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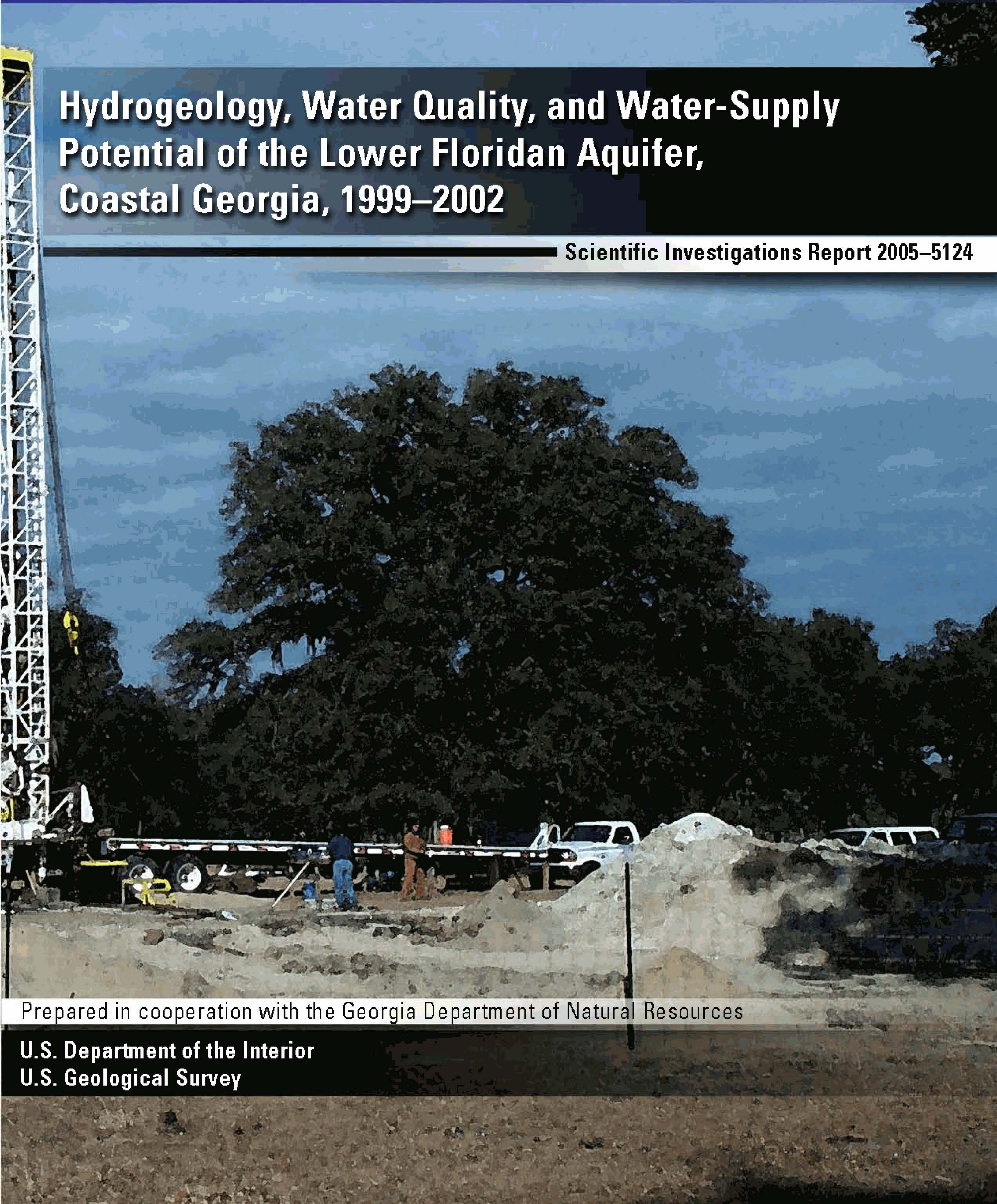
Hydrogeology, Water Quality, and Water-Supply Potential of the Lower Floridan Aquifer, Coastal Georgia, 1999–2002

Scientific Investigations Report 2005–5124



Prepared in cooperation with the Georgia Department of Natural Resources

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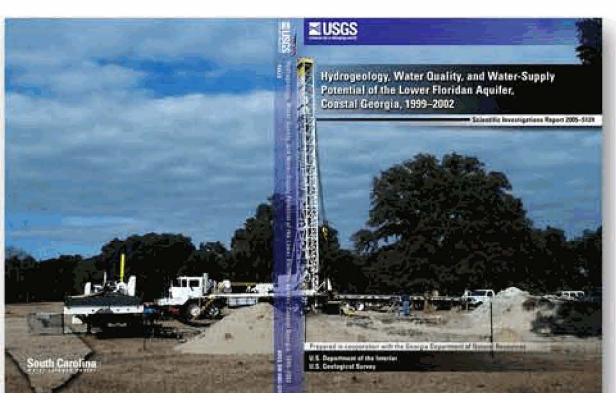

Cover Image:
Drill rig at the Shellmans Bluff site, McIntosh County, Georgia, November 2000.
Photography:
W. Fred Falls, U.S. Geological Survey
Design:
James R. Douglas, U.S. Geological Survey

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By W. Fred Falls, Larry G. Harrelson, Kevin J. Conlon, and Matthew D. Petkewich

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Conversion Factors

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Transmissivity	
foot squared per day (ft^2/d)	0.0929	meter squared per day

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

°C = (°F – 32) / 1.8

Datums

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88) unless otherwise noted; horizontal coordinate information is referenced to the North American Datum of 1927 (NAD 27).

In this report, altitude refers to distance above and below NAVD 88.

Acronyms and Abbreviations

AMS	accelerator mass spectrometer
cps	counts per second
CSSI	Coastal Sound Science Initiative
DIC	dissolved inorganic carbon
ft	feet
FAS	Floridan aquifer system
FL	Florida
FPZ	Fernandina permeable zone
GA	Georgia
GaEPD	Georgia Environmental Protection Division
LFA	Lower Floridan aquifer
µg/L	micrograms per liter
µS/cm	microsiemens per centimeter at 25 degrees Celsius
mg/L	milligrams per liter
Mgal/d	million gallons per day
PDB	Peedee Belemnite
pmc	percent modern carbon
SC	South Carolina
SCDHEC	South Carolina Department of Health and Environmental Control
SJRWMD	St Johns River Water Management District
TDS	total dissolved solids
TU	tritium unit
UFA	Upper Floridan aquifer
USGS	U.S. Geological Survey
V-SMOW	Vienna-Standard Mean Ocean Water

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Abstract

The hydrogeology and water quality of the upper permeable and Fernandina permeable zones of the Lower Floridan aquifer were studied at seven sites in the 24-county study area encompassed by the Georgia Coastal Sound Science Initiative. Although substantially less than the Upper Floridan aquifer in coastal Georgia, transmissivities for the Lower Floridan aquifer are in the same range as other water-supply aquifers in Georgia and South Carolina and could meet the needs of public drinking-water supply. Water of the upper permeable zone of the Lower Floridan aquifer exceeds the Federal secondary drinking-water standards for sulfate and total dissolved solids at most coastal Georgia sites and the Federal secondary drinking-water standard for chloride at the Shellman Bluff site.

The top of the Lower Floridan aquifer correlates within 50 feet of the previously reported top, except at the St Simons Island site where the top is more than 80 feet higher. Based on the hydrogeologic characteristics, the seven sites are divided into the northern sites at Shellman Bluff, Richmond Hill, Pembroke, and Pineora; and southern sites at St Marys, Brunswick, and St Simons Island. At the northern sites, the Lower Floridan aquifer does not include the Fernandina permeable zone, is thinner than the overlying Upper Floridan aquifer, and consists of only strata of the middle Eocene Avon Park Formation. Transmissivities in the Lower Floridan aquifer are 8,300 feet squared per day at Richmond Hill and 6,000 feet squared per day at Shellman Bluff, generally one tenth the transmissivity of the Upper Floridan aquifer at these sites. At the southern sites, the upper permeable zone of the Lower Floridan aquifer is thicker than the Upper Floridan aquifer and consists of porous limestone and dolomite interbedded with nonporous strata of the middle Eocene Avon Park and early Eocene Oldsmar Formations. Transmissivities for the upper permeable zone of the Lower Floridan aquifer are 500 feet squared per day at the St Simons Island site and 13,000 feet squared per day at the St Marys site. The Lower Floridan aquifer at the Brunswick and St Marys sites includes the Fernandina permeable zone, which consists of saltwater-bearing dolomite.

Hydrographs of Coastal Sound Science Initiative wells and other nearby wells open to the Upper Floridan aquifer, and the upper permeable and Fernandina permeable zones of the Lower Floridan aquifer have similar trends. Water levels in wells open to the Upper and Lower Floridan aquifers are below land surface at the northern sites and the St Simons Island site, and above land surface at the Brunswick and St Marys sites, as of January 1, 2004.

Freshwater is present in the Lower Floridan aquifer at Pineora, Pembroke, and St Marys, and from 1,259 to 1,648 feet below land surface at Brunswick. Slightly saline water is present in the Lower Floridan aquifer at Richmond Hill, Shellman Bluff, St Simons Island, and from 1,679 to 1,970 feet below land surface in well 34H495 at Brunswick. The upper permeable zone of the Lower Floridan aquifer contains bicarbonate water at the Pembroke site, sulfate-bicarbonate water at the Brunswick site, and sulfate water at the St Simons Island, Shellman Bluff, St Marys, and Richmond Hill sites. The bicarbonate, sulfate-bicarbonate, and sulfate waters are saturated relative to calcite and dolomite, and undersaturated with gypsum and anhydrite.

The Fernandina permeable zone in well 34H495 includes moderately saline water, very saline water, and brine. The Fernandina permeable zone of the Lower Floridan aquifer beneath downtown Brunswick contains chloride water that is slightly undersaturated to saturated with gypsum and anhydrite. Concentrations of total dissolved solids, sulfate, and chloride exceeded the Federal secondary drinking-water standards. The chloride-contaminated plumes beneath downtown Brunswick would require at least a 12- to 20-percent contribution of very saline water from the Fernandina permeable zone to result in observed concentrations in the Upper Floridan aquifer.

Waters from the upper permeable zone of the Lower Floridan aquifer at the St Marys, Brunswick, Richmond Hill, and Pembroke sites had carbon-14 concentrations and stable oxygen and hydrogen isotopic compositions that were similar to waters from the Upper Floridan aquifer at these respective sites. The data indicate that waters in both aquifers at a specific well site probably entered the recharge area under similar climatic conditions and, therefore, could have similar ages. Two freshwater samples from the upper permeable zone of the Lower Floridan aquifer at Pembroke and St Marys have

strontium isotope ratios that fall in the range of Oligocene or Miocene seawaters. Four ground-water samples from the upper permeable zone of the Lower Floridan aquifer at Shellman Bluff, Richmond Hill, and St Simons Island, and St Marys well 33D074 have strontium isotope ratios in the range of Eocene seawater.

Introduction

Since the 1880s, coastal counties in Georgia (GA) and adjacent coastal counties in South Carolina (SC) and Florida (FL) have developed the freshwater resource of the Floridan aquifer system for municipal and industrial water supplies. This development has resulted in substantial water-level declines, particularly in the Upper Floridan aquifer, and in documented saltwater intrusion in Beaufort County, SC, Glynn County, GA, and Duval County, FL (Gill and Mitchell, 1979; Krause and Randolph, 1989; Clarke and others, 1990; Smith, 1993; Spechler, 1994; Landmeyer and Belval, 1996; Phelps and Spechler, 1997; Krause and Clarke, 2001). For more than a century, the abundant yield of high-quality water from the Upper Floridan aquifer has provided most of the water pumped in the coastal counties of Georgia, and until the late 1990s, generally limited the need to explore the Lower Floridan aquifer as a water supply (Miller, 1986; Krause and Randolph, 1989; Clarke and others, 1990; Clarke and Krause, 2000).

The Coastal Sound Science Initiative (CSSI) was implemented by the Georgia Environmental Protection Division (GaEPD) and coordinated with the South Carolina Department of Health and Environmental Control as a series of scientific and feasibility studies to support the development of Georgia's final water-management strategy for mitigating saltwater intrusion and the development of water-resource alternatives to the Upper Floridan aquifer in 24 coastal counties in Georgia, Beaufort and Jasper Counties, SC, and Duval and Nassau Counties, FL (Georgia Environmental Protection Division, 1997; fig. 1). As part of the CSSI, the State of Georgia funded an investigation in cooperation with the U.S. Geological Survey (USGS) to assess the hydrogeology of the Lower Floridan aquifer and its water quality in the 24-county study area of coastal Georgia from 1999 to 2002.

Several previous investigations described the hydrogeology of the permeable zones of the Floridan aquifer system in the 24 coastal counties of the CSSI study area (Miller, 1986; Krause and Randolph, 1989; Clarke and others, 1990); however, Miller (1986) was the only investigator to map the altitude of the top of the Lower Floridan aquifer in all 24 coastal counties in Georgia. For this investigation, the USGS designed the construction of wells to evaluate the hydrogeology and water quality of the Lower Floridan aquifer, as delineated by Miller (1986). The upper permeable zone of the Lower Floridan aquifer was examined as a potential water supply. The Fernandina permeable zone of the Lower Floridan aquifer is a known saltwater-bearing zone beneath parts of Glynn County, GA, and Duval County, FL, and is a potential saltwater source for contamination of freshwater zones of the Upper and Lower Floridan aquifers (fig. 2). This investigation examined the water quality and extent of the Fernandina permeable zone beneath the coastal counties of Georgia.

Purpose and Scope

The purpose of this report is to document the results of a hydrogeologic field investigation of the Lower Floridan aquifer and to compare the Lower Floridan aquifer to the Upper Floridan aquifer as an alternative water supply in the CSSI 24-county study area. These results provide GaEPD and other water managers in the study area with field verification of the hydrogeology and the water quality of the upper permeable and Fernandina permeable zones of the Lower Floridan aquifer beneath the 24-county study area. The results also support the USGS efforts to develop ground-water flow and solute-transport models of the study area, which are integral to help the State develop Georgia's final water-management strategy for the water resources of the Floridan aquifer system. This investigation makes an important contribution to the understanding of coastal-zone issues of water use and saltwater intrusion that affect water resources in Georgia and elsewhere in the Nation (U.S. Geological Survey, 1999).

This report summarizes the hydrogeology, hydraulic properties, and water quality for the Upper Floridan aquifer and the upper permeable and Fernandina permeable zones of the Lower Floridan aquifer, based on data collected from 10 wells at seven sites in the CSSI 24-county study area (fig. 1). The hydrogeology of the Floridan aquifer system, as delineated by Miller (1986), was used to design wells for investigation of the Lower Floridan aquifer. Eight wells were drilled at six sites: well 34S011 at the Pineora site in Effingham County; well 33R045 at the Pembroke site and wells 35P109 and 35P110 at the Richmond Hill site in Bryan County; well 35L085 at the Shellman Bluff site in McIntosh County; wells 34H495 and 34H500 at the Brunswick site in Glynn County; and well 33D073 at the St Marys site in Camden County (fig. 1; table 1). These eight wells were installed as part of the CSSI between 1999 and 2002 as monitoring wells to obtain hydrogeologic and water-quality data for the Floridan aquifer system. Also as part of this study, the State of Georgia and the USGS coordinated with Glynn County to explore the water resources of the Lower Floridan aquifer in well 35H068 at the St Simons Island site in 2002. In 2002, the St Johns River Water Management District of Florida drilled well 33D074 to investigate the Floridan aquifer system at the St Marys site in Georgia, and made available the hydrogeologic, geophysical, and water-quality results for the interval from 1,500 to 2,126 feet (ft) below land surface for inclusion in this report.

The field investigation, conducted from 1999 to 2002, included the collection of rock samples (cuttings), water levels, water-quality samples, and geophysical logs during

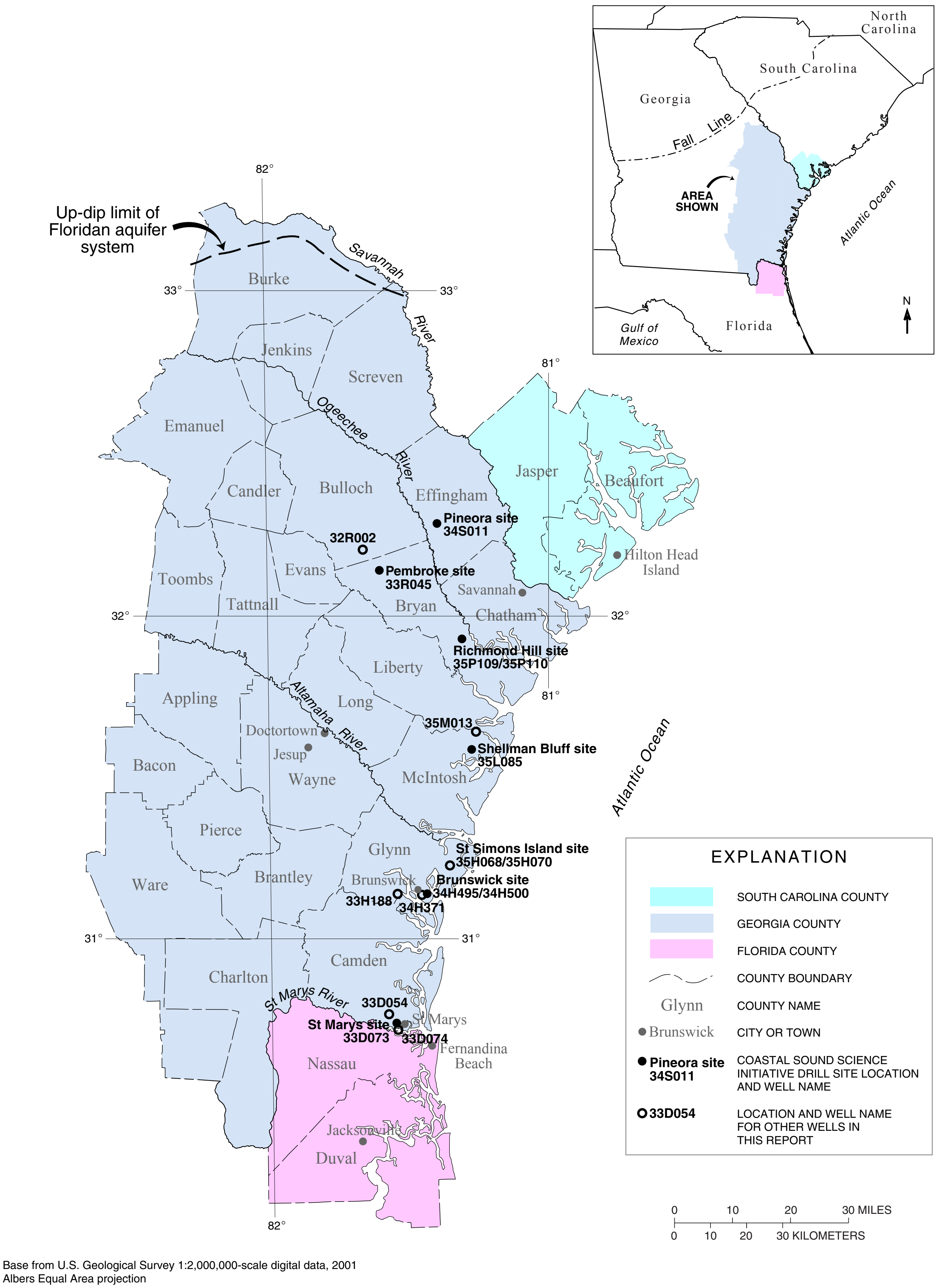
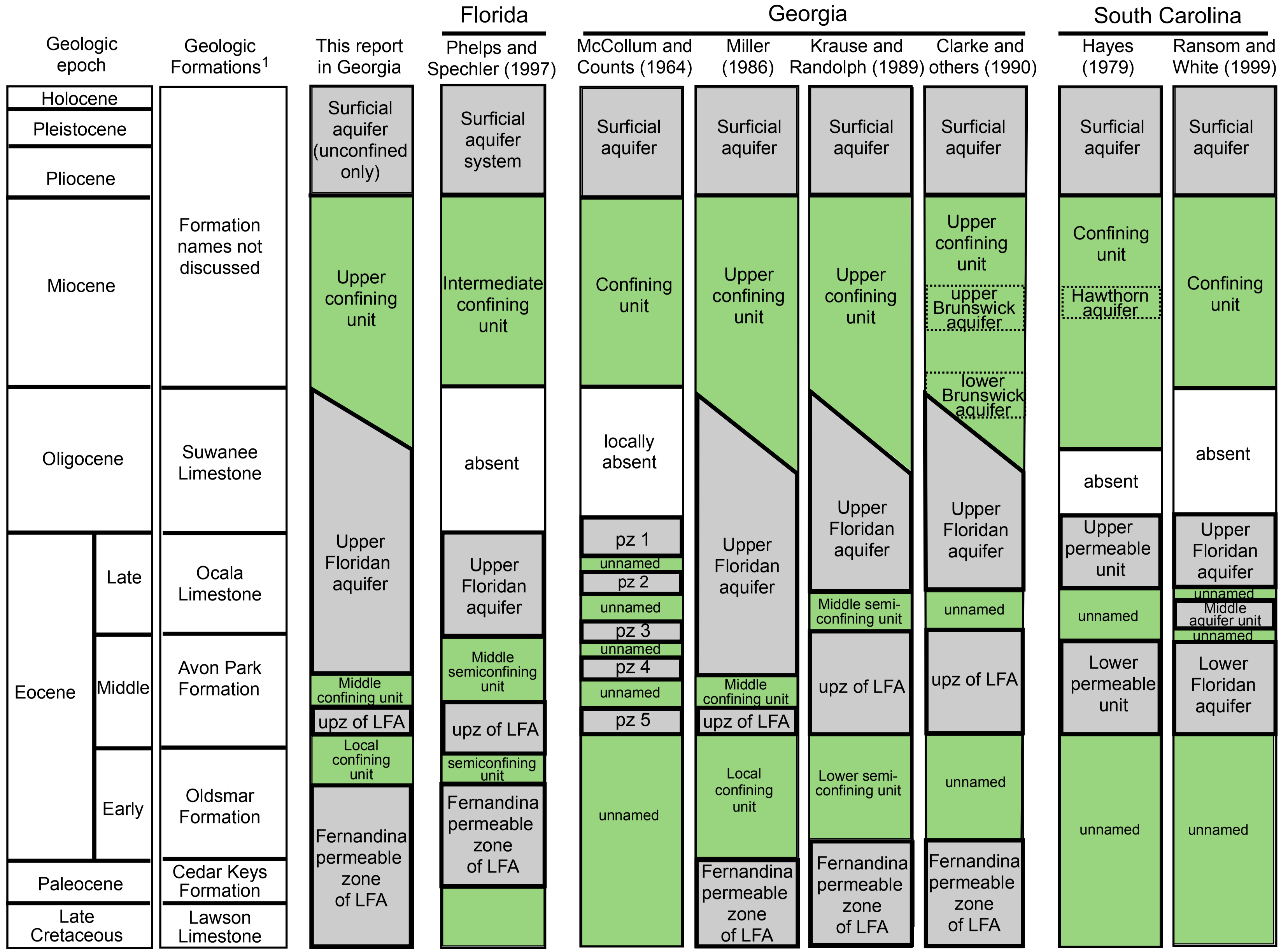


