Prepared in cooperation with the
Georgia Department of Natural Resources
Environmental Protection Division

Effects of Decreased Ground-Water Withdrawal on Ground-Water Levels and Chloride Concentrations in Camden County, Georgia, and Ground-Water Levels in Nassau County, Florida, From September 2001 to May 2003

Scientific Investigations Report 2004-5295

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

Cover: Left photograph – Waterwheel powered by flowing artesian well at Burnt Fork, Georgia, 1938. State Geologist Photographs and Negative Files, Department of Mines, Mining and Geology, RG 50-2-33, box 2, Camden County folder, Georgia Archives. Photograph by A.C. Munyon.

Right photograph – Production well at Durango Paper Mill, St. Marys, July 1999, Georgia. Photograph by Alan M. Cressler, U.S. Geological Survey.

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U.S. Department of the Interior
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Conversion Factors and Datum

Multiply	By	To obtain
Length		
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
Area		
acre	4,047	square meter (m^2)
acre	0.4047	hectare (ha)
acre	0.4047	square hectometer (hm^2)
acre	0.004047	square kilometer (km^2)
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
Flow rate		
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
Transmissivity*		
foot squared per day (ft^2/d)	0.09290	meter squared per day (m^2/d)

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

°F = (1.8 x °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 have been converted to NAVD 88 for this publication.

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83). Historical data collected and stored as North American Datum 1927 have been converted to NAD 83 for this publication.

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

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

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

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

NOTE TO USGS USERS: Use of hectare (ha) as an alternative name for square hectometer (hm^2) is restricted to the measurement of small land or water areas.

Effects of Decreased Ground-Water Withdrawal on Ground-Water Levels and Chloride Concentrations in Camden County, Georgia, and Ground-Water Levels in Nassau County, Florida, From September 2001 to May 2003

By Michael F. Peck, Keith W. McFadden, and David C. Leeth

Abstract

During October 2002, the Durango Paper Company (formerly Gillman Paper Company) in St. Marys, Georgia, shutdown paper-mill operations; the shutdown resulted in decreased ground-water withdrawal in Camden County by 35.6 million gallons per day. The decrease in withdrawal resulted in water-level rise in wells completed in the Floridan aquifer system and the overlying surficial and Brunswick aquifer systems; many wells in the St. Marys area flowed for the first time since the mill began operations during 1941.

Pumping at the mill resulted in the development of a cone of depression that coalesced with a larger adjacent cone of depression at Fernandina Beach, Florida. Since closure of the mill, the cone at St. Marys is no longer present, although the cone still exists at Fernandina Beach, Florida. Historical water-level data from the production wells at the mill indicate that the pumping water level ranged from 68 to 235 feet (ft) below North American Vertical Datum of 1988 (NAVD 88) and averaged about 114 ft when the mill was operating. Since the shutdown, it is estimated that water levels at the mill have risen about 140 ft and are now at about 30 ft above NAVD 88. The water-level rise in wells in outlying areas in Camden County was less pronounced and ranged from about 5 to 10 ft above NAVD 88. Because of the regional upward water-level trend in the Upper Floridan aquifer that started during 1999–2000 in most of the coastal area, combined with a steeper upward trend beginning during October 2002, it was not possible to determine if the 5–10 ft rise in water levels in wells away from St. Marys was due to the mill closure. In addition to water-level rise of 22–26 ft in the Floridan aquifer system, water-level rises in the overlying surficial and Brunswick aquifer systems at St. Marys after the shutdown indicate upward leakage of water. Water levels had stabilized in the confined surficial and Upper and Lower Floridan aquifers by April–May 2003; however, the water level in the upper Brunswick aquifer was still rising as of May 2003.

Chloride concentrations in the Upper Floridan aquifer in Camden County do not exceed the State and Federal drinking-water standard of 250 milligrams per liter (mg/L). With the exception of three wells located at St. Marys, all of the wells sampled during this study (from September 2002 to May 2003) had chloride concentrations ranging from 30 to 50 mg/L, which are considered within background levels for the Upper Floridan aquifer in this area. The three wells—two at the Durango Paper Company and the other an old unused City of St. Marys well—had chloride concentrations that ranged from 74 to 175 mg/L, which are above the background level, but were still below the 250-mg/L drinking-water standard. The source has not been determined for the elevated chloride concentration in these wells; the chloride concentration in one of the wells has decreased slightly since the paper-mill shutdown. Chloride concentrations throughout Camden County showed little change after the paper-mill shutdown.

Introduction

In the coastal area of Georgia and northeastern Florida, the Floridan aquifer system, which consists of the Upper and Lower Floridan aquifers, is heavily used for water supply by the pulp and paper industry and local municipalities. From 1985 to 2000, industrial and municipal ground-water withdrawal in Camden County, Georgia, and Nassau County, Florida, ranged from about 81 to 90 million gallons per day (Mgal/d) primarily from the Floridan aquifer system (Frick and others, 2002). Concern about saltwater intrusion at Hilton Head Island, South Carolina, and Brunswick, Georgia, has resulted in restrictions on permitted ground-water withdrawal from the Upper Floridan aquifer by the State of Georgia. During 1997, the State Environmental Protection Division (GaEPD) issued an interim strategy (Georgia Environmental Protection Division, 1997) that capped withdrawal from the Upper Floridan aquifer at 1997 rates in Glynn and Chatham Counties and parts of Effingham and Bryan Counties, and restricted additional permits in the other coastal counties to a total of 36 Mgal/d. The 36-Mgal/d limit was reached during 2001, which effectively capped permitted withdrawal of the Upper Floridan aquifer in the entire 24-county coastal area, causing increased competition for the currently allocated permits.

During October 2002, the Durango Paper Company (formerly Gillman Paper Company) at St. Marys, Camden County, Georgia (fig. 1*A* and *B*), shutdown paper-mill operations, resulting in a 35.6-Mgal/d decrease in ground-water withdrawal from the Floridan aquifer system in Camden County (J.L. Fanning, U.S. Geological Survey, written commun., October 24, 2003). The decrease in withdrawal affected water levels in the Floridan aquifer system and in the overlying surficial and Brunswick aquifer systems (fig. 2), resulting in flow from many wells in the St. Marys area for the first time since the mill began operations during 1941.

To assess the impact of the Durango Paper Company shutdown on ground-water levels and chloride concentrations in Camden County, Georgia, and ground-water levels in Nassau County, Florida, the U.S. Geological Survey (USGS)—in cooperation with the GaEPD—conducted an investigation from September 2002 to May 2003. Results of this investigation will provide water managers with information to help manage water resources in coastal Georgia.

Purpose and Scope

This report describes changes in ground-water levels in the Floridan aquifer system and overlying upper Brunswick and confined surficial aquifers and chloride concentration in the Upper Floridan aquifer, resulting from a large decrease in ground-water withdrawal because of closure of a paper mill at St. Marys, Georgia, during October 2002 (fig. 1*A* and *B*). As part of this study, synoptic water-level measurements were made during three time periods in 55 wells open to the Upper Floridan aquifer in Camden County, Georgia, and Nassau County, Florida, prior to the mill shutdown (September 2002) and after the shutdown (January and May 2003). Sixty-one water samples were collected from 31 wells in Camden County, Georgia, during the same three time periods, to evaluate possible changes in chloride concentration in the Upper Floridan aquifer. Potentiometric-surface maps were constructed for each time period to show changes in ground-water flowpaths and to help determine the areal extent of water-level rise. Hydrographs from six continuously monitored wells in Camden County, Georgia, and two wells in Nassau County, Florida (fig. 1*A*), were used to evaluate water-level trends and the effect of decreased ground-water withdrawal on a regional scale and to assess interaquifer leakage response. Water-use data for these areas were compiled and compared to water-level data from continuous recorders to evaluate the effects of industrial withdrawal.

Description of the Study Area

Camden County, Georgia, encompasses about 660 square miles (mi^2) in the extreme southeastern part of the Coastal Plain physiographic province of Georgia (accessed October 17, 2003, at *http://www.camdencounty-ga.com/*). GaEPD defines the coastal area of Georgia as encompassing the 6 coastal counties and the adjacent 18 counties. GaEPD has further subdivided this area into three subareas, consisting of the northern, central, and southern areas; the latter encompass Camden County. Topographic relief is largely controlled by a series of relict shorelines formed during Pliocene-Pleistocene time as a result of global sea-level decline (Leeth, 1999; Leve, 1966). Relief ranges from 0 feet (ft) along the coast to a maximum elevation of about 80 ft in the western part of the county. The climate in the Camden County area is humid subtropical, from about 52 to 54 inches of precipitation occurring annually, most of which falls from June through September (Leeth, 1999). Nassau County, Florida, has similar physiography and climate as Camden County and encompasses about 650 mi^2 (accessed October 29, 2003, at *http://www.nassauclerk.org/county/vitalstats.htm*).

Hydrogeologic Framework

Hydrogeologic units underlying the study area in Camden County include the surficial aquifer system, Brunswick aquifer system, and the Floridan aquifer system (fig. 2). The surficial aquifer system in Camden County includes three water-bearing zones consisting of fine to medium quartz sand and coarse to very coarse quartz sand and gravel (Leeth, 1999). These three water-bearing zones are separated by layers of silt and clay, which form the unconfined water-table zone, the confined upper water-bearing zone, and the confined lower water-bearing zone (fig. 2). The Brunswick aquifer system consists of two water bearing zones: the upper Brunswick aquifer and the lower Brunswick aquifer (Clarke, 2003). 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; Leeth, 1999). The lower Brunswick aquifer consists of poorly sorted, fine to coarse, phosphatic, dolomitic sand (Clarke and others, 1990). In the coastal area of Georgia, the Floridan aquifer system is divided into the Upper and Lower Floridan aquifers (fig. 2). These aquifers consist of massive limestone and dolomite that are more than 2,000 ft thick in the Camden County area (Clarke and others, 1990). Because of the large ground-water withdrawal in the coastal area, cones of depression have developed in the potentiometric surface of the Upper Floridan aquifer at Savannah, Jesup-Riceboro, Brunswick, and St. Marys, Georgia (Peck and others, 1999) (fig. 3).

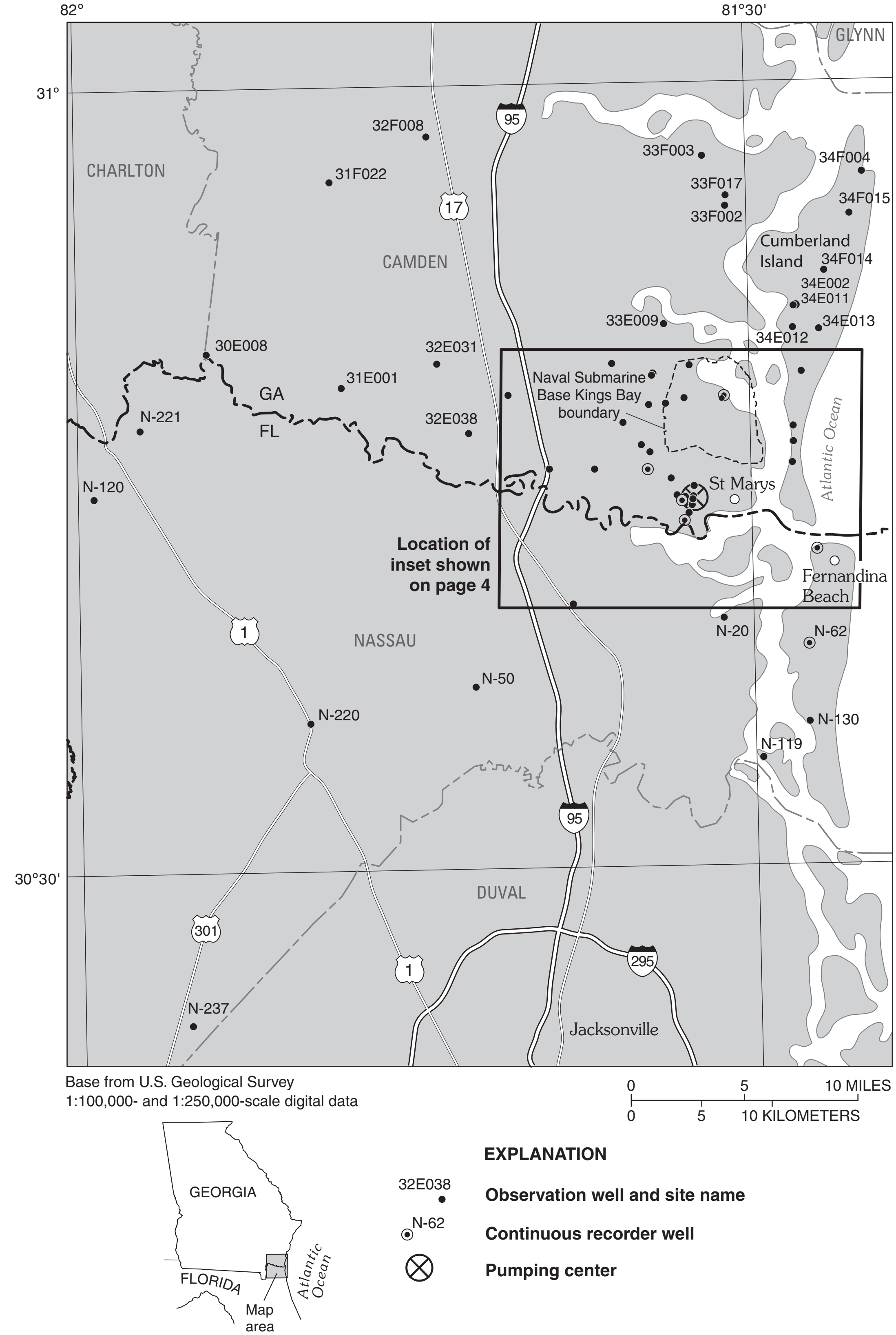


Figure 1A. Location of study area and selected ground-water-level and chloride monitoring sites in Camden County, Georgia, and Nassau County, Florida.

