downtown Brunswick area, the Georgia Environmental Protection Division (GaEPD) has limited further development of the UFA to areas outside the chloride plume and development must be performed in a way that will minimize migration of groundwater with high-chloride concentrations and maintain hydraulic-head gradients toward active pumping centers in the area. The U.S. Geological Survey (USGS), in cooperation with the Brunswick-Glynn County Joint Water and Sewer Commission (BGJWSC) and the GaEPD, revised an existing groundwater model to simulate the effects of pumping on the migration of high-chloride water in the Brunswick/Glynn County area, thereby providing scientific information essential for managing water resources in the area.

An existing regional groundwater-flow model (Payne and others, 2005) was modified by Cherry (2015) to greater horizontal and vertical resolution to enable more detailed simulation of the effects of pumping in the vicinity of the chloride plume. Modifications to the regional model include (1) reducing grid dimensions to a minimum of 500 feet (ft) per side in the vicinity of the chloride plume, (2) subdividing the Brunswick aquifer system into the upper and lower Brunswick aquifers, (3) subdividing the UFA into the upper and lower water-bearing zones (UWBZ and LWBZ, respectively), and (4) establishing new hydraulic-property geographic zones in the UFA to improve model calibration in the Brunswick/Glynn County area. The modified steady-state model (Cherry, 2015) has been updated to include October 2015 pumping rates presented in this report as a 2015 Base Case simulation in the Brunswick/Glynn County area and calibrated using local water-level measurements from observation wells to confirm simulated response to changing pumping rates. The 2015 Base Case simulation was compared to five groundwater-management scenarios whereby pumping in existing and hypothetical wells was adjusted in varying amounts. Information from these scenarios can be used by water managers in the area to make informed decisions.

Purpose and Scope

The purpose of this report is to document the simulation of groundwater flow in the Brunswick/Glynn County area during October 2015 and evaluate seven groundwater-management scenarios using the revised groundwater-flow model, which represents a 2015 Base Case simulation. The original regional model and the revised groundwater-flow model used a previously published application of the USGS modular finite-difference computer program (MODFLOW-2000; Harbaugh and others, 2000). The original regional model by Payne and others (2005) was developed to simulate regional groundwater flow along the Georgia coast in the Brunswick and Floridan aquifer systems during 1980 and 2000. The purpose of the groundwater-flow model revised by Cherry (2015) was to simulate the steady-state effect of changing pumping rates during 2000 and 2004 on groundwater levels and evaluate changes in hydraulic-head gradients near pumping centers in the Brunswick area. Revisions to the original model include (1) increased spatial resolution near the downtown Brunswick, Ga., area, (2) additional hydraulic-property geographic zones in the UFA near the Brunswick/Glynn County area, (3) subdivision of the Brunswick aquifer system, and (4) subdivision of the Floridan aquifer system into separate model layers to better represent the local hydrogeology.

This report describes revisions to the groundwater-flow model by Cherry (2015) for the Brunswick/Glynn County area, including calibration of simulated heads to observed heads (residuals, simulated heads minus observed heads). The simulated heads determine general groundwater-flow directions and relative rates of movement, and selected potentiometric profiles provide an assessment of horizontal hydraulic-head gradients near downtown Brunswick. The adjusted 2015 Base Case steady-state simulation was used as a comparison to simulated heads and water budgets for five groundwater-management scenarios. Simulated particle-tracking analyses can be used to identify and calculate time of travel from pumping centers backward toward recharge areas. Model input and output data generated during this study are available as a USGS data release (Cherry, 2019).

Description of the Study Area

Glynn County is located in the Coastal Plain physiographic province on Georgia's Atlantic Coast about 80 miles (mi) south of Savannah, Ga., and about 60 mi north of Jacksonville, Florida (fig. 1). The county encompasses about 422 square miles (mi^2) and is bordered on the north by the Altamaha River, which empties into the Atlantic Ocean north of St. Simons Island. The Little Satilla River forms the boundary to the south, and the county is bordered by Wayne and Brantley Counties to the west. Altitudes in Glynn County range from 0 ft along the coast to as high as 67 ft (above North American Vertical Datum of 1988) in the southwestern part of the county.

The city of Brunswick is located on a peninsula in Glynn County and encompasses about 50 mi^2. The city is bordered by St. Simons and Jekyll Islands to the east and by the Brunswick and Little Satilla Rivers to the west and south, respectively (fig. 1*B*). Both rivers form tidally influenced estuaries in the Brunswick area.

In 2015 the population of Glynn County was 83,579 (U.S. Census Bureau, 2017). The primary population center of Glynn County is the city of Brunswick, and a secondary population center has developed in the southern part of St. Simons Island. Outside these urban areas, land use in Glynn County is a mixture of forest, grazed woodland, marsh, and swampland.

Coastal Plain sediments consist of consolidated to unconsolidated layers of sand and clay, to semiconsolidated to dense layers of limestone and dolomite, which range in age from Late Cretaceous to Holocene. In general, these hydrogeologic units have been divided into aquifers and confining units on the basis of their water-yielding characteristics, with relatively high permeability layers forming aquifers and low-permeability layers forming confining units (fig. 2). These sedimentary units unconformably overlie igneous, metamorphic, and sedimentary rocks of Paleozoic to Mesozoic age and reach a maximum thickness of 5,500 ft just south of Glynn County in Camden County (Wait and Davis, 1986). The thickness of sedimentary units varies and is influenced by major structural features in the area, such as the Southeast Georgia Embayment, Beaufort Arch, and Gulf Trough (fig. 1*A*). Another feature, less prominent than the Gulf Trough, is the Satilla Line, which is a postulated hydrologic boundary identified by GaEPD that could influence groundwater flow in the UFA. The feature's existence is based on a change in the configuration of the potentiometric surface of the UFA, and by linear changes depicted on aeromagnetic, aeroradioactivity, gravity, and isopach maps; however, its geologic origin and nature are unknown. In general, the surficial and Brunswick aquifer systems are composed predominantly of sands, silts, and minor limestone with transmissivities ranging from 14 to 6,000 feet squared per day (ft^2/d; Clarke, 2003). The highest transmissivity values for both aquifer systems were reported near the Southeast Georgia Embayment where the units reach a maximum thickness. In the Glynn County area and outside this feature, the Brunswick aquifer system thins, or is discontinuous, and has a greater percentage of fine-grained sediments (Clarke, 2003). The Brunswick aquifer system is separated from the underlying Floridan aquifer system by a confining unit consisting of layers of silty clay and dense phosphatic dolomite of Oligocene age (Clarke, 2003).

The primary focus of the current report is the Floridan aquifer system, which consists of the UFA and Lower Floridan aquifer (LFA), composed of mostly Paleocene to Oligocene carbonate rocks that locally include Upper Cretaceous rocks (Miller, 1986; Krause and Randolph, 1989; fig. 2). The Floridan aquifer system extends from coastal areas in southeastern South Carolina, westward across the coastal plain of Georgia and Alabama, and southward, encompassing Florida. The thickness of the Floridan aquifer system in the model area varies from less than 100 ft in aquifer outcrop areas of South Carolina to about 1,700 ft near the city of Brunswick (fig. 3; Williams and Kuniansky, 2015). The UFA is highly productive and consists of Eocene to Oligocene-age limestone and dolomite (Clarke and others, 1990). In the Brunswick/Glynn County area, Wait and Gregg (1973) identified upper and lower water-bearing zones (UWBZ and LWBZ, respectively) within the UFA, with the upper zone having higher production as indicated by pumping data from a well that tapped both zones. The UFA is underlain by a confining unit of dense recrystallized limestone and dolomite of middle to late Eocene age that hydraulically separates the UFA from the LFA by varying degrees. Locally in the Brunswick area, the confining unit is breached by fractures or solution openings that enhance the exchange of water between the UFA and LFA (Krause and Randolph, 1989; Maslia and Prowell, 1990). The LFA is composed mainly of dolomitic limestone of early and middle Eocene age; at the city of Brunswick, however, the LFA includes highly permeable limestone of Paleocene and Late Cretaceous age (Krause and Randolph, 1989). In southeastern Georgia and northeastern Florida, the LFA includes a saline water-bearing unit known as the Fernandina permeable zone, which is deeply buried, cavernous, and highly permeable (Krause and Randolph, 1989). The Fernandina permeable zone is present at a depth of about 2,100 ft in a USGS test well (TW–26) on Colonels Island (fig. 1*B*). The test well is 2,727 ft deep and is important in the Brunswick area because it indicates the local source of saline water in the Fernandina permeable zone (Jones and others, 2002).

Glynn County has a warm temperate and fully humid climate, with warm summers (Kottek and others, 2006). The average temperature for the climate-normal period of 1981–2010 was 68.1 degrees Fahrenheit based on data compiled at St. Simons Island, Ga. (National Oceanic and Atmospheric Administration, 2014). Mean-annual precipitation for the same period is 45.0 inches, with the heaviest rainfall occurring during the months of June, August, and September. Glynn County is located in the central subarea of the 24-county coastal area designated by the GaEPD, which subdivided the area into northern, central, and southern subareas to facilitate water-management practices (fig. 1*A*).

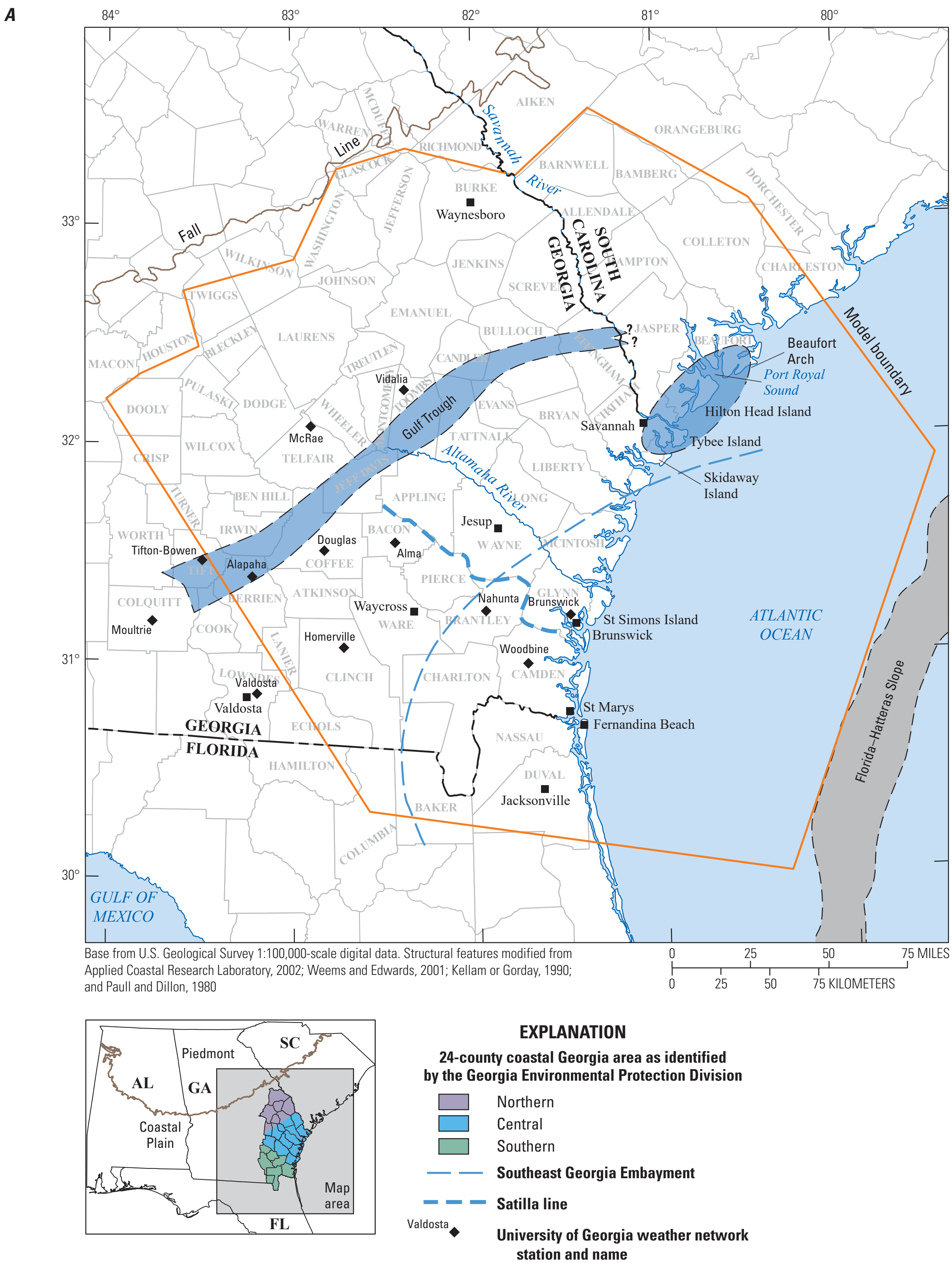


Figure 1. Maps showing location of (*A*) 24-county coastal Georgia area, model area, major structural features, and (*B*) 250-milligram-per-liter chloride concentration isochlor for June 2001 and 2005 near Brunswick, Georgia.

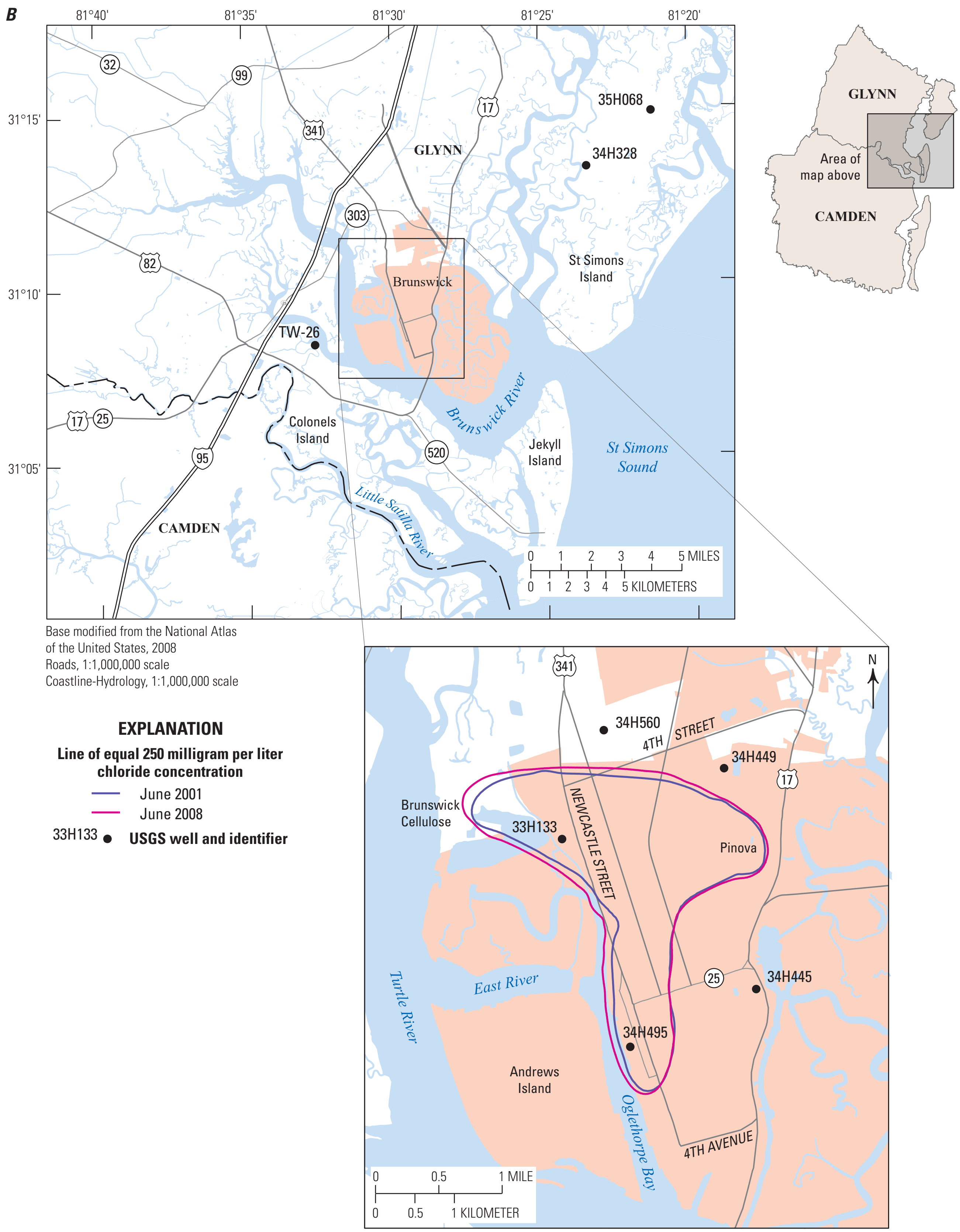
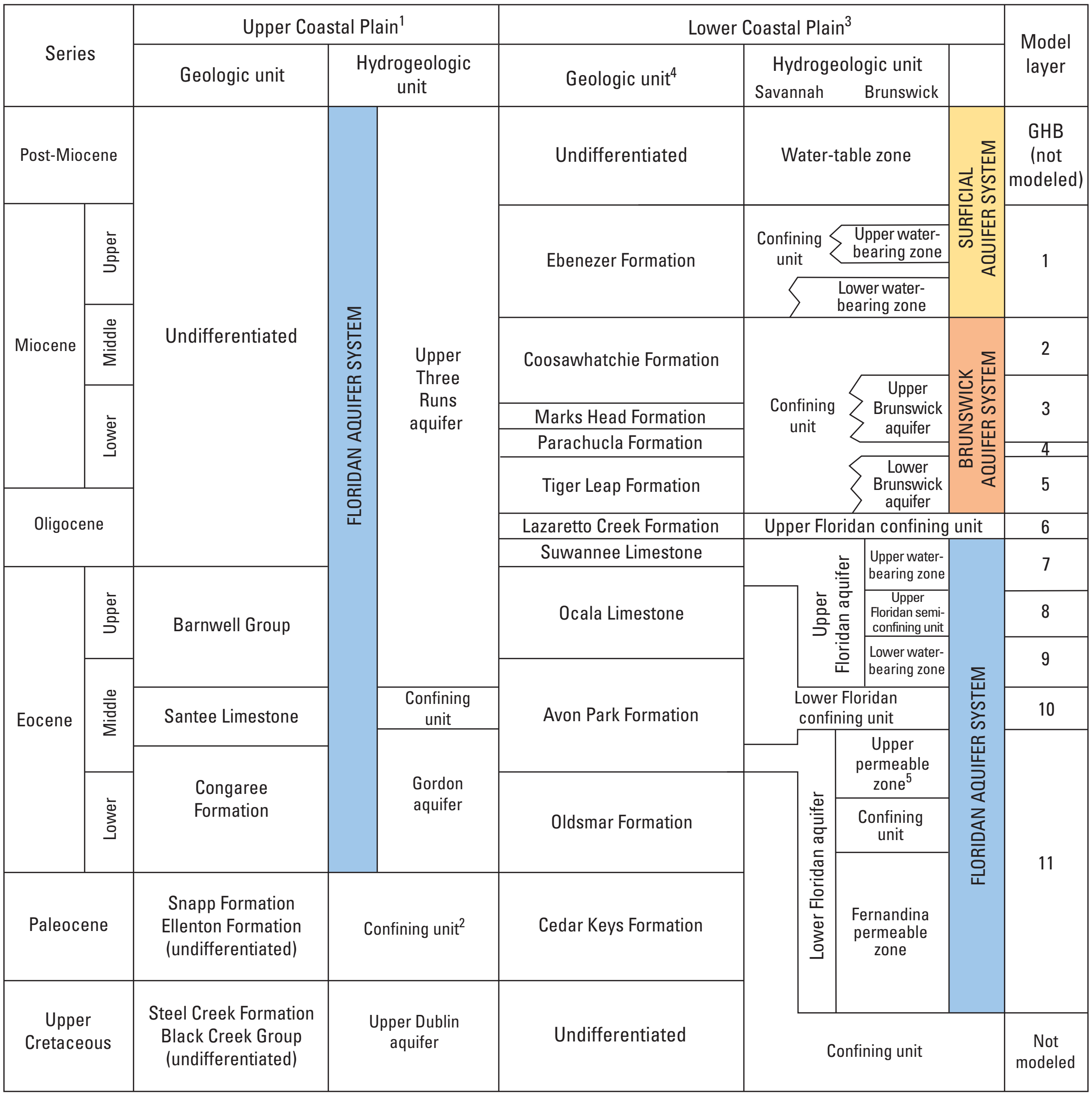


Figure 1. —Continued



[1]Modified from Falls and others, 1997.
[2]In local areas includes Millers Pond aquifer.
[3]Modified from Randolph and others, 1991; Clarke and Krause, 2000.
[4]Modified from Randolph and others, 1991; Weems and Edwards, 2001.
[5]Clarke and others, 1990; Krause and Randolph, 1989.

Figure 2. Generalized correlation chart of geologic and hydrogeologic units in the Upper and Lower Coastal Plain and model layers used in the groundwater-flow model revised by Cherry (2015).

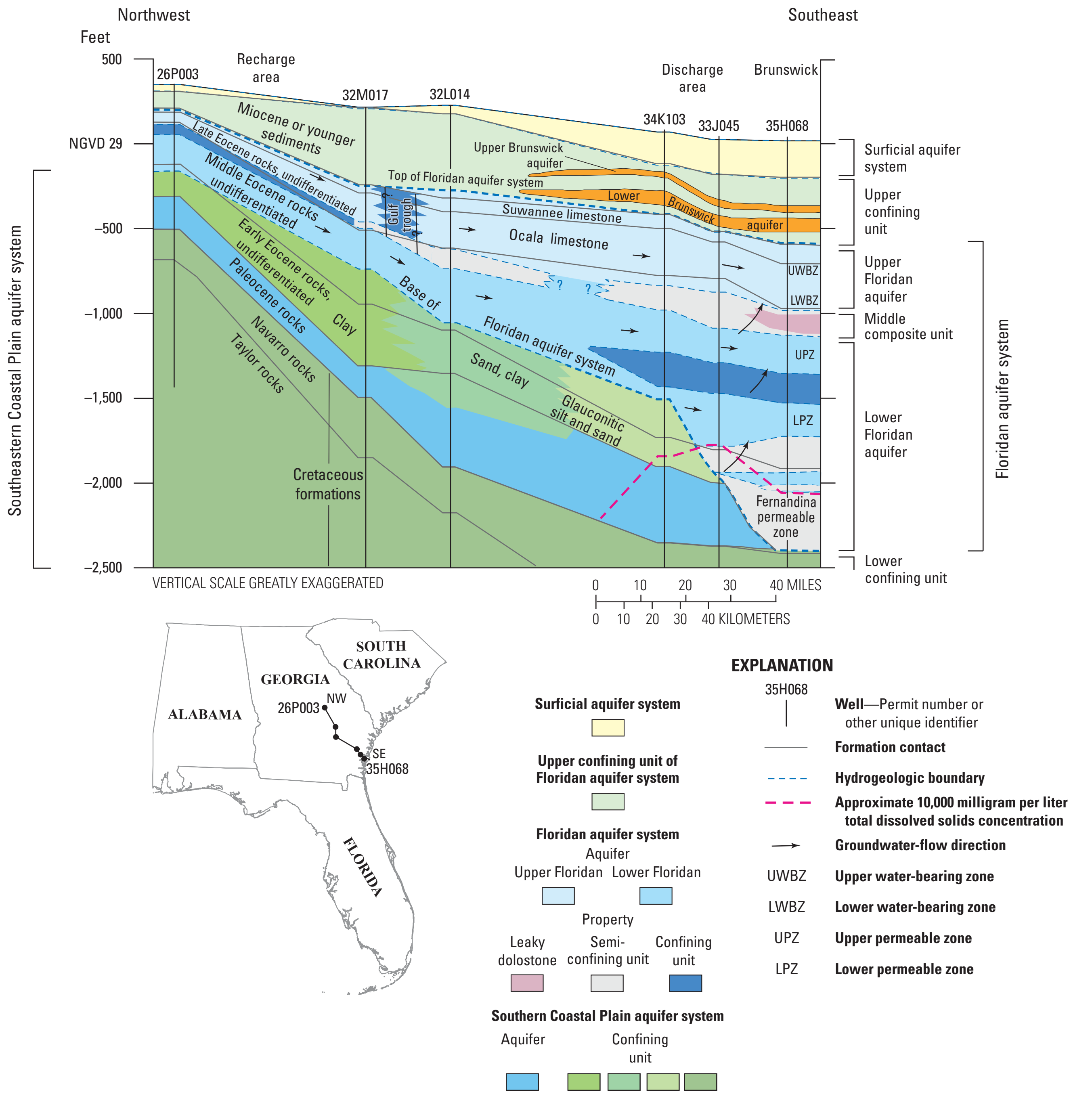


Figure 3. Generalized hydrogeologic cross section and groundwater-flow directions in the Brunswick/Glynn County area of Georgia.

Chloride Contamination in the Brunswick Area

In the Brunswick area, saline water has been contaminating the UFA since the late 1950s and has constrained development of the aquifer (Wait, 1965). Analyses of water samples collected in 2015 showed chloride concentrations greater than or equal to 250 mg/L covered a 2-mi² area near downtown Brunswick. Chloride concentrations within the area exceeded 2,000 mg/L (fig. 4; Cherry and Peck, 2017), well above the 250-mg/L State and Federal secondary drinking-water standard (Georgia Environmental Protection Division, 1997; U.S. Environmental Protection Agency, 2000).

Since the late 1950s, the USGS has collected water samples from the UFA in the Brunswick area and documented increasing chloride concentrations in response to increased groundwater withdrawals. Extensive pumping in the UFA resulted in lowered water levels and an upward hydraulic-head gradient between the saline portions of the Fernandina permeable zone and the typically freshwater of the UFA (fig. 5). Saline water is most likely entering the UFA through localized, vertically oriented conduits of relatively high permeability and moving laterally in response to pumping within the UWBZ. Acoustic televiewer images from test well 33H188 (TW-26) provide evidence of features that appear to be high-angle fault and (or) fracture zones at a depth near 2,475 ft (Jones and others, 2002). The chloride concentration of seawater is about 20,000 mg/L, and the water taken from the bottom of the Fernandina permeable zone at well 33H188 in 1982 was about 30,000 mg/L (Krause and Randolph, 1989). Discrete water samples collected during the drilling of well 34H495, located in the southern part of the chloride plume, in July 2000 at a depth of 2,243 ft indicate a chloride concentration of 18,000 mg/L (Falls and others, 2005). The chloride plume has stabilized in recent years, most likely because local horizontal hydraulic-head gradients have been maintained and groundwater withdrawals by local industry and by regional groundwater users over the coastal region have decreased (Cherry, 2007; Cherry and Clarke, 2008; Cherry and others, 2010 and 2011; Cherry and Peck, 2017).

Groundwater Levels, 2004–15

Groundwater levels vary seasonally and are affected by precipitation, evapotranspiration, and pumping. Groundwater levels generally are highest in the winter through early spring when evapotranspiration is lowest and irrigation withdrawals are minimal; groundwater levels generally are lowest during summer and fall when evapotranspiration and pumping rates are highest. In the Brunswick area, a water-level hydrograph for well 33H133 (fig. 1*B*), open to the UWBZ of the UFA, shows water-level fluctuations during 2004–15 (fig. 6). The hydrograph indicates relatively stable water levels during 2004–05, followed by a downward trend during 2006–07, and then a general upward trend during 2008–15. Rainfall data from 12 stations located in the southeastern part of Georgia indicate the driest years occurred during 2006, 2007, and 2011, with annual rainfall totals below 40 inches (University of Georgia Weather Network, 2018; table 1). The wettest year occurred during 2009 with mean annual rainfall of 57.3 inches; above-normal rainfall characterized the period during 2013–15. The peaks in the water-level hydrograph over the 12-year period of record represent rapid water-level recovery during partial shutdowns of the Brunswick Cellulose well field, which generally occur once a year.

In the Brunswick/Glynn County area, discrete water-level measurements from seven observation wells open to the Brunswick aquifer system indicate a general water-level rise from 2004 to 2015 (table 2). Overall, changes in water levels from 2004 to 2015 ranged from –1.84 ft (well 34H437) to 8.23 ft (well 34J077), with an average increase of 2.35 ft in the upper Brunswick aquifer and 1.53 ft in the lower Brunswick aquifer. Observation wells 34J077, 34J080, and 34J081 are located near active production wells open to the upper and lower Brunswick aquifers, and water levels are likely influenced by local pumping.

In the UWBZ of the UFA, discrete water-level measurements made in 14 wells during 2004 and 2015 indicate water-level declines and rises ranging from –0.62 to 5.22 ft, with an average water-level rise of 3.11 ft (table 2). Water levels in well 33H133 show a water-level rise during 2004 to 2015 of 4.43 ft, with more than 12 ft of the rise occurring from August 2007 to October 2015 (fig. 6). Water-level observations for the LWBZ of the UFA are sparse but indicate water-level rises consistent with the UWBZ, with well 33H154 indicating a water-level increase of 26.0 ft. This well is located near the Brunswick Cellulose well field, and increases in water levels are influenced by decreases in pumping from the LWBZ of the UFA.

In the LFA, discrete water-level measurements made in three wells from 2004 to 2015 indicate water-level rises ranging from 2.00 to 4.59 ft. These water-level changes are consistent with water-level rises in the Brunswick aquifer system and the UWBZ and LWBZ of the UFA. During the previous calibration period from 2000 to 2004, water-level recoveries were observed in the Brunswick and Floridan aquifer systems because of the shutdown of the Durango Paper Company mill located in St. Marys, Camden County, Ga., during 2002 (fig. 1; Peck and others, 2005).

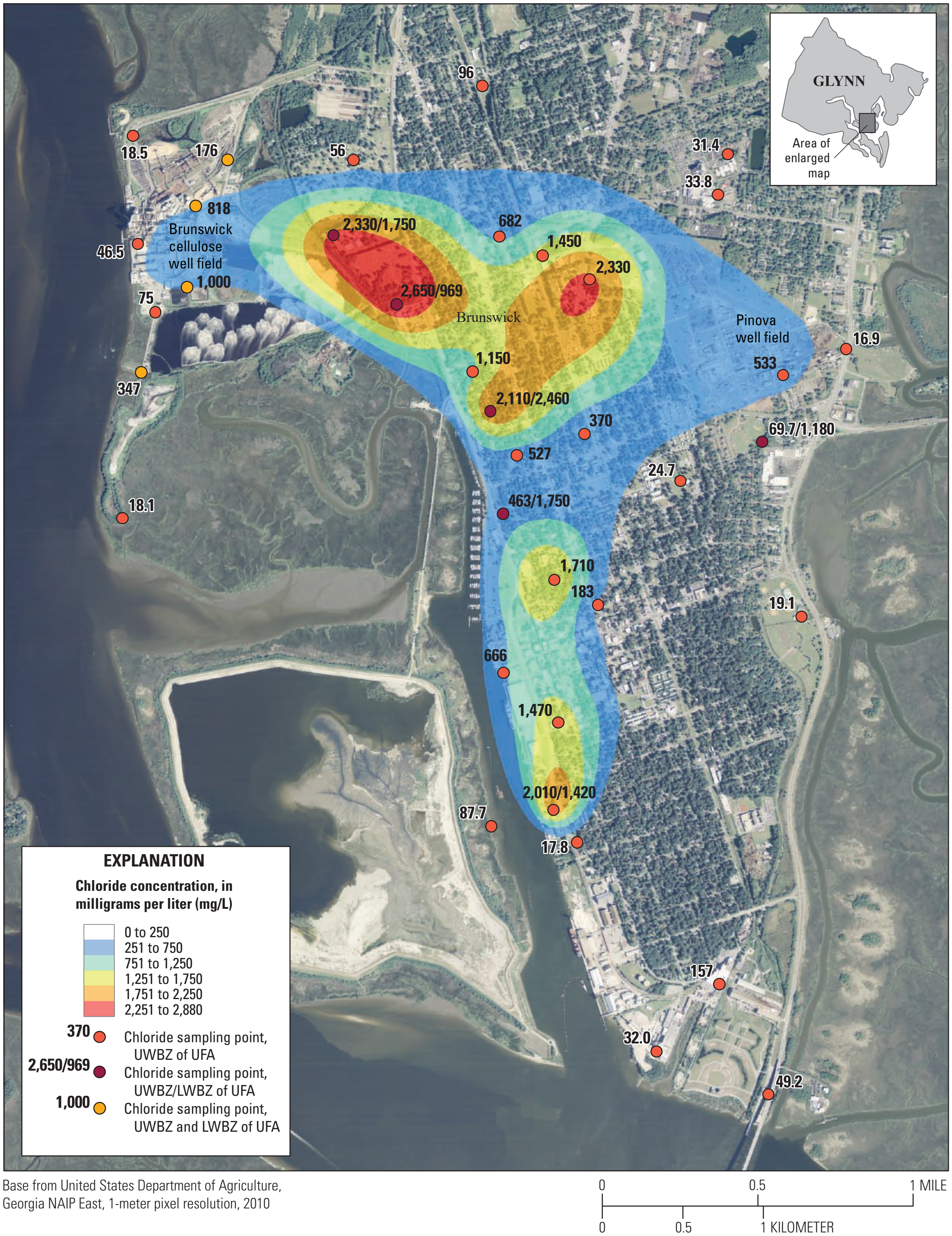


Figure 4. Map showing chloride concentration in the Upper Floridan aquifer in the area near downtown Brunswick, October 2015 [UWBZ, upper water-bearing zone; UFA, Upper Floridan aquifer; LWBZ, lower water-bearing zone].

