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Groundwater Conditions in the Brunswick–Glynn County Area, Georgia, 2009

Scientific Investigations Report 2011–5087

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

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Cover photograph. U.S. Highway 17, Sidney Lanier Bridge, from north side of Brunswick River, Brunswick, Glynn County, Georgia (by Alan M. Cressler, USGS).

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KEN SALAZAR, Secretary

U.S. Geological Survey
Marcia K. McNutt, Director

U.S. Geological Survey, Reston, Virginia: 2011

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Conversion Factors and Datums

Multiply	By	To obtain
	Length	
inch	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square foot (ft^2)	0.09290	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	3.785	liter (L)
Million gallons (Mgal)	3,785	cubic meter (m^3)
	Flow rate	
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)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F = (1.8 \times °C) + 32$$

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

$$°C = (°F - 32) / 1.8$$

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Historical data collected and stored as National Geodetic Vertical Datum of 1929 (NGVD 29).

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

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

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25 °C).

Georgia Well-Identification System

Wells described in this report are assigned a well identifier according to a system based on the index of USGS 7.5-minute topographic maps of Georgia. Each map in Georgia has 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 NWIS database, this information is stored in the "Station Name" field; in NWIS Web, it is labeled "Site Name."

Acknowledgments

The authors appreciate the support and guidance provided by Keith Morgan and Billy Simmons of the Brunswick–Glynn County Joint Water and Sewer Commission. Thanks are extended to John Day, of the Jekyll Island Authority, for logistical support during the collection of water-level measurements. Assistance was provided by Ricky Manning of Pinova Inc., and Kenneth Hase of Georgia–Pacific Cellulose LLC to ensure that the records from chloride sampling at each facility were complete. Several USGS employees played an important role in the collection, processing, and quality assurance of groundwater data, including Michael D. Hamrick, O. Gary Holloway, and Alan M. Cressler. Special thanks are extended to David C. Leeth of the USGS for his assistance with water-level trend analysis and all associated summary statistics.

Groundwater Conditions in the Brunswick–Glynn County Area, Georgia, 2009

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Abstract

The Upper Floridan aquifer is contaminated with saltwater in a 2-square-mile area of downtown Brunswick, Georgia. The presence of this saltwater has limited the development of the groundwater supply in the Glynn County area. Hydrologic, geologic, and water-quality data are needed to effectively manage water resources. Since 1959, the U.S. Geological Survey (USGS) has conducted a cooperative water program with the City of Brunswick and Glynn County to monitor and assess the effect of groundwater development on saltwater intrusion within the Floridan aquifer system. The potential development of alternative sources of water in the Brunswick and surficial aquifer systems also is an important consideration in coastal areas.

During calendar year 2009, the cooperative water program included continuous water-level recording of 13 wells completed in the Floridan, Brunswick, and surficial aquifer systems; collecting water levels from 46 wells to map the potentiometric surface of the Upper Floridan aquifer in Glynn County during August 2009; and collecting and analyzing water samples from 55 wells completed in the Floridan aquifer system, of which 27 wells were used to map chloride concentrations in the upper water-bearing zone of the Upper Floridan aquifer in the Brunswick area during August 2009. Periodic water-level measurements also were collected from two wells completed in the Upper Floridan aquifer and four wells completed in the Brunswick aquifer system on Jekyll Island. Equipment was installed on one well to enable real-time specific conductance monitoring in the area surrounding the chloride plume.

During 2008–2009, water levels in 30 of the 32 wells monitored in the Brunswick–Glynn County area rose at a rate of 0.24 to 7.58 feet per year (ft/yr). The largest rise of 7.58 ft/yr was in the Upper Floridan aquifer. These rises corresponded to a period of above normal precipitation and decreased pumping. Declines during 2008–2009 were recorded in wells completed in the Brunswick aquifer system (0.37 ft/yr) and Lower Floridan aquifer (0.83 ft/yr).

Chloride data collected by two local industrial groundwater users at their well fields since 1958 were compiled and compared with data collected by the USGS during the same period. The results indicate that chloride concentrations at the two well fields have continued to rise despite modification of production wells to eliminate deep saline zones and decreases in pumpage at both facilities. One of the industrial users, Pinova Inc., plugged the lower portions of nine production wells in the mid to late 1960s, which generally decreased chloride concentrations to less than 100 milligrams per liter (mg/L) for a period of 10 to 20 years. However, chloride concentrations eventually returned to previous levels despite decreases in pumpage. During 1990–2009, chloride concentrations at the other industrial user's well field (Georgia–Pacific Cellulose LLC) generally increased despite a 16 million gallon per day decrease in pumpage during this period. Data from the Georgia–Pacific Cellulose well field and additional chloride data from USGS observation wells located to the east indicate continued movement of chloride from the source area located southeast of the site toward the well field.

Introduction

In the Brunswick–Glynn County, Georgia, area (figs. 1, 2), saltwater has been entering the Upper Floridan aquifer for about 50 years. As of 2009, within a 2-square-mile (mi^2) area in downtown Brunswick, the aquifer yielded water with a chloride concentration greater than 2,000 milligrams per liter (mg/L), which exceeds the State and Federal secondary drinking-water standard of 250 mg/L (Georgia Environmental Protection Division, 1997; U.S. Environmental Protection Agency, 2000). Saltwater contamination has limited further development of the Upper Floridan aquifer in the Brunswick area, prompting interest in the development of alternative sources of water supply, primarily from the shallower surficial and Brunswick aquifer systems. Monitoring groundwater conditions and conducting studies to better define the occurrence of saltwater contamination and assess alternative water sources is important for management of water resources in the Brunswick–Glynn County area.

In response to concerns about saltwater intrusion within the Upper Floridan aquifer, a cooperative water program (CWP) between the U.S. Geological Survey (USGS), the City of Brunswick, and Glynn County has been in existence since 1959. Since its inception, the CWP has placed emphasis on providing the necessary information about the Floridan aquifer system to manage saltwater intrusion and evaluate water-resources data. During 2009, cooperating entities were the Brunswick–Glynn County Joint Water and Sewer Commission (JWSC) and the Jekyll Island Authority.

The current study addresses one of the six USGS science strategy goals, “A water census of the United States: Quantifying, forecasting, and securing freshwater for America’s future” (U.S. Geological Survey, 2007). The study also addresses two priority issues of the USGS 2007 Federal-State Water Cooperative Program: Understanding ecosystems and predicting ecosystem change and the role of environment and wildlife in human health (U.S. Geological Survey, 2007). Finally, this study meets the science plan goal of the USGS Georgia Water Science Center to support Federal and State water-resources programs through support for increasing the scientific understanding of the occurrence and nature of groundwater in the coastal region of Georgia.

Purpose and Scope

This report documents the hydrologic, geologic, and water-quality data in the Brunswick–Glynn County area during 2009, which are needed to effectively manage water resources in the coastal area of Georgia. During calendar year 2009, the CWP, which includes all of Glynn County (fig. 2), was continued and included continuous water-level and specific conductance monitoring of 13 wells completed in the Floridan, Brunswick, and surficial aquifer systems (table 1). Groundwater levels and trends in the surficial, Brunswick, and Floridan aquifer systems are presented for selected wells throughout Glynn County. Estimated annual water-level change (trend) is reported for the period of record and for 2008–2009.

The potentiometric surface of the Upper Floridan aquifer was mapped based on water-level measurements in 46 wells during August 2009 (table 2). On Jekyll Island, periodic water-level measurements were collected in six wells completed in the Upper Floridan and Brunswick aquifers during 2009–2010, with additional data during 2002–2009 obtained from the Jekyll Island Authority.

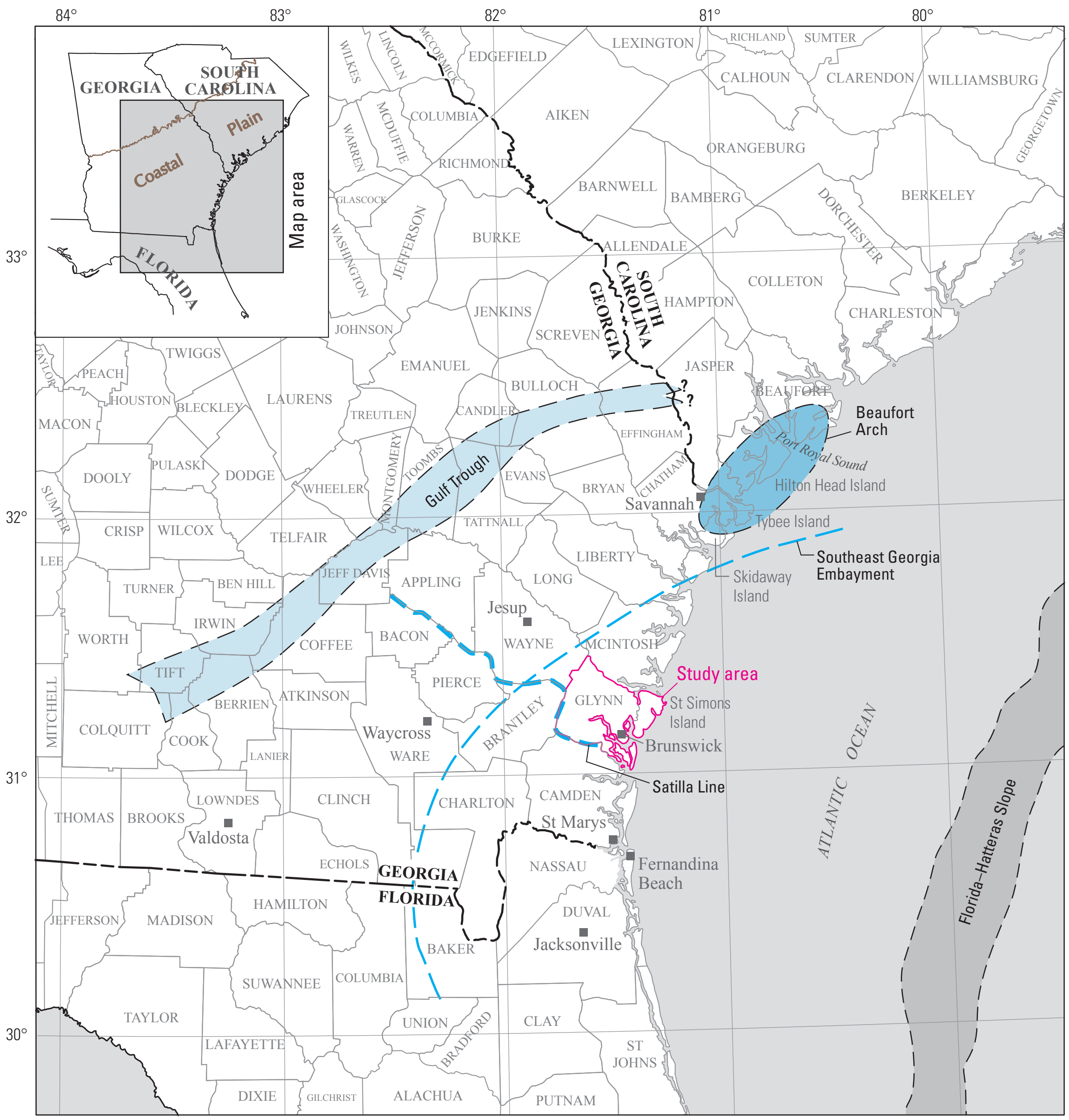
In the Floridan aquifer system, water samples were collected and analyzed for chloride concentration from 55 wells in August 2009 (table 3). These data were used to map the configuration of the chloride plume in the Upper Floridan aquifer at the city of Brunswick. Additional chloride data from 37 production wells were obtained from two local industries dating back to 1958, which helped assess how the configuration of the chloride plume has developed over time (tables 4, 5). During 2009, an additional well was equipped with real-time specific-conductance monitoring capability just north of the chloride plume (34H134; table 1).

Description of Study Area

Glynn County is located on the Atlantic Coast about 80 miles (mi) south of Savannah, GA, and about 87 mi north of Jacksonville, Florida (fig. 1). The county covers an area of 422 mi² and includes the barrier islands of St. Simons, Little St. Simons, and Jekyll (fig. 2). The primary population center is the city of Brunswick, which is located on a peninsula and has an incorporated area that covers approximately 50 mi² and a secondary population center outside the city limits on the southern part of St. Simons Island. The city of Brunswick serves as the county seat and is bounded on the east by the offshore islands of St. Simons, Little St. Simons, and Jekyll. Brunswick is bounded on the west and south by tidally influenced estuaries and rivers, including the Brunswick River and the Little Satilla River. Glynn County is bounded on the north by the Altamaha River, which empties into the Atlantic Ocean north of Little St. Simons Island (fig. 2).

Glynn County is located in the Coastal Plain Physiographic Province (fig. 1), and altitudes range from 0 feet (ft) along the coast to 40 ft (North American Vertical Datum of 1988; NAVD 88) in the northwestern part of the county. Outside the urbanized areas near the city of Brunswick and St. Simons Island, land use in Glynn County is a mix of forest, grazed woodland, marsh, and swampland. Glynn County has a mild climate with warm humid summers and mild winters with an average temperature of 70 degrees Fahrenheit (°F) for the period 1971–2000 (National Oceanic and Atmospheric Administration, 2002). Mean-annual precipitation for the same period is about 49 inches in the Brunswick area, and rainfall occurs most often during June, July, and August (Priest, 2004).

Coastal Plain sediments consist of consolidated to unconsolidated layers of sand and clay and semiconsolidated to very dense layers of limestone and dolomite, which range in age from Late Cretaceous to Holocene. In general, these geologic units have been divided into aquifers and confining units based upon the water-bearing characteristics, with the more permeable layers forming the aquifers and strata of low permeability making up the confining units (fig. 3). These sedimentary units unconformably overlie igneous, metamorphic, and sedimentary rocks of Paleozoic to Mesozoic age and reach a maximum thickness of 5,500 ft in Camden County to the south of Glynn County (Wait and Davis, 1986). The thickness of Coastal Plain sediments varies and is influenced by major structural features in the area, such as the Southeast Georgia Embayment, which is a shallow east-to-northeast plunging syncline that allows Coastal Plain sediments to reach a maximum thickness in the Glynn County area (figs. 1, 4). It is postulated that subsidence occurred at a moderate rate from the Late Cretaceous to late Cenozoic (Miller, 1986).



Base from U.S. Geological Survey 1:100,000-scale digital data
Structural features modified from Applied Coastal Research Laboratory, 2002;
Weems and Edwards, 2001; Kellam and Gorday, 1990; and Paull and Dillon, 1980.

Figure 1. Location of study area, Brunswick–Glynn County, Georgia, and major structural features in coastal Georgia and South Carolina (modified from Payne and others, 2005).

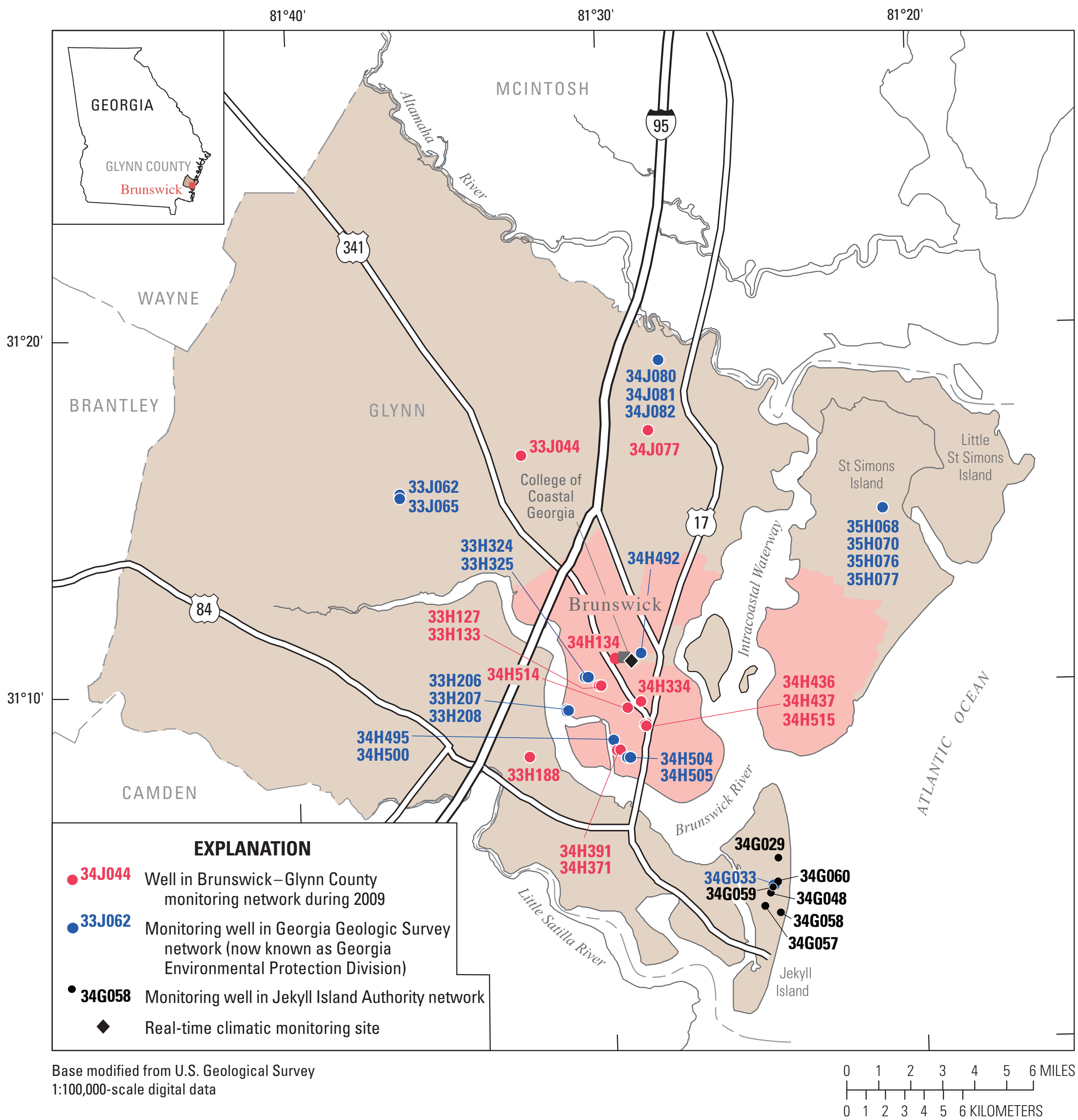
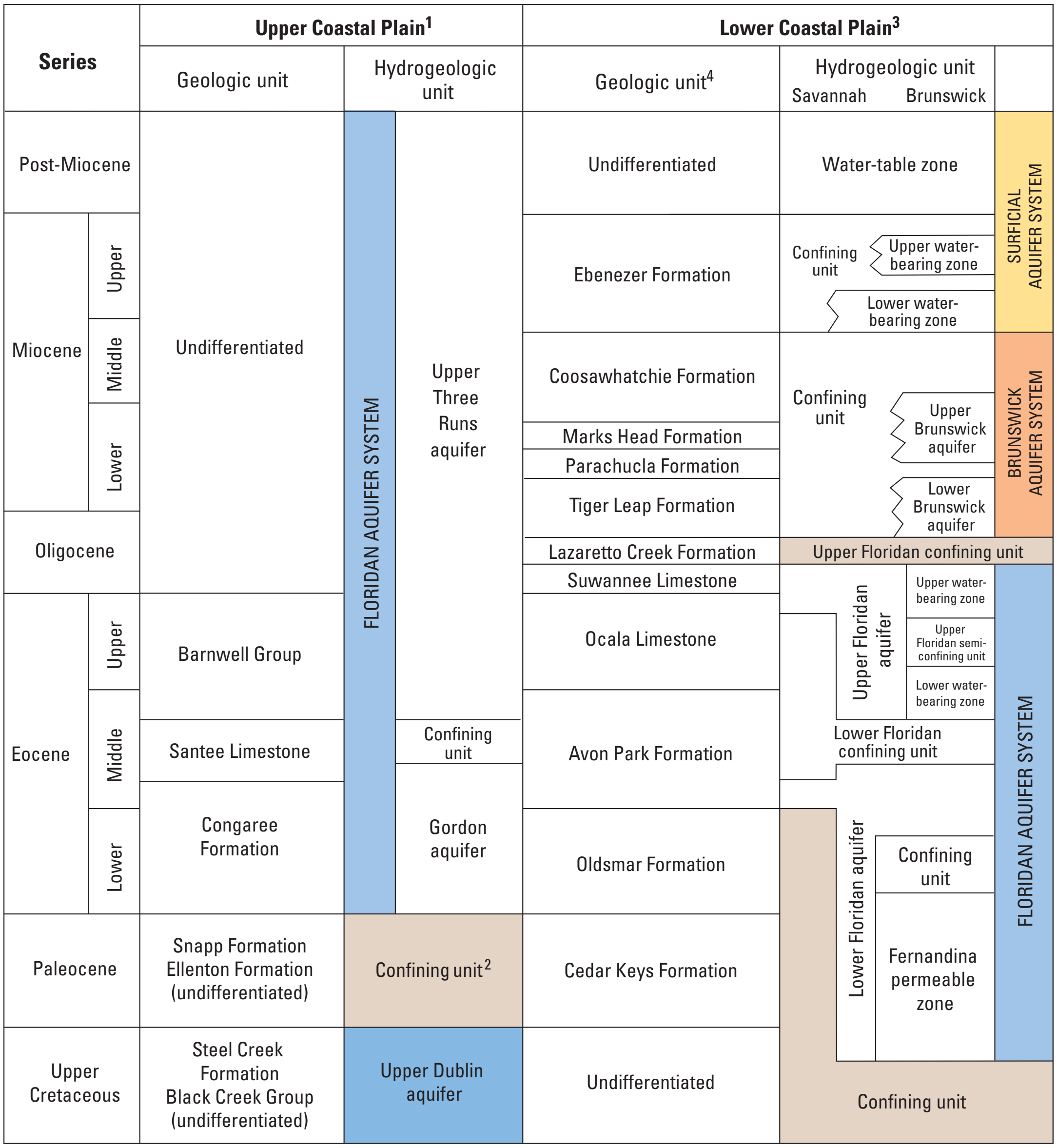


Figure 2. Location of continuous groundwater-level monitoring networks for the Brunswick–Glynn County area, Georgia.



[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.

Figure 3. Generalized correlation of geologic and hydrogeologic units in the Coastal Plain of Georgia (modified from Payne and others, 2005).

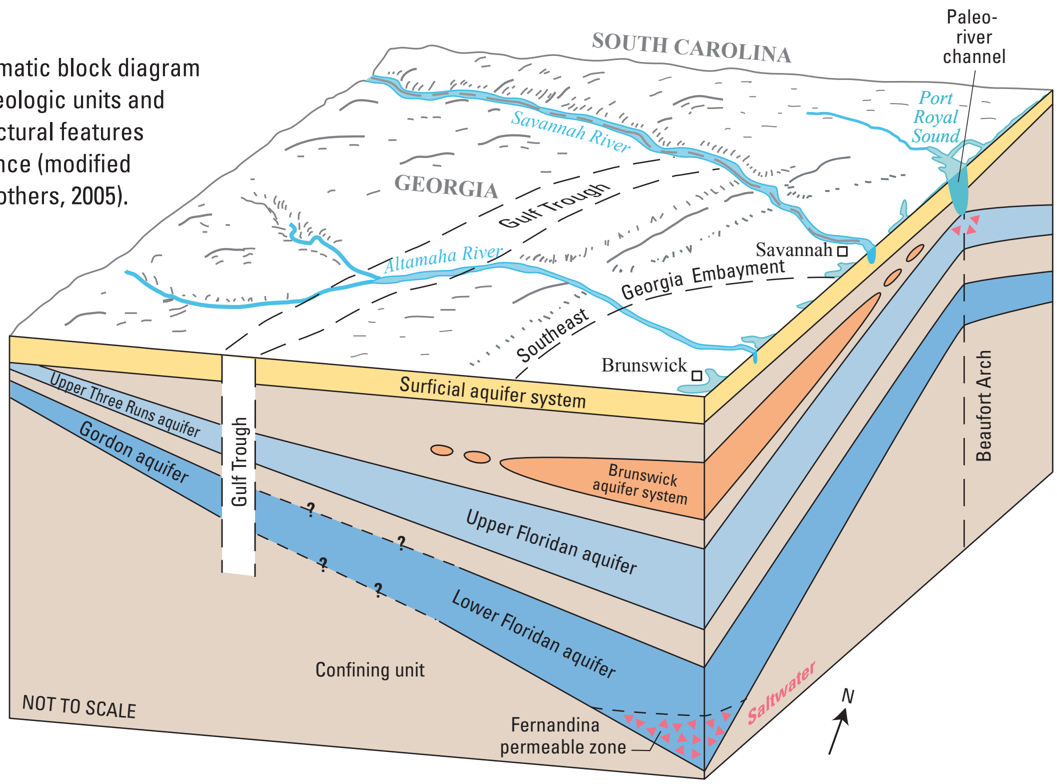


Figure 4. Schematic block diagram showing hydrogeologic units and influence of structural features on their occurrence (modified from Payne and others, 2005).

Methods

Continuous water-level measurements were obtained from 32 wells during 2009. Each well was equipped with electronic data recorders that recorded water levels at 60-minute intervals, and the data generally were retrieved bimonthly. Five wells had real-time satellite telemetry that recorded water levels at 60-minute intervals. Three of the real-time sites were equipped to monitor water levels and specific conductance and the other two sites recorded water levels only. An additional site monitored specific conductance and the real-time satellite telemetry recorded data at 15-minute intervals because of irregular pumping schedules at the site, which is an active production well. Real-time satellite telemetry data are transmitted every 1 to 4 hours (based on equipment) for display on the USGS Georgia Water Science Center Web site at *http://waterdata.usgs.gov/ga/nwis/current?type=gw/*.

Additional water-level measurements were measured at 46 wells using either a pressure transducer or graduated steel tape. Land-surface altitude at each of these well sites, in feet above NAVD 88, is either based on land-surface contours taken from a map or surveyed using leveling or global positioning system equipment. To estimate water-level trends, the Levenberg–Marquardt (LMA) method for minimization of a weighted least-squares merit function (Janert, 2010) was used to determine a straight-line fit to both recent (2008–2009) and period-of-record monthly-mean groundwater levels. Estimated water levels from these straight-line fits were used to compute an annual rate of change (yearly slope) for the period of record and for 2008–2009. A more thorough discussion of the LMA method is presented at the end of this report along with associated summary statistics for each well and for straight-line fits (appendix).

Determination of chloride concentration of USGS samples collected after 1966 but before 1983 were analyzed using field titration with silver nitrate (Jones and Maslia, 1994). During 1983–2006, all USGS samples were analyzed at the USGS laboratory in Ocala, FL. Chloride concentrations of groundwater samples analyzed by the USGS laboratory were determined by using ion chromatography according to U.S. Environmental Protection Agency (USEPA) method 300.0 (Pfaff, 1999). Since 2006, all samples have been analyzed by TestAmerica Laboratories, Inc., in Savannah, GA, using USEPA method 325.1. Water samples collected at the Pinova Inc. and Georgia–Pacific Cellulose LLC well fields were analyzed at their onsite laboratories using titration with silver nitrate (Julie Dickens, Georgia–Pacific Cellulose LLC, written commun., 2010; Ricky Manning, Pinova Inc., written commun., 2010).

Hydrogeology

The primary source of water for all uses in the coastal areas of Georgia is the Floridan aquifer system, which consists of the Upper and Lower Floridan aquifers (Miller, 1986; Krause and Randolph, 1989). Secondary sources of water include the surficial and Brunswick aquifer systems (Clarke, 2003), which consist mostly of Miocene- to Holocene-age sand separated by confining units of much lower permeability (fig. 3).

The Brunswick aquifer system consists of two water-bearing zones—the upper Brunswick aquifer and the lower Brunswick aquifer (Clarke, 2003; fig. 3). The upper Brunswick aquifer consists of poorly sorted, fine to coarse, slightly phosphatic and dolomitic quartz sand and dense phosphatic limestone (Clarke and others, 1990). The lower Brunswick aquifer consists of poorly sorted, fine to coarse, phosphatic, dolomitic sand (Clarke and others, 1990). In general, the upper Brunswick aquifer is thinner, and as a result, has smaller transmissivity than the lower Brunswick aquifer. Outside Glynn County, the Brunswick aquifer system thins, or is discontinuous, and has a higher percentage of fine-grained sediments (Clarke, 2003).

The Floridan aquifer system consists of the Upper Floridan and Lower Floridan aquifers, which are composed of mostly carbonate rocks that vary in age from predominantly Paleocene to Oligocene that locally include Upper Cretaceous rocks (Miller, 1986; Krause and Randolph, 1989; fig. 3). The Floridan aquifer system extends from coastal areas in southeastern South Carolina, west across the coastal plain of Georgia and Alabama, and south covering Florida. The Upper Floridan aquifer is overlain by a confining unit consisting of layers of silty clay and dense phosphatic dolomite of Oligocene age that separate the aquifer from the Brunswick aquifer system (Clarke, 2003).