Figure 1. Coastal Sound Science Initiative study area and wells, Georgia, Florida, and South Carolina.



[1] Cretaceous, Paleocene, Eocene, and Oligocene epochs and formations based on Miller (1986)

Fm, Formation; LFA, Lower Floridan aquifer; upz, upper permeable zone; pz, permeable zone; , aquifers recognized within the upper confining unit

Figure 2. Generalized geology and hydrogeology of the surficial aquifer, upper confining unit, and Floridan aquifer system in the Coastal Sound Science Initiative study area, Florida, Georgia, and South Carolina.

Table 1. Georgia wells used for water-level monitoring, aquifer testing, and water-quality samping in the Coastal Sound Science Initiative study area, Georgia.

[NAVD 88, North American Vertical Datum of 1988; CSSI, Coastal Sound Science Initiative; USGS, U.S. Geological Survey; SJRWMD, St Johns River Water Management District; GGS, Georgia Geologic Survey; SHE, Savannah Harbor Expansion; Aquifer: UPZLF, upper permeable zone of Lower Floridan aquifer; UF, Upper Floridan aquifer; UB, upper Brunswick aquifer; SC, surficial aquifer; P, Paleocene unit beneath Lower Floridan aquifer; FPZLF, Fernandina permeable zone of Lower Floridan aquifer; NGVD 29, National Geodetic Vertical Datum of 1929]

County	Well name	USGS well identification	Other identifier	Latitude	Longitude	Land-surface altitude, in feet, NAVD 88[a]	Date con-structed	Top of open interval, depth in feet	Bottom of open interval, depth in feet	Aquifer	Water-level record	Water-quality results	Aquifer test, as part of this study
Bryan	33R045	320754081364301	CSSI Pembroke Lower Floridan test well	32°07'55"	81°36'42"	84.0	11/29/2001	745	994	UPZLF	x	x	
Bryan	35P109	315443081185901	CSSI Richmond Hill Lower Floridan test well	31°54'43"	81°18'59"	10.0	3/12/2000	1,010	1,275	UPZLF	x	x	x
Bryan	35P110	315443081185902	CSSI Richmond Hill Upper Floridan test well	31°54'43"	81°18'59"	9.5	4/4/2000	315	441	UF	x	x	x
Camden	33D054	304450081333401	City of St Marys well-2	30°44'50"	81°33'34"	10.0	3/10/1965	563	1,001	UF		x	
Camden	33D069	304314081325901	National Park Service-Cumberland Island	30°43'14"	81°32'59"	7.0	2/1/1994	467	575	UF	x		
Camden	33D071	304406081330502	USGS St Marys test well-2	30°44'07"	81°33'04"	9.0	5/15/1997	325	365	UB	x		
Camden	33D072	304406081330503	USGS St Marys test well-3	30°44'07"	81°33'04"	9.0	6/30/1997	225	255	SC	x		
Camden	33D073	304406081330504	CSSI St Marys test well-4	30°44'06"	81°33'05"	8.8	12/3/1999	1,365	1,500	UPZLF	x	x	x
Camden	33D074	304406081330505	SJRWMD St Marys test well-5	30°44'06"	81°33'05"	8.8	10/18/2002	1,840	2,126	UPZLF		x	
Chatham	38Q002	320202080541201	GGS test well Fort Pulaski	32°02'02"	80°54'12"	7.0	2/1/1956	110	348	UF	x		
Chatham	38Q201	320151080540501	GGS test well Fort Pulaski	32°01'51"	80°54'05"	6.0	2/19/1986	1,358	1,546	P			
Chatham	39Q003	320123080510101	USGS test well 7 P-3	32°01'23"	80°51'01"	6.1	10/9/1961	129	600	UF	x		
Chatham	39Q024	320128080511101	GGS Tybee Island, test well-1	32°01'28"	80°51'11"	9.0	3/25/1996	840	888	UPZLF	x		
Chatham	39Q028	320128080511102	TYBEE-SHE-Monitoring Well-2-COE	32°01'28"	80°51'11"	9.1	12/1/1997	94	104	UB	x		

Table 1. Georgia wells used for water-level monitoring, aquifer testing, and water-quality samping in the Coastal Sound Science Initiative study area, Georgia. — Continued

[NAVD 88, North American Vertical Datum of 1988; CSSI, Coastal Sound Science Initiative; USGS, U.S. Geological Survey; SJRWMD, St Johns River Water Management District; GGS, Georgia Geologic Survey; SHE, Savannah Harbor Expansion; Aquifer: UPZLF, upper permeable zone of Lower Floridan aquifer; UF, Upper Floridan aquifer; UB, upper Brunswick aquifer; SC, surficial aquifer; P, Paleocene unit beneath Lower Floridan aquifer; FPZLF, Fernandina permeable zone of Lower Floridan aquifer; NGVD 29, National Geodetic Vertical Datum of 1929]

County	Well name	USGS well identification	Other identifier	Latitude	Longitude	Land-surface altitude, in feet, NAVD 88[a]	Date con-structed	Top of open interval, depth in feet	Bottom of open interval, depth in feet	Aquifer	Water-level record	Water-quality results	Aquifer test, as part of this study
Chatham	39Q029	320128080511103	TYBEE-SHE-Monitoring Well-1-COE	32°01'28"	80°51'11"	9.1	12/1/1997	17	37	SW	x		
Effingham	34S008	321743081234801	USGS PINEORA EB-1	32°17'43"	81°23'48"	74.0	9/26/2000	155	175	UB			
Effingham	34S011	321742081234904	CSSI Pineora Lower Floridan test well	32°17'43"	81°23'48"	79.0	12/14/2001	651	870	UPZLF	x	x	
Glynn	33H188	310810081323401	USGS test well-26	31°08'10"	81°32'34"	8.3	10/1/1978	2,138	2,720	FPZLF		x	
Glynn	34G002	310727081285301	USGS-Lanier Bridge	31°07'27"	81°28'53"	10.1	1/1/1956	585	750	UF		x	
Glynn	34H371	310819081293501	USGS test well-11	31°08'19"	81°29'35"	8.5	10/1/1966	606	700	UF	x		
Glynn	34H391	310819081294101	USGS test well-16	31°08'19"	81°29'41"	6.1	4/1/1968	1,070	1,158	UPZLF			
Glynn	34H393	310825081294201	USGS test well-17	31°08'25"	81°29'42"	7.0	10/1/1968	615	723	UF		x	
Glynn	34H495	310835081294501	CSSI USGS test well-29	31°08'35"	81°29'45"	9.0	8/2/2000	2,089	2,720	FPZLF	x	x	
Glynn	34H500	310835081294502	CSSI USGS test well-30	31°08'35"	81°29'45"	9.0	10/10/2000	1,217	1,400	LPZLF	x	x	
Glynn	35H068	311456081210501	St Simons Island, Lawrence Road well	31°14'56"	81°21'05"	20.0	5/21/2002	1,391	1,591	LPZLF		x	x
Glynn	35H070	311456081210502	GGS, St Simons Island, Lawrence Road well	31°14'56"	81°21'05"	20.0	5/15/2002	638	743	UF		x	
Liberty	34N089	315215081235201	USGS test well-1	31°52'15"	81°23'52"	16.0	1/1/1967	410	789	UF	x		
McIntosh	35L085	313608081182701	CSSI Shellman Bluff Lower Floridan test well	31°36'08"	81°18'27"	9.0	2/8/2001	1,144	1,422	LPZLF	x	x	x
McIntosh	35M013	313824081154101	U.S. Fish and Wildlife Service	31°38'24"	81°15'41"	15.3	1/1/1942	376	553	UF	x		

[a]Datum shift (NAVD 88 minus NGVD 29) ranges from -0.82 to -1.2 feet for CSSI and St Simons Island sites.

drilling and installation of each well. The investigation also included aquifer tests at selected wells. Water-level data are presented from well completion through January 1, 2004. Water-level and water-quality data collected at other wells open to the Upper Floridan aquifer in the Georgia part of the study area are used for comparison of water levels and water quality between the Upper and Lower Floridan aquifers. Aquifer test results are presented in this report, but details of field methods and data analysis are presented in Harrelson and Falls (2003).

Location of the Study Area

The study area is in the Coastal Plain Physiographic Province and includes the 24-county study area in Georgia (fig. 1). The CSSI study area is bound by the Savannah River to the north and the St Marys River to the south and includes the six Georgia counties on the Atlantic coast and 18 inland counties. Although the discussion of the Floridan aquifer system includes relevant published information from Jasper and Beaufort Counties, SC, and Nassau and Duval Counties, FL, the field investigation did not extend into these counties.

Previous Investigations

The geology, hydrology, hydraulic properties, water quality, and water-supply potential of the Floridan aquifer system in Georgia have been documented in several regional studies (Miller, 1986; Bush and Johnston, 1988; Krause and Randolph, 1989; Sprinkle, 1989; Clarke and others, 1990; Garza and Krause, 1996; Clarke and others, 2004). The reports for these studies also document the extensive list of publications that correlate and name the aquifers at regional and local scales, and the history and the effects of saltwater intrusion on the Floridan aquifer system in coastal Georgia and in adjacent States.

The results of county-scale investigations of the Upper Floridan aquifer provide details about the local hydrogeology and the issue of saltwater intrusion in Beaufort and Jasper Counties, SC, and in Chatham County, GA (Warren, 1944; Counts and Donsky, 1963; McCollum and Counts, 1964; Siple, 1965; Hayes, 1979; Hassen, 1985; Burt and others, 1987; Smith, 1988, 1993; Hughes and others, 1989; Clarke and others, 1990; Burt, 1993; Landmeyer and Belval, 1996; U.S. Army Corps of Engineers, 1998; Ransom and White, 1999; Warner and Aulenbach, 1999); in Glynn and Camden Counties, GA (Wait and Gregg, 1973; Gregg and Zimmerman, 1974; Maslia and Prowell, 1990; Jones and Maslia, 1994; Warner and Aulenbach, 1999; Rose, 2001; Jones and others, 2002); and in Nassau and Duval Counties, FL (Fairchild and Bentley, 1977; Frazee and McClaugherty, 1979; Brown, 1980; Brown and others, 1984; Brown and others, 1985; Spechler, 1994; German and Taylor, 1995; Phelps and Spechler, 1997; Phelps, 2001). Hydraulic properties have been summarized for the Upper and Lower Floridan aquifers in coastal Georgia, including the CSSI Upper and Lower Floridan aquifer test results (Harrelson and Falls, 2003; Clarke and others, 2004).

Well-Identification System

Each well installed as part of this investigation and other Georgia wells discussed in this report were assigned a Georgia well name and a 15-digit USGS site identification number (table 1). The location of each CSSI well was determined by using a global positioning system to accurately assign well identification numbers.

The Georgia well name is based on the USGS index of topographic maps of Georgia. Beginning in the southeastern corner of the topographic grid, the 7.5-minute topographic quadrangles are numbered consecutively from “1” eastward along the horizontal axis of the grid and alphabetized consecutively from “A” northward along the vertical axis. Wells in each quadrangle are numbered in the order in which they are inventoried. Thus, the Lower and Upper Floridan wells (wells 35P109 and 35P110, respectively) installed at Richmond Hill site, Bryan County, GA, are both in the Richmond Hill 7.5-minute quadrangle (designated quadrangle 35P), and were the 109th and 110th wells inventoried in this quadrangle.

The 15-digit ground-water site identification number is composed of the 6 digits of latitude and 7 digits of longitude in degrees, minutes, and seconds for the well site, and a 2-digit sequential well number for wells drilled at that same latitude and longitude. For example, wells 35P109 and 35P110 at Richmond Hill were drilled at latitude 31°54'43" N. and longitude 081°18'59" W.; thus, the wells were assigned site identification numbers 315443081185901 and 315443081185902, respectively, in the USGS Ground-Water Site Inventory database.

Acknowledgments

The authors thank Dr. William H. McLemore, Georgia State Geologist, and the Technical Advisory Committee of the Georgia Coastal Sound Science Initiative for their guidance and support in the planning and the implementation of this scientific investigation. Roy Roundtree and Mark Hall of the GaEPD assisted the USGS during the field investigation with the selection of suitable well sites and the geophysical logging of wells.

Bob M. Massey, Bobby Griner, John Disk, and H.L “Bud” Rowe, Jr., Rowe Drilling Company, provided technical support during drilling activities at the well sites. The authors also thank Bill Osburn, Nolan Col, and Robert Brooks of the St Johns River Water Management District (SJRWMD), Palatka, FL, for providing hydrogeologic, water-quality, and geophysical results for the Lower Floridan aquifer in well 33D074 at the St Marys site, GA. The authors also thank Ray Shell and Todd Kline of Glynn County; Chris Stovall of Thomas and Hutton Engineering Company, Savannah, GA; and Richard H. Johnston (USGS emeritus and technical consultant for Glynn County) for coordinating with the USGS during the installation of well 35H068 at the St Simons Island site, GA. Jim Harris of the Georgia Department of Natural Resource, Brunswick, GA, arranged for analyses of water samples from well 35H068 by the GaEPD laboratory in Brunswick.

Methods of Data Collection and Analysis

During the drilling of the Floridan aquifer system and the construction of each well, the USGS collected rock cuttings, and monitored changes in drill-bit penetration rates, water levels or pressures, and water quality. Water samples were collected from the boreholes of CSSI and non-CSSI wells and analyzed to characterize the quality of water discharged from the Lower Floridan aquifer and compared to the water quality of the Upper Floridan aquifer. Geophysical logs also were collected upon completion of the open boreholes.

Test Well Drilling and Completion

To obtain data on the hydrogeology and water-quality characteristics of the Lower Floridan aquifer for comparison with the Upper Floridan aquifer, eight monitoring wells were installed at six sites in the CSSI 24-county study area as part of this investigation (fig. 1; table 1). A well open to the upper permeable zone of the Lower Floridan aquifer, as defined by Miller (1986), was installed at each of these sites. In addition, wells 34H495 and 35P110 were installed to monitor and sample the Fernandina permeable zone at the Brunswick site and the Upper Floridan aquifer at the Richmond Hill site, respectively. Wells 35H068 and 33D074 were installed by Glynn County at the St Simons Island site in Glynn County and by the SJRWMD at the St Marys site.

Reverse-air rotary drilling was used to drill the limestone and dolomite rocks of the Floridan aquifer system. Each of the wells open to the upper permeable zone of the Lower Floridan aquifer at the six sites was constructed in four stages (table 2). Well 35P110 in Bryan County and well 34H495 in Glynn County were completed in three and five stages, respectively.

Well 35H068 at the St Simons Island site was constructed as a production well by Glynn County, and was designed to have an open-borehole interval in the upper permeable zones of the Lower Floridan aquifer. As part of the CSSI investigation, the open borehole of the Lower Floridan aquifer was explored in an effort to determine the depth to the saline water of the Fernandina permeable zone. Well 33D074 was part of an investigation by SJRWMD to determine the thickness of the freshwater in the upper permeable zone of the Lower Floridan aquifer, the depth to the top of the Fernandina permeable zone, and the presence or absence of saline water near the top of the Fernandina permeable zone at the St Marys site. Well 33D074 was drilled approximately 25 ft southwest of CSSI well 33D073 at the St Marys site.

Hydrogeologic Data Collection

The USGS collected rock cuttings and monitored drill-bit penetration rates during drilling of the Upper and Lower Floridan aquifers for hydrogeologic interpretations. Reflected-light microscopy was used to describe the mineralogy and texture of rock cuttings. Changes in drill-bit penetration rates were compared to lithologic changes observed in cuttings to determine contacts between rock units and voids, including solution cavities or fracture zones, in the subsurface.

To characterize head relations of the permeable zones in the Floridan aquifer system, water levels or pressures were monitored during drilling and after completion of the wells. Water levels in non-flowing wells were measured and recorded with an electric tape before daily drilling activities commenced. Water levels in flowing wells were determined by sealing the wellhead with a watertight cap at the end of each day and measuring water pressure with a calibrated pressure gage through a sampling port in the cap each morning before removing the cap. Following completion of the eight CSSI wells at the six sites, the USGS installed and maintained equipment for continuous monitoring of ground-water levels (Coffin and others, 2004). Equipment installed at each well measured hourly water levels, which were used to calculate the daily mean water levels for all CSSI and non-CSSI wells discussed in this report and denoted in table 1. The period of record used in this report for each CSSI well begins following completion of the well and ends January 1, 2004. Water levels were not monitored in well 35H068 at the St Simons Island site and in well 33D074 at the St Marys site.