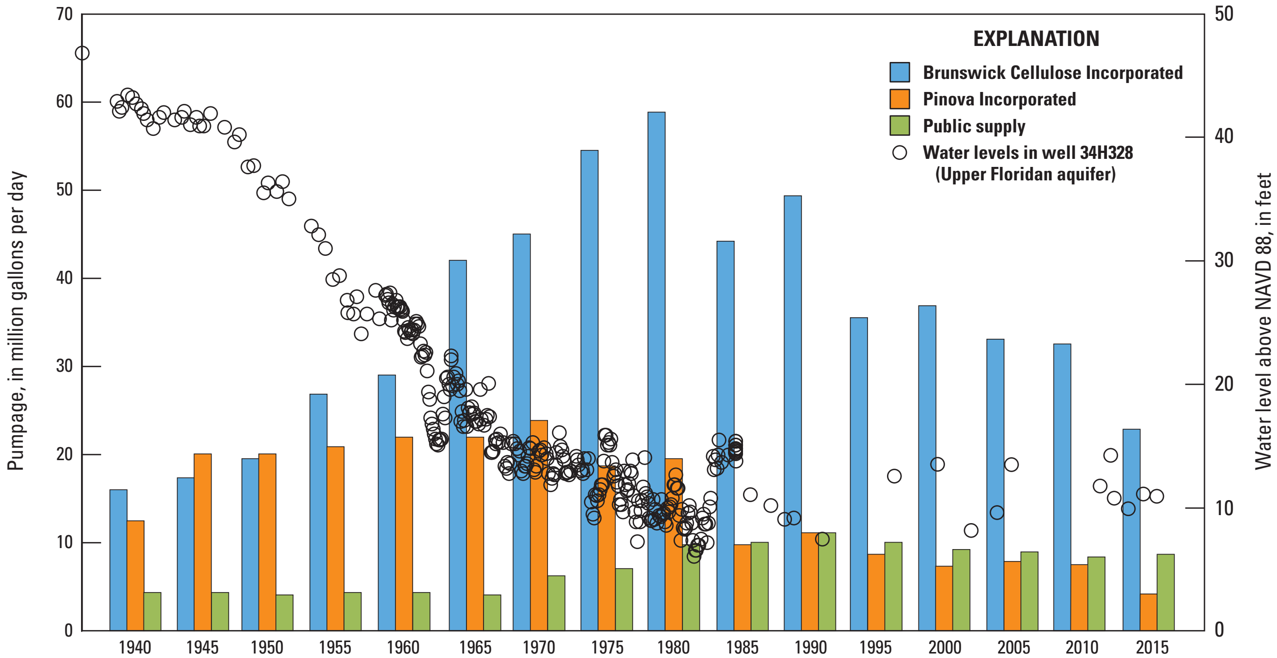


Figure 5. Graph showing major groundwater pumpage from the Upper Floridan aquifer in the Brunswick/Glynn County area, Georgia, 1940–2015, and water levels in well 34H328, 1939–2013.

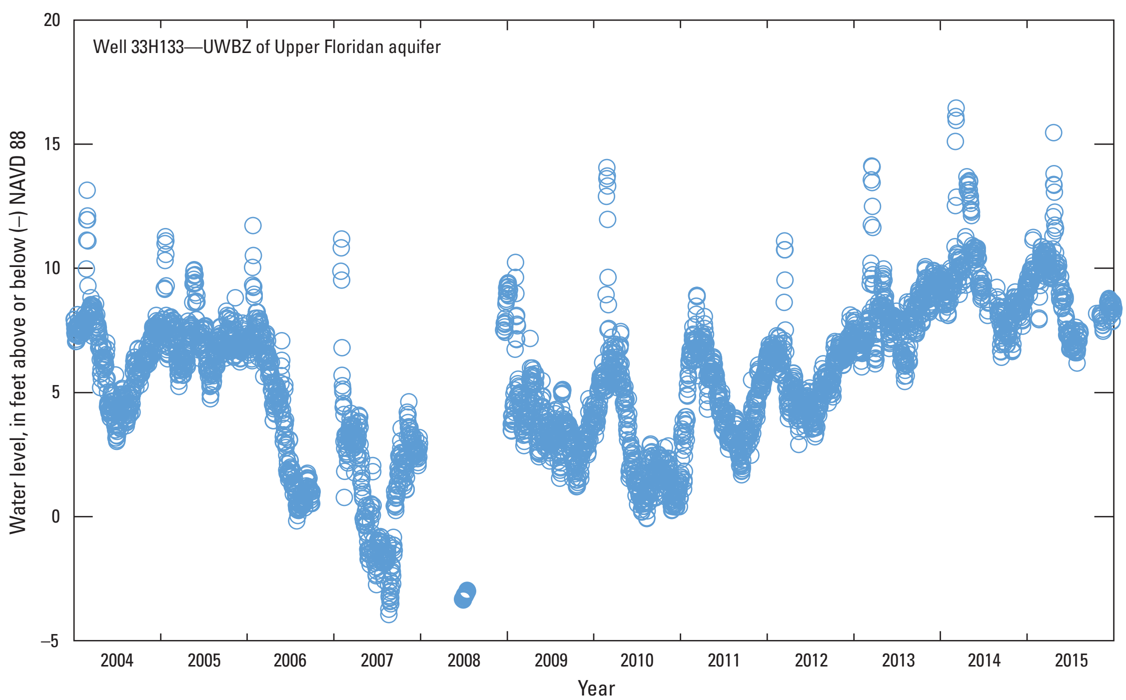


Figure 6. Graph showing water-level of well 33H133 open to the upper water-bearing zone of the Upper Floridan aquifer in the Brunswick, Georgia, area, 2004–15.

Table 1. Annual precipitation during 2004–2015 for University of Georgia weather network stations located in southeastern Georgia.

[—, not available; see figure 1 for station locations]

UGA station name	Annual precipitation, in inches per year												
	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	Annual average
Brunswick, Glynn County	51.80	76.12	36.56	34.51	40.04	56.12	37.43	33.20	47.62	45.13	56.45	47.69	**46.89**
Woodbine, Camden County	—	—	33.45	45.13	53.13	52.26	40.59	37.84	57.67	46.22	55.48	56.77	**47.85**
Nahunta, Brantley County	64.49	52.48	30.32	40.49	37.21	54.66	36.90	49.43	42.33	44.52	48.75	46.45	**45.67**
Homerville, Clinch County	56.81	51.18	32.21	35.92	49.95	55.38	39.18	39.55	49.08	60.73	49.08	44.53	**46.97**
Alma, Bacon County	48.25	45.52	38.53	40.25	48.76	56.70	38.89	32.60	39.49	55.21	49.78	49.48	**45.29**
Douglas, Coffee County	—	—	28.42	35.52	42.11	56.12	39.55	30.55	44.02	46.87	41.73	45.67	**41.06**
Alapaha, Berrien County	56.06	40.04	39.97	37.01	48.11	53.51	40.12	36.64	40.20	49.63	46.48	38.98	**43.90**
Valdosta, Lowndes County	48.14	59.16	40.59	37.51	52.24	53.65	47.56	46.47	47.27	50.50	55.42	58.35	**49.74**
Moultrie, Colquitt County	—	—	30.08	47.38	48.50	56.91	43.06	39.88	38.96	60.23	66.46	47.90	**47.94**
Tifton-Bowen, Tift County	51.61	52.66	37.99	33.79	45.31	58.72	39.80	30.41	40.05	56.97	46.04	49.35	**45.23**
McRae, Telfair County	50.22	41.36	40.90	39.29	48.72	61.89	40.48	36.51	44.33	67.71	50.02	49.32	**47.56**
Vidalia, Toombs County	50.98	33.11	30.87	45.42	47.36	71.60	45.84	34.26	44.85	56.20	50.72	44.31	**46.29**
Average	**53.15**	**50.18**	**34.99**	**39.35**	**46.79**	**57.29**	**40.78**	**37.28**	**44.66**	**53.33**	**51.37**	**48.23**	**46.20**

Table 2. Water-level measurements taken during June 2004 and October 2015 and observed water-level change from 2004 to 2015 in the Brunswick/Glynn County area, Georgia.

[NAVD 88, North American Vertical Datum of 1988; see fig. 1–1 for well locations]

Well identifier	Water level, in feet above or below NAVD 88		Water-level change, from 2004 to 2015, in feet
	2004	2015	
Upper Brunswick aquifer (UBA)			
34J081	–2.50	2.02	4.52
34J077	–13.54	–5.31	8.23
33J065	11.87	12.23	0.36
34H144	3.60	4.08	0.48
34H437	8.92	7.08	–1.84
		Mean	**2.35**
Lower Brunswick aquifer (LBA)			
34J080	8.52	10.68	2.16
33J062	22.09	22.98	0.89
		Mean	**1.53**
Upper water-bearing zone of Upper Floridan aquifer (UWBZ of UFA)			
33H120	3.08	7.98	4.90
33H130	2.18	6.83	4.65
33H133	3.77	8.20	4.43
33H207	8.09	13.31	5.22
34G009	38.73	39.77	1.04
34G016	28.28	28.78	0.50
34G020	30.10	31.15	1.05
34H112	12.85	15.85	3.00
34H125	12.38	11.76	–0.62

Table 2. Water-level measurements taken during June 2004 and October 2015 and observed water-level change from 2004 to 2015 in the Brunswick/Glynn County area.—Continued

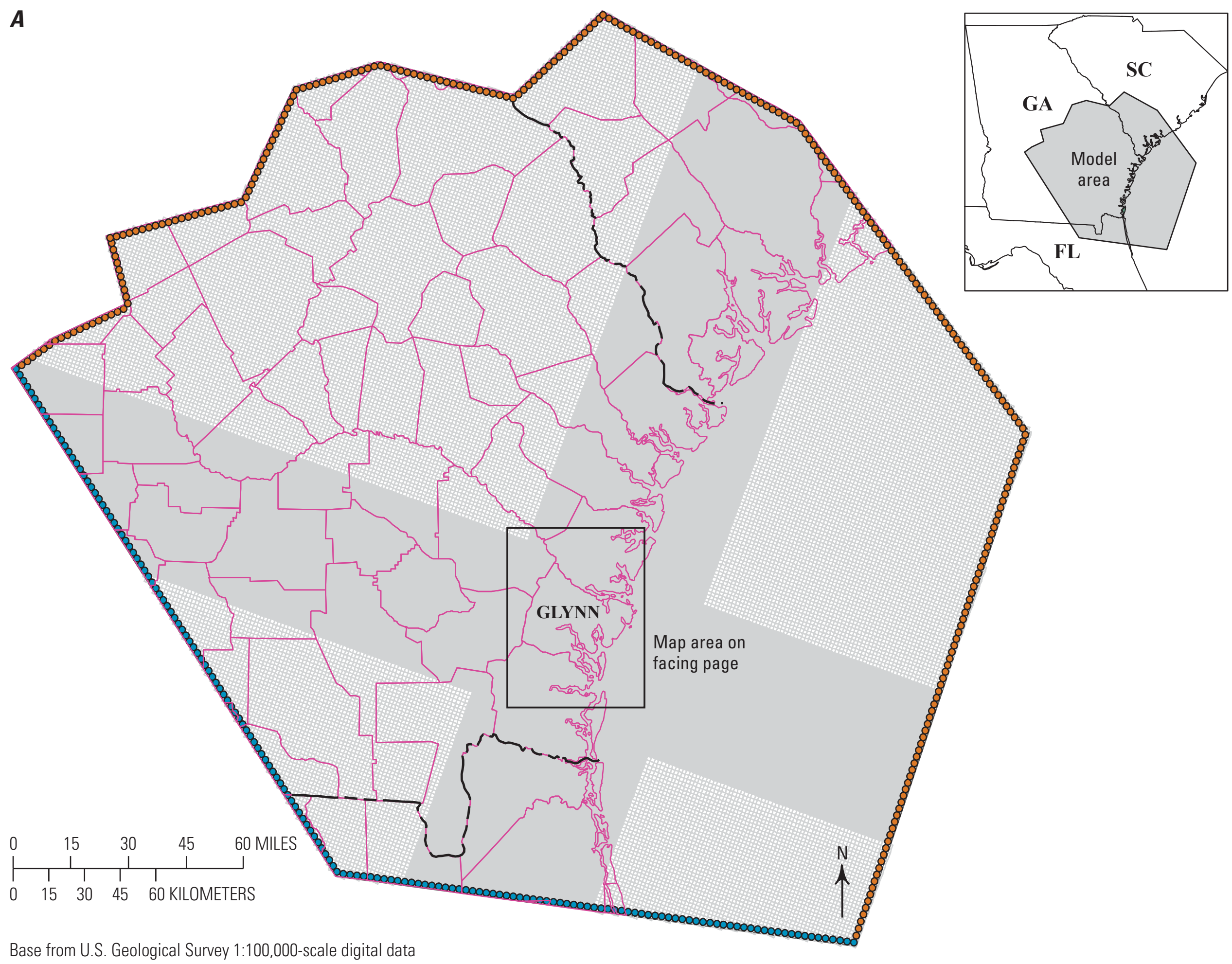
[NAVD 88, North American Vertical Datum of 1988; see fig. 1–1 for well locations]

Well identifier	Water level, in feet above or below NAVD 88		Water-level change, from 2004 to 2015, in feet
	2004	2015	
Upper water-bearing zone of Upper Floridan aquifer (UWBZ of UFA)—Continued			
34H355	8.46	12.51	4.05
34H371	15.54	18.96	3.42
34H373	3.98	8.81	4.83
34H393	14.56	16.72	2.16
34H469	6.61	11.49	4.88
		Mean	**3.11**
Lower water-bearing zone of Upper Floridan aquifer (LWBZ of UFA)			
33H127	7.85	12.76	4.91
33H154	–17.85	8.20	26.05
34H334	12.42	16.50	4.08
		Mean	**11.68**
Lower Floridan aquifer (LFA)			
33H206	14.41	16.41	2.00
34H391	11.87	16.46	4.59
34H436	15.72	19.33	3.61
		Mean	**3.40**

Simulation of Groundwater Flow

A single-density, digital groundwater-flow model (herein called the original model) developed to simulate regional confined groundwater flow in the coastal area of Georgia, Florida, South Carolina, and adjacent offshore areas (Payne and others, 2005) was modified to provide more detailed simulations in the Glynn County area. The original model was developed using the USGS finite-difference code MODFLOW-2000 (Harbaugh and others, 2000) and was used to simulate steady-state flow for predevelopment, 1980, and 2000 conditions. The original model was revised (Cherry, 2015) to simulate the long-term, steady-state effect of changes in mean-annual pumping during 2000 and 2004 on groundwater levels and to evaluate changes in hydraulic-head gradients near pumping centers in the Brunswick area (fig. 7*A–B*). The revisions to the original model made for this study included (1) increased spatial resolution near the downtown Brunswick area, (2) the addition of hydraulic-property geographic zones within the UFA near the Brunswick/Glynn County area, (3) subdivision of the Brunswick aquifer system, and (4) subdivision of the Floridan aquifer system into separate model layers to represent the local hydrogeology (fig. 8). The groundwater-flow model revised by Cherry (2015) was updated to include mean monthly pumping rates during October 2015 for selected production wells near the downtown Brunswick area, and was used to delineate 2015 Base Case conditions and as the basis to evaluate simulated changes in five groundwater-management scenarios presented in the current report. The reader is referred to Cherry (2015) for a complete discussion of revisions to the original model of Payne and others (2005) and calibration to observed water levels during 2000 and 2004.

The original model by Payne and others (2005) encompasses 42,155 mi^2 and consists of 119 rows and 108 columns, with cell sizes ranging from 4,000 x 5,000 ft (0.7 mi^2) to 16,500 x 16,500 ft (9.8 mi^2). The focus on the Brunswick/Glynn County area for the current study and that of Cherry (2015) required a greater grid density to simulate steeper hydraulic-head gradients (cones of depression) in the UFA near pumping centers. The groundwater-flow model revised by Cherry (2015) used graphical grid-generation tools from the graphical user interface ARGUS, which enabled visual adjustment of grid position, orientation, and density. The revised model with new grid configuration has the same orientation, but the number of rows and columns has been increased to 424 and 452, respectively (fig. 7*A*).



EXPLANATION

Area of dense model grid—Grid spacing progressively increases by a factor of 1.5 from a minimum of 500 feet to a maximum of 5,000 feet

Model grid

Line of equal 250 milligram per liter chloride concentration 2004—Modified from Leeth and others, 2007

Model-boundary nodes

Specified head

No-flow

Figure 7. Maps showing (*A*) revised model grid of Cherry (2015) and (*B*) major production wells, observation wells used during October 2015, and outline of the 2004 chloride plume for the Upper Floridan aquifer in the Brunswick, Georgia, area.

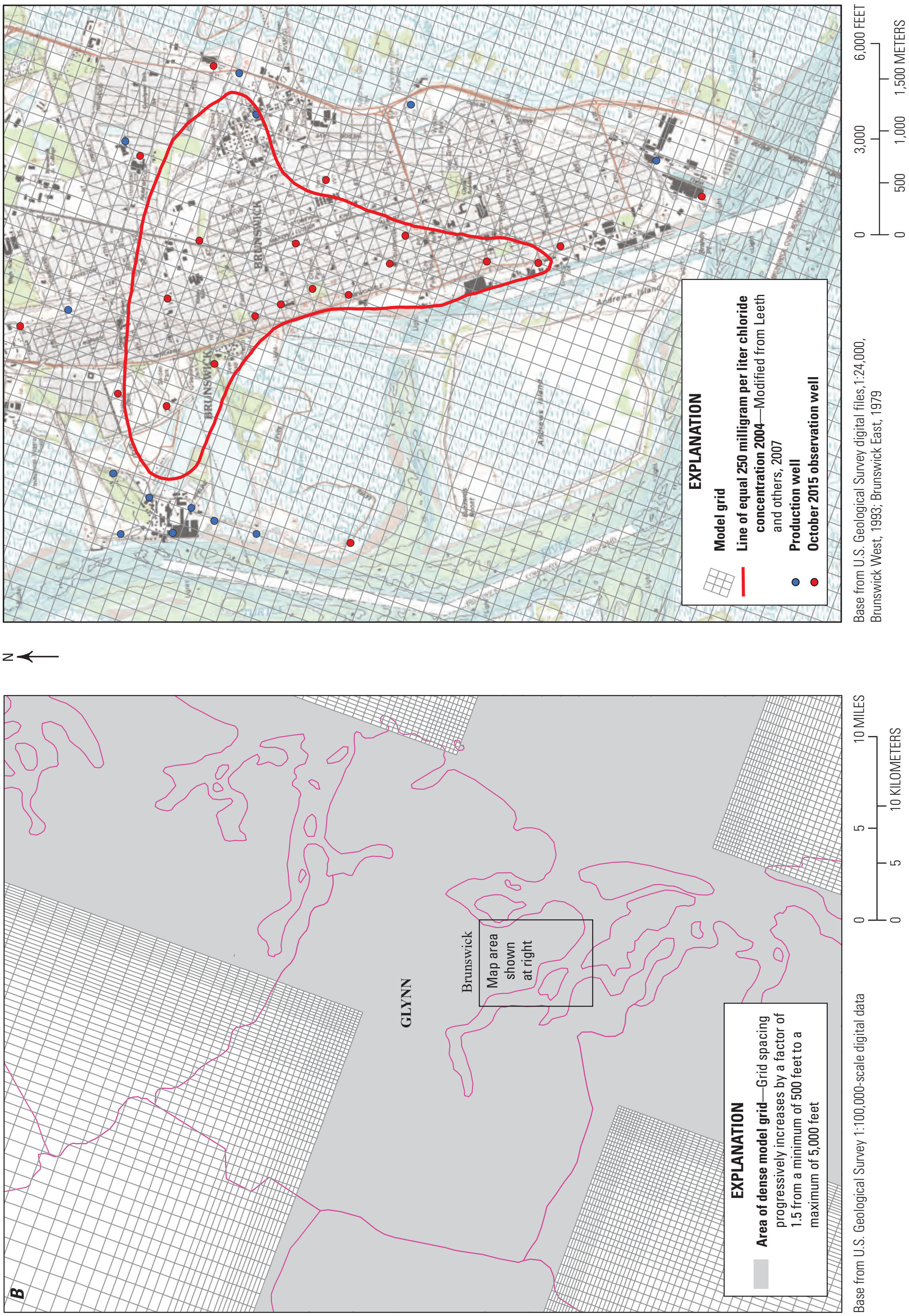


Figure 7. —Continued

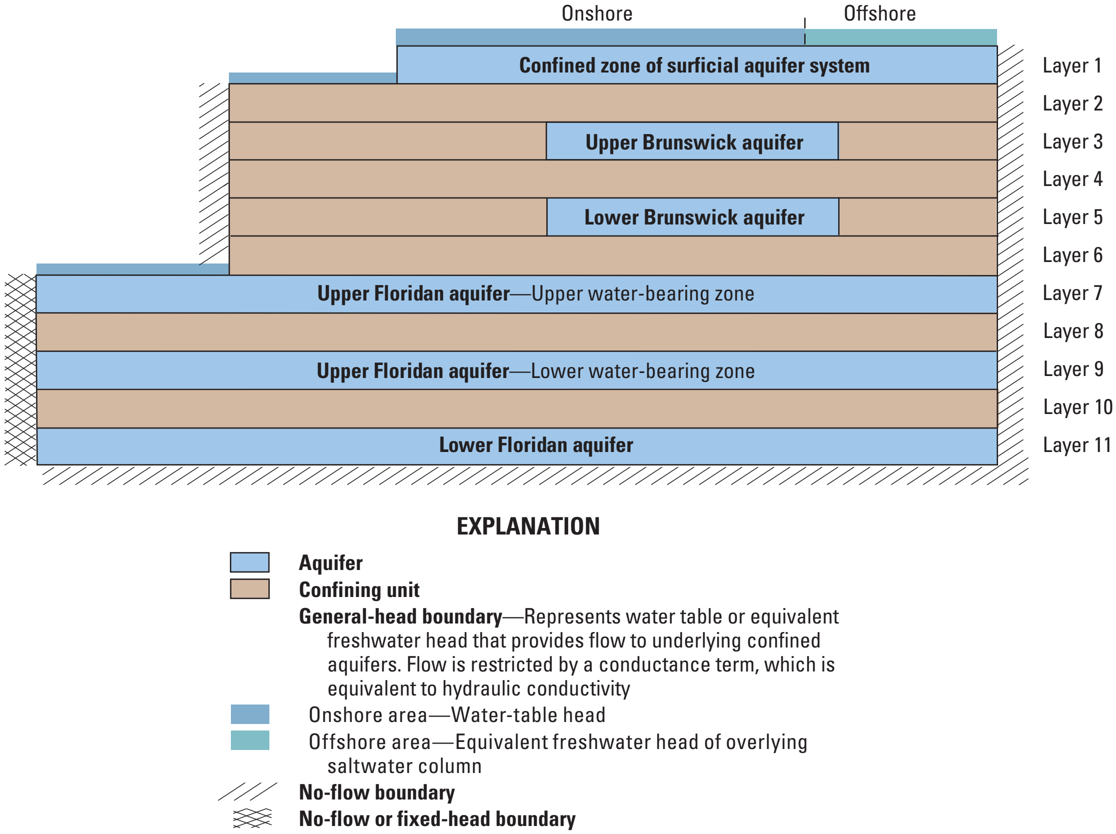
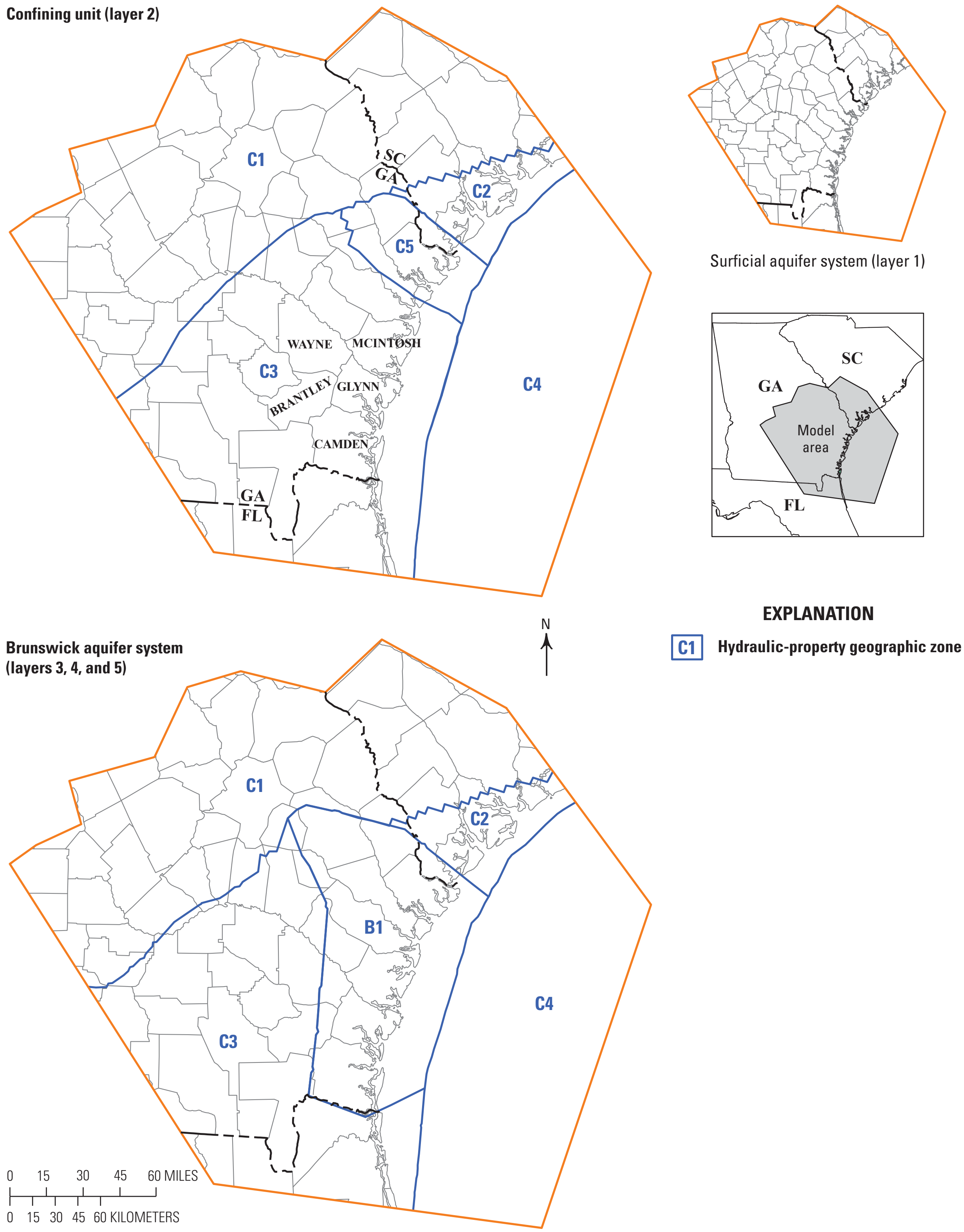


Figure 8. Schematic diagram showing revised model (Cherry, 2015) layers and boundary conditions.

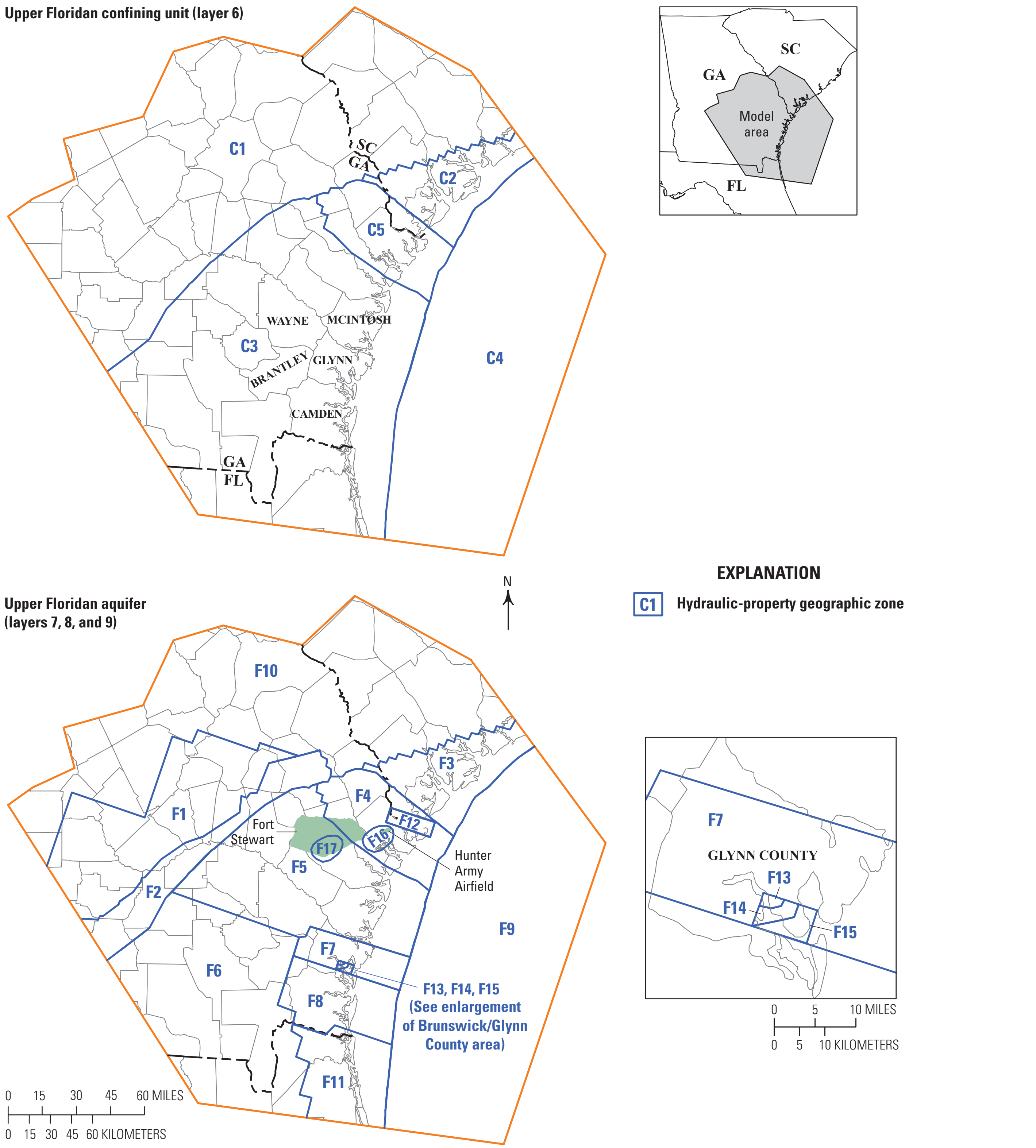
The variable cell sizes range from 500 x 500 ft (0.009 mi²) in the city of Brunswick to 5,000 x 5,000 ft (0.90 mi²) near the edges of the model (Cherry, 2015). The irregular grid configuration results in elongated cells, having aspect ratios as large as 10:1 between row and column spacings along the outer margins of the model. This large aspect ratio is approaching the recommended limit above which numerical errors could occur (de Marsily, 1986, p. 351). The pumping rates in the groundwater-flow model revised by Cherry (2015) have been updated to include adjusted rates during October 2015 for selected production wells located in the Brunswick/St. Simons Island area, which includes wells within or adjacent to the chloride plume in downtown Brunswick. The recalibrated model represents a 2015 Base Case simulation and was used as the basis to evaluate five groundwater-management scenarios.

In the Brunswick/Glynn County area, the original model by Payne and others (2005) contained designated homogeneous and isotropic hydraulic-property geographic zones within model layers (herein referred to as “geographic zones”) representing all aquifers and confining units except the UFA, which consisted of three zones within Glynn County (F5, F7, and F8). For the groundwater-flow model revised by Cherry (2015), additional zones were designated on the basis of available aquifer-test and geologic data (Clarke and others, 2004; fig. 9; table 3). Additional zones were created (F13, F14, and F15) within the UFA (layers 7–9) near the Brunswick area to further adjust hydraulic properties within geographic zone F7 of the original model. In the revised model, three model layers (3, 4, and 5) vertically subdivide the Brunswick aquifer system, and geographic zone B1 represents a less permeable part of the aquifer (layer 4) juxtaposed between two more permeable parts (layers 3 and 5), with each layer assigned a uniform value for horizontal and vertical hydraulic conductivity (Kh and Kv, respectively; table 3). To enable more detailed simulation of groundwater flow in the Brunswick/Glynn County area than was available using the original model, the UFA in the revised model has been vertically subdivided into the UWBZ (layer 7) and LWBZ (layer 9), separated by a semi-confining unit (layer 8; fig. 8). In the UFA, each of these new layers contained the same 12 geographic zones used in the original model of Payne and others (2005), plus an additional 3 geographic zones in the Brunswick area to represent lateral variations in horizontal hydraulic conductivity (fig. 9; table 3). In addition, two geographic zones (F16 and F17; fig. 9) were based on the revised model’s ability to simulate interaquifer leakage from the UFA to the LFA through the confining unit caused by pumping in newly constructed LFA wells near Hunter Army Airfield and Fort Stewart, Georgia (Clarke and others, 2010, 2011). Overall, the values assigned to the 17 geographic zones for model layers 7 and 9 assigned by Cherry (2015) range from 20 to 3,415 feet per day (ft/d) with an average of 540 ft/d.