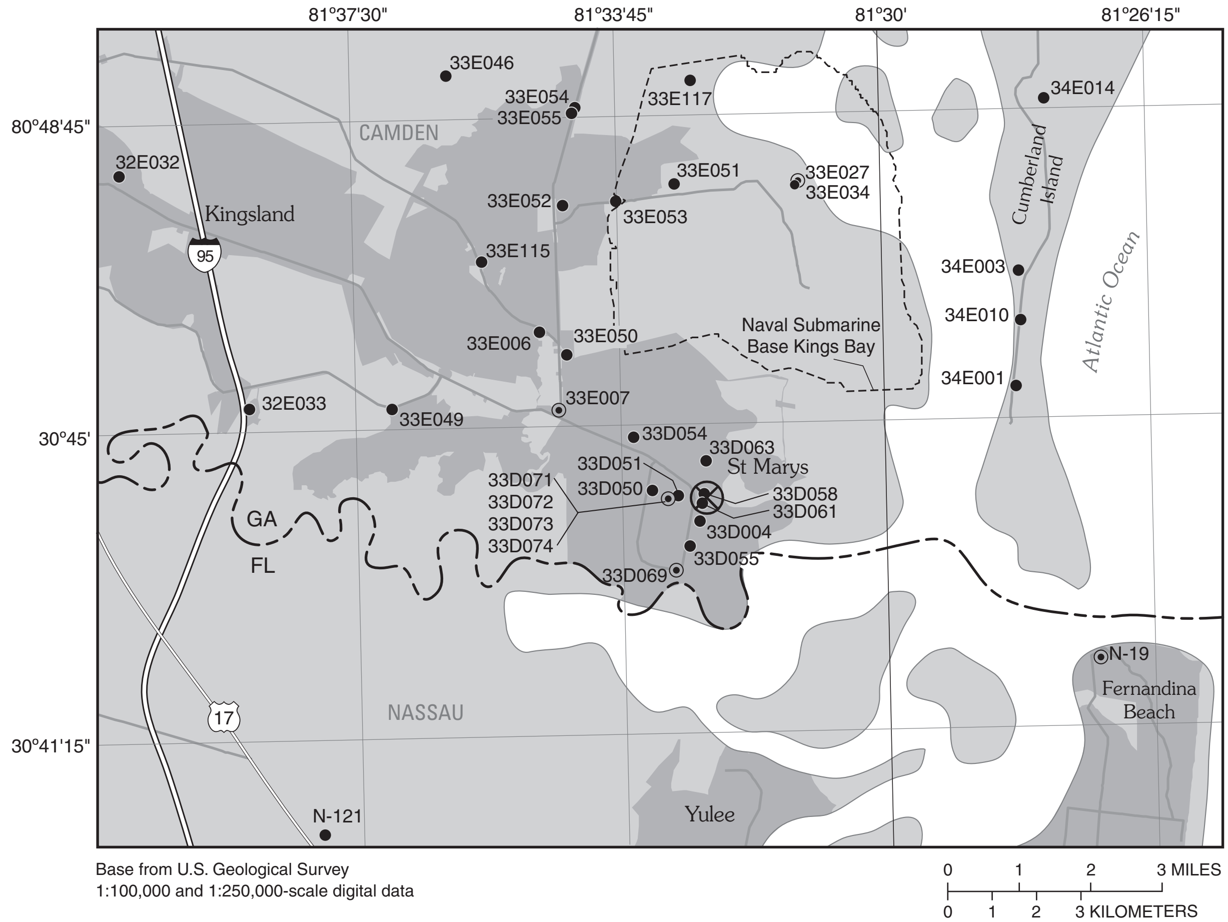
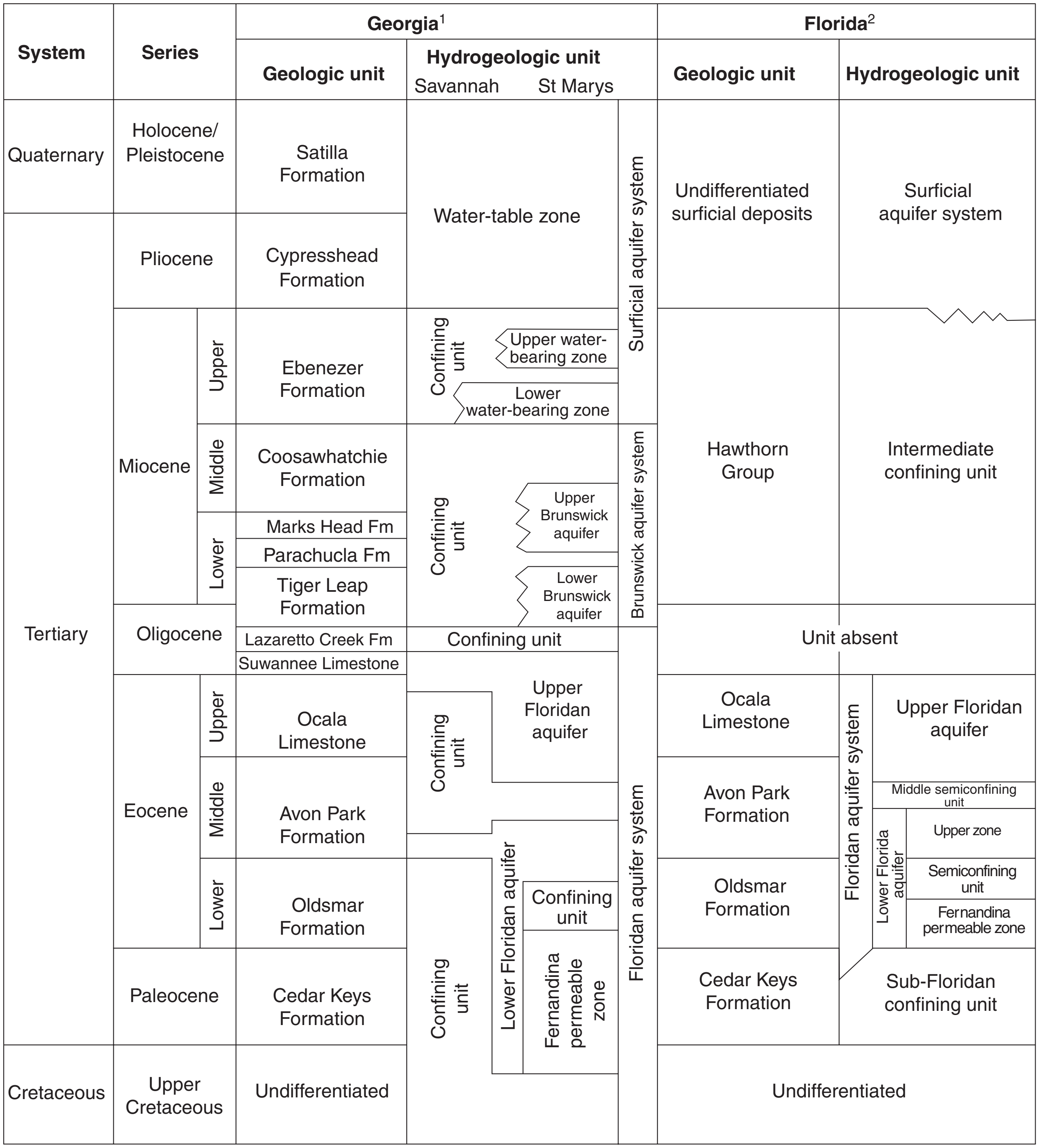


Figure 1B. Location of study area and selected ground-water-level and chloride monitoring sites in the St. Marys, Georgia, area.

Aquifer-test data indicate that the Upper Floridan aquifer in the St. Marys area has the highest transmissivity in the coastal area of Georgia. Transmissivity ranges from 32,000 to 40,000 feet squared per day (ft^2/d) in the Savannah area (Warner and Aulenbach, 1999), from 33,000 to 40,000 ft^2/d in the Brunswick area (Clarke and others, 1990), and from 98,000 to 170,000 ft^2/d in the St. Marys area (Warner and Aulenbach, 1999).

Hydrogeologic units underlying the study area in Nassau County, Florida, include the surficial aquifer system, an intermediate confining unit, and the Floridan aquifer system (fig. 2). The surficial aquifer system consists of sand, shell, and clay with some layers of dolomitic limestone and is divided into two water-bearing zones that range from semiconfined to unconfined (Phelps, 2001). The surficial aquifer system is underlain by the intermediate confining unit, which consists of varying layers of clay, silt, sand, dolomite, and limestone and contains ubiquitous phosphate that ranges in size from sand- to pebble-size particles (Phelps, 2001). In northeastern Florida, the Floridan aquifer system is divided into the Upper and Lower Floridan aquifers, as in southeastern Georgia; however, the Lower Floridan aquifer is further subdivided into two water-bearing zones. The transmissivity of the Upper Floridan aquifer in northeastern Florida ranges from 20,000 to 50,000 ft^2/d (Phelps, 2001). Because of the large ground-water withdrawal in the Fernandina Beach area (fig. 1*A*), a cone of depression has developed in the potentiometric surface of the Upper Floridan aquifer (fig. 3).



[1]Modified from Randolph and others, 1991; Clarke and Krause, 2000
[2]Modified from Phelps and Spechler, 1997

Figure 2. Geologic and hydrogeologic units in the coastal area of Georgia (modified from Clarke, 2003; Clarke and others, 2004).

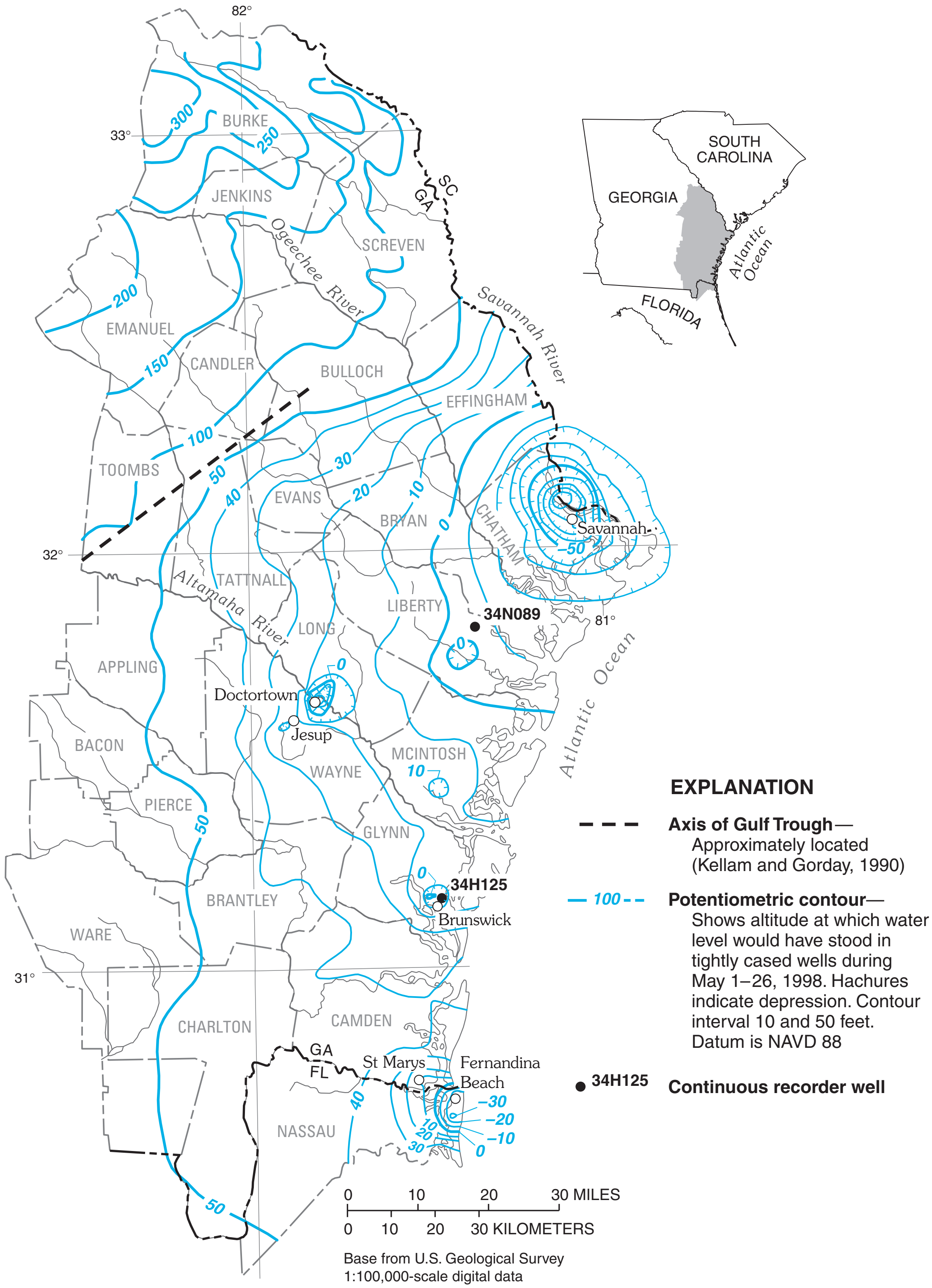


Figure 3. Potentiometric surface of the Upper Floridan aquifer in the coastal area of Georgia, May 1998 (modified from Peck and others, 1999).

Methods of Investigation

Continuous ground-water-level data were evaluated and compared to water-use data to determine the effect of the industrial shutdown and extent of water-level rise and changes in chloride concentration in the Upper Floridan aquifer, and to assess changes in water levels in the overlying surficial and Brunswick aquifer systems. Because water-level hydrographs typically show a strong seasonal component, the ability of the human eye to discern the central tendency or pattern inherent in long-term water-level hydrographs is poor; the range of data dominates visual impression (Helsel and Hirsch, 1992). A procedure for decomposing time series into a trend, a seasonal component and a remainder, has been used in this report to aid in discerning patterns in the long-term water-level hydrographs. This procedure, known as STL (Cleveland and others, 1990), has a simple design based on applying a sequence of locally weighted scatterplot smooths (LOESS) to the data. LOESS is a computationally intensive form of smoothing that involves fitting at least 2^n weighted least squares (WLS) equations. At every X_0, a - is computed from a WLS regression whose weights are a function of both the distance from X_0 and the magnitude of the residual from the previous regression—an iterative procedure (Helsel and Hirsch, 1992). While more complex than traditional “smoothers,” LOESS allows the data analyst the opportunity to use various residual weights and window sizes according to the purpose for which the smooth is used. Because estimates for the trend and seasonal components from this procedure are robust, they are not distorted by aberrant behavior in the data and, thus, are preferable to smoothing techniques based on the mean or median.

Water-level data were used to construct potentiometric-surface maps of the Upper Floridan aquifer and were compared to historical water levels to determine water-level change throughout the study area. Initially, the potentiometric surface for each measurement period was derived and modeled from the calculated water-surface altitudes (land-surface altitude minus depth to water) at each well location using ArcGIS™ Spatial Analyst and Geostatistical AnalySt. The contours were used as a first draft of the potentiometric surface and then adjusted by hand. The data values were analyzed for spatial autocorrelation using a semivariogram to identify potential outliers. Values showing significant differences from the estimated surface trend were checked for validity and, in some cases, removed from further analysis. Potential causes for such outliers were traced to measurement errors, temporal differences from surrounding data, incorrect aquifer designations, well-construction flaws, or wells open to multiple aquifers. A tensioned-spline method was chosen to interpolate a raster-based prediction map of the water surface using a 100-meter grid cell size. This method was selected in order to maintain a surface that more closely adheres to the range of measured values, particularly at sampled locations. A weight factor of “2” with a 24-point neighborhood allowed for more distant points to have greater influence over the surface, particularly in areas with sparse coverage. The surface was interpolated to the county boundaries; however, areas beyond the geographic extent of the data points should not be considered as valid. The contours were derived from the surface model at 10-ft intervals. These contours were then adjusted by hand to produce the final potentiometric surface. A water-level difference map was derived by subtracting the September 2001 surface from the May 2003 surface.

Water samples were collected from 31 wells in Camden County, Georgia, during September 2002 and January and May 2003, to determine if chloride concentrations changed in the Upper Floridan aquifer because of decreased withdrawal. The USGS Georgia District Laboratory analyzed water samples, and chloride concentrations were determined by ion chromatography using Environmental Protection Agency method 300.0 (Pfaff, 1999).

Previous Investigations

Detailed investigations of the geology and hydrology of the Floridan aquifer system in the southeastern Coastal Plain of Georgia have been compiled in a variety of previous publications. Warner and Aulenbach (1999) analyzed hydraulic characteristics of the Upper Floridan aquifer at sites in Savannah and at St. Marys, Georgia. Clarke and others (1990) described the surficial aquifer (confined and unconfined zones) and the upper and lower Brunswick aquifers throughout 13 counties in the coastal area of Georgia. Hughes and Henry (1995) conducted a review of all existing data for the Neogene surficial and upper and lower Brunswick aquifers in Glynn and Camden Counties. Leeth (1999) described the hydrogeology of the surficial aquifer at the Naval Submarine Base Kings Bay, Camden County. Brown (1984), Spechler (1994), Phelps and Spechler (1997), and Phelps (2001) described the geology and hydrogeology of northeastern Florida.

Warren (1944), Johnston and others (1980), Krause and Hayes (1981), Clarke (1987), Peck (1991), Peck and others (1999), and Peck and McFadden (2004) presented maps showing the potentiometric surface of the Upper Floridan aquifer in the coastal area of Georgia. Warren (1944) presented one of the earliest potentiometric surface maps of the Upper Floridan aquifer. Johnston and others (1980) presented an estimated potentiometric surface of the Upper Floridan aquifer prior to development during 1880. The maps by Clarke (1987) and Peck and others (1999) also included a discussion of water-level trends in the Upper Floridan aquifer, 1980–85 and 1990–98, respectively. Fanning (1999) compiled water-use data for coastal Georgia and evaluated trends in water use from 1980 to 1997 and provided an update of total water use by county for 2000 (Fanning, 2003).

Several investigations have examined the potential for saltwater intrusion in the Floridan aquifer system because of increased development in southeastern Georgia and northeastern Florida. Rose (2001, 2002) summarized existing data describing the potential for saltwater intrusion in Camden County, Georgia. Brown (1984) reported on the impact of development on the availability and quality of water from the Floridan aquifer system in Nassau County, Florida, and Camden County, Georgia. Spechler (1994) investigated the potential for saltwater intrusion in Nassau, Duval, and St. Johns Counties, Florida. Phelps (2001) documented the chemical and isotopic characteristics of water from different water-bearing zones in the Floridan aquifer system in northeastern Florida to determine the source of mineralized water detected in wells in Duval County.