The USGS, with the assistance of a contract drilling crew, planned and conducted single-well aquifer tests in four CSSI wells. Aquifer tests were completed to estimate transmissivity for the Upper Floridan aquifer in CSSI well 35P110 at Richmond Hill and for the upper permeable zone of the Lower Floridan aquifer in CSSI wells 35P109 at Richmond Hill, 35L085 at Shellman Bluff, and 33D073 at St Marys, GA. For each single-well test, water levels were monitored for a 24-hour drawdown period and a 24-hour recovery period. Water-level data from the drawdown period were used to calculate transmissivity (Theis, 1935; Cooper and Jacob, 1946; Hantush, 1961). The calculated transmissivities from these aquifer tests are included in the descriptions of the Upper and Lower Floridan aquifers in this report. The details of field procedures, data collection, and analysis for these four aquifer tests were previously published (Harrelson and Falls, 2003).

For the purpose of interpreting the hydrogeologic distribution of water quality, specifically chloride, the specific conductance of the discharge water was monitored with a calibrated water-quality meter to determine changes in borehole water quality as drilling progressed. After drilling the length of each drill pipe, which ranged in length from 28 to

Table 2. Construction details for the Coastal Sound Science Initiative and St Simons Island wells used in this investigation, Georgia.

[ft, feet]

Georgia well name, community, county (fig. 1)	Start–completion dates	Nominal diameters and depth below land surface of borehole/casing in each stage of well construction				
		Stage 1	Stage 2	Stage 3	Stage 4	Stage 5
33D073 St Marys, Camden County	09/21/1999–12/08/1999	21-inch borehole to 80 ft/16-inch casing to 78 ft	15-inch borehole to 563 ft/12-inch casing to 560 ft	11-inch borehole to 1,365 ft/8-inch casing to 1,360 ft	7-inch borehole from 1,365 to 1,500 ft/no casing	
34H495 Brunswick, Glynn County	02/07/2000–08/04/2000	30-inch borehole to 120 ft/24-inch casing to 103 ft	21-inch borehole to 604 ft/16-inch casing to 584 ft	15-inch borehole to 1,405 ft/12-inch casing to 1,396 ft	11-inch borehole to 2,089 ft/8-inch casing to 2,084 ft	7-inch borehole from 2,089 to 2,720 ft/no casing
34H500 Brunswick, Glynn County	08/21/2000–10/10/2000	20-inch borehole to 120 ft/16-inch casing to 104 ft	15.75-inch borehole to 590 ft/12-inch casing to 584 ft	11-inch borehole to 1,217 ft/8-inch casing to 1,212 ft	7-inch borehole from 1,217 to 1,400 ft/no casing	
35H068 St Simons Island, Glynn County	01/28/2002–05/21/2002	30-inch borehole to 108 ft/24-inch casing to 105 ft	23-inch borehole to 645 ft/18-inch casing to 640 ft	17-inch borehole to 1,394 ft/12-inch casing to 1,391 ft	11-inch borehole from 1,391 to 2,200 ft/grouted from 1,591 to 2,200 ft/open hole from 1,391 to 1,591 ft	
35L085 Shellman Bluff, McIntosh County	11/08/2000–02/16/2001	21-inch borehole to 85 ft/16-inch casing to 81 ft	15-inch borehole to 500 ft/12-inch casing to 488 ft	11-inch borehole to 1,148 ft/8-inch casing to 1,144 ft	7-inch borehole from 1,148 to 1,863 ft/grouted from 1,422 to 1,863 ft/open hole from 1,148 to 1,422 ft	
35P109 Richmond Hill, Bryan County	0110/2000–03/15/2000	21-inch borehole to 84 ft/16-inch casing 81.5 ft	15-inch borehole to 328 ft/12-inch casing to 324 ft	11-inch borehole to 1,015 ft/8-inch casing to 1,010 ft	7-inch borehole from 1,015 to 1,677 ft/grouted from 1,275 to 1,677 ft/open hole from 1,015 to 1,275 ft	
35P110 Richmond Hill, Bryan County	03/22/2000–04/05/2000	16-inch borehole to 84 ft/12-inch casing to 82 ft	11-inch borehole to 320 ft/8-inch casing to 315 ft	7-inch borehole from 320 to 440 ft/no casing		
33R045 Pembroke, Bryan County	09/17/2001–10/29/2001	21-inch borehole to 127 ft/16-inch casing to 121 ft	15-inch borehole to 359 ft/12-inch casing to 354 ft	11-inch borehole to 745 ft/8-inch casing 741 ft	7-inch borehole from 745 to 994 ft/no casing	
34S011 Pineora, Effingham County	11/15/2001–12/19/2001	21-inch borehole to 83 ft/16-inch casing to 80 ft	15-inch borehole to 295 ft/12-inch casing to 290 ft	11-inch borehole to 654 ft/8-inch casing 651 ft	7-inch borehole from 654 to 870 ft/no casing	

31 ft, water samples were collected from reverse-air discharge water for chloride analysis.

Water-Quality Sampling

For a more complete analysis of water quality of an aquifer or a permeable zone of the Floridan aquifer system, samples were collected to document the bulk water quality of the open-borehole interval or of a specific depth in the borehole. Wells were developed with reverse-air rotary discharge, pumps, or artesian flow prior to the collection of water samples. Water samples included 16 samples collected from eight CSSI wells and 9 samples collected from seven non-CSSI wells (table 1). Samples were analyzed to determine the ion concentrations and the stable hydrogen and oxygen isotopic compositions of the water, and the carbon-14 and stable carbon isotopic compositions of the dissolved inorganic carbon (DIC) in the water. Water samples from four non-CSSI wells and one CSSI well were analyzed for tritium. Water samples from four non-CSSI wells and seven CSSI wells were analyzed for strontium isotopes. Concentrations of total dissolved solids were computed based on ionic compositions. Quality-control samples included duplicate samples collected from the Upper Floridan aquifer in well 33D054 and the upper permeable zone of the Lower Floridan aquifer in well 35H068.

Several methods were used to collect water-quality samples from the open-borehole intervals and specific zones within the open-borehole intervals. Submersible and turbine pumps were used to withdraw water for seven samples and two duplicate samples. A peristaltic pump was used to withdraw and bottle water discharging from well 33H188, a flowing well near Brunswick, GA.

In addition to pumps, a wireline water sampler was used to collect water samples at specific depths in the open boreholes. The wireline water sampler was lowered in the open boreholes of eight wells and opened at specific depths to collect 13 water samples. To collect two water samples from well 34H495, the wireline sampler was lowered into the drill pipe with the drill bit at 2,243 and 2,720 ft, respectively. After retrieving the wireline sampler from the drill pipe, a peristaltic pump was used to pump water from the wireline sampler into sample bottles.

Prior to collecting water samples for carbon-14 analysis, the wireline water sampler was purged with laboratory-grade nitrogen gas to eliminate atmospheric carbon dioxide from the sample chamber. For all carbon-14 samples, a 1-liter sample bottle also was purged with nitrogen gas and filled with water from the bottom of the bottle to displace the nitrogen gas and minimize the potential for contamination of the sample with atmospheric carbon-14.

Water samples for ion analysis were filtered using 0.45-micrometer capsule filters and analyzed at the USGS laboratory in Ocala, FL. Unfiltered water samples collected for stable hydrogen and oxygen isotopic analysis and filtered water samples collected for carbon-14 and stable carbon isotopic analysis of the DIC in the water were analyzed by the USGS Isotope Fractionation Laboratory in Reston, Virginia, and a laboratory under contract to the USGS National Water Quality Laboratory in Denver, Colorado, respectively. Unfiltered water samples were collected at selected wells and analyzed for tritium and strontium isotopes (strontium-87/strontium-86) by a USGS laboratory in Menlo Park, California.

Geophysical Logging

Geophysical logs were collected in the open boreholes of the third, fourth, and fifth stages of well construction. The geophysical logs included natural gamma, spontaneous-potential, borehole-fluid resistivity and temperature, single-point resistance, formation-resistivity, and caliper logs. The natural-gamma log was used to correlate hydrogeologic units in the wells at the CSSI and St Simons Island sites.

The spontaneous-potential, single-point resistance, and formation-resistivity logs are of minimal use in this investigation because of borehole effects. The boreholes produced by reverse-air rotary drilling of the Floridan aquifer system are filled with formation waters from the permeable limestone and dolomite beds encountered during drilling. When the salinities in the permeable zones and the borehole are similar, a straight-line or minimum response on the spontaneous-potential log can result (Keys, 1988). Therefore, the log does not always reflect changes in spontaneous potential caused by formation water quality and lithology. The boreholes also can have considerable variation in diameter; this has a noticeable effect on the response of formation-resistivity logs (Keys, 1988). High- and low-resistivity responses of the logs at the CSSI wells commonly correlated to intervals of minimum- and expanded-borehole diameter, respectively, and not to true variability in formation resistivity associated with water quality and permeability. This was particularly noticeable in wells 34H495 and 34H500 in Glynn County and wells 33D073 and 33D074 in Camden County, where interbedded dolomite and limestone, and solution cavities in the Lower Floridan aquifer resulted in considerable variation in the borehole diameter.

Hydrogeologic Setting

The Coastal Plain strata beneath the CSSI study area range in age from Cretaceous through Holocene (Gohn, 1988; Weems and others, 2004; fig. 2). Several aquifers and aquifer systems are recognized in these strata; however, the abundant supply of potable water from the Eocene and Oligocene strata of the Upper Floridan aquifer generally has limited the need for exploration of other water resources in older strata. Consequently, the availability of data to study these older strata is limited, particularly in the pre-Tertiary strata beneath most of the coastal counties of the CSSI study area.

Investigators in the 1970s and 1980s recognized and correlated Early and Late Cretaceous strata beneath the Floridan aquifer system in the study area (Maher, 1971; Hathaway and others, 1979; Scholle, 1979; Chowns and Williams, 1983; Gohn, 1988; Miller, 1992). Weems and others (2004) reassigned all Cretaceous strata beneath eastern Georgia and western South Carolina to the Late Cretaceous. The Cretaceous strata and aquifers below the Floridan aquifer system are not the subject of this report and are not discussed in further detail.

The Tertiary and Quaternary strata are partially penetrated by thousands of wells in the CSSI study area, which provided earlier investigators with an abundance of subsurface data for the interpretation and correlation of geologic strata and the hydrogeologic units, including the surficial aquifer, the upper confining unit, and the Upper Floridan aquifer (fig. 2). Miller (1986) mapped the stratigraphic boundaries of the Paleocene, Eocene, Oligocene, Miocene, and post-Miocene strata in the southeastern United States as a framework for regional correlation of hydrogeologic units in and above the Floridan aquifer system. Detailed lithostratigraphy, stratigraphic type sections, and stratigraphic nomenclature for the Oligocene and younger strata in Georgia were described by Huddlestun (1988, 1993). Subsequent work by Weems and Edwards (2001) modified the stratigraphy of the Oligocene and younger strata in the CSSI study area on the basis of paleontological results from sediment.

Surficial Aquifer and Upper Confining Unit

As mapped by Miller (1986), the hydrogeologic units in the Tertiary and Quaternary strata of the CSSI study area included the surficial aquifer in the post-Miocene strata, the upper confining unit in the Miocene strata, and the aquifers of the Floridan aquifer system in the Late Cretaceous through Oligocene strata (fig. 2). Miller (1986) reported that the Oligocene strata, depending on its hydraulic properties, locally functioned as part of the upper confining unit or the Upper Floridan aquifer.

The surficial aquifer generally consists of Pliocene, Pleistocene, and Holocene formations of sand and clay that overlie the upper confining unit (Miller, 1986; Krause and Randolph, 1989; Clarke and others, 1990). These strata include the unsaturated zone and the water table in the study area. The surficial aquifer also includes the semiconfined permeable zone or zones in the late Miocene strata (Clarke and others, 1990; Leeth, 1999; Weems and Edwards, 2001; Leeth and others, 2003). The semiconfining units and permeable zones of the surficial aquifer generally are present in the clay and sand of the late Miocene (Weems and Edwards, 2001), although these strata have been identified as the middle Miocene in previous reports (Clarke and others, 1990; Leeth, 1999; fig. 2).

The strata of the upper confining unit in most of the study area were originally interpreted as middle and late Miocene strata, and locally included the Oligocene (Miller, 1986; Krause and Randolph, 1989; fig. 2). Weems and Edwards (2001) reassigned these strata to the early and middle Eocene, and early and late Oligocene. The early and middle Miocene strata are predominantly sand, silt, and clay with a few thin layers of limestone and dolomite. The early and late Oligocene strata consist of limestone and sandy limestone, respectively (Miller, 1986; Weems and Edwards, 2001).

The upper confining unit includes permeable zones of sand and limestone and is a water-supply source in parts of the study area, but with less yield of freshwater than the Upper Floridan aquifer (Hayes, 1979; Clarke and others, 1990; Spechler, 1994; fig. 2). The upper and lower Brunswick aquifers, as described in Georgia, are used as an alternate water supply to the Upper Floridan aquifer in Camden and Glynn Counties for residential and commercial water use (Clarke and others, 1990). A low-yield permeable zone in Miocene strata of South Carolina is known locally as the Hawthorn aquifer and correlates to the upper Brunswick aquifer of Georgia (Hayes, 1979; Clarke and others, 1990). The upper confining unit in northeastern Florida is referred to as the intermediate confining unit, and contains permeable layers and lenses of limestone and sand, which locally are used as low-yield aquifers for residential-water supply (Spechler, 1994).

Floridan Aquifer System

The Floridan aquifer system, as defined by Miller (1986), is a continuous vertical section of carbonate strata that includes the Eocene strata and all or part of the Oligocene strata in coastal Georgia, and also includes Paleocene and Cretaceous carbonate strata in Glynn and Camden Counties, GA, and in northeastern Florida (Miller, 1986; Clarke and others, 1990; Spechler, 1994; Phelps and Spechler, 1997; Jones and others, 2002; fig. 2). The Floridan aquifer system predominantly consists of limestone and dolomite rock strata, but locally includes thin beds of clay and nodules of gypsum and chert. For the following section, the hydrogeologic units and names of Miller (1986) are used.

At the CSSI and St Simons Island sites, the top of the Floridan aquifer system is defined as the top of the early Oligocene, except at the St Marys site (pl. 1; tables 3, 4). In the absence of the early Oligocene at the St Marys site, the top of the Floridan aquifer system correlates to the top of the late Eocene strata.

Permeable zones in the Floridan aquifer system are grouped into the Upper and Lower Floridan aquifers (Miller, 1986; Krause and Randolph, 1989; Clarke and others, 1990). Five permeable zones were recognized in flowmeter studies of production wells drilled near Savannah, GA, and were successfully correlated beneath parts of Chatham County, GA, and Beaufort County, SC (McCollum and Counts, 1964). The permeable zones, numbered from 1 to 5 in descending order, were not consistently grouped into the Upper and Lower Floridan aquifers by previous investigators (fig. 2). In Glynn

Table 3. Geology of the Coastal Sound Science Initiative and St Simons Island sites, Georgia.

[Altitudes in feet above and below (-) North American Vertical Datum of 1988]

Georgia well name, community, county (fig. 1)	Land surface	Top of early Oligocene Suwannee Limestone	Top of late Eocene Ocala Limestone	Top of middle Eocene Avon Park Formation	Top of early Eocene	Top of Paleocene	Top of clay below marl
33D073/33D074 St Marys, Camden County	8.8	not present	-504	-806	-1,844	not penetrated	not penetrated
34H495/34H500 Brunswick, Glynn County	9.0	-531	-595	-870	-1,860	-2,150	not penetrated
35H068 St Simons Island, Glynn County	20.0	-598	-652	-915	-1,894	top of marl -2,044	-2,170
35L085 Shellman Bluff, McIntosh County	9.0	-412	-475	-718	top of marl -1,409	not interpreted	-1,841
35P109/35P110 Richmond Hill, Bryan County	9.5/10.0	-319	-385	-575	top of marl -1,284	not interpreted	-1,615
33R045 Pembroke, Bryan County	84.0	-242	-273	-449	not penetrated	not penetrated	not penetrated
34S011 Pineora, Effingham County	79.0	-197	-210	-385	top of marl -737	not penetrated	not penetrated

and Camden Counties, GA, upper and lower permeable zones are recognized in the Upper and Lower Floridan aquifers (Miller 1986; Krause and Randolph, 1989; Clarke and others, 1990; Jones and others, 2002).

The Upper Floridan aquifer generally consists of permeable zones in the upper part of the middle Eocene and in the late Eocene and, where permeable, the overlying Oligocene carbonates (Miller, 1986; Krause and Randolph, 1989). The late Eocene Ocala Limestone consists of interbedded porous and nonporous limestone and generally has greater than 10-percent interparticle pores in one or more porous stratigraphic intervals. Compared with the overlying Suwannee Limestone and underlying Avon Park Formation, the Ocala Limestone generally does not contain glauconite and phosphate and, therefore, has the lowest counts per second (0 to 10 cps) on the natural gamma logs of these three formations. As in the late Eocene strata, the upper part of the middle Eocene Avon Park Formation in the Upper Floridan aquifer also consists of interbedded porous and nonporous limestone, but also includes thin and thick beds of dolomite in Georgia and Florida. The dolomite varies in texture from nonporous to porous and has intercrystalline and moldic pores. In South Carolina, the Upper Floridan aquifer correlates to the permeable zone near the top of the late Eocene beneath Jasper and Beaufort Counties and simply is referred to as the upper permeable unit of the Floridan aquifer system or as the principal artesian aquifer (Hayes, 1979; Hughes and others, 1989; Ransom and White, 1999).

The middle confining unit predominantly consists of low-porosity, low-permeability strata that divide the porous, permeable strata of the Floridan aquifer system into the Upper and Lower Floridan aquifers (pl. 1). This unit consists of limestone and dolomite in the middle Eocene Avon Park Formation. From the Atlantic coastline to its western boundary, the extent of the middle confining unit includes 12 of the 24 coastal counties in Georgia, the two South Carolina counties, and the two Florida counties in the CSSI study area, and defines the extent of the underlying Lower Floridan aquifer (Miller, 1986).

The Lower Floridan aquifer beneath the northern coastal counties of Georgia, including McIntosh, Liberty, Bryan, and Chatham Counties, generally consists of a permeable zone in the lower part of the middle Eocene that contains saline water with a total dissolved solids concentration greater than 1,000 milligrams per liter (mg/L; Miller, 1986; U.S. Army Corps of Engineers, 1998; Falls and others, 2001; fig. 2). The altitude of the top of the Lower Floridan aquifer, as mapped by Miller (1986), correlates approximately in Chatham County to the top of permeable zone 5 of McCollum and Counts (1964). The Lower Floridan aquifer in Glynn and Camden Counties,

Table 4. Hydrogeology of the Coastal Sound Science Initiative and St Simons Island sites, Georgia.