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

Figure 9. Maps showing hydraulic-property geographic zones for the groundwater-flow model revised by Cherry (2015) near Brunswick/Glynn County, Georgia.



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

Figure 9. —Continued

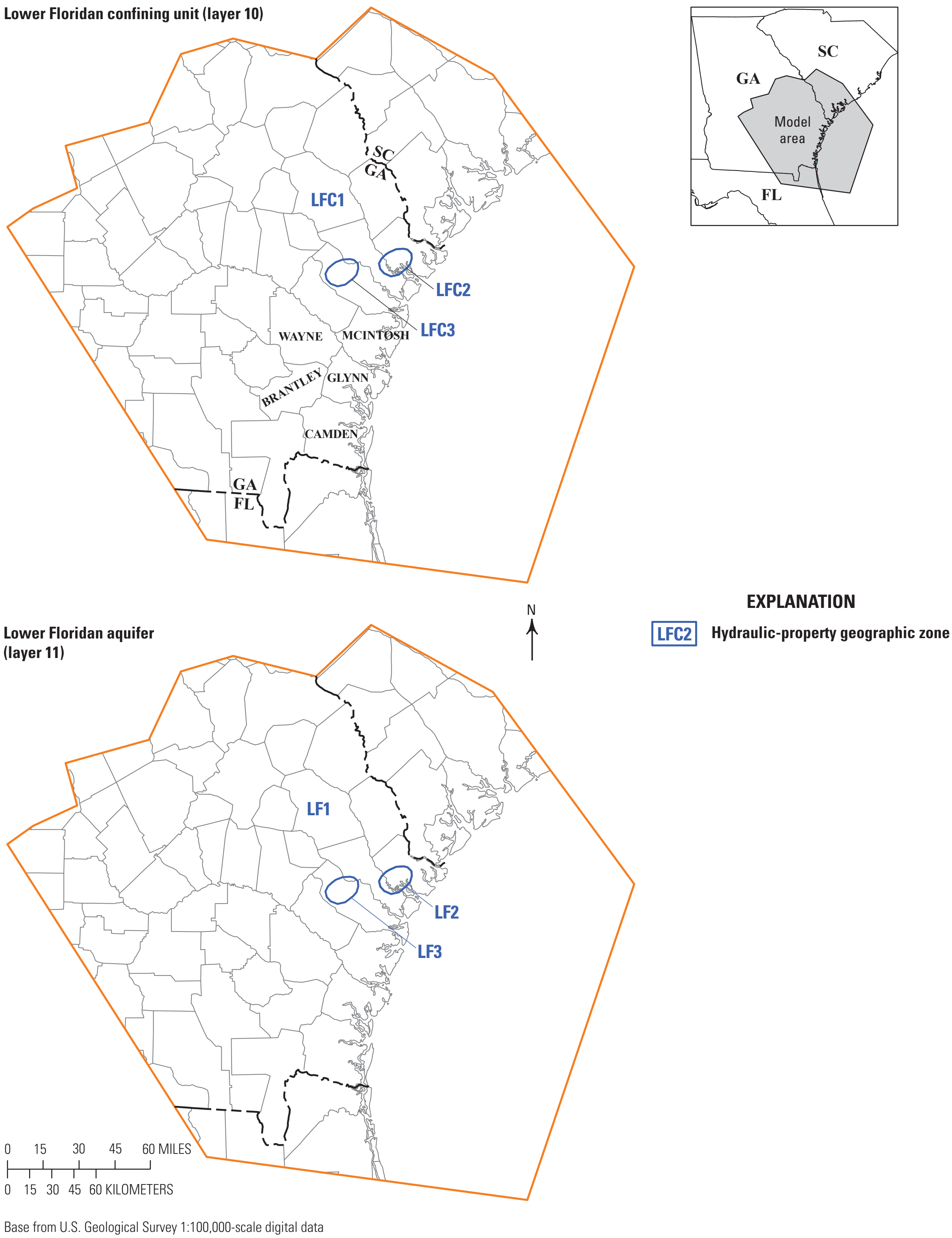


Figure 9. —Continued

Table 3. Horizontal and vertical hydraulic conductivity values assigned to hydraulic-property geographic zones for the groundwater-flow model revised by Cherry (2015) in the Glynn County area and adjacent counties in Georgia.

[—, not applicable; UWBZ, upper water-bearing zone; LWBZ, lower water-bearing zone; Kh, horizontal hydraulic conductivity; Kv, vertical hydraulic conductivity]

Unit	Layer	Revised model	
		Hydraulic-property geographic zone (fig. 9)	Hydraulic conductivity, Kh and Kv, in feet per day
Surficial aquifer	1	—	105
Confining unit	2	C3	0.00001
Upper Brunswick aquifer	3	B1	10
		C3	0.00001
Confining unit	4	B1	0.02
		C3	0.00001
Lower Brunswick aquifer	5	B1	20
		C3	0.00001
Confining unit	6	C3	0.00001
UWBZ of Upper Floridan aquifer	7	F5	225
		F6	3,415
		F7	750
		F8	3,000
		F13	300
		F14	240
		F15	200
Confining unit	8	F5	225
		F6	3,415
		F7	0.2
		F8	0.2
		F13	0.2
		F14	0.2
		F15	0.2
LWBZ of Upper Floridan aquifer	9	F5	225
		F6	3,415
		F7	750
		F8	3,000
		F13	270
		F14	200
		F15	125
Confining unit	10	LFC1	0.02000
Lower Floridan aquifer	11	LF1	10

Model performance for 2004 and 2015 Base Case conditions was evaluated on the basis of differences (residuals are defined here as the simulated head minus the observed "water level") as well as the corresponding mean, median, and root-mean-square error (RMSE) statistics. The mean residual is a good indicator of bias in the differences between simulated and observed heads. The median residual is more robust than the mean in the presence of outlier values. RMSE, derived from residuals as the square root of the average deviation of the residuals from zero, yields a measure of overall fit of simulated heads to observed groundwater levels. The calibration criteria used near the Brunswick/Glynn County area in the revised model were more stringent than those used in the original model because of the relatively low topographic relief in the area and the availability of 5-ft contour intervals on local topographic maps. For altitudes determined from topographic maps near the downtown Brunswick area, one-half the contour interval (2.5 ft) is considered to be the accuracy of well data, including groundwater-level measurements, formation altitudes, and so forth. For the revised model, the calibration target (established error criteria) for the 2000 and 2004 simulations was 10 ft for areas outside Glynn County and 5 ft near downtown Brunswick. The primary objective of the 2004 and 2015 Base Case calibrations was to achieve the best possible match of simulated heads to observed groundwater levels in the UWBZ of the UFA near the Brunswick/Glynn County area. The 2015 Base Case calibration only evaluated residuals in the Brunswick/Glynn County area because 2004 pumping rates were not updated for the remaining areas of the regional model.

For the 2004 calibration, residuals (simulated head minus observed head) from 32 observation wells in model layer 7, UWBZ of the UFA, ranged from −18.9 to 3.98 ft, with a mean of −2.56 ft, median of −1.50 ft, and an RMSE of 5.34 ft (table 4). For model layer 9, LWBZ of the UFA, residuals from five wells located near downtown Brunswick ranged from −6.15 to 20.8 ft, with a mean of 1.20 ft and a median of −3.30 ft. In the Brunswick/Glynn County area, the distribution of water-level residuals in the UWBZ of the UFA (layer 7) indicates an acceptable match, with a mean residual of −2.56 ft and 75 percent of the values within the established error criterion of 5 ft. However, the map showing the distribution of water-level residuals indicates an acceptable match in the downtown Brunswick area with four large negative values (outliers) for wells located on Jekyll Island.

Table 4. Calibration statistics for simulated heads for 2004 conditions in Glynn County, Georgia (Cherry, 2015).

[Residual equals simulated minus observed head; —, not calculated because less than 10 values; UWBZ, upper water-bearing zone; LWBZ, lower water-bearing zone]

Calibration statistic	Upper Brunswick aquifer (layer 3)	Lower Brunswick aquifer (layer 5)	UWBZ of Upper Floridan aquifer (layer 7)	LWBZ of Upper Floridan aquifer (layer 9)	Lower Floridan aquifer (layer 11)
			2004		
Number of observations	6	2	32	5	7
Range of observations (feet)	33.8	13.6	42.9	34.2	12.1
Minimum residual (feet)	–13.7	–12.5	–18.9	–6.15	–10.9
Maximum residual (feet)	9.30	–6.26	3.98	20.8	1.98
Mean residual (feet)	–0.77	–9.38	–2.56	1.20	–4.50
Median residual (feet)	–0.66	—	–1.50	–3.30	–3.73
Root-mean-square error residual (feet)	—	—	5.34	—	—
Residuals within 10-foot error criteria (percent)	83	50	91	80	86
Residuals within 5-foot error criteria (percent)	67	0	75	60	71

Simulated potentiometric surfaces of the UFA (layers 7 and 9) for 2004 (Cherry, 2015) indicate groundwater flow is from upland areas in the west, eastward toward the Savannah area (fig. 10). Groundwater also flows from the Brunswick/Glynn County area roughly parallel to the coast northeastward toward the Savannah area. Simulated potentiometric surface maps of the UFA (represented in the model by layers 7 and 9) for 2004 show steep potentiometric gradients in the upland areas north and west of the Gulf Trough, with groundwater-flow directions toward coastal Georgia (figs. 1 and 10). Groundwater-flow directions are influenced by a cone of depression centered in the Savannah area that alters the coastward flow pattern. The broad area of influence for this cone of depression is evident by the 0-ft contour, which extends to an area of pumping to the southwest near Jesup, Ga., and north into Jasper and Beaufort Counties, S.C. (fig. 1). Simulated potentiometric contours in the Savannah area show water-level altitudes below −80 ft in layers 7 and 9. In the Brunswick/Glynn County area, potentiometric contours indicate groundwater flow from the southwest to northeast, with a cone of depression near downtown Brunswick locally altering the coastward flow pattern (model layer 7 shown in fig. 11).

2015 Base Case Condition

For the 2015 Base Case calibration, residuals from 26 observation wells in model layer 7, UWBZ of UFA, ranged from −17.3 to 5.48 ft, with a mean of −0.25 ft, median of 1.00 ft, and an RMSE of 4.89 ft (table 5). For model layer 9, LWBZ of UFA, residuals from five wells located near downtown Brunswick ranged from −3.20 to 1.50 ft, with a mean of −0.64 ft and a median of −0.50 ft. In the Brunswick/Glynn County area, the distribution of water-level residuals in the UWBZ of the UFA (layer 7) indicates an acceptable match, with a mean residual of −0.25 ft and 81 percent of the values within the established error criterion of 5 ft. The map showing the distribution of water-level residuals also indicates an improved match in the downtown Brunswick area with four large negative values for wells located on Jekyll Island (fig. 11).

The simulated results from the 2015 Base Case indicate predominant groundwater-flow directions across Glynn County from the southwest and south and moving in a northeast direction into neighboring McIntosh County. The potentiometric surface map for model layer 7, UWBZ of the UFA, indicates simulated heads greater than 25 ft in the southwest corner of Glynn County with the 15-ft contour in close proximity to the boundary with McIntosh County (fig. 11). Near downtown Brunswick, the cone of depression influences groundwater-flow directions along the Brunswick peninsula with flow components from all directions toward the center of pumping at Brunswick Cellulose. The 15-ft contour encompasses most of downtown Brunswick with groundwater-flow directions toward the 0-ft contour, which surrounds the Brunswick Cellulose well field. The horizontal hydraulic-head gradient in groundwater flow from the west, southwest, and south toward Brunswick ranges from 7 to 8 ft/mi. The gradient from the east and northeast toward the pumping center is about 3 ft/mi and is influenced by other active production wells in the area.

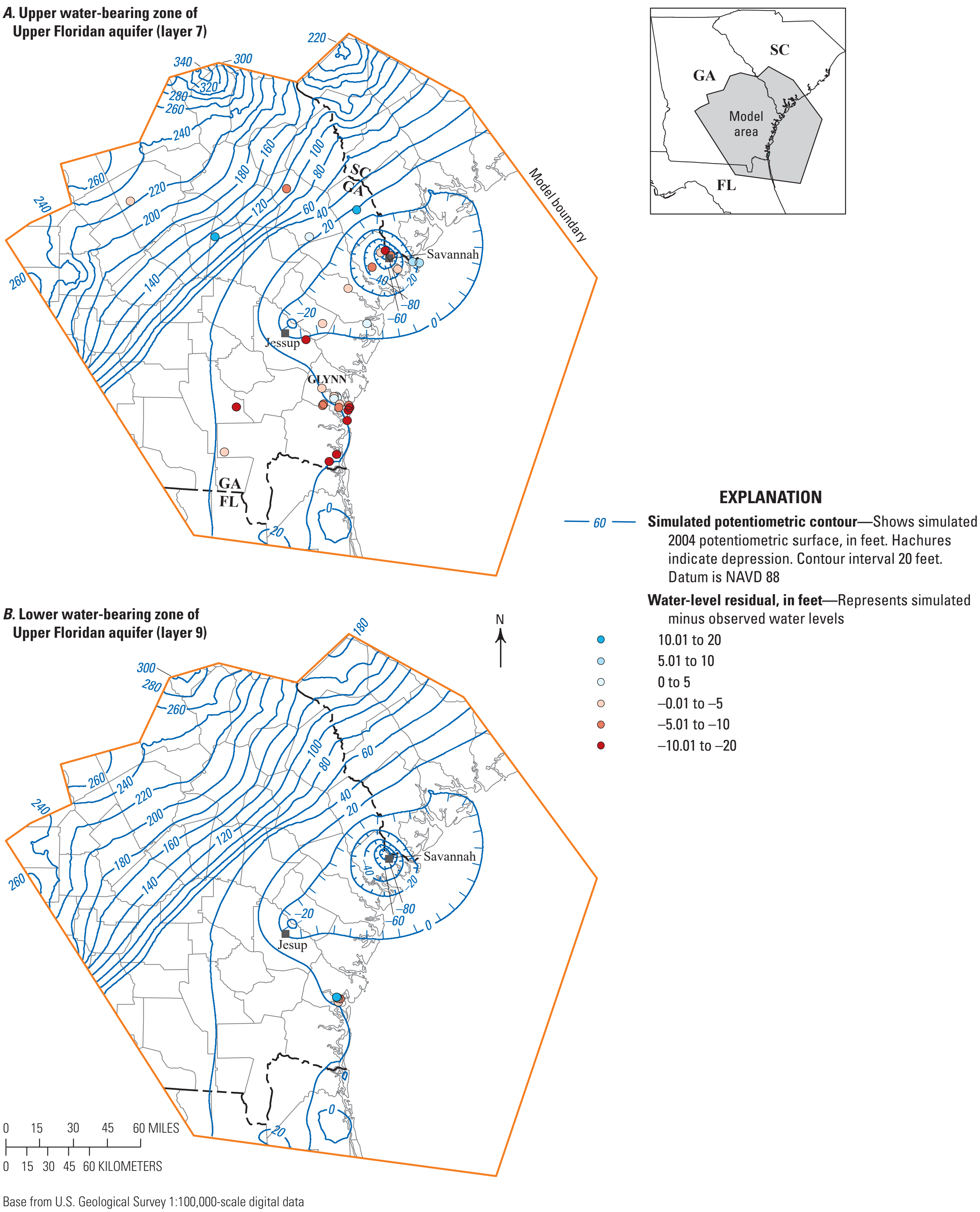


Figure 10. Maps showing simulated 2004 potentiometric surfaces and water-level residuals by model layer: (*A*) layer 7, upper water-bearing zone of the Upper Floridan aquifer; and (*B*) layer 9, lower water-bearing zone of the Upper Floridan aquifer, Brunswick/Glynn County area, Georgia.

Table 5. Calibration statistics for simulated heads for 2015 Base Case in Glynn County, Georgia.

[Residual equals simulated minus observed head; —, not calculated because less than 10 values; UWBZ, upper water-bearing zone; LWBZ, lower water-bearing zone]

Calibration statistic	Upper Brunswick aquifer (layer 3)	Lower Brunswick aquifer (layer 5)	UWBZ of Upper Floridan aquifer (layer 7)	LWBZ of Upper Floridan aquifer (layer 9)	Lower Floridan aquifer (layer 11)
2015 Base Case					
Number of observations	5	2	26	5	4
Range of observations (feet)	17.5	12.3	32.9	9.30	13.3
Minimum residual (feet)	–1.83	10.7	–17.3	–3.20	–12.2
Maximum residual (feet)	3.80	23.0	5.48	1.50	0.80
Mean residual (feet)	0.92	–9.76	–0.25	–0.64	–3.73
Median residual (feet)	1.61	—	1.00	–0.50	–1.75
Root-mean-square error residual (feet)	—	—	4.89	—	—
Residuals within 10-foot error criteria (percent)	100	50	96	100	75
Residuals within 5-foot error criteria (percent)	100	0	81	100	75

Steady-state simulations of water levels for 2004 and 2015 indicate groundwater-level rises in the UFA within Glynn County, corresponding to a decrease in the rate of pumping during this period. The simulated water-level changes for the 2015 Base Case compared to the 2004 calibrated simulation for each grid cell indicate a range from –2.0 ft to greater than +7 ft (fig. 12). In Glynn County, simulated water-level increases in the UFA (layers 7 and 9) were caused by decreases in pumping rates represented in the steady-state models from 2004 to 2015 Base Case. Simulated groundwater-level increases generally range between 1 and 7 ft, with the greatest simulated increase occurring near downtown Brunswick (appendix 1). Decreases in pumping rates in the UFA from 55.2 million gallons per day (Mgal/d) during 2004 to 45.2 Mgal/d during 2015 Base Case, represented in the models, contributed to the rises in simulated water levels. The simulated water-level change contours near the Brunswick Cellulose well field indicate about 10 ft of change due to variable pumping rates and one production well that was represented in the simulation during 2015 Base Case but was inactive during 2004. Simulated water levels (and changes) indicate water-level rises in Glynn County, corresponding to a decrease in pumping during this period, with the exception of the Brunswick aquifer system (layers 3 and 5), which had similar pumping rates from 2004 to 2015.

Simulated horizontal potentiometric gradients for the 2015 Base Case approximated observed gradients in the five potentiometric profiles (*A–A′* to *E–E′*) that were constructed in close proximity to the chloride plume (fig. 13). Water-level data available for well 33H211 allowed the 2004 potentiometric profiles to be constructed in close proximity to the Brunswick Cellulose well field. Water-level data were not available for well 33H211 during October 2015, but the simulated head allowed a comparison to the 2004 potentiometric profiles (fig. 13; table 6). The simulated heads for the 2015 Base Case and the constructed profiles (*A–A′* to *E–E′*) show substantially higher heads as a result of lower pumping rates. The simulated head differences were calculated using the simulated heads at the endpoints for each of the profiles (table 7). For the 2004 simulation, higher pumping rates yield simulated head differences that range between 8.64 and 12.4 ft. In profiles *A–A′* to *D–D′*, simulated potentiometric gradients range between 7.6 and 11.0 ft/mi near the Brunswick Cellulose well field and 3.6 ft/mi in profile *E–E′* oriented in a general north to south direction. The lower pumping rates for the 2015 Base Case simulation, in general, reduce the cone of depression near pumping centers and decrease simulated head differences along the profiles, which range from 7.70 to 9.42 ft. The simulated potentiometric gradients for the 2015 Base Case range between 6.7 and 9.8 ft/mi in profiles *A–A′* to *D–D′* located near the Brunswick Cellulose well field and 2.8 ft/mi in profile *E–E′*.

Simulated Water Budget

The simulated 2004 and 2015 Base Case water budgets consist of the following major components of inflow and outflow to the groundwater-flow system: (1) inflow from the general-head boundaries, (2) inflow across county boundaries, (3) outflow to the general-head boundary, (4) discharge to wells, and (5) outflow across county boundaries. The 2004 and 2015 Base Case flows were characterized using the MODFLOW postprocessor ZONEBUDGET (Harbaugh, 1990). Flow calculations were summarized by model layer and by zone within each layer.

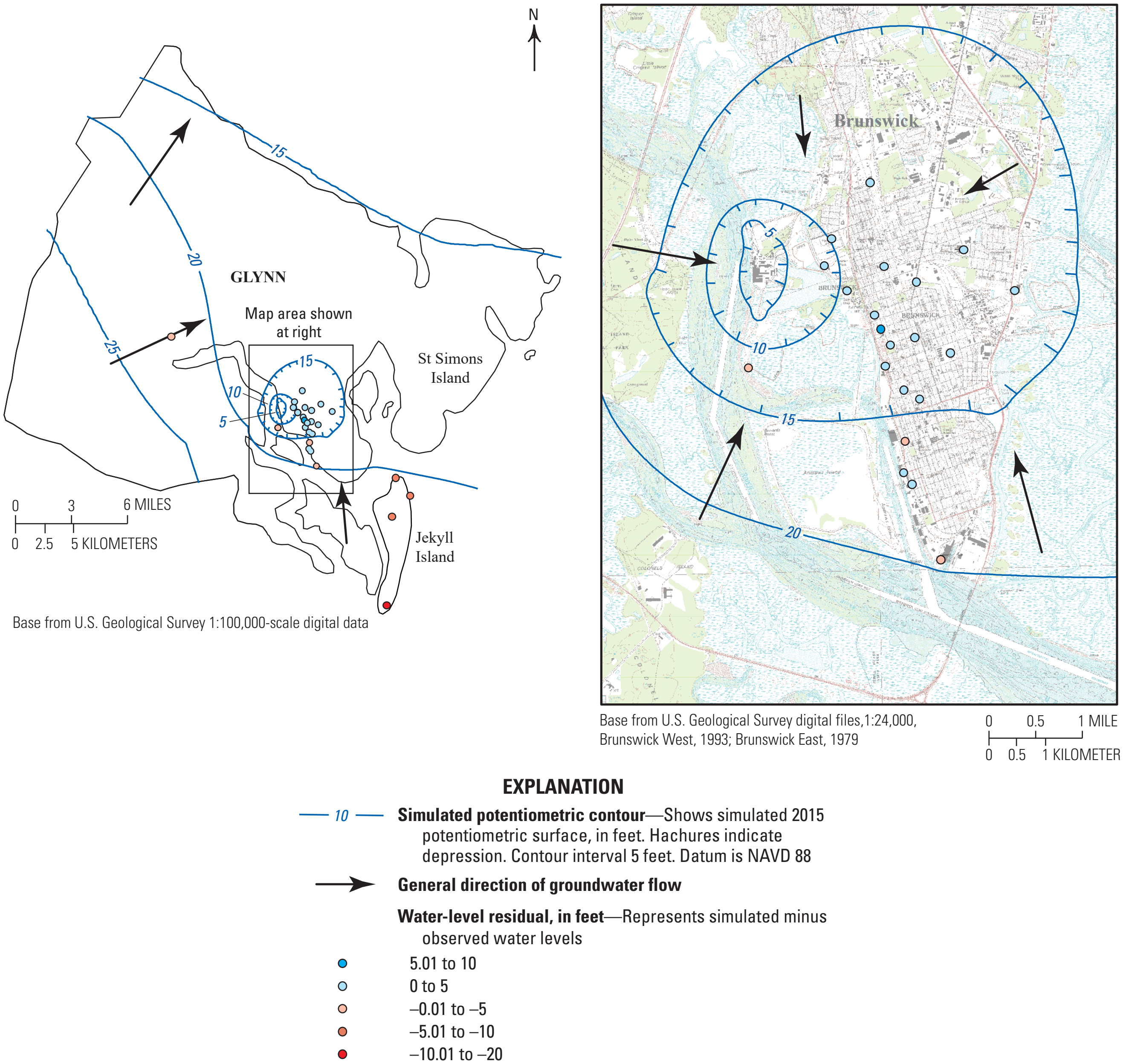


Figure 11. Maps showing simulated 2015 Base Case potentiometric surfaces and water-level residuals for model layer 7, upper water-bearing zone of the Upper Floridan aquifer, Glynn County and Brunswick area (enlargement), Georgia.

An analysis similar to that described for general-head boundaries in the Brunswick/Glynn County area indicates that specified-head boundaries located along the southern and southwestern model boundaries contribute greatly to the water budget (fig. 7). In the Brunswick/Glynn County area, simulated pumping totaled 55.2 Mgal/d during 2004 and 45.2 Mgal/d during 2015 Base Case. Outflows to the general-head boundary in model layer 1 of 5.8 and 6.3 Mgal/d (for simulated 2004 and 2015 Base Case conditions, respectively) exceeded inflows of 0.21 along the same boundary (fig. 14; table 8). For the 2004 simulation, 19.6 Mgal/d of pumping was assigned to model layer 7 (UWBZ of UFA) and 34.1 Mgal/d to model layer 9 (LWBZ of UFA). For the 2015 Base Case simulation, a determination was made to assign greater pumping of 31.2 Mgal/d to model layer 7 on the basis of depth of production wells in the study area. An additional 12.4 Mgal/d of pumping was assigned to model layer 9 on the basis of well information that includes five production wells that tap the LWBZ of the UFA.

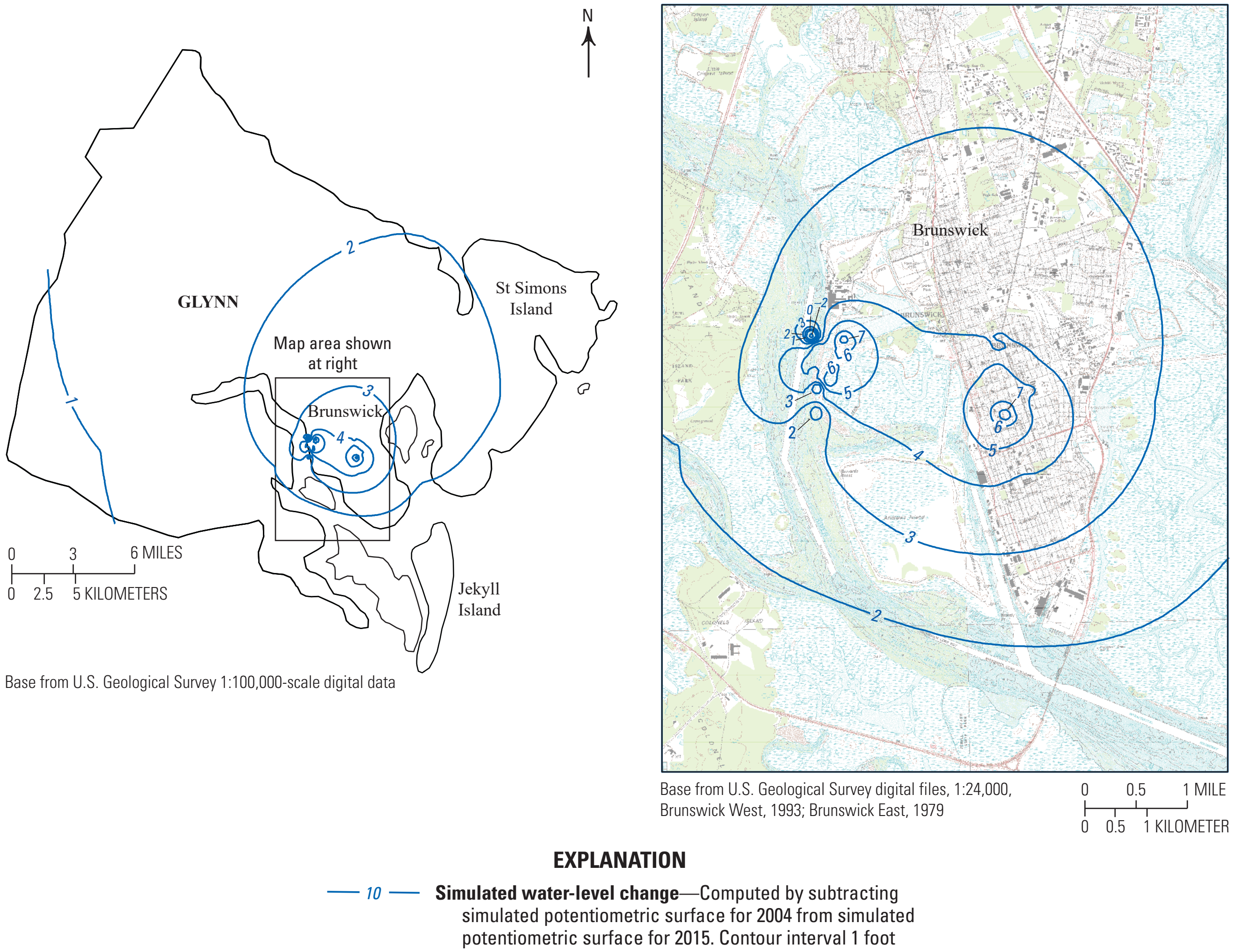


Figure 12. Maps showing simulated water-level change from 2004 to 2015 Base Case for model layer 7, upper water-bearing zone of Upper Floridan aquifer in the Brunswick/Glynn County area in Georgia.

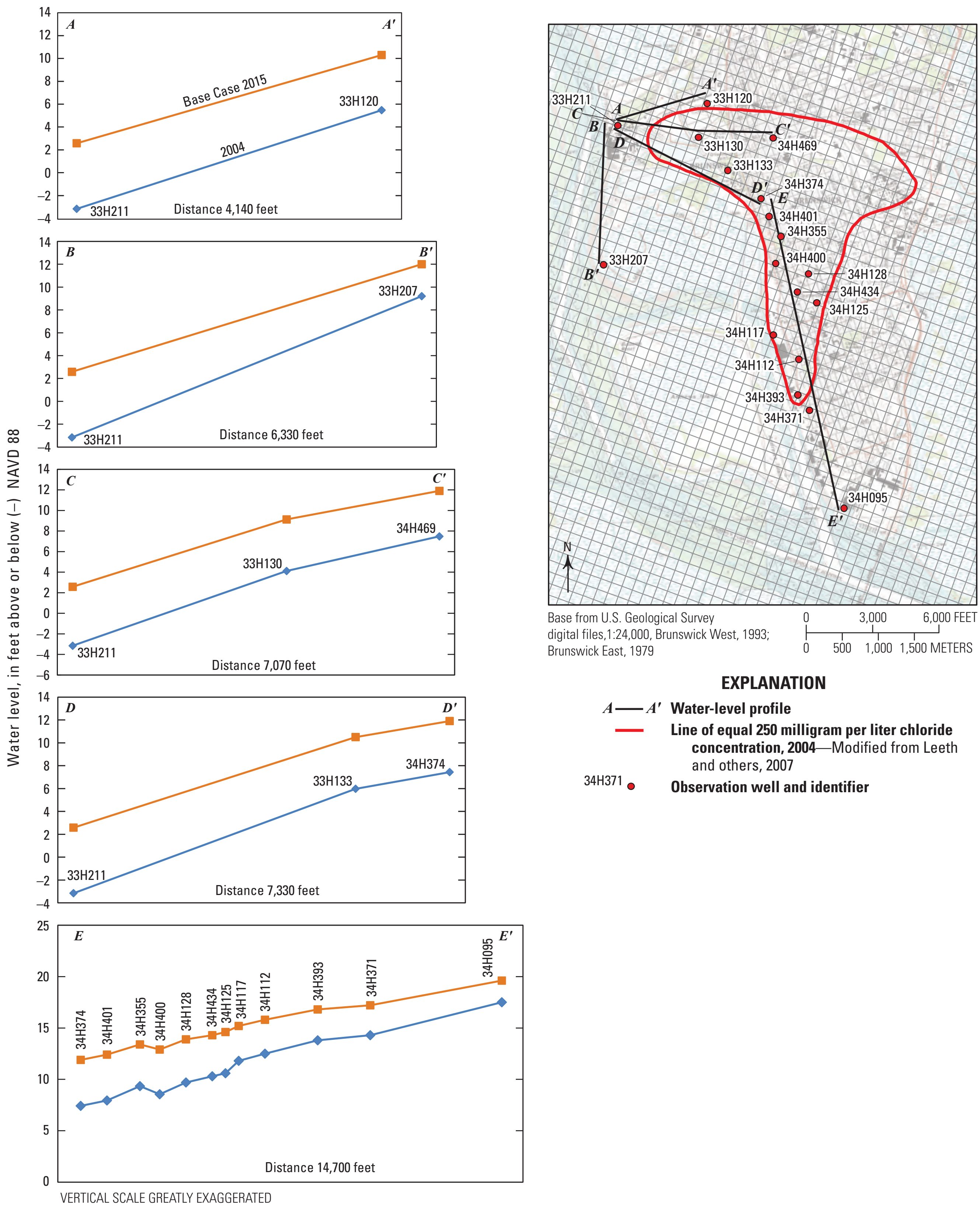


Figure 13. Graphs showing simulated potentiometric profiles near the chloride plume in the Upper Floridan aquifer near downtown Brunswick, Georgia, during 2004 and 2015 Base Case.

Table 6. Simulated and observed groundwater levels and water-level changes, 2004 and 2015 Base Case, for model layer 7, upper water-bearing zone of the Upper Floridan aquifer in the Brunswick/Glynn County area, Georgia.