Well-Numbering System

Wells in Georgia are given a well number according to a system based on the USGS index of topographic maps of Georgia. Each 7½-minute topographic quadrangle in the State has been assigned a three- to four-digit number and letter designation (for example, 33D or 33E) 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 01. Thus, the fourth well inventoried in the 33D quadrangle is designated 33D004. In the USGS National Water Information System (NWIS) database, this information is stored under the field "Well Name" (*http://waterdata.usgs.gov/ga/nwis/gw*).

Wells in Florida are given a well number based on the county in which they are located. The USGS assigned local well numbers to wells in each county in northeastern Florida as each well was inventoried. The prefix N- in a well number denotes Nassau County and is followed by a sequential number that denotes the order in which the well was inventoried (Phelps, 2001).

Acknowledgments

The water-level and water-quality data collected during this study were obtained through the cooperation of the City of St. Marys, Durango Paper Company, St. Johns River Water Management District, and numerous private well owners throughout Camden County. Welby Stayton (USGS, Georgia) collected water levels and water samples in Georgia. Sandra Kinnaman, Darryl Williams, and Larry Thomas (USGS, Florida) provided water-level data for Nassau County, Florida. Richard L. Marella (USGS, Florida) provided water-use data for Nassau County, Florida.

Ground-Water Withdrawal

In Camden County, Georgia, and Nassau County, Florida, ground-water withdrawal increased from about 0.5 Mgal/d during 1938 to a total of about 105 Mgal/d during 1977 (Brown, 1984). Much of the increase occurred during the 1940s when three major paper mills—one at St. Marys, Georgia, and two at Fernandina Beach, Florida—began operation (fig. 4*A*). By 1980, total pumpage in this area decreased to about 91 Mgal/d (Brown, 1984), and from 1985 to 2000 ranged from about 81 to 90 Mgal/d (Frick and others, 2002).

Most of the wells in the study area are completed in the Upper Floridan aquifer; however, some wells at the Durango Paper Company are completed in both the Upper Floridan aquifer and the upper part of the Lower Floridan aquifer (fig. 2; table 1). Miller (1986) reported that the top of the Lower Floridan aquifer in the St. Marys area is about 1,250 ft below land surface. Falls and others (2001), however, delineated the top of the Lower Floridan aquifer at about 1,185 ft below land surface. Four wells at the Durango Paper Company are completed to depths ranging between 1,199–1,259 ft below land surface (table 1). Falls and others (2001) interpretation of the top of the Lower Floridan aquifer is based on data obtained from two recently drilled test wells located about 0.2 miles (mi) southwest of the Durango Paper Company.

In the 24-county coastal area of Georgia, ground-water withdrawal decreased from about 388 Mgal/d during 1980 to 386 Mgal/d during 2000 (Fanning, 2003). During the same period, ground-water withdrawal in Camden County, Georgia, increased from 37.48 Mgal/d to 42.6 Mgal/d (fig. 4*A*), with most of the pumpage attributed to the Durango Paper Company at St. Marys, Georgia (Fanning, 2003). During 2000, the mill withdrew an average of about 35.6 Mgal/d from wells primarily completed in the Upper Floridan aquifer (fig. 4*A*). During 2002, the mill also pumped an average of about 35.6 Mgal/d, before it closed during early October (fig. 4*B*). The shutdown decreased total ground-water withdrawal in Camden County to 5.7 Mgal/d (J.L. Fanning, U.S. Geological Survey, written commun., October 24, 2003).

In Nassau County, Florida, ground-water withdrawal was about 46.3 Mgal/d during 2002, mostly for industrial and public supply. Industrial ground-water withdrawals in Nassau County decreased from the late 1970s to the present; this decrease is attributed to the overall decline in pulp production and more efficient use of water by the pulp and paper industry (R.L. Marella, U.S. Geological Survey, written commun., April 29, 2003). In addition, the St. Johns River Water Management District issued new regulations pertaining to withdrawal permits, limiting the amount of water consumed by major industrial users during the 1980s.

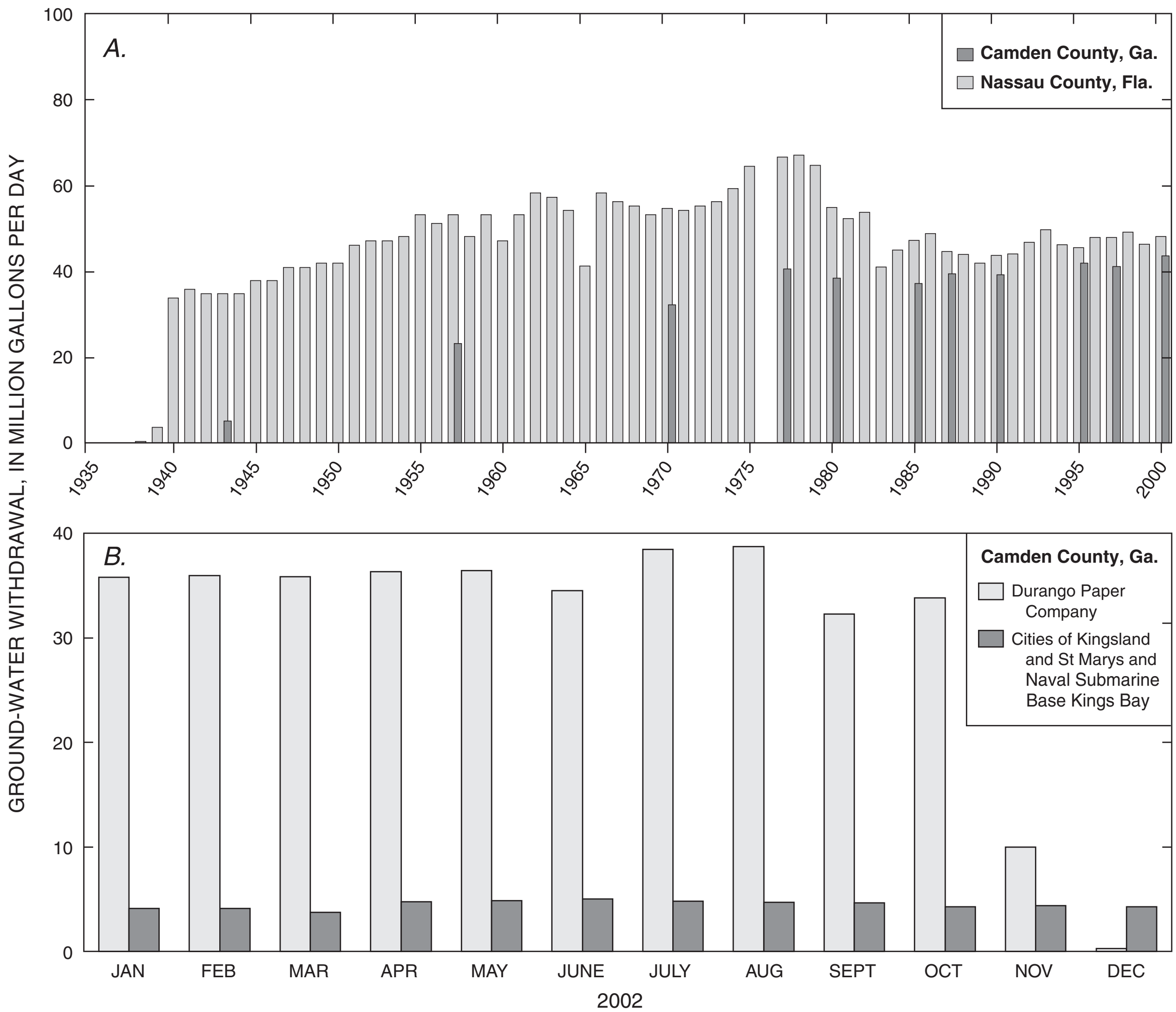


Figure 4. (*A*) Estimated ground-water withdrawal in Camden County, Georgia, and Nassau County, Florida, 1938–2000 (modified from Frick and others, 2002), and (*B*) monthly water use, in Camden County, Georgia, 2002.

Table 1. Location and construction information for wells used in this study, September 2001–May 2003.

[ID, identification; °, degree; ', minute; ", second; FAS, Floridan aquifer system; UF, Upper Floridan; LF, Lower Floridan; UB, upper Brunswick; GGS, Georgia Geologic Survey; —, data not available; *, no name]

Well ID	Well name	Latitude	Longitude	Land-surface altitude (feet)	Well depth (feet)	Casing depth (feet)	Casing diameter (inch)	Aquifer	Construction date
30E008	Lester Varn	30°49'53"	81°54'11"	13.34	460	235	4	FAS	Feb. 16, 1982
31E001	E. Brown	30°48'31"	81°48'11"	21	500	400	3	UF	Jan. 1, 1958
31F022	J. Van	30°56'24"	81°48'34"	18.89	650	422	3	UF	May 1973
32E031	B&S Chicken Farm	30°49'23"	81°43'54"	19.84	750	504	3	UF	—
32E032	E. Gross (1950)	30°48'08"	81°40'45"	27.02	516	466	3	UF	Jan. 1, 1950
32E033	Georgia Welcome Center	30°45'17"	81°38'58"	17.1	600	420	6	UF	Sept. 1974
32E038	J.D. Peeples	30°46'42"	81°42'32"	15.84	720	483	3	FAS	Oct. 1968
32F008	H. Williams	30°58'05"	81°44'12"	4.87	872	399	3	UF	Dec. 1965
33D004	E. Floyd	30°43'49"	81°32'38"	8.82	600	400	2	UF	1952
33D006	Gillman Paper Co. 8	30°44'27"	81°32'33"	7.81	1,199	560	—	UF	—
33D022	Gillman Paper Co. 3	30°44'02"	81°32'36"	9	860	517	20	UF	Mar. 8, 1950
33D048	Gillman Paper Co. 9	30°44'07"	81°32'34"	8.82	1,183	530	—	FAS	—
33D049	Gillman Paper Co. 6	30°44'14"	81°33'24"	13.82	1,259	520	20	FAS	Feb. 1956
33D050	Gillman Paper Co. 5	30°44'12"	81°33'18"	13.82	1,215	529	20	FAS	Nov. 4, 1953
33D051	Gillman Paper Co. 4	30°44'08"	81°32'56"	8.81	1,220	519	18	FAS	Oct. 1953
33D053	Gillman Paper Co. 1	30°44'12"	81°32'31"	8.81	1,063	516	18	UF	Jan. 26, 1941
33D054	St. Marys Georgia 2	30°44'51"	81°33'33"	20.81	1,001	563	12	UF	Jan. 1, 1965
33D055	St. Marys Georgia 1	30°43'31"	81°32'47"	9.82	761	500	6	UF	July 1, 1953
33D058	Gillman Paper Co. 7	30°44'09"	81°32'34"	8.82	1,041	530	26	UF	—
33D061	Gillman Paper Co. 11	30°44'02"	81°32'36"	8.82	1,088	550	26	UF	Nov. 28, 1981
33D062	Gillman Paper Co. 2	30°44'35"	81°32'31"	9	1,285	557	20	FAS	Oct. 5, 1946
33D063	Gillman Paper Co. 10	30°44'33"	81°32'32"	8.81	1,099	560	26	UF	—
33D069	National Park Service	30°43'14"	81°32'59"	7	575	467	4	UF	Jan. 1, 1900
33D071	GGS Test Well 2 St. Marys	30°44'07"	81°33'04"	9	365	325	4	UB	May 15, 1997
33D072	GGS Test Well 3 St. Marys	30°44'07"	81°33'04"	9	255	225	4	Surficial	June 30, 1997
33D073	St. Marys Deep Test Well	30°44'06"	81°33'05"	8.82	1,500	1,360	8	LF	Dec. 3, 1999
33D075	Durango Paper Co. 12	30°44'36"	81°32'48"	12.5	1,100	577	30	UF	June 19, 1998
33E006	Finn and neighbor	30°46'09"	81°34'51"	10.83	750	—	—	FAS	—
33E007	Huntly-Jiffy	30°45'12"	81°34'36"	16.82	760	552	3	UF	Apr. 1, 1964
33E008	Crocked River State Park	30°50'38"	81°33'22"	15	470	261	4	UF	—
33E009	American Legion St. Marys	30°50'46"	81°33'45"	10.83	565	250	4	FAS	1930
33E027	U.S. Navy, Kings Bay, test well 1	30°47'57"	81°31'10"	9.25	990	555	8	UF	Feb. 8, 1979

Table 1. Location and construction information for wells used in this study, September 2001–May 2003.—Continued

[ID, identification; °, degree; ', minute; ", second; FAS, Floridan aquifer system; UF, Upper Floridan; LF, Lower Floridan; UB, upper Brunswick; GGS, Georgia Geologic Survey; —, data not available; *, no name]

Well ID	Well name	Latitude	Longitude	Land-surface altitude (feet)	Well depth (feet)	Casing depth (feet)	Casing diameter (inch)	Aquifer	Construction date
33E034	U.S. Navy Kings Bay 4	30°47'53"	81°31'11"	12.11	810	500	12	UF	Aug. 1, 1955
33E046	Joiner-Green-Crocker-Onel	30°49'17"	81°36'06"	9	650	548	3	UF	Nov. 11, 1983
33E049	Osprey Cove Inc.	30°45'15"	81°36'57"	13	840	522	12	UF	Jan. 19, 1990
33E050	St. Marys Georgia 3	30°45'52"	81°34'28"	23	982	560	18	UF	Apr. 3, 1986
33E051	U.S. Navy Kings Bay 6	30°47'55"	81°32'54"	17.29	900	560	18	UF	Sept. 30, 1983
33E052	U.S. Navy Kings Bay No. 1 (1984)	30°47'41"	81°34'29"	30.57	900	590	18	UF	Mar. 20, 1984
33E053	U.S. Navy Kings Bay No. 2 (1984)	30°47'43"	81°33'44"	23.33	900	570	18	UF	Feb. 15, 1984
33E054	Rayland Company No. 1	30°48'51"	81°34'17"	27	640	381	10	UF	1900
33E055	Gillette	30°48'48"	81°34'20"	27	—	—	—	FAS	—
33E115	St. Marys Georgia No. 4	30°47'01"	81°35'39"	15	805	563	8	UF	May 19, 1980
33E117	U.S. Navy Kings Bay Etowah Park	30°49'10"	81°32'39"	19	620	480	4	UF	May 23, 1997
33F002	Union Carbide 2	30°55'15"	81°30'55"	8.85	806	513	12	UF	Sept. 20, 1963
33F003	Union Carbide 3	30°57'11"	81°31'54"	18.86	847	508	12	UF	Sept. 14, 1963
33F017	Union Carbide 4	30°55'39"	81°30'53"	10.86	832	534	24	UF	Dec. 1, 1981
34E001	Cumberland Island GGS TW 1	30°45'23"	81°28'12"	16	645	540	4	UF	—
34E003	Cumberland Island Greyfield 2	30°46'47"	81°28'08"	12.84	730	538	8	UF	1931
34E010	Cumberland Island Rockefeller 32	30°46'11"	81°28'08"	9	750	550	4	UF	—
34E011	NPS Plum Orchard	30°51'23"	81°27'55"	11.86	—	—	4	UF	1900
34E012	Reddick	30°50'33"	81°28'00"	10.85	—	—	—	UF	—
34E013	Yankee Paradise Trail Well	30°50'29"	81°26'50"	15.86	—	—	—	UF	—
34E014	Foster	30°48'52"	81°27'39"	25.85	—	—	—	UF	1900
34F004	Mr. Botsford	30°56'31"	81°24'42"	7.9	743	571	3	UF	Jan. 1, 1966
34F014	Squawtown Well	30°52'43"	81°26'33"	6.87	—	—	—	UF	—
34F015	Candler at water tower	30°54'53"	81°25'22"	13.89	—	—	—	UF	—
N-0220	Nassau County Fairgrounds	30°35'41"	81°49'48"	18.94	650	458	6	FAS	Nov. 1, 1994
N-0221	*	30°46'59"	81°57'11"	20.4	812	539	6	FAS	Nov. 8, 1994
N-0237	Carey State Forest	30°24'10"	81°55'15"	79.06	500	450	6	FAS	—
N-119	Charles Allen	30°33'58"	81°29'55"	8.86	—	—	—	FAS	—
N-120	Humphreys Mining No. 2	30°44'23"	81°59'17"	95.14	923	525	12	FAS	—
N-121	Baker Oil Test	30°40'06"	81°38'01"	20.89	645	460	4	FAS	—
N-130	Amelia City, Florida	30°35'19"	81°27'49"	14.76	600	515	4	FAS	—
N-19	Ft. Clinch State Park	30°42'11"	81°27'07"	7.26	710	—	5	FAS	—
N-20	*	30°39'40"	81°31'25"	10.86	—	—	—	FAS	—
N-50	*	30°36'59"	81°42'25"	16.95	569	—	2	FAS	1938
N-62	ITT Rayonier No. 8	30°38'24"	81°27'32"	16.45	565	565	12	FAS	—

Ground-Water Levels

Ground-water levels in the St. Marys area were affected substantially by the reduction in ground-water withdrawal at the Durango Paper Company. Continuous water-level data from wells completed in the confined surficial, upper Brunswick, Upper Floridan, and Lower Floridan aquifers show a pronounced water-level rise after the shutdown during early October 2002 (fig. 5). Data are not available for the lower Brunswick aquifer in the St. Marys area because during the study period there were no observation wells completed in this aquifer.