[Altitudes in feet above and below (-) North American Vertical Datum of 1988]

Georgia well name, community, county (fig. 1)	Land surface, top of surficial aquifer	Top of upper confining unit	Top of Floridan aquifer system/ Upper Floridan aquifer	Base of Upper Floridan aquifer	Lower Floridan aquifer				
					Top of upper permeable zone	Base of upper permeable zone	Top of Fernandina permeable zone	Base of Floridan aquifer system	Base of marl/ top of clay
33D073/33D074 St Marys, Camden County	8.8	-84	-504	-1,220	-1,260	-2,021	-2,106	not penetrated	not penetrated
34H495/34H500 Brunswick, Glynn County	9.0	-94	-531	-1,187	-1,240	-1,961	-2,078	not penetrated	not penetrated
35H068 St Simons Island, Glynn County	20.0	-85	-598	-1,103	-1,325	-1,925	not present	-2,044	-2,170
35L085 Shellman Bluff, McIntosh County	9.0	-69	-412	-819	-1,181	-1,409	not present	-1,409	-1,841
35P109/35P110 Richmond Hill, Bryan County	9.5/10.0	-90	-319	-794	-941	-1,284	not present	-1,284	-1,615
33R045 Pembroke, Bryan County	84.0	-26	-242	-636	-684	-777	not present	not penetrated	not penetrated
34S011 Pineora, Effingham County	79.0	-6	-197	-541	-581	-738	not present	-738	not penetrated

GA, and Duval and Nassau Counties, FL, includes at least two permeable zones. The upper permeable zone is in the limestone and dolomite strata of the early and middle Eocene beneath the middle confining unit and can include multiple fresh and saline water zones. The Fernandina permeable zone of the Lower Floridan aquifer is correlated to predominantly dolomite in the early Eocene Oldsmar Formation and Paleocene Cedar Keys Formation, and also includes dolomite of the Cretaceous Lawson Limestone in parts of Glynn County, GA (Miller, 1986; Clarke and others, 1990; Falls and others, 2001; fig. 2). The Fernandina is a known saltwater-bearing zone beneath Glynn County, GA, and a known freshwater- and saltwater-bearing zone beneath Duval and Nassau Counties, FL (Phelps and Spechler, 1997; Jones and others, 2002).

Ground-Water Supply

Water use from the Lower Floridan aquifer historically has been small compared to water use from the Upper Floridan aquifer; however, the tremendous quantity of water withdrawn from the Upper Floridan aquifer has affected water levels in the Upper and Lower Floridan aquifers. The Upper Floridan aquifer initially was developed in Georgia in the late 1880s near Savannah and became the principal source of ground-water supply in most of the counties of the CSSI study area during the 20th century. Water use is limited from the Lower Floridan aquifer in the South Carolina and Georgia parts of the CSSI study area and more extensively developed in Duval and Nassau Counties, FL (Krause and Randolph, 1989; Marella, 1999).

Ground-water use from the Upper Floridan aquifer steadily increased from 1887 to the late 1930s in the CSSI study area along with increasing population, commerce, and agriculture, all of which affected water levels locally. Beginning in the late 1930s, further development of water resources primarily from the Upper Floridan aquifer expanded, particularly with industrial development in Chatham, Glynn, Camden, and Wayne Counties, GA, and Duval and Nassau Counties, FL (Krause and Randolph, 1989; Clarke and others, 1990; Spechler, 1994; Krause and Clarke, 2001).

In the Georgia part of the CSSI study area, total ground-water use, most of which is from the Upper Floridan aquifer, has decreased in the 24 counties from 385 million gallons per day (Mgal/d) in 1980 to 347 Mgal/d in 1997 (Fanning, 1999). Of the 347 Mgal/d in 1997, five counties—Chatham, Glynn, Liberty, Camden, and Wayne Counties—used 263 Mgal/d. These five counties historically have been the dominant users of ground water from the Floridan aquifer system in the 24-county study area. The paper and chemical industries, operating in these five counties from the 1930s to 1950s, quickly became the dominant ground-water users. When compared with the other counties, total ground-water use in 1997 was greatest in Chatham County at 76 Mgal/d, which was down from peak usage of approximately 85 Mgal/d in the late 1980s and early 1990s (Clarke and others, 1990; Fanning, 1999). Total ground-water use in Glynn County was as high as 122 Mgal/d in the 1960s but declined to 100 Mgal/d in 1980 and to 65 Mgal/d in 1997 (Wait and Gregg, 1973; Krause and others, 1984; Fanning, 1999). Total ground-water use in Wayne County declined from 74 Mgal/d in 1980 to 64 Mgal/d in 1997. Camden County had a slight increase in water use from 37 Mgal/d in 1980 to 40 Mgal/d in 1997; however, the county's water use decreased by 35 Mgal/d with the closure of a paper mill in October 2002 (Peck and others, 2005).

In Nassau and Duval Counties, FL, more than 90 percent of the ground-water use in 1995 was derived from the Floridan aquifer system. Total ground-water use in Nassau County peaked at 66 Mgal/d in 1978 and ranged from 40 to 50 Mgal/d from 1983 to 2000 (Frick and others, 2002). Since 1940, the pulp and paper industry at the northern end of Fernandina Beach in Nassau County has been the dominant ground-water user in the county. This industry used more than 90 percent of the 44.5 Mgal/d total ground-water use reported in 1995 (Marella, 1999). In Duval County, ground-water use peaked at about 170 Mgal/d in 1970, declined to 167 Mgal/d in 1988, and declined further to 145 Mgal/d in 1995 (Spechler, 1994). Unlike Nassau County, industrial ground-water use in Duval County equaled only about 22 percent in 1995, including industrial use from public- and self-supplied industries (Marella, 1999).

In Beaufort and Jasper Counties, SC, ground-water use from the Upper Floridan aquifer is small compared with ground-water use in the previously mentioned Georgia and Florida counties. The Upper Floridan aquifer also is the principal source of ground water for public and domestic supply. Ground-water use began in the late 1880s in Beaufort County and equaled 6.8 Mgal/d by 1980 and 17.5 Mgal/d by 1990 (Hayes, 1979; South Carolina Water Resources Commission, 1983, 1992). Ground-water use in Jasper County was 1.2 Mgal/d in 1980 and 1.8 Mgal/d in 1990.

Historical Water Levels

Ground-water use in the CSSI study area has resulted in regional declines in water levels and localized depressions in the potentiometric surface of the Upper Floridan aquifer in the CSSI study area (fig. 3). Water-level data from numerous Upper Floridan wells in the study area were used by previous investigators to document the potentiometric surface at specific time periods in all or parts of the CSSI study area (Warren, 1944; Counts and Donsky, 1963; Hayes, 1979; Johnston and others, 1981; Burtell, 1990; Clarke and others, 1990; Peck, 1991; Ransom and White, 1999; Peck and others, 1999; Peck and McFadden, 2004). The effects of regional declines in water levels were particularly noticeable in the coastal counties of the CSSI study area where artesian flow ceased as water levels, previously above land surface, progressively declined below land surface (Johnston and others, 1981; Krause and Randolph, 1989).

In addition to regional water-level declines, localized depressions formed in the Upper Floridan aquifer potentiometric surface (fig. 3). These depressions centered on industrial-municipal well fields near Savannah, Brunswick, and Jesup, GA, and the combined area of St Marys, GA, and Fernandina Beach, FL (Johnston and others, 1981; Krause and Randolph, 1989; Clarke and others, 1990). A subtle depression centered on the well field in Jacksonville, FL, is noticeable on some regional maps of the Upper Floridan potentiometric surface; however, the transmissivity of the Floridan aquifer system is so large in Duval County when compared with transmissivities in Georgia and South Carolina that, even considering the largest rate of ground-water use in the study area, the scale of the depression in Duval County is small and generally requires a smaller contour interval to be delineated (Burtell, 1990).

Ground-Water Flow, Salinity, and Potential for Saltwater Contamination

Occurrences of saltwater contamination of the Upper Floridan aquifer in the CSSI study area have been documented in Beaufort County, SC, Glynn County, GA, and Duval County, FL (Wait and Gregg, 1973; Krause and Randolph, 1989; Spechler, 1994; Landmeyer and Belval, 1996; Phelps and Spechler, 1997). The hydrogeology and the presence of a saltwater source have been constant; however, since the 1880s, regional and local declines in head in the Upper Floridan aquifer have altered the horizontal and vertical head gradients within the Floridan aquifer system and between the surficial and Upper Floridan aquifers (fig. 4). As a consequence, these changes in the head gradients resulted in the local occurrence of saltwater contamination of the freshwater resources in the Upper Floridan aquifer.

The distribution of freshwater and saltwater prior to the 1880s was controlled by the confining units within and above the Floridan aquifer system, the flow potential created by horizontal and vertical head gradients in the ground-water flow system, and water density. The head gradient was west to east beneath the onshore CSSI study area and the offshore continental shelf (Krause and Randolph, 1989; figs. 3, 4). The head gradient between the surficial and Upper Floridan aquifers generally was downward in most of the inland counties of the CSSI study area, with the exception of river valleys. In river valleys and counties bordering the Atlantic Ocean, the head gradient was upward. The freshwater of the confined Upper and Lower Floridan aquifers was bounded

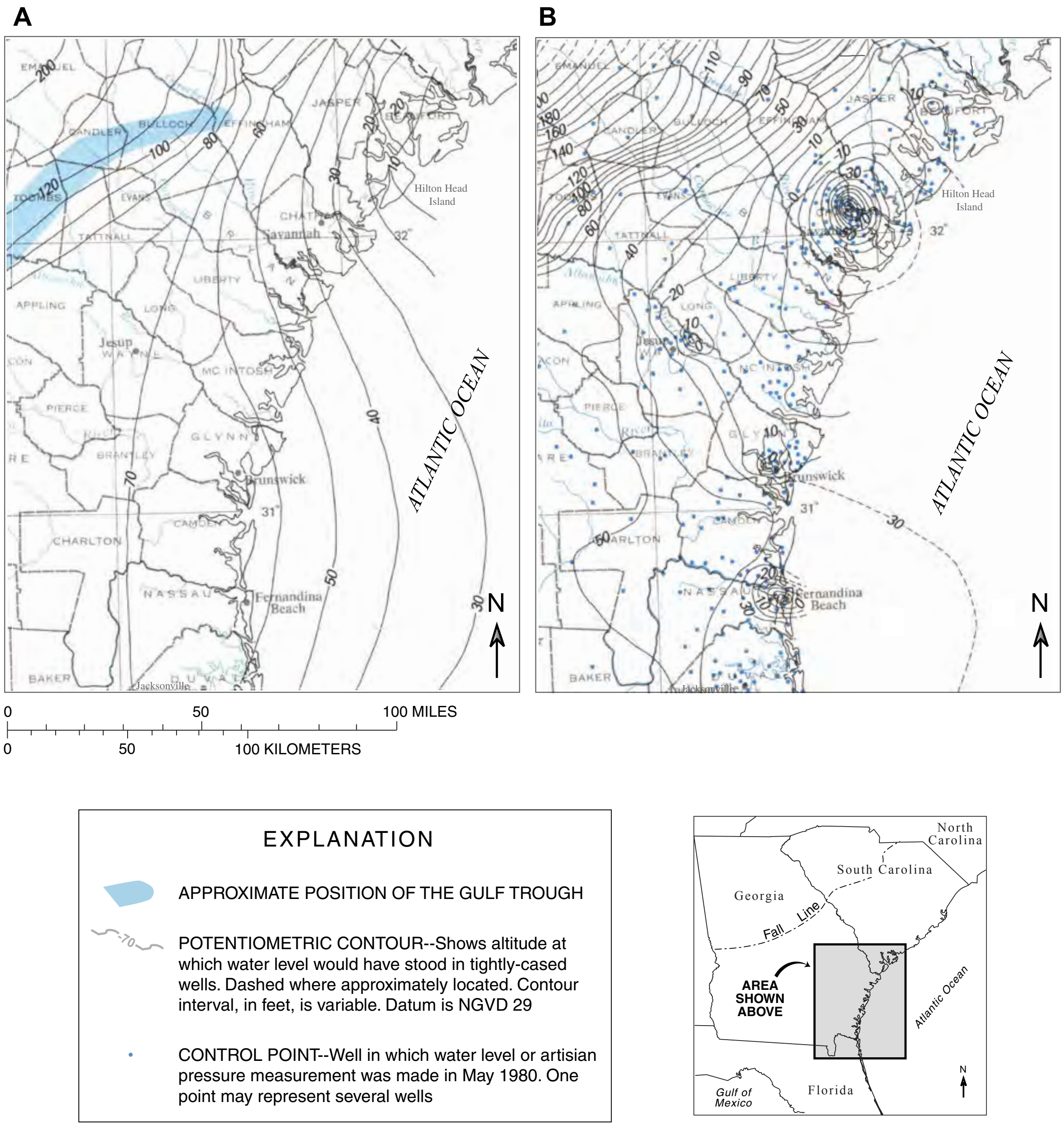


Figure 3. (A) Estimated altitudes of predevelopment (pre-1880s) and (B) May 1980 potentiometric surfaces of the Upper Floridan aquifer in the Coastal Sound Science Initiative study area, Georgia, Florida, and South Carolina (from Johnston and others, 1980; 1981).

along its eastern margins by saltwater beneath the continental shelf (fig. 4). Except for the area north of Port Royal Sound in Beaufort County, SC, the freshwater/saltwater interface in the confined Upper Floridan aquifer was held seaward of the coastline by the freshwater head in the Floridan aquifer system. The upward flow potential from the Upper Floridan aquifer to the overlying surficial aquifer created upward leakage of freshwater from the Upper Floridan aquifer, and prohibited the downward leakage of saline water from surface water and the surficial aquifer.

With onshore development of the freshwater resource of the Upper Floridan aquifer, water levels generally declined in all the coastal counties. Development altered head gradients within the Floridan aquifer system and between the Upper Floridan aquifer and the overlying surficial aquifer (Krause and Randolph, 1989; figs. 3, 4). In Beaufort County, SC, changes in head gradient resulted in the potential for downward leakage of modern saltwater through breaches in the upper confining unit and lateral encroachment of relict saltwater along the freshwater/saltwater interface in the Floridan aquifer system beneath Port Royal Sound (Krause and Randolph, 1989; Landmeyer and Belval, 1996). In Glynn County, GA, and Duval County, FL, changes in head gradients resulted in upward intrusion of saltwater from the Fernandina permeable zone along vertical fractures or faults, contaminating freshwater in the Upper Floridan aquifer (Wait and Gregg,

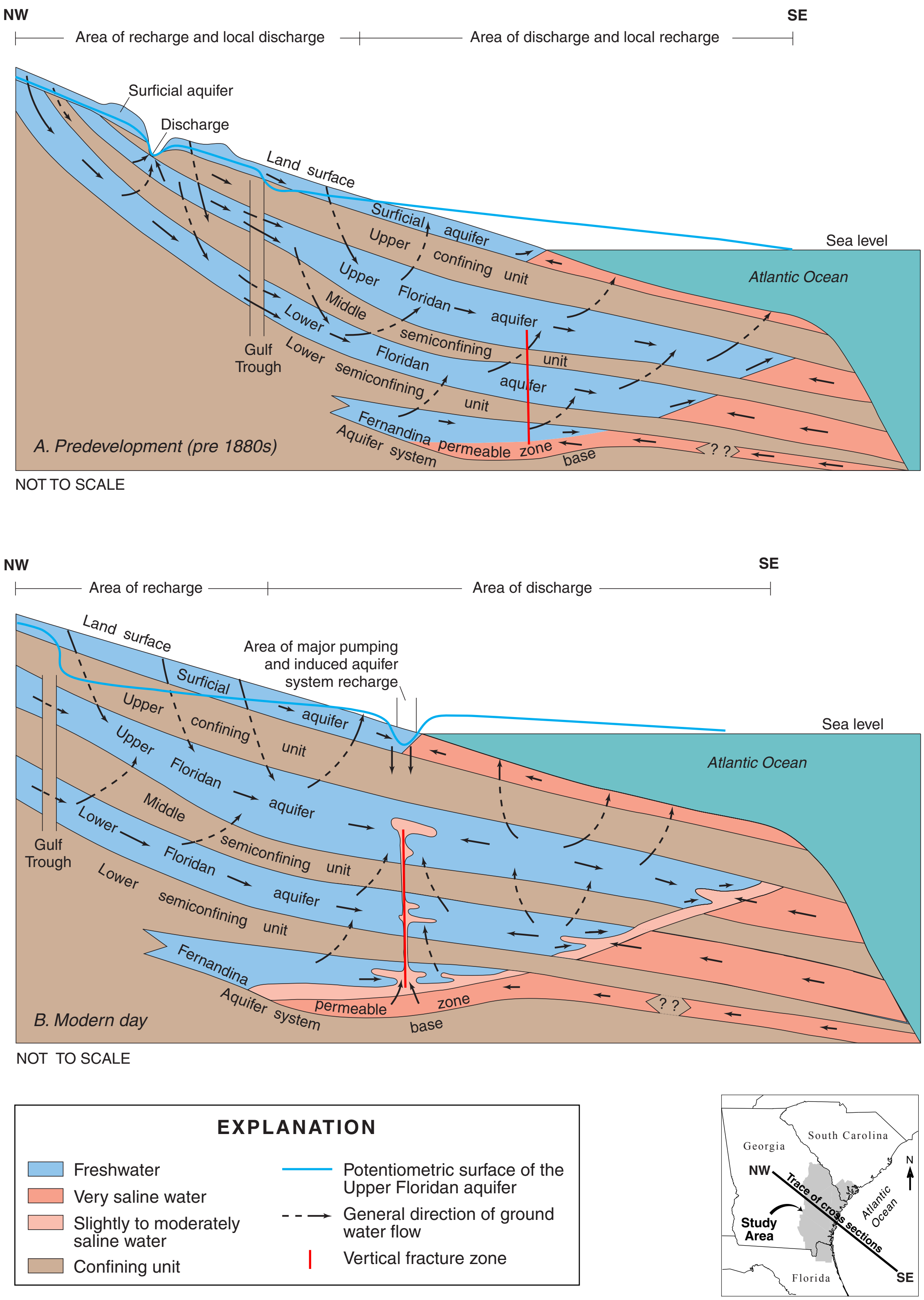


Figure 4. Conceptual models of (A) predevelopment (pre-1880s) and (B) modern-day (May 1985) ground-water flow in the Floridan aquifer system from the outcrop area in the northwest to the offshore area in the southeast, coastal Georgia (from Krause and Randolph, 1989).

1973; Krause and Randolph, 1989; Maslia and Prowell, 1990; Spechler, 1994; Phelps and Spechler, 1997; fig. 4).

Hydrogeology of the Lower Floridan Aquifer

Hydrogeologic data for the Lower Floridan aquifer collected at the six CSSI sites and the St Simons Island site were compiled to create a hydrogeologic cross section for the study area from wells 33D073 and 33D074 at the St Marys site to well 34S011 at the Pineora site (tables 3, 4; pl. 1). The altitudes of the top of the Lower Floridan aquifer and the base of the Floridan aquifer system at each site were compared with the altitudes of hydrogeologic contacts of the Floridan aquifer system mapped by Miller (1986).

The semiconfined permeable zones of the surficial aquifer and the upper and lower Brunswick aquifers in the upper confining unit were not evaluated as part of this investigation at the CSSI and St Simons Island sites. Therefore, the surficial aquifer, as presented in the cross section, represents only the unconfined surficial aquifer at each site (pl. 1; table 4). The upper confining unit includes the semiconfined part of the surficial aquifer and the upper and lower Brunswick aquifers, although the permeable zones and aquifers are not represented on the cross section.

The following discussion focuses on the hydrogeology of the carbonate strata of the Lower Floridan aquifer. The strata containing the surficial aquifer and upper confining unit are not discussed in further detail.

Upper Permeable Zone

The top of the upper permeable zone of the Lower Floridan aquifer does not correlate to a specific formation contact but correlates lithologically to the top of the porous carbonate strata in the middle Eocene Avon Park Formation below the relatively nonporous strata of the middle confining unit at all seven sites (table 4; pl. 1). The top of the upper permeable zone at the six CSSI sites correlates within 50 ft of the top of the Lower Floridan aquifer, as mapped by Miller (1986; fig. 5). The top of the porous strata of the upper permeable zone at the St Simons Island site, however, was more than 80 ft higher than Miller's top of the Lower Floridan aquifer, based on the distribution of porous strata observed in well 35H068.