[Simulated and observed groundwater levels are above or below (–) NAVD 88; observed values for 2004 are during June; observed values for 2015 are during October; see fig. 1–1 for well locations; —, no data]

Well identifier	Groundwater levels, in feet				Water-level change, in feet	
	2004 calibration		2015 Base Case calibration		2015 minus 2004	
	Simulated	Observed	Simulated	Observed	Simulated	Observed
33G002	22.40	23.48	23.70	—	1.30	—
33G008	22.20	23.16	23.60	—	1.40	—
33G024	24.20	29.87	25.40	—	1.20	—
33H120	5.48	3.08	10.30	7.98	4.82	4.90
33H130	4.12	2.18	9.13	6.83	5.01	4.65
33H133	5.97	3.77	10.50	8.20	4.53	4.43
33H177	23.90	28.20	25.10	—	1.20	—
33H180	9.20	—	13.00	10.10	3.80	—
33H193	20.50	22.38	22.10	24.95	1.60	2.57
33H207	9.21	8.09	12.00	13.30	2.79	5.21
33H211	–3.16	–4.16	2.58	—	5.74	—
33H213	–0.19	–1.72	5.23	—	5.42	—
34G002	17.90	22.40	20.00	—	2.10	—
34G003	21.60	25.90	23.00	—	1.40	—
34G009	21.30	38.70	22.50	39.77	1.20	1.07
34G016	19.40	28.30	20.80	28.80	1.40	0.50
34G017	18.70	26.10	20.30	26.30	1.60	0.20
34G020	20.60	30.10	21.90	31.10	1.30	1.00
34H062	8.54	—	13.10	11.40	4.56	—
34H095	17.50	17.90	19.60	20.50	2.10	2.60
34H112	12.50	12.90	15.80	15.90	3.30	3.00
34H117	11.80	10.50	15.20	—	3.40	—
34H125	10.60	12.40	14.60	11.80	4.00	–0.60
34H128	9.70	8.13	13.90	—	4.20	—
34H344	7.68	6.22	13.20	—	5.52	—
34H355	9.34	8.46	13.40	12.50	4.06	4.04
34H371	14.30	15.50	17.20	16.20	2.90	0.70
34H373	8.37	3.98	13.10	8.81	4.73	4.83
34H374	7.43	7.20	11.90	10.00	4.47	2.80
34H393	13.80	14.60	16.80	16.70	3.00	2.10
34H400	8.56	4.34	12.90	8.07	4.34	3.73
34H401	7.95	2.53	12.40	6.92	4.45	4.39
34H424	7.86	—	12.60	12.40	4.74	—
34H434	10.30	6.13	14.30	12.60	4.00	6.47
34H469	7.48	6.61	11.90	11.50	4.42	4.89
34H514	8.50	—	13.60	12.60	5.10	—
34H552	8.99	—	13.30	10.40	4.31	—

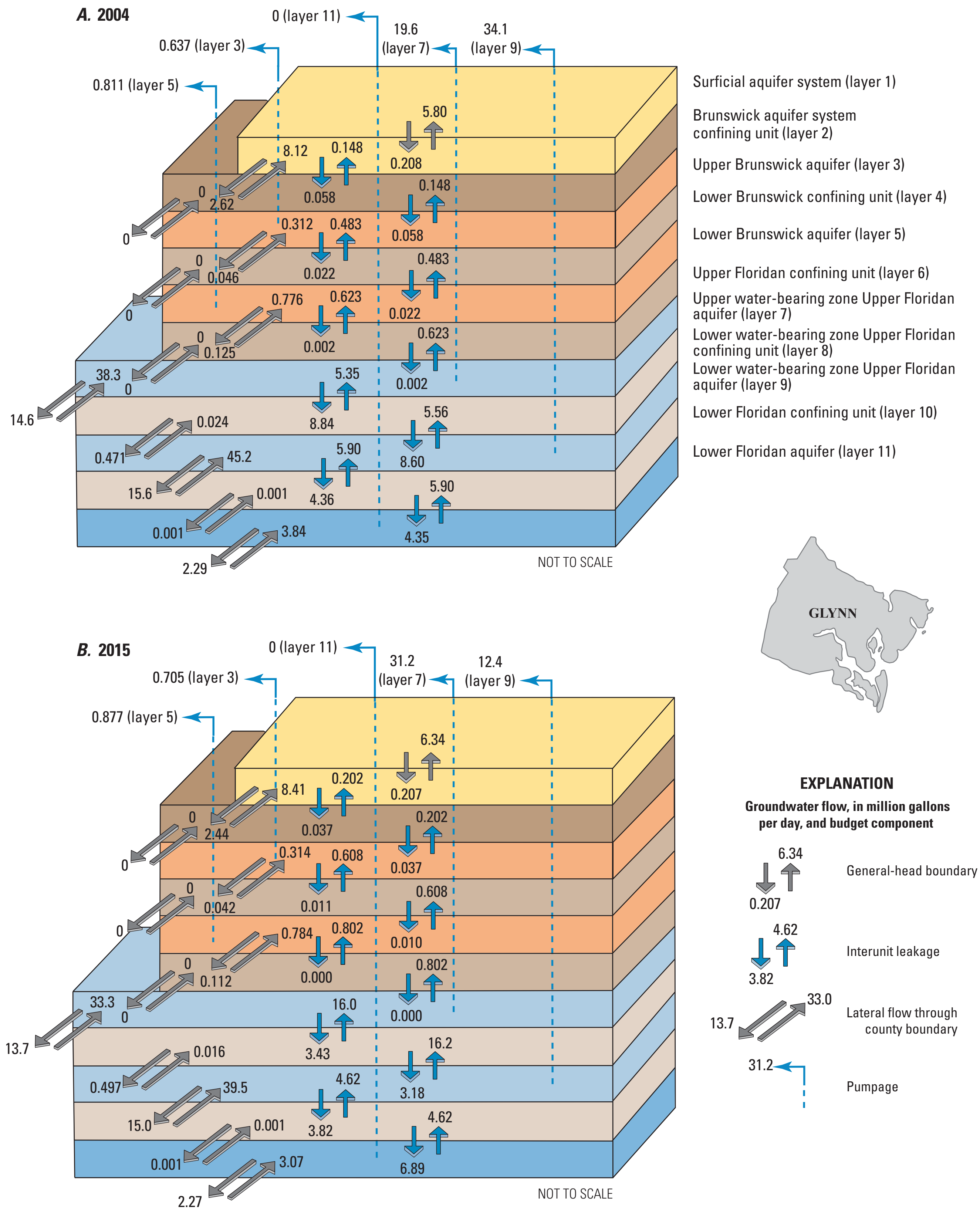


Figure 14. Schematic diagram showing simulated water budgets in Glynn County, Georgia, during (*A*) 2004 and (*B*) 2015 Base Case.

Table 7. Simulated head difference and horizontal potentiometric gradients for 2004 and 2015 Base Case along profiles *A–A′*, *B–B′*, *C–C′*, *D–D′*, and *E–E′* in the upper water-bearing zone of the Upper Floridan aquifer in the downtown area of Brunswick, Georgia.

[Horizontal hydraulic-head gradients calculated using simulated heads at the endpoints of profile; see fig. 13 for location of profiles]

Profile	Number of wells	Distance, in miles	Simulated head difference, in feet		Simulated potentiometric gradient, in feet per mile	
			2004	2015	2004	2015
A–A′	2	0.78	8.64	7.72	11.0	9.8
B–B′	2	1.20	12.37	9.42	10.3	7.9
C–C′	3	1.34	10.64	9.32	7.9	7.0
D–D′	3	1.39	10.59	9.32	7.6	6.7
E–E′	12	2.78	10.07	7.70	3.6	2.8

Table 8. Flow-budget components for 2004 and 2015 Base Case in the Brunswick/Glynn County area of Georgia.

[Results from MODFLOW model; all values in million gallons per day; —, not applicable]

Model layer	From general-head boundary, onshore	Across county boundaries	Total	To general-head boundary, onshore	Across county boundaries	Discharge to wells	Total
	2004 inflow			2004 outflow			
1	0.21	8.12	8.33	5.80	2.62	—	8.42
2	—	—	—	—	—	—	—
3	—	0.31	0.31	—	0.05	0.64	0.69
4	—	—	—	—	—	—	—
5	—	0.78	0.78	—	0.12	0.81	0.93
6	—	—	—	—	—	—	—
7	—	38.31	38.31	—	14.56	19.64	34.20
8	—	0.02	0.02	—	0.47	—	0.47
9	—	45.19	45.19	—	15.64	34.14	49.78
10	—	—	—	—	—	—	—
11	—	3.84	3.84	—	2.29	0.00	2.29
Total, all units	**0.21**	**96.57**	**96.78**	**5.80**	**35.75**	**55.23**	**96.78**
Percentage of total flow	**0.2**	**99.8**	**100.0**	**6.0**	**36.9**	**57.1**	**100.0**
	2015 Base Case inflow			2015 Base Case outflow			
1	0.21	8.42	8.63	6.34	2.44	—	8.78
2	—	—	—	—	—	—	—
3	—	0.31	0.31	—	0.04	0.71	0.75
4	—	—	—	—	—	—	—
5	—	0.78	0.78	—	0.11	0.88	0.99
6	—	—	—	—	—	—	—
7	—	33.26	33.26	—	13.74	31.23	44.97
8	—	0.02	0.02	—	0.50	—	0.50
9	—	39.53	39.53	—	14.95	12.38	27.33
10	—	—	—	—	—	—	—
11	—	3.07	3.07	—	2.27	0.00	2.27
Total, all units	**0.21**	**85.39**	**85.60**	**6.34**	**34.05**	**45.20**	**85.59**
Percentage of total flow	**0.2**	**99.8**	**100.0**	**7.4**	**39.8**	**52.8**	**100.0**

Groundwater-Management Scenarios

The revised model is used primarily to simulate groundwater flow in close proximity to pumping centers located near the area of chloride contamination in the city of Brunswick. The grid of the original model was refined to finer resolution in these areas to evaluate simulated horizontal-head gradients and cones of depressions near pumping centers. As a 2015 Base Case simulation for the current study, the revised model was updated to include pumping rates during October 2015 for selected production wells in the Brunswick/St. Simons Island area (fig. 15; table 9). The time of the 2015 Base Case simulation period was selected because of availability of water-level measurements during October 2015 in the Brunswick/Glynn County area. The model calibration of the 2015 Base Case simulation is a good indicator that residuals (simulated heads minus observed heads) are within reasonable ranges to allow further evaluation of a variety of groundwater-management scenarios. The focus of the scenarios is the addition of pumping for new hypothetical wells in areas of projected growth along with adjustments in pumping rates for existing production wells and evaluation of simulated changes in hydraulic head (water levels) and hydraulic-head gradients near the chloride plume. Previous analyses for the original and revised model determined that simulated heads are most sensitive to changes in pumping rates followed by changes in horizontal hydraulic conductivity (Payne and others, 2005; Cherry, 2015). Calibration of the 2015 Base Case using residuals confirms model sensitivity to changes in pumping because no other changes were made. Horizontal and vertical hydraulic-head gradients determine local groundwater-flow directions and influence rates of groundwater movement and possible migration of the chloride plume.

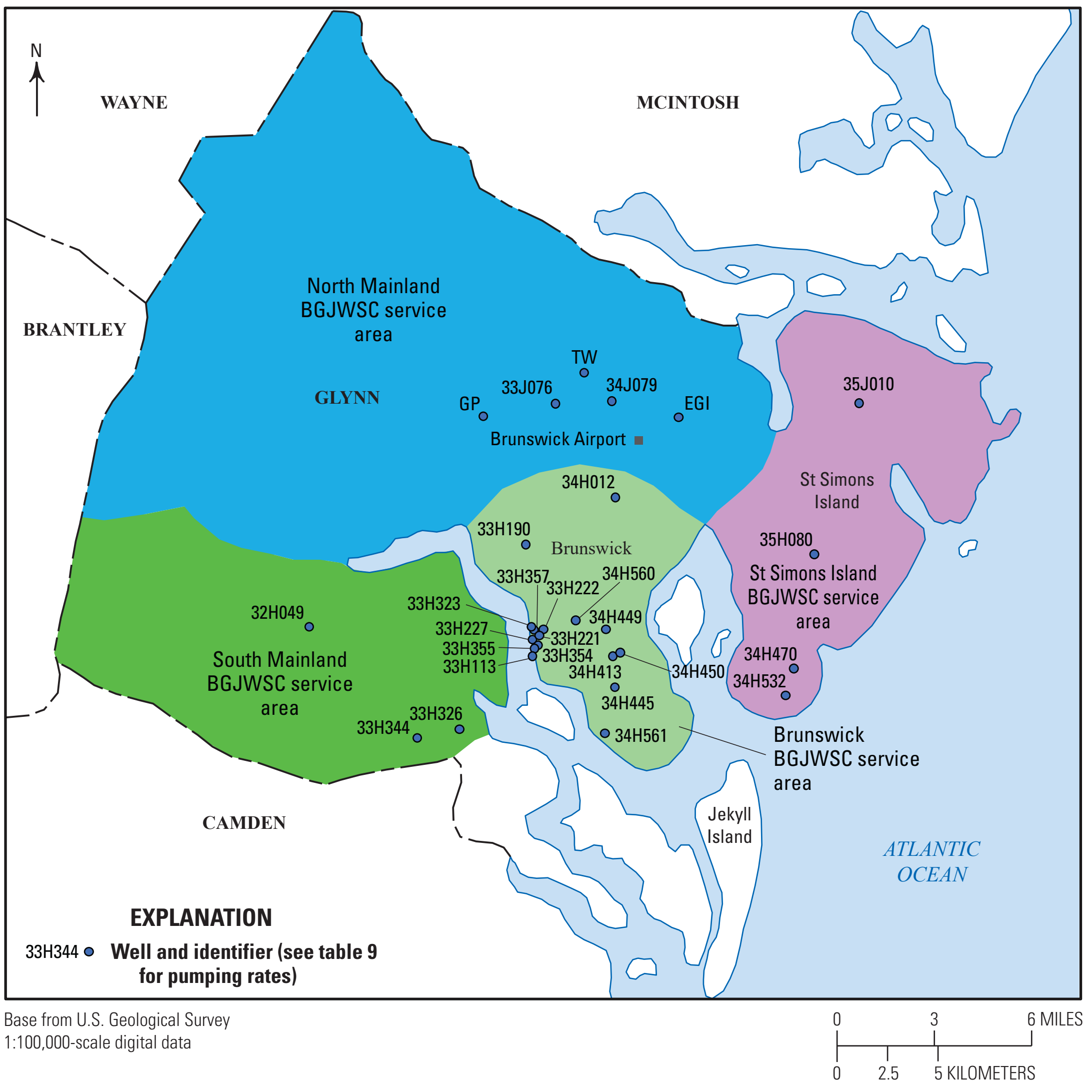


Figure 15. Map showing location of Brunswick-Glynn County Joint Water and Sewer Commission service areas (shaded) and production wells used for the 2015 Base Case simulation and groundwater-management scenarios.

Table 9. Simulated pumping at selected production wells for the 2015 Base Case simulation and model Scenarios A–E.

[BAS, Brunswick aquifer system; Brunswick Cellulose, formerly Brunswick Pulp & Paper Company; BGJWSC, Brunswick–Glynn County Joint Water and Sewer Commission; Pinova, Pinova Inc.–formerly Hercules Inc.; LWBZ, lower water-bearing zone of Upper Floridan aquifer (UFA); SSI, St. Simons Island; UWBZ, upper water-bearing zone of UFA; —, not applicable; *, pumping rates adjusted from Scenario D1 (12.5 percent), Scenario D2 (25 percent), and Scenario D3 (50 percent) of 2015 Base Case amount; see figure 15 for well locations]

Well identifier	Well name	Aquifer	Latitude (Decimal degrees (NAD 83))	Longitude (Decimal degrees (NAD 83))	2015 Base Case	Simulated pumping rate, in million gallons per day — Scenario A	B	C	D1–D3	E
North Mainland service area										
34J079	BGJWSC Golden Isles 1	BAS	31.278139	–81.476972	0.301	0.301	0.301	0.301	0.301	0.301
33J076	BGJWSC Golden Isles 2	BAS	31.277681	–81.506469	0.229	0.229	0.229	0.229	0.229	0.229
TW	BGJWSC Tradewinds/Altma	UWBZ	31.291086	–81.491107	0.000	0.750	0.750	0.000	0.000	0.000
EGI	BGJWSC Eastgate/Golden Isles	UWBZ	31.270275	–81.442528	0.000	0.000	0.750	0.000	0.000	0.000
GP	BGJWSC Georgia Pacific	UWBZ	31.272625	–81.544322	0.000	0.000	0.750	0.000	0.000	0.000
City of Brunswick service area										
34H012	BGJWSC FLETC	UWBZ	31.235278	–81.476111	0.437	0.911	1.197	0.437	0.437	0.437
33H190	BGJWSC I-95	UWBZ	31.215167	–81.523556	0.801	1.275	0.981	0.801	0.801	0.801
34H560	BGJWSC Brunswick Villa	UWBZ	31.180889	–81.498528	0.947	0.000	0.769	0.947	0.947	0.947
34H449	BGJWSC Goodyear Park	UWBZ	31.176528	–81.482750	0.790	0.790	1.290	0.790	0.790	0.790
33H323	Brunswick Cellulose 4	UWBZ	31.178394	–81.521406	6.650	6.650	6.650	0.000	1.662*	6.650
33H222	Brunswick Cellulose 7	UWBZ/LWBZ	31.177006	–81.515242	0.730	0.730	0.730	0.000	0.182*	0.730
33H221	Brunswick Cellulose 8	UWBZ/LWBZ	31.174328	–81.517444	5.860	5.860	5.860	0.000	1.465*	5.860
33H227	Brunswick Cellulose 1	UWBZ	31.172564	–81.521014	3.200	3.200	3.200	0.000	0.800*	3.200
33H354	Brunswick Cellulose 2	UWBZ/LWBZ	31.169950	–81.518172	1.030	1.030	1.030	0.000	0.258*	1.030
33H355	Brunswick Cellulose 5	UWBZ	31.168600	–81.520194	5.950	5.950	5.950	0.000	1.488*	5.950
33H113	Brunswick Cellulose 6	UWBZ/LWBZ	31.165217	–81.521147	4.520	4.520	4.520	0.000	1.130*	4.520
33H357	Brunswick Cellulose 3 (new)	UWBZ	31.176996	–81.520088	0.000	0.000	0.000	0.000	0.000	5.000
34H450	Pinova V	UWBZ	31.166114	–81.475419	1.410	1.410	1.410	0.000	0.352*	1.410
34H413	Pinova S	UWBZ/LWBZ	31.164433	–81.479314	2.000	2.000	2.000	0.000	0.500*	2.000
34H445	BGJWSC Howard Coffin Park	UWBZ	31.150667	–81.478583	0.730	0.730	1.230	0.730	0.730	0.730
34H561	King & Prince Seafood	UWBZ	31.130194	–81.484500	0.110	0.110	0.110	0.110	0.110	0.110
St. Simons Island service area										
35J010	BGJWSC Hampton South	UWBZ	31.274833	–81.347694	0.040	0.040	0.400	0.040	0.040	0.040
35H080	BGJWSC Harrington	UWBZ	31.208083	–81.373167	0.630	0.630	0.980	0.630	0.630	0.630
34H470	BGJWSC SSI Airport	UWBZ	31.157306	–81.385083	1.016	1.016	1.016	1.016	1.016	1.016
34H532	BGJWSC Mallory	UWBZ	31.145306	–81.389583	0.856	0.856	0.856	0.856	0.856	0.856
South Mainland service area										
32H049	BGJWSC Brookman	UWBZ	31.180389	–81.637500	0.000	0.000	0.790	0.000	0.000	0.000
33H326	BGJWSC Fancy Bluff	BAS	31.133278	–81.560222	0.252	0.252	0.252	0.252	0.252	0.252
33H344	BGJWSC Exit-29 Southport	UWBZ	31.129889	–81.582194	0.001	0.001	0.790	0.001	0.001	0.001

Data sources: 2015 Base Case pumping rates were obtained to estimate groundwater withdrawal from the Upper Floridan aquifer during October 2015. B. Simmons (Brunswick/Glynn County Joint Water and Sewer Commission, written commun., 2015) provided estimates for BGJWSC public–supply wells. J.H. Dickens (Brunswick Cellulose Inc., written commun., 2017) provided estimates for industrial wells located at Brunswick Cellulose. M.A. Gray (Pinova Inc., written commun., 2017) provided estimates for industrial wells located at Pinova.

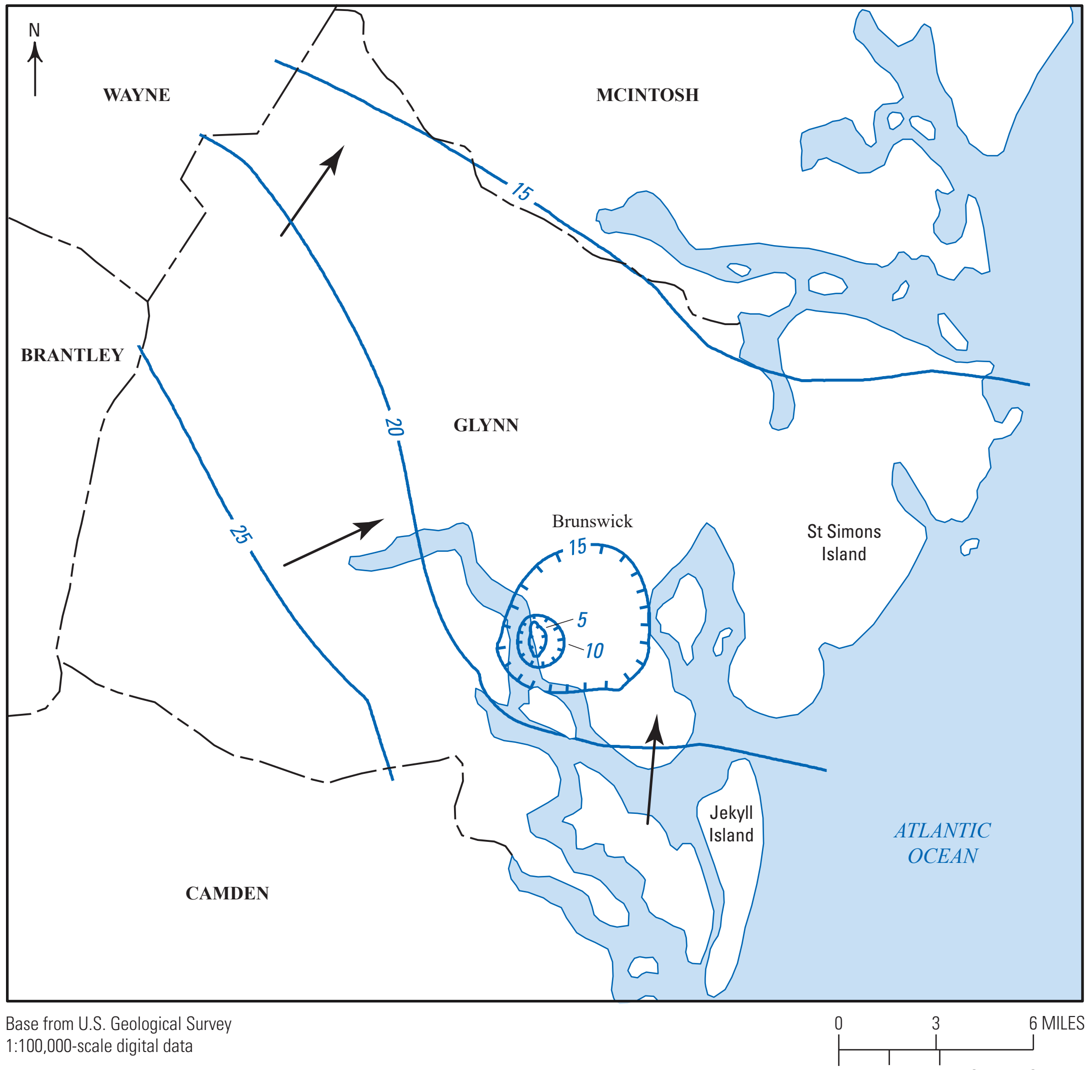
The revised calibrated 2015 Base Case regional model with local grid refinement was used to simulate the potential effect of seven distinct pumping scenarios on local groundwater flow in the Brunswick/St. Simons Island area. Alteration of hydraulic-head gradients near the chloride plume could change local groundwater-flow directions and allow solute movement toward nearby public-supply wells. The 2015 Base Case simulation represents local pumping rates during October 2015 calibrated by comparison of simulated to observed heads. In addition, the 2015 Base Case simulation is used as the basis to assess changes to the groundwater-flow system for each of the seven groundwater-management scenarios. Two scenarios (Scenarios A and B) simulate additional pumping at existing public-supply wells located near the chloride plume with the addition of planned public-supply wells located to the north of Brunswick. Scenario C simulates the event of a shutdown at two industrial facilities (Brunswick Cellulose and Pinova) and the resulting deactivation of nine production wells pumping a total of 31.3 Mgal/d during 2015. Scenario D (three scenarios) simulates 12.5, 25, and 50 percent (designated D1, D2, and D3, respectively) of the 31.3 Mgal/d 2015 Base Case pumping rates at Brunswick Cellulose and Pinova. This scenario can help determine pumping rates that may reverse horizontal hydraulic-head gradients toward pumping centers and allow groundwater flow across the Brunswick peninsula in a northeasterly direction. Scenario E simulates an additional 5 Mgal/d of pumping at a recently constructed production well within the Brunswick Cellulose well field.

Scenario A

Scenario A simulates deactivation of the Brunswick Villa public-supply well (34H560) and redistribution of the pumping rate between two nearby public-supply wells (33H190 and 34H012). Scenario A simulates projected water demand to the year 2020 on the basis of anticipated growth in the North Mainland service area. The Brunswick Villa production well (34H560) is located outside the chloride plume area in the northern part of Brunswick (fig. 1*B*) and is influenced by pumping at the Brunswick Cellulose well field. The Brunswick Villa well was constructed in 1943 and originally tapped the UWBZ and LWBZ of the UFA (Cherry and others, 2011). Chloride concentrations steadily increased in the well from near background levels (20 to 30 mg/L) during June 2000 (32.0 mg/L) to 96 mg/L during October 2015 (Cherry and Peck, 2017). Modifications were made to the well in July 2015 to reduce water inflow from the deeper part of the aquifer. The bottom of the well, depths of 942–724 ft, was sealed with concrete grout, thereby eliminating water production from a 218-ft zone that yields higher chloride water. This approach effectively lowered the chloride concentration for a short period, but then the increases in chloride concentrations continued, which was an indication of either lateral movement of chloride in the UWBZ from the plume or the continued upward migration of chloride from the LWBZ. The BGJWSC recommended, as part of its Water and Sewer Master Plan Update 2015–2035, decommissioning the Brunswick Villa production well by 2020 (Applied Technology & Management, 2016). Scenario A simulates redistribution of pumping from the Brunswick Villa well (34H560; 0.947 Mgal/d) between I–95 and the Federal Law Enforcement Training Center (FLETC) public-supply wells (33H190 and 34H012). In addition, the BGJWSC Master Plan projects additional water demand in the North Mainland service area, which is planned to be met with the construction of a public-supply well near the Tradewinds/Altama developments located northwest of the Brunswick airport (Applied Technology & Management, 2016). Scenario A simulates the new public-supply well using a pumping rate of 0.75 Mgal/d.

The simulated results from Scenario A indicate minor water-level declines with groundwater-flow directions remaining nearly the same as the 2015 Base Case condition. For the Scenario A simulation, the potentiometric surface map of model layer 7 (UWBZ of UFA) indicates general groundwater-flow directions are from southwest to northeast in the southwestern part of the county and from south to north near Jekyll Island (fig. 16). Near the Brunswick peninsula, pumping in the Brunswick Cellulose and Pinova well fields creates a cone of depression with water levels below 15 ft, which is evident by the 5-ft and 10-ft contours surrounding the Brunswick Cellulose well field. The tight spacing of the water-level contours indicates steep horizontal-head gradients with groundwater-flow directions toward the center of pumping at Brunswick Cellulose.

The simulated water-level changes for Scenario A when compared to 2015 Base Case indicate a range from +0.3 ft to –0.9 ft with tight concentric contours indicating locations of wells where pumping has been modified. The location of the Brunswick Villa production well is the center near the +0.3 ft contour. For Scenario A, this simulated recovery was due to changes in pumping from the 2015 Base Case pumping rate of 0.947 Mgal/d to 0 Mgal/d (table 9). The planned construction of a BGJWSC public-supply well (TW) near the Tradewinds/Altama development is simulated in Scenario A, using a pumping rate of 0.75 Mgal/d (fig. 15). The simulated water-level change in model layer 7 (UWBZ of UFA) near the planned production well is –0.9 ft. The –0.1-ft water-level change contour extends from the southern tip of St. Simons Island westward over the Brunswick peninsula and remains outside the chloride plume area located near downtown Brunswick. In the chloride plume area, simulated water-level changes are minor, ranging from +0.1 ft (wells 33H133 and 34H469) to –0.1 ft (wells 34H434, 34H125, and 34H393; table 10).

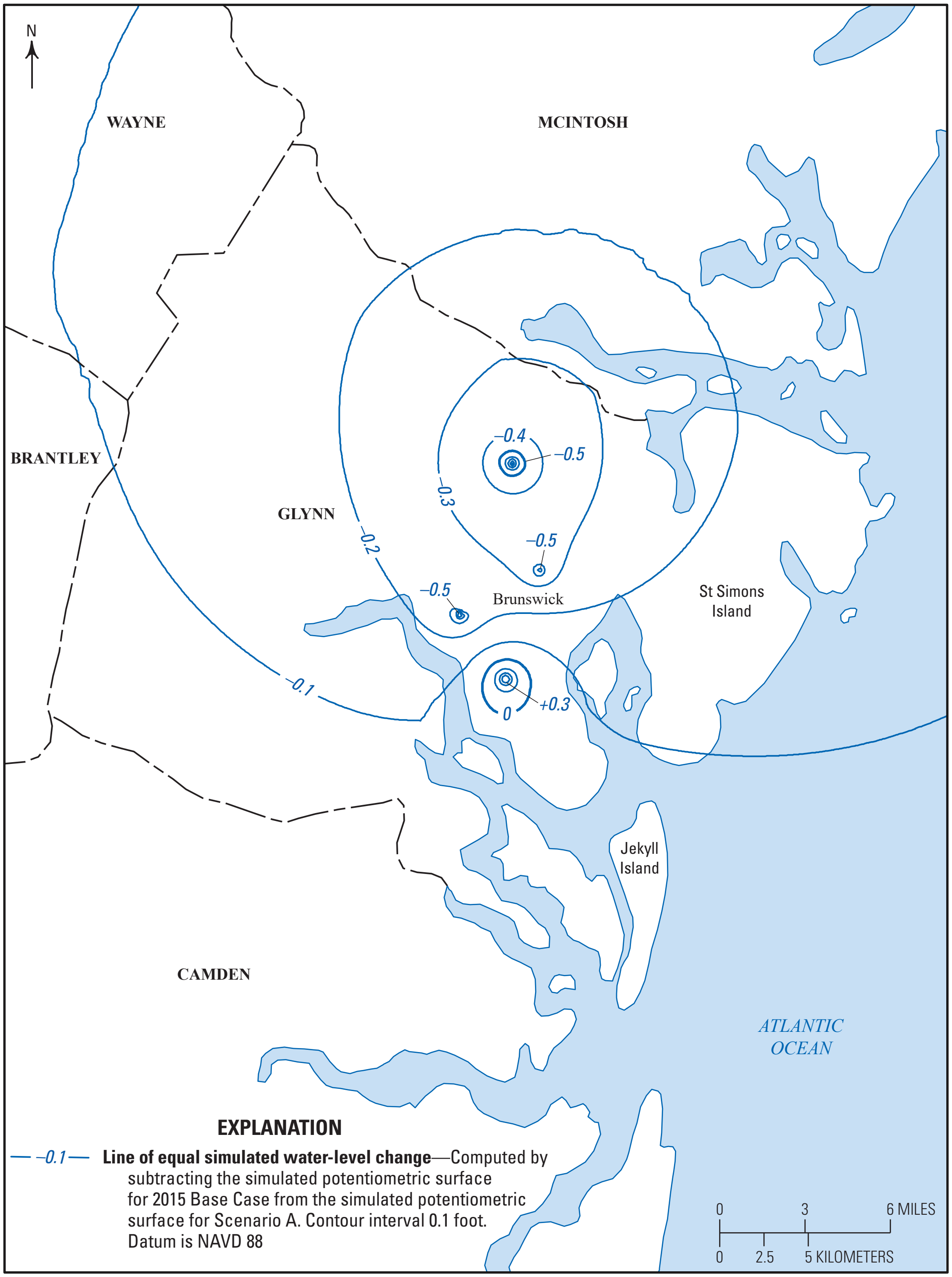


EXPLANATION

10 — **Simulated potentiometric contour**—Shows simulated Scenario A potentiometric surface, in feet. Hachures indicate depression. Contour interval 5 feet. Datum is NAVD 88

→ **General direction of groundwater flow**

Figure 16. Map showing Scenario A simulated potentiometric surface for model layer 7, upper water-bearing zone of the Upper Floridan aquifer, Brunswick/Glynn County area of Georgia.



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

Figure 17. Map showing simulated water-level change from 2015 Base Case to Scenario A in model layer 7, upper water-bearing zone of the Upper Floridan aquifer, Brunswick/Glynn County area of Georgia.