The Upper Floridan aquifer is highly productive and consists of Eocene- to Oligocene-age limestone and dolomite (Clarke and others, 1990). In the Brunswick–Glynn County area, the Upper Floridan aquifer is divided into an upper and lower water-bearing zone (UWBZ and LWBZ, respectively) identified by Wait and Gregg (1973). Large variability in the range of transmissivity where the Upper Floridan aquifer is largely carbonate may indicate the presence of fractures or solution openings and related anisotropic distribution of hydraulic properties (Warner and Aulenbach, 1999; Clarke and others, 2004). Maslia (1987) attributed greater anisotropy between local- and regional-scale tests at Brunswick to preferential flow along vertical solution channels associated with high-angle reverse faults and fractures. Wait and Gregg (1973) documented a well that tapped both the UWBZ and LWBZ, yet 70 percent of production was estimated to be contributed from the UWBZ and the remainder from the LWBZ, indicating that the UWBZ is more productive than the LWBZ. In the Brunswick area, the UWBZ is separated from the LWBZ by about 160 ft of soft limestone (Gregg and Zimmerman, 1974).

The Upper Floridan aquifer is underlain by a confining unit of dense recrystallized limestone and dolomite of middle Eocene age that hydraulically separates to varying degrees the Upper Floridan aquifer from the Lower Floridan aquifer (fig. 3). Locally in the Brunswick area, the confining unit is breached by fractures or solution openings, which enhance the exchange of water between the Upper and Lower Floridan aquifers (Krause and Randolph, 1989). These features have allowed saline water from the Fernandina permeable zone to migrate upward into primarily the UWBZ of the Upper Floridan aquifer, where water-level altitudes are lower because of large-scale pumping by local industry.

The Fernandina permeable zone is a deeply buried, cavernous, highly permeable, saline water-bearing unit that, in the Brunswick area, is included in the Lower Floridan aquifer, which is otherwise composed mainly of dolomitic limestone of early and middle Eocene age (Krause and Randolph, 1989; fig. 4). The lateral extent of this unit is uncertain. A deep drilling program conducted for the Coastal Sound Science Initiative (CSSI) identified the unit near downtown Brunswick, but further north the unit is absent on St. Simons Island and in McIntosh County (Payne and others, 2005). This unit is important in the Brunswick area because of a postulated system of vertically connected fractures and upward gradients caused by pumping in the Upper Floridan aquifer that allow the saline water to migrate upward (Maslia and Prowell, 1990; fig. 3).

Groundwater Conditions

Groundwater levels and chloride concentrations in the Brunswick–Glynn County area have been monitored for several decades as part of the CWP. Precipitation and groundwater pumpage are monitored to assess their influence on groundwater conditions. These data are used to guide water-management decisions by State and local authorities.

Groundwater Levels

During calendar year 2009, groundwater levels and specific conductance in the Brunswick–Glynn County area were continuously monitored in 33 wells; 13 wells were funded through the CWP, and 20 wells were funded through a similar program with the Georgia Department of Natural Resources, Environmental Protection Division (GaEPD; fig. 2; table 1). Of the 33 continuous water-level recorders, 13 are completed in the Upper Floridan aquifer, 8 in the Lower Floridan aquifer, 7 in the Brunswick aquifer system, and 5 in the surficial aquifer system.

Real-time water-level monitoring was continued at wells completed in the UWBZ and/or LWBZ of the Upper Floridan aquifer that surround the area of chloride contamination—Southside Baptist Church (34H504 and 34H505), Perry Park (34H514), and Georgia–Pacific Cellulose LLC (33H324 and 33H325; fig. 2). These sites also provide real-time specific conductance monitoring in the UWBZ and LWBZ of the Upper Floridan aquifer. The Brunswick Villa well (34H134) was instrumented during late 2009 and provides only real-time specific conductance data in the UWBZ and LWBZ of the Upper Floridan aquifer (table 1).

Factors Influencing Groundwater Levels

Fluctuations and long-term trends in groundwater levels occur as a result of changes in recharge to and discharge from an aquifer. Recharge rates vary in response to precipitation, evapotranspiration, and surface-water infiltration into an aquifer (Alley and others, 1999). Discharge occurs as natural flow from an aquifer to streams or springs, as evapotranspiration from shallow water-table aquifers, as leakage to vertically adjacent aquifers, and as withdrawal (pumpage) from wells. When recharge to an aquifer exceeds discharge, groundwater levels rise; when discharge from an aquifer exceeds recharge, groundwater levels decline. Water levels generally are highest in the winter/early spring when precipitation is greatest, evapotranspiration is lowest, and withdrawals are minimal; water levels are the lowest during summer and fall when evapotranspiration and pumpage are greatest (Payne and others, 2005). In the Glynn County area, the surficial and Brunswick aquifer systems show a more pronounced response to climatic effects than the deeper Upper and Lower Floridan aquifers, which show a less pronounced response because they are deeply buried and receive recharge from outcrop areas located to the northwest. Generally in the lower Coastal Plain, climatic effects are greatly diminished, and fluctuations are largely because of groundwater pumping (Priest, 2004).

Hydrographs from the network of monitoring wells show long-term (period of record) and recent (2008–2009) water-level changes, with monthly mean water levels presented together with maps in the following sections of this report. Water-level trends are reported in feet per year of change and were computed by generating a straight-line fit to both the recent and period of record monthly-mean groundwater levels using the LMA (Moré, 1978) for minimization of a weighted least-squares merit function (Janert, 2010). Using estimated water levels from these straight-line fits, an annual rate of change (yearly slope) was calculated for the period of record and for 2008–2009 (Peck and others, 2011). These data are organized and presented for each aquifer. Water-level trends for 2008–2009 are presented on maps either by an upward arrow for a positive rate of change of 0.01 foot per year (ft/yr) or greater, or a downward arrow for a negative rate of change of 0.01 ft/yr or greater. A circle represents a water-level change of less than ± 0.01 ft/yr. Additional well information can be obtained from the USGS National Water Information System (NWIS) at *http://waterdata.usgs.gov/ga/nwis/gw/*.

Precipitation

Precipitation in the Brunswick–Glynn County area influences groundwater levels in the shallow surficial aquifer system and, to a lesser degree, in the Brunswick aquifer system. In addition, changes in precipitation affect quantities of groundwater withdrawn from deeper aquifers and, therefore, have an indirect effect on groundwater levels in the Upper Floridan aquifer. The mean-annual rainfall of 49 inches is not evenly distributed throughout the year, and maximum rainfall generally occurs during the summer months of June, July, and August (Priest, 2004). These maximum rainfall amounts are often associated with tropical systems during the hurricane season that produce heavy rainfall along the coast. A real-time climatic site was established as part of the CSSI at the College of Coastal Georgia campus at Brunswick to monitor precipitation in the Brunswick–Glynn County area (see location, fig. 2). Real-time monitoring data for this site are accessible on the Web at *http://www.georgiaweather.net* accessed on May 29, 2010).

Table 1. Brunswick–Glynn County, Georgia, groundwater-level monitoring network, 2009.

Well number	Aquifer	Subunit	Year monitoring began
34H515[a]	Surficial	Deeper (confined) zone	2005
34H437	Upper Brunswick	None	1983
34J077	Upper Brunswick	None	1998
33H127	Upper Floridan	Lower water-bearing zone	1962
33H133	Upper Floridan	Upper water-bearing zone	1964
34H134[b]	Upper Floridan	Upper and lower water-bearing zones	2009
34H334	Upper Floridan	Lower water-bearing zone	1962
34H371	Upper Floridan	Upper water-bearing zone	1967
34H514[c]	Upper Floridan	Upper water-bearing zone	2007
33H188	Lower Floridan	Fernandina permeable zone	1978
33J044	Lower Floridan	Undifferentiated	1979
34H391	Lower Floridan	Brackish water zone	1970
34H436	Lower Floridan	Brackish water zone	1983
Additional wells (funded by Georgia Environmental Protection Division)			
33H208	Surficial	Deeper (confined) zone	1983
34H492	Surficial	Water-table zone	1999
34J082	Surficial	None	2002
35H076	Surficial	Deeper (confined) zone	2007
33J065	Upper Brunswick	None	2001
34J081	Upper Brunswick	None	2002
33J062	Lower Brunswick	None	2001
34J080	Lower Brunswick	None	2002
35H077	Lower Brunswick	None	2005
33H207	Upper Floridan	Upper water-bearing zone	1983
33H324[c]	Upper Floridan	Upper water-bearing zone	2007
33H325[c]	Upper Floridan	Lower water-bearing zone	2007
34G033	Upper Floridan	None	2004
34H504[c]	Upper Floridan	Upper water-bearing zone	2007
34H505[c]	Upper Floridan	Lower water-bearing zone	2007
35H070	Upper Floridan	Upper water-bearing zone	2007
33H206	Lower Floridan	Brackish water zone	1983
34H495	Lower Floridan	Fernandina permeable zone	2001
34H500	Lower Floridan	Fresh water-bearing zone	2001
35H068	Lower Floridan	Fresh water-bearing zone	2007

[a] Replaces 34H438

[b] Real-time station—specific conductance only

[c] Real-time station

Precipitation data and cumulative departure from normal during 2000–2009 are shown in figure 5. The cumulative departure from normal precipitation for the period of record can be used to evaluate trends in precipitation, which typically relate to recharge of shallow aquifers. Cumulative departure describes the long-term surplus or deficit of precipitation during a designated period and is derived by adding successive values of departures from normal precipitation. In this report, normal precipitation for a given day is defined as the average of total daily precipitation during the period of record (2000–2009). A downward trend in slope indicates a period of below-normal precipitation, whereas an upward trend indicates above-normal precipitation.

Cumulative departure data indicate a period of below-normal precipitation from January 2000 to June 2004. Between June 2004 and October 2005, precipitation was mostly above normal with one short period of below-normal precipitation between November 2004 and February 2005. Rainfall was mostly below normal from November 2005 to March 2009 and mostly above normal from March to October 2009 (fig. 5*A*). The maximum amount of rainfall recorded in a 24-hour period was 6.05 inches on October 5, 2005 (fig. 5*B*). During a 6-day period (October 2–7, 2005), rainfall associated with Tropical Storm Tammy totaled nearly 18 inches in the area, and the cumulative departure went from just over 4 inches to more than 21 inches (fig. 5*A*).

Groundwater Withdrawals

The locations of groundwater pumping centers and amounts of water withdrawn from these centers may substantially affect groundwater levels in the Brunswick–Glynn County area. Changes in pumping rates and the addition of new pumping centers may alter the configuration of potentiometric surfaces, reverse groundwater flow directions, and increase seasonal and long-term fluctuations in the aquifers. During 2009, about 48 million gallons per day (Mgal/d) were withdrawn from the Upper Floridan aquifer in Glynn County, of which 7.97 Mgal/d was for public supply and 39.7 Mgal/d

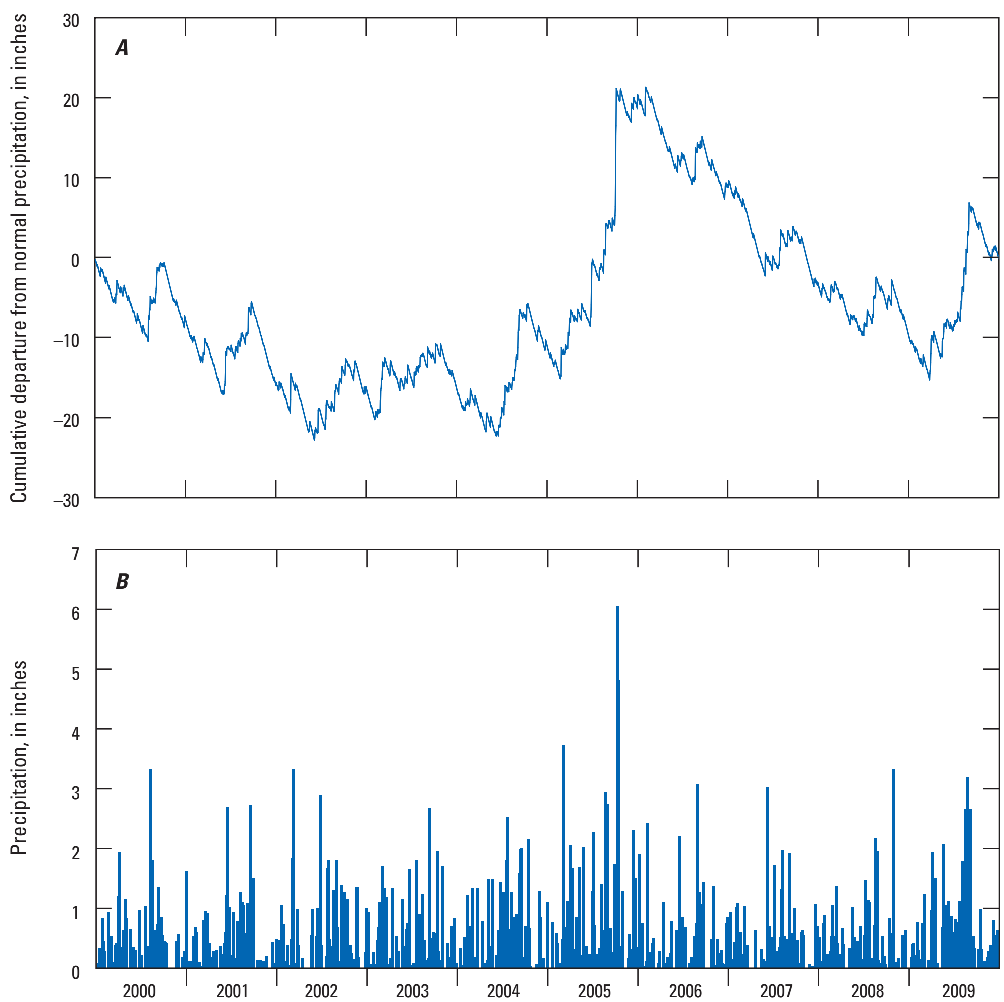


Figure 5. *(A)* Cumulative departure from normal precipitation and *(B)* total daily precipitation at real-time climatic monitoring site, College of Coastal Georgia, Georgia, January 2000–December 2009 (see figure 2 for location).

was for industry (Julia Fanning, U.S. Geological Survey, written commun., May 2010).

Pumpage from the Upper Floridan aquifer in Glynn County during 2009 was slightly higher than in 2008, and was appreciably lower than in 1980. Pumpage decreased from 95.4 Mgal/d during 1980 to 47.7 Mgal/d during 2009. This decrease reflects increased water conservation by local industry and reduced usage by golf courses in Glynn County, which have shifted withdrawals to wells completed in the Brunswick aquifer system. During 2009, an estimated 2.03 Mgal/d was withdrawn from the Brunswick aquifer system for irrigation and municipal needs in Glynn County (Julia Fanning, U.S. Geological Survey, written commun., May 2010). The reduction in pumpage during 1980–2009 had a pronounced effect on groundwater levels in the area.

Historically, groundwater pumpage in Glynn County peaked in the early 1980s with the majority of groundwater withdrawals used for industrial purposes (fig. 6). In calendar year 1980, Georgia–Pacific Cellulose LLC (formerly Brunswick Pulp & Paper Company) and Pinova Inc. (formerly Hercules Inc.), withdrew 58.8 and 19.5 Mgal/d, respectively, and groundwater withdrawal for public supply averaged 9.8 Mgal/d (L.E. Jones, U.S. Geological Survey, written commun., March 2007). By 2009, withdrawals at the Georgia–Pacific Cellulose facility decreased to 32.6 Mgal/d and withdrawals at the Pinova facility decreased to 5.9 Mgal/d.

Water use for public supply has steadily increased due to the rise in population within Glynn County. Population was 21,920 during 1940, 54,980 in 1980, and 76,820 during 2009 (U.S. Census Bureau, accessed August 11, 2010, at *http://www.census.gov/popest/counties/CO-EST2009-01.html*). As a result, groundwater pumpage for public supply nearly doubled from 4.4 Mgal/d during 1940, to 8.0 Mgal/d during 2009, with a peak usage of 11.3 Mgal/d during 1990 (fig. 6). Despite the population increase during 1980–2009, pumpage for public supply during 2009 is less than during 1980 because of greater accountability in the water distribution systems, water conservation measures, and decreased losses due to system leakage (Keith Morgan, Brunswick–Glynn County Joint Water and Sewer Commission, oral commun., 2009). During 2009, withdrawal for public supply for Glynn County, was 8.1 Mgal/d compared to 9.8 Mgal/d during 1980.

Surficial Aquifer System

During 2009, water levels were monitored in five wells completed in the surficial aquifer system in the Brunswick–Glynn County area (fig. 7; table 1). Water-level hydrographs for these wells illustrate monthly mean water levels for the period of record (fig. 8). Seasonal variations are evident on the hydrographs, with periodic upward or downward trends that indicate a surplus or deficit in rainfall. Water levels during the period of record in three of the wells show an upward trend with rates of change from 0.03 to 0.15 ft/yr and downward trends in two wells at rates of 0.08 and 0.19 ft/yr (fig. 7). During 2008–2009, water levels in all five wells rose at rates of 0.24 to 1.05 ft/yr, corresponding to a period of above-normal precipitation during most of 2009 (fig. 5).

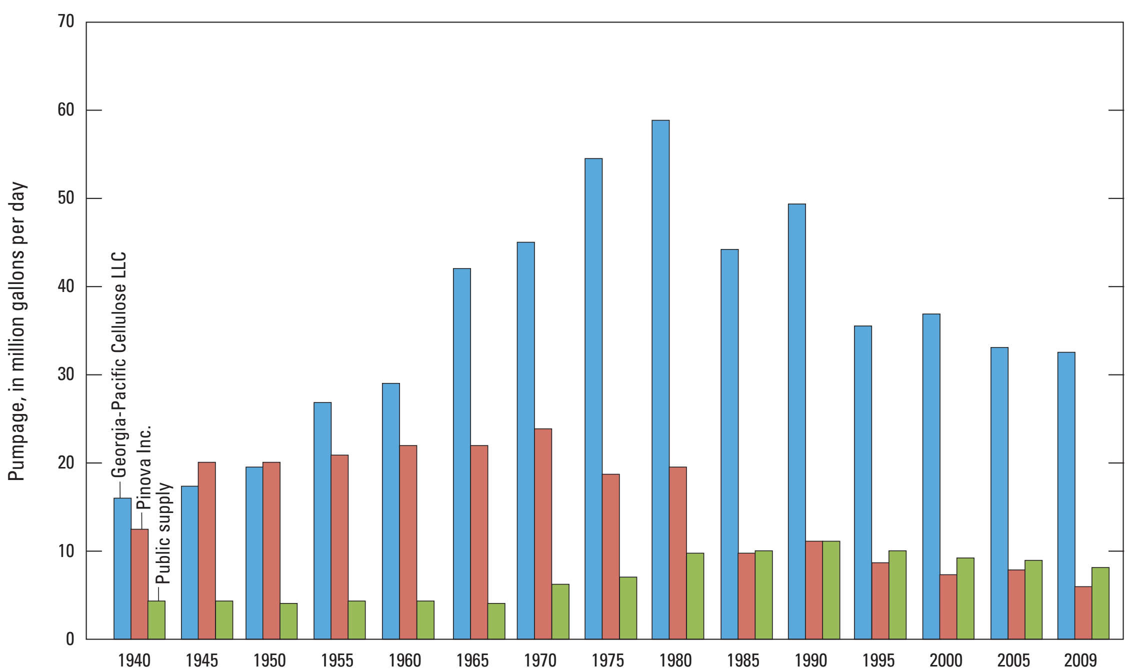
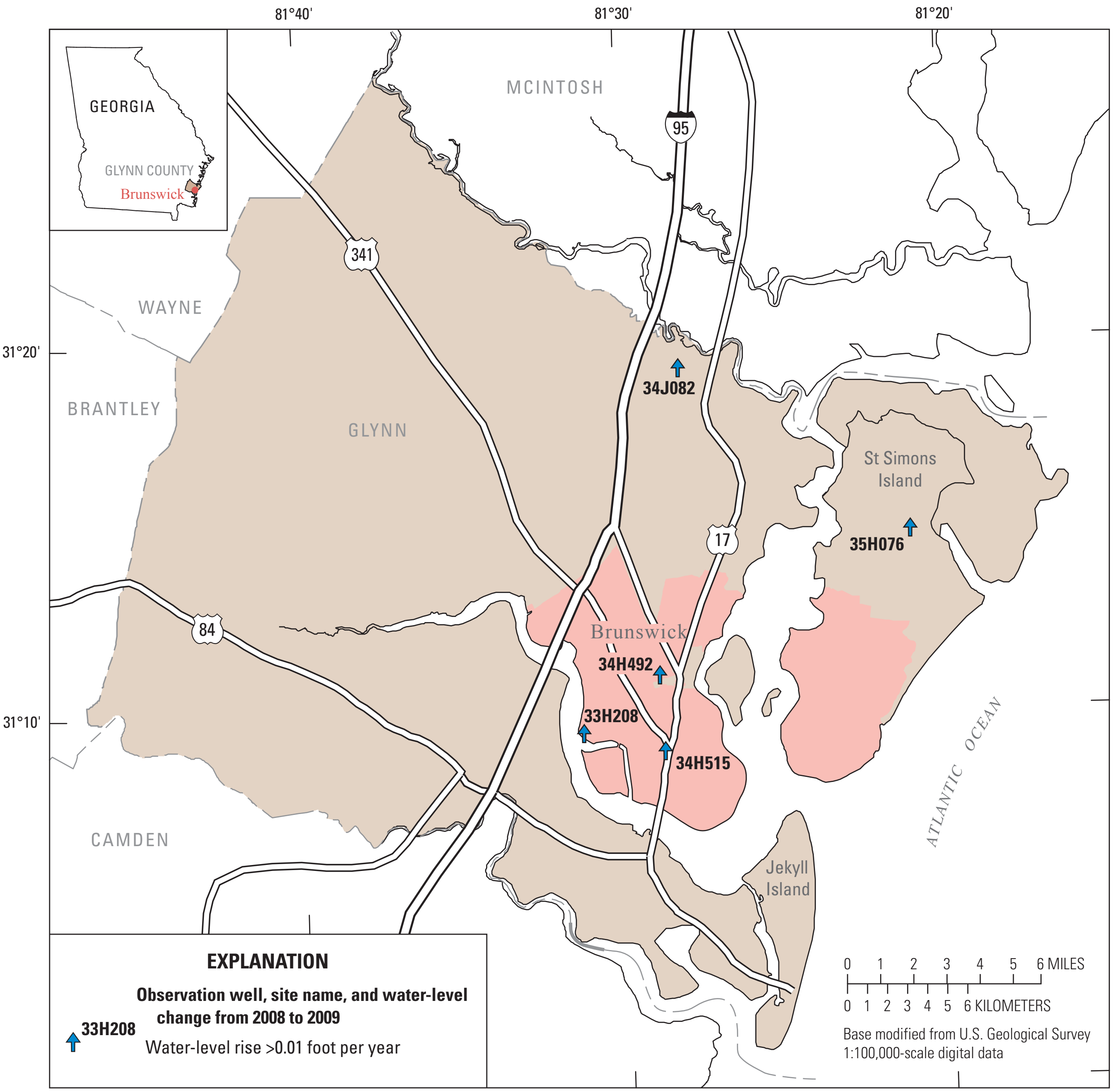


Figure 6. Major groundwater pumpage from the Upper Floridan aquifer in the Brunswick–Glynn County area, Georgia, 1940–2009.



Site name	Year monitoring began	Water-level trend, in feet per year[1]	
		Period of record	2008 to 2009
33H208	1983	0.15	1.05
34H492	1999	0.08	0.88
34H515	2005	0.03	0.24
34J082	2002	–0.08	0.40
35H076	2005	–0.19	0.43

[1]See appendix for summary statistics.

Figure 7. Groundwater-level monitoring network in the surficial aquifer system, Glynn County, Georgia, and water-level change for period of record and 2008–2009.

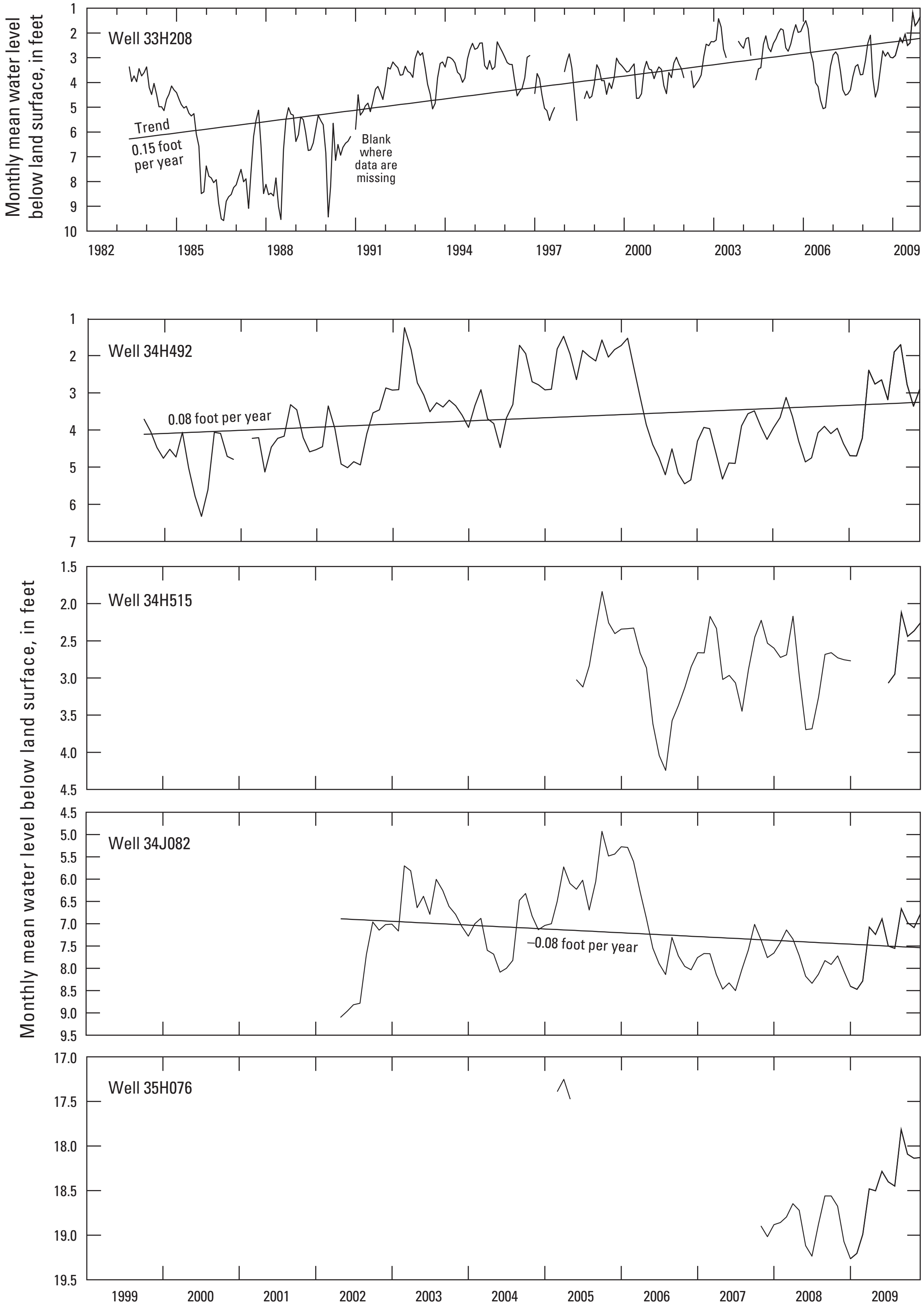


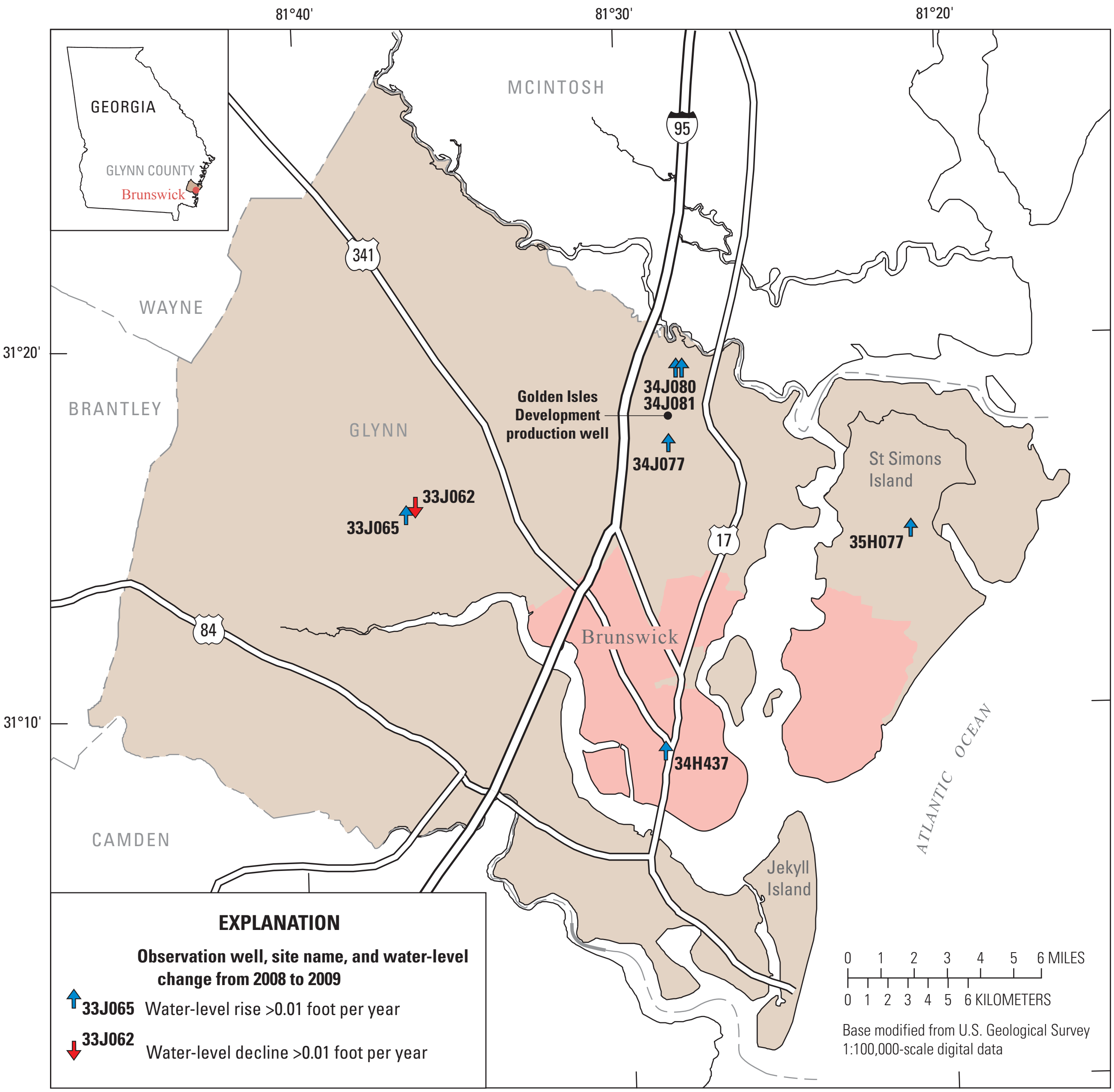
Figure 8. Monthly mean water levels and period-of-record trend line in wells in the surficial aquifer system, Glynn County, Georgia (note different periods of record and vertical scales; see figure 7 for well locations).