The six CSSI sites were easily divided into the northern sites (Shellman Bluff to Pineora) and the southern sites (St Marys and Brunswick) based on stratigraphic and hydrogeologic characteristics of the Lower Floridan aquifer and its relation to underlying carbonate and non-carbonate strata. The upper permeable zone of the Lower Floridan aquifer at the St Marys and Brunswick sites in this report refers only to the porous-permeable carbonate strata with relatively low-chloride (less than 500 mg/L) water, excluding the saltwater-bearing strata of the Fernandina permeable zone. The hydrogeology of the Floridan aquifer system at the St Simons Island site has stratigraphic and lithologic characteristics of both the southern and northern sites; however, the upper permeable zone of the Lower Floridan aquifer at the St Simons Island site is lithologically similar to the upper permeable zone at the St Marys and Brunswick sites. As a result, the St Simons Island site is included as one of the southern sites.

Northern Sites

The upper permeable zone at the northern sites from Shellman Bluff to Pineora consists of strata of the middle Eocene Avon Park Formation, based on the lithologies observed in cuttings and the altitude of the top of the early Eocene Oldsmar Formation, as mapped by Miller (1986). The base of the upper permeable zone of the Lower Floridan aquifer correlates to the base of the carbonate strata of the Floridan aquifer system (pl. 1; fig. 6).

At the Pineora and Pembroke sites, the upper permeable zone consists of strata dominated by nonporous limestone and dolomitic limestone with only a few beds of porous dolomite. The Lower Floridan aquifer at Pineora is a 157-ft-thick interval of carbonate strata from the base of the middle confining unit to the base of the Floridan aquifer system, but includes only three beds of porous dolomite with a cumulative thickness of 38 ft. The porous dolomite beds range from 8 to 18 ft thick and represent approximately 24 percent of the total thickness of the Lower Floridan aquifer at the Pineora site. Well 33R045 at the Pembroke site was drilled to a total depth of 994 ft but did not penetrate the base of the Floridan aquifer system. Based on the penetrated strata in well 33R045, the Lower Floridan aquifer is at least a 93-ft-thick interval with four dolomite beds. The four dolomite beds have a cumulative thickness of 41 ft and represent approximately 44 percent of the total thickness of the Lower Floridan aquifer. Intercrystalline porosity in the dolomite varies from 10 to 20 percent at the Pembroke site and is less than 10 percent at the Pineora site. At both sites, the nonporous limestone interbedded with the dolomite generally is fine grained and fossiliferous with 1 to 3 percent glauconite, as is typical of the Avon Park Formation at the other northern sites.

Aquifer tests were not conducted at the Pineora and Pembroke sites, but the ability of the aquifer to yield water can be inferred from observations made during the drilling of both wells. Reverse-air rotary discharge for the drill rig at these two sites was estimated to be 100 to 120 gallons per minute during routine drilling. In reverse-air rotary drilling, potable water is added to the well if the formation does not yield adequate water to return the cuttings. For the open borehole in the fourth stage of well 33R045 at Pembroke, potable water was added during the drilling of the first two porous dolomite beds from 684 to 695 ft and from 711 to 719 ft below the North American Vertical Datum of 1988 (NAVD 88); however, these two dolomite beds provided an adequate supply of water to

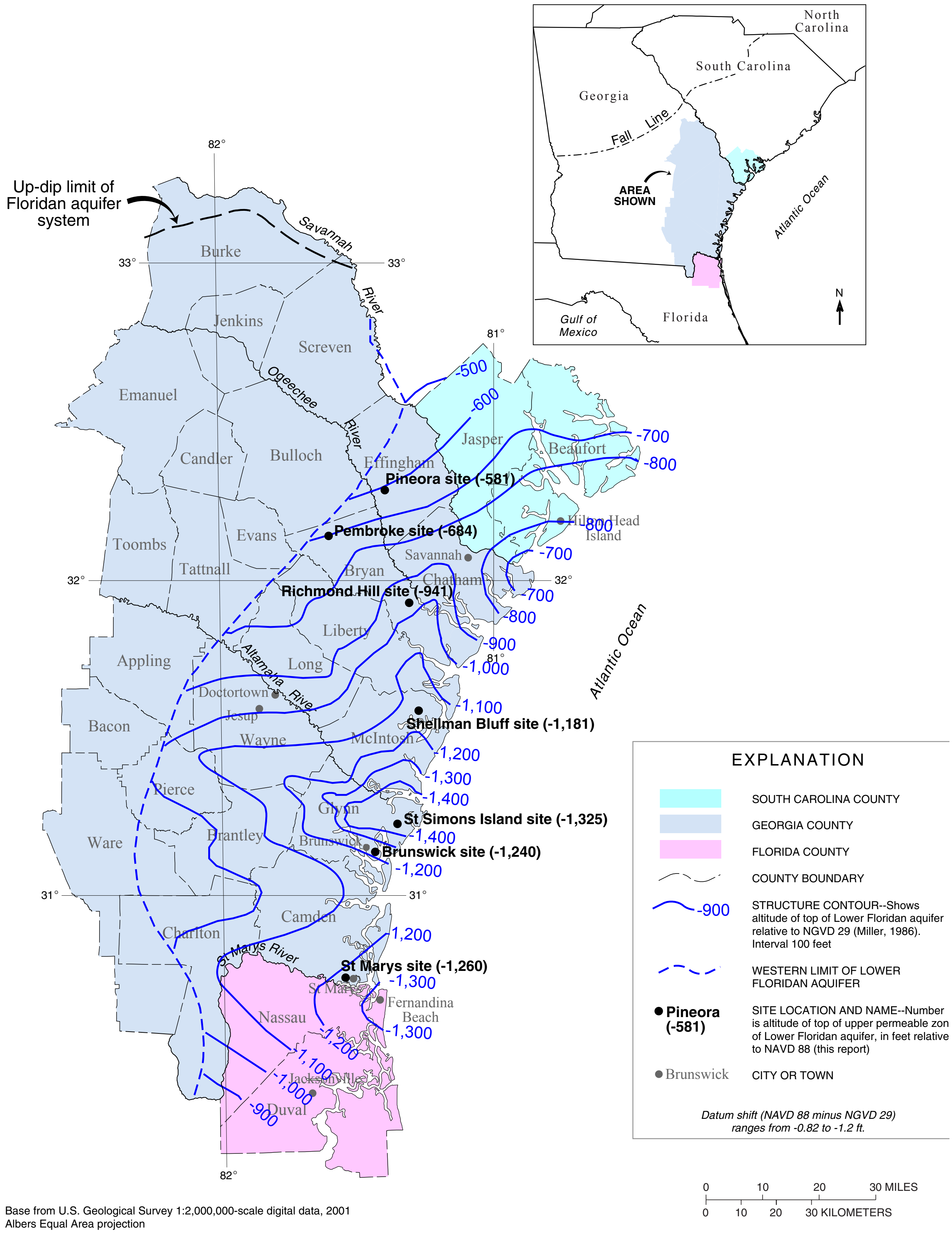


Figure 5. The altitude of the top of the Lower Floridan aquifer (Miller, 1986) and the tops of the upper permeable zone of the Lower Floridan aquifer as determined in this investigation at the Coastal Sound Science Initiative and St Simons Island sites, Georgia, Florida, and South Carolina.

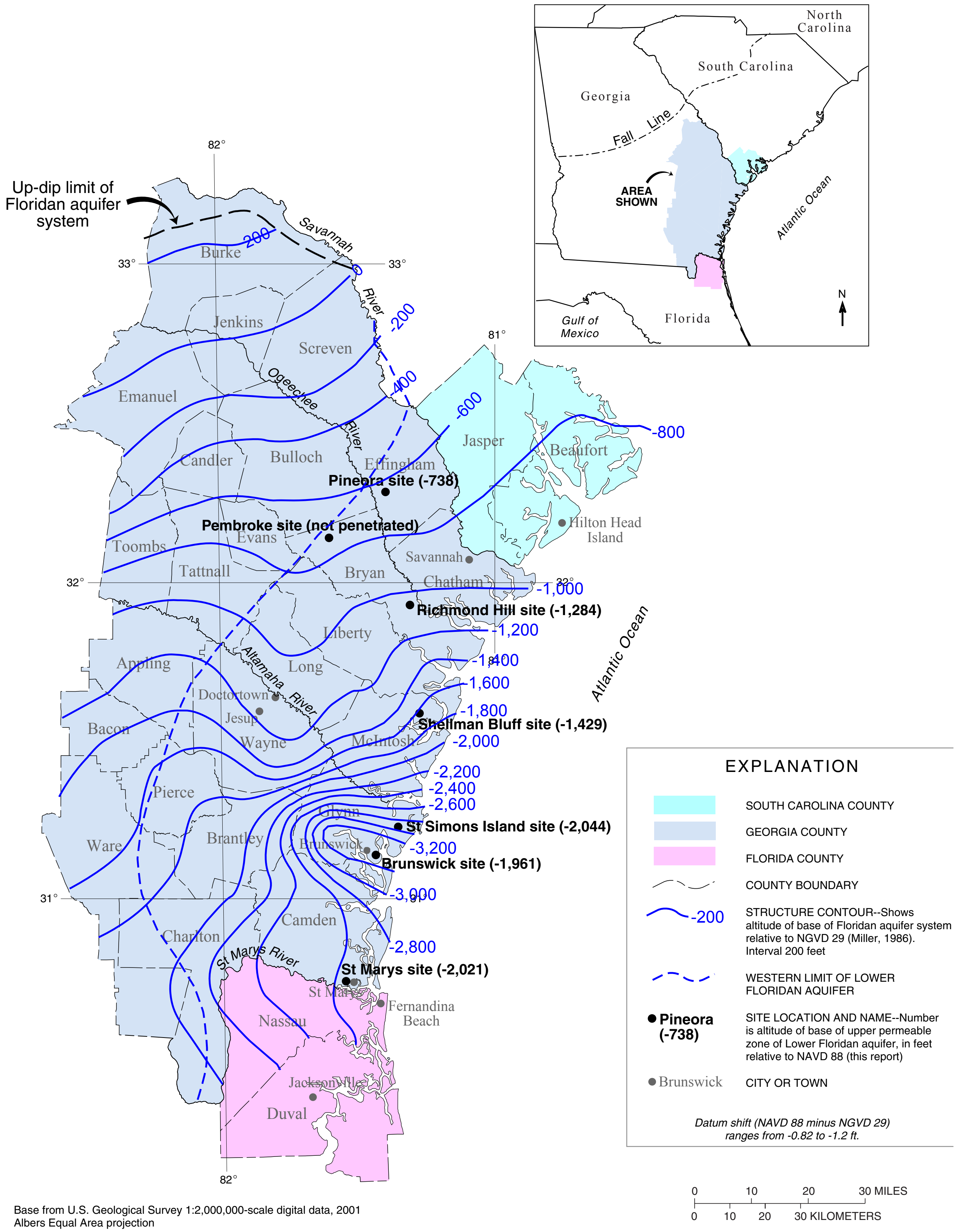


Figure 6. The altitude of the base of the Floridan aquifer system (Miller, 1986) and the bases of the upper permeable zone of the Lower Floridan aquifer as determined in this investigation at the Coastal Sound Science Initiative and St Simons Island sites, Georgia, Florida, and South Carolina.

the borehole to complete the drilling of the remainder of the open interval in the fourth stage without adding potable water to the well. Potable water was added during the drilling of the entire Lower Floridan aquifer interval in the fourth stage of well 34S011 at the Pineora site because the strata of the Lower Floridan aquifer could not yield enough water to the borehole to maintain the reverse-air rotary discharge for drilling, even with the borehole open to all three dolomite beds.

The Lower Floridan aquifer is 343 ft thick at the Richmond Hill site and 228 ft thick at the Shellman Bluff site. The predominantly porous limestone strata at the top of the upper permeable zone of the Lower Floridan aquifer are 140 ft thick at the Richmond Hill site and 35 ft thick at the Shellman Bluff site. The porous limestone at Richmond Hill is dolomitic and nondolomitic with minor amounts of chert and generally only 5- to 10-percent interparticle porosity, although a few intervals have as much as 20-percent interparticle porosity. The porous limestone at the Shellman Bluff site is nondolomitic and fossiliferous and has only 5- to 10-percent interparticle porosity. The porous limestone at the top of the Lower Floridan aquifer is separated from the base of the Floridan aquifer system by 203 and 213 ft of nonporous and low-porosity limestone at the Richmond Hill and Shellman Bluff sites, respectively. The nonporous limestone is dolomitic, sandy, and glauconitic near the base of the Floridan aquifer system and also includes intervals with chert. The altitude of the top of the Lower Floridan aquifer of Miller (1986) approximates the altitudes of the tops of the Lower Floridan aquifer at the Richmond Hill and Shellman Bluff sites and the top of permeable zone 5 of McCollum and Counts (1964) in Chatham County. Therefore, the Lower Floridan aquifer at Richmond Hill and Shellman Bluff, as recognized in this report, correlates to only permeable zone 5 of McCollum and Counts (1964).

Transmissivities calculated for the upper permeable zone of the Lower Floridan aquifer were 8,300 feet squared per day (ft^2/d) in well 35P109 at the Richmond Hill site and 6,000 ft^2/d in well 35L085 at the Shellman Bluff sites. In comparison, transmissivities for the Upper Floridan aquifer were 70,000 ft^2/d for well 35P110 at the Richmond Hill site, and ranged from 20,000 to 50,000 ft^2/d in Chatham County, and from 130,000 to 160,000 ft^2/d in Liberty County, GA (Harrelson and Falls, 2003; Clarke and others, 2004).

Southern Sites

The upper permeable zone of the Lower Floridan aquifer at the St Marys, Brunswick, and St Simons Island sites is thicker than the Upper Floridan aquifer and has total thicknesses ranging from 600 to 760 ft. The aquifer consists of porous limestone and dolomite of the middle Eocene Avon Park Formation interbedded with nonporous carbonate strata and includes the upper part of the early Eocene Oldsmar Formation, unlike the northern sites (pl. 1; apps. 1, 2). The porous limestone and dolomite strata represent about 20 to 30 percent of the total thicknesses of the upper permeable zone of the Lower Floridan aquifer at the southern sites. The upper permeable zone includes 191, 101, and only 31 ft of the early Eocene Oldsmar Formation at the St Marys, Brunswick, and St Simons Island sites, respectively. The limestone in the early Eocene strata at these three sites commonly is pelleted and fossiliferous, in contrast to the generally fossiliferous texture of the middle Eocene strata. Chert nodules and glauconite pellets are present in the limestone.

The abundance of porous and nonporous dolomite in the upper permeable zone is one of the distinctive characteristics of the Avon Park Formation at the three southern sites, particularly in comparison with the limestone-dominated strata at the Shellman Bluff and Richmond Hill sites. Beds of dolomite in the early and middle Eocene strata vary in thickness from a few feet to several tens of feet. Intercrystalline and moldic porosity in the porous dolomite varies from 10 to 35 percent. Voids—fractures and solution cavities—were detected during drilling of the Lower Floridan aquifer in well 34H495 at Brunswick, particularly in association with the thick dolomite beds from 1,673 to 1,965 ft below NAVD 88 (app. 2). Solution cavities also were penetrated at 1,260 and 2,060 ft below NAVD 88 during the drilling of well 33D074 (Mr. Nolan Col, St Johns River Water Management District, written commun., January 8, 2002). Interparticle porosity in the porous limestone of the upper permeable zone is generally 5 to 10 percent in the early and middle Eocene strata.

In addition to limestone and dolomite, Miller (1986) also described gypsum—a calcium sulfate mineral—in the early and middle Eocene strata of the upper permeable zone of Camden and Glynn Counties, GA. Gypsum is present only below the top of the early Eocene Oldsmar Formation at the Brunswick and St Simons Island sites (pl. 1). Natural-gamma logs were used to correlate the top of the early Eocene at the Brunswick site to 1,844 ft below NAVD 88 in well 33D074 at the St Marys site. The first appearance of gypsum in well 33D074 at the St Marys site is in an interval of dense dolomite from approximately 1,610 to 1,620 ft below NAVD 88 (Mr. Nolan Col, St Johns River Water Management District, written commun., January 8, 2002). This places the first appearance of gypsum at 224 ft above the top of the early Eocene at the St Marys sites.

Calculated transmissivity in the upper permeable zone of St Marys well 33D073 open from 1,356 to 1,491 ft is 13,000 ft^2/d, considerably lower than the range of transmissivity of 19,000 to 130,000 ft^2/d for the Upper Floridan aquifer in Camden County (Clarke and others, 2004). Aquifer tests were not completed for well 33D074 at St Marys and well 34H500 at Brunswick, which are open to the upper permeable zone of the Lower Floridan aquifer. The calculated transmissivity of the Lower Floridan aquifer for the interval open from 1,371 to 1,571 ft below NAVD 88 in well 35H068 at the St Simons Island site was 500 ft^2/d (Mr. Richard H. Johnston, Glynn County Water Resource Advisory Committee, written commun., June 2002).

The upper permeable zone of the Lower Floridan aquifer at the St Marys and Brunswick sites is separated from the Fernandina permeable zone by an interval of nonporous and low-porosity limestone and dolomite in the early Eocene Oldsmar Formation. Miller (1986) informally referred to this interval as the local confining unit because of its limited extent beneath the southern coastal counties of Georgia and the northeastern counties of Florida. The strata of Miller's local confining unit are 85 ft thick in well 33D074 at St Marys and 118 ft thick in well 34H495 at Brunswick (table 4).

Fernandina Permeable Zone

Of the seven sites described in this report, the Fernandina permeable zone was present only at the St Marys and Brunswick sites. The extent of the Fernandina permeable zone, as mapped by Miller (1986), included all of Camden and Glynn Counties and parts of McIntosh, Charlton, and Ware Counties, GA, and all or parts of seven counties in northeastern Florida (fig. 7). The Floridan aquifer system, however, at the St Simons Island site in coastal Glynn County and Shellman Bluff in northeastern McIntosh County did not include the Fernandina permeable zone, which constrains the Fernandina permeable zone to a smaller part of coastal Georgia than was proposed by Miller (1986; fig. 7).

The top of the Fernandina permeable zone was penetrated by well 34H495 at the Brunswick site and by well 33D074 at the St Marys site at altitudes of 2,078 and 2,106 ft below NAVD 88, respectively (fig. 7; table 4). At both sites, the top of the Fernandina permeable zone is above the top of the Paleocene Cedar Keys Formation, as mapped by Miller (1986) and, therefore, in the early Eocene Oldsmar Formation (pl. 1; table 4).

Well 33D074 at the St Marys site was terminated after penetrating 11 ft of porous and nonporous dolomite below the top of the Fernandina permeable zone. Well 34H495 at the Brunswick site penetrated 633 ft of the Fernandina permeable zone from 2,078 to 2,711 ft below NAVD 88, including 72 ft of porous to nonporous dolomite and nonporous limestone of the early Eocene Oldsmar Formation and 561 ft of porous and nonporous dolomite of the Paleocene Cedar Keys Formation. Well 34H495 did not penetrate the base of the Floridan aquifer system. In addition to dolomite and limestone, gypsum is present in association with the dense dolomite from 2,400 to 2,711 ft below NAVD 88 in well 34H495. Small clasts of argillaceous mudstone also were observed in dolomite cuttings from 2,610 to 2,711 ft below NAVD 88.

Intercrystalline porosity in the porous dolomite ranges from 10 to as much as 35 percent. Moldic porosity, resulting from the dissolution of carbonate shells, was noticeable in the interval from 2,580 to 2,711 ft below NAVD 88 and ranged from 5 to 10 percent. In addition to microscopic pores, six voids of at least 1 to 4 ft in height, interpreted as fracture zones and solution cavities, were detected between 2,231 and 2,668 ft below NAVD 88 during the drilling of the Fernandina permeable zone in well 34H495 (app. 2). After penetrating the fracture zone at 2,231 ft, sand-sized fragments of dolomite spilled into the open borehole for several hours. Aquifer tests were not conducted in CSSI well 34H495 in downtown Brunswick and well 33H188 on Colonels Island to the west of the Brunswick site.