Confined Surficial Aquifer

Water-level data for the surficial aquifer system in Camden County are sparse; and only the lower confined zone is monitored continuously at well 33D072 (fig. 6), located approximately 0.2 mi southwest of the Durango Paper Company (see location fig. 1*B*). In Camden County, most of the pumpage from the surficial aquifer system is either from the water-table zone or the upper and lower confined zones. The water-table zone is used by homeowners who install shallow-driven or jetted wells for landscape irrigation. At the Naval Submarine Base Kings Bay, located about 4.8 mi north of well 33D072, about 0.2 Mgal/d are withdrawn annually from the confined zones of the surficial aquifer system for irrigation (J.L. Fanning, U.S. Geological Survey, written commun, July 2003).

Water levels in the confined surficial aquifer at St. Marys have been monitored continuously in well 33D072 since early 1998, and range from 5 to 8 ft below land surface for the period of record prior to the mill shutdown (fig. 6). A regional water-level rise that began during 2000 (fig. 7) in the deeper Brunswick and Floridan aquifer systems is not evident on the hydrograph for well 33D072. On October 6, 2002, the water level in well 33D072 began to rise from 6.38 ft below land surface and continued to rise through March 2003. A record high water level of 1.58 ft below land surface was recorded on March 13, 2003; by May 2003, the water level appeared to have stabilized, declining slightly to 2.5 ft below land surface on May 15, 2003. Overall, the water level in the confined surficial aquifer at St. Marys rose 4.8 ft from September 2002 to May 2003.

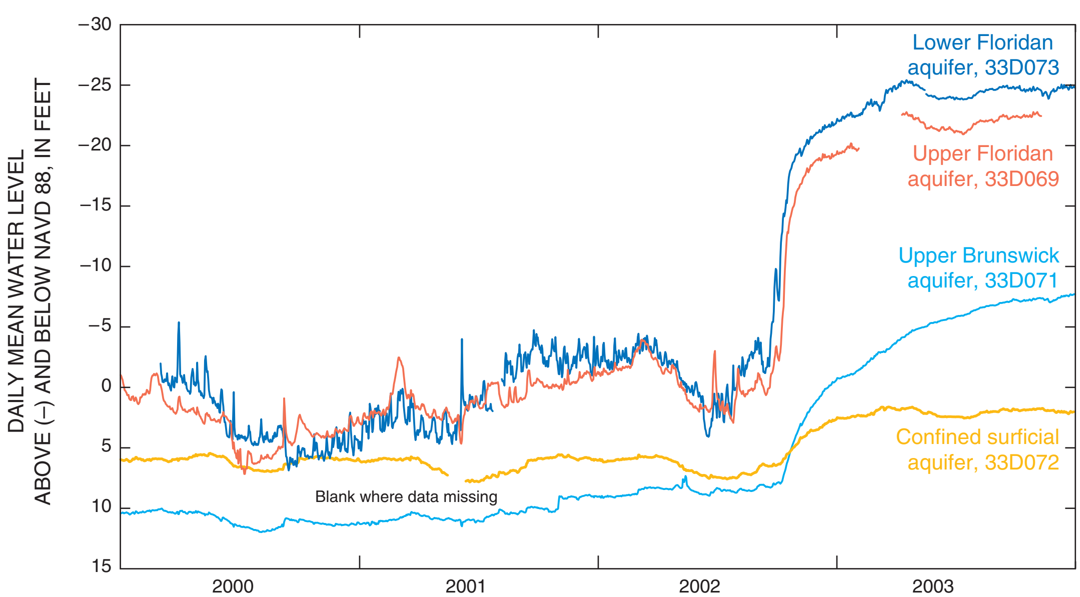


Figure 5. Hydrographs for the St. Marys well cluster (33D071, 33D072, and 33D073) and nearby National Park Service well (33D069), Camden County, Georgia, 2000–2003.

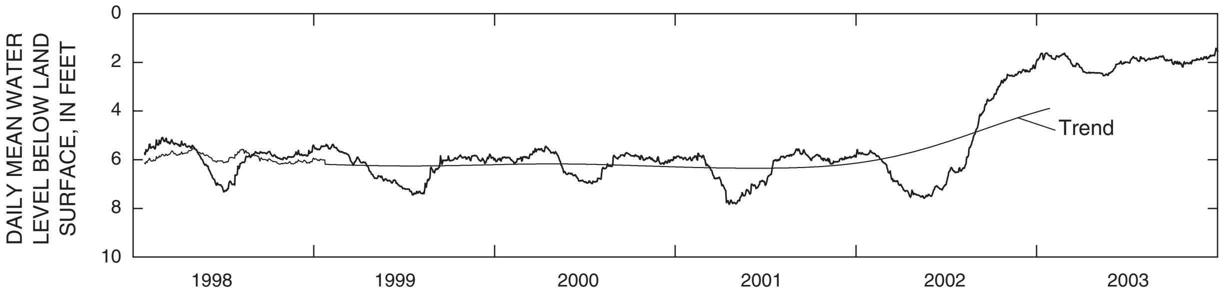


Figure 6. Period-of-record hydrograph for well 33D072 (confined surficial aquifer), Camden County, Georgia, 1998–2003.

Upper Brunswick Aquifer

In the St. Marys–Camden County area, the Brunswick aquifer system is not heavily used; therefore, water-level and water-use data are sparse. Water levels in the upper Brunswick aquifer are monitored continuously in only one well, 33D071 (fig. 8), located approximately 0.2 mi southwest of the Durango Paper Company (see location fig. 1*B*). Water levels in well 33D071 have been monitored continuously since 1998 and range from about 7.3 to 12 ft below land surface for the period of record prior to the mill shutdown (fig. 8). Since late 2000, there has been a slight upward water-level trend in this well similar to the water-level rise in the Upper Floridan aquifer throughout the coastal area (fig. 7). On October 7, 2002, the water level in well 33D071 began to rise at an accelerated rate, starting at 7.97 ft below land surface, and continued to rise through May 2003. On December 18, 2002, the water level in well 33D071 rose above land surface; and by mid-May, the water level was 5.0 ft above land surface, a record high. As of May 2003, the water level was still rising and did not appear to be stabilizing as was the case for the confined surficial aquifer. Overall, the water level in the upper Brunswick aquifer at St. Marys rose 12.9 ft from September 2002 to May 2003. The longer recovery period for the upper Brunswick aquifer is likely the result of low-permeability clays that confine the aquifer and inhibit the inter-aquifer flow of water.

Floridan Aquifer System

In the Camden County area, the Floridan aquifer system is deeply buried and far from its outcrop area; thus, water levels are not directly influenced by variations in precipitation and are primarily affected by industrial and municipal withdrawal (Clarke and others, 1990). Cones of depression have formed in the potentiometric surface of the Upper Floridan aquifer around the industrial pumping centers at Savannah, Jesup-Riceboro, Brunswick, and St. Marys, Georgia, and Fernandina Beach, Florida (Peck and others 1999) (fig. 3).

Upper Floridan Aquifer

Johnston and others (1980) estimated that the altitude of the predevelopment (prior to 1880) potentiometric surface of the Upper Floridan aquifer in Camden County ranged from about 70 ft in the western part of the county to 60 ft along the coast. Warren (1944) published one of the earliest postdevelopment Upper Floridan potentiometric-surface maps (fig. 9), showing that the altitude of the water surface in 1942 Camden County ranged from 60 ft in the west to 50 ft along most of the coastal area of the county. This 1942 surface also shows large cones of depression centered at Savannah, Georgia, and Fernandina Beach, Florida, and includes a smaller cone at St. Marys, resulting from industrial withdrawal for the then-recently opened Gillman (now Durango) Paper Company. This configuration is typical of most potentiometric-surface maps of the Upper Floridan aquifer in coastal Georgia that have been constructed to the present (2004), with the exception of the addition of two other major cones of depression: one centered at Brunswick in Glynn County and the other centered at Jesup in Wayne County (fig. 3), both owing to industrial withdrawal. The altitude of the 1998 potentiometric surface of the Upper Floridan aquifer in Camden County is about 40 ft throughout most of the county, with the exception of St. Marys, where the altitude of the surface is about zero, indicating a decline of at least 50 ft since industrial withdrawal began during the early 1940s.

The 1998 potentiometric surface does not depict the total depth of the cone of depression at St. Marys because water-level measurements were not obtainable from production wells at the mill. Based on historical water-level measurements made in the active production wells during mill operation, however, the altitude of the cone of depression at the center of pumping at the mill was estimated to range from 68 to 235 ft below NAVD 88 and averaged about 114 ft below NAVD 88 during mill operation. To evaluate the effects of the Durango Paper Company shutdown, potentiometric-surface maps for the Upper Floridan aquifer were constructed for September 2001 and September 2002, prior to the Durango Paper Company ceasing operations, January 2003 during the water-level recovery, and May 2003 when the water level had stabilized (table 2; figs. 10–11).

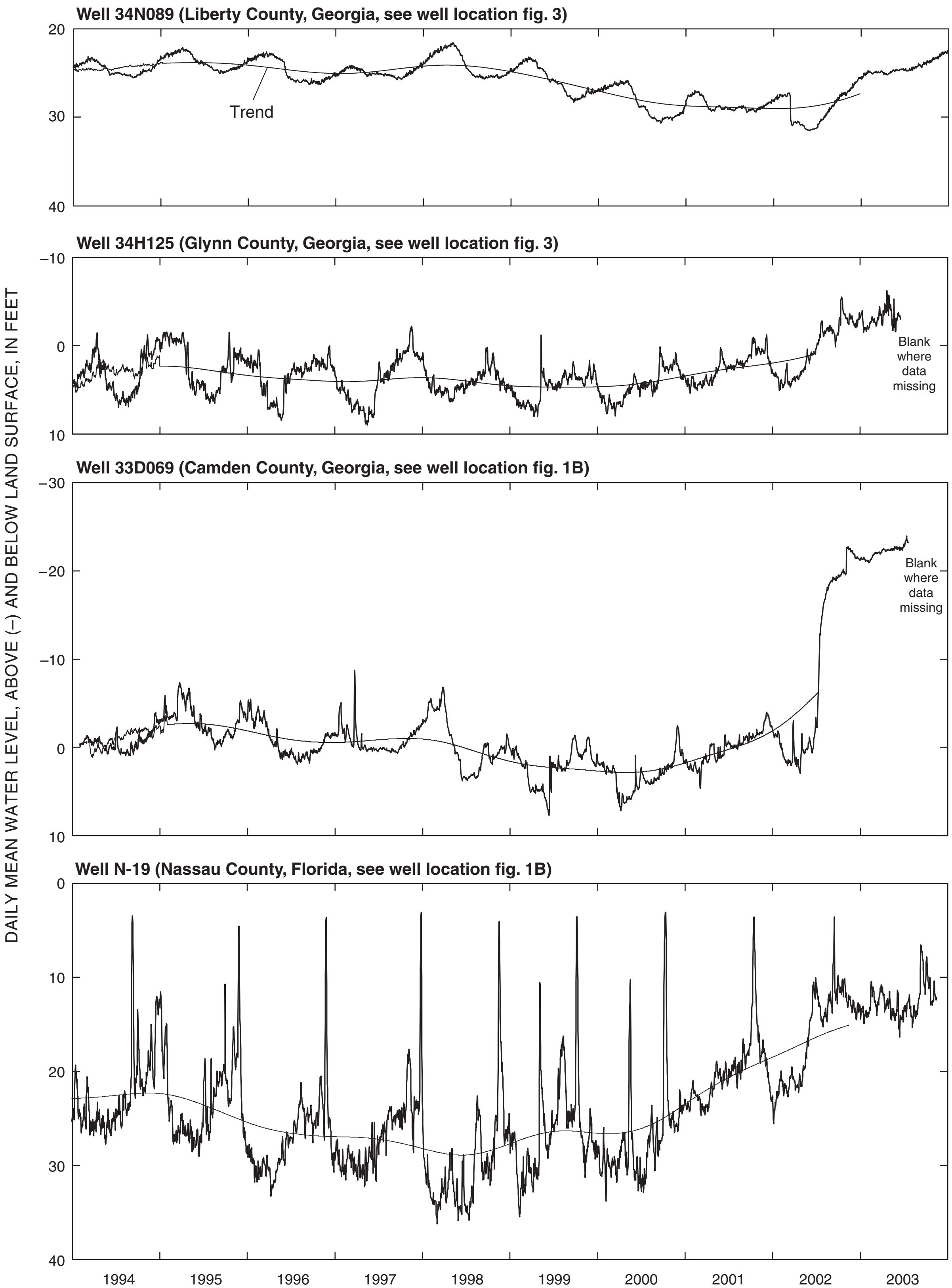


Figure 7. Hydrographs and regional water-level trends for wells completed in the Upper Floridan aquifer, coastal Georgia and northeastern Florida, 1994–2003.

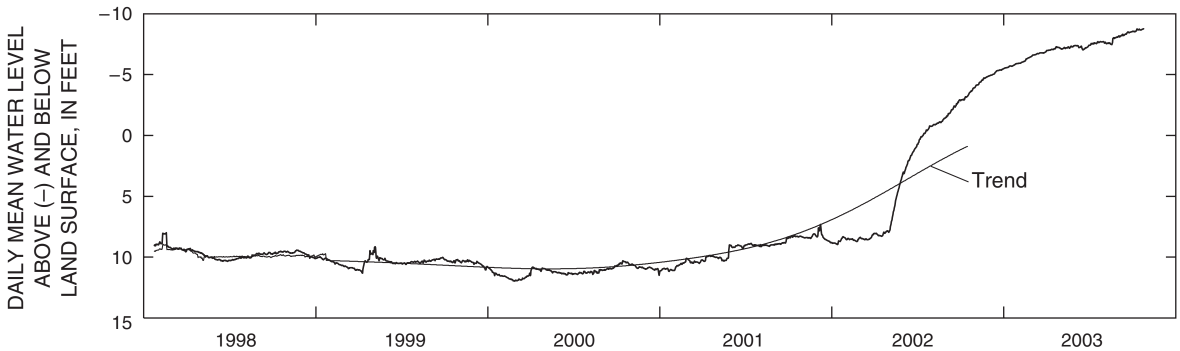


Figure 8. Period-of-record hydrograph for well 33D071 (upper Brunswick aquifer), Camden County, Georgia, 1998–2003.