Brunswick Aquifer System

Water levels in the Brunswick aquifer system are monitored continuously in four wells completed in the upper Brunswick aquifer and three wells completed in the lower Brunswick aquifer (figs. 9–11; table 1). Water-level fluctuations reflect changes in local pumping, interaquifer-leakage effects, and recharge. Water-level hydrographs showing monthly mean water levels for the period of record indicate periodic upward or downward trends that reflect surplus rainfall or deficits in rainfall and changes in pumping. During the period of record, water levels in four of the wells declined at rates of 0.06 to 0.94 ft/yr, remained about the same in two wells, and rose in one well at a rate of 0.16 ft/yr (fig. 9). During 2008–2009, water levels in six of the wells rose at rates of 0.32 to 2.30 ft/yr and declined in one well at a rate of 0.37 ft/yr. The water-level rises corresponded to a period of above-normal precipitation during most of 2009 (fig. 5).

Water levels in the Brunswick aquifer system in north-central Glynn County are influenced by pumpage at the Golden Isles development, which began pumping from the Brunswick aquifer system in 1999, and is one of the earliest users of the Brunswick aquifer system in coastal Georgia. During 1999–2009, average annual pumping ranged from 0.26 to 0.68 Mgal/d (Vicki Trent, Georgia Environmental Protection Division, written commun., November 15, 2010). Monitoring at well 34J077 (fig. 9), located about 0.6 mi from a production well located at the Golden Isles development, provides a long-term record of the effects of pumping on the Brunswick aquifer system. During 1999–2008, the water level in well 34J077 dropped about 20 ft, followed by recovery at a rate of 2.3 ft/yr during 2008–2009 (fig. 10). Well 34J080, open to the Lower Brunswick aquifer, is also influenced by pumping at Golden Isles, and the decline since the well began recording water levels in 2002 has been at a rate of 0.52 ft/yr (figs. 9, 11).

Periodic water-level measurements also are collected from five wells completed in the Brunswick aquifer system located on Jekyll Island (fig. 2, 12). Periodic measurements were collected by the USGS during 2009–2010 and the Jekyll Island Authority during 2002–2009 (John Day, Jekyll Island Authority, written commun., October 13, 2010). Hydrographs showing these periodic measurements indicate no appreciable water-level trend with water levels above land surface throughout the period of record.



Site name	Year monitoring began	Water-level trend, in feet per year[1]		Aquifer[2]
		Period of record	2008 to 2009	
33J062	2001	<0.01	–0.37	L
34J080	2002	–0.52	1.46	L
35H077	2005	–0.06	1.58	L
33J065	2001	<0.01	0.32	U
34H437	1983	0.16	0.52	U
34J077	1998	–0.94	2.30	U
34J081	2002	–0.16	1.30	U

[1]See appendix for summary statistics.
[2]L, lower Brunswick aquifer; U, upper Brunswick aquifer

Figure 9. Groundwater-level monitoring network in the Brunswick aquifer system, Glynn County, Georgia, and water-level change for period of record and 2008–2009.

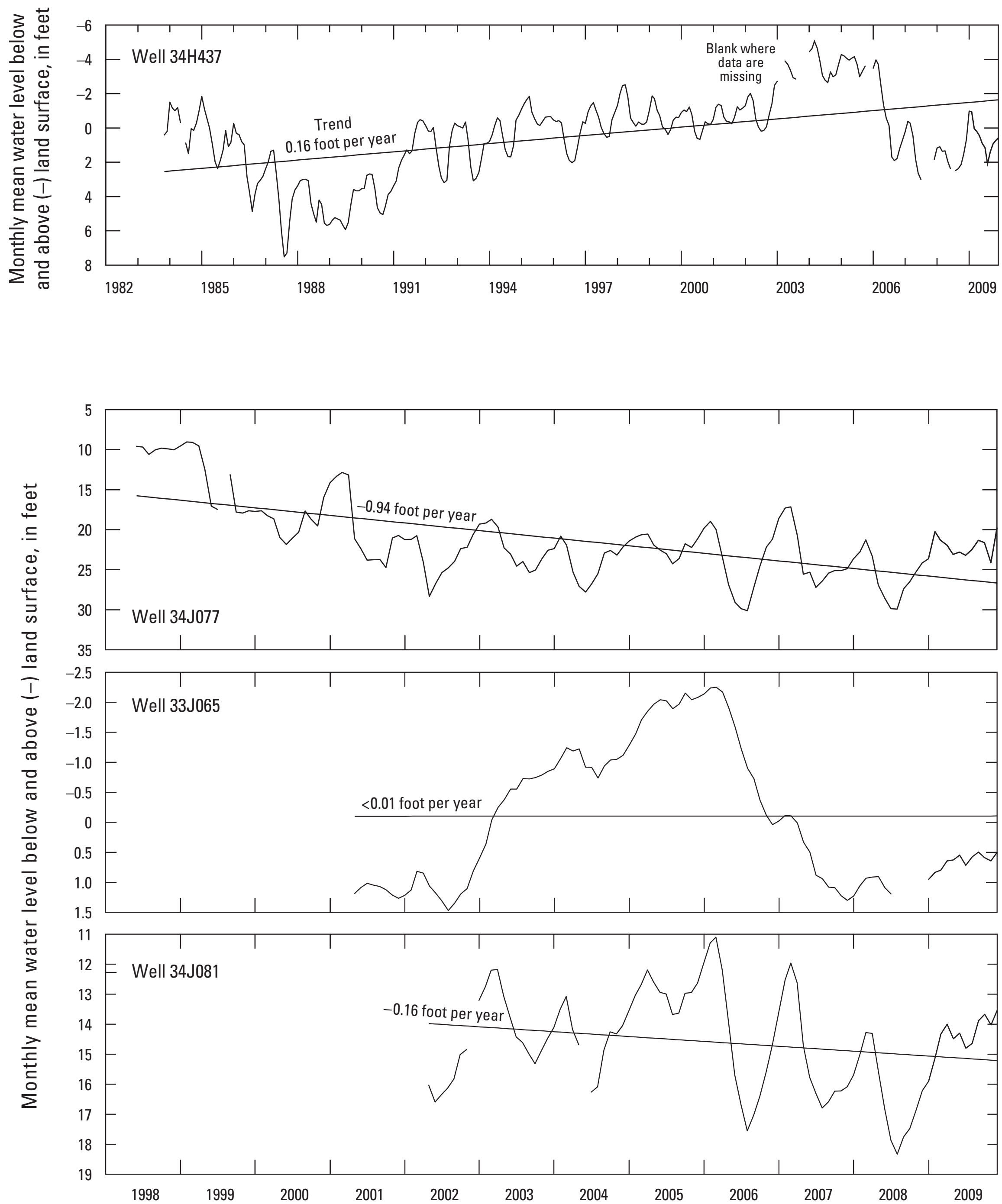


Figure 10. Monthly mean water levels and period-of-record trend line in wells in the upper Brunswick aquifer, Glynn County, Georgia (note different periods of record and vertical scales; see figure 9 for well locations).

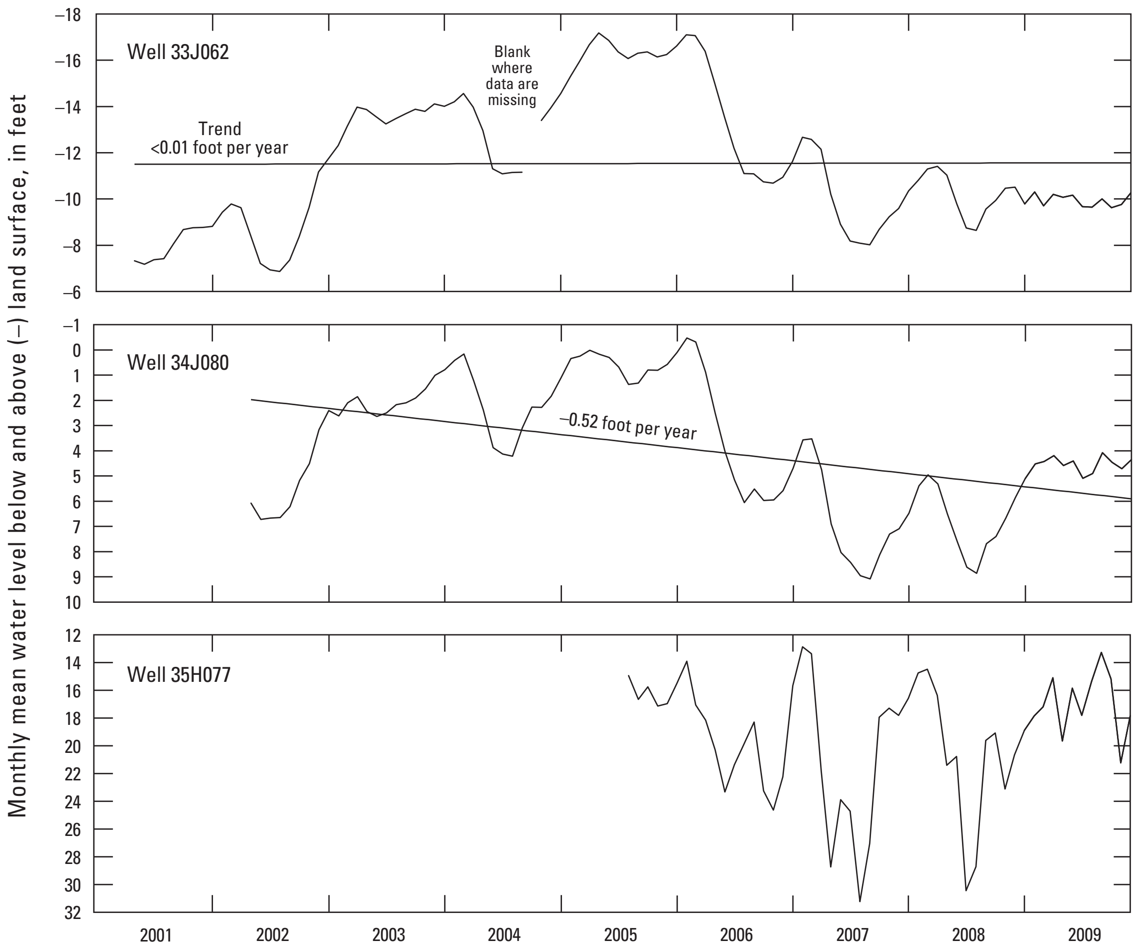


Figure 11. Monthly mean water levels and period-of-record trend line in wells in the lower Brunswick aquifer, Glynn County, Georgia (see figure 9 for well locations).

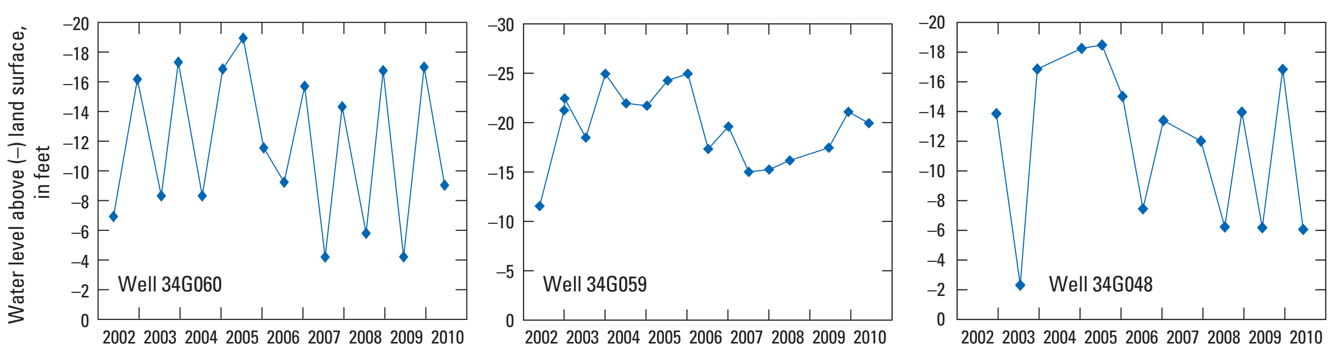


Figure 12. Periodic water-level measurements in wells in the Brunswick aquifer system, Jekyll Island, Glynn County, Georgia (note vertical scales vary; see figure 2 for well locations).

Floridan Aquifer System

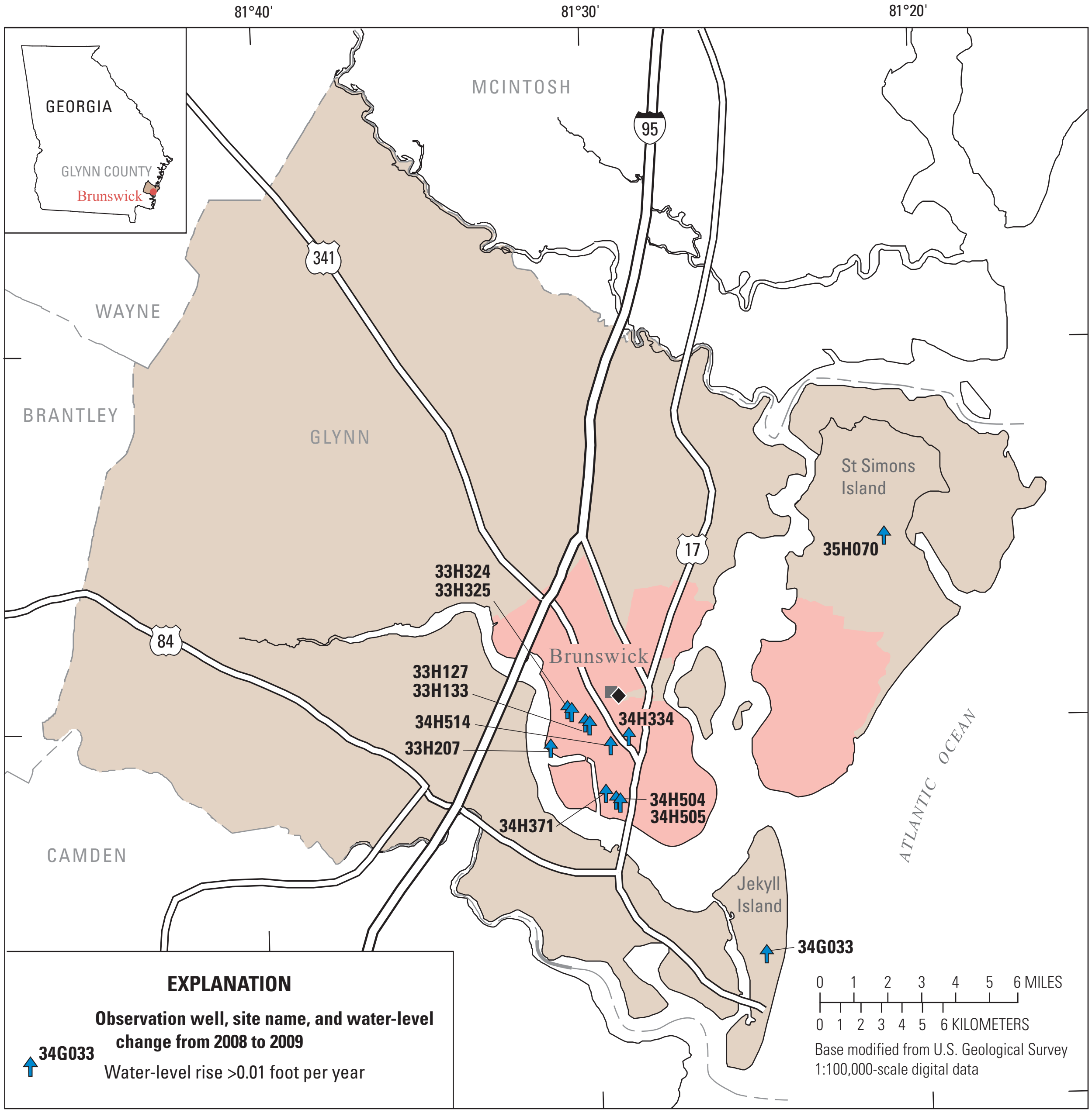
Water levels in the Floridan aquifer system in the Brunswick–Glynn County area are continuously monitored in 12 wells completed in the Upper Floridan aquifer and 8 wells completed in the Lower Floridan aquifer (figs. 13–17; table 1). Water levels in the Upper and Lower Floridan aquifers are influenced primarily by changes in pumping.

During the period of record, water levels in 11 of the 12 Upper Floridan aquifer wells had rising trends with rates of change ranging from 0.05 to 4.26 ft/yr (figs. 13, 14). The highest rates of annual water-level rise were generally in wells where monitoring began after 2004 (fig. 13). Well 34G033 had a declining trend of 1.49 ft/yr; however, the period of record for this well begins in 2004 and misses much of the earlier period in which water levels were rising in the area because of decreases in pumpage during the 1990s (fig. 6). The downward trend in well 34G033 reflects a regional decline during 2004–2008 that was evident in most of the wells in the area. During 2008–2009, water levels in all 12 wells rose at rates of 0.85 to 7.58 ft/yr (fig. 13).

Periodic water-level measurements are also collected from well 34G029 completed in the Upper Floridan aquifer on Jekyll Island (fig. 15). The water-level hydrograph for this well illustrates periodic measurements collected by the USGS during 2009–2010 and historical measurements collected by the Jekyll Island Authority prior to 2009 (John Day, Jekyll Island Authority, written commun., October 13, 2010). Water levels in the well rose during 2002–2003, declined during 2003–2008, rose from 2008 to the end of 2009, and declined through June 2010 (fig. 15).

In the Lower Floridan aquifer, water levels during the period of record rose at rates of 0.09 to 1.22 ft/yr in five wells, declined in two wells at rates of 0.06 and 0.08 ft/yr, and remained the same in one well (figs. 16, 17). Water levels in each of the wells showed a pronounced rise during 2002 that marked the end of a prolonged drought and response to a pumping shutdown by a major industrial user in the St. Marys area of Camden County (Peck and others, 2005; fig. 17). According to Payne and others (2006), the simulated steady-state water-level change in the Lower Floridan aquifer in the Glynn County area due to this shutdown ranged between 2 and 4 ft. During 2008–2009, water levels in seven of the wells rose at rates ranging from 1.41 to 1.98 ft/yr and declined in well 33H188 at a rate of 0.83 ft/yr.

In addition to continuous recorders, synoptic water-level measurements were collected in 46 wells completed in the Upper Floridan aquifer during August 2009, and a potentiometric-surface map was prepared based on the data (fig. 18; table 2). The map indicates the continued presence of a cone of depression created by large industrial withdrawals in the northern and western parts of the Brunswick area, with the principal direction of groundwater flow toward the cone of depression.



Site name	Year monitoring began	Water-level trend, in feet per year [1]	
		Period of record	2008 to 2009
33H127	1962	0.05	2.07
33H133	1964	0.27	2.43
33H207	1983	0.47	0.89
33H324	2007	1.73	2.24
33H325	2007	4.26	7.58
34G033	2004	–1.49	1.38
34H334	1962	0.17	1.54
34H371	1967	0.14	1.28
34H504	2007	1.15	1.34
34H505	2007	0.76	1.28
34H514	2007	1.29	1.60
35H070	2005	0.88	0.85

[1]See appendix for summary statistics.

Figure 13. Groundwater-level monitoring network in the Upper Floridan aquifer in Glynn County, Georgia, and water-level change for period of record and for 2008–2009.

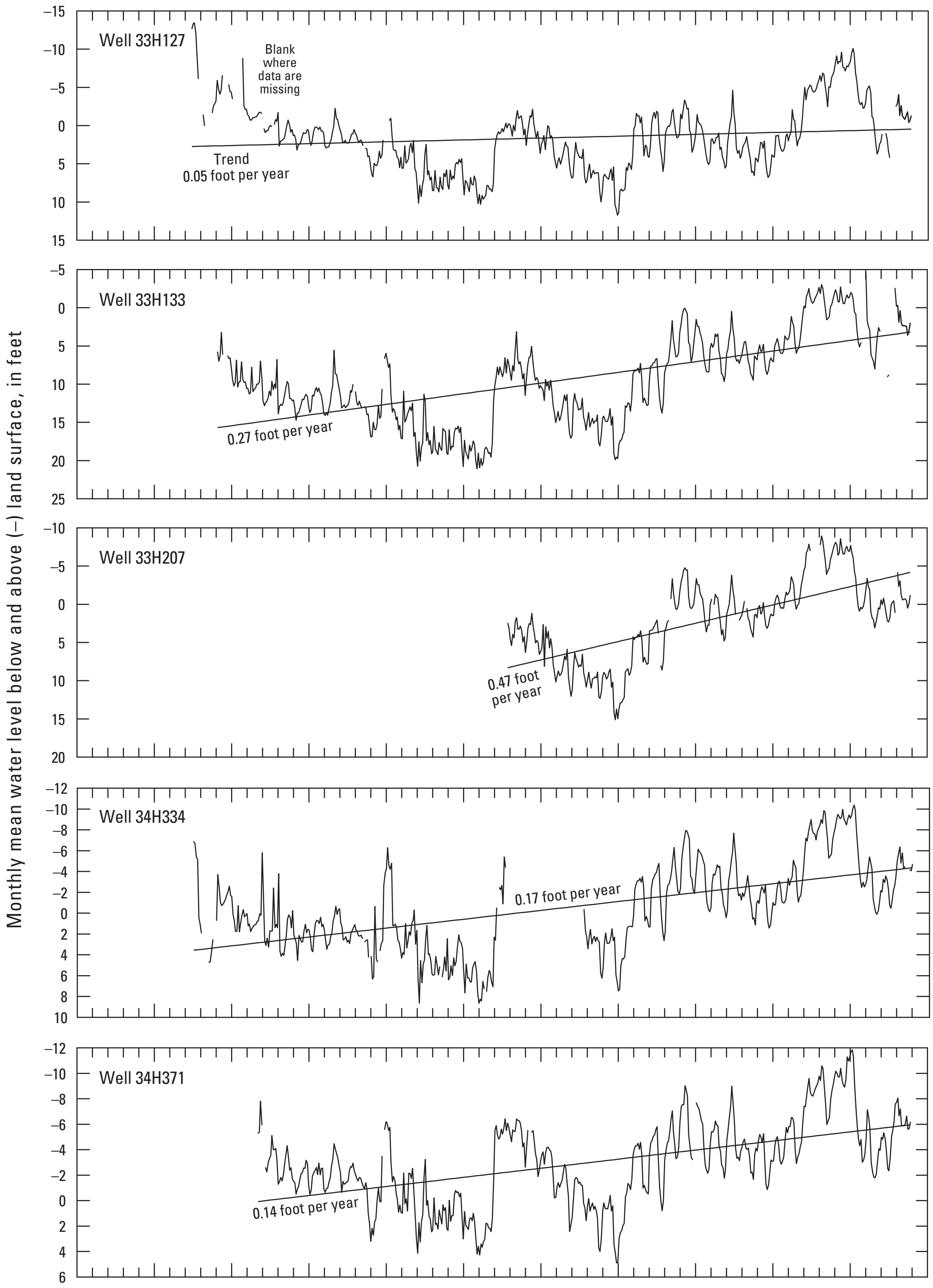


Figure 14. Monthly mean water levels and period-of-record trend line in wells in the Upper Floridan aquifer, Glynn County, Georgia (note different periods of record and vertical scales; see figure 13 for well locations).