Scenario B

Scenario B represents the additional projected pumping required to meet the demand for public supply through the year 2035. The BGJWSC had consulting firms prepare a 5-year update to the BGJWSC Water and Sewer Master Plan for the 20-year planning period 2015–35 (Applied Technology & Management, 2016). The BGJWSC water and sewer systems incorporate four service areas: the North Mainland, the City of Brunswick, the South Mainland, and St. Simons Island. According to the Master Plan, the population in the four service areas is expected to increase from 61,684 in 2015 to 118,556 by the year 2035, with the water demand for public supply increasing by 6.48 Mgal/d. Currently (2015), the BGJWSC water distribution system has 11 production wells tapping the UFA and another 3 open to the Brunswick aquifer system (table 9). The North Mainland service area includes four water production facilities, with two wells tapping the Brunswick aquifer system and another two tapping the UWBZ of the UFA that have been used only in emergencies and are not included in table 9. According to the Master Plan, the water demand will increase 2.43 Mgal/d by the year 2035 due to expected growth in the North Mainland service area. This projected demand exceeds the permitted capacity, but the recently completed interconnection between the City of Brunswick and North Mainland service areas will likely extend the time needed to tap additional water sources (Applied Technology & Management, 2016). In the North Mainland service area, the Scenario B simulation adds the proposed Tradewinds/Altama production well (TW) at a pumping rate of 0.75 Mgal/d (Scenario A) along with the proposed UFA production wells at Eastgate/Golden Isles (EGI) and Georgia Pacific (GP) each with an estimated pumping rate of 0.75 Mgal/d (fig. 15). Because the Brunswick aquifer system production wells in the North Mainland service area were pumping at rates near the sustainable yield of the aquifer during 2015, pumping was not increased for Scenario B. According to the Master Plan, the City of Brunswick service area will need an additional 1.76 Mgal/d from the UFA by the year 2035, with the increase in pumping for Scenario B distributed equally between the BGJWSC FLETC, I–95, Goodyear Park, and Howard Coffin Park public-supply wells (34H012, 33H190, 34H449, and 34H445; table 9). These same projections indicate an additional 0.71 Mgal/d will be needed from the UFA in the St. Simons Island service area, with the increase in pumping for Scenario B distributed between BGJWSC Hampton South and Harrington UFA production wells (35J010 and 35H080). The South Mainland service area has two active production wells tapping the UWBZ of the UFA and another well open to the Brunswick aquifer system with an estimated 1.58 Mgal/d of groundwater required by the year 2035. This additional demand will be met by increasing pumping rates at BGJWSC Brookman and Exit-29 Southport UFA production wells (32H049 and 33H344).

The simulated results from Scenario B indicate groundwater-flow directions shifting to a west to east component near new production wells in the BGJWSC North Mainland service area. For Scenario B, the potentiometric surface map (5-ft contours) of model layer 7, the UWBZ of the UFA, indicates general groundwater-flow directions from southwest to northeast in the western part of the county and from south to north near Jekyll Island (fig. 18). The shift in the 15-ft contour shows that a portion of groundwater flow is redirected toward the Brunswick peninsula and pumping centers located near downtown Brunswick. Near the Brunswick peninsula, movement of groundwater is from northeast to southwest toward a cone of depression in the Brunswick Cellulose well field, which is evident by the 5-ft and 10-ft contours. The tight spacing of these water-level contours indicates steep horizontal-head gradients and a substantial area of influence for active production wells.

The simulated water-level changes for Scenario B compared to 2015 Base Case indicate a range from –0.6 ft to –1.8 ft for model cells within Glynn County (fig. 19; table 10). The simulated increase in pumping is due to projected population growth to the year 2035 with the water demand for public supply increasing by 6.48 Mgal/d. The concentric contours (–1.0, –1.4, –1.6, and –1.8 ft) identify simulated production well locations and show local drawdown caused by increased pumping (fig. 19). The water-level change contours of –1.8 ft are located north of Brunswick where three public-supply wells are proposed to meet future water demand. On St. Simons Island, combined simulated increases in pumping by BGJWSC at Hampton South (well 35J010) and Harrington (well 35H080) of 0.71 Mgal/d produce local simulated water-level changes of –1.4 ft. The –1.0 ft water-level change contour extends offshore near St. Simons Island and covers the southern part of McIntosh County and western part of Glynn County. Near the chloride plume in downtown Brunswick, simulated increases in pumping at BGJWSC Goodyear Park and Howard Coffin Park wells (34H449 and 34H445) generate local simulated water-level changes of –1.7 ft (well 34H552; table 10). The simulated water-level change within the chloride plume area generally ranges between –1.0 and –1.5 ft.

Simulated potentiometric gradients for Scenario B in the five potentiometric profiles (*A–A′* to *E–E′*) constructed in close proximity to the chloride plume show horizontal hydraulic-head gradients similar to those of the 2015 Base Case simulation. A comparison of simulated heads for the 2015 Base Case and Scenario B along constructed profiles *A–A′* to *E–E′* show decreased heads as a result of higher pumping rates. The simulated head differences are calculated using the simulated heads at the endpoints for each of the profiles (table 10). For the Scenario B simulation, higher pumping rates yield simulated head differences that range between 7.60 and 9.59 ft. In profiles *A–A′* to *D–D′*, simulated potentiometric gradients range between 6.6 and 9.7 ft/mi near the Brunswick Cellulose well field and 2.9 ft/mi in profile *E–E′*, oriented in a general south to north direction. The higher pumping rates for Scenario B, in general, reduce simulated heads with potentiometric gradients remaining similar to the 2015 Base Case because of changes in pumping occurring away from the downtown Brunswick area.

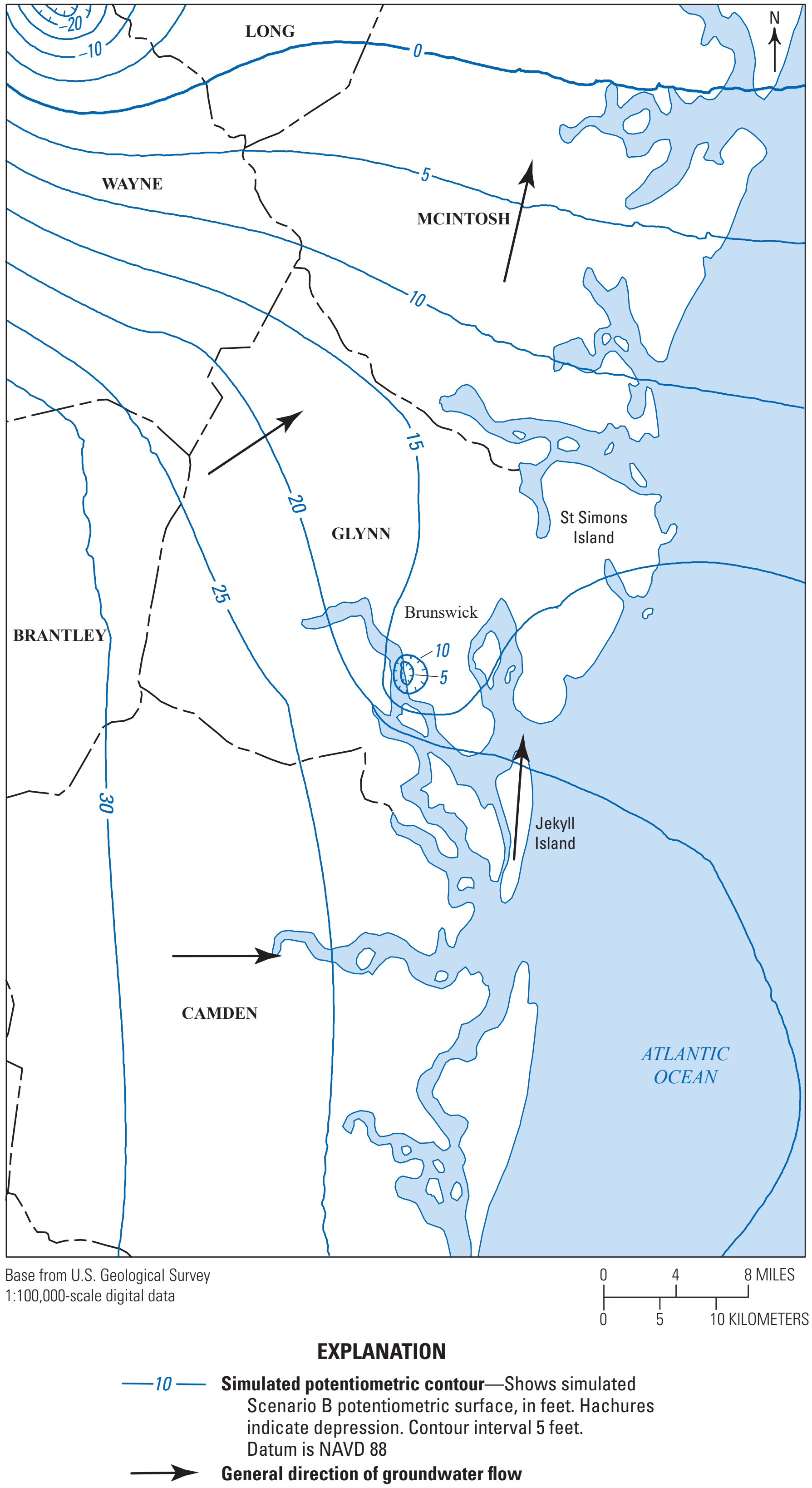
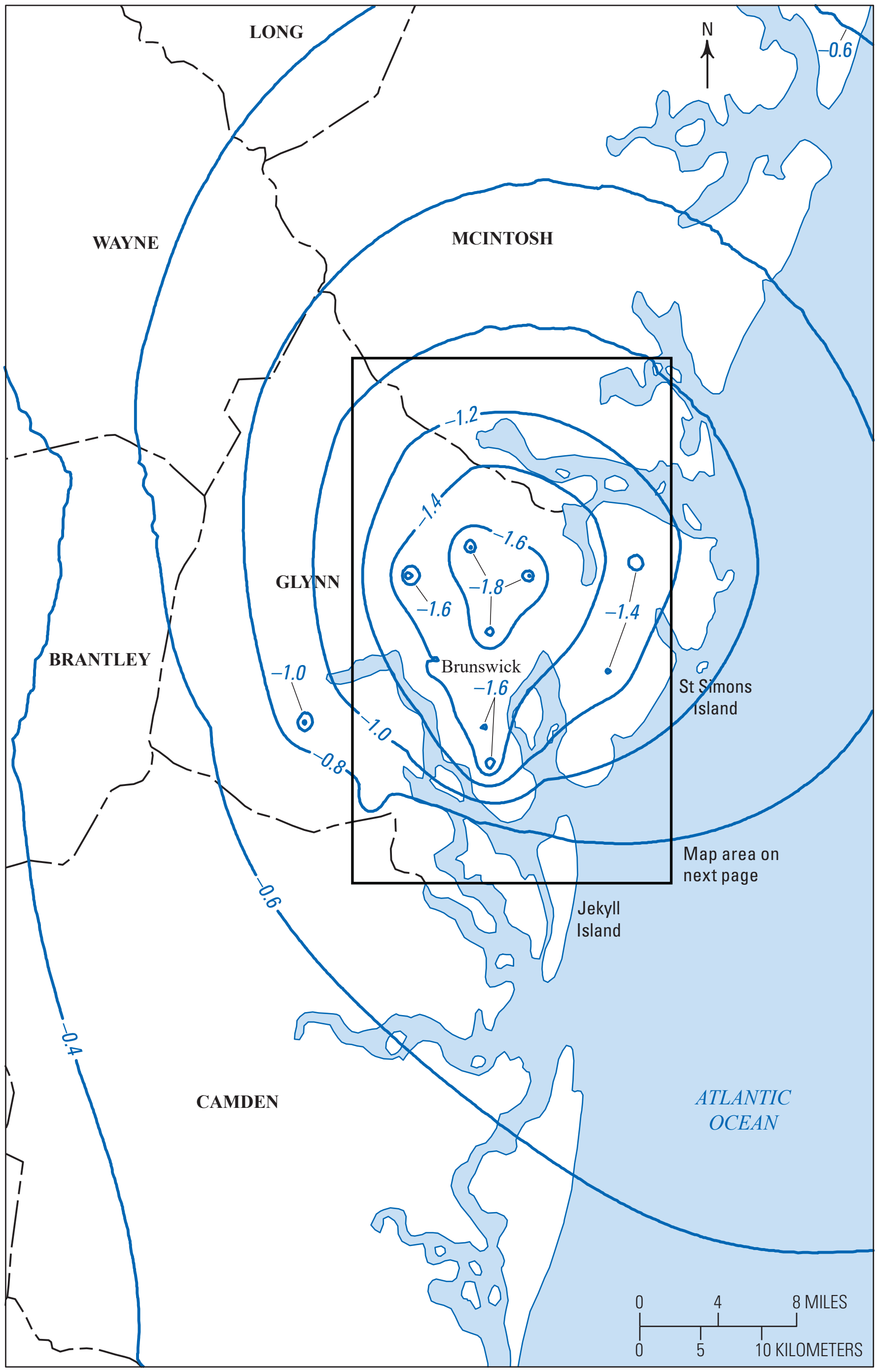


Figure 18. Map showing Scenario B simulated potentiometric surface for model layer 7, upper water-bearing zone of the Upper Floridan aquifer, Brunswick/Glynn County area of Georgia.

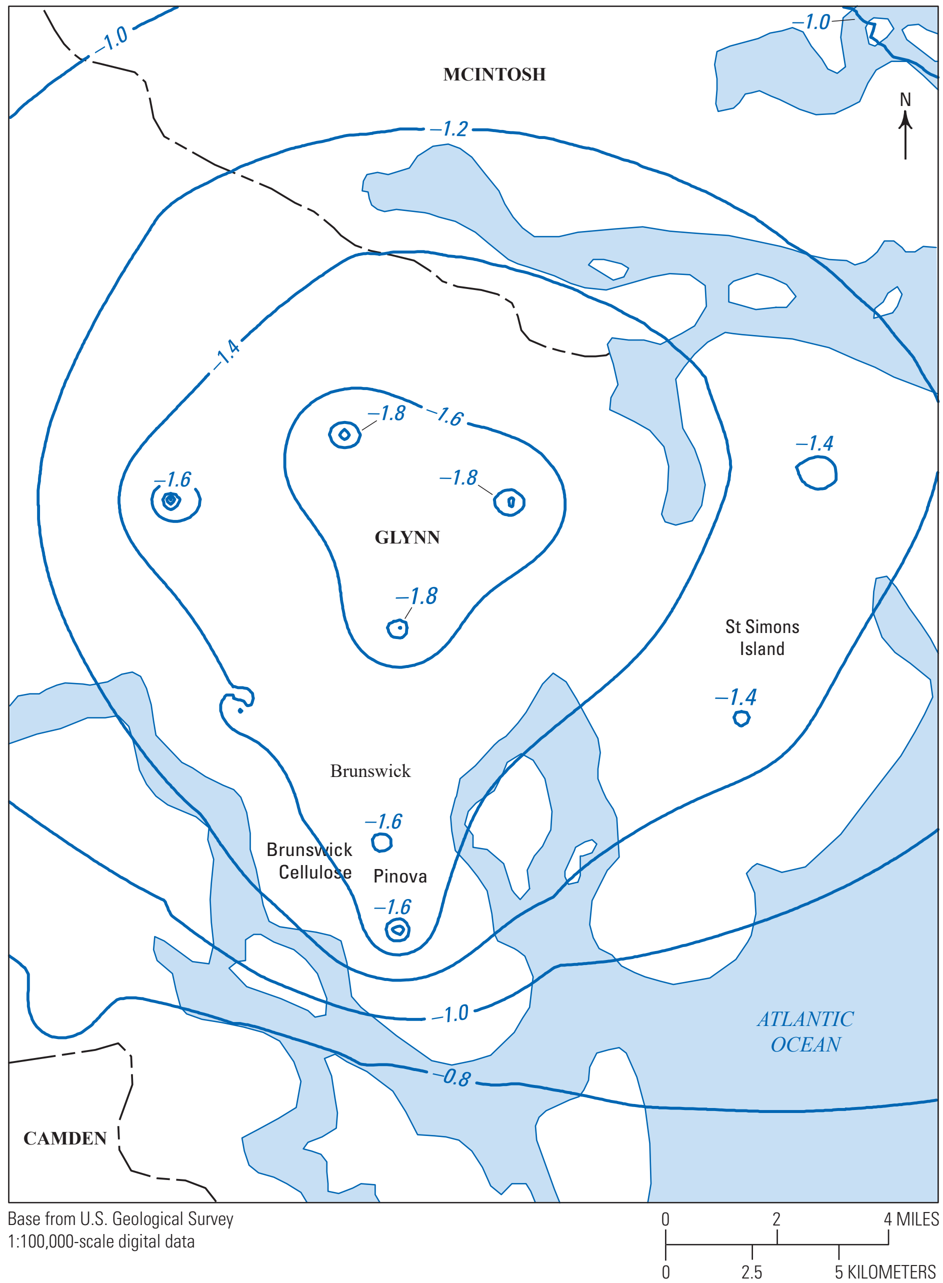


Base from U.S. Geological Survey
1:100,000-scale digital data

EXPLANATION

−0.4 **Line of equal simulated water-level change**—Computed by subtracting the simulated potentiometric surface for 2015 Base Case from the simulated potentiometric surface for Scenario B. Contour interval 0.2 foot. Datum is NAVD 88

Figure 19. Maps showing simulated water-level change from 2015 Base Case to Scenario B in model layer 7, upper water-bearing zone of the Upper Floridan aquifer, Brunswick/Glynn County area of Georgia.



EXPLANATION

—— −1.4 —— **Line of equal simulated water-level change**—Computed by subtracting the simulated potentiometric surface for 2015 Base Case from the simulated potentiometric surface for Scenario B. Contour interval 0.2 foot. Datum is NAVD 88

Figure 19. —Continued

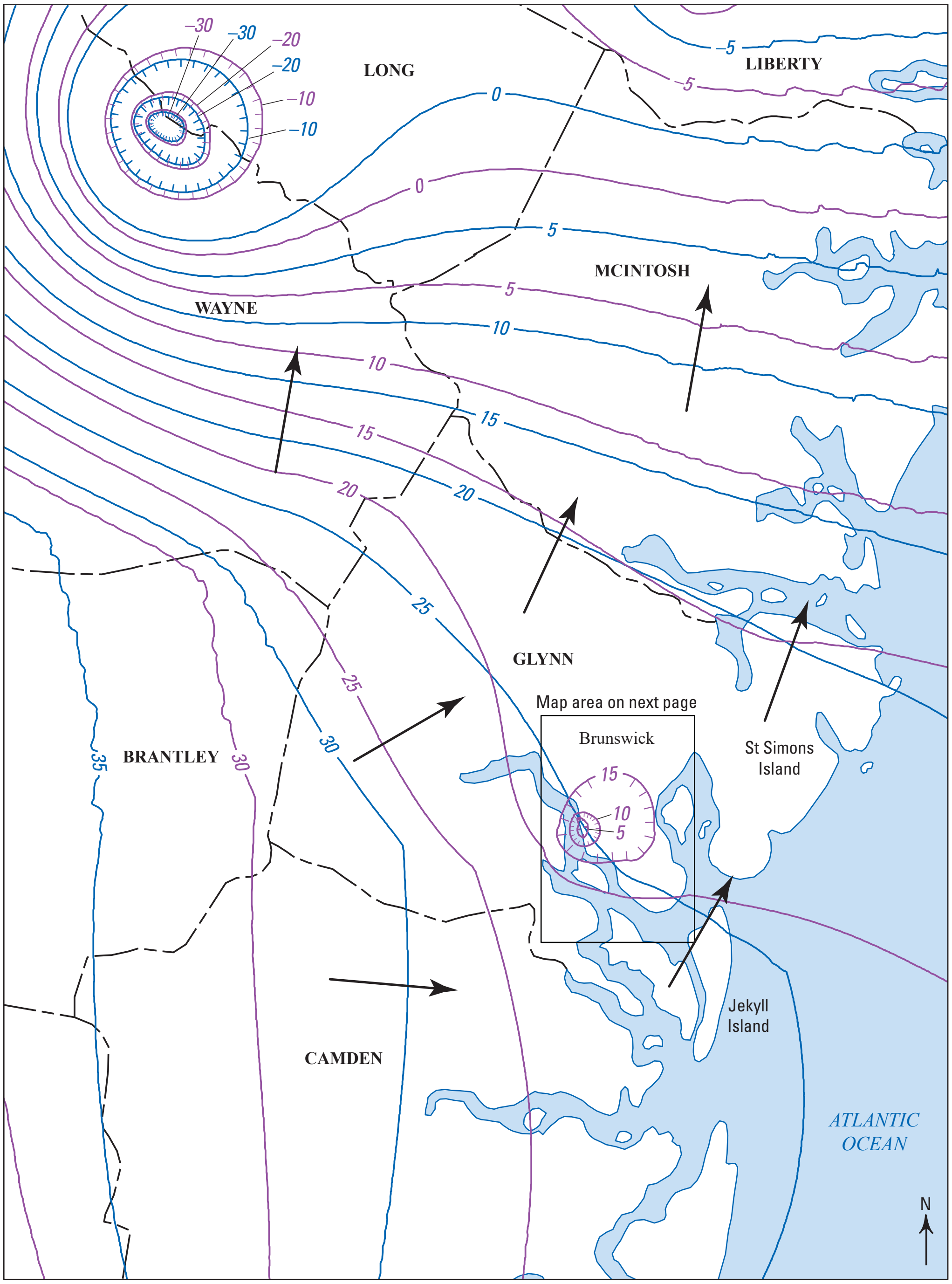
Scenario C

Scenario C represents the elimination of pumping at Brunswick Cellulose and Pinova located in northern Brunswick within or adjacent to the chloride plume area. This scenario highlights the hypothetical case of economic conditions that would lead to plant closures at Brunswick Cellulose and Pinova. Ceasing operations at these facilities would require the deactivation of nine production wells that produced 31.3 Mgal/d during October 2015 (table 9). A similar case was documented in Camden County, Ga., during October 2000, when the Durango Paper Company shut down the facility, resulting in a decrease of about 36 Mgal/d in groundwater pumpage from the Upper and Lower Floridan aquifers (Peck and others, 2005). This plant closure was simulated in one of the scenarios, documented in Payne and others (2005), in which water-level rises in the UFA ranged from 2 to 4 ft in the Glynn County area. The simulated potentiometric contour map for 2015 Base Case indicates the groundwater pumping from seven production wells (27.9 Mgal/d; table 9) located at Brunswick Cellulose created the main cone of depression with water levels below 0 ft surrounding active wells. The two production wells (3.41 Mgal/d; table 9) at Pinova Inc. are located east of the main cone of depression with simulated water levels just below 5 ft. For Scenario C, all other production wells remained active and were simulated at 2015 (Base Case) pumping rates.

The simulated results from Scenario C indicate major changes in the groundwater-flow directions near the city of Brunswick. The elimination of 31.3 Mgal/d pumping in the Brunswick area alters the groundwater-flow direction toward Brunswick from the north and east and shifts flow paths toward directions dominated by flow from the southwest toward the northeast (fig. 20). The 2015 Base Case simulation shows the 5- and 10-ft contours surrounding Brunswick Cellulose, which is an indication of the cone of depression caused by pumping at seven production wells at the facility. Irregular patterns in the 23.5- and 24-ft contours indicate the influence of active production wells on local groundwater-flow directions. Simulated heads in the downtown Brunswick area rebound as shown by the 25-ft contour for Scenario C and influence the shape and extent of a secondary cone of depression located in parts of Wayne and Long Counties (fig. 20). This secondary cone of depression is centered near the Jesup facility, which pumped an estimated 57.8 Mgal/d from the UFA during 2010 (Lawrence, 2015). In Scenario C, the horizontal hydraulic-head gradient in the UWBZ of the UFA across the Brunswick peninsula ranges from 0.6 to 1.0 ft/mile with groundwater-flow directions from the southwest toward the northeast.

The simulated water-level changes for Scenario C compared to 2015 Base Case indicate a range from 3 ft to greater than 25 ft within Glynn County. The simulated water-level changes represent the expected water-level rise if Brunswick Cellulose and Pinova were to close and 31.3 Mgal/d of pumping was eliminated from nine production wells. The 2-ft water-level change contour extends across Camden, Brantley, Wayne, and Long Counties (fig. 21). On the basis of simulation results, a water-level rise of 3 ft could be expected in parts of Camden, Glynn, Wayne, and McIntosh Counties. The maximum simulated water-level change of greater than 25 ft encompasses a small area within the Brunswick Cellulose well field. Inside the chloride plume in downtown Brunswick, simulated water-level changes generally range between 8 and 15 ft and are greater than 20 ft near the Brunswick Cellulose well field (table 10). Pumping from the Pinova well field influences the shape of the 10-ft contour, which has shifted east to include the facility.

Simulated potentiometric gradients for Scenario C in the five potentiometric profiles (*A–A′* to *E–E′*) constructed in close proximity to the chloride plume show horizontal hydraulic gradients changing due to elimination of pumping at the industrial facilities. Profiles *A–A′*, *C–C′*, and *D–D′* indicate groundwater-flow directions have reversed and now flow is in a northwest, east, and southeast direction away from the Brunswick Cellulose well field (fig. 22). The simulated heads for Scenario C along the constructed profiles *A–A′* to *E–E′* show significantly higher heads as a result of lower pumping rates. The simulated head differences are calculated using the simulated heads at the endpoints for each of the profiles (table 11). The lower pumping rates for the Scenario C simulation reduce simulated head differences, which range from 0.6 to 1.2 ft. The result is simulated potentiometric gradients that range between 0.4 and 0.9 ft/mi in profiles *A–A′* to *D–D′* located nearest the industrial well field and 0.4 ft/mi in profile *E* oriented in a general south to north direction. The hydraulic-head gradients in profiles *B–B′* and *E–E′* are reduced to 0.7 and 0.4 ft/mi, respectively, but the general groundwater-flow direction remains from the south toward the north.



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

0 5 MILES
0 5 KILOMETERS

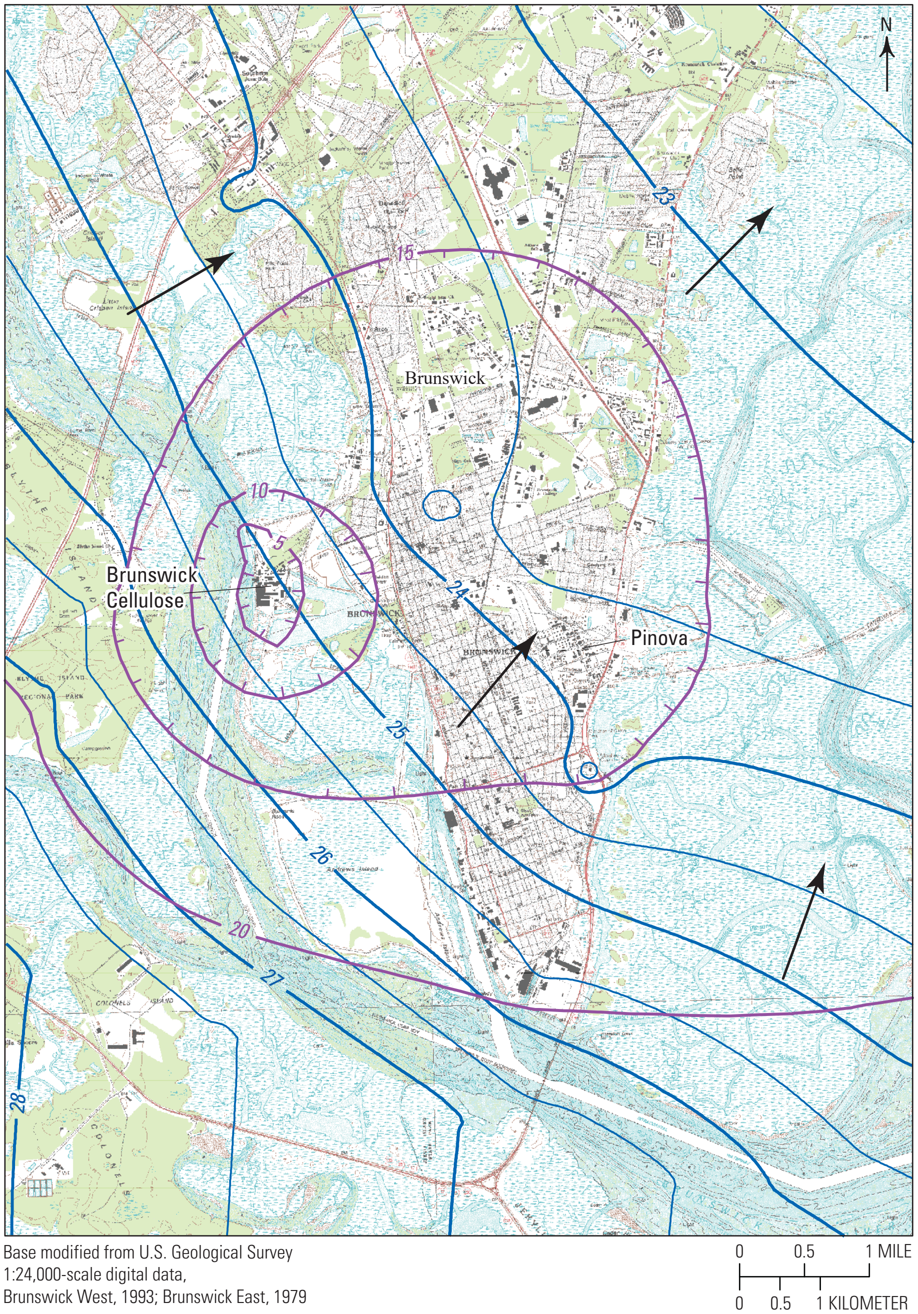
EXPLANATION

10 — **Simulated potentiometric contour**—Shows simulated Scenario C potentiometric surface, in feet. Hachures indicate depression. Contour interval 5 feet. Datum is NAVD 88

10 — **Simulated potentiometric contour**—Shows simulated 2015 Base Case potentiometric surface, in feet. Hachures indicate depression. Contour interval 5 feet. Datum is NAVD 88

→ **General direction of groundwater flow (Scenario C)**

Figure 20. Maps showing simulated 2015 Base Case and Scenario C potentiometric surface for model layer 7, upper water-bearing zone of the Upper Floridan aquifer, Brunswick/Glynn County area of Georgia.



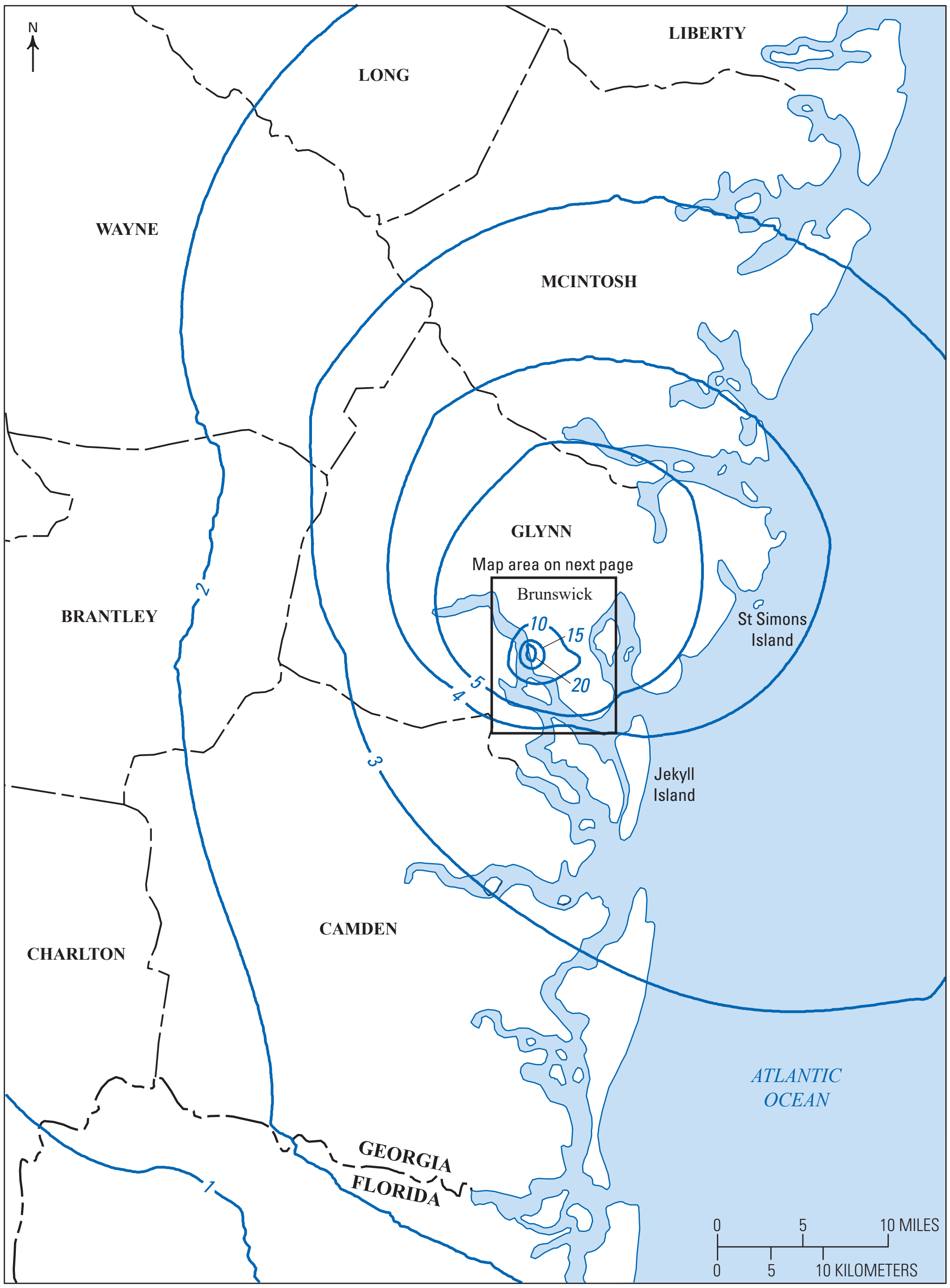
EXPLANATION

25 **Simulated potentiometric contour**—Shows simulated Scenario C potentiometric surface, in feet. Contour interval 0.5 foot. Datum is NAVD 88

10 **Simulated potentiometric contour**—Shows simulated 2015 Base Case potentiometric surface, in feet. Hachures indicate depression. Contour interval 5 feet. Datum is NAVD 88

General direction of groundwater flow (Scenario C)

Figure 20. —Continued



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

EXPLANATION

Line of equal simulated water-level change—Computed by subtracting the simulated potentiometric surface for 2015 Base Case from the simulated potentiometric surface for Scenario C. Contour interval, in feet, is variable. Datum is NAVD 88

Figure 21. Maps showing simulated water-level change from 2015 Base Case to Scenario C in model layer 7, upper water-bearing zone of the Upper Floridan aquifer, Brunswick/Glynn County area of Georgia.