Lower Confining Unit

At the four northern sites and the St Simons Island site, marl underlying the base of the Floridan aquifer system was penetrated. Given its fine-grained texture, the marl is assumed to represent confinement between the Floridan aquifer system and the underlying aquifers in the Cretaceous strata, and is referred to as the lower confining unit by Miller (1986). Well 33D074 at the St Marys site and well 34H495 at the Brunswick site did not penetrate the base of the Floridan aquifer system and the marl of the lower confining unit.

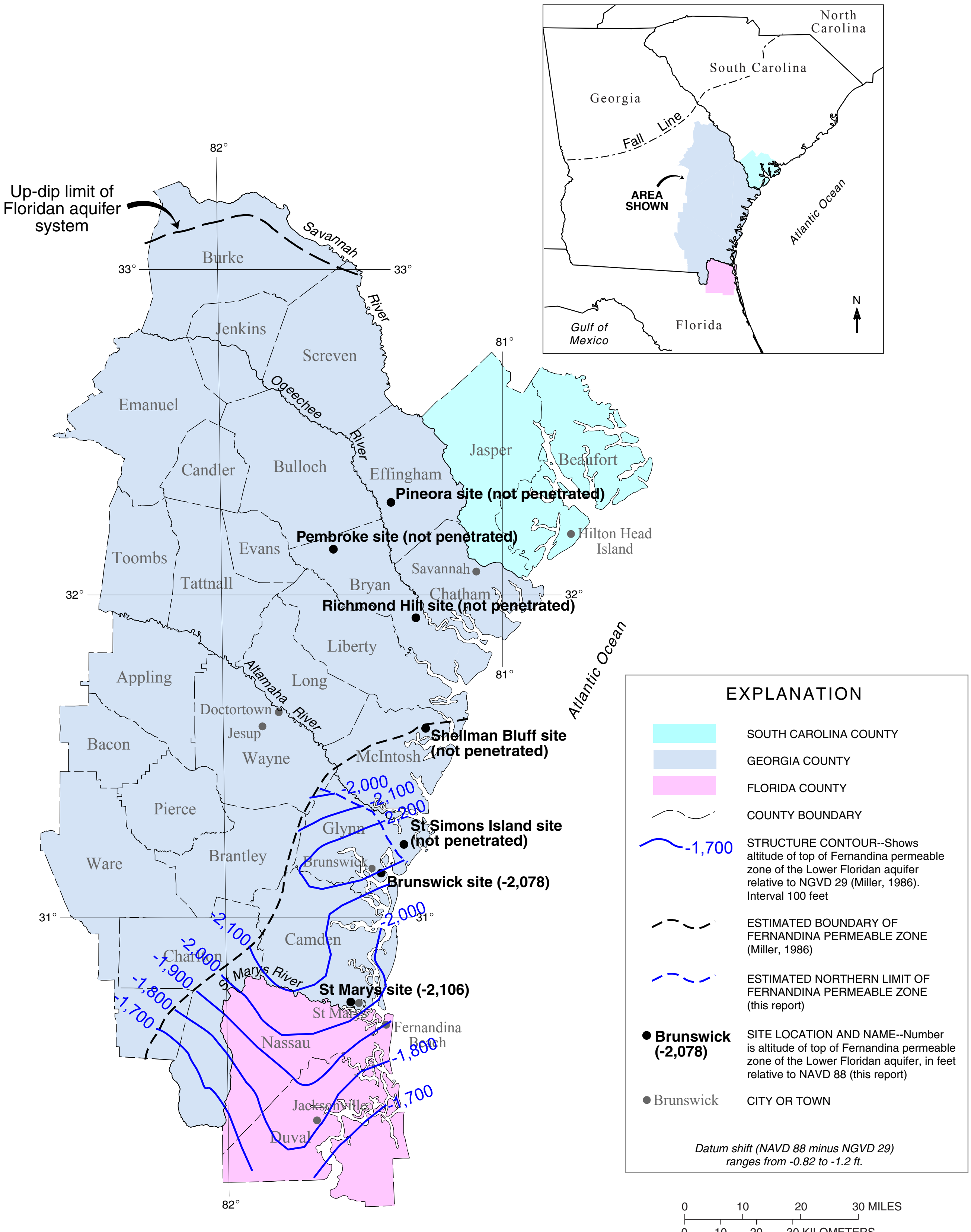
Marl, as referenced in this report, is a lithologic term applied to a semi-indurated, fine-grained mixture of carbonate, clay, silt, and sand and generally is dominated by clay and silt. The actual lithologies collectively referred to as marl include calcareous claystone and siltstone, and a few beds of calcareous sandstone, and generally are olive gray to light green. The marl generally contains pellets of glauconite and phosphate, and nodules of chert.

The base of the Floridan aquifer system and the underlying marl is recognized easily in cuttings during drilling and on the natural-gamma log, which shows a sharp increase in counts per second from carbonate strata to the marl (pl. 1). The boreholes of wells 35P109 and 35L085 penetrated soft black clay beneath the marl for a total marl thickness of 331 ft at Richmond Hill and 432 ft at Shellman Bluff, respectively.

Water Levels in the Floridan Aquifer System

Water-level hydrographs for CSSI and other nearby wells opened to the Upper Floridan aquifer, and the upper permeable and Fernandina permeable zones of the Lower Floridan aquifer, recorded similar responses of the Floridan aquifer system to changes in hydraulic head relative to annual recharge cycles and to local and regional ground-water use from the Upper Floridan aquifer. These hydrographs also recorded the response of the Floridan aquifer system in coastal Georgia to the effects of a regional drought from spring 1998 to summer 2002.

Water-level trends are similar in the three hydrogeologic units, but the altitudes of measured water levels can be similar or dissimilar, depending on confinement, head gradients, and local water use. The concentrations of total dissolved solids (TDS) in water samples collected from the CSSI and St Simons Island wells also are considered in the following discussion of measured water-level altitudes because water in the upper permeable and Fernandina permeable zones of the Lower Floridan aquifer typically have greater TDS concentrations than water in the Upper Floridan aquifer (Falls and others, 2001). Consequently, measured water levels typically



Base from U.S. Geological Survey 1:2,000,000-scale digital data, 2001
Albers Equal Area projection

Figure 7. The extent and altitude of the top of the Fernandina permeable zone of the Lower Floridan aquifer (Miller, 1986) and the extent and the altitudes of the tops of the Fernandina permeable zone as determined in this investigation at the Coastal Sound Science Initiative and St Simons Island sites, Georgia, Florida, and South Carolina.

do not represent true freshwater head in the Lower Floridan aquifer.

The density of water is a function of the TDS concentration. With increased density, the altitude to which water rises in a well cased in a confined aquifer reduces relative to an equivalent freshwater head. The relation is described by Cooper and others (1964) using the following formula:

$$l_f = l_s p_s / p_f$$

where:

l_f is the calculated water column length for equivalent freshwater in feet above the bottom of the casing,

l_s is the measured water column length for saline water in feet above the bottom of the casing, and

p_s / p_f is the ratio of saline-water density in the casing to freshwater.

Consideration of the TDS concentration and the need to make density corrections for water levels is important, given the length of casings for wells opened to the Lower Floridan aquifer in coastal Georgia. For example, the water level in a well with a 1,000-ft-long column of saltwater in the well casing would have what is termed an equivalent freshwater head that is 24 ft higher, assuming a saltwater to freshwater density ratio of 1.024. With the exception of the Pineora and Pembroke sites, the CSSI and St Simons Island wells that are open to the Lower Floridan aquifer have more than 1,000 ft of casing. Even if the density ratio was only 1.001, the equivalent freshwater head for a 1,000-ft-long column of water in the casing would be as much as 1 ft higher than the measured head.

Measured heads, not equivalent freshwater heads, are presented in the hydrographs in this report. The effects of density on water levels are discussed, if considered necessary, to explain head relations between the Upper and Lower Floridan aquifers at the CSSI and St Simons Island sites. The discussion of the effects of density on water levels is based on the calculated TDS concentrations for water samples collected after the development of each well. The TDS concentrations were calculated using the software program, WATEQ4F, which summed the concentrations of dissolved constituents from laboratory analyses of water samples collected from the Floridan aquifer system (Ball and Nordstrom, 1991). The following discussion assumes that the TDS concentration of the water in each well casing remained constant after developing and sampling the well for the period of record of each hydrograph.

Northern Sites

Wells open to the Upper and Lower Floridan aquifers at the northern sites from Shellman Bluff to Pineora as of January 1, 2004, were non-flowing wells. Prior to the 1880s, the potentiometric surface of the Upper Floridan aquifer, and probably the Lower Floridan aquifer, was above land surface at the Shellman Bluff and Richmond Hill sites, and approximately 20 ft below land surface at the Pineora and Pembroke sites (fig. 3). Water levels in the Upper and Lower Floridan aquifers at these sites are influenced by regional water use in coastal Georgia and were below land surface at all four sites during the period of record.

Wells 35P109 and 35P110 at the Richmond Hill site in Bryan County, GA, are open to the Upper and Lower Floridan aquifers, respectively, and have nearly identical hydrographs for the period from June 2000 to January 1, 2004 (fig. 8). Water levels in both wells generally have annual water-level highs in late winter and early spring (March–April) and annual water-level lows in late summer (August–September) in response to the regional effects of annual recharge to the Floridan aquifer system. Prior to August 2002, the drought resulted in differences between annual water-level highs and lows at this site that ranged from 2 to 4 ft. With abundant rainfall in the late summer and fall of 2002, water levels rose by more than 7 ft in both wells and continued to rise during 2003. The difference between water-level altitudes in the Upper and Lower Floridan aquifers generally ranges from 0 to 0.2 ft, but was as much as 0.5 ft in October 2000. Measured water levels for the Lower Floridan aquifer are not consistently higher or lower than measured water levels in the Upper Floridan aquifer at this site. The TDS concentration in the water sample from the Lower Floridan aquifer was 1,627 mg/L, compared with 247 mg/L in the Upper Floridan aquifer at the Richmond Hill site. If the heads were corrected for density, then the Lower Floridan aquifer would have a freshwater head equal to or greater than the head in the Upper Floridan aquifer for the period of record.

The hydrograph for well 35L085, opened to the Lower Floridan aquifer at the Shellman Bluff site, was compared with the hydrograph for well 35M013 (fig. 9). Well 35M013 is 3.6 miles northeast of well 35L085 and is the closest well with a water-level recorder open to the Upper Floridan aquifer (fig. 1). Given the distance between the two wells, the head relation between the two wells does not represent the head relation between the Upper and Lower Floridan aquifer at the Shellman Bluff site. As in the hydrograph for the Richmond Hill wells, hydrographs for the two wells in McIntosh County

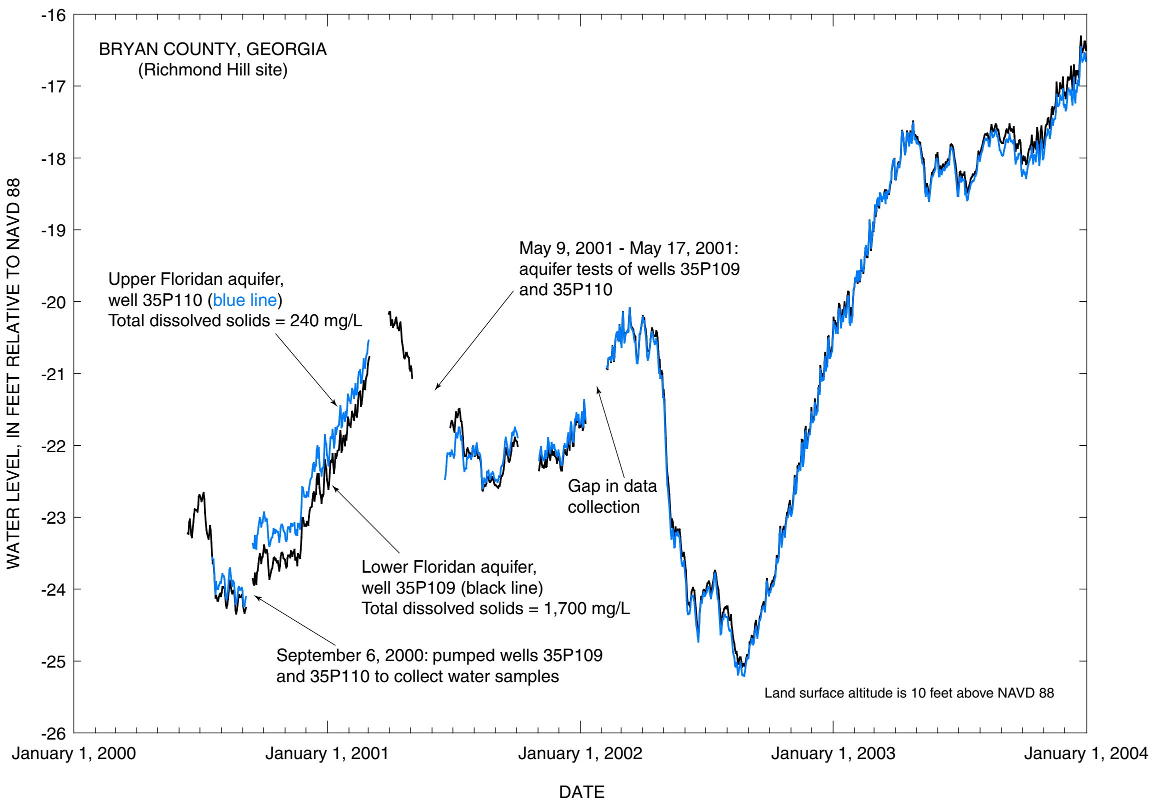


Figure 8. Daily mean water levels in Richmond Hill wells 35P109 and 35P110, Bryan County, Georgia, June 13, 2000, to January 1, 2004.

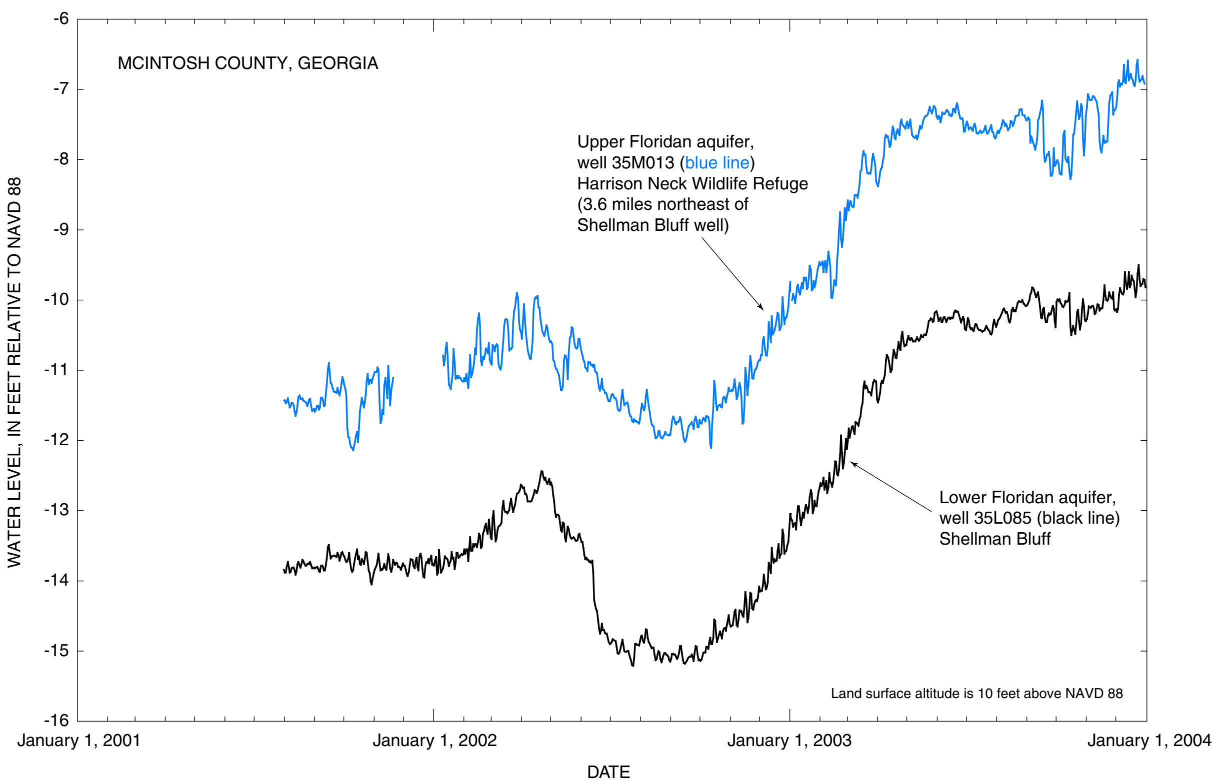


Figure 9. Daily mean water levels in Shellman Bluff well 35L085 and nearby well 35M013, McIntosh County, Georgia, August 1, 2001, to January 1, 2004.

are similar for the period of record and have highs and lows in response to annual recharge. The water-level decline of 2.5 ft from April to late August 2002 and rise of 4.9 ft from late August 2002 to June 2003 for the Lower Floridan aquifer were slightly greater than the decline of 2 ft and rise of 4.5 ft for the Upper Floridan aquifer. The TDS concentration in water collected from the Lower Floridan aquifer in well 35L085 was 2,800 mg/L. With 1,144 ft of casing and an estimated water density ratio of 1.001, the equivalent freshwater head in well 35L085 would be at least 1 ft higher than the measured head.

Wells 33R045 and 34S011 at the Pembroke and Pineora sites, respectively, are open to the Lower Floridan aquifer and have a period of record only from May 2002 to January 1, 2004 (fig. 10). Continuous water-level records for an equivalent period of record are not available for the Upper Floridan aquifer for either site. Water-level trends for the Lower Floridan aquifer at these two sites were compared with water levels in well 32R002 in Bulloch County, GA, which has a water-level recorder and is located approximately 6.5 miles northwest of the Pembroke site (fig. 1). As in the previous hydrographs, the water-level trends for the Lower Floridan aquifer at the two CSSI sites declined from spring 2002 to a low in late August and rose in fall and winter 2002 by approximately 6.5 and 7.5 ft in wells 34S011 and 33R045, respectively. The water-level trend for the Upper Floridan aquifer in well 32R002 is similar to trends in two Lower Floridan wells and has a slightly greater magnitude of recovery following the drought, in comparison to the trends in the two Lower Floridan wells. Water samples from the Upper and Lower Floridan aquifers at the Pembroke site and the Lower Floridan aquifer at Pineora had TDS concentrations of 231, 284, and 204 mg/L, respectively; so no corrections were made for density.

Southern Sites

Hydrographs for wells open to the upper permeable zone of the Lower Floridan aquifer at the Brunswick and St Marys sites, and the Fernandina permeable zone of the Lower Floridan aquifer at the Brunswick site, were compared with hydrographs of nearby monitoring wells open to the Upper Floridan aquifer (figs. 11, 12). Well 34H371 is 0.3 mile south of the CSSI wells in downtown Brunswick, GA, and is not within the chloride-contamination plume underlying downtown Brunswick (fig. 13). Well 33D069 is approximately 1.0 mile south of the CSSI wells at the St Marys site (fig. 12). Both Upper Floridan wells are farther from the industrial production wells in downtown Brunswick and St Marys than the CSSI wells. As at the Shellman Bluff, Pembroke, and Pineora sites, water levels at the Brunswick and St Marys sites can be compared to the offsite Upper Floridan wells for trends, but may not reflect the true head relations at the CSSI sites.