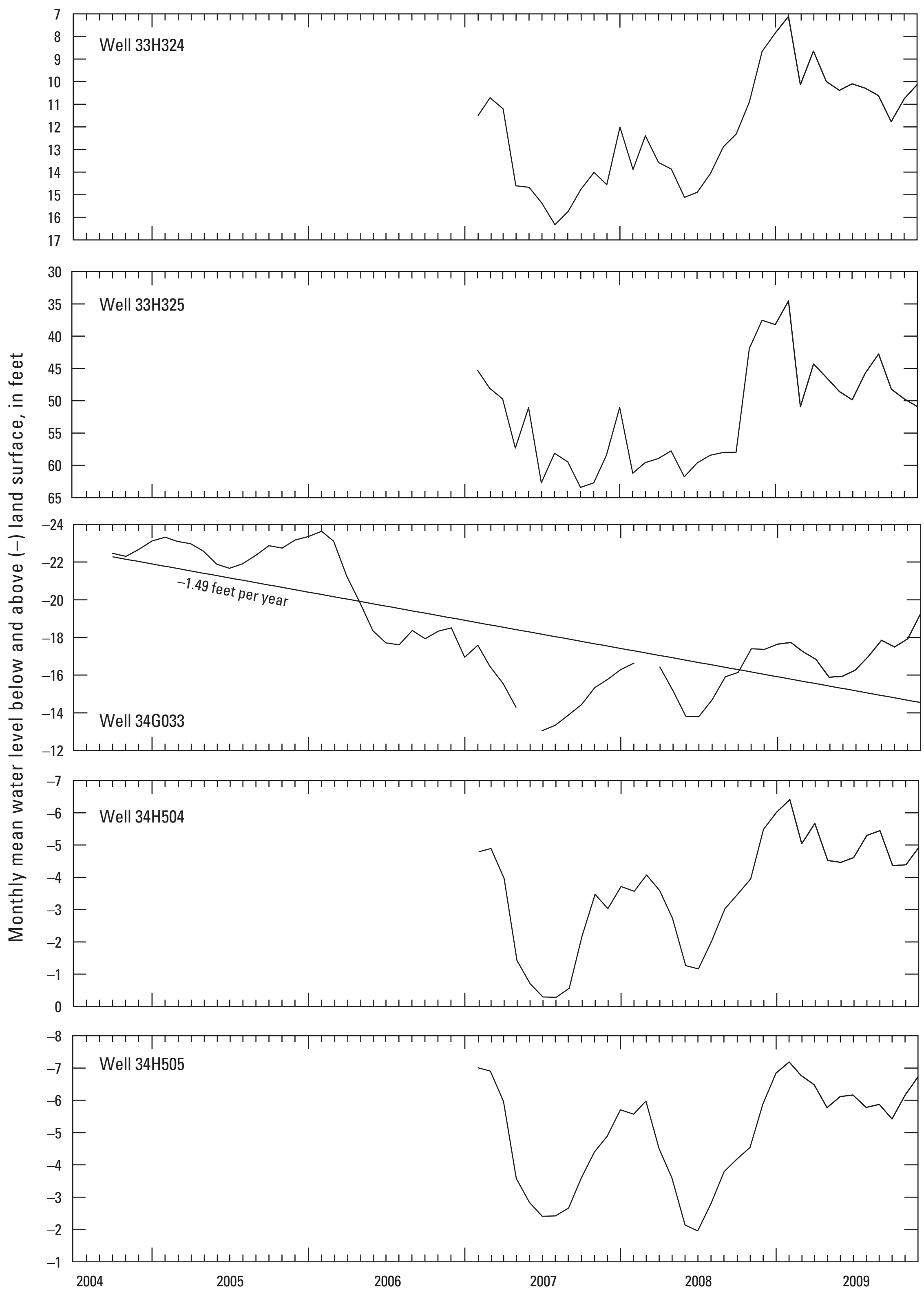


Figure 14. Monthly mean water levels and period-of-record trend line in wells in the Upper Floridan aquifer, Glynn County, Georgia (note different periods of record and vertical scales; see figure 13 for well locations).—Continued

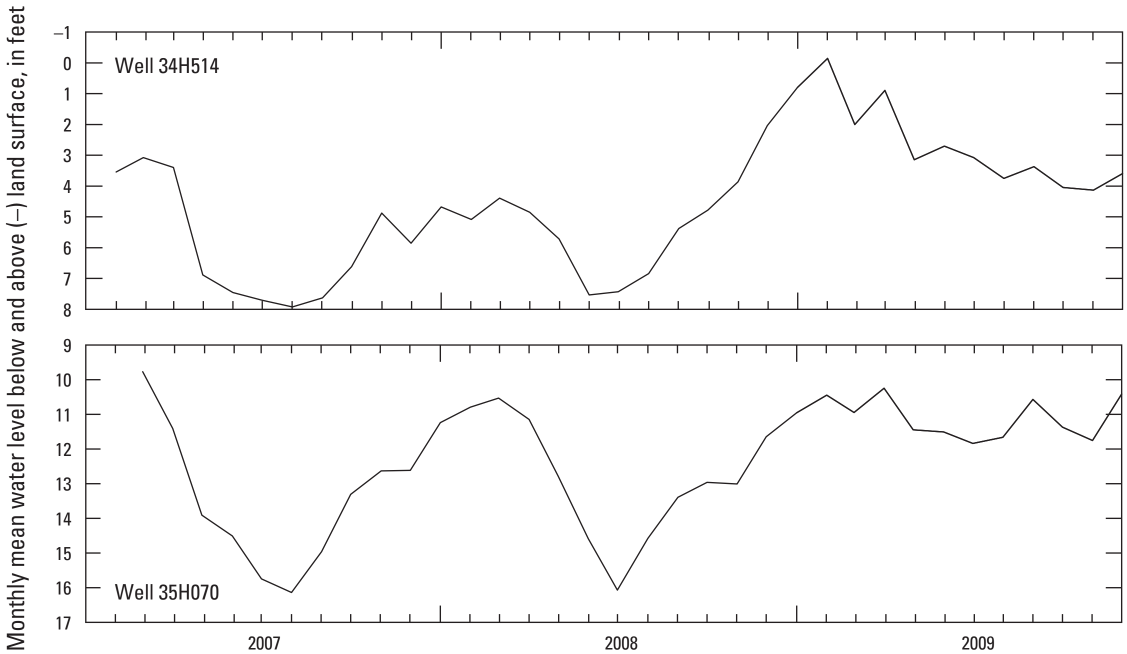


Figure 14. Monthly mean water levels and period-of-record trend line in wells in the Upper Floridan aquifer, Glynn County, Georgia (note different periods of record and vertical scales; see figure 13 for well locations).—Continued

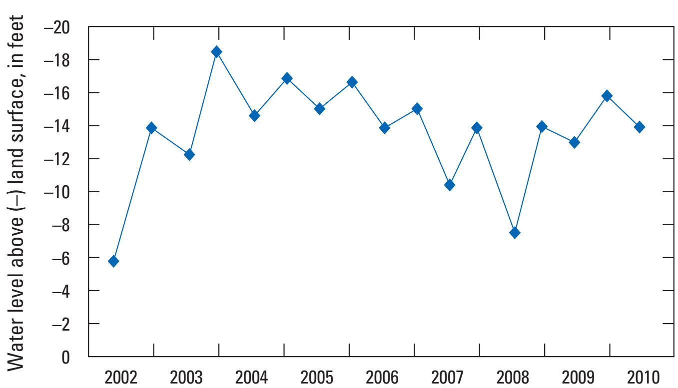
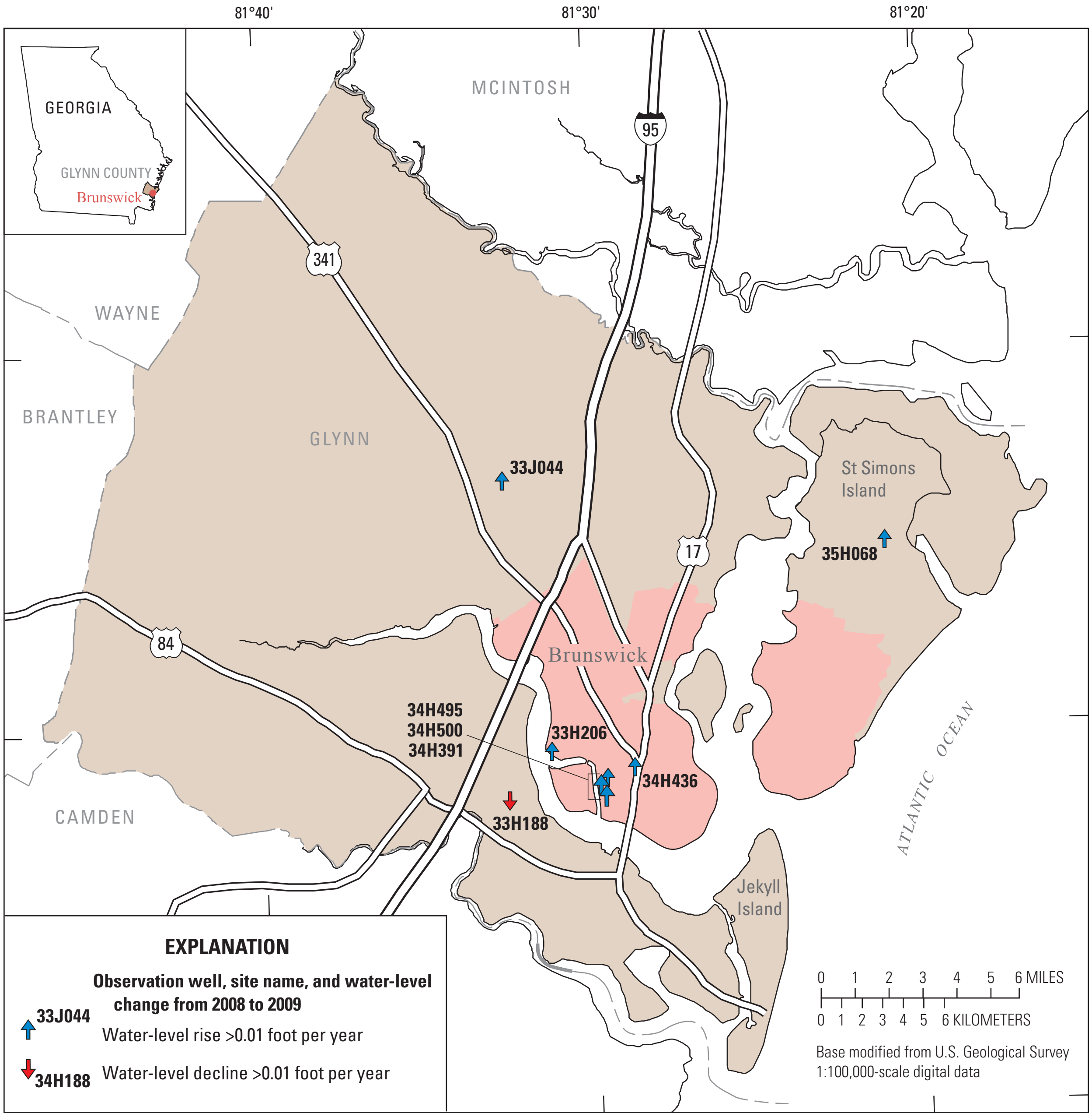


Figure 15. Periodic water-level measurements in well 34G029, Upper Floridan aquifer, Jekyll Island, Glynn County, Georgia (see figure 2 for well location).



Site name	Year monitoring began	Water-level trend, in feet per year[1]	
		Period of record	2008 to 2009
33H188	1978	–0.08	–0.83
33H206	1983	0.25	1.54
33J044	1979	0.09	1.98
34H391	1975	0.17	1.57
34H436	1983	0.18	1.46
34H495	2001	1.22	1.63
34H500	2001	–0.06	1.90
35H068	2007	<0.01	1.41

[1]See appendix for summary statistics.

Figure 16. Groundwater-level monitoring network in the Lower Floridan aquifer, Glynn County, Georgia, and water-level change for period of record and 2008–2009.

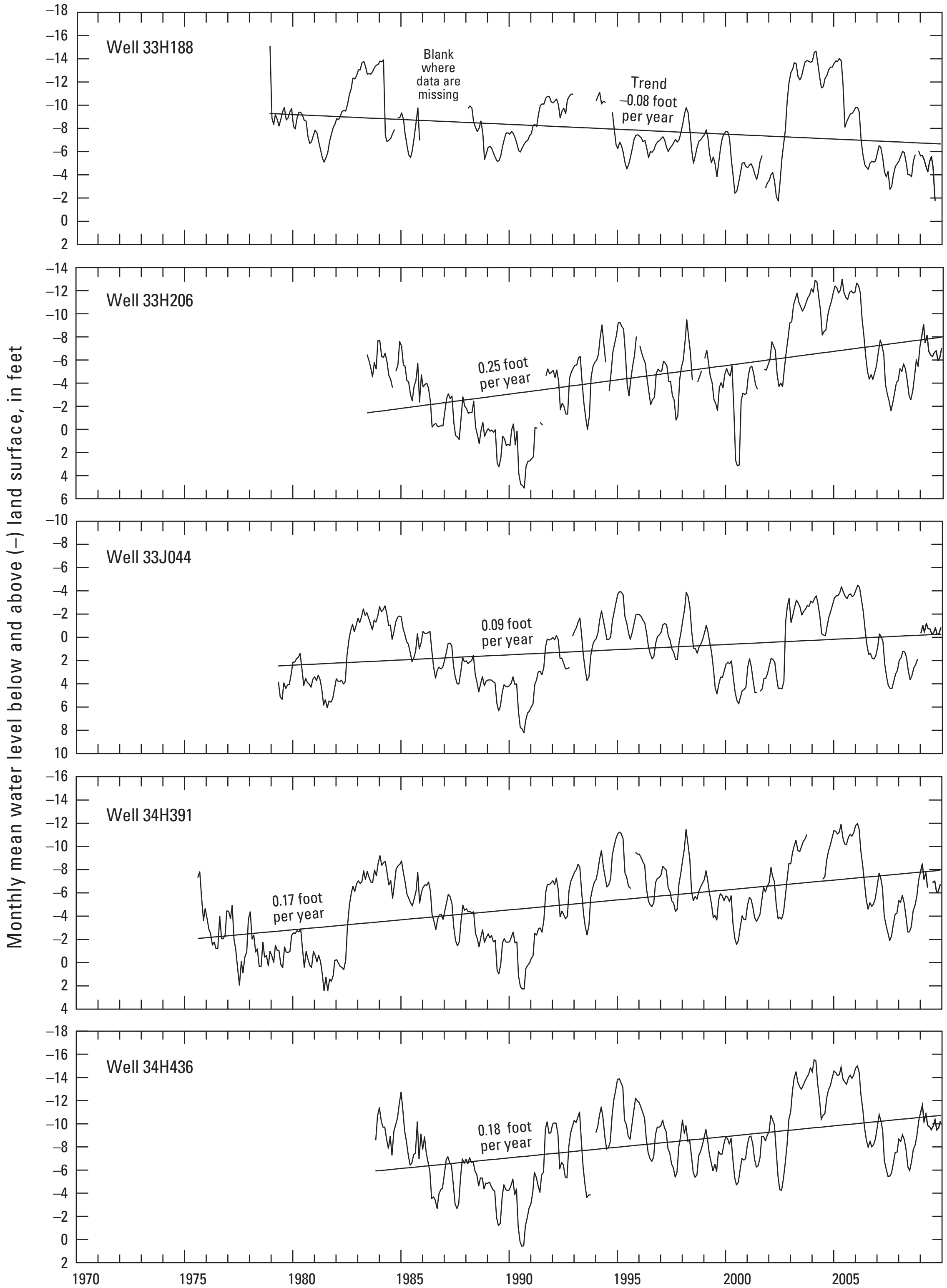


Figure 17. Monthly mean water levels and period-of-record trend line in wells in the Lower Floridan aquifer, Glynn County, Georgia (note different periods of record and vertical scales; see figure 16 for well locations).

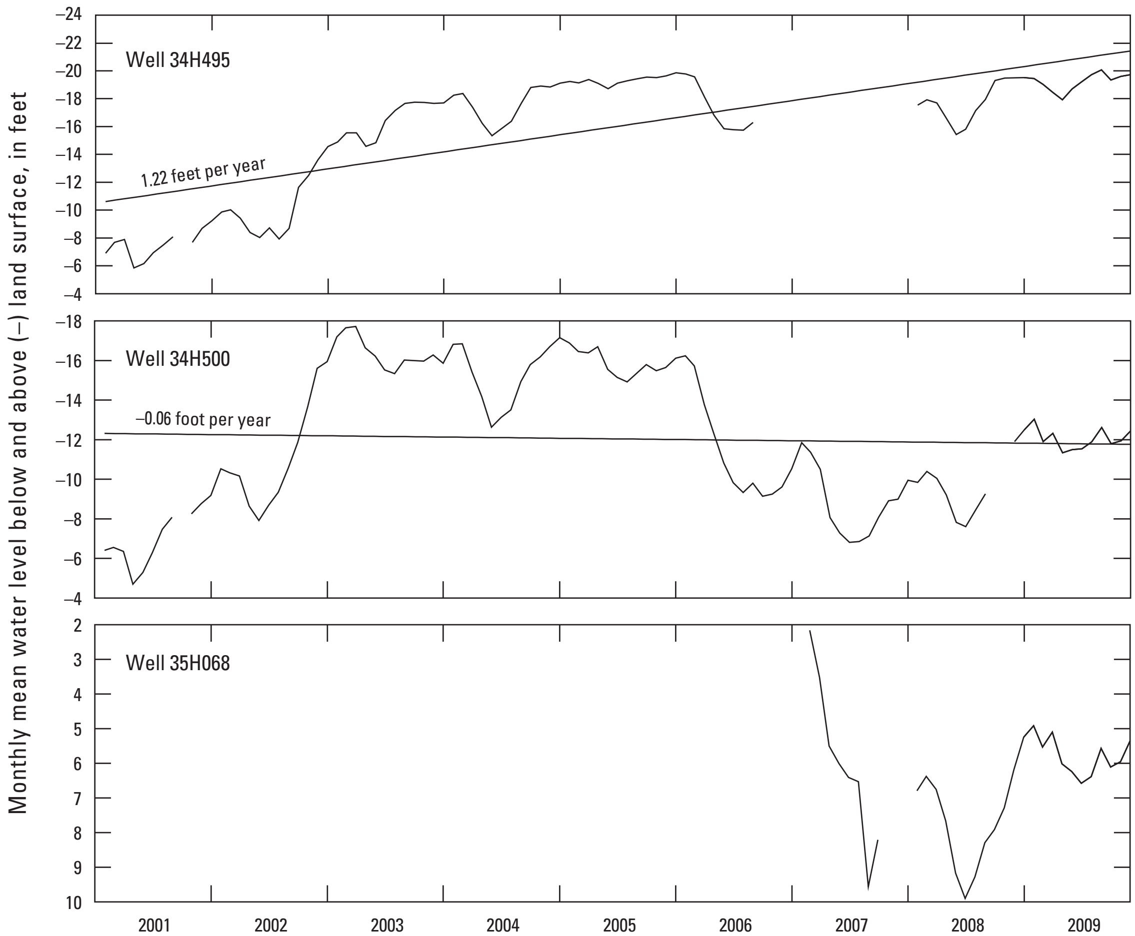


Figure 17. Monthly mean water levels and period-of-record trend line in wells in the Lower Floridan aquifer, Glynn County, Georgia (note different periods of record and vertical scales; see figure 16 for well locations).—Continued

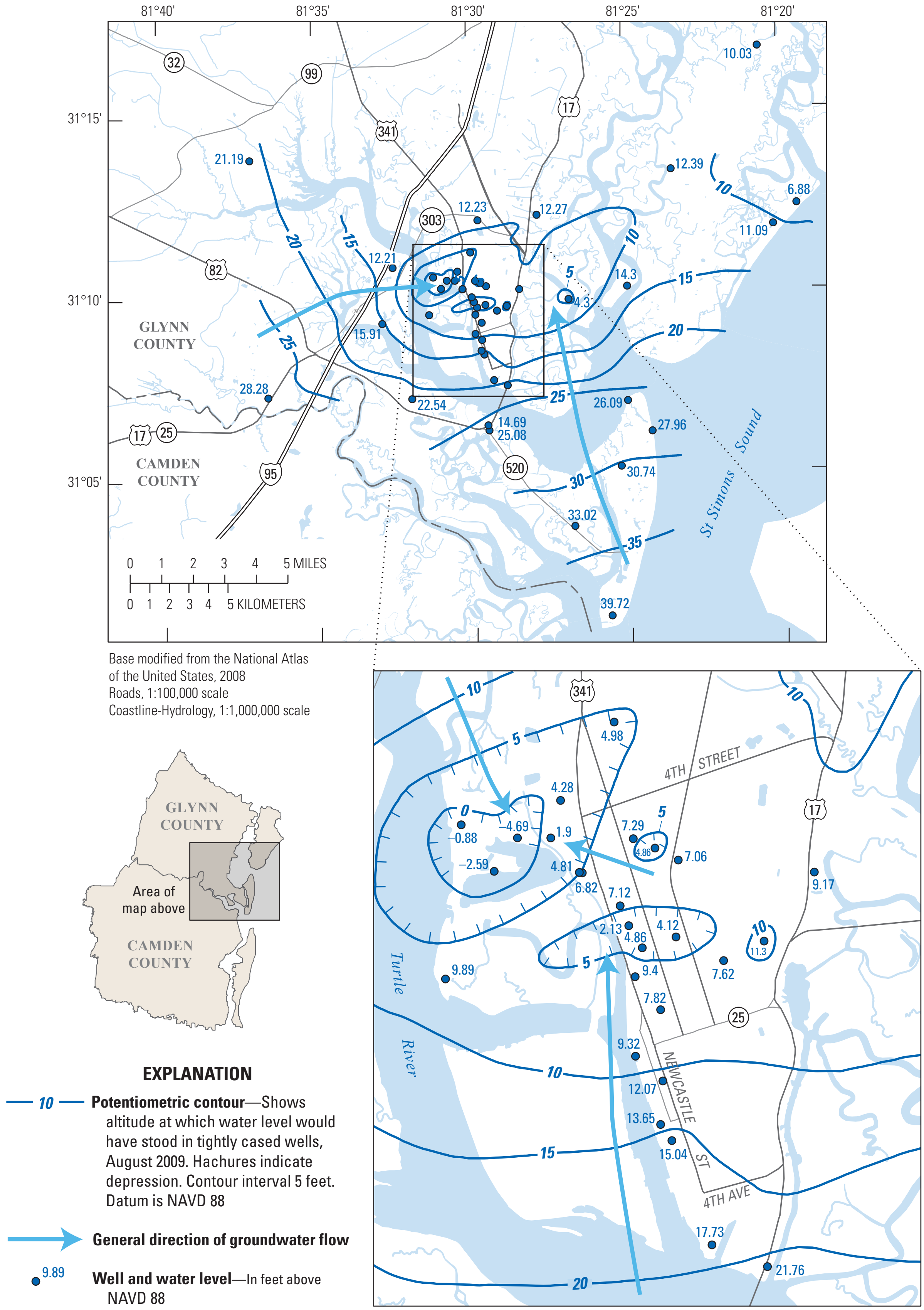


Figure 18. Potentiometric surface of the Upper Floridan aquifer, Brunswick–Glynn County, Georgia, August 17–21, 2009.

Table 2. Potentiometric and periodic groundwater-level monitoring networks in the Upper Floridan aquifer, Brunswick–Glynn County, Georgia.

[NAVD 88, North American Vertical Datum of 1988; T, transducer; S, steel tape; negative values for depth to water represent measurements above land surface]

Well number	Latitude[a]	Longitude[a]	Measurement date	Altitude[b] (feet above NAVD 88)	Depth to water below land surface[c] (feet)	Water level altitude (feet above NAVD 88)	Method of water-level measurement
	Degrees, minutes, seconds NAD 83						
33G008	31°07'06.8"N	81°31'58.1"W	08-20-2009	6.41	–16.13	22.54	T
33G024	31°07'12.7"N	81°36'36.1"W	08-19-2009	6.92	–21.36	28.28	T
33H120	31°10'36"N	81°30'26"W	08-17-2009	10.88	6.60	4.28	S
33H127	31°10'06.6"N	81°30'16.5"W	08-18-2009	5.14	–1.68	6.82	T
33H130	31°10'21"N	81°30'31"W	08-18-2009	9.78	7.88	1.90	S
33H133	31°10'06.82"N	81°30'16.5"W	08-18-2009	5.70	0.89	4.81	S
33H141	31°10'44"N	81°32'31"W	08-17-2009	11.53	–0.68	12.21	T
33H180	31°11'07"N	81°30'00"W	08-20-2009	14	9.02	4.98	S
33H193	31°13'45"N	81°37'04"W	08-18-2009	8.99	–12.20	21.19	T
33H207	31°09'25"N	81°31'22"W	08-20-2009	5.97	–3.92	9.89	T
33H209	31°09'12"N	81°32'53"W	08-18-2009	8.95	–6.96	15.91	T
33H211	31°10'27"N	81°31'13"W	08-17-2009	11.59	12.47	–0.88	S
33H213	31°10'08"N	81°30'58"W	08-17-2009	5.58	8.17	–2.59	S
33H324	31°10'22"N	81°30'46"W	08-18-2009	4	8.69	–4.69	S
34G002	31°07'26.6"N	81°28'53.1"W	08-17-2009	9.04	–12.72	21.76	T
34G009	31°01'03"N	81°25'40"W	08-19-2009	8.96	–30.76	39.72	T
34G016	31°06'07"N	81°24'15"W	08-19-2009	8.89	–19.07	27.96	T
34G017	31°06'58"N	81°25'01"W	08-19-2009	6.04	–20.05	26.09	T
34G020	31°05'10"N	81°25'16"W	08-19-2009	9.01	–21.73	30.74	T
34G041	31°03'32"N	81°26'48"W	08-19-2009	9	–24.02	33.02	T
34G054	31°06'21"N	81°29'31.8"W	08-17-2009	7	–7.69	14.69	T
34G056	31°06'13.6"N	81°29'29.6"W	08-18-2009	8.96	–16.12	25.08	T
34H062	31°10'05"N	81°28'27"W	08-20-2009	7.71	–1.46	9.17	T
34H095	31°07'35.7"N	81°29'19.1"W	08-20-2009	4	–13.73	17.73	T
34H112	31°08'42.2"N	81°29'40.6"W	08-18-2009	7.57	–4.50	12.07	T
34H117	31°08'52.4"N	81°29'53.2"W	08-18-2009	5.69	–3.63	9.32	T
34H144	31°09'47"N	81°26'52"W	08-18-2009	10	5.70	4.30	S
34H328	31°13'19"N	81°23'29"W	08-20-2009	11.40	–0.99	12.39	T
34H334	31°09'37.6"N	81°28'51.5"W	08-20-2009	7.33	–3.97	11.30	T
34H355	31°09'24.3"N	81°29'52.6"W	08-17-2009	12.97	3.57	9.40	S
34H371	31°08'18.1"N	81°29'36.8"W	08-18-2009	8.48	–6.56	15.04	T
34H373	31°09'40"N	81°29'33"W	08-18-2009	8.28	4.16	4.12	S
34H374	31°09'53"N	81°29'59"W	08-18-2009	16	8.88	7.12	S
34H393	31°08'24.6"N	81°29'42.1"W	08-18-2009	5.94	–7.71	13.65	T
34H400	31°09'36"N	81°29'49"W	08-18-2009	11.49	6.63	4.86	S
34H401	31°09'45"N	81°29'55"W	08-18-2009	12.15	10.02	2.13	S
34H408	31°08'18.8"N	81°29'41.5"W	08-20-2009	17	4.77	12.23	S
34H410	31°12'07"N	81°27'50.5"W	08-18-2009	5.51	–6.76	12.27	T
34H424	31°10'11"N	81°29'31"W	08-20-2009	14	6.94	7.06	S
34H427	31°10'16"N	81°29'42"W	08-20-2009	13	8.14	4.86	S
34H434	31°09'10.8"N	81°29'40.8"W	08-18-2009	9	1.18	7.82	S
34H444	31°10'07"N	81°24'58"W	08-19-2009	4.63	–9.67	14.30	T
34H469	31°10'20"N	81°29'52"W	08-18-2009	12.91	5.62	7.29	S
34H514	31°09'31"N	81°29'10"W	08-18-2009	10	2.38	7.62	S
35H050	31°12'20"N	81°19'27"W	08-19-2009	7.03	0.15	6.88	S
35H051	31°11'46"N	81°20'13"W	08-19-2009	7.03	–4.06	11.09	T
35J004	31°16'40"N	81°20'37"W	08-18-2009	9	–1.03	10.03	T

[a]Accuracy varies based on method of measurement. Values reported to tenths of a second represent measurement made by global positioning techniques.

[b]Accuracy varies based on method of measurement. Values reported to tenths or hundreths of a foot represent measurement made by surveying or global positioning techniques.

[c] Values reported to hundreth of a foot.

Chloride Concentrations

Chloride concentrations have been monitored in the Brunswick area since the late 1950s when saltwater was first detected in wells completed in the Upper Floridan aquifer in the southernmost part of Brunswick (Wait, 1965). Saltwater has migrated upward from deep saline zones through breaches in confining units as a result of reduced hydraulic head in water-bearing zones of the Upper Floridan aquifer. By the 1960s, chloride-contaminated groundwater had migrated northward toward two major industrial pumping centers. As of 2009, the USGS collects and analyzes samples from a network of 81 wells on an annual basis for the CWP (figs. 19*A*, *B*; table 3).