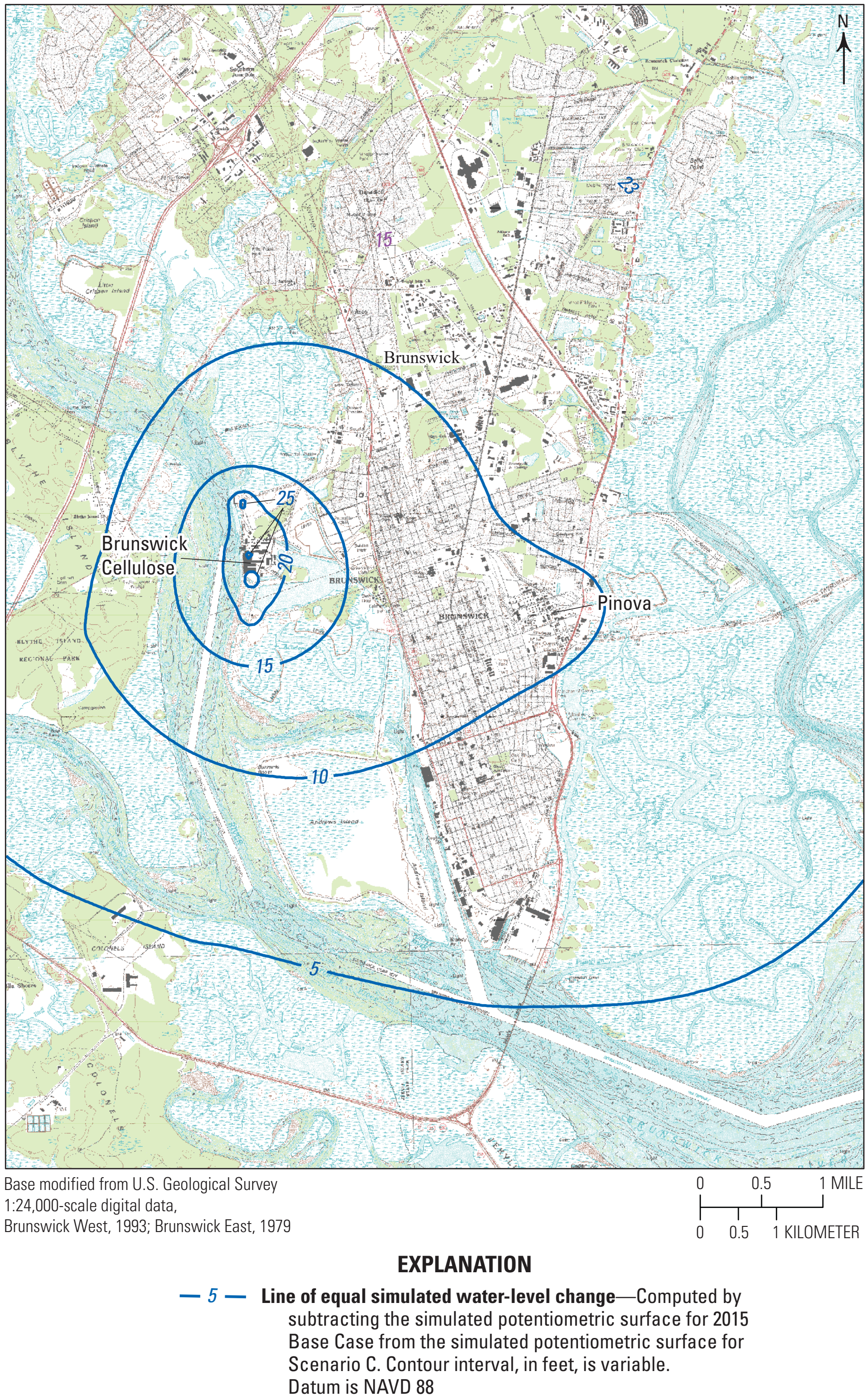


Figure 21. —Continued

Table 10. Simulated groundwater levels for 2015 Base Case, Scenarios A, B, C, and D1–D3 at selected wells for model layer 7, upper water-bearing zone of the Upper Floridan aquifer, Brunswick/Glynn County area of Georgia.

[Simulated groundwater levels are feet above NAVD 88; see fig. 1–1 for well locations]

Well identifier	Simulated groundwater levels, in feet						
	2015 Base Case	Scenario A	Scenario B	Scenario C 0 percent	Scenario D		
					D1 (12.5 percent)	D2 (25 percent)	D3 (50 percent)
33G002	23.70	23.70	23.00	27.80	27.30	26.80	25.80
33G008	23.60	23.50	22.80	27.60	27.10	26.60	25.60
33G024	25.40	25.30	24.60	29.00	28.60	28.10	27.20
33H120	10.30	10.30	8.91	24.30	22.50	20.70	17.20
33H130	9.13	9.15	7.79	24.50	22.60	20.60	16.80
33H133	10.50	10.60	9.21	24.50	22.70	21.00	17.50
33H177	25.10	25.00	24.30	28.90	28.40	27.90	27.00
33H180	13.00	13.10	11.60	23.70	22.40	21.00	18.30
33H193	22.10	22.00	21.10	27.00	26.40	25.80	24.50
33H207	12.00	12.00	10.90	25.80	24.00	22.30	18.80
33H211	2.58	2.53	1.31	25.00	22.20	19.40	13.70
33H213	5.23	5.20	3.97	25.00	22.50	20.00	15.00
34G002	20.00	19.90	19.00	25.70	25.00	24.30	22.80
34G003	23.00	22.90	22.20	26.90	26.40	25.90	24.90
34G009	22.50	22.40	21.80	25.90	25.50	25.00	24.20
34G016	20.80	20.80	20.00	24.90	24.40	23.90	22.80
34G017	20.30	20.20	19.50	24.70	24.20	23.60	22.50
34G020	21.90	21.80	21.20	25.60	25.20	24.70	23.70
34H062	13.10	13.10	11.60	23.60	22.30	20.90	18.30
34H095	19.60	19.50	18.60	25.60	24.90	24.10	22.60
34H112	15.80	15.80	14.60	25.10	23.90	22.70	20.40
34H117	15.20	15.20	14.00	25.10	23.80	22.60	20.10
34H125	14.60	14.50	13.20	24.60	23.40	22.10	19.60
34H128	13.90	13.90	12.60	24.60	23.20	21.90	19.20
34H344	13.20	13.20	11.70	23.90	22.60	21.20	18.50
34H355	13.40	13.40	12.10	24.70	23.30	21.90	19.00
34H371	17.20	17.20	16.10	25.30	24.30	23.30	21.30
34H373	13.10	13.10	11.70	24.30	22.90	21.50	18.60
34H374	11.90	11.90	10.50	24.40	22.90	21.30	18.10
34H393	16.80	16.70	15.60	25.30	24.20	23.10	21.00
34H400	12.90	12.90	11.60	24.50	23.10	21.60	18.70
34H401	12.40	12.40	11.00	24.50	23.00	21.40	18.40
34H424	12.60	12.60	11.10	23.90	22.50	21.10	18.20
34H434	14.30	14.20	12.90	24.70	23.40	22.10	19.40
34H469	11.90	12.00	10.50	24.00	22.50	21.00	17.90
34H514	13.60	13.60	12.20	24.20	22.80	21.50	18.90
34H552	13.30	13.30	11.60	23.20	22.00	20.70	18.20

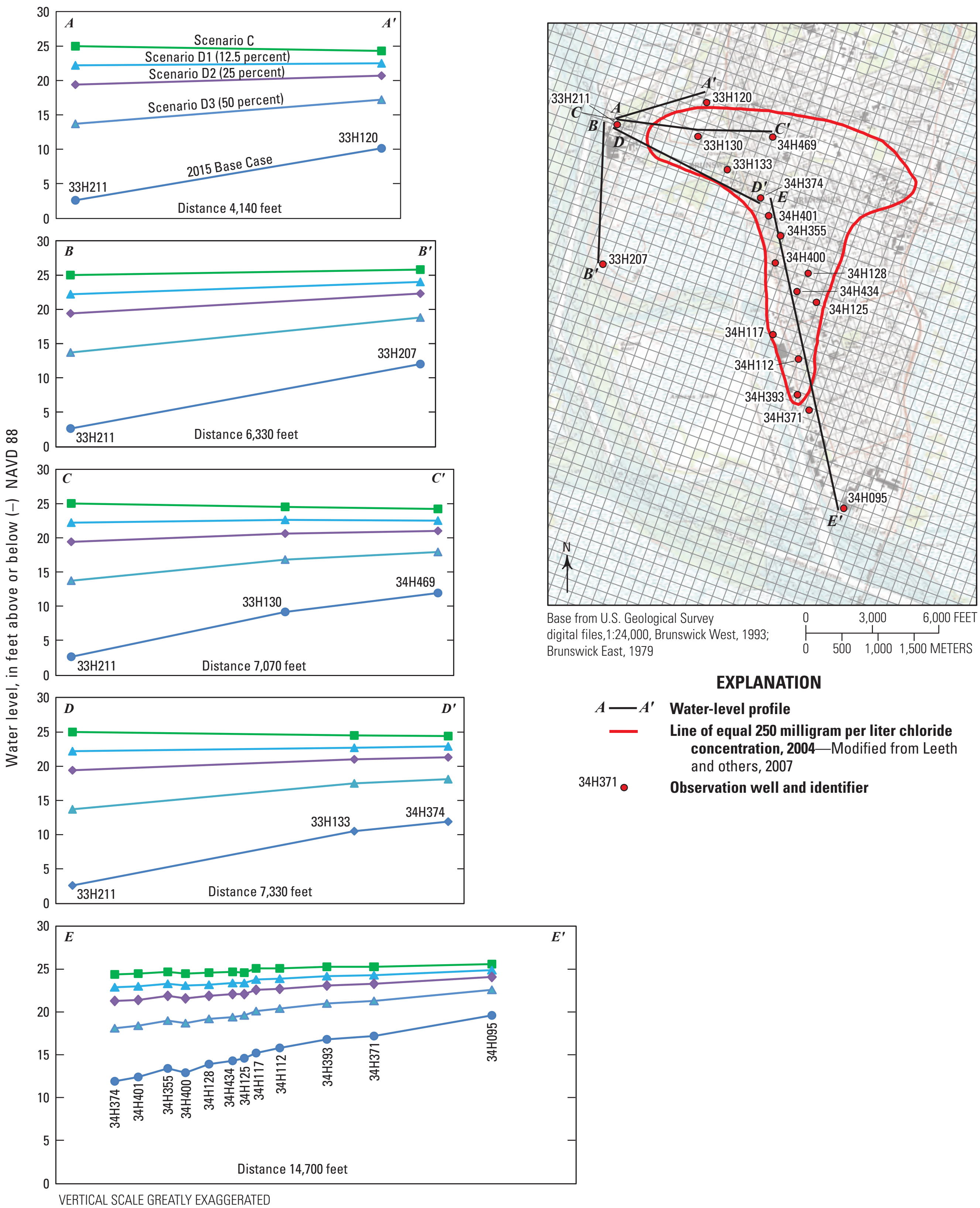


Figure 22. Graphs showing simulated potentiometric profiles near the chloride plume in the Upper Florida aquifer near downtown Brunswick, Georgia, for 2015 Base Case and Scenarios C and D.

Table 11. Simulated head difference and horizontal potentiometric gradients for 2015 Base Case and Scenarios A, B, C, D1, D2, and D3 along profiles *A–A′*, *B–B′*, *C–C′*, *D–D′*, and *E–E′* in the upper water-bearing zone of the Upper Floridan aquifer (model layer 7) in the downtown Brunswick area of Georgia.

[Horizontal hydraulic-head gradients calculated using simulated heads at the endpoints of profile; values in bold indicate groundwater-flow direction has reversed from 2015 Base Case simulation; Scenario C (0 percent); Scenario D1 (12.5 percent); Scenario D2 (25 percent); Scenario D3 (50 percent); see figures 13 and 22 for location of profiles]

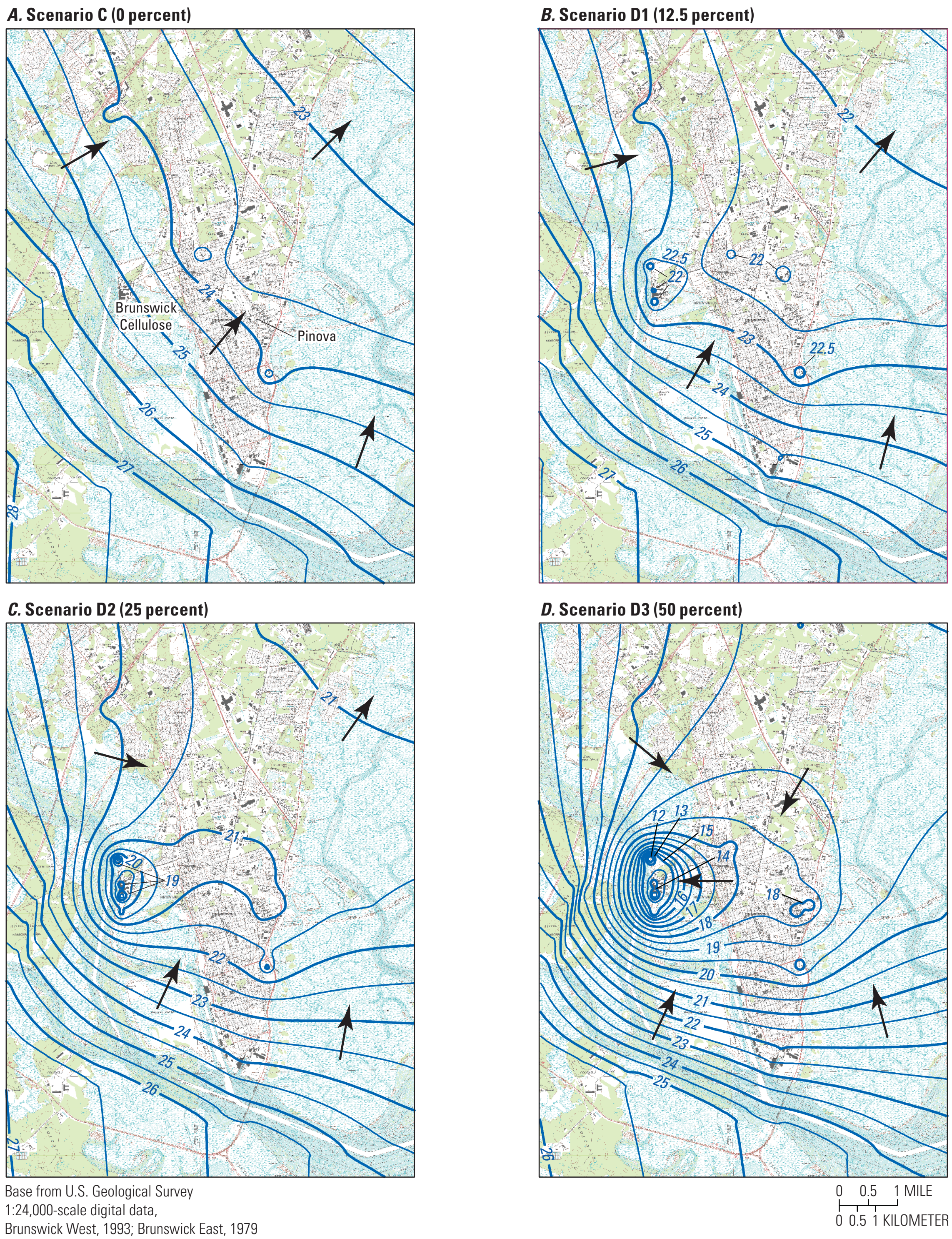
Profile	Number of wells	Distance, in miles	Simulated head difference, in feet							Simulated potentiometric gradient, in feet per mile						
			2015 Base Case	Scenario						2015 Base Case	Scenario					
				A	B	C	D1	D2	D3		A	B	C	D1	D2	D3
A–A′	2	0.78	7.72	7.77	7.60	**0.70**	0.30	1.30	3.50	9.8	9.9	9.7	**0.9**	0.4	1.7	4.5
B–B′	2	1.20	9.42	9.47	9.59	0.80	1.80	2.90	5.10	7.9	7.9	8.0	0.7	1.5	2.4	4.3
C–C′	3	1.34	9.32	9.47	9.19	**1.00**	0.30	1.60	4.20	7.0	7.1	6.9	**0.7**	0.2	1.2	3.1
D–D′	3	1.39	9.32	9.37	9.19	**0.60**	0.70	1.90	4.40	6.7	6.7	6.6	**0.4**	0.5	1.4	3.2
E–E′	12	2.78	7.70	7.60	8.10	1.20	2.00	2.80	4.50	2.8	2.7	2.9	0.4	0.7	1.0	1.6

Scenario D

Scenario D represents changing pumping rates at the industrial facilities in northern Brunswick to determine pumping rates required to reverse the horizontal hydraulic-head gradients. Prior to groundwater development, flow directions were toward the coast in a general west to east direction (Krause and Randolph, 1989). The combined Brunswick Cellulose and Pinova facilities had nine active production wells during 2015, with a pumping rate of 31.3 Mgal/d. The previous scenario (Scenario C) represents plant closures and the elimination of pumping at these nine active production wells, whereas Scenario D decreases pumping at these wells to 12.5, 25, and 50 percent of the 2015 Base Case simulation pumping rates (designated Scenarios D1, D2, and D3, respectively). These conditions represent scaled-back operations at the facilities or less groundwater from the Floridan aquifer system needed for cooling. The changes in simulated pumping rates were applied equally among the nine active industrial production wells, and the results were compared to the 2015 Base Case simulation to determine local head gradients and groundwater-flow directions.

The simulated results from Scenario D indicate that small changes in pumping rates at Brunswick Cellulose alter the natural groundwater-flow direction from southwest to northeast.

For Scenario C, the horizontal hydraulic-head gradient in the UWBZ of the UFA across the Brunswick peninsula ranges from 0.4 to 0.9 ft/mile, with groundwater-flow directions toward the northeast (fig. 23*A*). The potentiometric surface map for Scenario C indicates flatter horizontal hydraulic-head gradients (0.4 ft/mi) near downtown Brunswick. These gradients are influenced by three active production wells for public supply. The closed contours and the shift in the 23.5-ft contour indicate the general locations of these wells with groundwater-flow directions toward the northeast. For 12.5 percent (Scenario D1) of industrial pumping, general groundwater-flow directions are maintained with minor cones of depressions caused by active productions wells (fig. 23*B*). The closed 22- and 22.5-ft contours near downtown Brunswick highlight the locations of active production wells. Additional pumping deepens the cone of depression and increases the horizontal hydraulic-head gradients, which range between 1.2 and 1.8 ft/mi, to the south and southwest of Brunswick, with more gentle head gradients of approximately 0.4 ft/mi extending to the northeast. For 25 percent (Scenario D2) of industrial pumping, the cone of depression is more pronounced, with steeper horizontal hydraulic-head gradients upgradient of Brunswick Cellulose (fig. 23*C*). In addition, some groundwater flow from the north and northeast is redirected to the south and southwest toward the Brunswick Cellulose well field. The horizontal hydraulic-head gradients range from 1.7 ft/mi to 2.4 ft/mi, with groundwater-flow directions from the southwest to northeast (fig. 23*C*; table 11). The shape of the contours indicate groundwater-flow directions shift to a northwesterly direction toward the center of industrial pumping. A small component of groundwater flow is east to west across the northern part of the chloride plume. Horizontal hydraulic-head gradients are relatively flat in the northern part of Brunswick, with groundwater-flow directions influenced by active production wells. For 50 percent (Scenario D3) of industrial pumping, the cone of depression is deep enough to capture groundwater flow in the northeastern portion of the map and redirect flow toward the pumping center (fig. 23*D*). The groundwater-flow component from the southwest toward the Brunswick Cellulose well field yields horizontal hydraulic-head gradients of 4.5 ft/mi within the UWBZ of the UFA (model layer 7). The horizontal hydraulic-head component from groundwater flowing from east to west toward the cone of depression approaches 4 ft/mi. The component of groundwater flow from the northeast toward the pumping center in the southwest is about 2.2 ft/mi. The pumping at the Pinova facility produces a secondary cone of depression evident by the 18-ft contour surrounding the facility.



EXPLANATION

25 **Simulated potentiometric contour**—Shows simulated Scenario C potentiometric surface, in feet. Contour interval 0.5 foot. Datum is NAVD 88

General direction of groundwater flow (Scenario C)

Figure 23. Maps showing simulated potentiometric surface for various percentages of industrial pumping in model layer 7, upper water-bearing zone of the Upper Florida aquifer, Brunswick/Glynn County, Georgia: (*A*) Scenario C (0 percent); (*B*) Scenario D1 (12.5 percent); (*C*) Scenario D2 (25 percent); and (*D*) Scenario D3 (50 percent).

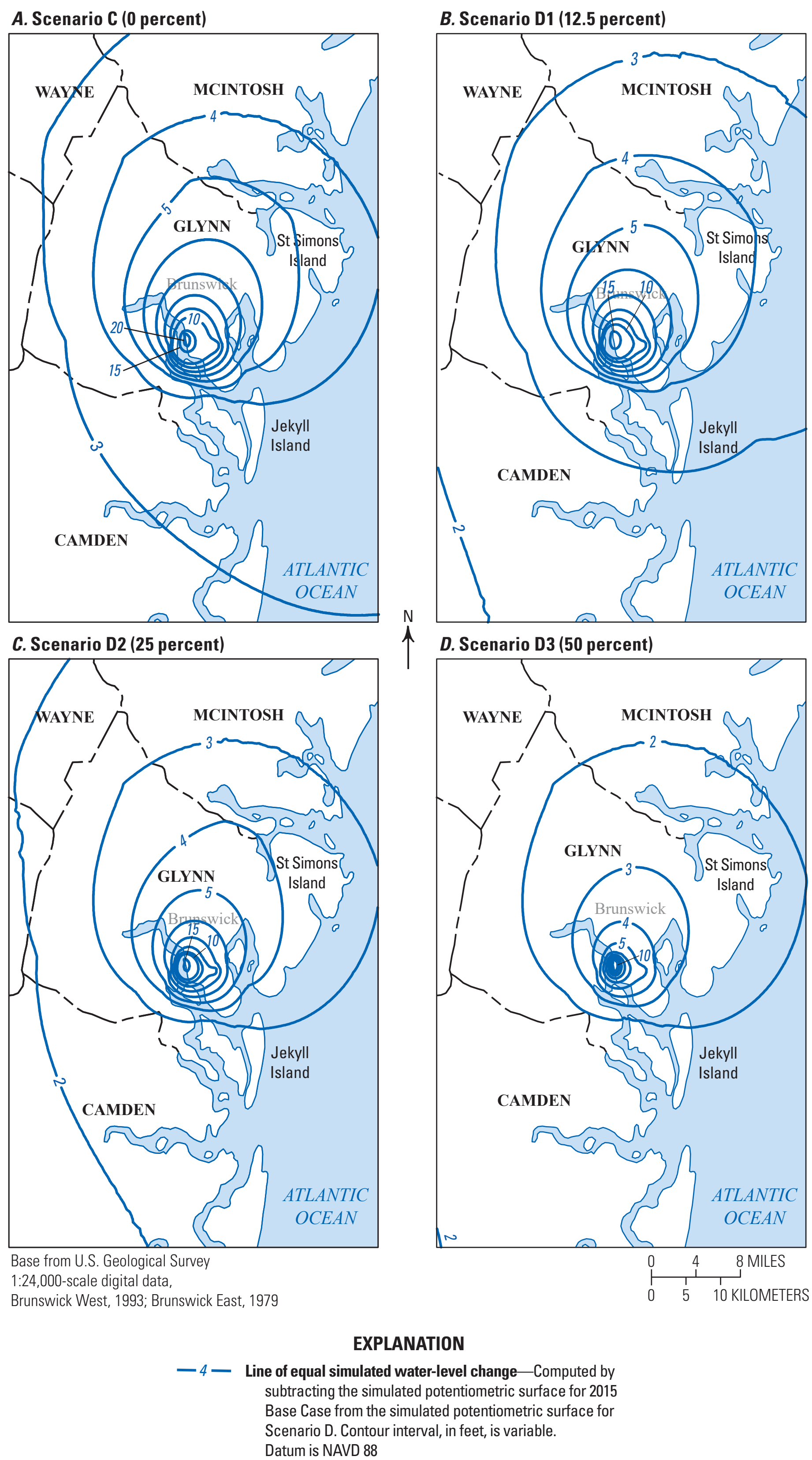


Figure 24. Maps showing simulated water-level change from 2015 Base Case to (*A*) Scenario C (0 percent); (*B*) Scenario D1 (12.5 percent); (*C*) Scenario D2 (25 percent); and (*D*) Scenario D3 (50 percent) industrial pumping in model layer 7, upper water-bearing zone of the Upper Floridan aquifer, Brunswick/Glynn County, Georgia.

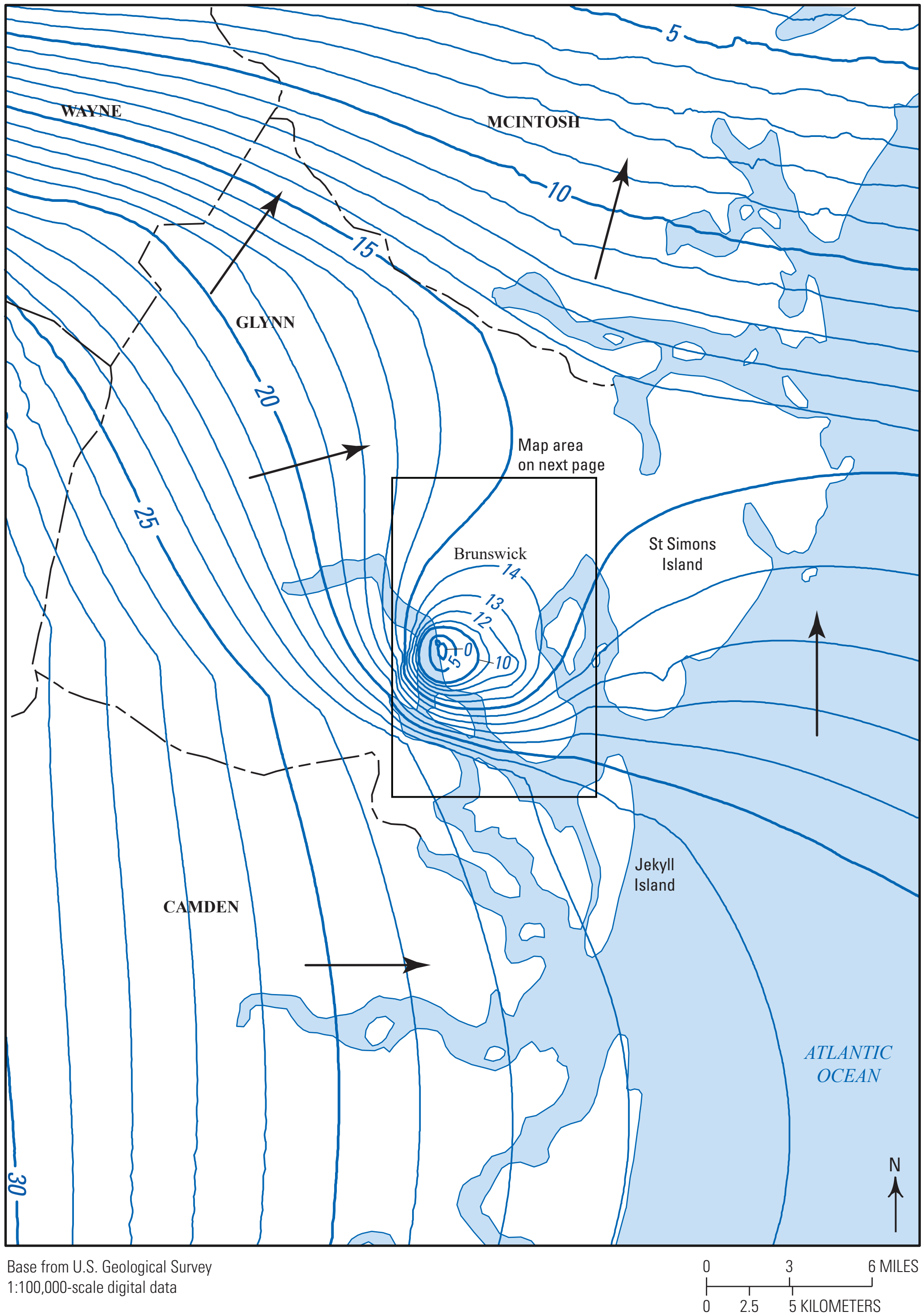
The simulated water-level changes for Scenario D compared to 2015 Base Case indicate a range from less than 2 ft to greater than 15 ft within Glynn County. Scenario D represents variable industrial pumping with 12.5, 25, and 50 percent (designated D1, D2, and D3, respectively) of the pumping rates documented in the 2015 Base Case condition. Scenario C indicates the maximum simulated water-level change of greater than 25 ft encompasses small areas within the Brunswick Cellulose well field, and the 3-ft contour extends to areas outside Glynn County (fig. 24*A*). For 12.5 and 25 percent (Scenarios D1 and D2) of industrial pumping rates, the simulated water-level changes indicate differences of greater than 3 ft covering most of Glynn County (fig. 24*B*–*C*). The maximum simulated water-level change for these simulations is greater than 15 ft and covers a small area surrounding the Brunswick Cellulose well field (table 10). For the 50 percent (Scenario D3) of industrial pumping simulation, water-level changes range from 2 ft in the western part of Glynn County to greater than 10 ft within the Brunswick Cellulose well field (fig. 24*D*).

Scenario E

Scenario E represents additional pumping of 5 Mgal/d at a newly constructed Brunswick Cellulose industrial production well within the existing well field (table 9). This scenario simulates the future expansion at the Brunswick Cellulose facility and increased demand for water production from the well field (Bradford Price, Brunswick Cellulose Inc., written commun., February 2017). The new Brunswick Cellulose production well (33H357) is located about 0.2 mi northwest of the chloride plume in the northern part of the facility. During October 2015, the Brunswick Cellulose well field had seven active production wells with a combined production of 27.9 Mgal/d. The additional production well simulated for Scenario E increases the well field pumping rate to 32.9 Mgal/d, well within the GaEPD permitted capacity of 45 Mgal/d. The high pumping rates from the well field at Brunswick Cellulose create the cone of depression near downtown Brunswick and encompasses the northwest portion of the chloride plume in the UWBZ of the UFA.

The simulated results from Scenario E indicate water-level declines with groundwater-flow directions toward the main cone of depression in the downtown Brunswick area. For Scenario E, the potentiometric-surface map of model layer 7 (UWBZ of UFA) indicates general groundwater-flow directions from southwest to northeast in the western part of the county and from south to north near Jekyll Island (fig. 25). The addition of an industrial well pumping at a rate of 5 Mgal/d steepens the cone of depression near the Brunswick Cellulose well field. The tight spacing of the water-level contours indicates steep horizontal hydraulic-head gradients of about 7 ft/mi, with groundwater-flow directions toward the center of pumping at Brunswick Cellulose. In Glynn County, groundwater not captured by pumping near downtown Brunswick flows in a northeasterly direction toward neighboring McIntosh County.

The simulated water-level changes for Scenario E compared to 2015 Base Case indicate a range from –0.5 ft to less than –7 ft and affecting most of Glynn County. The –1.0 ft contour extends beyond the Brunswick peninsula in a northerly direction (fig. 26). Near the chloride plume area, simulated water-level changes in model layer 7, UWBZ of the UFA, generally range between –1.5 and –3 ft. The water-level change contours from –4 to –7 ft surround the simulated new production well 33H357 and are located on the boundary of the chloride plume.



EXPLANATION

25 **Simulated potentiometric contour**—Shows simulated Scenario E potentiometric surface, in feet. Contour interval, in feet, is variable. Datum is NAVD 88

General direction of groundwater flow (Scenario E)

Figure 25. Maps showing Scenario E simulated potentiometric surface for model layer 7, upper water-bearing zone of the Upper Floridan aquifer, Brunswick/Glynn County, Georgia.