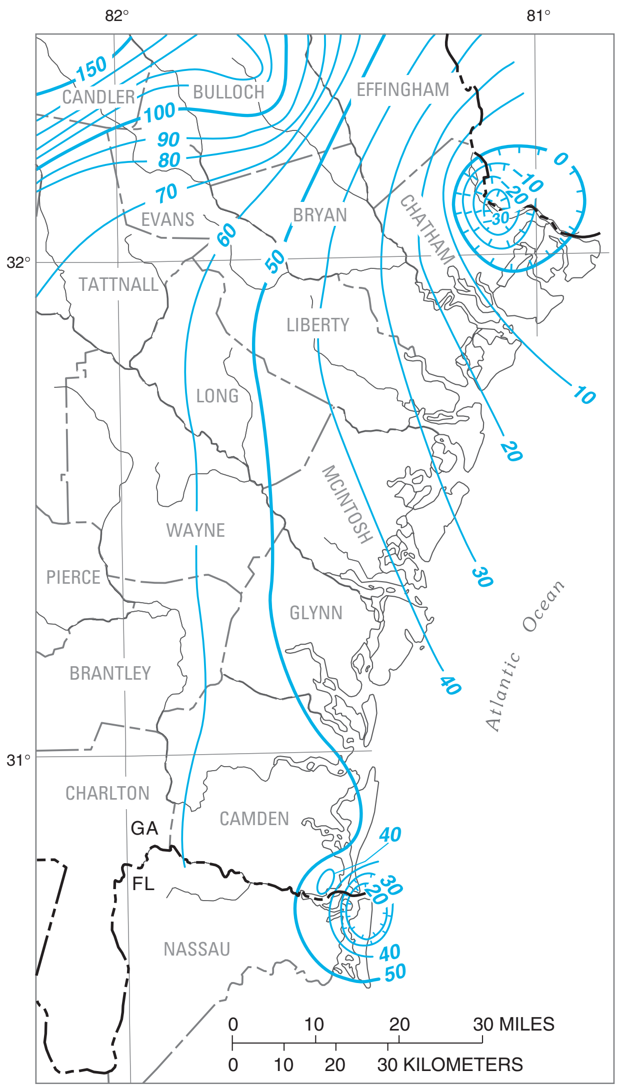
Prior to the shutdown during October 2002, potentiometric-surface maps for September 2001 and September 2002 (fig. 10*A* and *B*) show a small cone of depression centered at St. Marys (as indicated by the –10-ft contour) that coalesces with a larger cone of depression centered at Fernandina Beach, Florida. The maps indicate that the Fernandina Beach cone of depression (as indicated by the 30-ft contour extends about 4.7 mi west and 5.2 mi north of St. Marys). Although water levels in St. Marys began to rise from 24 to 48 hours after the shutdown, the cone of depression from Fernandina Beach remains, extending north and west of St. Marys (fig. 11*A* and *B*).

The most prominent changes in the potentiometric surface after the industrial shutdown are the disappearance of the cone of depression centered at St. Marys, Georgia, the decreased Fernandina Beach cone, and the development of the 40-ft ground-water mound northwest of St. Marys (fig. 11*A* and *B*). The water level in the Upper Floridan aquifer at St. Marys ranged from about 10 ft below land surface to 10 ft above during September 2001 (fig. 10*A*); by May 2003 (fig. 11*B*), the water level had risen to about 30 ft, which is 20 ft lower than the predevelopment potentiometric surface of Johnston and others (1980). A water-level change map was constructed by comparing water-level data for September 2001 and May 2003 (fig. 12). The September 2002 water-level data were not used for the water-level change map because fewer paired well data were available for both time periods (table 2). Water levels during September 2001 were slightly lower than September 2002; thus, the amount of recovery depicted on the map (fig. 12) is somewhat greater than would be expected between September 2002 and May 2003. Despite this difference, the general configuration of the September 2001 and 2002 potentiometric surfaces is similar; thus, the extent of water-level rises likely would be similar for September 2002 and May 2003.

The water-level changes resulting from the shutdown are greatest in the St. Marys area and are less pronounced and more difficult to distinguish from regional trends the farther away from the center of pumping. Analysis of continuous water-level data from wells in coastal Georgia and Nassau County, Florida, indicates a regional upward water-level trend in the Upper Floridan aquifer prior to the Durango Paper Company closing (fig. 7). Because of the high transmissivity of the Upper Floridan aquifer and the localized nature of the cone of depression centered at St. Marys, it appears that the ground-water withdrawal from the Durango Paper Company affected only wells located within several miles of the St. Marys area (based on the water-level data through May 2003). For wells located farther away in Liberty and Glynn Counties, Georgia, and Nassau County, Florida, the response to the mill shutdown is not discernible because of the overall regional water-level rise and the effects of ground-water withdrawal (fig. 7).

The USGS continuously monitored water levels in the Upper Floridan aquifer in four wells in Camden County, Georgia (three of which are discussed herein), and two wells in Nassau County, Florida (see locations, fig. 1*B*). Well 33D069 is closest to the Durango Paper Company wellfield, located about 1.1 mi south of the center of pumping. The water level has been monitored continuously since 1994 and ranged from about 8 ft below land surface to 9 ft above land surface for the period of record prior to the industrial shutdown, with an upward trend since early 2000 (fig. 13). After pumping ceased, the water level in the well rose to 2.12 ft above land surface on October 5, 2002, and continued to rise through April 2003. A record high water level of 23.62 ft above land surface was recorded on April 17, 2003; as of early May 2003, the water level appeared to have stabilized with a total rise of 21.5 ft from September 2002 to May 2003.

The water level in well 33E007, located about 2 mi northwest of the Durango Paper Company (fig. 1*B*), has been monitored continuously since 1993. Water levels ranged from about 7.5 ft below land surface to 5.5 ft above land surface for the period of record prior to the mill shutdown and showed an upward trend since early 2000 (fig. 14). Following the shutdown, the water level rose to 1.39 ft below land surface on October 6, 2002, and continued to rise through May 2003. A record high water level of 15.3 ft above land surface was recorded on April 12, 2003; as of early May, the water level had stabilized, with a total rise of about 18 ft from September 2002 to May 2003.



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

EXPLANATION

— 50 — **Potentiometric contour**—Shows altitude at which water level would have stood in tightly cased wells during 1942. Hachures indicate depression. Contour interval 10 feet. Datum is NGVD 29

Figure 9. Potentiometric surface of the Upper Floridan aquifer in the coastal area of Georgia and Nassau County, Florida, 1942 (modified from Warren, 1944).

Table 2. Ground-water altitudes in selected wells in Camden County, Georgia, and Nassau County, Florida, September 2001–May 2003.

[ID, identification; –, indicates below NAVD 88; —, data not available; altitudes in feet]

Well ID	2001	2002		2003	
	Sept.	May	Sept.	Jan.	May
30E008	31.18	31.60	32.08	34.26	37.00
31E001	34.1	33.65	37.31	37.88	39.95
31F022	34.7	34.41	40.63	41.69	41.29
32E031	34.83	33.7	37.76	37.9	40.76
32E032	34.03	33.14	31.33	35.24	38.44
32E033	30.71	29.85	29.32	35.89	38.22
32E038	27.07	25.9	26.76	30.06	33.52
32F008	35.55	33.97	37.61	38.43	40.63
33D004	—	6.72	—	—	—
33D050	—	—	—	—	24.71
33D054	11.62	7.6	9.21	31.26	—
33D055	3.02	0.71	—	23.8	25.93
33D058	−2.93	−2.48	−2.51	—	—
33D061	—	—	—	—	22.71
33D063	−12.34	−11.21	−10.13	—	—
33D069	7.18	6.79	7.16	26.97	28.28
33D073	—	8.46	10.08	—	—
33E006	19.94	19.49	—	22.75	—
33E007	11.98	14.28	13.63	28.48	30.75
33E009	35.44	33.43	35.49	36.75	39.47
33E027	—	26.4	24.47	36.69	—
33E034	24.76	—	—	35.79	36.94
33E046	35.02	31.81	39.08	44.99	45.02
33E049	28.22	26.46	26.63	32.65	35.71
33E050	18.4	15.81	17.18	30.75	30.9
33E051	25.04	33.69	28.21	28.51	35.74
33E052	27.47	27.67	—	32.65	35.14
33E053	26.69	25.01	23.54	29.55	35.41
33E054	—	27	33.17	39.24	—
33E055	—	30.89	33.88	39.5	43.8
33E115	23.56	26.59	25.89	27.62	30.89
33E117	31.75	30.12	29.82	39.02	40.92
33F002	32.37	35.65	30.89	35.87	38.47
33F003	28.73	32.27	25.94	31.57	34.06
33F017	34.15	37.57	32.92	35.57	40.48
34E001	18.62	17.02	16.11	18.5	29.92
34E003	23.06	—	—	—	—
34E010	21.32	—	—	28.23	31.46
34E012	30.11	—	—	36.01	37.59
34E013	29.49	—	—	35.12	36.8
34E014	29.47	—	—	36.89	38.01
34F004	—	—	—	—	41.52
34F014	32.98	—	—	37.16	—
34F015	37	—	—	41.31	43.55
N-119	28.73	28.03	28.53	34.67	34.67
N-120	36.51	—	—	—	—
N-121	25.91	24.71	25.21	34.22	33.82
N-130	20.7	—	20.6	14.76	23.26
N-19	−10.61	−11.67	—	−1.35	−2.27
N-20	2.93	0.99	3.02	9.75	10.42
N-220	37.64	37.44	38.24	41.95	44.45
N-221	36.52	35.75	34.43	40.13	42.78
N-237	36.14	34.56	34.76	40	41.24
N-50	33.14	32.44	33.94	—	—
N-62	−13.1	−19.64	−14.17	−3.46	−8.42

The water level in well 33E027, located at the Naval Submarine Base Kings Bay about 4.6 mi northeast of the Durango Paper Company (fig. 1*B*), has been monitored continuously since 1979. Water levels ranged from about 10 to 25 ft above land surface for the period of record prior to the mill shutdown and showed an upward trend since early 2000 (fig. 15). After the shutdown, the water level rose to 16.66 ft above land surface on October 6, 2002, and continued to rise through May 2003. A record high water level of 29.77 ft above land surface was recorded on February 17, 2003; as of early May, the water level had stabilized with a total rise of 11.5 ft from September 2002 to May 2003.

In Nassau County, Florida, the USGS continuously monitored water levels in two wells. Wells N-19 (fig. 16) and N-62 (fig. 17)—located at Fernandina Beach, Florida, about 6.2 and 8.5 mi, respectively, southeast of the Durango Paper Company (figs. 1*A* and *B*)—have been monitored continuously since 1986 and 1994, respectively. Hydrographs for both wells show an upward water-level trend starting during early to mid-2000, which became more pronounced during October 2002, similar to the trends observed in wells completed in the Upper Floridan aquifer throughout coastal Georgia (fig. 7). The water level in well N-62 in Nassau County, Florida, began rising during July 2002, about 3 months prior to the Durango Paper Company shutdown, and continued to rise through February 2003 when the water level began to decline. The water-level decline from February to late June 2003 at Fernandina Beach, Florida, is not evident on hydrographs of wells at St. Marys, indicating the decline resulted from increased local water use. The water level in well N-19 (fig. 16) began to rise in mid-September 2002 and rose steeply until mid-November 2002, when the water level stabilized. Statistical filtering of data from wells N-19 and N-62 (figs. 16 and 17) indicates that the higher water levels during 2003 are not directly related to the Durango Paper Company shutdown.

Lower Floridan Aquifer

Water levels in the Lower Floridan aquifer in well 33D073, located about 0.2 mi southwest of the Durango Paper Company, have been monitored continuously since 2000 (fig. 1*B*). Water levels in the well ranged from about 7 ft below land surface to 10 ft above land surface for the period of record prior to the mill shutdown and showed a water-level rise since mid-2000 (fig. 18). After the shutdown, the water level rose to 7.45 ft above land surface on October 5, 2002, and continued to rise through May 2003. A record-high water level of 25.67 ft above land surface was recorded on April 17, 2003; as of early May 2003, the water level appeared to have stabilized, with a total rise of 18.2 ft from September 2002 to May 2003.

Interaquifer Leakage

At St. Marys, water levels in the confined surficial, upper Brunswick, and Upper and Lower Floridan aquifers showed a pronounced rise following the Durango Paper Company shutdown, and continued to rise through May 2003, indicating interaquifer leakage (fig. 5). Clarke and others (1990) stated that the confining units in the coastal area above and below the Upper Floridan aquifer are not impermeable and may allow movement of water from the underlying and overlying aquifers. The rate of leakage of water from the Upper Floridan aquifer to the Brunswick and surficial aquifers systems depends on the thickness and hydraulic conductivity of the confining units and differences in hydraulic heads between water-bearing zones (Clarke and others, 1990; Gram and Parks, 1986). Leakage can occur in areas of heavy pumping where the cone of depression produces a steepened hydraulic gradient with adjacent aquifers. Hydrographs from wells completed in the confined surficial, upper Brunswick, and Upper and Lower Floridan aquifers at St. Marys are shown in figure 5. Prior to the Durango Paper Company shutdown throughout most of Camden County, hydraulic head increased with depth, with an upward hydraulic gradient from the Floridan aquifer system to the overlying Brunswick and surficial aquifer systems, typical of an aquifer discharge area. At the center of pumping at St. Marys, however, the gradient was reversed. Water levels in the Upper Floridan aquifer during early October at the center of pumping were about 162 ft below NAVD 88 and at a site 0.2 mi west of the center of pumping, water levels in the overlying aquifers ranged from about 2 ft below to 3 ft above NAVD 88, resulting in a downward gradient and the potential for downward leakage from the surficial and Brunswick aquifers to the Upper Floridan aquifer. At present (2004), the rate of leakage has not been determined between the three aquifer systems in the St. Marys area.

Away from the center of pumping, the hydraulic gradient was less pronounced. The head in the upper Brunswick was the lowest observed, indicating the aquifer was a hydrologic "sink" that had the potential to receive flow from both the overlying confined surficial and the underlying Upper Floridan aquifers (fig. 5). Reasons are unclear for the depressed head in the upper Brunswick aquifer. Clarke and West (1998) reported a similar condition near the Savannah River site in Burke County, Georgia, and concluded that the anomalous low head might result from (1) subsurface pinch out of the aquifers, which influences flow patterns in the stream aquifer system; (2) hydraulic connection of the aquifers to river alluvium and associated high ground-water discharge rates that lowers heads; (3) water-level declines as a result of pumpage; or (4) any combination of these reasons. Because the upper Brunswick aquifer is deeply buried and not incised by nearby streams and is not utilized extensively in the Camden County area, the most likely cause of the low-head condition is subsurface pinch out of the aquifer. Clarke (2003) reported the presence of discontinuous permeable layers in the Brunswick aquifer system in coastal Georgia.

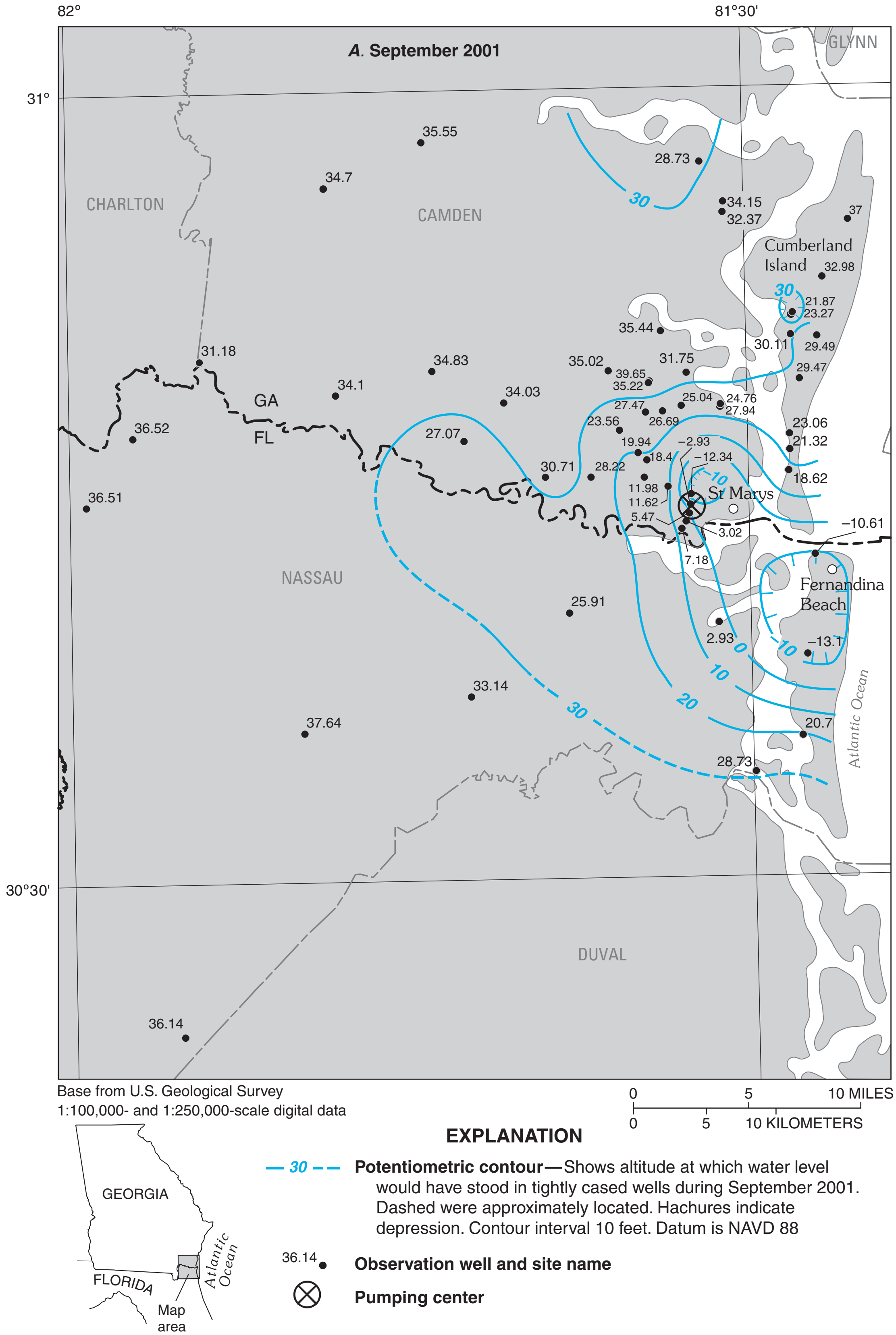


Figure 10. Potentiometric surface of the Upper Floridan aquifer in Camden County, Georgia, and Nassau County, Florida, (*A*) September 2001 and (*B*) September 2002.