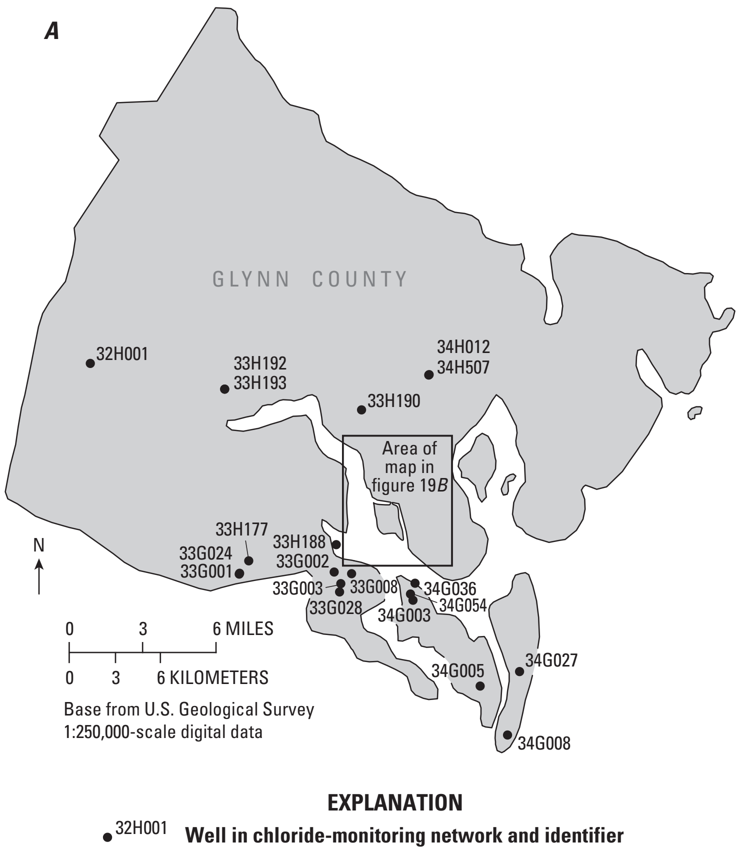
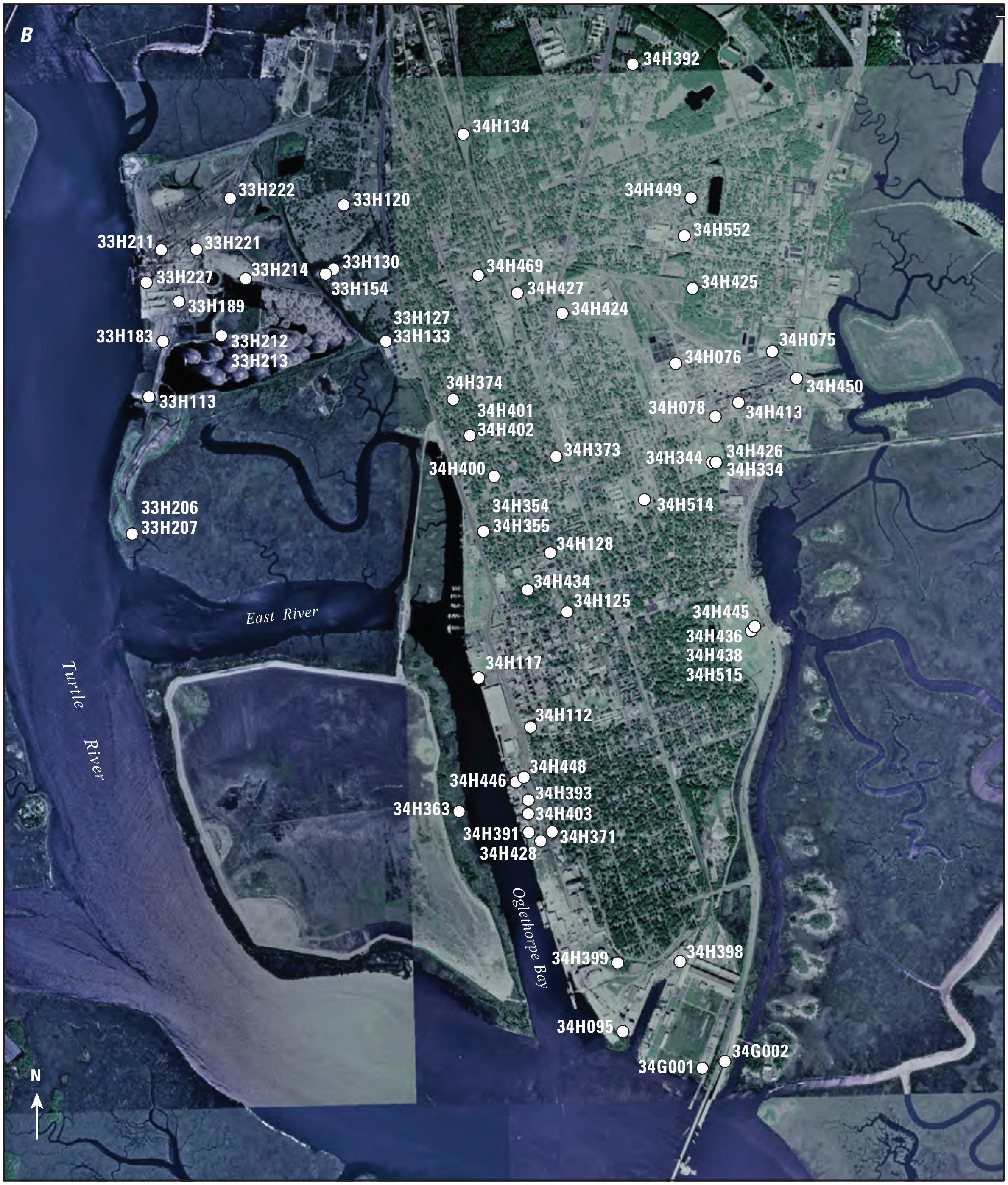


Figure 19. Chloride-monitoring network for the Brunswick–Glynn County area, Georgia. *(A)* Location and *(B)* enlarged area.



Base from U.S. Geological Survey
1:100,000 scale digital orthophotos for Glynn County

0 0.25 0.5 MILE
0 0.25 0.5 KILOMETER

EXPLANATION

○ 34G002 **Well with chloride concentration data and site name**

Figure 19. Chloride-monitoring network for the Brunswick–Glynn County area, Georgia. *(A)* Location and *(B)* enlarged area.—Continued

Table 3. Chloride concentrations in water samples collected from wells in the Brunswick–Glynn County area, Georgia, June 2003–2005, July 2006, July and August 2007, July 2008, and August 2009, and change in chloride concentration from 2008 to 2009.

[Well locations shown in fig. 19; aquifer or system: S–Surficial, BAS–Brunswick aquifer system, LBA–lower Brunswick aquifer, UFA–Upper Floridan aquifer, FAS–Floridan aquifer system, LFA–Lower Floridan aquifer; —, no data]

Well number	Aquifer or system	June 2003	June 2004	June 2005	July 2006	July and August 2007	July 2008	August 2009	Change 2008–2009
		Chloride concentration, in milligrams per liter							
34H428	S	13.9	12.8	11.3	14.0	13.3	13.5	13.6	0.1
34H438	S	2,870	2,540	—	—	—	—	—	—
34H448	S	20.7	18.3	15.3	19.0	—	—	—	—
34H515[a]	S	—	—	5,370	5,130	5,250	5,450	5,850	400
33G028	BAS	—	14.0	12.4	15.2	14.8	—	—	—
34H446	LBA	285	285	297	290	—	—	—	—
33G002	UFA	—	70.5	72.8	76.8	73.4	76.3	—	—
33G008	UFA	—	24.1	23.7	29.8	30.0	32.7	31.2	–1.5
33G024	UFA	18.6	16.8	14.7	18.8	17.7	18.2	17.5	–0.7
34G002	UFA	37.1	79.1	77.3	78.0	72.1	79.8	74.7	–5.1
34G003	UFA	136	150	153	—	150	—	—	—
34G005	UFA	—	—	22.9	27.4	26.4	26.5	26.7	0.2
34G008	UFA	—	—	—	170	—	—	—	—
34G027	UFA	—	—	—	—	27.6	—	—	—
34G054	UFA	—	—	—	45.7	44.5	45.3	43.1	–2.2
32H001	UFA	30.2	25.3	24.8	—	27.9	28.5	29.2	0.7
33H113	UFA	—	381	—	—	—	—	—	—
33H120	UFA	23.0	19.3	17.5	23.0	22.5	25.4	28.5	3.1
33H130	UFA	3,010	2,460	2,690	2,620	2,540	2,480	2,320	–160
33H133	UFA	2,050	1,950	2,160	2,230	2,180	2,080	2,160	80
33H177	UFA	28.7	24.2	22.4	27.0	25.0	24.3	—	—
33H183	UFA	25.4	23.7	31.1	30.0	—	23.8	21.6	–2.2
33H190	UFA	25.2	20.8	19.1	23.9	22.5	22.3	22.8	0.5
33H193	UFA	—	—	—	19.5	18.0	18.6	18.9	0.3
33H207	UFA	21.0	15.5	15.9	17.3	23.2	16.1	27.9	11.8
33H211	UFA	15.6	14.2	16.1	82.2	21.3	18.2	17.7	–0.5
33H213	UFA	58.1	48.4	35.0	45.4	49.1	33.7	41.7	8.0
33H221	UFA	1,180	1,130	834	800	—	372	1,130	758
33H222	UFA	595	303	626	—	—	—	423	—
33H227	UFA	35.8	125	247	300	—	—	—	—
34H012	UFA	—	26	—	—	—	—	—	—
34H095	UFA	—	26	27.1	32.2	30.8	28.9	21.2	–7.7
34H112	UFA	1,660	1,580	1,620	1,590	1,450	1,430	1,400	–30
34H117	UFA	527	497	499	531	551	545	554	9
34H125	UFA	605	496	479	431	360	321	—	—
34H128	UFA	727	682	706	710	—	—	—	—
34H334	UFA	1,120	1,080	1,070	1,480	1,090	1,070	1,040	–30
34H344	UFA	26.9	25.7	18.6	72.2	30.0	26.2	—	—
34H355	UFA	237	313	321	334	326	341	340	–1
34H363	UFA	—	—	—	73.8	80.9	—	—	—
34H371	UFA	17.0	14.5	12.7	15.0	15.2	15.4	15.6	0.2
34H373	UFA	381	402	387	369	353	349	338	–11

Table 3. Chloride concentrations in water samples collected from wells in the Brunswick–Glynn County area, Georgia, June 2003–2005, July 2006, July and August 2007, July 2008, and August 2009, and change in chloride concentration from 2008 to 2009.—Continued

[Well locations shown in fig. 19; aquifer or system: S–Surficial, BAS–Brunswick aquifer system, LBA–lower Brunswick aquifer, UFA–Upper Floridan aquifer, FAS–Floridan aquifer system, LFA–Lower Floridan aquifer; —, no data]

Well number	Aquifer or system	June 2003	June 2004	June 2005	July 2006	July and August 2007	July 2008	August 2009	Change 2008–2009
		Chloride concentration, in milligrams per liter							
34H374	UFA	959	985	1,040	1,080	981	995	978	–17
34H392	UFA	—	—	—	19.8	18.7	19.2	19.2	0
34H393	UFA	2,130	1,820	1,980	1,940	1,870	1,880	1,800	–80
34H400	UFA	425	412	422	438	433	422	409	–13
34H401	UFA	2,200	1,790	2,280	1,900	1,800	1,890	1,940	50
34H413	UFA	623	587	471	—	—	416	393	–23
34H424	UFA	—	—	—	2,330	2,180	2,220	2,150	–70
34H425	UFA	—	—	—	263	269	241	221	–20
34H427	UFA	1,470	1,520	1,520	1,500	1,390	1,360	1,290	–70
34H434	UFA	2,040	1,740	1,840	1,820	1,620	1,460	1,420	–40
34H445	UFA	17.6	16.4	15.9	19.4	18.4	18.9	19.3	0.4
34H449	UFA	31.0	24.9	24.0	28.9	27.5	27.8	28.2	0.4
34H450	UFA	21.7	17.9	15.3	17.4	16.6	16.9	17.0	0.1
34H469	UFA	1,350	1,140	—	1,020	894	878	728	–150
34H507	UFA	—	—	24.9	30.0	—	—	—	—
34H552	UFA	—	—	—	—	31.3	—	—	—
33G003	FAS	—	68.1	27.4	35.6	39.5	—	—	—
34G001	FAS	—	—	—	74.0	—	—	—	—
33H127	FAS	879	907	906	974	863	902	915	13
33H154	FAS	1,970	2,060	2,210	2,310	2,210	2,200	2,170	–30
33H189	FAS	—	—	—	410	—	—	—	
33H212	FAS	1,210	1,130	1,160	1,180	1,100	1,170	1,170	0
33H214	FAS	—	—	—	—	124	—	—	
34H075	FAS	29.0	42.8	51.3	170	—	—	—	
34H076	FAS	—	—	—	1,030	974	936	977	41
34H078	FAS	222	334	—	—	—	—	—	—
34H134	FAS	46.7	38.9	45.3	52.8	34.8	57.6	55.0	–3
34H354	FAS	1,360	1,360	1,330	1,440	1,440	1,460	1,450	–10
34H398	FAS	126	135	140	140	137	137	128	–9
34H402	FAS	2,740	2,020	2,210	2,280	2,350	2,340	2,320	–20
34H403	FAS	1,310	1,240	1,420	1,380	1,380	1,380	1,320	–60
33G001	LFA	34.9	32.7	33.2	36.2	34.0	35.1	26.1	–9.0
34G036	LFA	305	438	453	476	479	477	489	12
33H188	LFA	—	8,170	10,285	9,830	9,910	9,750	10,700	950
33H192	LFA	—	—	—	784	744	700	651	–49
33H206	LFA	357	404	416	411	389	567	427	–140
34H391	LFA	3,030	2,340	2,470	2,540	2,740	2,640	2,550	–90
34H399	LFA	6,590	5,910	6,440	6,710	6,940	7,530	6,870	–660
34H426	LFA	—	854	881	790	542	482	—	—
34H436	LFA	22.9	20.2	18.9	22.1	20.8	20.7	20.7	0

[a] Replaces 34H438

Upper Floridan Aquifer

The area of chloride contamination in the Upper Floridan aquifer at Brunswick during August 2009 was mapped based on sample data from 27 wells (fig. 20). During this period, the chloride concentration was greater than the 250-mg/L State and Federal secondary drinking-water standard (Georgia Environmental Protection Division, 1997; U.S. Environmental Protection Agency, 2000) in an approximate 2-mi^2 area, and exceeded 2,250 mg/L in part of the area. The August 2009 map is similar to the previously published map for 2008 (Cherry and others, 2010) and shows that areas of highest concentration are in the northern part of the city, as well as near the original area of contamination in the southern part of the city.

Yearly fluctuations of chloride concentration indicate increases of as much as 80 mg/L and decreases of as much as 160 mg/L from July 2008 to August 2009, which are largely the result of local pumping variations (fig. 21; table 3). Graphs of chloride concentrations in water samples from wells with open intervals in the upper and lower water-bearing zones of the Upper Floridan aquifer are shown for the southern Brunswick area (34H393 and 34H403; fig. 22) and northern Brunswick area (33H133 and 33H127; fig. 23). Chloride concentrations in water from the Lower Floridan aquifer are shown for well 34H391 in the southern Brunswick area (fig. 22). During August 2009, chloride concentrations in the Brunswick area generally were lower than in 2008, with decreases of as much as 160 mg/L in the northwestern part of the area and 100 mg/L in the central part of the area (fig. 21). In the northern Brunswick area, chloride concentrations generally have increased since the 1960s, reflecting influences of local pumping (fig. 23). During 2008–2009, chloride concentrations increased in well 33H133 and increased slightly in well 33H127 (fig. 23; table 3). Chloride concentrations in the southern Brunswick area for wells 34H393 and 34H403 continued a downward trend begun in the 1990s (fig. 22). Well 34H391 shows a slight increase over the period of record.

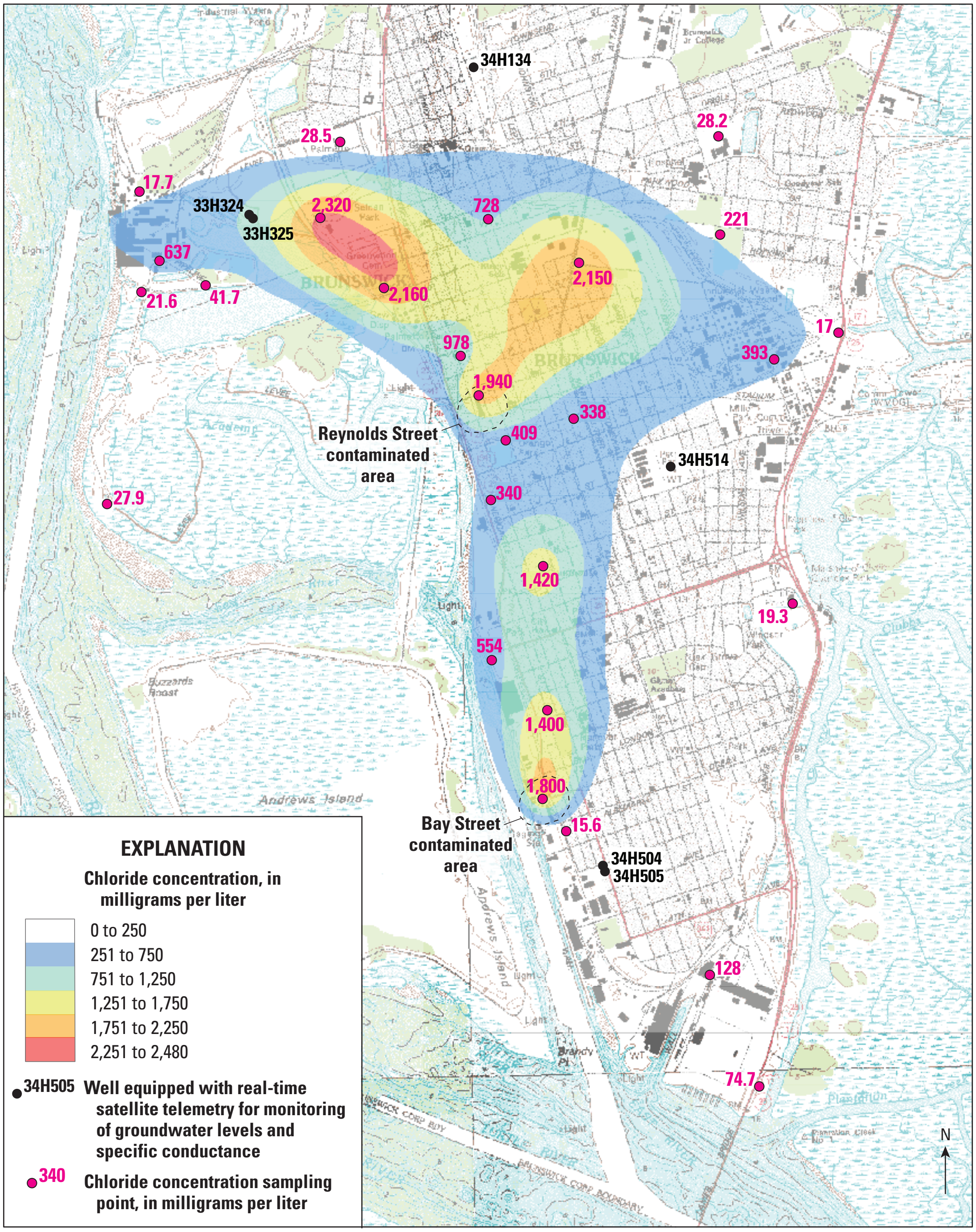
Outside the plume area, chloride concentrations are less than the 250-mg/L drinking-water standard (fig. 20; table 3). However, local areas have chloride concentrations greater than 50 mg/L, which is considered to be greater than background levels of 20 to 30 mg/L. This includes elevated chloride concentrations in wells 34G002 and 34H398. The reason for elevated chloride concentrations in these wells remains unclear, but elevated concentrations could be related to failed or improperly installed well-casing seals (Hall and Peck, 2005).

Long-Term Records at Industrial Well Fields

Since beginning operations in Brunswick, the two primary industrial groundwater users have met their water needs by pumping groundwater from well fields that draw water from the UWBZ and LWBZ of the Upper Floridan aquifer. Pinova Inc. began operations in 1920, and Georgia–Pacific Cellulose LLC opened their facility in 1937. Increased pumpage at the two industrial well fields has resulted in elevated chloride concentrations in the Upper Floridan aquifer over an approximate 2-mi^2 area of Brunswick. Groundwater withdrawals reached a maximum at the Pinova well field during 1970 (24 Mgal/d; Cherry and others, 2010) and at the Georgia–Pacific Cellulose well field during 1980 (59 Mgal/d; Cherry and others, 2010).

To track changes in chloride concentration, a monthly sampling program was initiated at each well field during the late 1950s. Data spanning 1958–2009 were compiled and used to assess how the configuration of the chloride plume has developed over time (*http://waterdata.usgs.gov/ga/nwis/nwis*). The source of water for each discrete sample is from the open interval of the well. Data from several long-term USGS monitoring sites were included in the analysis to provide a history of the chloride plume movement in the Brunswick area.

Gregg and Zimmerman (1974) identified two source areas of elevated chloride in the Brunswick area (Reynolds Street and Bay Street; fig. 20) and concluded that faulting in these areas created breaches in the confining unit of the Lower Floridan aquifer that has allowed brackish water with chloride concentrations between 2,200 and 3,000 mg/L to migrate upward into the UWBZ and LWBZ and move northward toward industrial pumping centers. In addition to lateral movement from these areas, wells drilled into the LWBZ or deeper may create conduits for upward movement of brackish water from greater depths into the fresh UWBZ. Groundwater pumping at the industrial well fields has created vertical gradients that facilitate upward movement of brackish groundwater into freshwater zones.



Base from U.S. Geological Survey 1:24,000-scale digital data
Brunswick West, 1993; Brunswick East, 1979

0 0.5 1 MILE

0 0.5 1 KILOMETER

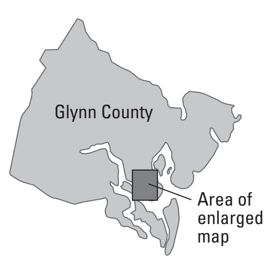
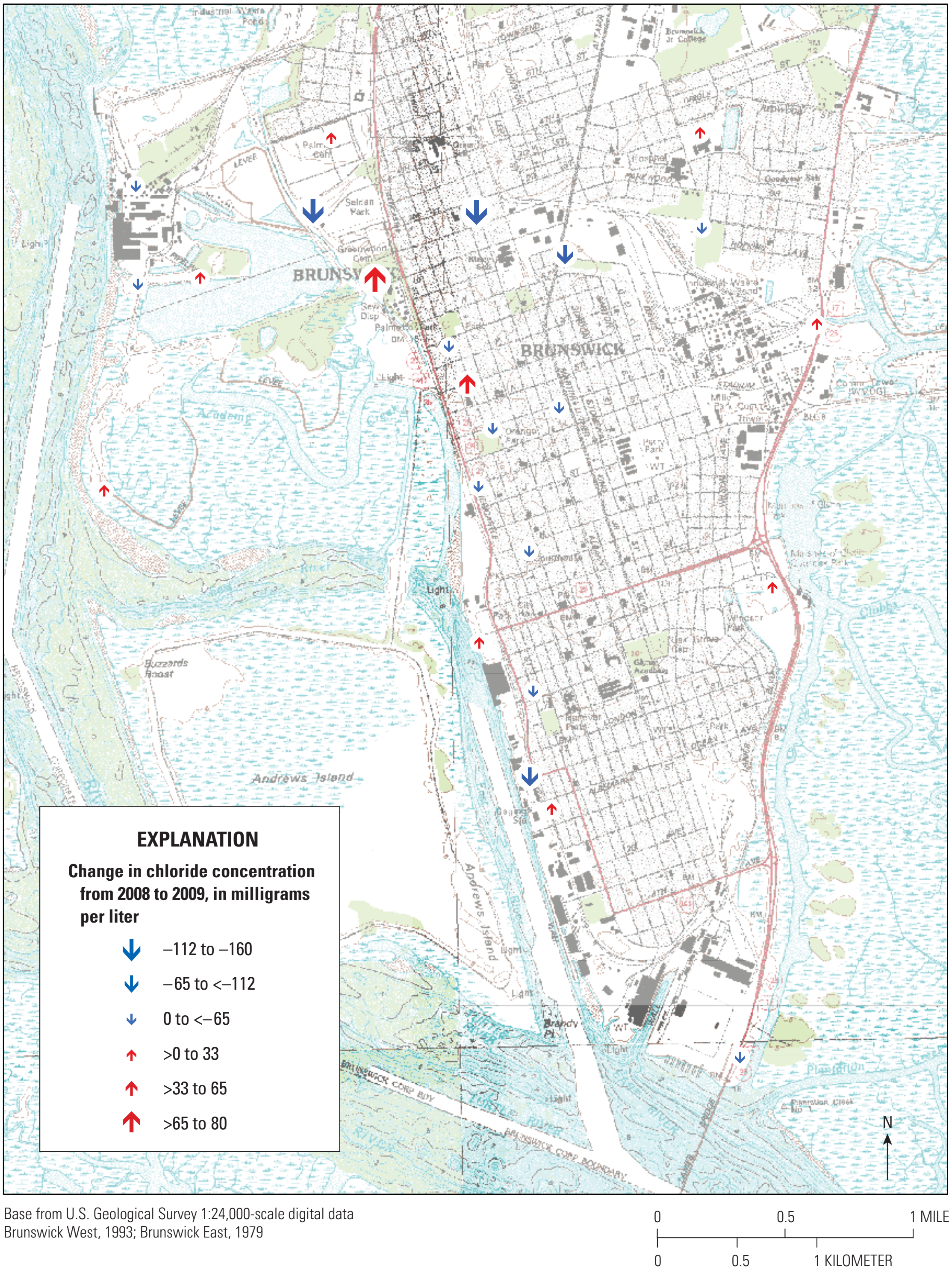


Figure 20. Chloride concentration in the Upper Floridan aquifer in the Brunswick area, Georgia, August 2009.



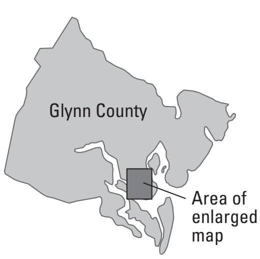


Figure 21. Change in chloride concentration in the Upper Floridan aquifer in the Brunswick area, Georgia, from 2008 to 2009.

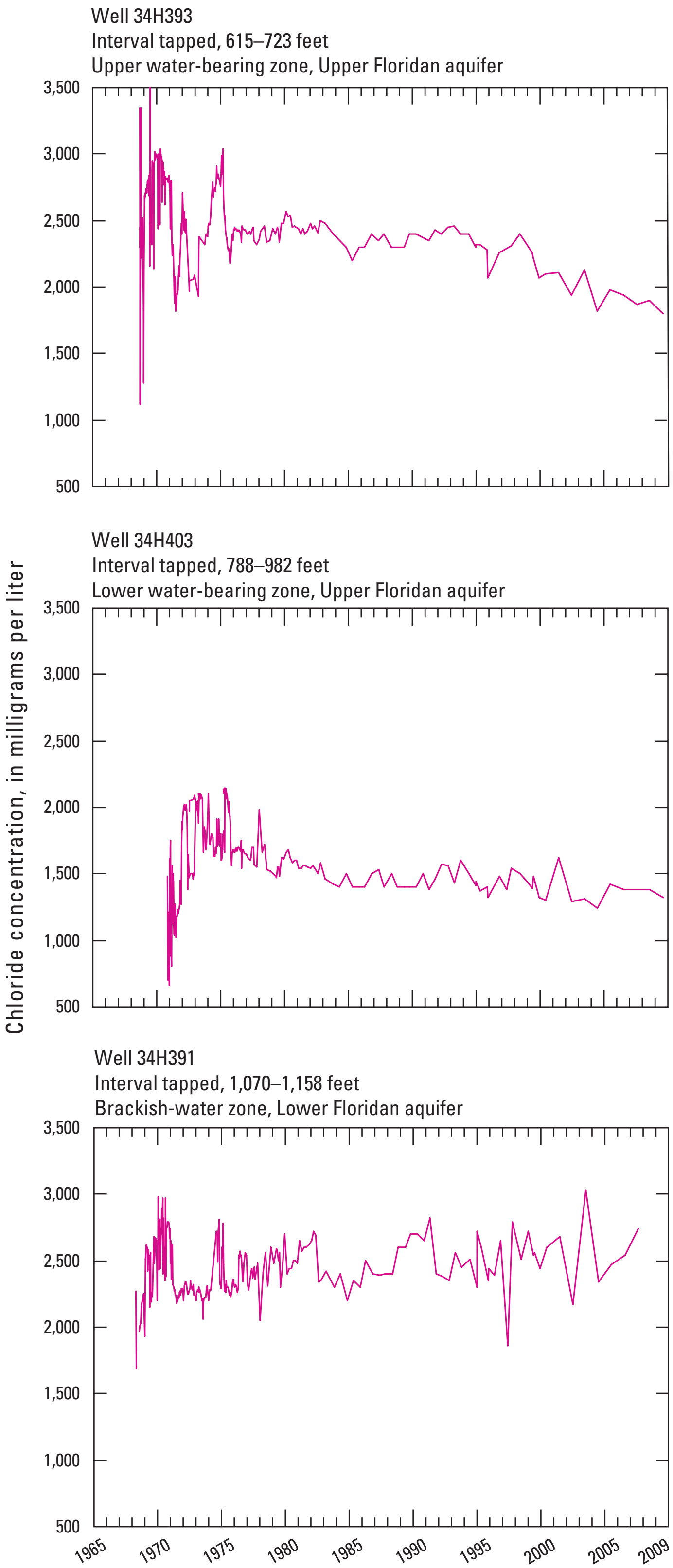


Figure 22. Chloride concentration in water for selected wells in the southern Brunswick–Glynn County area, Georgia, 1968–2009 (see figure 19*B* for well locations).

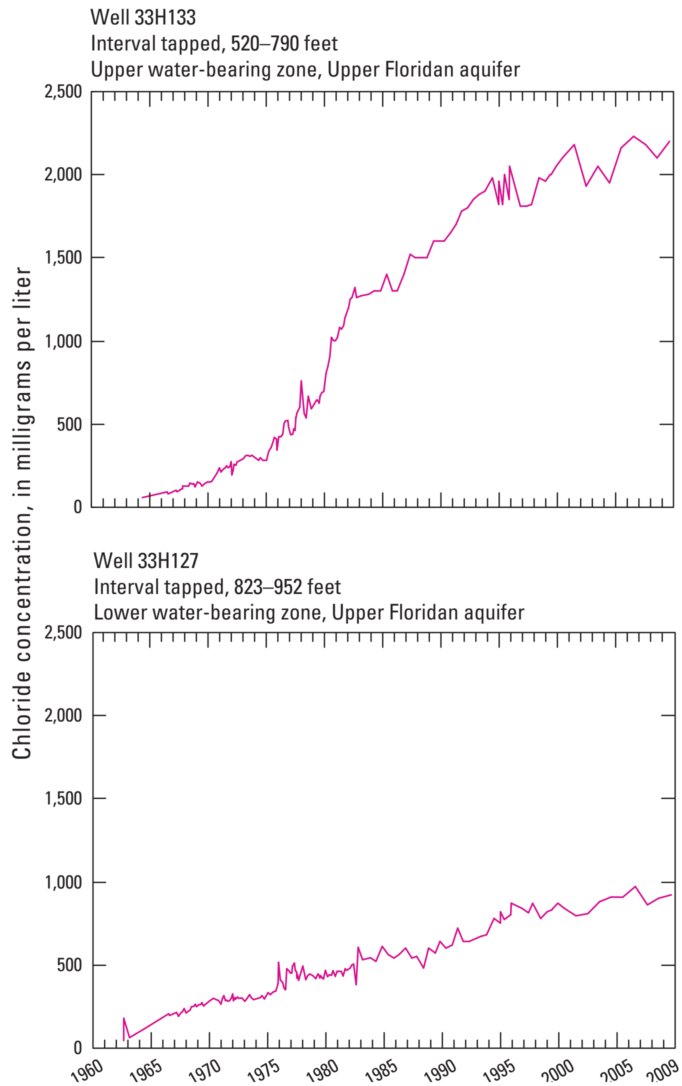


Figure 23. Chloride concentration in water for selected wells in the northern Brunswick–Glynn County area, Georgia, 1968–2009 (see figure 19*B* for well locations).