CSSI wells 34H500 and 34H495 are open to the upper permeable and Fernandina permeable zones of the Lower Floridan aquifer, respectively, at the Brunswick site. Measured water levels in the hydrographs for these two wells were very similar and, although higher in altitude, had the same annual

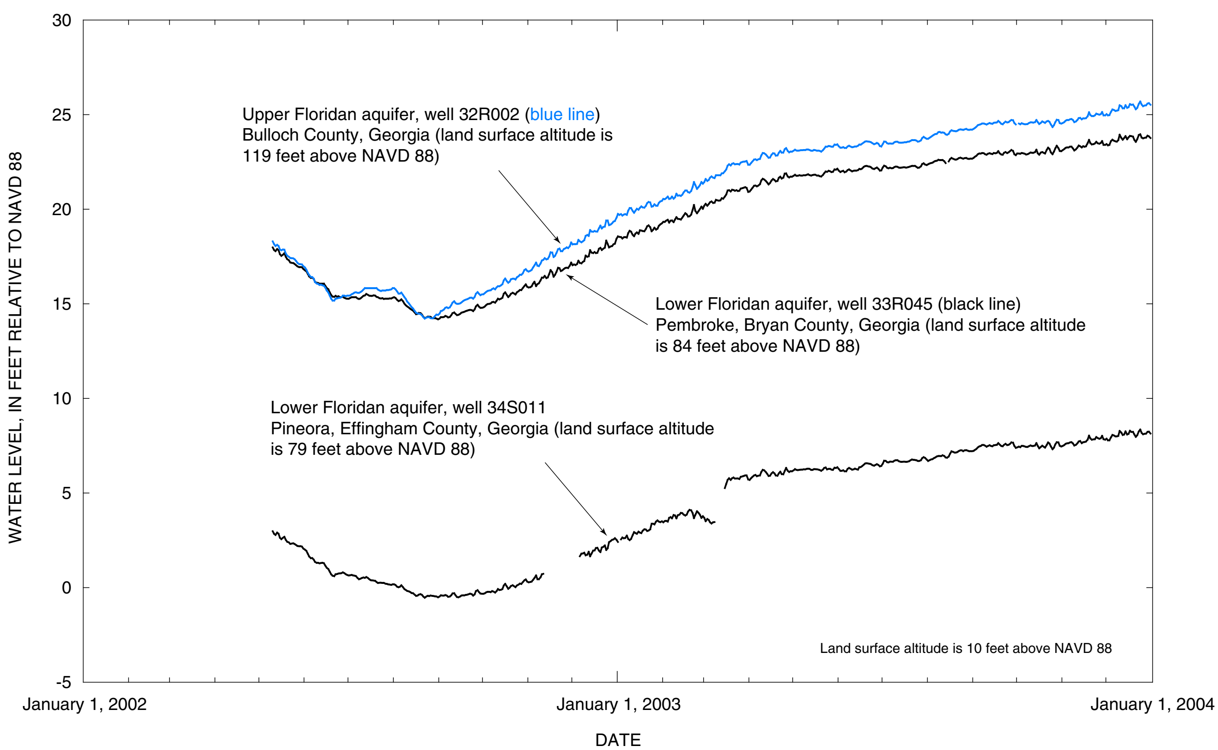


Figure 10. Daily mean water levels in Pineora well 34S011 in Effingham County, Pembroke well 33R045 in Bryan County, and well 32R002 in Bulloch County, Georgia, May 10, 2002, to January 1, 2004.

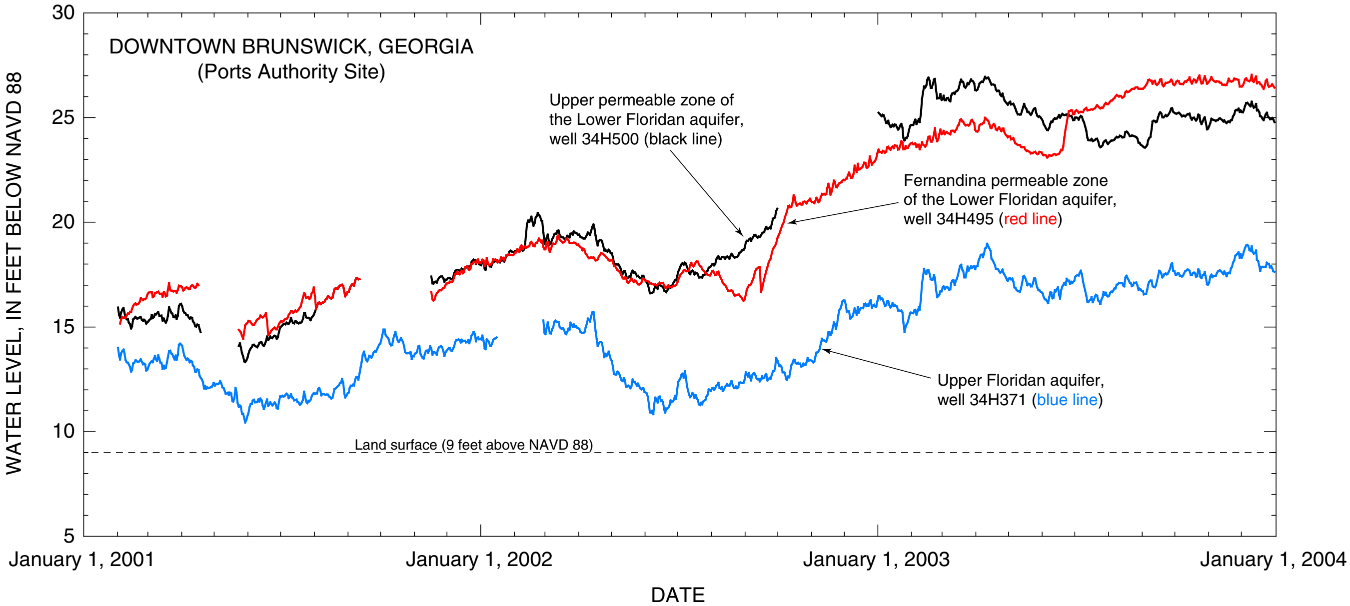


Figure 11. Daily mean water levels in wells 34H495 and 34H500 at the Brunswick site, and in nearby well 34H371 in downtown Brunswick, Glynn County, Georgia, February 1, 2001, to January 1, 2004.

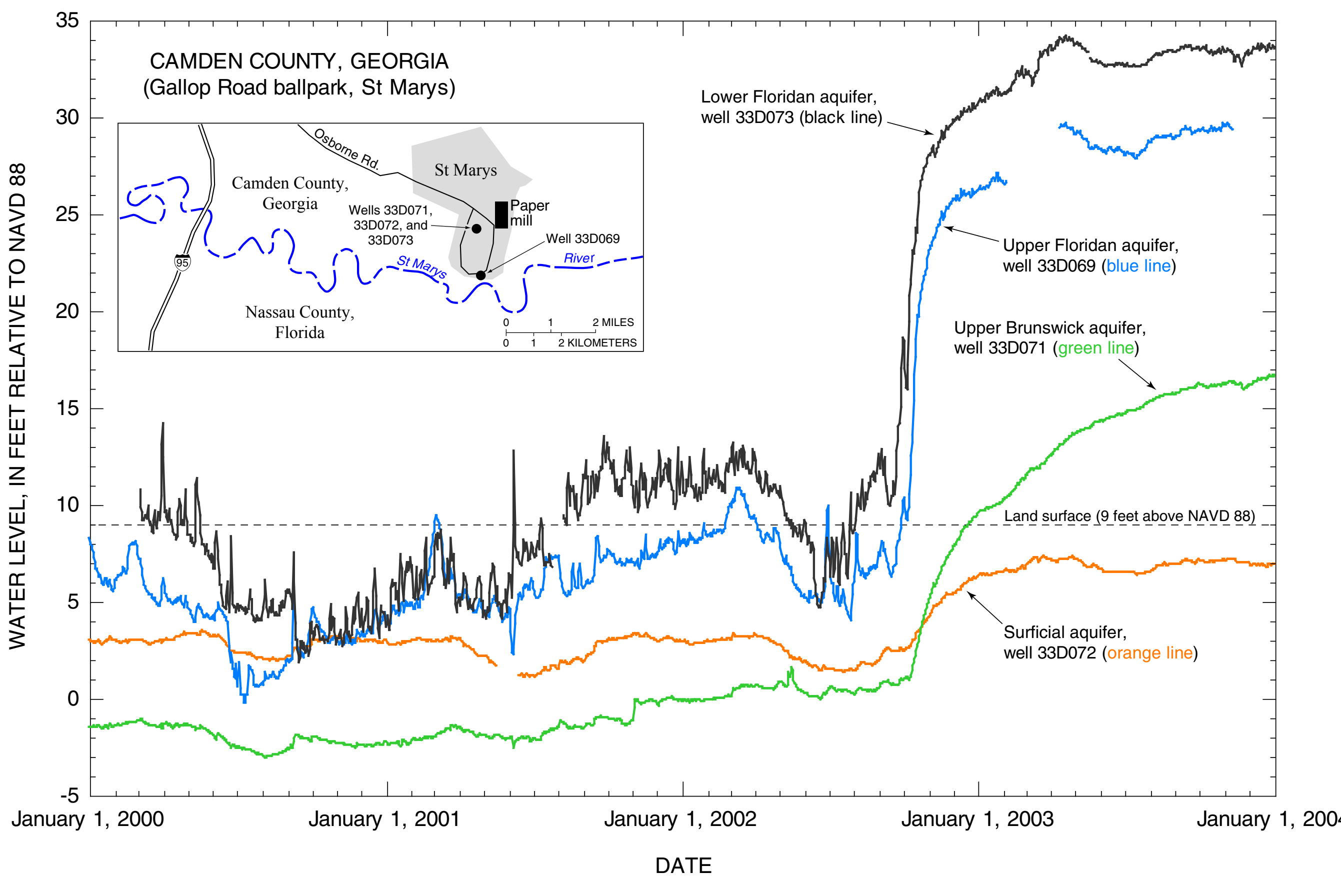


Figure 12. Daily mean water levels in wells 33D071, 33D072, and 33D073 at the St Marys site, and in nearby well 33D069 in downtown St Marys, Camden County, Georgia, January 1, 2000, to January 1, 2004.

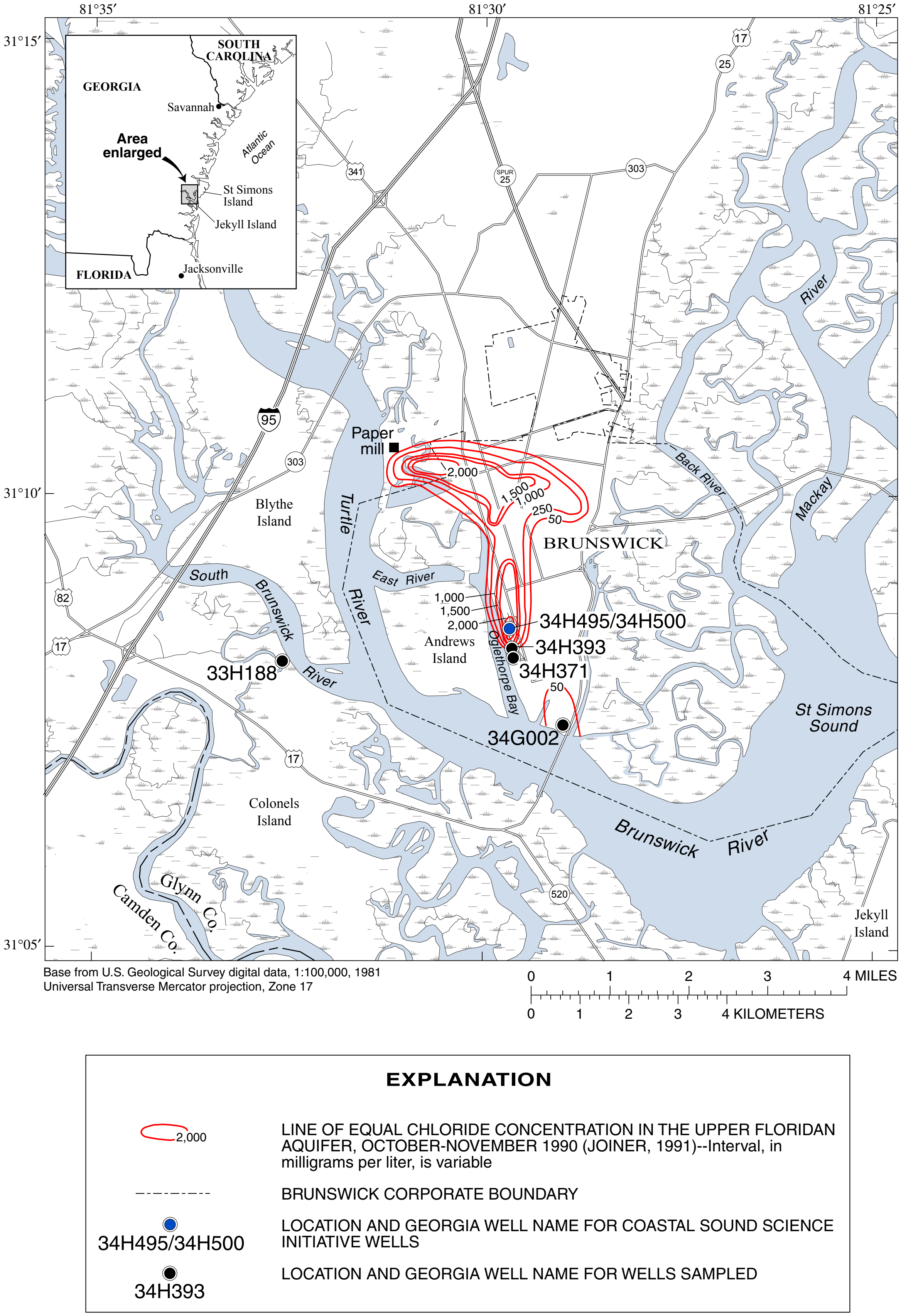


Figure 13. Locations of wells sampled for this report and extent of chloride-contamination plume in downtown Brunswick, and well sampled on Colonels Island, Glynn County, Georgia (modified from Jones and others, 2002).

highs and lows as the water levels in the Upper Floridan aquifer in nearby monitoring well 34H371 (fig. 11). For the period of record, water levels in all three wells were above land surface. Water-level altitudes in the CSSI wells were approximately 4 to 5 ft higher than in well 34H371 prior to August 2002 and 6 to 8 ft higher than in well 34H371 after August 2002, which may reflect changes in ground-water withdrawal in downtown Brunswick.

In the upper permeable zone of the Lower Floridan aquifer, TDS concentrations were 840 mg/L in well 34H500. In three samples collected in the Fernandina permeable zone of well 34H495 at the Brunswick site, TDS concentrations increased downward from 4,400 mg/L near the top of the permeable zone to 33,700 and 48,400 mg/L. The specific conductance of water discharging from the Fernandina permeable zone in well 34H495 was approximately 30,000 microsiemens per centimeter (µS/cm) at 25 degrees Celsius and is assumed to be similar in density to water discharging from well 33H188 at Colonels Island, which has a specific conductance of 29,900 µS/cm and a TDS concentration of 20,100 mg/L. With over 2,000 ft of casing and an approximate water density ratio of 1.013, the equivalent freshwater head would be 26 ft higher than the measured head for well 34H495.

At the St Marys site, well 33D073 is open to the upper permeable zone of the Lower Floridan aquifer and is within 0.5 mile of a paper mill in downtown St Marys (fig. 12). Withdrawals from the mill's production wells and the town's water-supply wells are from the Upper Floridan aquifer. The hydrograph includes measured water levels in the Lower Floridan, upper Brunswick, and surficial aquifers in wells 33D073, 33D071, and 33D072, respectively, at the CSSI St Marys site and in the Upper Floridan aquifer in well 33D069 (fig. 12). Prior to August 2002, water levels in the Lower Floridan aquifer in well 33D073 periodically were equal to and more than 2 ft greater than water levels in the Upper Floridan aquifer at well 33D069, but generally followed the same trend. Following the annual water-level low in July and August 2002, ground-water levels gradually increased until October, when the mill's production wells were turned off. Not only did water levels in the Upper and Lower Floridan aquifers increase by more than 19 ft in wells 33D069 and 33D073, but an increase greater than 15 ft also was observed in water levels in well 33D071 in the upper Brunswick aquifer. These increases resulted in artesian flow from wells 33D069, 33D072, and 33D073 and numerous Upper Floridan wells in the St Marys area. The gradual increases in water level after August 2002 were partially attributed to recovery of the aquifers after the drought, but the timing of the abrupt increase in October is attributed largely to the mill terminating ground-water withdrawal of more than 35 Mgal/d. Following the termination of industrial water use by the mill, water levels in well 33D073 in the Lower Floridan aquifer were approximately 4 ft greater than water levels in well 33D069 in the Upper Floridan aquifer. Concentrations of TDS were 571 and 569 mg/L for two Upper Floridan water samples collected from well 33D054 and 722 mg/L for the Lower Floridan water sample collected from well 33D073. Density corrections would be small and approximately the same to convert measured water levels in both wells to true freshwater head.

Water Quality

Water-quality results include chloride analyses of reverse-air rotary discharge water and field and laboratory analyses of water samples collected after well development. Chloride analyses of reverse-air rotary discharge-water samples collected during the drilling of the CSSI wells are used to document the distribution of chloride water in the Floridan aquifer system (table 5). Field and laboratory results for water samples collected from the CSSI wells and other wells in the study area are used to describe water-chemistry and isotopic compositions of water from the upper permeable and Fernandina permeable zones of the Lower Floridan aquifer relative to water from the Upper Floridan aquifer in coastal Georgia and to water-quality standards (tables 6–8). The chemical content of modern ocean water described in this report includes the ion chemistry reported in Hem (1989) and the isotopic results reported in Phelps (2001).

Chloride Results for Reverse-Air Rotary Discharge-Water Samples

Water samples from the reverse-air rotary discharge of the drill rig were collected in wells at the CSSI and St Simons Island sites during the drilling of the Floridan aquifer system and analyzed for dissolved chloride (table 5). Chloride results for these samples were compared with chloride results for wireline samples collected at specific depths in the borehole and for bulk water samples pumped from the open borehole intervals of wells (tables 6–8). Results were compared to the Federal secondary drinking-water standard of 250 mg/L for chloride (U.S. Environmental Protection Agency, 2000).

Chloride concentrations in water samples collected from the Upper Floridan aquifer and the upper permeable zone of the Lower Floridan aquifer were less than 6 mg/L at the Pineora and Pembroke sites, and ranged from 21 to 36 mg/L at the St Simons Island site and from 8 to 60 mg/L at the St Marys site (tables 4, 5). Chloride results for samples collected by wireline sampler and submersible pump from the open borehole also are similar to concentrations in the reverse-air rotary discharge samples (tables 6, 8). The highest chloride concentrations generally were near the bottom of the upper permeable zone of the Lower Floridan aquifer at St Simons Island and St Marys. In well 33D074 at St Marys, chloride concentrations were 350 and 410 mg/L in samples collected during the drilling of the local confining unit at the base of the upper permeable zone of the Lower Floridan aquifer and 3,200 mg/L in a sample collected at the top of the Fernandina permeable zone (table 5). No other water samples had chloride concentrations at the four drill sites that exceeded the

Table 5. Chloride analyses for reverse-air rotary discharge-water samples collected in the Floridan aquifer system at the Coastal Sound Science Initiative and St Simons Island wells in Georgia, and unpublished results for well 33D074 drilled by St Johns River Water Management District of Palatka, Florida, at the St Marys site, Georgia, 1999–2002.