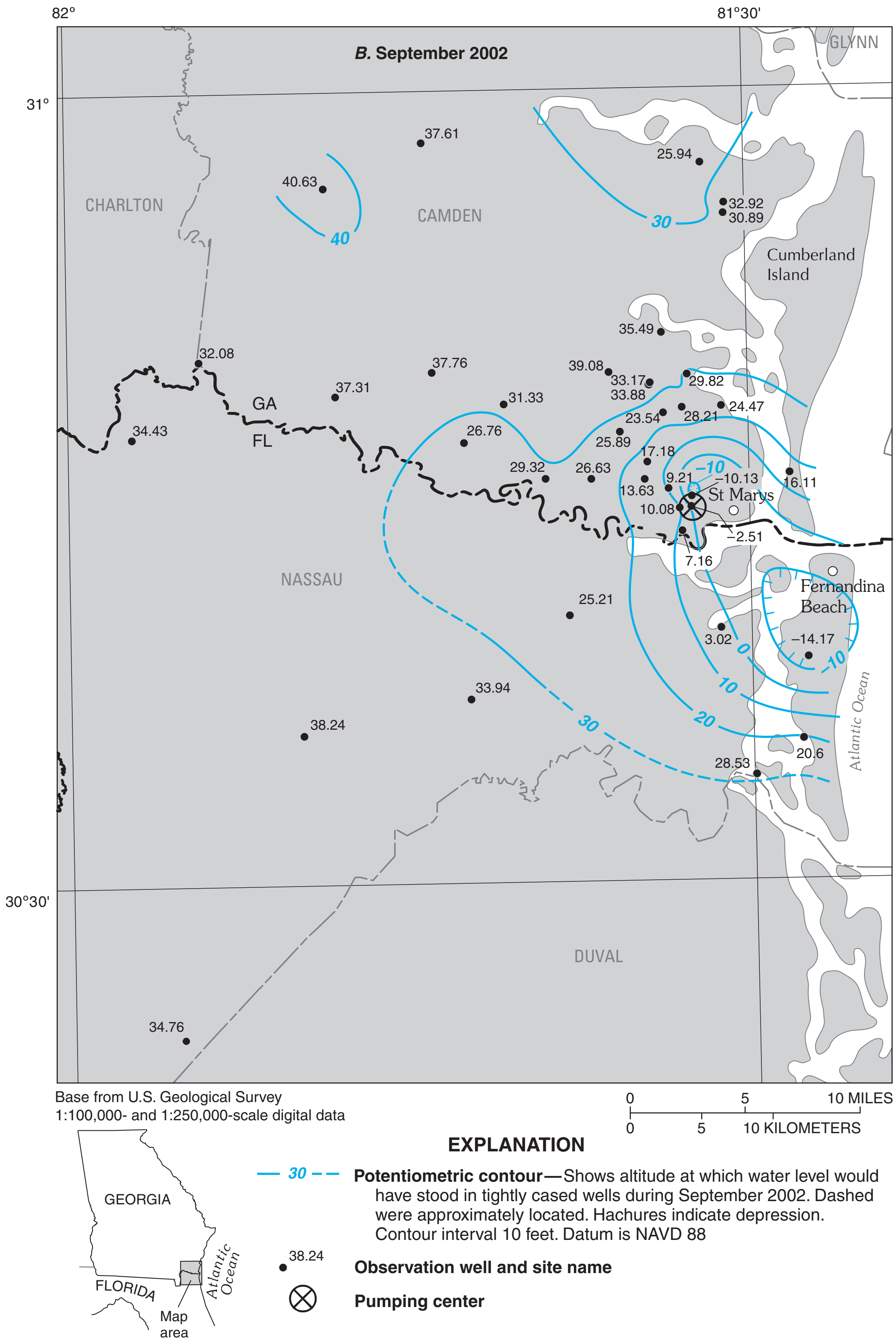


Figure 10. Potentiometric surface of the Upper Floridan aquifer in Camden County, Georgia, and Nassau County, Florida, (*A*) September 2001 and (*B*) September 2002—Continued.

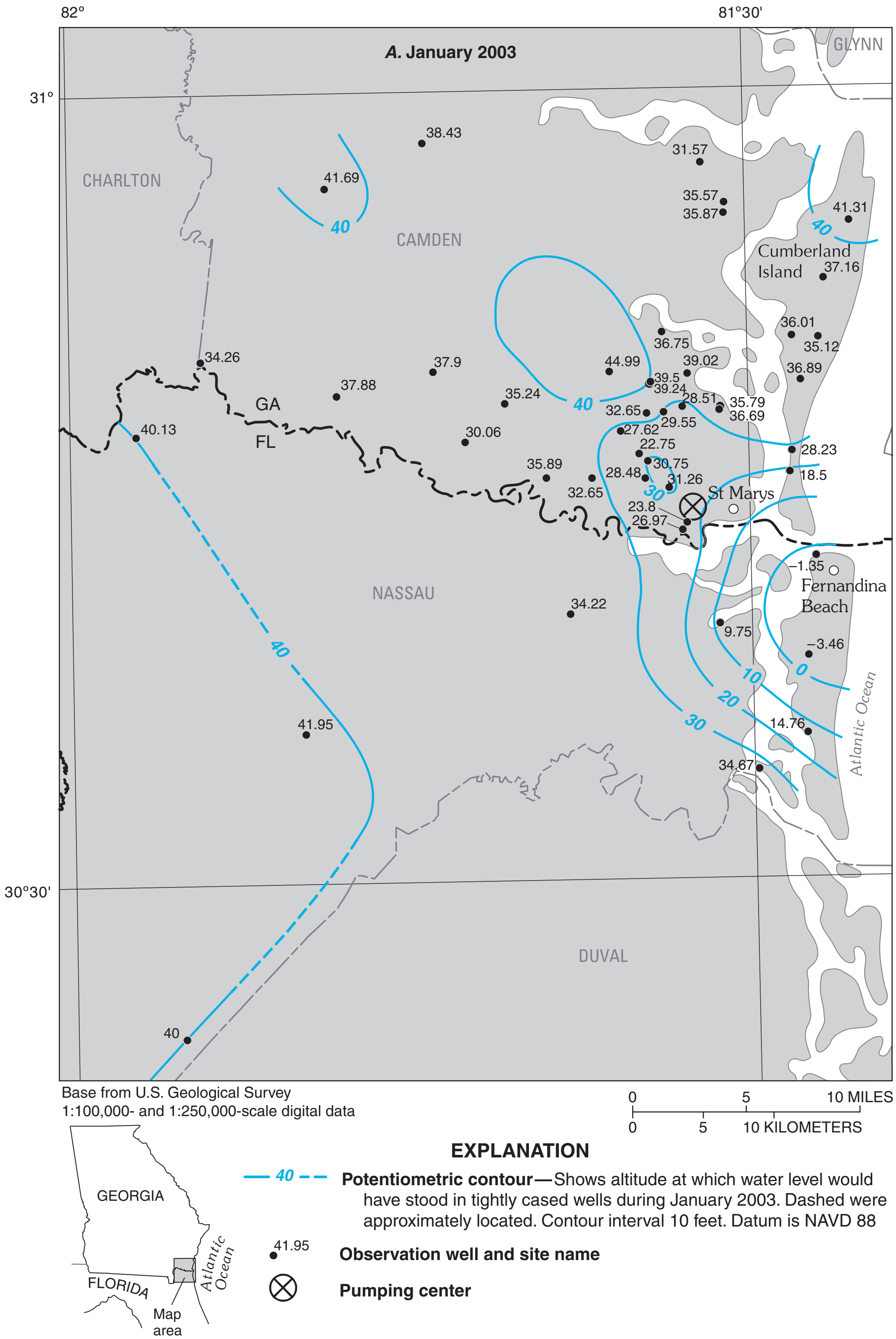


Figure 11. Potentiometric surface of the Upper Floridan aquifer in Camden County, Georgia, and Nassau County, Florida, (*A*) January 2003 and (*B*) May 2003.

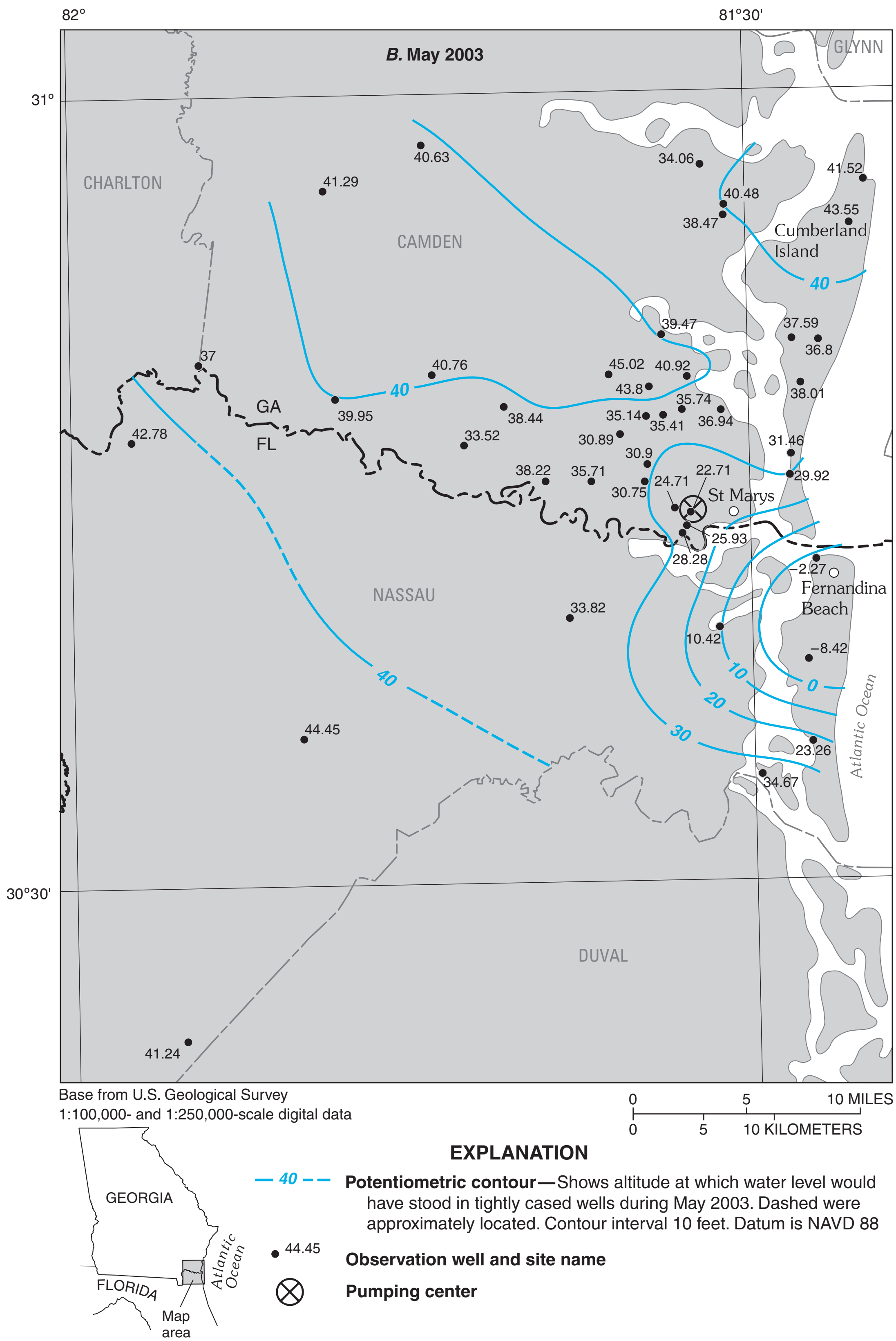


Figure 11. Potentiometric surface of the Upper Floridan aquifer in Camden County, Georgia, and Nassau County, Florida, (*A*) January 2003 and (*B*) May 2003—Continued.

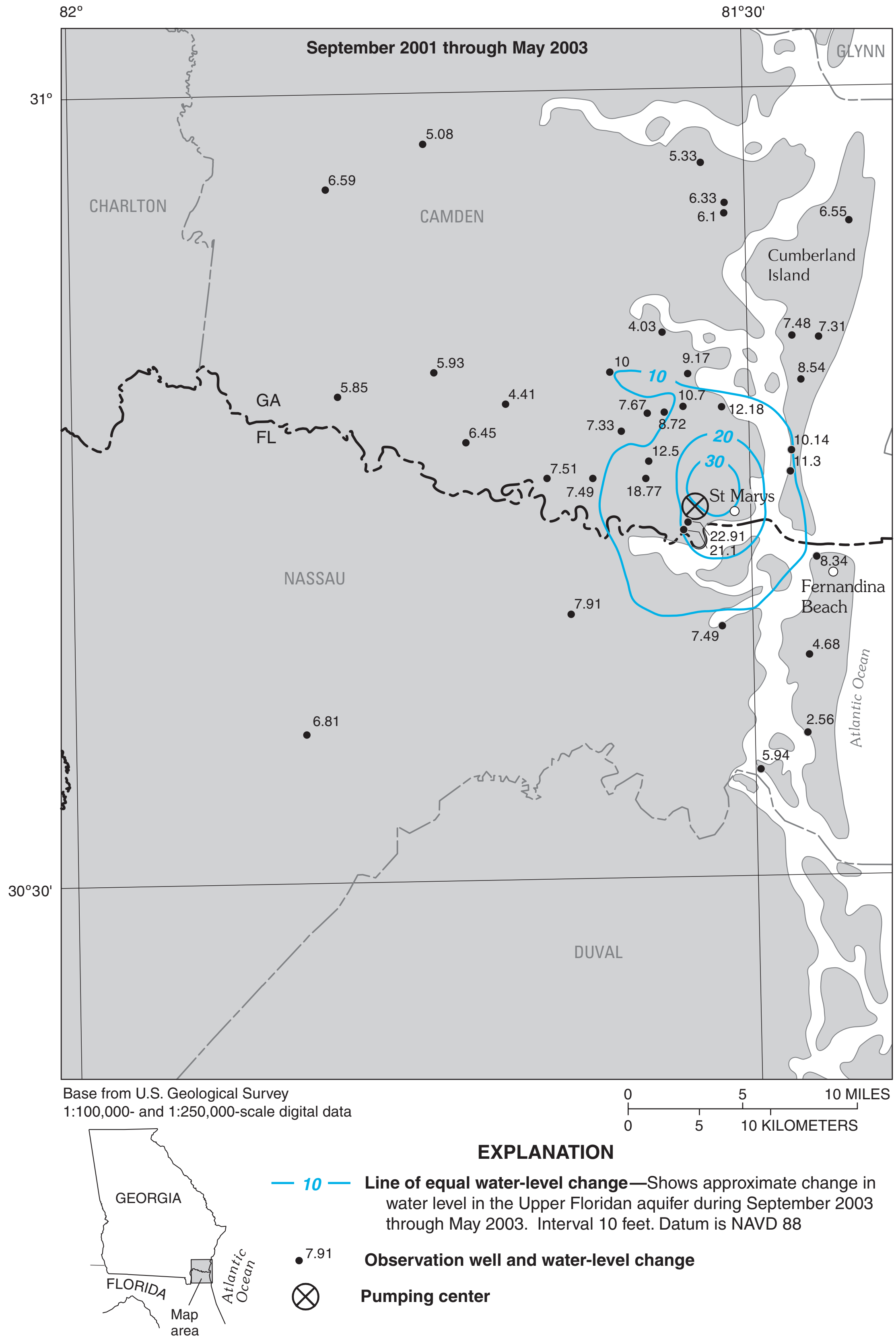


Figure 12. Observed water-level change from September 2001 through May 2003 in wells completed in the Upper Floridan aquifer in Camden County, Georgia, and Nassau County, Florida.