Pinova Well Field

At the Pinova well field, chloride monitoring began during 1958 and has continued through 2009 with samples taken each month from wells that were in use and actively pumping (fig. 24; table 4). Graphs of chloride concentrations for selected wells are presented in figures 25 and 26. Maps showing active production wells with chloride concentration exceeding the State and Federal secondary drinking-water standard of 250 mg/L (Georgia Environmental Protection Division, 1997; U.S. Environmental Protection Agency, 2000) for selected time intervals during 1958–2009 are shown in figure 25. Table 5 provides a summary of maximum and minimum chloride concentrations in well field wells, together with mean annual chloride concentrations during 2008–2009.

Production wells constructed in the 1920s through the 1950s at the Pinova well field were completed in the UWBZ and LWBZ of the Upper Floridan aquifer at depths ranging from 668 to 1,062 ft (Jones and Maslia, 1994; table 4; fig. 24). During 1960–1970, chloride concentrations increased to levels above the 250-mg/L drinking-water standard in five wells completed in both the UWBZ and LWBZ at the Pinova well field (fig. 27). This increase corresponded to a slight increase in groundwater pumping from Pinova production wells from 22 Mgal/d during 1960 to 24 Mgal/d during 1970 (Cherry and others, 2010). To help decrease chloride contamination, nine production wells were backfilled in the 1960s to seal off the LWBZ and reduce the chloride contamination (Jones and Maslia, 1994). The original depths of the nine production wells ranged from 880 to 1,062 ft and the wells tapped into a brackish zone below the LWBZ of the Upper Floridan aquifer (table 4). These wells were plugged to depths of 887–932 ft, and were open to the UWBZ and upper part of the LWBZ (Jones and Maslia, 1994; table 4). Plugging the lower portion of the nine production wells decreased the chloride concentrations to less than 100 mg/L, indicating that the plugged zones were the source of chloride contamination (fig. 25). Smaller chloride levels in the UWBZ are also indicated by concentrations of less than 50 mg/L measured in wells 34H065 and 34H067, completed in the UWBZ, during the 1960s (table 5).

During the 1970s and 1980s, chloride concentrations increased in most of the production wells at the Pinova well field even though overall pumpage decreased from 24 Mgal/d during 1970 to 11.3 Mgal/d during 1990 (figs. 6, 25). This increase suggests continued vertical movement of brackish groundwater from the LWBZ into the UWBZ. Following modification of production wells during the 1960s to backfill and seal off brackish zones beneath the UWBZ, all production wells at the Pinova well field were completed solely in the UWBZ. In well 34H413, chloride concentration showed a steady increase during the 1970s and mid-1980s, with concentrations exceeding the 250-mg/L State and Federal secondary drinking-water standard (Georgia Environmental Protection Division, 1997; U.S. Environmental Protection Agency, 2000) in 1983, and reaching a maximum of 1,520 mg/L during 1988 (fig. 25; table 5). In well 34H073, chloride concentrations increased steadily from 48 mg/L in 1970, to above the 250-mg/L drinking-water standard in 1986, and concentrations continued to rise during the 1990s and 2000s (fig. 25). On the east side of the facility, chloride concentrations at production well 34H075 remained near or below 50 mg/L during 1970–1980 (fig. 25). Chloride concentrations at USGS observation wells located south of the Pinova well field indicate concentrations near background in the UWBZ (34H344), while concentrations in the LWBZ (34H334) exceeded the 250-mg/L drinking-water standard in the early 1970s and continued to rise through 2009 (fig. 26). During the 1980s, chloride concentrations at the Pinova well field generally increased, and by April 1990, five of the eight active production wells in the well field exceeded the 250-mg/L drinking-water standard (fig. 27).

During the 1990s and 2000s, chloride concentrations at the Pinova well field generally increased despite a decrease in pumpage to less than 9 Mgal/d during 1995–2009 (fig. 6). The mid-2000s was a period when maximum chloride concentrations were reached at wells 34H065, 34H073, 34H075, 34H076, 34H424, and 34H450 (table 5). Chloride concentrations at wells 34H413 and 34H425 reached levels of 760 and 460 mg/L, respectively, during 2000 and have since decreased (fig. 25). The most notable change during this period occurred at well 34H425, with chloride concentrations generally below 50 mg/L during 1990 and increasing to levels above 250 mg/L during 1995 (fig. 25). This rapid increase in chloride concentration during the 1990s suggests lateral movement of the chloride plume further northward from the main Pinova well field, and concentration levels have declined to below 250 mg/L in recent years (figs. 20, 25).

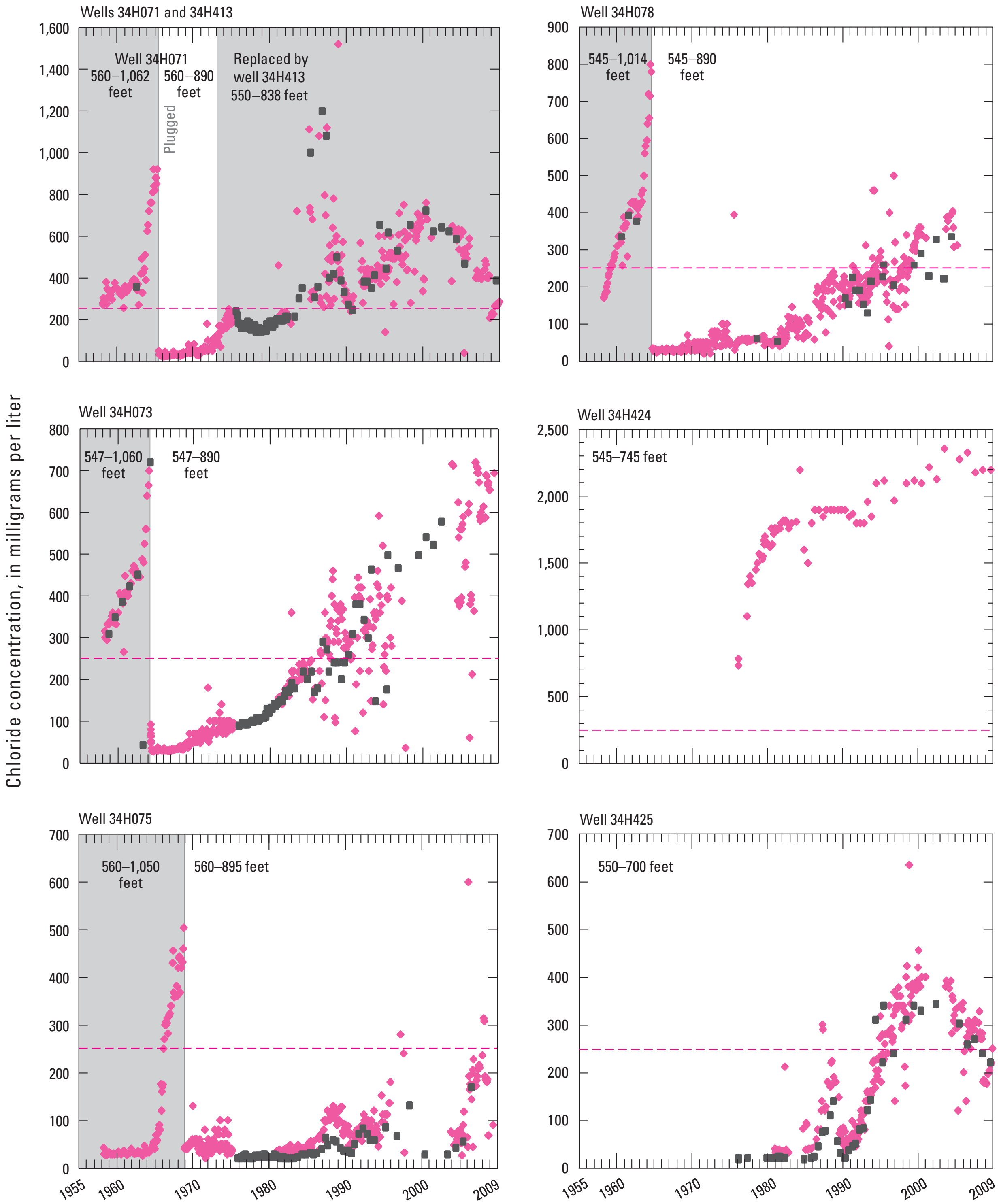
A comparison of chloride concentrations at wells operational during 2008–2009 indicates the mean annual chloride concentration slightly increased at Pinova well 34H076 from 680 mg/L during 2008 to 700 mg/L during 2009 (table 5). Chloride concentrations in wells 34H413 and 34H425 decreased during the same period and remained stable in wells 34H424 and 34H450 (table 5). During July 2008 and August 2009, samples taken in well 34H334, about 1,000 ft south of the Pinova facility, indicate a 100-mg/L decrease in chloride concentrations (fig. 26; table 5).

Figure 24. Well locations in the vicinity of the Pinova Inc. (formerly Hercules Inc.) facility in Brunswick, Georgia (see table 4 for well information).

Table 4. Well information in the vicinity of the Pinova Inc. (formerly Hercules Inc.) facility in Brunswick, Georgia (data from Jones and Maslia, 1994).

[U, upper; L, Lower; ft, feet; USGS TW, U.S. Geological Survey test well; see figure 24 for well locations]

Well number	Well name	Latitude	Longitude	Date drilled	Depth, in feet below land surface		Water-bearing zone in Upper Floridan aquifer	Remarks
		Degrees, minutes, seconds NAD 83			Casing	Well		
34H065	Hercules, Inc. A	31°09'50"N	81°28'51"W	1920	455	664	U	Original depth 971 ft, plugged to 664 ft
34H066	Hercules, Inc. B	31°09'51"N	81°28'49"W	1920	384	646	U	Original depth 973 ft, plugged to 646 ft
34H067	Hercules, Inc. C	31°09'49"N	81°28'43"W	1921	500	621	U	Original depth 668 ft, plugged to 621 ft
34H070	Hercules, Inc. F	31°09'55"N	81°28'50"W	08-1929	557	887	U/L	Original depth 880 ft; deepened to 1,025 ft, 1935; plugged to 887 ft, 1965; destroyed 1986
34H071	Hercules, Inc. H	31°09'51"N	81°28'46"W	10-1939	560	890	U/L	Original depth 1,062 ft; plugged, May 1965; destroyed, replaced by 34H413, February 1973
34H072	Hercules, Inc. I	31°09'52"N	81°28'43"W	06-1941	498	950	U/L	Taps multiple water-bearing zones
34H073	Hercules, Inc. J	31°09'51"N	81°28'57"W	08-1942	547	890	U/L	Original depth 1,060 ft, plugged to 890 ft, April 1964
34H074	Hercules, Inc. K	31°09'59"N	81°28'44"W	03-08-1946	560	894	U/L	Original depth 1,053 ft, plugged to 894 ft, January 1966
34H075	Hercules, Inc. L	31°10'02"N	81°28'37"W	02-1945	560	895	U/L	Original depth 1,050 ft, plugged to 895 ft, November 1968
34H076	Hercules, Inc. M	31°09'59"N	81°29'01"W	02-1950	480	911	U/L	Original depth 1,015 ft, plugged to 911 ft, October 1965
34H077	Hercules, Inc. N	31°10'07"N	81°29'03"W	08-14-1953	555	932	U/L	Original depth 1,050 ft, plugged to 932 ft, June 1967; destroyed 1972
34H078	Hercules, Inc. O	31°09'48"N	81°28'52"W	09-27-1955	545	890	U/L	Original depth 1,014 ft, plugged to 890 ft, July 1964
34H079	Hercules, Inc. P	31°09'58"N	81°28'39"W	08-26-1957	549	912	U/L	Original depth 1,040 ft, plugged to 912 ft, August 1970
34H334	USGS TW 4	31°09'38"N	81°28'53"W	09-1962	800	980	L	None
34H344	USGS TW 7	31°09'38"N	81°28'52"W	04-1964	504	770	U	None
34H412	Hercules, Inc. Q	31°10'19"N	81°29'22"W	11-02-1972	548	630	U	None
34H411	Hercules, Inc. R	31°10'03"N	81°28'57"W	05-1972	540	698	U	None
34H413	Hercules, Inc. S	31°09'51"N	81°28'46"W	02-27-1973	550	838	U	Replaced 34H071
34H424	Hercules, Inc. T	31°10'11"N	81°29'31"W	02-1976	550	745	U	None
34H425	Hercules, Inc. U	31°10'16"N	81°28'58"W	05-12-1976	550	700	U	None
34H450	Hercules, Inc. V	31°09'56"N	81°28'31"W	08-28-1990	557	750	U	None



EXPLANATION

Maximum contaminant level—250 milligrams per liter (Georgia Environmental Protection Division, 1997; U.S. Environmental Protection Agency, 2000)

Pinova Inc. sample

USGS sample

Figure 25. Chloride concentration in selected Upper Floridan aquifer production wells in the vicinity of the Pinova Inc. (formerly Hercules Inc.) well field in Brunswick, Georgia (values in feet are open-well interval; note vertical scales vary; see table 4 for well information; see figure 24 for well locations).

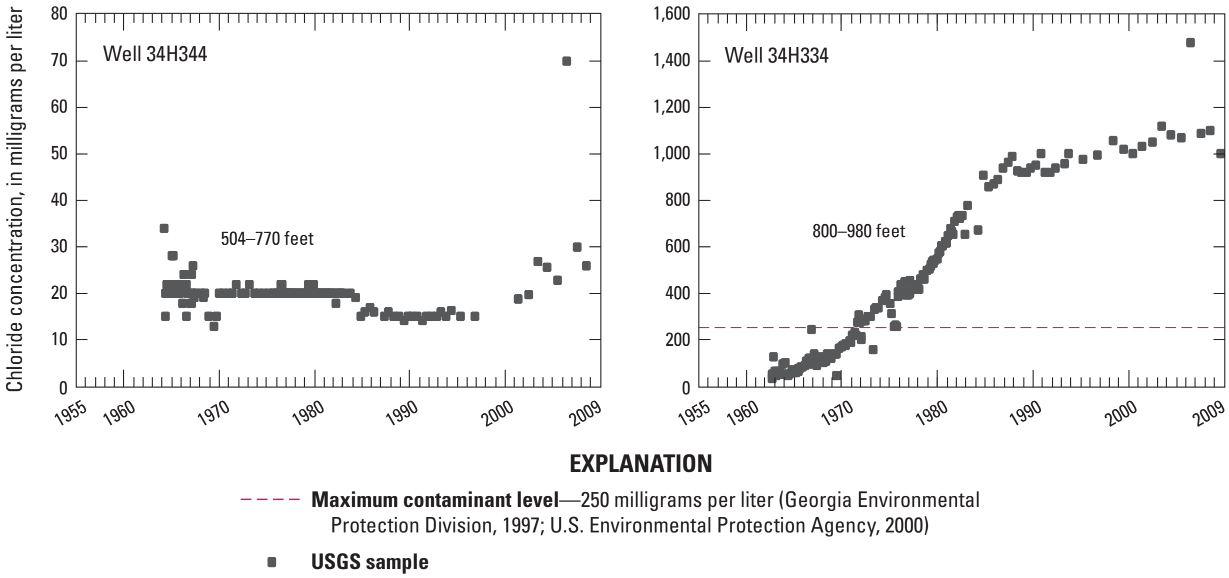


Figure 26. Chloride concentration in USGS observation wells 34H344 and 34H334 in the Upper Floridan aquifer (UFA) in the vicinity of the Pinova Inc. (formerly Hercules Inc.) well field in Brunswick, Georgia (values in feet are open-well interval; note vertical scales vary; see table 4 for well information; see figure 24 for well locations).

Table 5. Chloride data available for production wells and selected observation wells in the vicinity of the Pinova Inc. (formerly Hercules Inc.) facility in Brunswick, Georgia.

[mg/L, milligram per liter; NA, data not available; USGS TW, U.S. Geological Survey test well; see figure 24 for well locations]

Well number	Well name	Year monitoring		Minimum chloride concen-tration, in mg/L	Date	Maximum chloride concen-tration, in mg/L	Date	Number of chloride samples, monitoring period	Mean annual chloride concentration, in mg/L	
		Began	Ended						2008	2009
34H065	Hercules Inc. A	1958	2003	20	7-12-1960	787	6-27-2003	262	NA	NA
34H066	Hercules Inc. B	NA	NA	NA	NA	NA	NA	0	NA	NA
34H067	Hercules Inc. C	1958	1989	19	4-10-1968	810	12-7-1988	230	NA	NA
34H070	Hercules Inc. F	1958	1985	38	2-28-1969	1,100	11-1-1984	243	NA	NA
34H071	Hercules Inc. H	1958	1973	23	2-8-1966	920	4-8-1965	150	NA	NA
34H072	Hercules Inc. I	1958	1994	20	3-25-1982	800	11-14-1988	301	NA	NA
34H073	Hercules Inc. J	1958	2009	27	9-5-1964	720	11-28-2006	443	652	NA
34H074	Hercules Inc. K	1958	1976	58	4-17-1969	530	1-6-1966	185	NA	NA
34H075	Hercules Inc. L	1958	2009	20	8-16-1971	600	2-28-2006	455	187	NA
34H076	Hercules Inc. M	1958	2009	38	4-10-1985	1,030	7-19-2006	449	680	700
34H077	Hercules Inc. N	1958	1972	82	3-4-1958	750	1-7-1972	148	NA	NA
34H078	Hercules Inc. O	1958	2005	20	7-9-1971	800	6-4-1964	455	NA	NA
34H079	Hercules Inc. P	1958	1989	24	3-4-1958	548	11-18-1968	257	NA	NA
34H334	USGS TW 4	1962	2009	36	9-11-1962	1,480	7-19-2006	177	1,100[a]	1,000[b]
34H344	USGS TW 7	1964	2008	13	6-26-1969	70	7-19-2006	134	26[a]	NA
34H412	Hercules Inc. Q	1973	1990	24	11-4-1985	1,200	5-22-1989	136	NA	NA
34H411	Hercules Inc. R	1972	1996	30	2-27-1973	950	10-12-1993	64	NA	NA
34H413	Hercules Inc. S	1973	2009	40	5-31-2005	1,520	12-7-1988	319	360	280
34H424	Hercules Inc. T	1976	2009	730	2-9-1976	2,360	6-26-2003	73	2,200	2,200
34H425	Hercules Inc. U	1976	2009	17	11-1-1984	635	12-4-1998	268	250	210
34H450	Hercules Inc. V	1990	2009	15	2-28-2006	120	2-28-2005	193	38	38

[a] Discrete sample collected during July 2008.

[b] Discrete sample collected during August 2009.

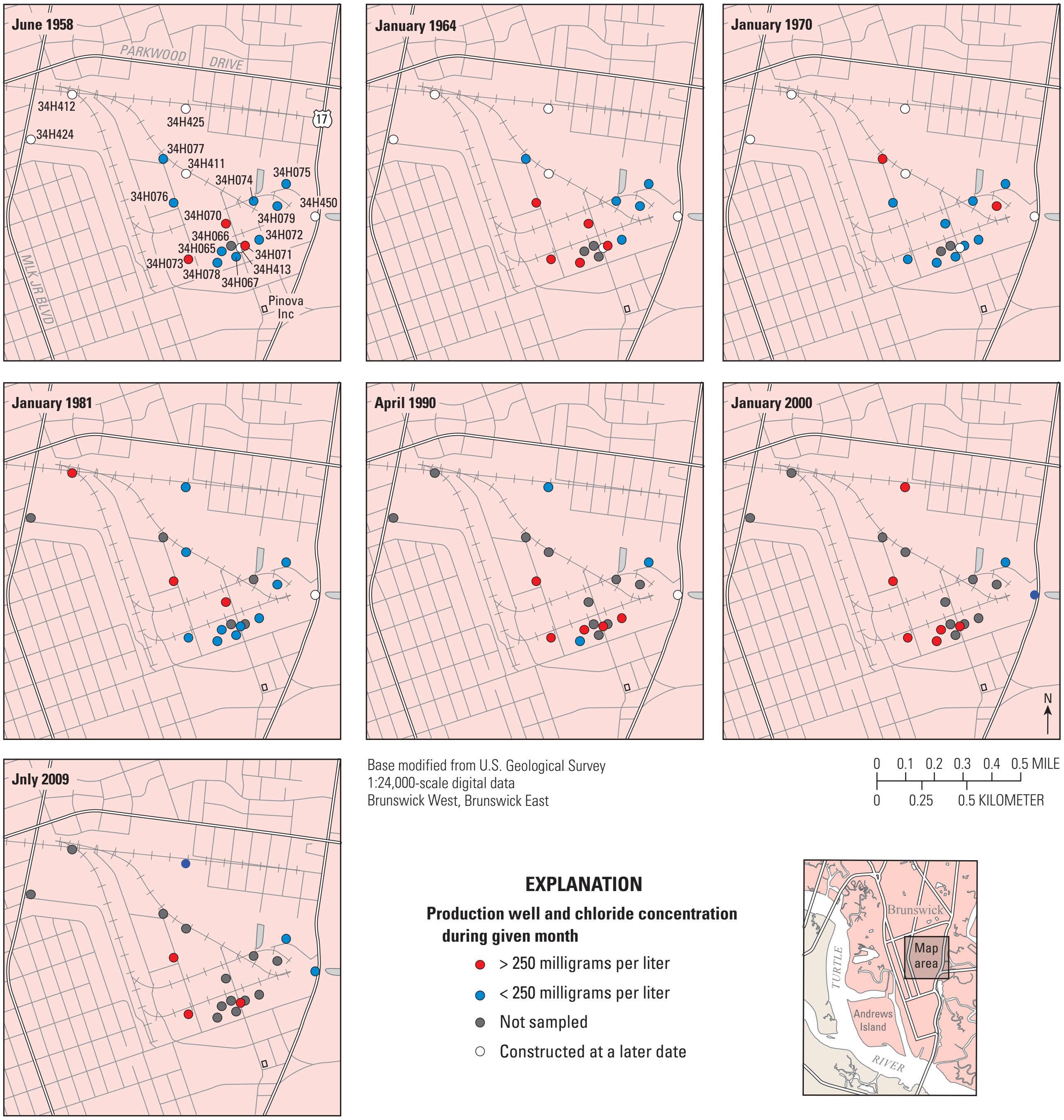


Figure 27. Chloride concentration exceeding the State and Federal secondary drinking-water standard of 250 milligrams per liter (red) in active Upper Floridan aquifer production wells in the vicinity of the Pinova Inc. (formerly Hercules Inc.) well field in Brunswick, Georgia, during June 1958, January 1964, January 1970, January 1981, April 1990, January 2000, and July 2009.

Georgia–Pacific Cellulose Well Field

At the Georgia–Pacific Cellulose well field, chloride monitoring began during 1958 and has continued through 2009 with samples taken each month from wells that were in use and actively pumping (fig. 28; table 6). Graphs of chloride concentrations for selected wells are presented in figures 29–30. Maps showing chloride concentration within selected wells during 1958–2009 are shown in figure 31. Table 7 provides a summary of maximum and minimum chloride concentrations in well field wells, together with mean annual chloride concentrations during 2008 and 2009.

Two of the original production wells at the Georgia–Pacific Cellulose well field constructed in the late 1930s were completed in the UWBZ (33H108 and 33H109), and a third well (33H110) was completed in both the UWBZ and LWBZ (table 6). The majority of wells constructed in the 1940s through the 1980s were completed in both the UBWZ and LWBZ. A general practice at the Georgia–Pacific Cellulose well field was to drill replacement production wells adjacent to abandoned, brackish wells once chloride concentrations generally rose above 300 mg/L. For example, well 33H108 was replaced by well 33H227, about 800 ft to the southwest of the original well, in 1989 when the chloride concentration rose from below 100 mg/L to above 200 mg/L during a 10-year period (fig. 29; table 7). To facilitate evaluation of chloride concentration trends, data for “old” and “new” wells are plotted on the same graph (fig. 29).

During 1960, Georgia–Pacific Pacific Cellulose had nine production wells in operation pumping an average of about 29 Mgal/d, and pumping increased to 45 Mgal/d during 1970 (Cherry and others, 2010; fig. 6). During this period, chloride concentrations increased in wells 33H113, 33H115, and 33H114, but remained below the drinking-water standard (less than 250 mg/L; figs. 28, 29). Chloride concentrations in USGS observation wells located to the east of the Georgia–Pacific Cellulose well field showed a steady increase during this period, indicating solute movement from source areas near Reynolds Street toward the well field (figs. 28, 30). Minimum chloride concentrations between 14 and 318 mg/L were observed in 11 wells during the late 1950s and the 1960s (table 7). During the 1950s and 1960s, the maximum chloride concentration near the well field occurred at 33H117 on October 23, 1961, yielding a sample result of 1,000 mg/L. A minimum chloride concentration of 318 mg/L was observed on April 10, 1968, at production well 33H116, indicating further migration of brackish water from source areas toward the well field (fig. 28; table 7).

During the 1970s and 1980s, groundwater pumping at the Georgia–Pacific well field reached a peak of about 59 Mgal/d in 1980 followed by a decline to 49 Mgal/d in 1990 (Cherry and others, 2010; fig. 6). In response to increased pumping, chloride concentrations at the majority of production wells increased steadily from between 50 and 100 mg/L during 1970 to between 200 and 900 mg/L during 1990 (fig. 29). Production wells 33H112 and 33H183 generally had chloride concentrations below 50 mg/L during this period. Chloride concentrations in production well 33H110 increased from about 50 mg/L in the late 1970s to greater than 400 mg/L by early 1983.

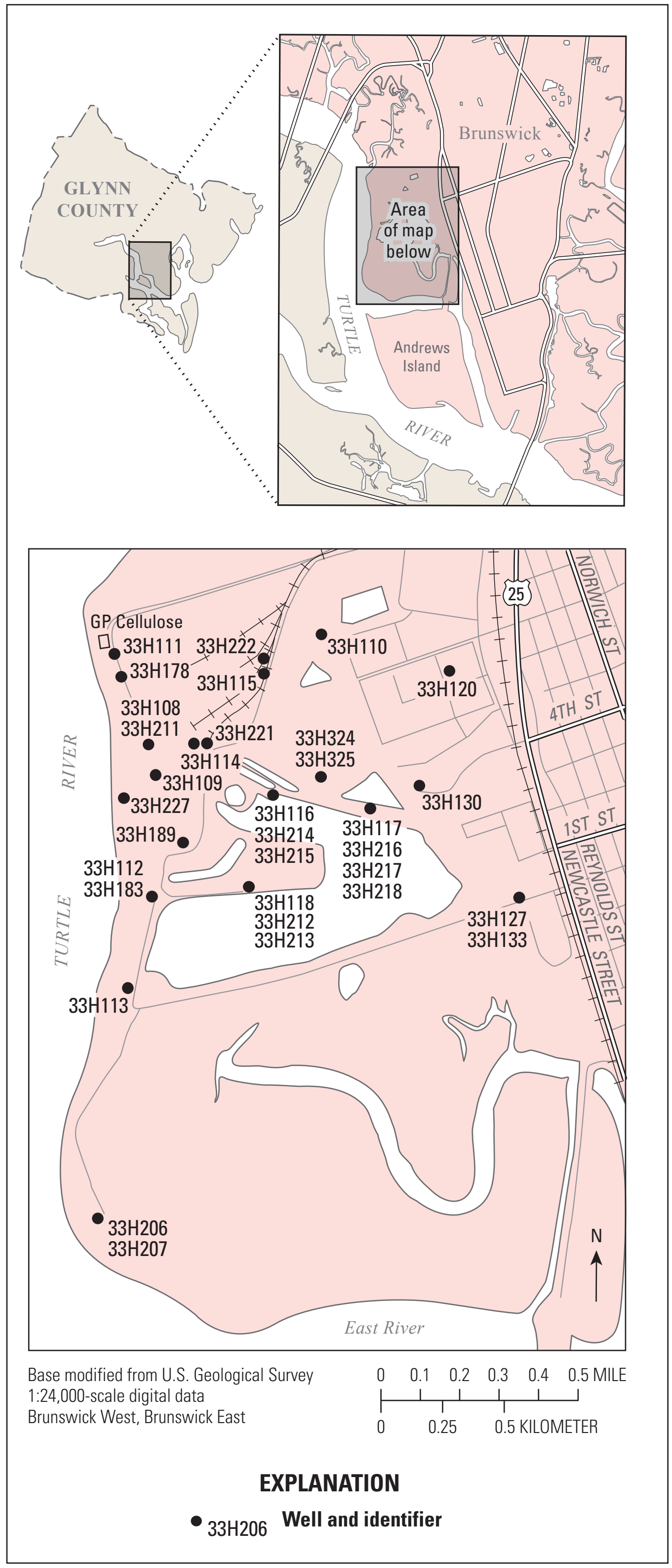


Figure 28. Well locations in the vicinity of the Georgia–Pacific (GP) Cellulose LLC (formerly Brunswick Pulp & Paper Company) facility in Brunswick, Georgia (see table 6 for well information).