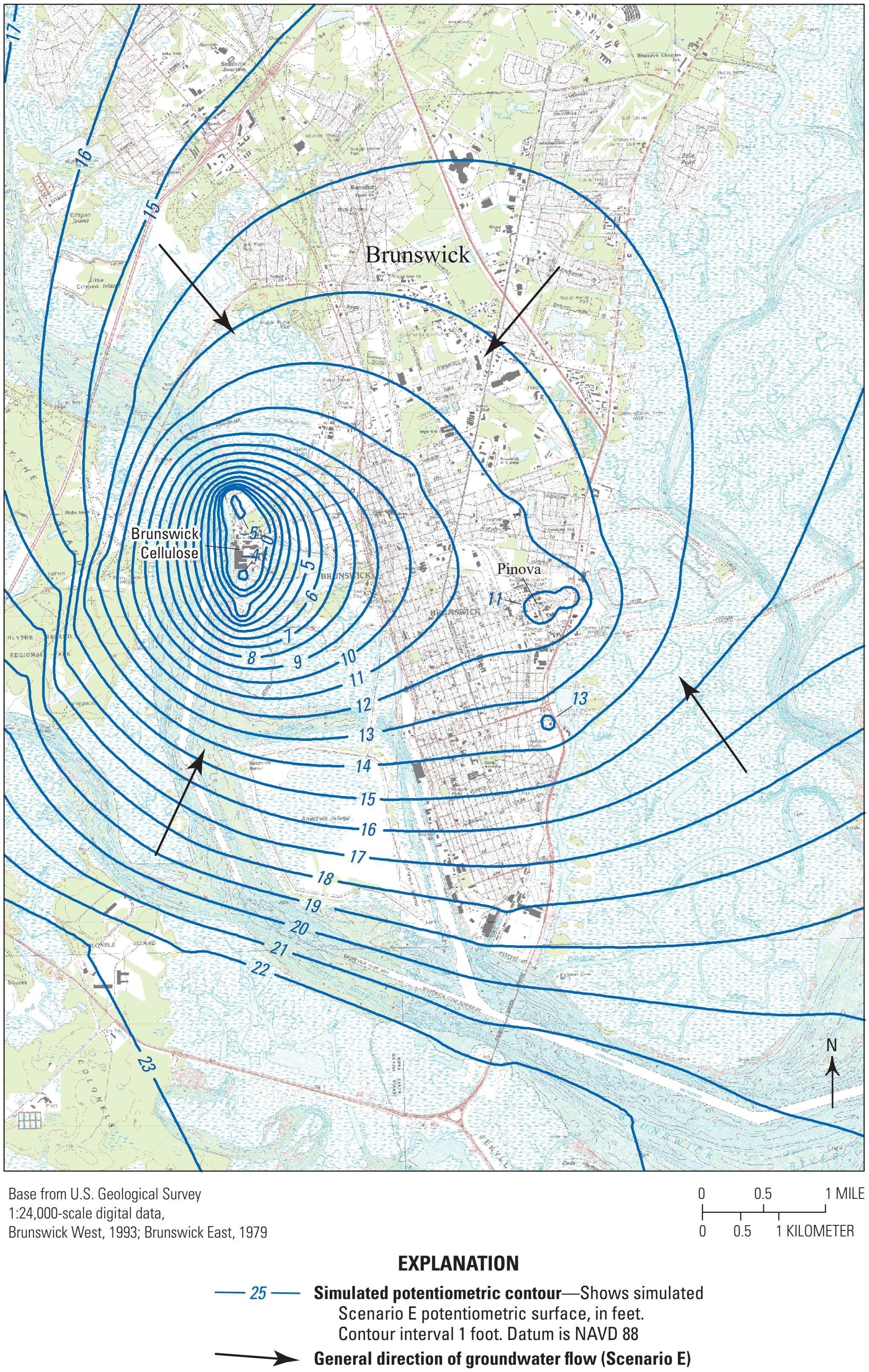


Figure 25. —Continued

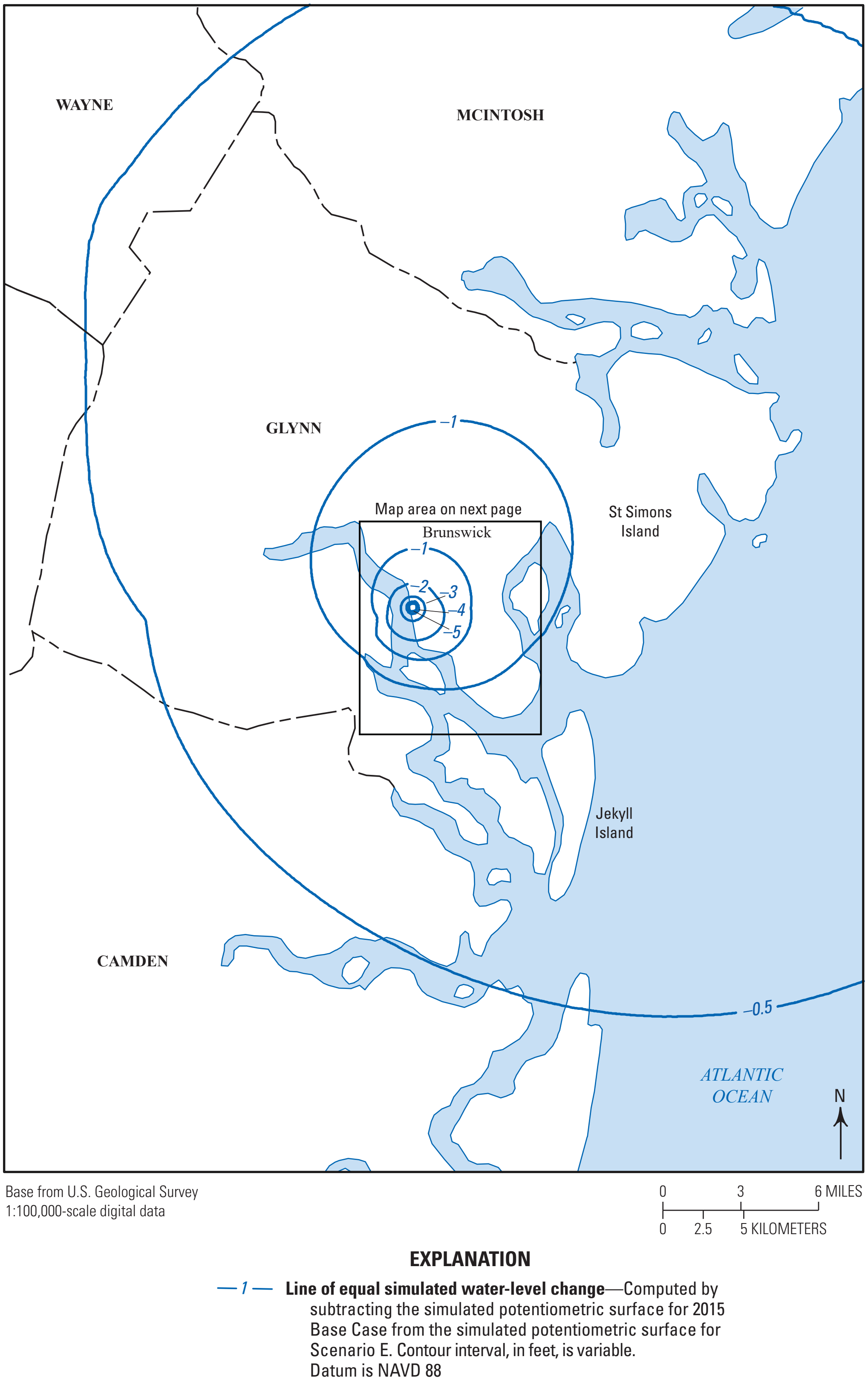


Figure 26. Maps showing simulated water-level change from 2015 Base Case to Scenario E in model layer 7, upper water-bearing zone of the Upper Floridan aquifer, Brunswick/Glynn County, Georgia.

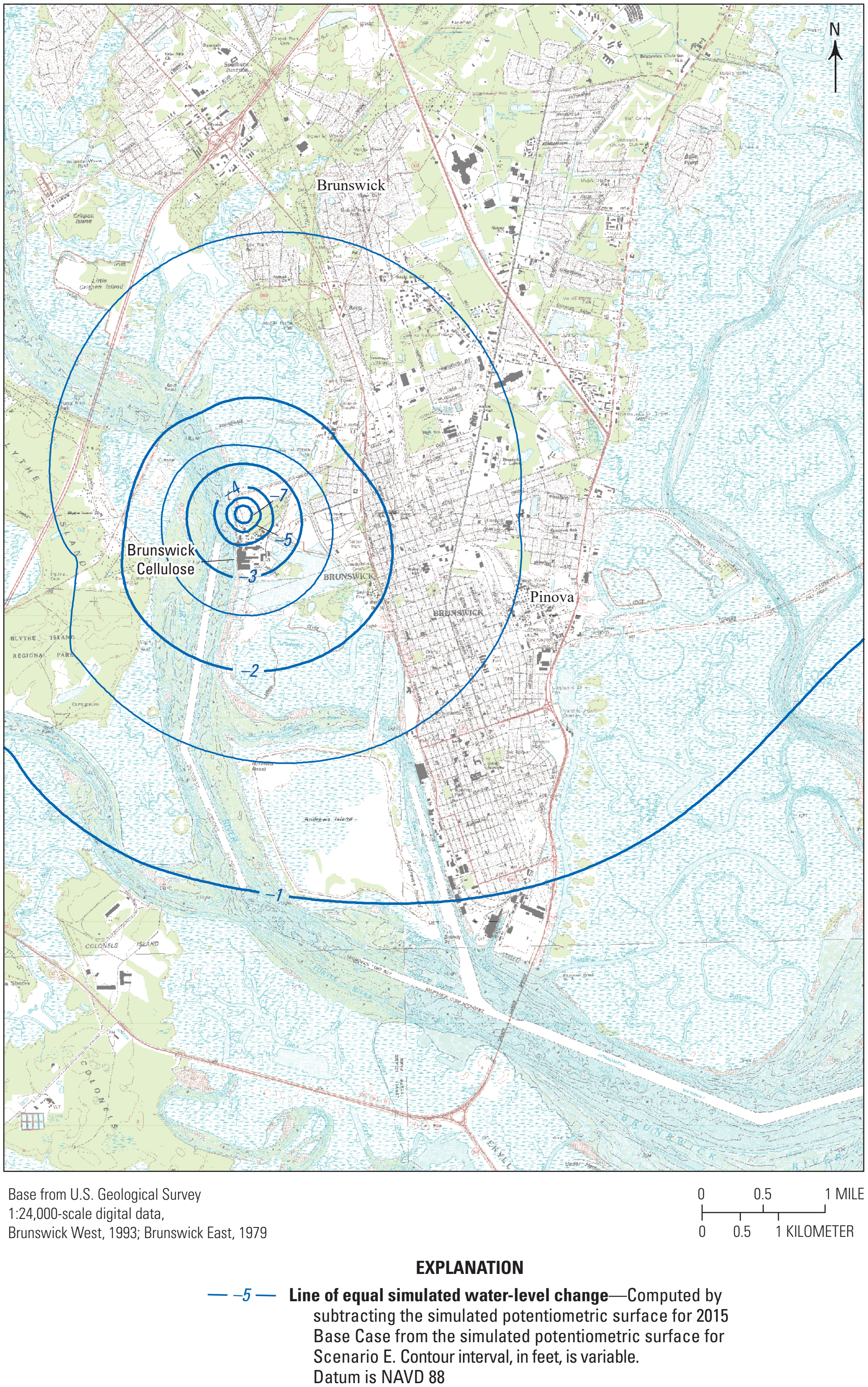


Figure 26. —Continued

Particle-Tracking Analysis

The USGS particle-tracking code MODPATH (Pollock, 1994) was used to generate advective water-particle pathlines and their associated time-of-travel based on MODFLOW 2015 Base Case simulation and Scenario C. The code MODPATH computes three-dimensional flow directions (x-, y-, and z-directions) and time-of-travel (feet per year) using particles in either a forward-tracking mode that follows the direction of groundwater flow toward groundwater discharge areas or a backtracking mode from discharge areas toward recharge areas. For the current study, MODPATH was used to assess groundwater flow in backtracking mode. For all simulations, the active aquifer model layers (layers 1, 3, 5, 7, 9, and 11) were assigned a uniform effective porosity of 30 percent, and the confining units (layers 2, 4, 6, 8, and 10) were assigned a value of 50 percent to match values from the previous model (Cherry, 2015, p. 27).

Three particle seed zones were established in the BGJWSC production wells where individual particles were observed from their point of discharge toward upgradient areas at time-of-travel intervals of 20 and 50 years. The time intervals were chosen on the basis of the BGJWSC Master Plan, with forecasting to the year 2035 and an additional period to determine pathlines outside the Brunswick peninsula. The particle-tracking analysis was performed for the 2015 Base Case and Scenario C to determine groundwater at a range of pumping rates and hydraulic-head gradients near the chloride plume. Eight particles were placed in each of three production wells (34H560, 34H449, and 34H445) at local z-direction coordinates of 0.25 and 0.75, with 1.0 representing the top of the UWBZ of the UFA (layer 7) and 0 representing the bottom.

MODPATH results indicate that for the 2015 Base Case simulation, the dominant groundwater-flow directions are from the northeast and east (wells 34H560 and 34H449) near the northern part of the chloride plume and from the south toward well 34H445. The vertical movement of particles indicates mean upward migration ranging from 31.8 to 53.5 ft over a 20- year interval and 30.8 to 60.0 ft over a 50-year interval. Results also indicate 50 percent of the particles placed in wells 34H560 and 34H449 backtrack to either the deeper confining unit (layer 8) or the LWBZ of the UFA (layer 9). During the 20-year time-of-travel period, the total distance traveled ranged from 5,530 to 8,270 ft with a mean distance traveled ranging from 276 to 413 feet per year (ft/yr; fig. 27; table 12). During the 50-year time-of-travel period, the total distance traveled ranged from 13,400 to 15,700 ft with a mean distance traveled ranging from 268 to 314 ft/yr. In addition, the mean yearly distance traveled was reduced from the initial 20-year period over the final 30-year period for wells 34H560 and 34H449, which is an indication of decreases in horizontal hydraulic-head gradient further away from the chloride plume area (appendix 2).

MODPATH results indicate that for the Scenario C simulation, the dominant groundwater-flow directions are from the west and southwest (wells 34H560 and 34H449) near the northern part of the chloride plume and from the southwest and south toward well 34H445 (fig. 28). The vertical movement of particles indicates mean upward migration ranging from 66.9 to 69.4 ft over a 20-year interval and 82.9 to 104.1 ft over a 50-year interval. Results also indicate that 54 percent of the particles placed in wells 34H560, 34H449, and 34H445 backtrack to the LWBZ of the UFA (layer 9). During the 20-year time-of-travel period, the total distance traveled ranged from 2,510 to 3,647 ft with a mean distance traveled ranging from 126 to 182 ft/yr (fig. 28; table 13). During the 50-year time-of-travel period, the total distance traveled ranged from 5,100 to 7,781 ft with a mean distance traveled ranging from 89 to 156 ft/yr. In addition, the mean distance traveled was reduced from the initial 20-year period over the final 30-year period for wells 34H560, 34H449, and 34H445 and is an indication of decreases in hydraulic gradient near the chloride plume area (appendix 2).

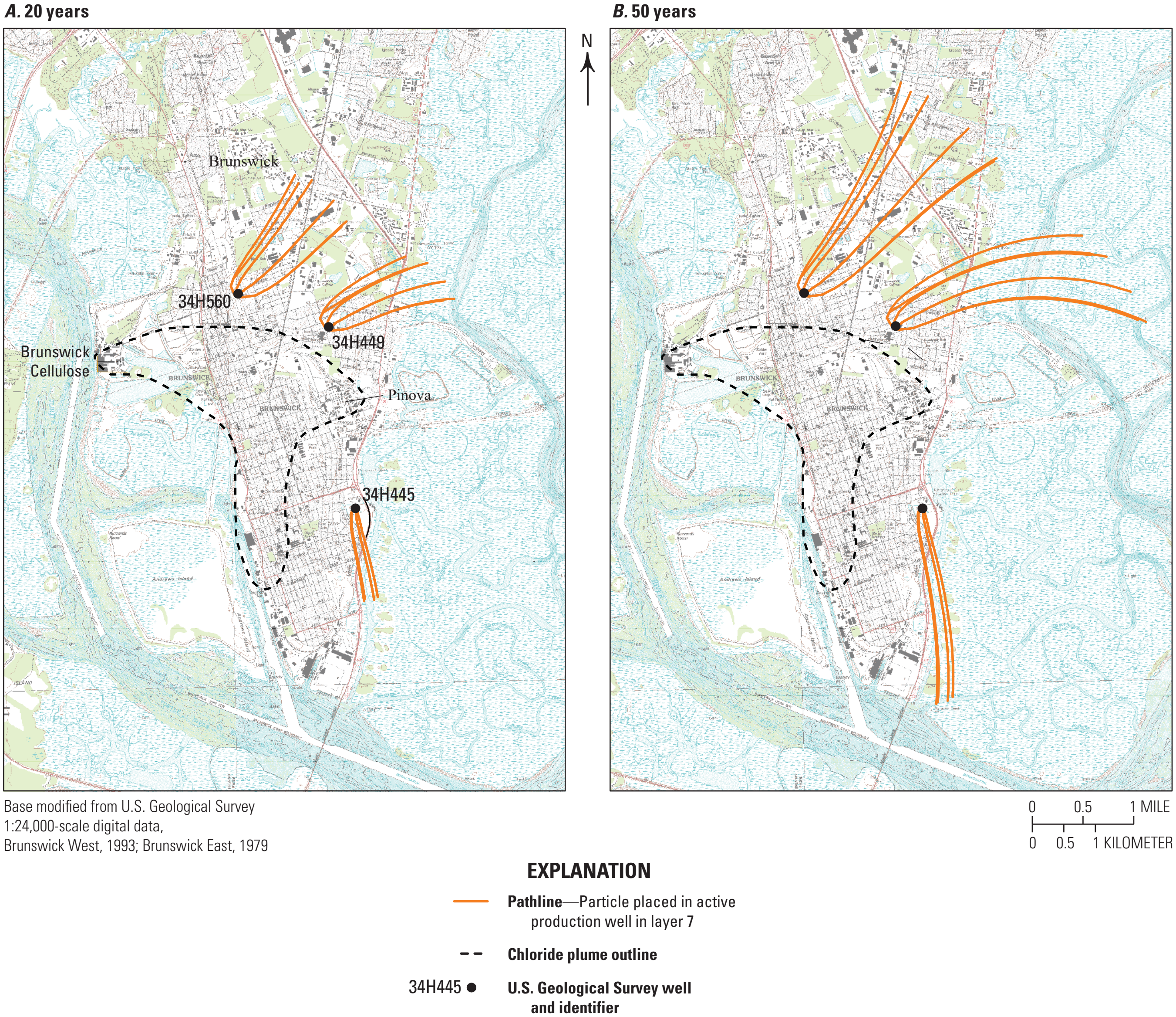


Figure 27. Map showing particle backtracking pathlines from the 2015 Base Case simulation with particles placed in Brunswick-Glynn County Joint Water and Sewer Commission production wells located near the chloride plume in downtown Brunswick, Georgia.

Table 12. Results of particle backtracking from Brunswick-Glynn County Joint Water and Sewer Commission production wells toward upgradient areas for 2015 Base Case simulation in the downtown Brunswick area of Georgia.

[Max, maximum; Min, minimum; negative values indicate downward movement in the groundwater-flow system; see fig. 27 for location of particle paths; particle number paths are summarized in table 2–1]

Well identifier	Particle numbers	Particle movement, in feet									Particle movement, in feet					
		x-direction			y-direction			z-direction			Total distance traveled			Yearly distance traveled		
		Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean
Time-of-travel, 20 years																
34H560	1–8	3,876	804	2,251	6,939	4,902	5,987	–7.56	–70.74	–31.80	9,464	7,312	8,270	473	366	413
34H449	9–16	5,493	2,611	3,992	4,917	3,449	4,178	–17.44	–88.82	–40.55	9,246	7,029	8,210	462	351	411
34H445	17–24	3,617	430	2,126	4,440	1,220	3,350	–26.17	–150.44	–53.51	6,680	3,394	5,529	334	170	276
Time-of-travel, 50 years																
34H560	1–8	6,826	1,071	3,846	12,091	9,456	10,862	–16.90	–81.07	–47.57	16,988	13,193	14,756	340	264	295
34H449	9–16	12,001	7,608	9,461	7,839	4,724	6,166	–35.25	–105.03	–60.01	16,825	13,300	15,688	337	266	314
34H445	17–24	4,707	4,289	4,463	9,207	8,694	8,920	–24.78	–40.94	–30.76	13,569	13,264	13,413	271	265	268

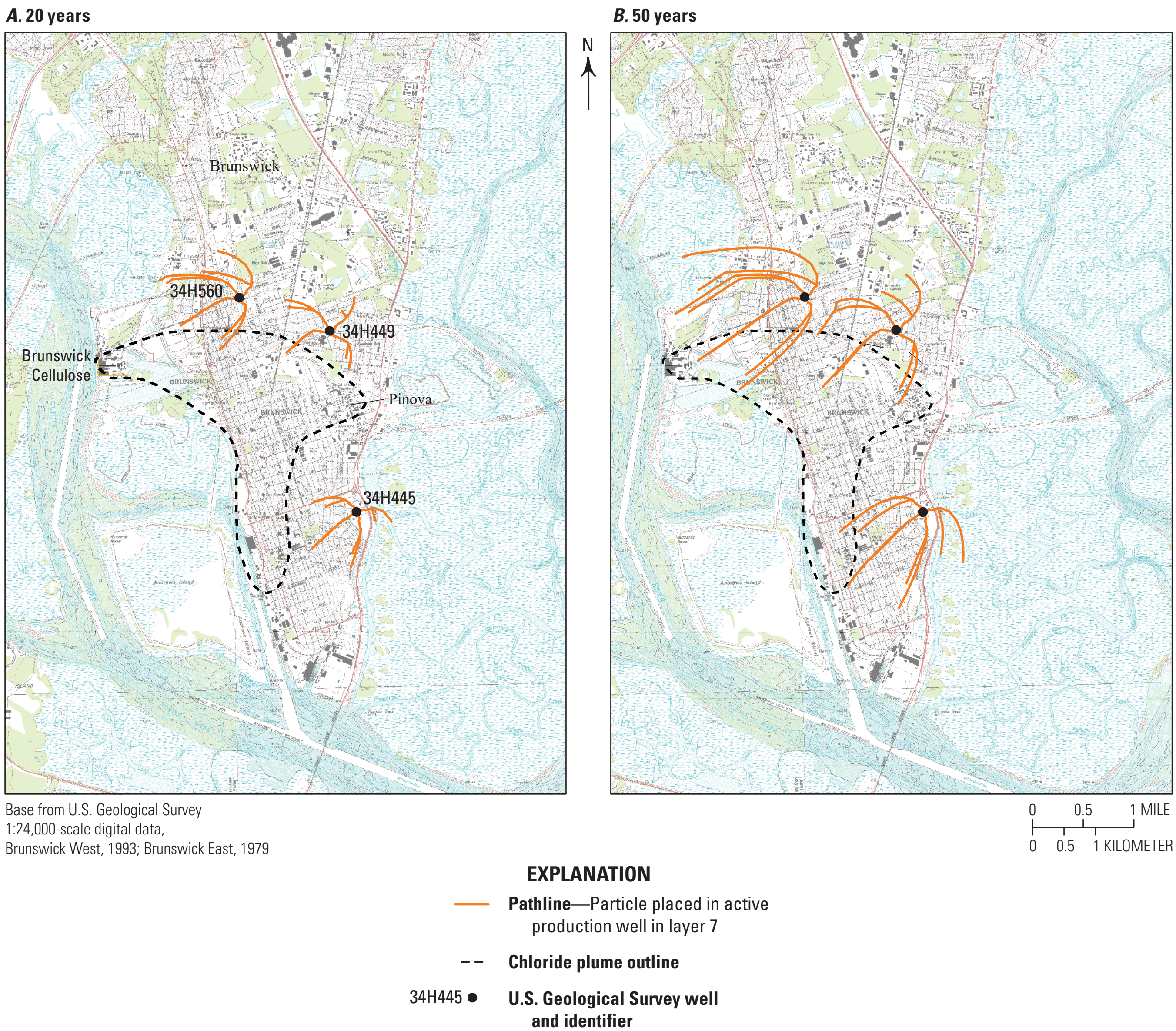


Figure 28. Map showing particle backtracking pathlines from the Scenario C simulation with particles placed in Brunswick-Glynn County Joint Water and Sewer Commission production wells located near the chloride plume in downtown Brunswick, Georgia.

Table 13. Results of particle backtracking from Brunswick-Glynn County Joint Water and Sewer Commission production wells toward upgradient areas for Scenario C simulation in the downtown Brunswick area of Georgia.

[Max, maximum; Min, minimum; negative values indicate downward movement in the groundwater-flow system; see fig. 28 for location of particle paths; particle number paths are summarized in table 2–1]

Well identifier	Particle numbers	Particle movement, in feet									Particle movement, in feet					
		x-direction			y-direction			z-direction			Total distance traveled			Yearly distance traveled		
		Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean
Time-of-travel, 20 years																
34H560	1–8	3,964	148	2,028	2,677	477	1,553	–33.02	–124.61	–66.91	4,704	2,441	3,647	235	122	182
34H449	9–16	2,537	117	1,360	1,929	267	1,122	–28.81	–119.09	–68.02	3,267	1,279	2,550	163	64	128
34H445	17–24	2,162	361	1,206	2,591	25	1,235	–30.03	–138.94	–69.44	3,823	1,302	2,510	158	65	126
Time-of-travel, 50 years																
34H560	1–8	6,807	1,690	4,314	5,340	422	3,383	–43.80	–147.10	–82.94	9,139	6,391	7,781	183	128	156
34H449	9–16	3,619	591	1,979	3,857	315	2,355	–39.25	–167.21	–104.08	6,395	3,065	4,437	128	61	89
34H445	17–24	3,635	230	1,891	4,668	1,783	3,116	–37.51	–180.71	–84.84	7,002	3,401	5,092	140	68	102

Limitations of Digital Simulation

The revised groundwater-flow model (Cherry, 2015) developed for the Brunswick/Glynn County area is subject to uncertainties inherent in groundwater models, including those documented for the original model by Payne and others (2005). The reader is referred to Payne and others (2005) for a complete discussion of the model limitations; those that relate to the modifications of the model are discussed in this section. A model is a simplification of a complex hydrogeologic system and is limited by the number of data points used to construct the framework of the model.

The original model was constructed to simulate groundwater flow in the Floridan aquifer system, which encompasses parts of Georgia, South Carolina, Alabama, and all of Florida. Decisions were made early on in the development of the model as to the spatial representation of the hydrogeologic units and discretization of the model layers. In the design phase of the original model, it was determined a specified-head boundary would be used to represent the Floridan aquifer system near the Florida/Georgia State boundary to allow groundwater flow to enter and exit the model in this region. It was impractical to include the Floridan aquifer system in Alabama and Florida when the focus of the study is the groundwater-flow regime in coastal Georgia.

The original model by Payne and others (2005) discretized the model grid cells into large 16,500 x 16,500-ft blocks along the edges of the model, with smaller grid cells in the study focus areas for the cities of Savannah and Brunswick. It became apparent when evaluating the model for localized scenarios in the Brunswick/Glynn County area that these grid-cell dimensions were not small enough to accurately simulate the cone of depression in the Brunswick area. A determination was made after some trial and error that a 500 x 500-ft grid cell was sufficient to simulate pumping in the UFA for the Brunswick area. Limits on computational space and model run times required the elimination of the finer grid mesh near the city of Savannah and affected the model calibration.

The UFA was modeled as one unit (model layer 5) in the original model by Payne and others (2005); however, the hydrogeology in the Brunswick/Glynn County area indicated there are two water-bearing units within the aquifer. On the basis of local hydrogeology, the UFA was subdivided into the UWBZ (model layer 7), intervening confining unit (model layer 8), and the LWBZ (model layer 9). This configuration is used in the Brunswick/Glynn County area and extends out to include hydraulic-property geographic zones F7 and F8, which encompasses Camden County to the south. Beyond these hydraulic-property geographic zones, the intervening confining unit was assigned the same hydraulic conductivity as the model layers above and below due to the uncertainty in the extent of distinct water-bearing zones of the UFA. The observation data for the LWBZ of the UFA (model layer 9) were limited to five wells and proved difficult to match the observed heads to the simulated heads in both 2004 and 2015. In general, the simulated heads were lower than those observed for 2004 and matched reasonably well in 2015. This could be caused in part by the pumping distribution between model layers 7 and 9, which assigned pumping rates on the basis of aquifer thickness in 2004 and assigned a higher rate of pumping from model layer 7 in 2015 on the basis of additional well data.

The groundwater-flow model was calibrated to hydrologic conditions during June 2004 and October 2015 using steady-state simulations. This type of simulation does not take into account small-scale changes and seasonal responses to recharge and pumping. To simulate a short-term response in the flow system, a transient simulation would be required along with greater temporal resolution of stresses, boundary conditions, and observation data (Payne and others, 2005).

Boundary conditions play an important role in the calibration of the model, but are also a large source of uncertainty. The flow budgets for the groundwater-flow model indicate the specified-head boundaries in model layers 7–11 account for nearly 80 percent of the inflows and about 60 percent of the outflows. The specified-head boundary becomes the simulated recharge to the groundwater system and can be increased by increasing pumping. The observed head data for 2004 were limited but were used to assign specified-head values along the extent of the boundary. Caution should be used in assuming that the specified-head boundary will supply limitless quantities of water in response to pumping and cannot be constrained by assigning recharge to specific areas of the model.

Pumping uncertainty results from limited or improper metering, errors in reporting, overestimating or underestimating countywide water use, and assigning the pumping to the wrong unit or model layer. If large discrepancies exist between site specific and non-site specific data, then non-site specific wells will be assigned higher pumping rates. This could in turn affect the assigned hydraulic-property data to a given area of the model.

The model is limited by the wide range of hydraulic conductivity assigned to the UFA (model layers 7 and 9). The values assigned to these groundwater-flow model layers assigned by Cherry (2015) range from 20 to 3,415 feet per day (ft/d) with an average of 540 ft/d. According to a sensitivity analysis conducted by Payne and others (2005), additional hydraulic conductivity data for the UFA in hydraulic-property geographic zones F4, F5, and F6 (fig. 9) may help improve model accuracy. The analysis also indicates that additional vertical hydraulic conductivity (layer 6 and parts of layers 2, 3, 4, and 5) data also could improve model accuracy and calibration.

The accuracy of MODPATH and associated pathlines depends on the extent to which the groundwater system can be realistically represented by a discrete network of finite-difference cells (Pollack, 1994). The analyses using MODPATH, however, were limited to the Brunswick peninsula, where the grid has the highest resolution within the model.

Summary

In the Brunswick, Georgia, area, saltwater has been contaminating the Upper Floridan aquifer (UFA) since the late 1950s and has constrained development of the aquifer within an area of several square miles in the downtown area. In this area, parts of the aquifer produce water that has a chloride concentration greater than 2,000 milligrams per liter (mg/L), which is above the 250-mg/L State and Federal secondary drinking-water standard. Further development of the UFA is limited to areas outside the chloride plume in a manner that will minimize future expansion of the plume and maintain horizontal hydraulic-head gradients toward active pumping centers in the area. To provide information to help manage water resources in the Brunswick area, the U.S. Geological Survey (USGS), in cooperation with the Brunswick-Glynn County Joint Water and Sewer Commission (BGJWSC) and the Georgia Environmental Protection Division (GaEPD), performed groundwater modeling simulations focused on hydraulic-head gradients in the vicinity of the chloride plume.

This report describes the results of simulations used to revise a regional MODFLOW groundwater-flow model of coastal Georgia and adjacent parts of Florida and South Carolina to evaluate a 2015 Base Case by using adjusted pumping rates in the Brunswick/St. Simons Island area. The revised recalibrated groundwater-flow model was used to evaluate seven groundwater-management scenarios with adjusted pumping rates in production wells located in the Brunswick/Glynn County area. The original model for the Brunswick/Glynn County area was modified because the discretization of 4,000 by 5,000 feet (ft) was not fine enough to simulate drawdown near active industrial production wells. The determination was made after some trial and error that grid cells with dimensions of 500 ft per side were adequate for the revised model to simulate large-scale pumping near downtown Brunswick.

For the revised model, additional hydraulic-property geographic zones were designated on the basis of available aquifer-test and geologic data. Three additional hydraulic-property geographic zones were created within the UFA (layers 7–9) near the Brunswick area to improve calibration of the original model. The Brunswick aquifer system (model layer 3 in the original model) was subdivided in the revised model to include the upper and lower Brunswick aquifers (layers 3 and 5). The UFA (model layer 5 in the original model) was subdivided in the revised model to include the upper and lower water-bearing zones (UWBZ and LWBZ) of the UFA (model layers 7 and 9). The subdivision of the UFA, however, was limited to Glynn and Camden County areas because of the uncertainty in extent of these units throughout the regional model area. The intervening confining units for the Brunswick aquifer system and UFA corresponded to layers 4 and 8 in the revised model.