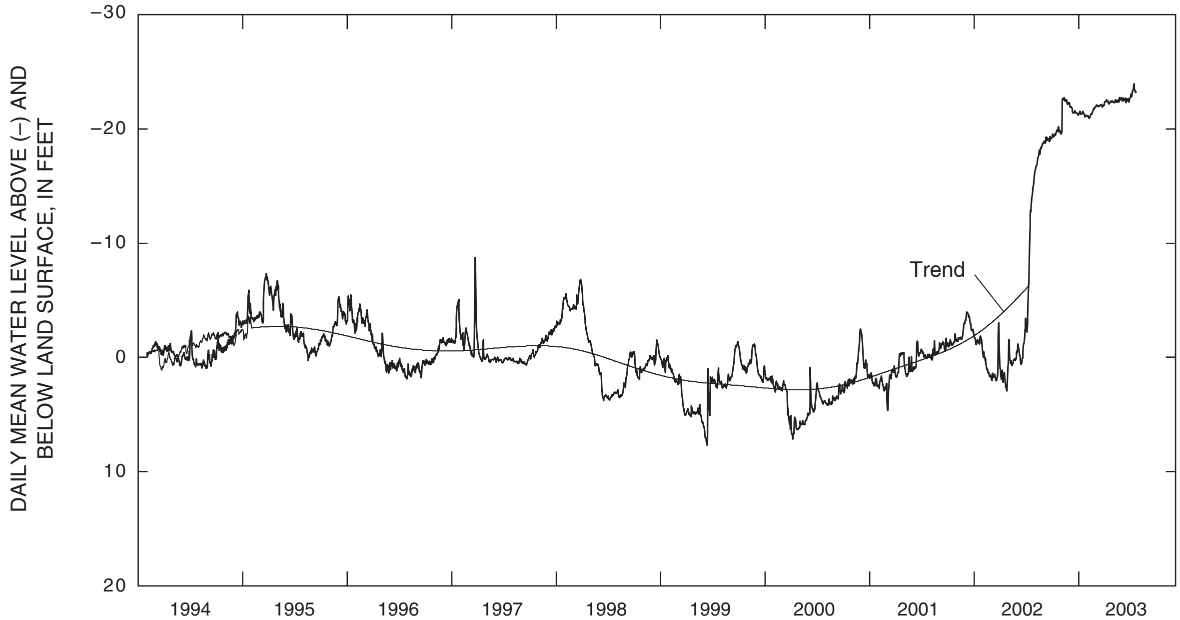


Figure 13. Period-of-record hydrograph for well 33D069 (Upper Floridan aquifer), Camden County, Georgia, 1994–2003.

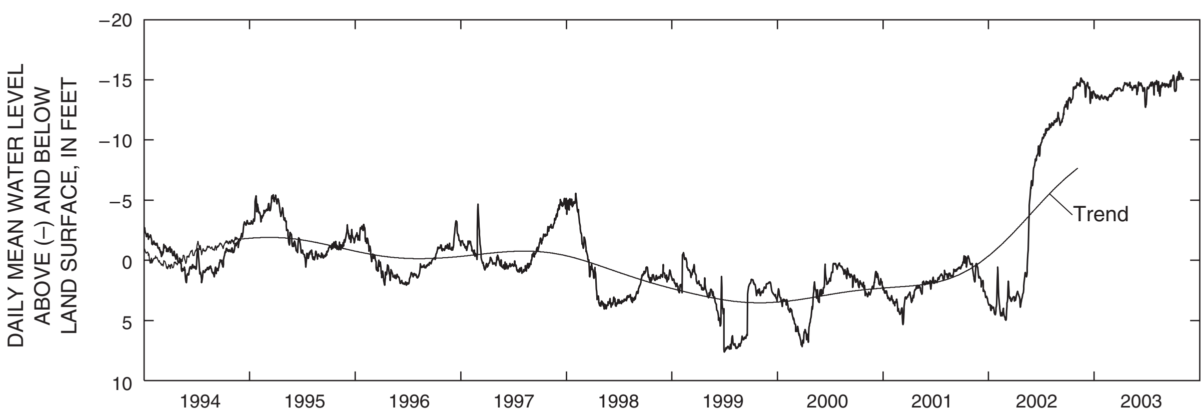


Figure 14. Period-of-record hydrograph for well 33E007 (Upper Floridan aquifer), Camden County, Georgia, 1994–2003.

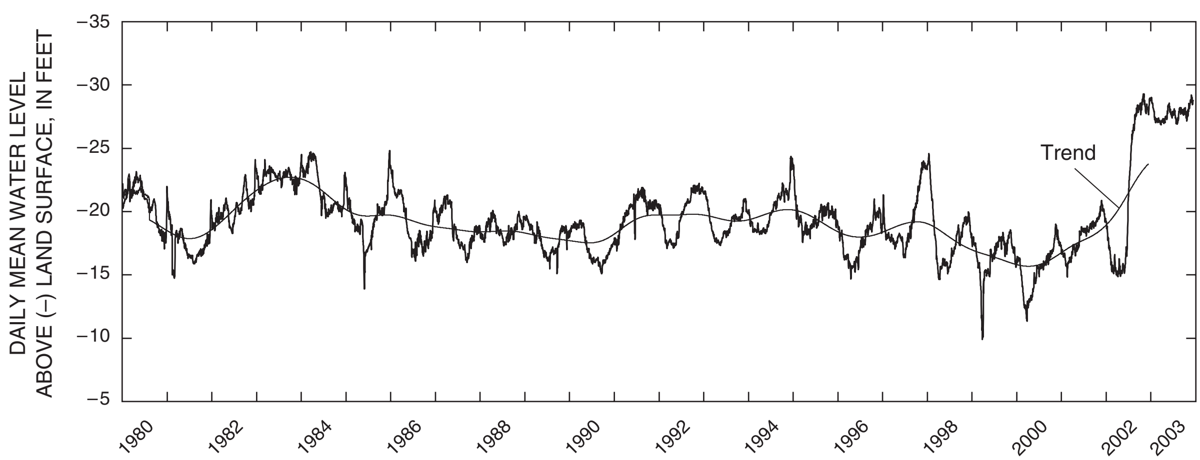


Figure 15. Period-of-record hydrograph for well 33E027 (Upper Floridan aquifer), Camden County, Georgia, 1980–2003.

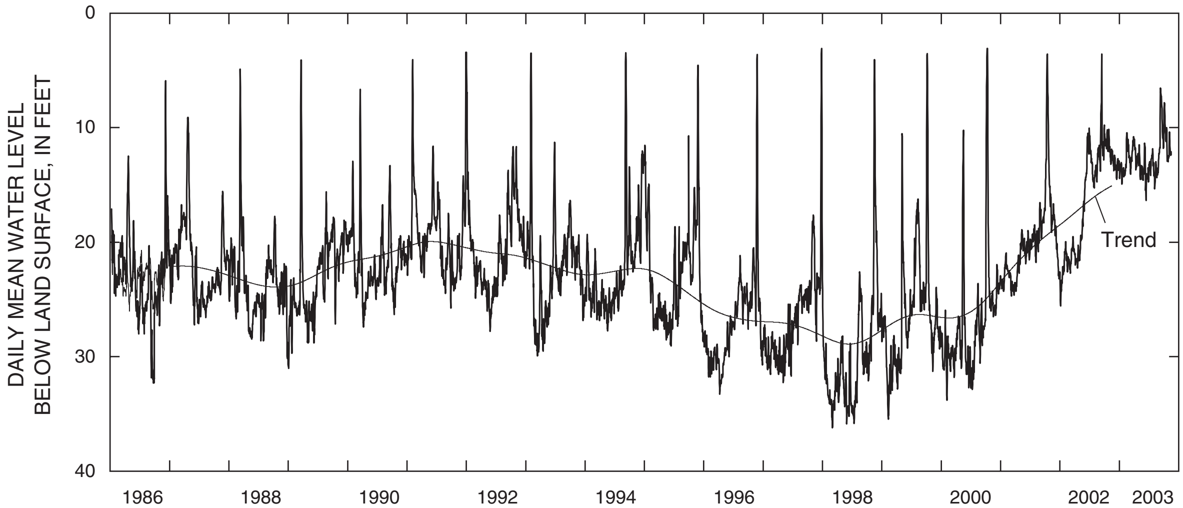


Figure 16. Period-of-record hydrograph for well N-19 (Floridan aquifer system), Nassau County, Florida, 1986–2003.

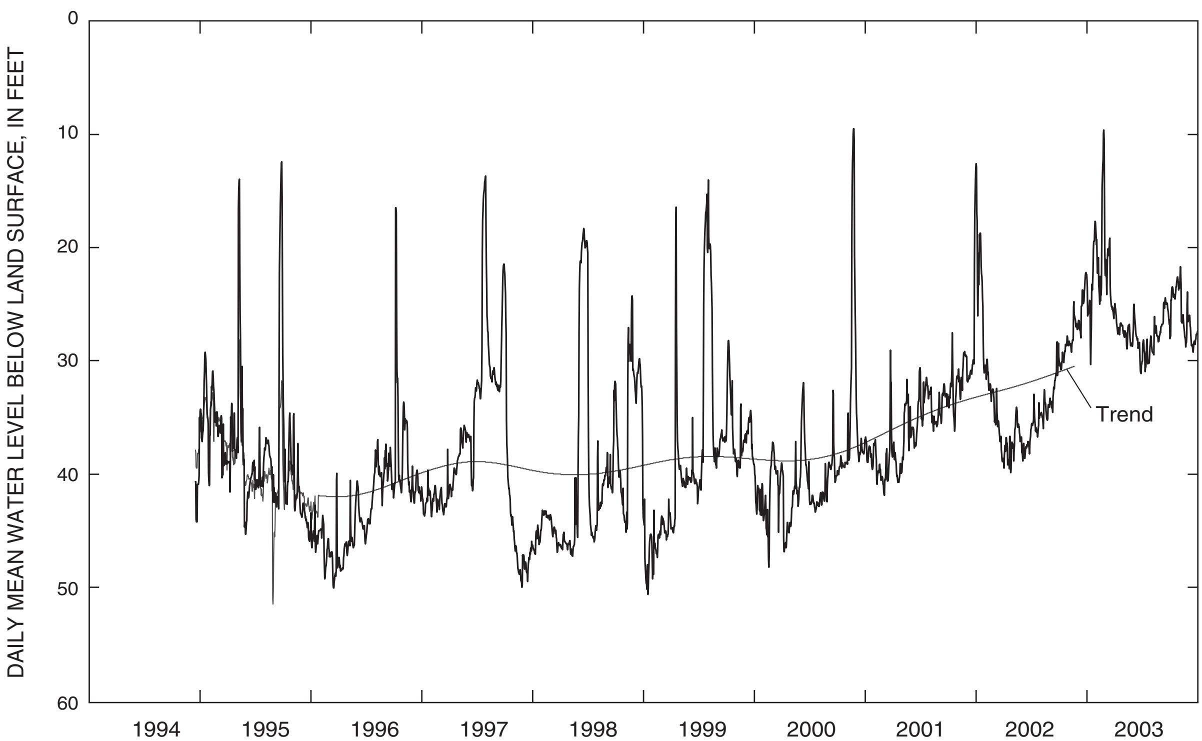


Figure 17. Period-of-record hydrograph for well N-62 (Floridan aquifer system), Nassau County, Florida, 1994–2003.

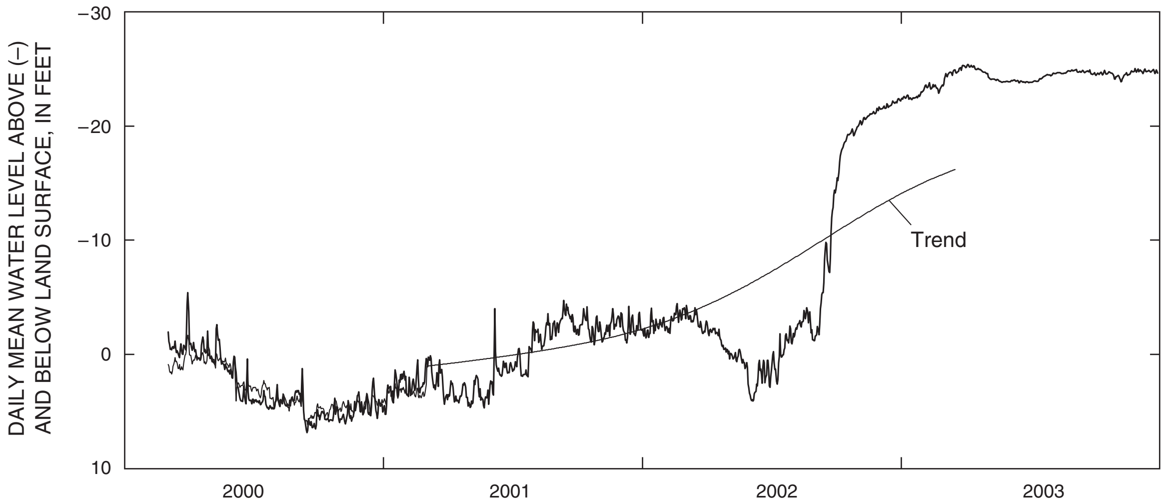


Figure 18. Period-of-record hydrograph for well 33D073 (Lower Floridan aquifer), Camden County, Georgia, 2000–2003.

After the mill ceased operations during October 2002, water levels in all aquifers rose, changing vertical hydraulic gradients and direction of flow between the confined surficial and upper Brunswick aquifers. The head in the upper Brunswick aquifer rose above the head in the confined surficial, reversing the vertical hydraulic gradient between the two aquifers (fig. 5). Prior to the shutdown, water levels in the confined surficial were 2–4 ft higher than in the upper Brunswick aquifer; following the shutdown the water level in the upper Brunswick aquifer rose above the confined surficial aquifer and the head separation between the aquifers was about 10 ft. Thus, the distribution of hydraulic head following the shutdown is more typical of an aquifer discharge area, whereby head increases with depth. Digital flow modeling could be used to estimate confining unit leakance rates and to study local interaquifer connection.

Chloride Concentrations in Camden County

Chloride concentrations in the Upper Floridan aquifer have been monitored periodically in the Camden County area since the 1960s and annually since 1994 (Leeth and others, 2003). Chloride concentrations in the Upper Floridan aquifer in Camden County do not exceed the State and Federal drinking-water standard of 250 mg/L (Georgia Environmental Protection Division, 1997; U.S. Environmental Protection Agency, 2000). Chloride concentrations in water samples collected from a recently drilled deep test well at St. Marys, Georgia, indicate that the chloride concentration in the Floridan aquifer system remained near background levels (from 30 to 50 mg/L) to a depth of 2,060 ft below land surface, at which point the chloride concentration increased to 350 mg/L (St. Johns River Water Management District, 2002). Water samples from Upper Floridan aquifer wells collected during this study (from September 2002 to May 2003) (table 3) had chloride concentrations that ranged from 23 to 43 mg/L, which is considered in the background, or uncontaminated, range (Rose, 2001; 2002). Water from three wells, however—two at Durango Paper Company and one unused City of St. Marys well—had chloride concentrations above the background range, but were still within the drinking-water limit of 250 mg/L (table 3). The chloride concentration in well 33D061 (Durango Paper Company well) ranged from 48.7 mg/L during1988 to 184 mg/L during 2000 (fig. 19). The other two wells with elevated chloride concentrations could be only sampled once during the study period. The unused City of St. Marys well 33D055 had a chloride concentration of 156.4 mg/L, and the Durango Paper Company well 33D048 had a chloride concentration of 74.9 mg/L. The source has not been determined for the elevated chloride concentrations in these wells.