Table 6. Construction, location, and contributing aquifer data for wells near the Georgia–Pacific Cellulose LLC facility in Brunswick, Georgia (from Jones and Maslia, 1994).

[BP&P, Brunswick Pulp & Paper Company; USGS, U.S. Geological Survey; GGS, Georgia Geologic Survey; TW, test well; U, upper; L, lower; UWBZ, upper water-bearing zone; LWBZ, lower water-bearing zone; see figure 28 for well locations]

Well number	Well name	Latitude	Longitude	Date drilled	Depth, in feet below land surface		Water-bearing zone in Upper Floridan aquifer	Remarks
		Degrees, minutes, seconds NAD 83			Casing	Well		
33H108	BP&P 1	31°10'27"N	81°31'13"W	06-1937	492	871	U	Replaced by 33H227, August 1985
33H109	BP&P 2	31°10'23"N	81°31'12"W	1937	488	849	U	Replaced by 33H189, May 1979
33H110	BP&P 3	31°10'41"N	81°30'46"W	1937	494	1,050	U/L	None
33H111	BP&P 4	31°10'39"N	81°31'18"W	04-1948	492	1,043	U/L	Replaced by 33H178, April 1974
33H112	BP&P 5	31°10'07"N	81°31'13"W	09-1950	517	1,019	U/L	Replaced by 33H183, January 1977
33H113	BP&P 6	31°09'55"N	81°31'17"W	11-1955	550	1,076	U/L	None
33H114	BP&P 8	31°10'27"N	81°31'06"W	06-1960	560	1,006	U/L	Replaced by 33H221, August 1985
33H115	BP&P 7	31°10'36"N	81°30'55"W	1960	560	935	U/L	Replaced by 33H222, plugged, March 1990
33H116	BP&P 9	31°10'20"N	81°30'54"W	12-07-60	557	928	U/L	Replaced by 33H214 and 33H215, November 1984
33H117	BP&P 10	31°10'18"N	81°30'39"W	12-10-60	558	1,030	U/L	Replaced by 33H216, 33H217, and 33H218, January 1985
33H118	BP&P 11	31°10'08"N	81°30'58"W	1961	550	1,003	U/L	Replaced by 33H212 and 33H213, December 1984
33H120	Palmetto Cemetary (north)	31°10'21"N	81°30'31"W	04-1963	530	700	U	None
33H127	USGS TW3	31°10'06"N	81°30'16"W	08-1962	823	952	L	None
33H130	Selden Park	31°10'21"N	81°30'31"W	04-1963	530	700	U	None
33H133	USGS TW6	31°10'06"N	81°30'16"W	03-1964	520	790	U	None
33H178	BP&P 4 (new)	31°10'36"N	81°31'17"W	04-01-74	492	1,043	U/L	Replaced 33H111
33H183	BP&P 5 (new)	31°10'07"N	81°31'13"W	01-11-77	550	850	U	Replaced 33H112
33H189	BP&P 2 (new)	31°10'14"N	81°31'08"W	05-1979	540	900	U/L	Replaced 33H109
33H206	USGS/GGS/ BP&P TW-1 (south)	31°09'25"N	81°31'22"W	02-23-83	1,000	1,100	L	None
33H207	USGS/GGS/ BP&P TW-2 (south)	31°09'25"N	81°31'22"W	02-23-83	620	720	U	None
33H211	USGS/BP&P 1	31°10'27"N	81°31'13"W	10-31-84	590	630	U	Replaced 33H108
33H212	USGS/BP&P 11 (lower)	31°10'08"N	81°30'58"W	12-13-84	870	1,007	L	Replaced 33H118
33H213	USGS/BP&P 11 (upper)	31°10'08"N	81°30'58"W	12-13-84	550	800	U	Replaced 33H118
33H214	USGS/BP&P 9 (lower)	31°10'20"N	81°30'54"W	11-1984	895	920	L	Replaced 33H116

Table 6. Construction, location, and contributing aquifer data for wells near the Georgia–Pacific Cellulose LLC facility in Brunswick, Georgia (from Jones and Maslia, 1994).—Continued

[BP&P, Brunswick Pulp & Paper Company; USGS, U.S. Geological Survey; GGS, Georgia Geologic Survey; TW, test well; U, upper; L, lower; UWBZ, upper water-bearing zone; LWBZ, lower water-bearing zone; see figure 28 for well locations]

Well number	Well name	Latitude	Longitude	Date drilled	Depth, in feet below land surface		Water-bearing zone in Upper Floridan aquifer	Remarks
		Degrees, minutes, seconds NAD 83			Casing	Well		
33H215	USGS/BP&P 9 (upper)	31°10'20"N	81°30'54"W	11-1984	557	800	U	Replaced 33H116
33H216	USGS/BP&P 10 (lower)	31°10'18"N	81°30'39"W	01-23-85	1,010	1,030	L	Replaced 33H117
33H217	USGS/BP&P 10 (middle)	31°10'18"N	81°30'39"W	01-23-85	885	907	L	Replaced 33H117
33H218	USGS/BP&P 10 (upper)	31°10'18"N	81°30'39"W	01-23-85	557	800	U	Replaced 33H117
33H221	BP&P 8 (new)	31°10'27"N	81°31'04"W	08-1985	556	1,006	U/L	Replaced 33H114
33H222	BP&P 7 (new)	31°10'38"N	81°30'55"W	12-1985	546	1,010	U/L	Replaced 33H115
33H227	BP&P 1 (new, 1989)	31°10'16"N	81°31'17"W	11-03-89	551	874	U	None
33H324	Georgia Pacific UWBZ	31°10'22"N	81°30'46"W	01-14-02	525	740	U	See section "Real-Time Monitoring of Specific Conductance and Water Levels"
33H325	Georgia Pacific LWBZ	31°10'22"N	81°30'46"W	01-14-02	860	1,000	L	See section "Real-Time Monitoring of Specific Conductance and Water Levels"

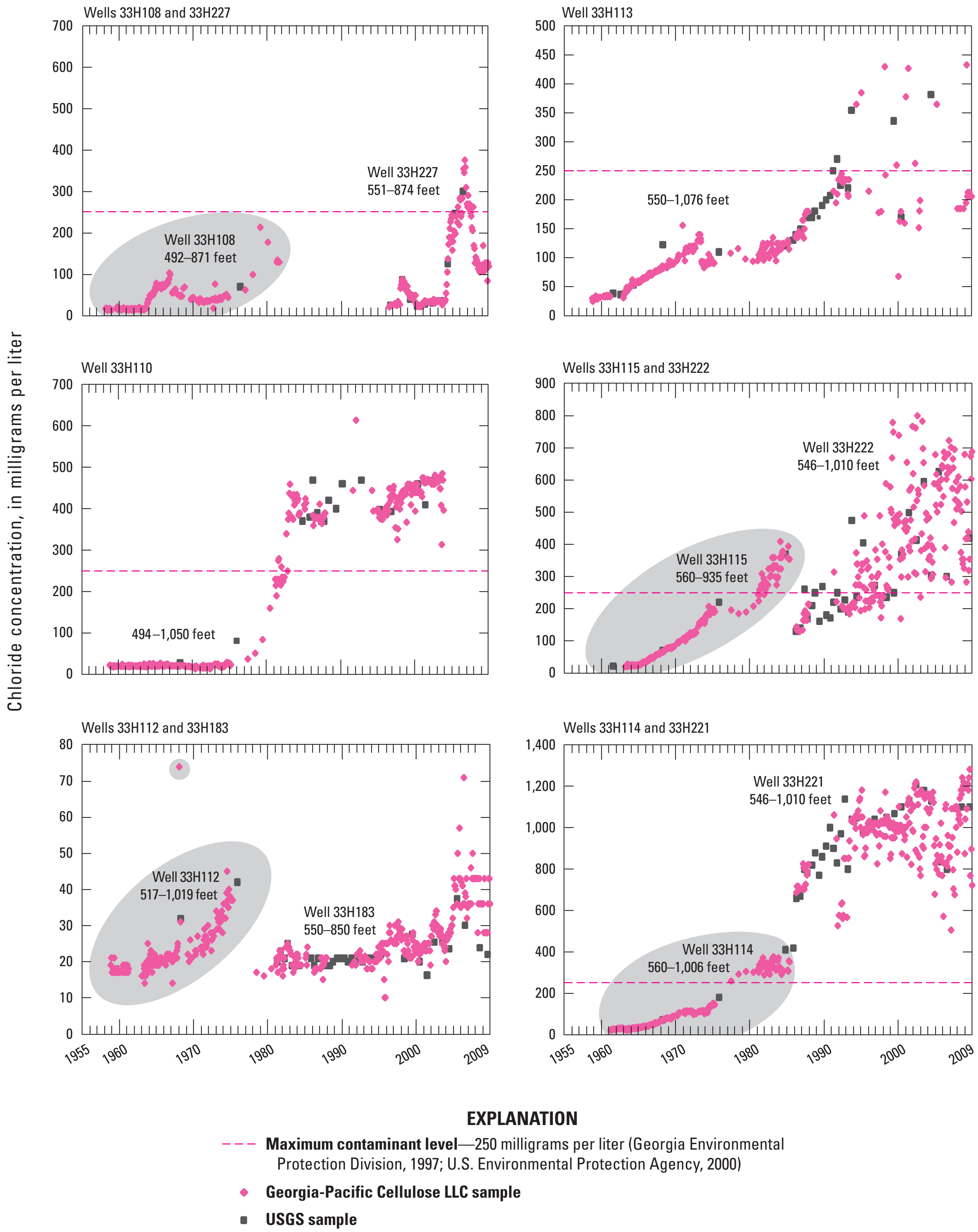


Figure 29. Chloride concentration in selected Upper Floridan aquifer (UFA) production wells in the vicinity of the Georgia–Pacific Cellulose LLC (formerly Brunswick Pulp & Paper Company) well field in Brunswick, Georgia (values in feet are open-well interval; note vertical scales vary; see table 6 for well information; see figure 28 for well locations).

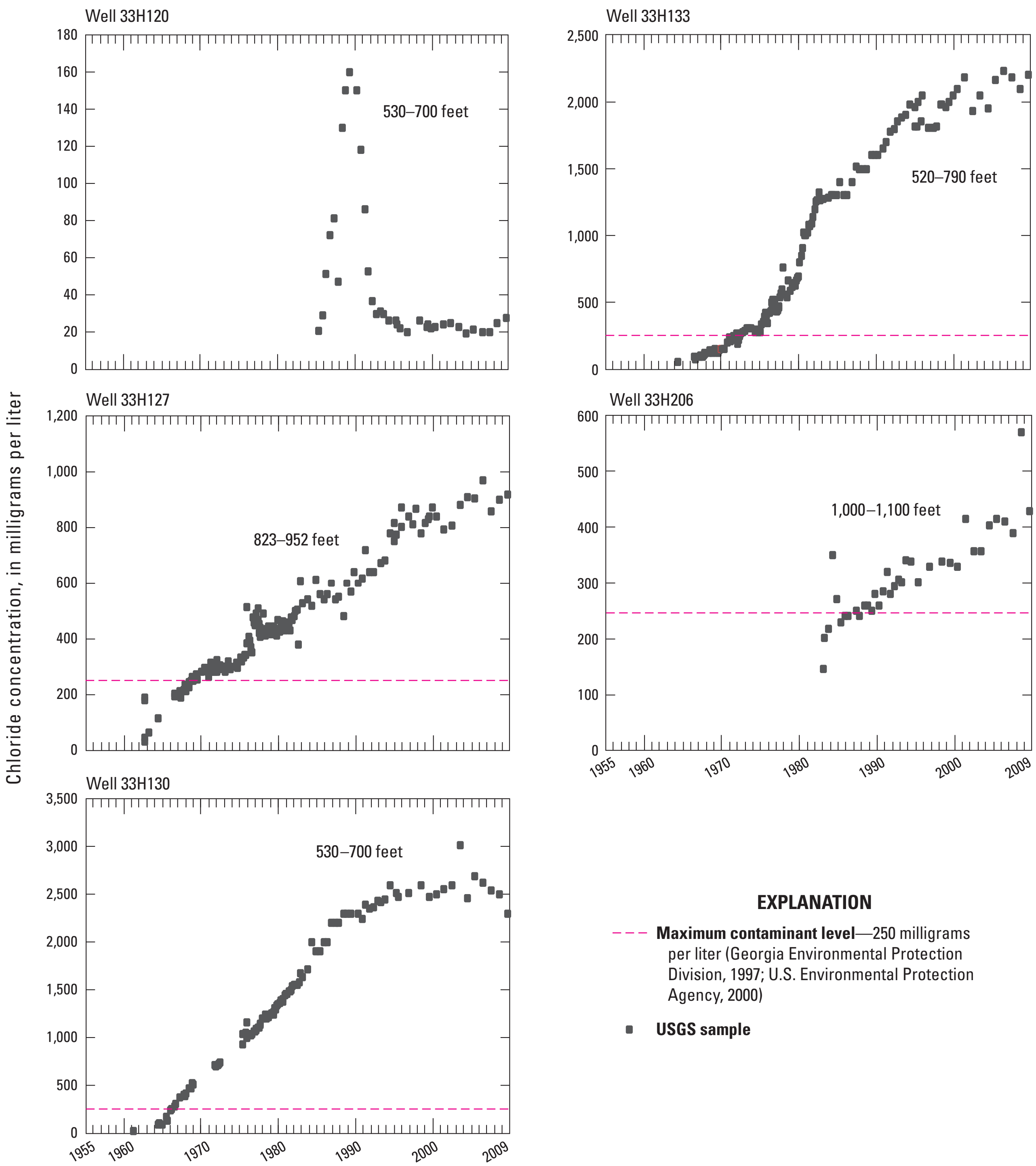


Figure 30. Chloride concentration in selected USGS Upper Floridan aquifer (UFA) observation wells in the vicinity of the Georgia–Pacific Cellulose LCC (formerly Brunswick Pulp & Paper Company) well field in Brunswick, Georgia (values in feet are open-well interval; note vertical scales vary; see table 6 for well information; see figure 28 for well locations).

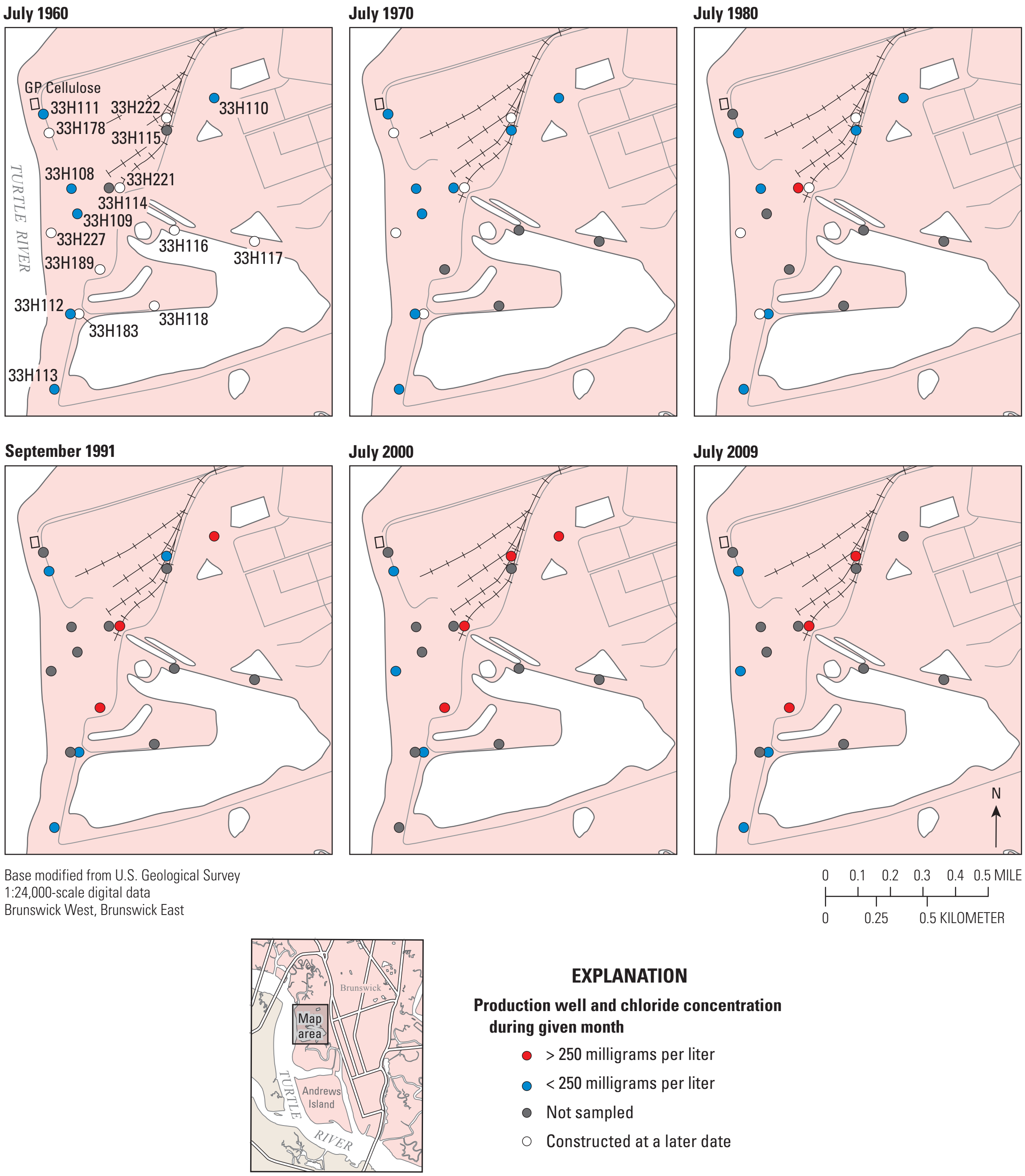


Figure 31. Chloride concentration exceeding the State and Federal secondary drinking-water standard of 250 milligrams per liter (red) in active Upper Floridan aquifer production wells in the vicinity of the Georgia–Pacific Cellulose LCC (formerly Brunswick Pulp & Paper Company) well field in Brunswick, Georgia, during July 1960, July 1970, July 1980, September 1991, July 2000, and July 2009.

Table 7. Chloride data available for production wells at the Georgia–Pacific Cellulose LLC facility in Brunswick, Georgia.

[mg/L, milligram per liter; BP&P, Brunswick Pulp & Paper Company; GGS, Georgia Geologic Survey; NA, data not available; see figure 28 for well locations]

Well number	Well name	Year monitoring		Minimum chloride concentration, in mg/L	Date	Maximum chloride concentration, in mg/L	Date	Number of chloride samples, monitoring period	Mean annual chloride concentration, in mg/L	
		Started	Ended						2008	2009
33H108	BP&P 1	1958	1982	14	2-2-1959	214	7-1-1979	165	NA	NA
33H109	BP&P 2	1958	1972	13	4-23-1971	6,100	2-24-1972	91	NA	NA
33H110	BP&P 3	1958	2003	13	5-30-1972	615	2-14-1992	355	NA	NA
33H111	BP&P 4	1958	1975	12	3-21-1974	23	5-31-1960	167	NA	NA
33H112	BP&P 5	1958	1975	14	6-4-1963	74	1-29-1968	157	NA	NA
33H113	BP&P 6	1958	2009	25	12-1-1958	433	4-29-2009	291	185	232
33H114	BP&P 8	1961	1985	19	6-18-1963	410	11-2-1984	204	NA	NA
33H115	BP&P 7	1961	1985	21	3-4-1963	410	2-14-1984	184	NA	NA
33H116	BP&P 9	1968	1985	318	4-10-1968	1,300	1-19-1980	5	NA	NA
33H117	BP&P 10	1961	1999	14	9-14-1961	1,000	10-23-1961	17	NA	NA
33H118	BP&P 11	1962	1980	26	1-14-1963	870	1-18-1980	146	NA	NA
33H120	Palmetto Cemetary (north)	1985	2009	19	6-22-2004	160	5-16-1989	36	25[a]	28[b]
33H127	USGS TW3	1962	2009	31	8-16-1962	970	7-18-2006	148	900[a]	920[b]
33H130	Selden Park	1961	2009	26	2-28-1961	3,010	6-24-2003	113	2,500[a]	2,300[b]
33H133	USGS TW6	1964	2009	56	5-13-1964	2,230	7-18-2006	150	2,100[a]	2,200[b]
33H178	BP&P 4 (new)	1975	2009	7	7-15-2006	57	7-15-2005	289	31	31
33H183	BP&P 5 (new)	1975	2009	10	10-15-1995	71	6-15-2006	294	37	37
33H189	BP&P 2 (new)	1981	2006	227	7-15-2006	875	7-15-1992	213	NA	NA
33H206	USGS/GGS/ BP&P TW-1 (south)	1983	2009	146	1-13-1983	570	7-24-2008	38	570[a]	430[b]
33H207	USGS/GGS/ BP&P TW-2 (south)	1983	2009	14	5-11-1987	28	8-20-2009	38	16[a]	28[b]
33H211	USGS/BP&P 1	1985	2009	14	10-23-1996	80	7-17-2006	33	18[a]	18[b]
33H212	USGS/BP&P 11 (lower)	1985	2009	1,000	4-24-1985	1,360	4-8-1993	35	1,200[a]	1,200[b]
33H213	USGS/BP&P 11 (upper)	1985	2009	12	10-30-1985	88	4-17-1995	33	34[a]	42[b]
33H214	USGS/BP&P 9 (lower)	1985	1995	1,200	10-30-1985	2,500	4-13-1995	19	NA	NA
33H215	USGS/BP&P 9 (upper)	1985	1995	1,400	10-30-1985	2,450	4-13-1995	19	NA	NA
33H216	USGS/BP&P 10 (lower)	1985	1995	1,700	3-31-1986	2,850	4-15-1991	18	NA	NA
33H217	USGS/BP&P 10 (middle)	1985	1995	1,500	10-30-1985	2,700	4-13-1992	18	NA	NA
33H218	USGS/BP&P 10 (upper)	1985	1995	1,800	10-30-1985	2,700	4-12-1995	19	NA	NA
33H221	BP&P 8 (new)	1985	2009	420	11-4-1985	1,280	8-31-2009	246	1,120	1,070
33H222	BP&P 7 (new)	1986	2009	130	3-31-1986	801	8-15-2002	238	476	478
33H227	BP&P 1 (new, 1989)	1990	2009	22	9-15-1996	376	10-15-2006	182	126	120

[a] Discrete sample collected during July 2008.

[b] Discrete sample collected during August 2009.

Chloride concentrations in samples from USGS observation wells located to the east of the Georgia–Pacific well field were between 30 and 520 mg/L prior to 1970, with concentrations increasing and remaining at levels above the 250-mg/L State and Federal secondary drinking-water standard (Georgia Environmental Protection Division, 1997; U.S. Environmental Protection Agency, 2000; figs. 28, 30) during the 1970s and 1980s. The chloride concentration at USGS observation wells 33H127, 33H130, and 33H133 indicated continued movement of solute from the source area near Reynolds Street toward the Georgia–Pacific Cellulose well field (fig. 30). By July 1980, one of the seven active production wells that were sampled had chloride concentrations above the drinking-water standard of 250 mg/L, and by September 1991, three of the seven production wells that were sampled had chloride concentrations above the drinking-water standard (fig. 31). Construction of replacement wells for 33H112 and 33H115 temporarily lowered chloride concentrations before chloride levels eventually increased to previous levels (fig. 29). Concentrations in replacement well 33H221 were initially similar to those in well 33H114 at the end of the well's operational period in 1985, with concentrations continuing to rise, reaching 1,060 mg/L in 1991 (fig. 29; table 7). Chloride concentrations in USGS observation well 33H120, located 0.3 mi east of the Georgia–Pacific Cellulose well field, increased to a maximum of 160 mg/L in the late 1980s, but returned to background levels by the early 1990s (figs. 28, 30).

During the 1990s and 2000s, chloride concentrations at the Georgia–Pacific Cellulose well field generally increased despite decreases in pumpage from 49 Mgal/d in 1990 to 33 Mgal/d in 2009 (Cherry and others, 2010; fig. 6). During the same period, chloride concentrations continued to increase although at a slower rate than the increase observed during the 1970s and 1980s. Chloride concentrations in production wells 33H113, 33H222, and 33H221 generally increased during the 1990s and 2000s, with large fluctuations possibly caused by pumps cycling on and off (fig. 29). Maximum chloride concentrations were observed during this period at production wells 33H113, 33H178, 33H183, 33H189, 33H221, 33H222, and 33H227. In production well 33H227, the chloride concentration increased from 30 mg/L in 1997 to more than 300 mg/L during 2006. By 2009, the mean annual concentrations in this well decreased to 120 mg/L. In production well 33H110, the chloride concentrations increased to a maximum of 615 mg/L during 1992, but did not increase any further; and the well was deactivated in the mid-2000s.

To provide information on chloride concentrations in the UWBZ and LWBZ, three production wells at the Georgia–Pacific Cellulose well field were taken out of production and modified by the USGS to isolate each zone. Well 33H116 was renamed well 33H215 in the UWBZ and well 33H214 in the LWBZ. Well 33H117 was modified into well 33H218 in the UWBZ and wells 33H216 and 33H217 in the LWBZ. Well 33H118 was modified into well 33H213 in the UWBZ and well 33H212 in the LWBZ (table 6). Available chloride data for 33H212 and 33H213 during 1985 to the mid-1990s indicate elevated chloride concentrations in the LWBZ and concentrations initially near background levels in the UWBZ (table 7).

Chloride concentrations at USGS observation wells 33H127and 33H133, completed in the LWBZ and UWBZ, respectively, and located 0.4 mi southeast of the Georgia–Pacific Cellulose well field, continued to steadily increase during the 1990s and gradually increase during the 2000s (fig. 30). In well 33H130, completed in the UWBZ and located about 0.1 mi east of the Georgia–Pacific Cellulose well field, concentrations generally increased during the 1990s, followed by a leveling off and decrease of concentrations in the 2000s.

Mean annual chloride concentrations in four of the six production wells (33H178, 33H183, 33H222, and 33H227) at the Georgia–Pacific Cellulose well field were generally the same during 2008 and 2009 with overall variations in the well field within ± 50 mg/L during this period (table 7). Chloride concentrations measured during August 2009 were within ± 20 mg/L of concentrations measured during July 2008 in six of nine wells sampled at and near the Georgia–Pacific Cellulose well field (table 7).

Observation wells 33H324 and 33H325, installed during 2002 in cooperation with the GaEPD as part of the CSSI, continuously monitor water levels and specific conductance in the UWBZ and LWBZ, respectively, at the Georgia–Pacific Cellulose well field (fig. 28). Both wells are equipped to monitor real-time water levels, and well 33H325 is instrumented to record specific conductance data in the LWBZ of the Upper Floridan aquifer. Data from these observation wells are presented in the next section.

Real-Time Monitoring of Specific Conductance and Water Levels

To monitor the extent of chloride contamination in the Brunswick area, four real time monitoring sites have been established around the chloride plume (fig. 20). Each site includes one or more wells completed in the UWBZ or LWBZ of the Upper Floridan aquifer. During 2009, the real time network included sites at:

- Perry Park, with well 34H514 completed in the UWBZ and monitored for both groundwater levels and specific conductance;
- Southside Baptist Church, with well 34H505 completed in the LWBZ and monitored for both groundwater levels and specific conductance, and well 34H504 completed in UWBZ and monitored for groundwater levels;
- Georgia–Pacific Cellulose, with well 33H325 completed in the LWBZ and monitored for both groundwater levels and specific conductance, and well 33H324 completed in the UWBZ and monitored for groundwater levels;
- Brunswick Villa, with well 34H134 completed in the UWBZ and LWBZ and monitored for specific conductance.

Specific conductance is a surrogate for chloride concentration, and is used to monitor the potential movement of saltwater into the freshwater zones of the Upper Floridan aquifer. A regression analysis was conducted to establish the relation between chloride concentration and specific conductance (Cherry and others, 2010; fig. 32). Measurement depths for specific conductance monitoring in each well were determined using borehole resistivity and temperature logs to delineate water-bearing zones vulnerable to saltwater contamination (Walls and others, 2009). The real-time data are available on the USGS Web site and can be accessed at: *http://waterdata.usgs.gov/ga/nwis/current/?type=gw*.