The revised model was calibrated for 2004 and 2015 conditions on the basis of differences (residuals) between simulated heads and observed water levels as well as their corresponding mean, median, and root-mean-square error (RMSE) statistics. For the 2004 calibration, residuals in the Brunswick/Glynn County area from 32 observation wells in model layer 7, UWBZ of the UFA, ranged from −18.9 to 3.98 ft, with a mean of −2.56 ft, median of −1.50 ft, and an RMSE of 5.34 ft. The distribution of water-level residuals in the UWBZ of the UFA (layer 7) indicates an acceptable match, with 75 percent of the values within the established error criterion of 5 ft. For the 2015 calibration, residuals in the Brunswick/Glynn County area from 26 observation wells in model layer 7, UWBZ of UFA, ranged from −17.3 to 5.48 ft, with a mean of −0.25 ft, median of 1.00 ft, and an RMSE of 4.89 ft. The distribution of water-level residuals in the UWBZ of the UFA (layer 7) indicates an acceptable match, with 81 percent of the values within the established error criterion of 5 ft. In the steady-state models for 2004 and 2015, simulated water-level increases in the UFA (layers 7 and 9) were caused by decreases in pumping rates, with groundwater-level increases generally ranging between 1 and 7 ft. During 2004, simulated potentiometric gradients ranged between 7.6 and 11.0 feet per mile (ft/mi) in profiles near the Brunswick Cellulose well field and 3.6 ft/mi in a profile oriented in a general north to south direction. During the 2015 Base Case, lower pumping rates reduced hydraulic-head gradients, which ranged between 6.7 and 9.8 ft/mi in profiles near the Brunswick Cellulose well field and 2.8 ft/mi in the profile oriented in a north to south direction.

Simulated water budgets in the Brunswick/Glynn County area indicate total pumping of 55.2 million gallons per day (Mgal/d) during 2004 and 45.2 Mgal/d during 2015 in the UWBZ and LWBZ of the UFA (model layers 7 and 9). Inflows and outflows are predominantly across county boundaries, with outflows to the general-head boundary in model layer 1 of 5.8 Mgal/d during 2004 and 6.3 Mgal/d during 2015, respectively. For the 2004 simulation, 19.6 Mgal/d of pumping was assigned to model layer 7 (UWBZ of the UFA) and 34.1 Mgal/d to model layer 9 (LWBZ of the UFA). For the 2015 Base Case simulation, greater pumping of 31.2 Mgal/d was assigned to model layer 7 on the basis of depth of production wells in the study area. An additional 12.4 Mgal/d of pumping was assigned to model layer 9 on the basis of well information that includes five production wells that tap the LWBZ of the UFA.

The revised calibrated 2015 Base Case regional model was used to simulate the potential effect of seven distinct groundwater-management scenarios in the Brunswick/St. Simons Island area. Two scenarios (Scenarios A and B) simulate additional pumping at existing public-supply wells located near the chloride plume and planned public-supply wells located to the north. Scenario C simulates the deactivation of industrial production wells totaling 31.3 Mgal/d of pumping. Scenario D consists of three scenarios, which simulate 12.5, 25, and 50 percent (designated D1, D2, and D3, respectively) of the 31.3 Mgal/d pumping rates at the Brunswick Cellulose and Pinova industrial facilities, to determine changes in horizontal hydraulic-head gradients within the chloride plume. Scenario E simulates pumping rates of 5 Mgal/d at a recently constructed industrial production well within the Brunswick Cellulose well field.

The simulated results from Scenario A indicate minor water-level declines with groundwater-flow directions remaining similar to those of the 2015 Base Case condition in the UWBZ of the UFA (layer 7). In the Scenario B simulation, moderate water-level declines were observed with groundwater-flow directions more pronounced toward the northeastern part of Glynn County. The simulated change in heads within the chloride plume area generally ranged between –1.0 and –1.5 ft. In the Scenario B simulation, potentiometric gradients in four profiles near the Brunswick Cellulose well field ranged between 6.6 and 9.7 ft/mi and were 2.9 ft/mi in a profile oriented in a general north to south direction. In the Scenario C simulation, elimination of 31.3 Mgal/d of pumping at Brunswick Cellulose and Pinova shifted groundwater-flow direction toward pumping centers from the north and east. This scenario also shifted flow paths across the Brunswick peninsula from the southwest toward the northeast. The simulated water-level changes for Scenario C compared to 2015 Base Case indicate a range from +3 ft to greater than +25 ft in Glynn County. In close proximity and inside the chloride plume, water-level changes ranged from +6.00 ft in well 34H095 to +22.4 ft in well 33H211. Simulated potentiometric gradients for Scenario C in the three potentiometric profiles constructed in close proximity to the Brunswick Cellulose well field show horizontal hydraulic-head gradients changing to 0.4 to 0.9 ft/mi due to discontinued pumping with groundwater-flow direction toward the northwest, east, and southeast. In the Scenario D1–D3 simulations, varying pumping rates of 31.3 Mgal/d of pumping at the Brunswick Cellulose and Pinova well fields by 12.5, 25, and 50 percent altered potentiometric gradients toward pumping centers from the north and east. These scenarios also shift flow paths across the Brunswick peninsula from the southwest toward the northeast. The simulated water-level changes for Scenario C compared to 2015 Base Case indicate a range from +3 ft to greater than +15 ft within Glynn County. Simulated potentiometric gradients for Scenarios D1–D3 in the four potentiometric profiles constructed in close proximity to the Brunswick Cellulose well field show horizontal hydraulic-head gradients ranging from 0.2 to 4.5 ft/mi due to changing pumping rates within the Brunswick Cellulose well field with groundwater-flow directions toward the northeast, west, and southwest. In the Scenario E simulation, results indicate general groundwater-flow directions from southwest to northeast in the western part of the county and from south to north near Jekyll Island. Near the chloride plume, simulated water-level changes from the 2015 Base Case in model layer 7, UWBZ of UFA, generally ranged between –1.5 and –3 ft. Water-level change contours from –4 to –7 ft surround the simulated production well and are located on the boundary of the northwestern part of the chloride plume.

MODPATH results indicate that for the 2015 Base Case simulation, particle backtracking from wells 34H560, 34H449 and 34H445 over a 20-year time-of-travel period show total distance traveled ranging from 5,529 to 8,270 ft with a mean annual distance traveled ranging from 276 to 413 ft. During the 50-year time-of-travel period, the total distance traveled ranged from 13,413 to 15,688 ft with a mean annual distance traveled ranging from 268 to 314 ft. In the Scenario C simulation, results from particle backtracking at the same wells show dominant groundwater-flow directions are from the west and southwest in wells 34H560 and 34H449 and from the southwest and south toward well 34H445. The total distance traveled over a 20-year period ranged from 2,510 to 3,647 ft with a mean annual distance traveled ranging from 126 to 182 ft. During the 50-year time-of-travel period, the total distance travelled ranged from 5,092 to 7,781 ft with a mean annual distance traveled ranging from 89 to 156 ft. The changes in the distance traveled between the separate simulations are attributable to decreases in hydraulic-head gradient near the chloride plume area.

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Appendix 1. Simulated and Observed Groundwater Levels, 2004 and 2015, for Wells Used in the Simulation of Groundwater Flow in the Brunswick/Glynn County Area of Georgia

Table 1–1. Simulated and observed groundwater levels, 2004 and 2015.

[Simulated and observed groundwater levels are above or below (–) NAVD 88; observed values for 2004 are during June; observed values for 2015 are during October; see fig. 1–1 for well locations; —, no data]

Well identifier	Model layer	Simulated and observed groundwater levels and difference, in feet						Water-level change, in feet, 2004–2015	
		2004 calibration			2015 calibration				
		Simulated	Observed	Difference	Simulated	Observed	Difference	Simulated	Observed
33J065	3	10.30	11.91	–1.61	10.40	12.23	–1.83	0.10	0.32
33G028	3	8.35	21.31	–12.96	7.61	—	—	–0.74	—
34H144	3	5.40	3.60	1.80	5.89	4.08	1.81	0.49	0.48
34H437	3	6.02	8.92	–2.90	6.28	7.08	–0.80	0.26	–1.84
34J077	3	–2.39	–12.46	10.07	–1.51	–5.31	3.80	0.88	7.15
34J081	3	3.04	–2.50	5.54	3.63	2.02	1.61	0.59	4.52
33J062	5	10.30	22.09	–11.79	10.50	22.98	–12.48	0.20	0.89
34J080	5	3.06	8.55	–5.49	3.64	10.68	–7.04	0.58	2.13
33G002	7	22.40	23.48	–1.08	23.70	—	—	1.30	—
33G008	7	22.20	23.16	–0.96	23.60	—	—	1.40	—
33G024	7	24.20	29.87	–5.67	25.40	—	—	1.20	—
33H120	7	5.48	3.08	2.40	10.30	7.98	2.32	4.82	4.90
33H130	7	4.12	2.18	1.94	9.13	6.83	2.30	5.01	4.65
33H133	7	5.97	3.77	2.2	10.50	8.20	2.30	4.53	4.43
33H177	7	23.90	28.20	–4.30	25.10	—	—	1.20	—
33H180	7	9.20	10.10	–0.90	13.00	10.10	2.90	3.80	0.00
33H193	7	20.50	22.38	–1.88	22.10	24.95	–2.85	1.60	2.57
33H207	7	9.21	8.09	1.12	12.00	13.30	–1.30	2.79	5.21
33H211	7	–3.16	–4.16	1.00	2.58	—	—	5.74	—
33H213	7	–0.19	–1.72	1.53	5.23	—	—	5.42	—
34G002	7	17.90	22.40	–4.50	20.00	—	—	2.10	—
34G003	7	21.60	25.90	–4.30	23.00	—	—	1.40	—
34G009	7	21.30	38.70	–17.40	22.50	39.77	–17.27	1.20	1.07
34G016	7	19.40	28.30	–8.90	20.80	28.80	–8.00	1.40	0.50
34G017	7	19.70	26.10	–6.40	20.30	26.30	–6.00	0.60	0.20
34G020	7	20.60	30.10	–9.50	21.90	31.10	–9.20	1.30	1.00
34H062	7	8.54	—	—	13.10	11.40	1.70	4.56	—
34H095	7	17.50	17.90	–0.40	19.60	20.50	–0.90	2.10	2.60
34H112	7	12.50	12.90	–0.40	15.80	15.90	–0.10	3.30	3.00
34H117	7	11.80	10.50	1.30	15.20	—	—	3.40	—
34H125	7	10.60	12.40	–1.80	14.60	11.80	2.80	4.00	–0.60
34H128	7	9.70	8.13	1.57	13.90	—	—	4.20	—
34H344	7	7.68	6.22	1.46	13.20	—	—	5.52	—
34H355	7	9.34	8.46	0.88	13.40	12.50	0.90	4.06	4.04

Table 1–1. Simulated and observed groundwater levels, 2004 and 2015.—Continued

[Simulated and observed groundwater levels are above or below (-) NAVD 88; observed values for 2004 are during June; observed values for 2015 are during October; see fig. 1–1 for well locations; —, no data]

Well identifier	Model layer	Simulated and observed groundwater levels and difference, in feet						Water-level change, in feet, 2004–2015	
		2004 calibration			2015 calibration				
		Simulated	Observed	Difference	Simulated	Observed	Difference	Simulated	Observed
34H371	7	14.30	15.50	–1.20	17.20	16.20	1.00	2.90	0.70
34H373	7	8.37	3.98	4.39	13.10	8.81	4.29	4.73	4.83
34H374	7	7.43	7.20	0.23	11.90	10.00	1.90	4.47	2.80
34H393	7	13.80	14.60	–0.80	16.80	16.70	0.10	3.00	2.10
34H400	7	8.56	4.34	4.22	12.90	8.07	4.83	4.34	3.73
34H401	7	7.95	2.53	5.42	12.40	6.92	5.48	4.45	4.39
34H424	7	7.86	—	—	12.60	12.40	0.20	4.74	—
34H434	7	10.30	6.13	4.17	14.30	12.60	1.70	4	6.47
34H469	7	7.48	6.61	0.87	11.90	11.50	0.40	4.42	4.89
34H514	7	8.50	—	—	13.60	12.60	1.00	5.10	—
34H552	7	8.99	—	—	13.30	10.40	2.90	4.31	—
33H127	9	5.98	7.85	–1.87	10.60	12.80	–2.20	4.62	4.95
33H154	9	4.42	–17.90	22.32	9.38	8.20	1.18	4.96	26.10
34H334	9	7.71	12.40	–4.69	13.30	16.50	–3.20	5.59	4.10
34H402	9	7.97	8.20	–0.23	12.40	10.90	1.50	4.43	—
34H403	9	14.00	16.30	–2.30	17.00	17.50	–0.50	3.00	1.20
33H188	11	18.70	20.10	–1.40	20.60	—	—	1.90	—
33H206	11	12.50	14.00	–1.50	15.40	16.20	–0.80	2.90	2.20
33J044	11	15.90	19.10	–3.20	17.90	—	—	2.00	—
34H391	11	15.30	11.90	3.40	17.90	17.10	0.80	2.60	5.20
34H436	11	13.50	15.80	–2.30	16.60	19.30	–2.70	3.10	3.50
34H495	11	14.50	24.00	–9.50	17.30	29.50	–12.20	2.80	5.50
34H500	11	14.50	21.40	–6.90	17.30	—	—	2.80	—

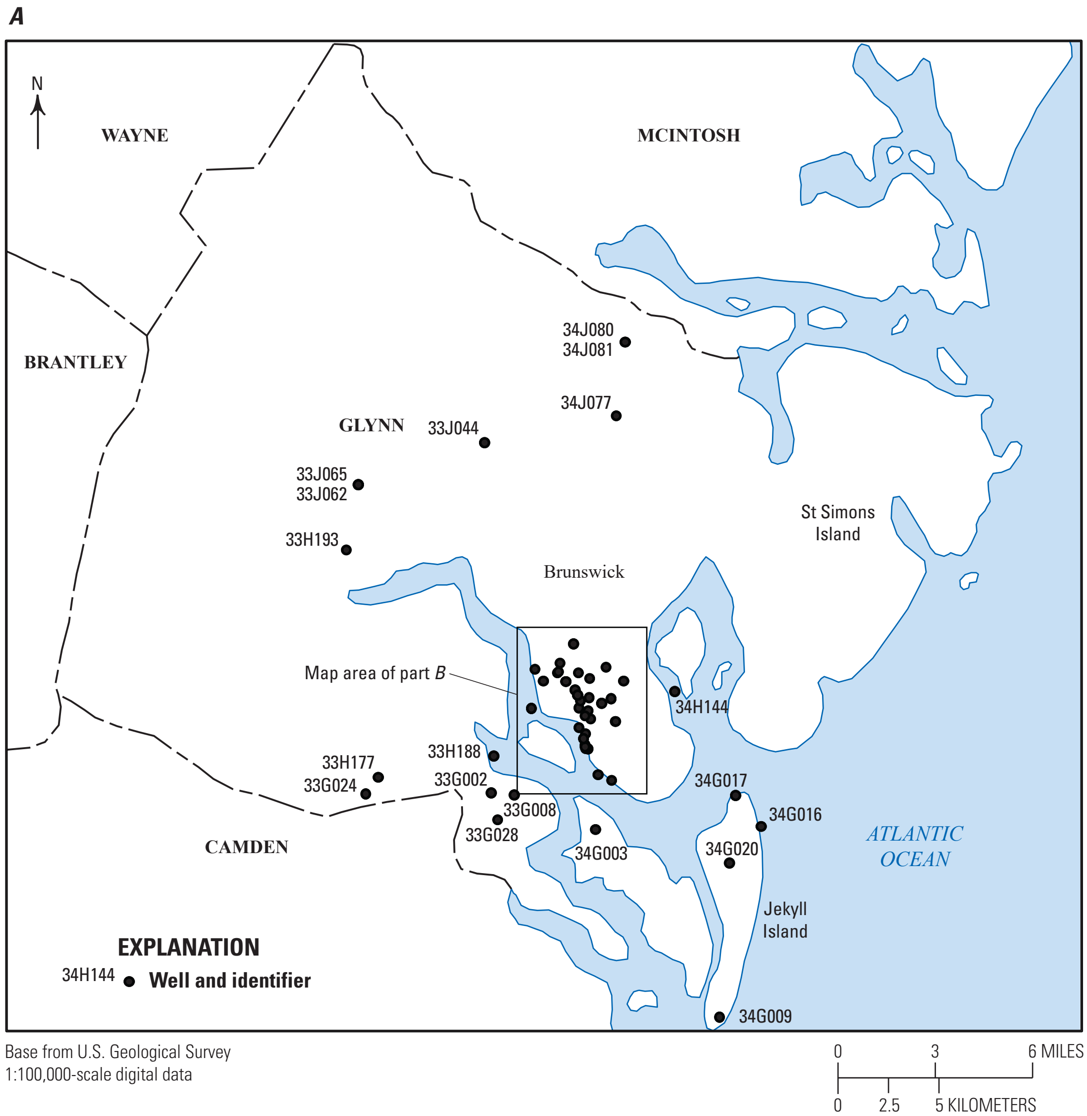

Figure 1–1. Maps showing location of wells used for 2004 and 2015 simulations in (*A*) Glynn County and (*B*) Brunswick, Georgia.

B

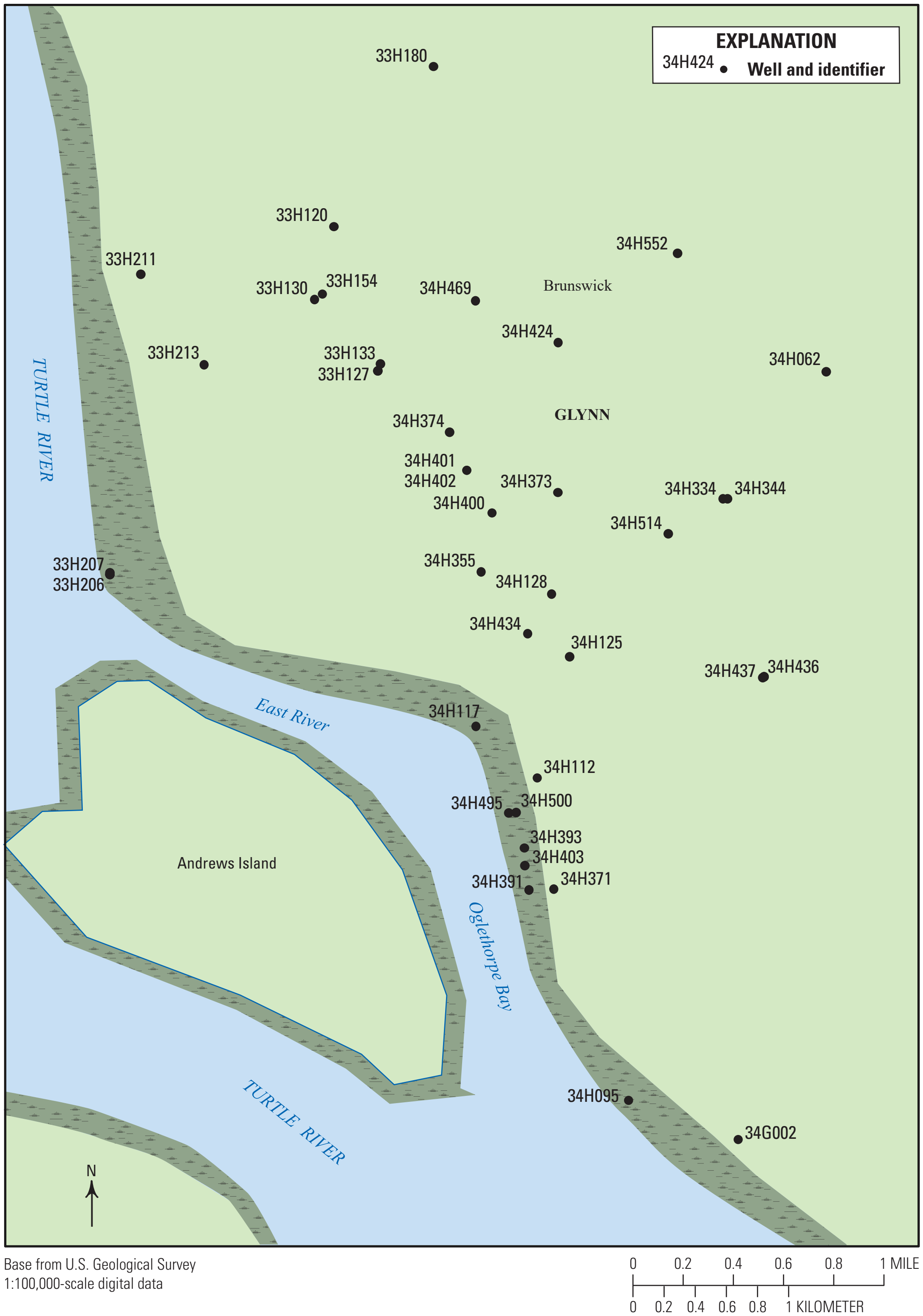

Figure 1–1. —Continued

Appendix 2. Particle Backtracking Summary for 2015 Base Case and Scenario C Simulations

Table 2–1. Particle backtracking summary for 2015 Base Case and Scenario C simulations.

[Local z-coordinate where 1.00 represents top of cell and 0 represents bottom; see figure 1 for station locations]

Particle No.	Model			Global coordinate, in feet			Local z-coordinate, in cell	Travel time, in days
	Column	Row	Layer	x-direction	y-direction	z-direction		
2015 base case, 20 and 50 year								
Well 34H560								
1	247	232	7	860,237	425,103	–649.86	0.25	0.00
1	249	219	9	861,353	431,706	–720.60	0.79	7,305.00
1	250	209	9	861,952	436,915	–730.93	0.75	18,262.50
2	247	232	7	860,237	425,103	–578.40	0.75	0.00
2	248	218	7	861,041	432,042	–603.13	0.59	7,305.00
2	249	208	7	861,308	437,194	–609.16	0.57	18,262.50
3	247	232	7	860,237	425,353	–649.86	0.25	0.00
3	250	220	9	861,724	431,136	–691.44	0.97	7,305.00
3	252	210	9	862,775	436,463	–702.27	0.93	18,262.50
4	247	232	7	860,237	425,353	–578.40	0.75	0.00
4	250	218	7	861,947	432,082	–591.51	0.65	7,305.00
4	252	208	7	862,874	436,995	–599.74	0.64	18,262.50
5	247	232	7	860,488	425,103	–649.86	0.25	0.00
5	255	222	9	864,227	430,339	–700.94	0.92	7,305.00
5	261	212	9	867,248	434,997	–715.28	0.87	18,262.50
6	247	232	7	860,488	425,103	–578.40	0.75	0.00
6	255	221	7	864,364	430,681	–588.41	0.64	7,305.00
6	261	212	7	867,314	435,200	–599.96	0.62	18,262.50
7	247	232	7	860,488	425,353	–649.86	0.25	0.00
7	252	222	8	862,885	430,255	–685.45	0.49	7,305.00
7	256	213	9	864,775	434,809	–697.06	0.96	18,262.50
8	247	232	7	860,488	425,353	–578.40	0.75	0.00
8	253	220	7	863,370	431,477	–585.96	0.66	7,305.00
8	257	210	7	865,425	436,148	–595.30	0.65	18,262.50
Well 34H449								
9	257	232	7	865,257	425,103	–650.01	0.25	0.00
9	263	224	9	868,165	429,461	–738.82	0.70	7,305.00
9	273	218	9	873,583	432,221	–755.04	0.66	18,262.50
10	257	232	7	865,257	425,103	–571.03	0.75	0.00
10	262	222	7	867,868	430,020	–599.70	0.57	7,305.00
10	272	217	7	872,865	432,942	–615.05	0.56	18,262.50
11	257	232	7	865,257	425,353	–650.01	0.25	0.00
11	263	224	9	868,186	429,405	–698.08	0.97	7,305.00
11	273	218	9	873,646	432,154	–715.20	0.93	18,262.50

Table 2–1. Particle backtracking summary for 2015 Base Case and Scenario C simulations.—Continued

[Local z-coordinate where 1.00 represents top of cell and 0 represents bottom; see figure 1 for station locations]

Particle No.	Model			Global coordinate, in feet			Local z-coordinate, in cell	Travel time, in days
	Column	Row	Layer	x-direction	y-direction	z-direction		
2015 base case, 20 and 50 year—Continued								
Well 34H449—Continued								
12	257	232	7	865,257	425,353	–571.03	0.75	0.00
12	264	222	7	869,056	430,104	–588.47	0.65	7,305.00
12	275	218	7	874,432	432,357	–606.29	0.64	18,262.50
13	257	232	7	865,508	425,103	–650.01	0.25	0.00
13	267	225	9	870,501	428,552	–708.08	0.94	7,305.00
13	280	223	9	877,080	429,827	–734.29	0.88	18,262.50
14	257	232	7	865,508	425,103	–571.03	0.75	0.00
14	268	225	7	871,001	428,834	–593.15	0.64	7,305.00
14	281	223	7	877,509	429,881	–617.48	0.62	18,262.50
15	257	232	7	865,508	425,353	–650.01	0.25	0.00
15	266	224	8	869,967	429,356	–693.19	0.91	7,305.00
15	273	221	9	873,402	430,699	–709.64	0.97	18,262.50
16	257	232	7	865,508	425,353	–571.03	0.75	0.00
16	267	223	7	870,252	429,514	–589.06	0.66	7,305.00
16	279	220	7	876,232	431,074	–611.25	0.65	18,262.50
Well 34H445								
17	266	248	7	869,776	417,102	–684.77	0.25	0.00
17	270	257	7	871,826	412,662	–736.03	0.02	7,305.00
17	274	267	7	874,065	407,529	–721.04	0.13	18,262.50
18	266	248	7	869,776	417,102	–606.10	0.75	0.00
18	270	257	7	871,826	412,662	–636.01	0.67	7,305.00
18	274	267	7	874,065	407,529	–634.86	0.70	18,262.50
19	266	248	7	869,776	417,352	–684.77	0.25	0.00
19	268	253	9	870,781	414,721	–835.21	0.49	7,305.00
19	274	267	7	874,097	407,645	–727.84	0.08	18,262.50
20	266	248	7	869,776	417,352	–606.10	0.75	0.00
20	267	255	7	870,206	413,715	–657.38	0.52	7,305.00
20	274	267	7	874,097	407,645	–637.12	0.69	18,262.50
21	266	248	7	870,027	417,102	–684.77	0.25	0.00
21	272	256	7	872,890	413,329	–728.35	0.06	7,305.00
21	275	267	7	874,560	407,895	–717.93	0.14	18,262.50
22	266	248	7	870,027	417,102	–606.10	0.75	0.00
22	272	256	7	872,890	413,329	–632.26	0.69	7,305.00
22	275	267	7	874,560	407,895	–633.34	0.71	18,262.50
23	266	248	7	870,027	417,352	–684.77	0.25	0.00
23	270	250	8	872,153	416,132	–733.23	0.86	7,305.00
23	276	266	7	874,734	408,158	–721.90	0.11	18,262.50
24	266	248	7	870,027	417,352	–606.10	0.75	0.00
24	273	254	7	873,644	414,464	–633.04	0.67	7,305.00
24	276	266	7	874,734	408,158	–633.91	0.70	18,262.50

Table 2–1. Particle backtracking summary for 2015 Base Case and Scenario C simulations.—Continued

[Local z-coordinate where 1.00 represents top of cell and 0 represents bottom; see figure 1 for station locations]

Particle No.	Model Column	Model Row	Model Layer	Global coordinate, in feet x-direction	Global coordinate, in feet y-direction	Global coordinate, in feet z-direction	Local z-coordinate, in cell	Travel time, in days
Scenario C, 20 and 50 year								
Well 34H560								
1	247	232	7	860,237	425,103	–649.86	0.25	0.00
1	243	236	9	858,348	423,236	–728.54	0.77	7,305.00
1	240	241	9	856,662	420,910	–744.89	0.69	18,262.50
2	247	232	7	860,237	425,103	–578.40	0.75	0.00
2	242	237	7	858,065	422,883	–611.42	0.58	7,305.00
2	239	242	7	856,212	420,346	–622.20	0.55	18,262.50
3	247	232	7	860,237	425,353	–649.86	0.25	0.00
3	240	233	9	856,674	424,685	–722.52	0.79	7,305.00
3	236	238	9	854,920	422,443	–739.25	0.71	18,262.50
4	247	232	7	860,237	425,353	–578.40	0.75	0.00
4	239	233	7	856,273	424,646	–611.61	0.59	7,305.00
4	235	238	7	854,333	422,164	–623.93	0.55	18,262.50
5	247	232	7	860,488	425,103	–649.86	0.25	0.00
5	247	236	9	860,252	423,005	–757.21	0.58	7,305.00
5	244	241	9	858,798	420,527	–774.40	0.51	18,262.50
6	247	232	7	860,488	425,103	–578.40	0.75	0.00
6	247	238	7	860,340	422,426	–615.00	0.53	7,305.00
6	244	243	7	858,757	419,763	–625.72	0.49	18,262.50
7	247	232	7	860,488	425,353	–649.86	0.25	0.00
7	243	231	9	858,174	425,830	–774.47	0.44	7,305.00
7	236	235	9	855,022	423,673	–796.96	0.33	18,262.50
8	247	232	7	860,488	425,353	–578.40	0.75	0.00
8	243	228	7	858,554	427,061	–627.52	0.42	7,305.00
8	234	233	7	853,681	424,931	–649.22	0.32	18,262.50
Well 34H449								
9	257	232	7	865,257	425,103	–650.01	0.25	0.00
9	254	235	9	863,939	423,821	–731.31	0.76	7,305.00
9	253	238	9	863,153	422,001	–750.67	0.66	18,262.50
10	257	232	7	865,257	425,103	–571.03	0.75	0.00
10	254	236	7	863,704	423,418	–599.84	0.59	7,305.00
10	252	240	7	862,758	421,246	–610.28	0.55	18,262.50
11	257	232	7	865,257	425,353	–650.01	0.25	0.00
11	252	231	9	862,965	425,620	–740.90	0.66	7,305.00
11	250	235	9	861,638	423,662	–795.42	0.34	18,262.50
12	257	232	7	865,257	425,353	–571.03	0.75	0.00
12	252	231	7	862,720	425,936	–603.92	0.54	7,305.00
12	250	232	9	862,028	425,038	–691.01	0.99	18,262.50

Table 2–1. Particle backtracking summary for 2015 Base Case and Scenario C simulations.—Continued

[Local z-coordinate where 1.00 represents top of cell and 0 represents bottom; see figure 1 for station locations]

Particle No.	Model			Global coordinate, in feet			Local z-coordinate, in cell	Travel time, in days
	Column	Row	Layer	x-direction	y-direction	z-direction		
Scenario C, 20 and 50 year—Continued								
Well 34H449—Continued								
13	257	232	7	865,508	425,103	–650.01	0.25	0.00
13	259	234	9	866,630	424,225	–769.10	0.54	7,305.00
13	259	237	9	866,559	422,579	–796.07	0.40	18,262.50
14	257	232	7	865,508	425,103	–571.03	0.75	0.00
14	260	235	7	866,971	423,792	–607.48	0.55	7,305.00
14	260	239	7	866,776	421,847	–622.16	0.49	18,262.50
15	257	232	7	865,508	425,353	–650.01	0.25	0.00
15	257	230	9	865,625	426,396	–768.73	0.49	7,305.00
15	254	229	9	864,039	426,782	–817.22	0.16	18,262.50
16	257	232	7	865,508	425,353	–571.03	0.75	0.00
16	258	228	7	865,984	427,282	–607.06	0.51	7,305.00
16	256	226	7	864,917	428,016	–633.94	0.33	18,262.50
Well 34H445								
17	266	248	7	869,776	417,102	–684.77	0.25	0.00
17	264	252	9	868,679	415,233	–766.54	0.83	7,305.00
17	262	256	9	867,781	413,393	–775.21	0.82	18,262.50
18	266	248	7	869,776	417,102	–606.10	0.75	0.00
18	263	253	7	868,382	414,703	–636.17	0.61	7,305.00
18	261	258	7	867,465	412,449	–643.60	0.62	18,262.50
19	266	248	7	869,776	417,352	–684.77	0.25	0.00
19	263	249	9	868,313	416,948	–792.86	0.63	7,305.00
19	260	252	9	867,048	415,155	–817.15	0.52	18,262.50
20	266	248	7	869,776	417,352	–606.10	0.75	0.00
20	261	249	7	867,614	416,906	–636.12	0.54	7,305.00
20	259	253	7	866,141	414,808	–650.68	0.50	18,262.50
21	266	248	7	870,027	417,102	–684.77	0.25	0.00
21	267	252	9	870,388	415,184	–772.28	0.82	7,305.00
21	267	255	9	870,278	413,587	–783.88	0.78	18,262.50
22	266	248	7	870,027	417,102	–606.10	0.75	0.00
22	267	253	7	870,560	414,511	–640.03	0.61	7,305.00
22	267	258	7	870,354	412,309	–648.82	0.60	18,262.50
23	266	248	7	870,027	417,352	–684.77	0.25	0.00
23	268	248	9	870,963	417,125	–823.71	0.48	7,305.00
23	269	251	9	871,464	415,569	–865.48	0.30	18,262.50
24	266	248	7	870,027	417,352	–606.10	0.75	0.00
24	270	248	7	871,730	417,377	–651.30	0.50	7,305.00
24	272	251	7	872,694	415,601	–665.40	0.45	18,262.50

For more information concerning the research in this report, contact
South Atlantic Water Science Center
U.S. Geological Survey
720 Gracern Road, Suite 129
Columbia, SC 29210

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Cherry—**Simulation of Groundwater Flow in the Brunswick Area, Georgia, for 2004 and 2015, and Selected Groundwater-Management Scenarios**—SIR 2019–5035