Saltwater intrusion into the Upper Floridan aquifer is a major concern in the coastal area. At Brunswick, Georgia, saltwater intrusion is the result of upward movement of highly saline water from deeper zones (Clarke and others, 1990); on the north end of Hilton Head Island, South Carolina, saltwater intrusion is the result of lateral encroachment of sea water attributed to the reduction of pressure in the freshwater zones (Clarke and others, 1990). The depth of the aquifer (about 560 ft) and the presence of freshwater in the aquifer as far offshore as 70 mi make lateral saltwater encroachment unlikely (Johnston and others, 1982). Although it is possible that the saltwater is derived from deeper zones, at St. Marys, the presence of freshwater in the aquifer to a depth of 2,060 ft makes upward movement of saline water unlikely. A possible mechanism for elevated chloride concentration is vertical movement along the annular space of the well bore, whereby saline marsh water moves downward into the Upper Floridan aquifer. Changes in chloride concentration in well 33D061 (fig. 19) support the hypothesis of saltwater movement along the annular well space.

Table 3. Water-quality data from selected wells in Camden County, Georgia, September 2002–May 2003.

[mg/L, milligrams per liter; µS/cm, microseimens per centimeter at 25 degrees Celsius; do., ditto; UF, Upper Floridan aquifer; FAS, Floridan Aquifer system; LF, Lower Floridan; —, data not available]

Well name	Date sampled	Chloride dissolved (mg/L)	Specific conductance (µS/cm)	Sulfate dissolved (mg/L)	Aquifer code
31E001	Jan. 30, 2003	31.76	731.72	30.30	UF
do.	May 15, 2003	29.92	741.69	162.51	UF
32E031	Jan. 30, 2003	35.85	725.82	36.22	UF
32E033	Sept. 17, 2002	30.23	534	—	UF
do.	Jan. 30, 2003	34.02	443.4	72.07	UF
do.	May 12, 2003	41	387	77	UF
do.	May 13, 2003	42.37	403.41	83.67	UF
32F008	Jan. 30, 2003	42.8	707.9	57.7	UF
do.	May 15, 2003	37.12	692.96	133.11	UF
33D006	Jan. 29, 2003	33.15	728.72	22.04	UF
33D048	Jan. 29, 2003	74.91	857.71	14.46	FAS
33D050	Jan. 29, 2003	32.01	689.44	25.19	FAS
do.	May 13, 2003	34.73	733.25	166.13	FAS
33D054	Sept. 16, 2002	30.88	709	—	UF
do.	Jan. 29, 2003	31.27	692.14	15.94	UF
do.	May 13, 2003	33.31	723.34	160.64	UF
do.	May 14, 2003	32	718	160	UF
33D055	Jan. 29, 2003	156.42	569.51	4.8	UF
33D058	Jan. 29, 2003	31.65	728.14	17.7	UF
33D061	Sept. 17, 2002	175.29	1150	—	UF
do.	Jan. 29, 2003	128.65	1026.29	4.81	UF
do.	May 14, 2003	110	988	170	UF
do.	May 14, 2003	143.3	1027.46	182.51	UF
33D073	Sept. 12, 2002	30.16	971.93	50	LF
do.	Sept. 12, 2002	27.23	829.83	50	LF
do.	Sept. 12, 2002	26.9	926.62	50	LF
do.	Sept. 12, 2002	26.72	855.27	50	LF
do.	May 16, 2003	29.24	629.43	212.48	LF
33E008	Jan. 30, 2003	23.34	679.67	43.75	UF
33E027	May 12, 2003	32.37	674.7	146.22	UF
33E046	Jan. 29, 2003	37.47	731.82	28.62	UF
do.	May 14, 2003	35.33	673.91	161.18	UF
33E049	Sept. 17, 2002	31.19	704	—	UF
do.	Jan. 30, 2003	32.33	637	21.2	UF
do.	May 12, 2003	33.00	720.00	160.00	UF
do.	May 12, 2003	37.43	747.13	170.47	UF
33E050	Jan. 29, 2003	34.07	724.09	27.18	UF

Table 3. Water-quality data from selected wells in Camden County, Georgia, September 2002–May 2003.—Continued

[mg/L, milligrams per liter; µS/cm, microseimens per centimeter at 25 degrees Celsius; do., ditto; UF, Upper Floridan aquifer; FAS, Floridan Aquifer system; LF, Lower Floridan; —, data not available]

Well name	Date sampled	Chloride dissolved (mg/L)	Specific conductance (µS/cm)	Sulfate dissolved (mg/L)	Aquifer code
33E051	Jan. 27, 2003	34	714.88	30.43	UF
do.	May 12, 2003	35.13	719.76	149.12	UF
33E052	Jan. 27, 2003	35.28	726.66	26.66	UF
do.	May 12, 2003	35.62	736.02	161.98	UF
33E053	Sept. 16, 2002	33.32	698	—	UF
do.	Jan. 27, 2003	34.89	713.63	34.12	UF
do.	May 12, 2003	36	711	150	UF
do.	May 12, 2003	36.11	739.93	163.62	UF
33E115	Jan. 29, 2003	34	729.25	24.12	UF
do.	May 14, 2003	33.39	712.65	170.91	UF
33F002	Jan. 27, 2003	38.4	673.35	59.46	UF
do.	May 14, 2003	36.16	501.4	92.24	UF
33F003	Jan. 27, 2003	39.51	481.49	71.08	UF
do.	May 14, 2003	43.6	471.66	79.95	UF
33F017	Jan. 27, 2003	39.5	674.67	52.92	UF
do.	May 14, 2003	41.6	690.97	139.11	UF
34E001	Jan. 28, 2003	31.82	738.48	19.79	UF
do.	May 13, 2003	33	723	160	UF
do.	May 13, 2003	30.61	732.56	160.07	UF
34E003	Jan. 28, 2003	31.51	740.41	219.42	UF
do.	May 13, 2003	31.7	697.9	157.91	UF
34E010	Jan. 28, 2003	32.27	731.75	11.94	UF
34E011	Jan. 28, 2003	35.92	612.4	46.45	UF
34E012	Jan. 28, 2003	36.09	697.59	49	UF
34E013	Jan. 28, 2003	35.93	710.05	40.11	UF
do.	May 12, 2003	33.66	738.12	177.52	UF
34E014	Jan. 28, 2003	34.91	711.75	31.44	UF
do.	May 13, 2003	37.99	711.86	149.71	UF
34F014	Jan. 28, 2003	36.88	700.17	40.6	UF

During 1982–2001, concentrations generally increased in well 33D061, a period during which the vertical hydraulic gradient was downward due to pumpage at the Durango Paper Company. Since 2001, concentrations in this well generally decreased, corresponding to changes in the direction and magnitude of the hydraulic gradient between the Upper Floridan aquifer and overlying unconfined surficial aquifer. The unconfined surficial aquifer is in contact with saline water from the nearby salt marsh. As the hydraulic gradient decreased, less saline water moved vertically along the annular space and into the Upper Floridan and, thus, concentrations decreased. Borehole geophysical data could verify the integrity of the grout seal in the annular space of the wells; however, it may be difficult to obtain access to these wells because of installed turbine pumps and high borehole flow rates. In addition, water-chemistry data could be used to determine the source of the saltwater.

Boxplots of water samples collected prior to (1969–September 2002) and after the mill shutdown (January–May 2003) are shown in figure 20. Except for wells 33D061, 33D055, and 33D048, chloride and sulfate concentrations have not changed appreciably since the reduction in ground-water withdrawal.

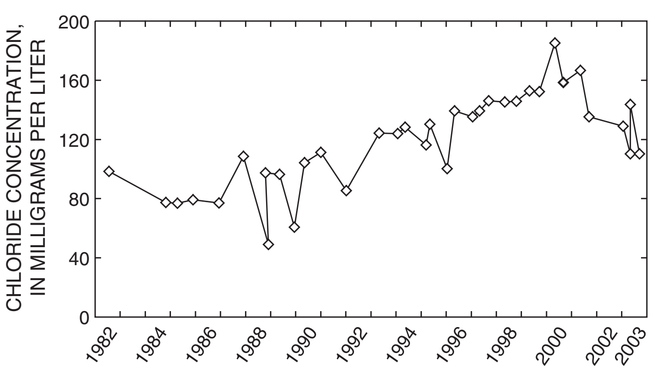


Figure 19. Chloride concentration in water from the Upper Floridan aquifer at well 33D061, Durango Paper Company, Camden County, Georgia, 1982–2003.

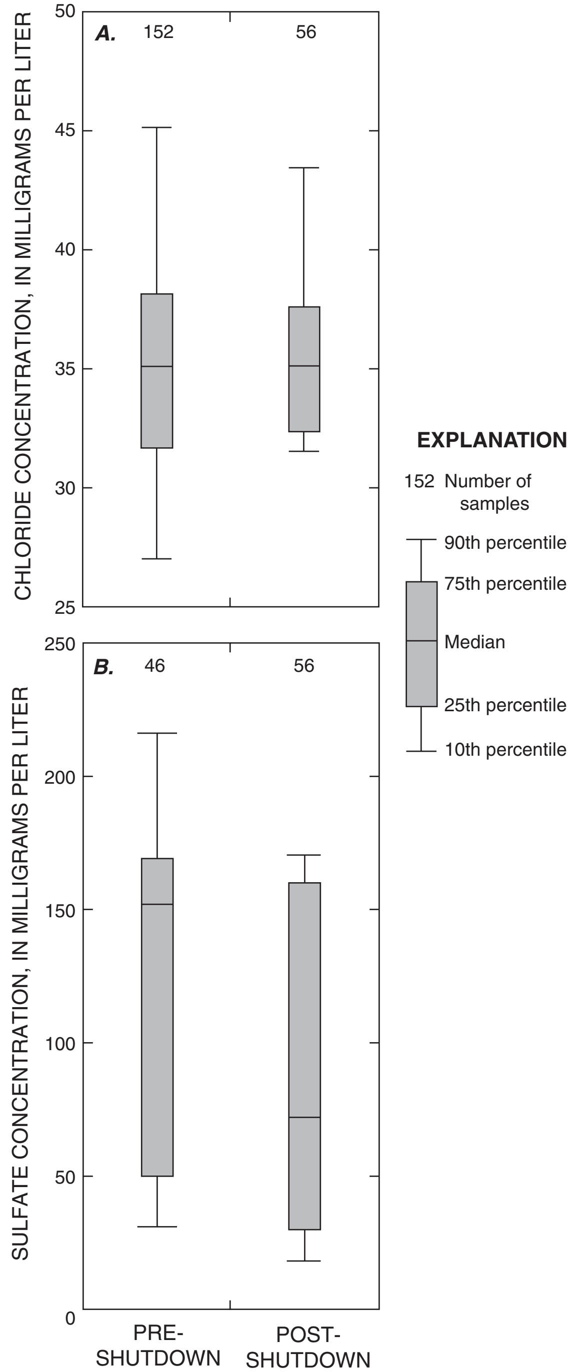


Figure 20. Boxplots of (*A*) chloride and (*B*) sulfate concentration in water from the Upper Floridan aquifer in Camden County, Georgia, prior to and after the Durango Paper Company shutdown, September 2002–May 2003.

Summary and Conclusions

During October 2002, the Durango Paper Company (formally Gillman Paper Company) at St. Marys, Georgia, shutdown paper-mill operations; the shutdown resulted in decreased ground-water withdrawal in Camden County by 35.6 million gallons per day. The reduction in withdrawal affected water levels in the Floridan aquifer system and the overlying surficial and Brunswick aquifer systems. As a result, many wells in the St. Marys area began to flow for the first time since the mill began operations during 1941.

The most prominent changes in the potentiometric surface of the Upper Floridan aquifer since the mill shutdown have been the disappearance of the cone of depression centered at St. Marys, Georgia, the decreased Fernandina Beach cone, and the development of the 40-foot (ft) ground-water mound northwest of St. Marys. The water level in the Upper Floridan aquifer at St. Marys ranged from about 10 ft below land surface to 10 ft above land surface during September 2001, and by May 2003 had risen to about 30 ft, which is 20 ft lower than predevelopment water levels. The water-level changes resulting from the mill shutdown are greatest in the St. Marys area and are less pronounced and more difficult to distinguish from regional trends the farther away from the center of pumping. Analysis of continuous water-level data from wells in coastal Georgia and Nassau County, Florida, indicates a regional upward water-level trend in many wells in the Upper Floridan aquifer beginning during 1999–2000. This trend became more pronounced during early October 2002 and continued through May 2003. Water-level rises resulting from the Durango Paper Company shutdown are easy to discern in wells located at St. Marys; however, for wells located farther away in Glynn County, Georgia, and Nassau County, Florida, the response to the mill shutdown is not discernible because of the overall regional water-level rise and the effects of ground-water withdrawal. Since the shutdown, water levels at the mill have risen about 140 ft and are now at about 30 ft above NAVD 88.

At St. Marys, the water levels in the Lower Floridan, Upper Floridan, upper Brunswick, and confined surficial aquifers began rising during early October 2002 after the mill shutdown and continued rising through May 2003, indicating interaquifer leakage. Throughout Camden County, the vertical hydraulic gradient is upward from the Floridan aquifer system to the overlying Brunswick and surficial aquifer systems. When the mill was operating, however, water levels in the Upper Floridan aquifer at the center of pumping ranged from 68 to 235 ft below NAVD 88, and water levels in the overlying aquifers ranged from about 2 ft below to 3 ft above NAVD 88, reversing the vertical hydraulic gradient within the cone of depression. This reverse in vertical gradient causes decreasing upward leakage from the Upper Floridan aquifer and creates the potential for downward leakage from the surficial and Brunswick aquifers to the Upper Floridan aquifer. At present (2004), the rate of leakage has not been determined for the three aquifer systems in the St. Marys area. Typical head relations in the four different zones being monitored at St. Marys were: the hydraulic head was highest in the Lower Floridan aquifer followed by the Upper Floridan aquifer, the confined surficial aquifer, and the upper Brunswick aquifer. After the mill ceased operations during October 2002, the hydraulic head separation between the aquifers increased and the head in the upper Brunswick rose above the head in the confined surficial, reversing the vertical hydraulic gradient. Digital modeling could be used to estimate confining unit leakance rates and to study local interaquifer connection.

Chloride concentrations in water from the Upper Floridan aquifer in Camden County do not exceed the State and Federal drinking-water standards of 250 milligrams per liter (mg/L). Concentrations in most of the wells sampled during this study (from September 2002 to May 2003) ranged from 30 to 50 mg/L, which is considered as the range for background concentrations in the Upper Floridan aquifer. Three wells in the St. Marys area, however, had chloride concentrations above the background range. Well 33D061 (Durango Paper Company well) has had an increase in chloride concentration since sampling began during 1982; however, these concentrations are below the drinking-water limit of 250 mg/L. The source has not been determined for the elevated chloride concentrations in this well, and chloride concentrations have decreased slightly since the Durango Paper Company shutdown. The depth of the aquifer (about 560 ft) and the presence of freshwater in the aquifer as far offshore as 70 miles makes lateral saltwater encroachment unlikely. In addition, the presence of freshwater in the aquifer to a depth of 2,060 ft makes upward movement of saline water unlikely. A possible mechanism for elevated chloride concentration is vertical movement along the annular space of the well bore, whereby saline marsh water moves downward into the Upper Floridan aquifer. Changes in chloride concentration in well 33D061 support the hypothesis of saltwater movement along the annular well space. Overall chloride concentrations in the Upper Floridan aquifer did not change appreciably after the reduction in ground-water withdrawal, and the sulfate concentration remained about the same. Borehole geophysical logging techniques could be used to determine if saltwater is entering the wells from the marsh.

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