The Perry Park well (34H514) is immediately outside the plume area and has specific conductance values that fluctuate in response to pumping changes. The specific conductance at this site during 2009 fluctuated from 419 to 1,060 microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25 °C), with less pronounced fluctuations during January through May when water levels were relatively higher (fig. 33). A correlation between chloride concentration and specific conductance indicates that this range in specific conductance values corresponds to chloride levels that are generally less than 100 mg/L (Cherry and others, 2010; fig. 32).

Water levels in the Georgia–Pacific Cellulose wells (33H324 and 33H325) indicate the gradient is downward from the UWBZ into the LWBZ of the Upper Floridan aquifer (figs. 13, 34). In general the water levels are between 30 and 40 ft higher in the UWBZ than the LWBZ. An exception to this occurred during early February 2009 when water levels in the LWBZ were briefly higher than water levels in the UWBZ (fig. 34). The water levels in these wells are affected by pumping from production wells located 1,600 ft away, which tap into the UWBZ and the LWBZ of the Upper Floridan aquifer. The specific conductance at this site during 2009 fluctuated from 6,440 to 7,640 µS/cm at 25 °C, with levels rising from January through May and levels rising slightly from June through December. Overall, the increase in specific conductance during 2009 corresponds to a period of declining water levels in well 33H325, and the water levels were nearly constant in well 33H324 during the same period. The estimated chloride concentration derived from specific conductance levels between 6,440 and 7,640 µS/cm at 25 °C ranges from 1,750 to 2,050 mg/L based on the regression analysis shown in figure 32 (Cherry and others, 2010).

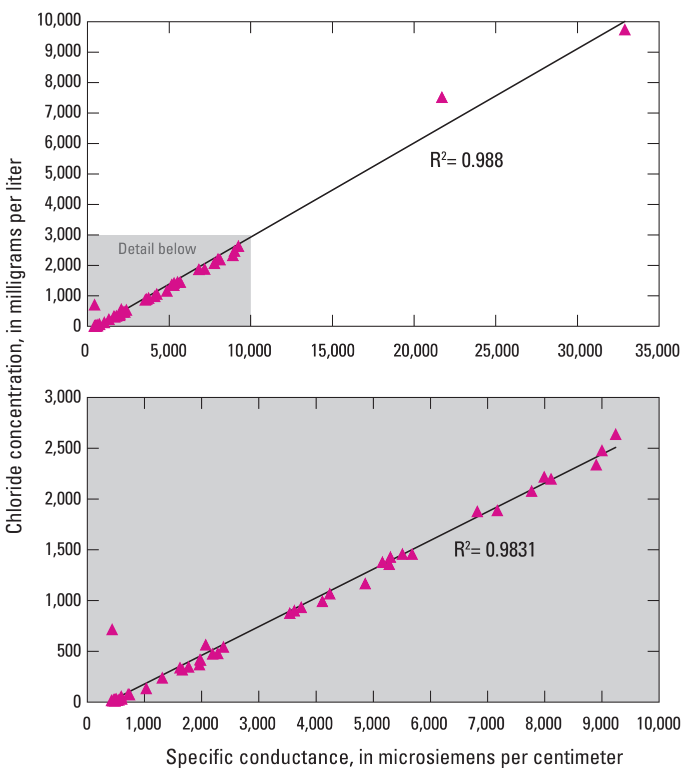


Figure 32. Correlation between chloride concentration and specific conductance from groundwater samples taken in the Brunswick–Glynn County area, Georgia, July 2008 (from Cherry and others, 2010).

The Southside Baptist Church wells (34H504 and 34H505) are located outside the plume area and are away from the pumping centers to the north (fig. 20). The water levels in these wells indicate that the natural gradient is upward from the LWBZ to the UWBZ of the Upper Floridan aquifer, with water levels generally higher in the LWBZ (figs. 13, 35). The specific conductance at this site during 2009 fluctuated from 1,710 to 1,920 µS/cm at 25 °C with no clear trend throughout the entire year. The correlation between chloride concentration and specific conductance indicates these values are indicative of chloride levels ranging between 300 and 500 mg/L (Cherry and others, 2010; fig. 33).

The Brunswick Villa well (34H134) is located outside the plume area to the north (fig. 20) and is likely influenced by pumping at the Georgia–Pacific Cellulose facility. The Brunswick–Glynn County JWSC noted fluctuations in chloride concentration with the operation of the Brunswick Villa public-supply well (34H134), which could indicate a northerly migration of the chloride plume (Billy Simmons, Brunswick–Glynn County Joint Water and Sewer Commission, written commun., 2009). This production well is operated intermittently and is open to the UWBZ and LWBZ of the Upper Floridan aquifer. Initially, equipment to measure specific conductance was installed on a temporary basis during September 2009, and data indicated that chloride concentrations had risen above background levels (20–30 mg/L; Billy Simmons, Brunswick–Glynn County Joint Water and Sewer Commission, written commun., 2009). The well became a permanent part of the real-time network during December 2009 when satellite telemetry, which allowed data to be transmitted to the USGS Georgia Water Science Center located in Atlanta, was installed. The specific conductance at this site during the latter part of 2009 fluctuated from 450 to 700 µS/cm at 25 °C with a baseline concentration of 570 µS/cm at 25 °C (fig. 36). The correlation between chloride concentration and specific conductance indicates these values are indicative of chloride levels of about 50 mg/L (Cherry and others, 2010; fig. 32).

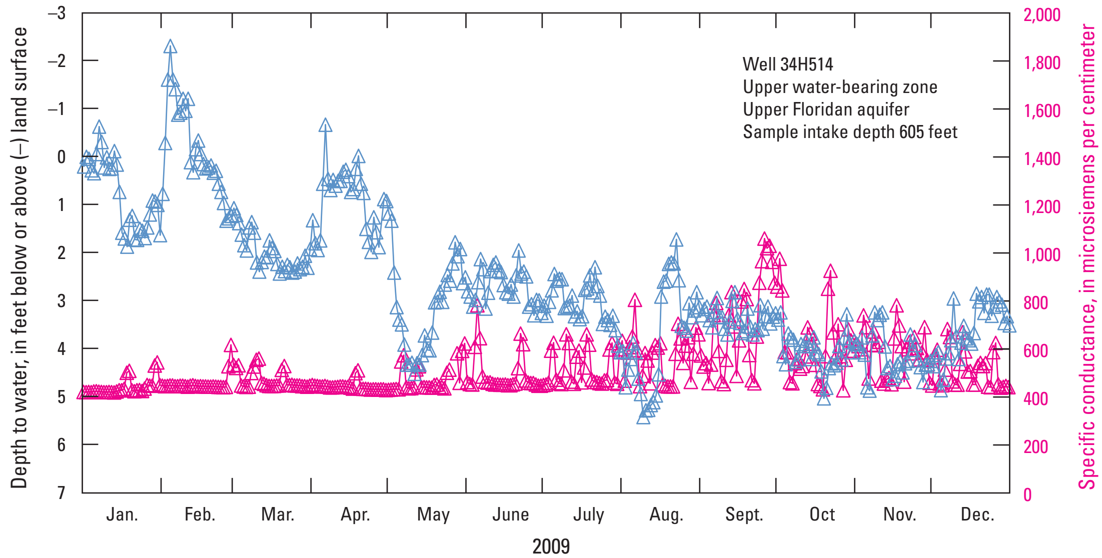


Figure 33. Daily mean groundwater levels and periodic specific conductance in the Upper Floridan aquifer at well 34H514, Perry Park, Brunswick–Glynn County area, Georgia, 2009 (see figure 20 for well location).

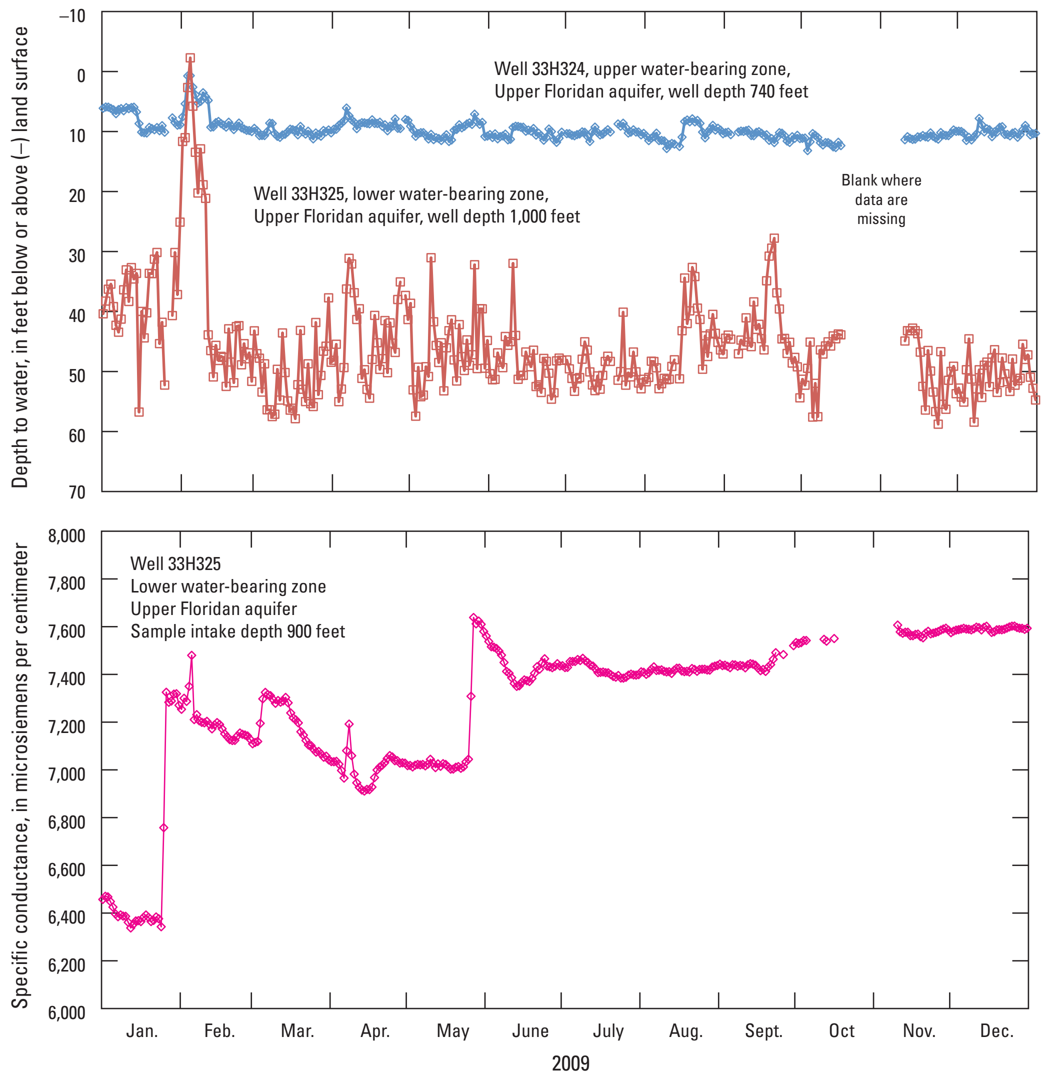


Figure 34. Daily mean water levels in wells 33H324 and 33H325, and specific conductance in well 33H325 Upper Floridan aquifer, Brunswick–Glynn County area, Georgia, 2009 (see figure 20 for well locations).

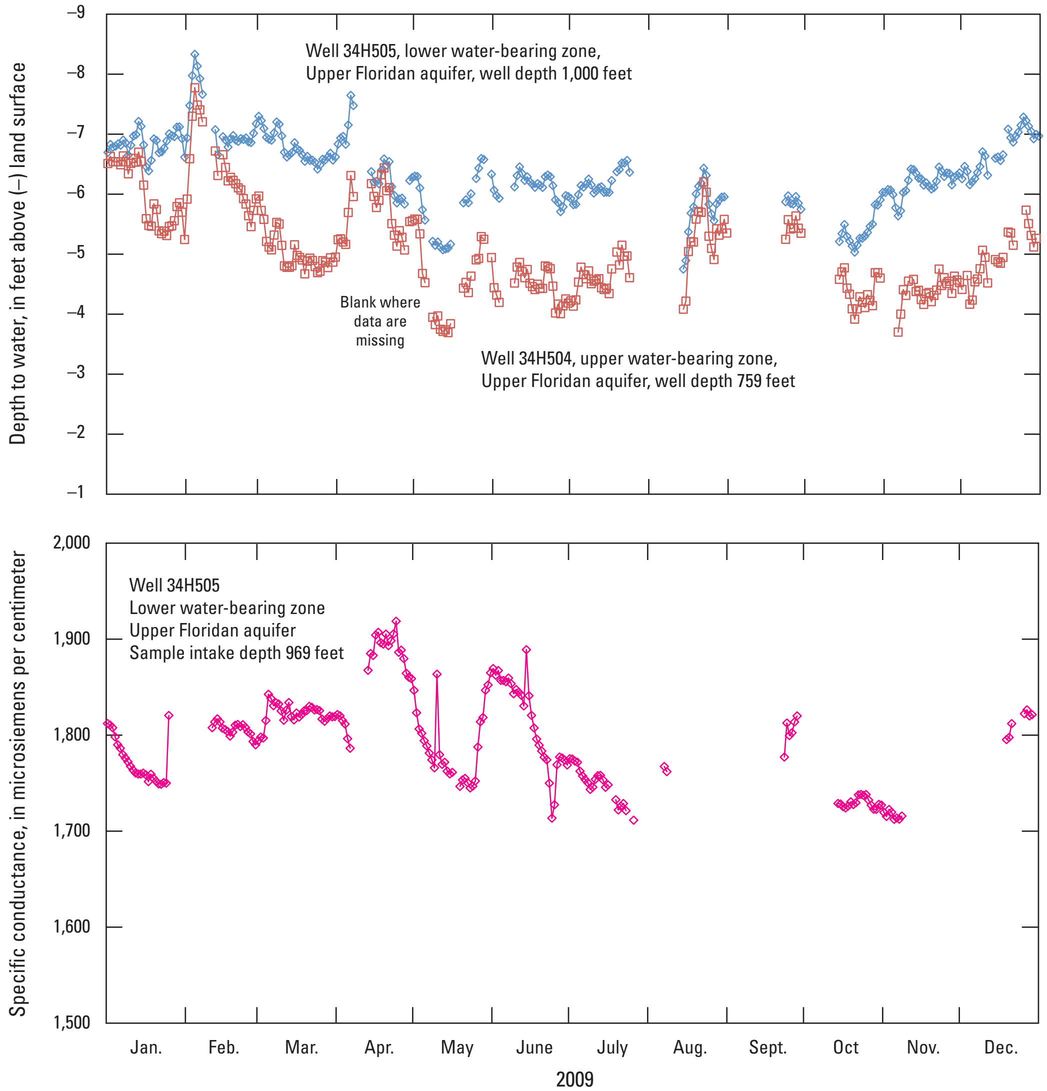


Figure 35. Daily mean groundwater levels and periodic specific conductance in the Upper Floridan aquifer at wells 34H504 and 34H505, Brunswick–Glynn County area, Georgia, 2009 (see figure 20 for well locations).

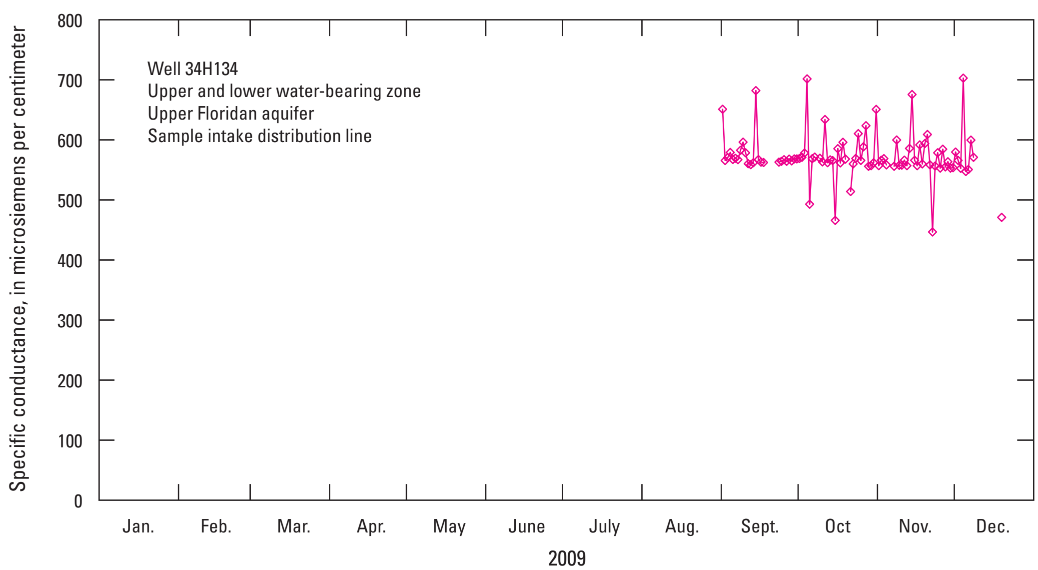


Figure 36. Periodic specific conductance in the Upper Floridan aquifer at well 34H134, Brunswick–Glynn County area, Georgia, 2009 (see figure 20 for well location).

Surficial Aquifer System

Historically, water-quality data-collection efforts in the Glynn County area have focused on the Floridan aquifer system. However, Clarke and others (1990) recognized that water-quality problems do exist locally in the surficial and Brunswick aquifer systems. These problems typically can be associated with (1) saltwater encroachment in shallow wells near the coast, tidal rivers, and estuaries; (2) upward leakage of water from underlying aquifers through semiconfining units or fractures as a result of natural or pumping-induced head gradients; or (3) failed well casing. Localized saltwater contamination has been recognized in a number of areas along the coast, including Vernonburg, GA, in Chatham County (Hall and Peck, 2005) and Sea Island, GA, in Glynn County (Julie Vann, Georgia Environmental Protection Division, written commun., July 2005).

During 2009, water samples were collected and analyzed for chloride concentration from two wells completed in the surficial aquifer system (table 3). Well 34H515 was drilled in 2005 as a replacement well for well 34H438, which had large increases in chloride concentration during 1996–2003 (figs. 19*B*, 37). Water in the new well had a chloride concentration of 5,850 mg/L during August 2009 verifying the concentration increase detected in well 34H438. This concentration is 400 mg/L greater than the concentration in the sample taken during July 2008. The reason for the increase is unknown. No known supply wells are completed in the surficial aquifer in the area, nor were there any changes in land-use practices in the immediate area. The well is located near a saltwater marsh and tidally influenced canals designed to prevent flooding during high tide. The monitoring of chloride concentrations in this well is ongoing. The other well open to the surficial aquifer system (well 34H428) continues to show chloride concentrations near background levels and below 20 mg/L (table 3).

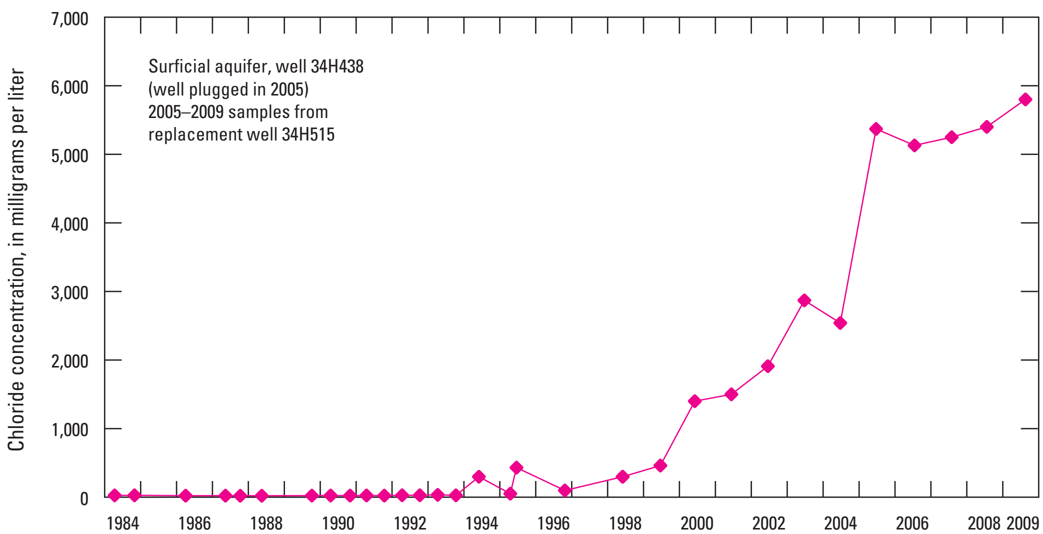


Figure 37. Chloride concentrations in well 34H438 and in replacement well 34H515, surficial aquifer system, in the Brunswick–Glynn County area, Georgia, 1984–2009 (see figure 19*B* for well locations).

Summary

During calendar year 2009, the Cooperative Water Program between the U.S. Geological Survey (USGS), Brunswick–Glynn County Joint Water and Sewer Commission, and the Jekyll Island Authority, continued to monitor groundwater levels and groundwater quality in the Brunswick–Glynn County area. This included:

- Continuous water-level monitoring of 13 wells completed in the Floridan, Brunswick, and surficial aquifer systems. Of the 13 wells, two were also equipped with real-time specific conductance monitors to provide an indication of possible migration of chlorides in the area surrounding the chloride plume.
- Collection of synoptic water-level measurements from 46 wells to map the potentiometric surface of the Upper Floridan aquifer during August 2009.
- Collection of periodic water-level measurements at Jekyll Island from six wells completed in the Upper Floridan aquifer and Brunswick aquifer system.
- Collection and analysis of water samples for chloride concentration from 55 wells completed in the Floridan aquifer system, 27 of which were used to map the configuration of the chloride plume in the upper water-bearing zone of the Upper Floridan aquifer during August 2009.
- Compilation of chloride data from two industrial well fields dating back to 1958; these data were used to assess how the configuration of the chloride plume has developed over time.

Groundwater levels in the Brunswick–Glynn County area are affected by changes in precipitation and groundwater pumpage. Water levels in the surficial and Brunswick aquifer systems are mostly affected by precipitation and to a lesser degree pumping. Groundwater withdrawals have the greatest influence on water levels in the Floridan aquifer system, with climatic effects less pronounced due to the depth of the water-bearing units and distance away from recharge areas. During 2009, rainfall was mostly below normal from January to February and mostly above normal from March to October. Groundwater withdrawal from the Upper Floridan aquifer in Glynn County was 47.7 million gallons per day (Mgal/d) in 2009, which was slightly higher than in 2008.

During 2008–2009, water levels in 30 of the 32 wells monitored in the Brunswick–Glynn County area rose at rates of 0.24 to 7.58 feet per year (ft/yr). The largest rise of 7.58 ft/yr was in the Upper Floridan aquifer. These rises corresponded to a period of above normal precipitation and decreased pumping. Declines during 2008–2009 were recorded in wells completed in the Brunswick aquifer system (0.37 ft/yr) and Lower Floridan aquifer (0.83 ft/yr).

A map showing the area of chloride contamination in the Upper Floridan aquifer during August 2009 is similar to the previously published map for 2008 (Cherry and others, 2010) and shows that areas of highest concentration are in the northern part of the city, as well as near the original area of contamination in the southern part of the city. During August 2009, chloride concentrations in the Brunswick area were generally lower than in 2008, with decreases as much as 160 milligrams per liter (mg/L) in the northwestern part of the area and 100 mg/L in the central part of the area.

Data from two large industrial well fields—Pinova Inc. and Georgia–Pacific Cellulose LLC, located in the northern part of the city of Brunswick—were compiled to assess how the configuration of the chloride plume has developed during the period from 1959–2009. The results indicate that chloride concentrations at the two well fields have continued to rise despite modification of production wells to eliminate deep saline zones and decreases in pumpage at both facilities. One of the industrial users, Pinova Inc, plugged the lower portions of nine production wells in the mid to late 1960s, which generally decreased chloride concentrations to less than 100 mg/L for a period of 10 to 20 years. However, chloride concentrations eventually returned to previous levels despite decreases in pumpage. During 1990–2009, chloride concentrations at the other industrial user's well field (Georgia–Pacific Cellulose LLC) generally increased despite a 16-Mgal/d decrease in pumpage during this period. Data from the Georgia–Pacific Cellulose well field and additional chloride data from USGS observation wells located to the east indicate continued movement of chloride from the source area located southeast of the site toward the well field.

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Appendix. Regression Statistics

The following is from Peck, M.F., Leeth, D.C., and Painter, J.A., 2011, Groundwater conditions and studies in Georgia, 2008–2009; U.S. Geological Survey Scientific Investigations Report 2011–5048, 83 p.

Water-level trends in this report were estimated by applying the Levenberg-Marquardt Algorithm (LMA) (Moré, 1978) to monthly mean water-level data for the period of record and during 2008–2009. Although the LMA typically is used for nonlinear fitting, it can also be used for deriving linear fits very near values derived using ordinary least squares fitting. In concept, LMA works by optimizing a mathematical function (called a merit function by statisticians) that measures how well the function represents the data. In this report, the merit function is the weighted sum of the squares of the differences (informally known as chi-squared and represented in equations and tables as χ^2).

In this report, the steps involved in minimizing this merit function were as follows.

1. Estimate a value for the slope and intercept, and calculate a line based on this estimate.
2. Calculate how far this line lies from the data (using the χ^2). Adjust the line so that it lies closer to the center of the data.
3. Repeat adjustments until they no longer affect the χ^2 value.

Each step is completed through manipulations of algebraic matrices, which are beyond the scope of this report, but are fully explained in Moré (1978).

Summary statistics for the straight line (linear) fits of water-level trends described in the main body of the report are provided here as an indicator of goodness of fit (Janert, 2010), and so that readers can make decisions based on their tolerance for risk. These include:

- The *degrees of freedom* representing the number of data points minus the variables used. For this evaluation, two variables are used—slope (m) and intercept (b). A general rule of thumb is that the residuals and the χ^2 should be in the same order of magnitude for the fit to be reasonable (with some exceptions).
- The *root mean square error* (RMSE) of the residuals is the square root of the average squared distance of a data point from the fitted line. RMSE units are in the same units as the quantity being estimated (in this report, feet).
- The *chi squared* is the sum of squared residuals (differences) between the monthly mean water level and the values computed by the algorithm after the final iteration. Thus, the term “least-squares” fitting. The χ^2 from the fit along with χ^2 distribution tables may be used to estimate confidence intervals.
- The *standard error* (SE) of a variable (m or b in this report), expressed as a percentage, is a measure of how well m or b has been estimated and affects the location of the regression line. The greater the standard error, the greater the scatter around the regression line. In other words, standard error is a measure of dispersion.

Table A–1. Regression statistics.

[Modified from Peck and others, 2011; %, percent]

Well name	Period of record summary statistics					2008–2009 summary statistics				
	Degrees of freedom	Root mean square error of residuals (RMSE)	Variance of residuals (χ^2)	Standard error of slope (SE_m %)	Standard error of intercept (SE_b %)	Degrees of freedom	Root mean square error of residuals (RMSE)	Variance of residuals (χ^2)	Standard error of slope (SE_m %)	Standard error of intercept (SE_b %)
33H127	537	4.34	18.81	29.57	27.96	16	1.80	3.25	35.67	36.86
33H133	528	4.54	20.60	5.58	4.77	13	2.94	8.67	71.39	64.43
33H188	325	2.87	8.23	20.45	2.42	19	0.98	0.97	46.30	28.02
33H206	306	3.30	10.86	9.80	3.70	22	1.38	1.91	31.58	55.24
33H207	303	3.81	14.51	5.99	48.12	21	1.46	2.14	58.34	60.90
33H208	303	1.38	1.91	6.66	2.32	22	0.61	0.37	20.40	15.91
33J044	363	2.64	6.96	17.52	26.36	21	1.05	1.11	18.82	18.10
33J062	107	2.74	7.49	24.07	4.13	22	0.65	0.42	61.75	15.33
33J065	97	1.18	1.38	9,726.00	285.30	17	0.11	0.01	12.49	9.79
34G033	59	2.21	4.87	12.28	4.68	21	1.08	1.16	28.73	87.47
34H334	492	3.43	11.78	6.48	7.86	19	1.37	1.88	34.48	46.85
34H371	507	2.87	8.23	7.30	3.79	22	1.31	1.70	36.01	70.07
34H391	399	2.82	7.94	8.34	2.84	20	1.39	1.92	32.36	55.03
34H436	310	2.92	8.55	11.86	2.01	22	1.21	1.45	29.14	96.02
34H437	298	2.09	4.39	10.12	286.80	21	0.92	0.84	63.33	51.45
34H492	119	1.06	1.13	38.80	4.59	22	0.75	0.57	30.10	20.78
34H495	88	2.85	8.13	9.29	7.15	21	0.94	0.88	21.66	85.01
34H500	102	3.52	12.38	218.40	6.61	20	1.14	1.31	21.30	58.57
34J077	136	3.77	14.18	10.15	2.99	22	2.58	6.65	39.52	18.35
34J080	90	2.33	5.42	21.19	92.57	22	1.19	1.42	28.74	20.11
34J081	88	1.60	2.57	47.25	3.70	22	1.27	1.62	34.50	14.93
34J082	90	0.89	0.80	49.25	4.10	22	0.50	0.25	43.80	14.19

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