[ft, feet below land surface; mg/L, milligrams per liter; brackets denote unpublished results for well 33D074 at the St Marys site]

St Marys well 33D073 [33D074], Camden County, Georgia		Brunswick well 34H495, Glynn County, Georgia				Brunswick well 34H500, Glynn County, Georgia	
Depth (ft)	Chloride (mg/L)	Depth (ft)	Chloride (mg/L)	Depth (ft)	Chloride (mg/L)	Depth (ft)	Chloride (mg/L)
624	35	668	1,500	2,089	1,100	700	1,600
749	34	700	1,600	2,092	1,100	716	1,700
873	35	732	1,700	2,123	1,200	731	1,700
904	35	763	1,700	2,155	1,400	761	1,700
996	32	795	1,700	2,186	2,000	793	1,700
1,042	34	827	1,700	2,217	17,000	823	1,600
1,072	31	859	1,700	2,249	17,000	855	1,700
1,103	31	890	1,800	2,281	17,000	887	1,700
1,149	36	922	1,700	2,311	17,000	918	1,600
1,224	40	953	1,700	2,343	17,000	950	1,700
1,271	34	984	1,800	2,354	17,000	982	1,700
1,302	34	1,016	1,700	2,375	17,000	1,013	1,700
1,319	35	1,047	1,500	2,407	17,000	1,044	1,700
1,334	34	1,079	1,400	2,438	17,000	1,076	1,700
1,350	35	1,111	2,800	2,470	17,000	1,107	2,700
1,365	33	1,143	2,900	2,533	17,000	1,139	2,900
1,385	32	1,174	2,800	2,564	17,000	1,237	850
1,399	32	1,206	2,200	2,595	17,000	1,269	530
1,430	33	1,237	2,400	2,626	17,000	1,301	470
1,462	31	1,269	2,200	2,657	17,000	1,332	460
1,494	31	1,301	2,300	2,689	27,000	1,364	440
[1,578]	25	1,333	2,200	2,720	26,000	1,396	280
[1,593]	25	1,365	2,300			1,400	290
[1,623]	30	1,405	2,000				
[1,655]	30	1,426	36				
[1,685]	8	1,447	14				
[1,716]	13	1,489	13				
[1,747]	15	1,521	13				
[1,783]	11	1,553	13				
[1,813]	12	1,585	12				
[1,844]	12	1,617	12				
[1,875]	20	1,648	12				
[1,906]	50	1,679	120				
[1,935]	60	1,709	100				
[1,966]	56	1,740	140				
[1,997]	52	1,772	140				
[2,028]	52	1,803	170				
[2,060]	350	1,837	220				
[2,091]	410	1,869	310				
[2,121]	3,200	1,899	320				
		1,931	340				
		1,962	340				
		1,994	220				
		2,026	210				
		2,057	180				

Table 5. Chloride analyses for reverse-air rotary discharge-water samples collected in the Floridan aquifer system at the Coastal Sound Science Initiative and St Simons Island wells in Georgia, and unpublished results for well 33D074 drilled by St Johns River Water Management District of Palatka, Florida, at the St Marys site, Georgia, 1999–2002.—Continued

[ft, feet below land surface; mg/L, milligrams per liter; brackets denote unpublished results for well 33D074 at the St Marys site]

St Simons Island well 35H068, Glynn County, Georgia		Shellman Bluff well 35L085, McIntosh County, Georgia		Richmond Hill well 35P109, Bryan County, Georgia		Pembroke well 33R045, Bryan County, Georgia		Pineora well 34S011, Effingham County, Georgia	
Depth (ft)	Chloride (mg/L)	Depth (ft)	Chloride (mg/L)	Depth (ft)	Chloride (mg/L)	Depth (ft)	Chloride (mg/L)	Depth	Chloride
1,079	24	560	20	375	4	405	3.7	374	4.6
1,111	24	592	11	406	5	437	3.8	404	4.6
1,143	24	623	11	435	5	467	3.9	435	4.8
1,174	24	655	12	466	5	499	3.8	467	4.6
1,206	24	686	13	497	5	529	3.8	497	4.4
1,238	24	717	14	528	5	560	4.1	528	4.2
1,269	24	748	14	560	5	591	3.8	556	4.3
1,301	24	778	15	590	5	622	3.8	590	4.2
1,332	24	808	15	622	5	653	3.8	622	4.0
1,362	24	808	15	653	5	684	3.8	654	4.0
1,394	24	839	16	685	5	715	3.9	750	4.0
1,423	21	870	16	715	5	745	4.0	808	3.1
1,455	23	900	19	746	5	778	5.7	870	3.2
1,486	23	931	20	778	5	809	5.8		
1,518	23	963	20	808	5	839	5.7		
1,550	24	994	21	840	5	870	5.6		
1,582	23	1,025	23	870	5	901	5.1		
1,612	26	1,056	22	901	5	932	4.8		
1,643	28	1,085	22	933	5	964	4.8		
1,675	29	1,116	22	963	5	994	5.2		
1,706	30	1,148	23	980	5				
1,738	30	1,181	180	980	5				
1,769	32	1,212	260	995	5				
1,801	33	1,243	280	1,060	9				
1,832	33	1,273	290	1,092	12				
1,894	36	1,305	290	1,122	34				
1,925	36	1,336	300	1,153	43				
1,957	38	1,367	310	1,185	86				
1,989	39	1,399	310	1,216	115				
2,020	41	1,419	310	1,248	152				
2,052	48	1,429	310	1,279	162				
2,084	48	1,461	310	1,310	160				
2,116	48	1,492	310	1,341	159				
2,147	48	1,523	310	1,372	160				
2,179	63	1,554	310	1,403	161				
2,200	55	1,585	310	1,434	162				
		1,605	310	1,465	160				
		1,645	310	1,497	160				
		1,675	310	1,526	160				
		1,706	310	1,557	162				
		1,737	310	1,589	161				
		1,768	310	1,650	159				
		1,800	310						
		1,832	310						
		1,863	310						

Table 6. Water-quality analyses of water samples collected from wells in Bryan and Camden Counties, Georgia, 1999–2002.

[°C, degrees Celsius; µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; CSSI, Coastal Sound Science Initiative; UFA, Upper Floridan aquifer; <, less than; UPZ of LFA, upper permeable zone of Lower Floridan aquifer; FAS, Floridan aquifer system; SJRWMD, data from St Johns River Water Management District, Palatka, Florida; —, no data; µg/L, micrograms per liter; δD, delta deuterium; $\delta^{18}O$, delta oxygen-18; $\delta^{13}C$, delta carbon-13; USGS, U.S. Geological Survey]

Sample number	Georgia well name, site name (fig. 1)	Aquifer	Sample depth, in feet below land surface	Date of sample collection	Development/ sample collection method	Temperature (°C)	Field specific conductance (µS/cm)	Total dissolved solids (mg/L)	Field pH standard units	Hardness, total as calcium carbonate (mg/L)	Nitrogen, ammonia dissolved (mg/L)	Nitrogen, nitrite plus nitrate dissolved (mg/L)	Phosphorus, dissolved (mg/L)	Phosphorus, ortho dissolved (mg/L)
Bryan County														
1	33R045, Pembroke CSSI	UFA	395	10/12/01	Reverse-air purge/ wireline sampler	24	204	231	8.1	96	0.11	0.02	<0.02	0.02
2	33R045, Pembroke CSSI	UPZ of LFA	800	11/29/01	Reverse-air purge/ wireline sampler	24	256	284	7.9	120	0.03	<0.02	0.02	<0.01
3	35P109, Richmond Hill CSSI	UPZ of LFA	1,010–1,275	9/6/00	Submersible pump/ submersible pump	29.5	2,600	1,700	7.6	740	0.46	<0.02	<0.02	<0.01
4	35P109, Richmond Hill CSSI	near base of FAS	1,320	3/12/00	Reverse-air purge/ wireline sampler	30.5	3,060	2,170	7.8	790	0.72	0.10	<0.02	<0.01
5	35P110, Richmond Hill CSSI	UFA	320–440	9/6/00	Submersible pump/ submersible pump	22.5	269	240	8.0	96	0.03	<0.02	<0.02	0.01
Camden County														
6	33D054, St Marys #2 City well	UFA	563–1,001	7/21/99	Turbine pump/ sample at well head	25	732	571	7.5	330	0.30	<0.02	<0.02	0.02
7	33D054, St Marys #2 Duplicate	UFA	563–1,001	12/18/02	Turbine pump/ sample at well head	25	670	569	7.3	340	0.21	<0.02	<0.02	<0.01
8	33D073, St Marys CSSI	UPZ of LFA	1,365–1,500	9/5/00	Submersible pump/ submersible pump	29.5	1,020	722	7.5	460	0.30	<0.02	<0.02	<0.01
9	33D074, St Marys SJRWMD	UPZ of LFA	1,840–2,045	10/4/02	Submersible pump/ wireline sampler	32	1,480	1,140	—	—	—	—	—	—

Table 6. Water-quality analyses of water samples collected from wells in Bryan and Camden Counties, Georgia, 1999–2002. — Continued

[°C, degrees Celsius; µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; CSSI, Coastal Sound Science Initiative; UFA, Upper Floridan aquifer; <, less than; UPZ of LFA, upper permeable zone of Lower Floridan aquifer; FAS, Floridan aquifer system; SJRWMD, data from St Johns River Water Management District, Palatka, Florida; —, no data; µg/L, micrograms per liter; δD, delta deuterium; $\delta^{18}O$, delta oxygen-18; $\delta^{13}C$, delta carbon-13; USGS, U.S. Geological Survey]

Sample number	Georgia well name, site name (fig. 1)	Calcium, dissolved (mg/L)	Magnesium, dissolved (mg/L)	Sodium, dissolved (mg/L)	Potassium, dissolved (mg/L)	Strontium, dissolved (mg/L)	Chloride, dissolved (mg/L)	Sulfate, dissolved (mg/L)	Fluoride, dissolved (mg/L)	Silica, dissolved (mg/L)	Alkalinity, as calcium carbonate (mg/L)	Hydrogen sulfide (mg/L)	Total organic carbon (mg/L)
						Bryan County							
1	33R045, Pembroke CSSI	28	6.3	7.8	1.8	0.3	3.8	6.1	0.3	49	104	<1.0	1.2
2	33R045, Pembroke CSSI	25	13	9.2	2.9	0.3	5.7	5.3	0.4	63	106	<1.0	1.1
3	35P109, Richmond Hill CSSI	140	93	240	18	3.8	160	880	1.8	22	115	<1.0	1.0
4	35P109, Richmond Hill CSSI	140	107	370	22	3.8	280	1,100	1.9	23	98	<1.0	1.5
5	35P110, Richmond Hill CSSI	23	9.3	14	2	0.4	4.9	6.2	0.4	46	109	<1.0	0.9
						Camden County							
6	33D054, St Marys #2 City well	70	37	24	2.2	0.6	32	160	0.56	36	165	4.3	3.4
7	33D054, St Marys #2 Duplicate	73	37	22	2.1	0.6	32	170	0.6	35	158	4.0	2.6
8	33D073, St Marys CSSI	91	56	22	2.4	0.9	28	300	0.6	33	148	3.4	3.3
9	33D074, St Marys SJRWMD	—	—	—	—	4,660	89	530	—	—	—	—	—

Table 6. Water-quality analyses of water samples collected from wells in Bryan and Camden Counties, Georgia, 1999–2002. — Continued

[°C, degrees Celsius; µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; CSSI, Coastal Sound Science Initiative; UFA, Upper Floridan aquifer; <, less than; UPZ of LFA, upper permeable zone of Lower Floridan aquifer; FAS, Floridan aquifer system; SJRWMD, data from St Johns River Water Management District, Palatka, Florida; —, no data; µg/L, micrograms per liter; δD, delta deuterium; $\delta^{18}O$, delta oxygen-18; $\delta^{13}C$, delta carbon-13; USGS, U.S. Geological Survey]

Sample number	Georgia well name, site name (fig. 1)	Iron, dissolved (µg/L)	Manganese, dissolved (µg/L)	Aluminum, dissolved (µg/L)	Lithium, dissolved (µg/L)	Bromide, dissolved (mg/L)	δD per mil (Vienna-Standard Mean Ocean Water)	$\delta^{18}O$ per mil (Vienna-Standard Mean Ocean Water)	Carbon-14, percent modern carbon	$\delta^{13}C$ per mil (Peedee Belemnite)	Tritium, tritium units	Strontium isotopes, ratio of strontium-87/strontium-86
Bryan County												
1	33R045, Pembroke CSSI	97	47	<3	11	<0.05	-18.7	-3.81	5.07	-5.18	—	0.708
2	33R045, Pembroke CSSI	828	8.4	15	8.5	<0.05	-18.4	-3.78	2.79	-4.54	—	0.708
3	35P109, Richmond Hill CSSI	700	5.4	3.4	47	<0.05	-19.7	-3.96	0.94	-0.22	—	0.707
4	35P109, Richmond Hill CSSI	3.2	49	6.3	68	1.00	-19.7	-3.96	—	—	—	—
5	35P110, Richmond Hill CSSI	0.02	1.1	3.3	6.7	0.05	-18.5	-3.99	0.66	-6.60	—	0.708
Camden County												
6	33D054, St Marys #2 City well	19	0.4	4.1	8.0	0.1	-10.9	-2.68	1.70	-9.36	<0.3	—
7	33D054, St Marys #2 Duplicate	19	<1.0	4.7	8.5	0.14	-10.6	-2.72	0.95	-9.08	—	0.708
8	33D073, St Marys CSSI	214	7.6	<3.0	8.9	0.8	-10.8	-2.76	0.91	-6.98	—	0.708
9	33D074, St Marys SJRWMD	—	—	—	—	—	—	—	—	—	—	0.70782 USGS data

Table 7. Water-quality analyses of water samples collected from wells in Glynn County, Georgia, 1999–2002.

[°C, degrees Celsius; µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; FPZ, Fernandina permeable zone of Lower Floridan aquifer; <, less than; UFA, Upper Floridan aquifer; USGS, U.S. Geological Survey; TW, test well; CSSI, Coastal Sound Science Initiative; UPZ of LFA, upper permeable zone of Lower Floridan aquifer; —, no data; µg/L, micrograms per liter; δD, delta deuterium; $\delta^{18}O$, delta oxygen-18; $\delta^{13}C$, delta carbon-13]

Sample number	Georgia well name, site name (fig. 1)	Aquifer	Sample depth, in feet below land surface	Date of sample collection	Development/ sample collection method	Temperature (°C)	Field specific conductance (µS/cm)	Total dissolved solids (mg/L)	Field pH standard units	Hardness, total as calcium carbonate (mg/L)	Nitrogen, ammonia dissolved (mg/L)	Nitrogen, nitrate plus nitrite dissolved (mg/L)	Phosphorus, dissolved (mg/L)	Phosphorus, ortho dissolved (mg/L)
10	33H188, Colonels Island	FPZ	2,140–2,720	7/21/1999	Flowing well/ sample port at wellhead	33.5	29,900	20,100	6.7	4,600	1.9	<0.2	0.04	0.04
11	34G002, Brunswick Lanier Bridge	UFA	585–750	7/21/1999	Submersible pump/sampled at wellhead	23	736	522	7.6	260	0.1	<0.2	<0.2	<0.1
12	34H393, Brunswick USGS TW-17	UFA	615–723	7/201999	Centrifugal/ sampled at well head	28.5	7,900	4,480	7.3	1,100	0.4	<0.2	0.02	0.01
13	34H495, Brunswick CSSI	UPZ of LFA	1,380	3/29/2000	Reverse-air purge/wireline sampler	28.5	486	355	7.9	190	0.1	<0.02	<0.2	<0.1
14	34H495, Brunswick CSSI	UPZ of LFA	1,675	5/22/2000	Submersible pump with wireline sample in drill pipe	32	2,050	1,360	7.1	780	—	—	—	—
15	34H495, Brunswick CSSI	FPZ	2,084–2,091	7/11/2000	Flowingwell/ sampled at wellhead	35	6,480	4,400	8.2	1,700	0.7	<0.02	<0.2	<0.1
16	34H495, Brunswick CSSI	FPZ	2,243	7/17/2000	Submersible pump with wireline sample in drill pipe	35.5	49,100	33,700	7.4	6,200	2.4	<0.02	0.03	0.07
17	34H495, Brunswick CSSI	FPZ	2,720	8/2/2000	Submersible pump with wireline sample in drill pipe	35.5	67,000	48,400	7.1	7,700	8.9	0.70	0.06	<0.1
18	34H500, Brunswick CSSI	UFA	1,185	9/21/2000	Reverse-air purge/wireline sampler	28.5	3,970	2,300	7.6	590	0.3	<0.02	0.02	<0.01
19	34H500, Brunswick CSSI	UPZ of LFA	1,212–1,400	10/9/2000	Flowing well/ sampled at well head	29.5	1,420	840	7.4	—	0.1	<0.02	<0.02	<0.01

Table 7. Water-quality analyses of water samples collected from wells in Glynn County, Georgia, 1999–2002. — Continued

[°C, degrees Celsius; µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; FPZ, Fernandina permeable zone of Lower Floridan aquifer; <, less than; UFA, Upper Floridan aquifer; USGS, U.S. Geological Survey; TW, test well; CSSI, Coastal Sound Science Initiative; UPZ of LFA, upper permeable zone of Lower Floridan aquifer; —, no data; µg/L, micrograms per liter; δD, delta deuterium; $\delta^{18}O$, delta oxygen-18; $\delta^{13}C$, delta carbon-13]

Sample number	Georgia well name, site name (fig. 1)	Aquifer	Sample depth, in feet below land surface	Date of sample collection	Development/ sample collection method	Temperature (°C)	Field specific conductance (µS/cm)	Total dissolved solids (mg/L)	Field pH standard units	Hardness, total as calcium carbonate (mg/L)	Nitrogen, ammonia dissolved (mg/L)	Nitrogen, nitrate plus nitrite dissolved (mg/L)	Phosphorus, dissolved (mg/L)	Phosphorus, ortho dissolved (mg/L)
10	33H188, Colonels Island	FPZ	2,140–2,720	7/21/1999	Flowing well/ sample port at wellhead	33.5	29,900	20,100	6.7	4,600	1.9	<0.2	0.04	0.04
11	34G002, Brunswick Lanier Bridge	UFA	585–750	7/21/1999	Submersible pump/sampled at wellhead	23	736	522	7.6	260	0.1	<0.2	<0.2	<0.1
12	34H393, Brunswick USGS TW-17	UFA	615–723	7/201999	Centrifugal/ sampled at well head	28.5	7,900	4,480	7.3	1,100	0.4	<0.2	0.02	0.01
13	34H495, Brunswick CSSI	UPZ of LFA	1,380	3/29/2000	Reverse-air purge/wireline sampler	28.5	486	355	7.9	190	0.1	<0.02	<0.2	<0.1
14	34H495, Brunswick CSSI	UPZ of LFA	1,675	5/22/2000	Submersible pump with wireline sample in drill pipe	32	2,050	1,360	7.1	780	—	—	—	—
15	34H495, Brunswick CSSI	FPZ	2,084–2,091	7/11/2000	Flowingwell/ sampled at wellhead	35	6,480	4,400	8.2	1,700	0.7	<0.02	<0.2	<0.1
16	34H495, Brunswick CSSI	FPZ	2,243	7/17/2000	Submersible pump with wireline sample in drill pipe	35.5	49,100	33,700	7.4	6,200	2.4	<0.02	0.03	0.07
17	34H495, Brunswick CSSI	FPZ	2,720	8/2/2000	Submersible pump with wireline sample in drill pipe	35.5	67,000	48,400	7.1	7,700	8.9	0.70	0.06	<0.1
18	34H500, Brunswick CSSI	UFA	1,185	9/21/2000	Reverse-air purge/wireline sampler	28.5	3,970	2,300	7.6	590	0.3	<0.02	0.02	<0.01
19	34H500, Brunswick CSSI	UPZ of LFA	1,212–1,400	10/9/2000	Flowing well/ sampled at well head	29.5	1,420	840	7.4	—	0.1	<0.02	<0.02	<0.01

Table 7. Water-quality analyses of water samples collected from wells in Glynn County, Georgia, 1999–2002. — Continued

[°C, degrees Celsius; µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; FPZ, Fernandina permeable zone of Lower Floridan aquifer; <, less than; UFA, Upper Floridan aquifer; USGS, U.S. Geological Survey; TW, test well; CSSI, Coastal Sound Science Initiative; UPZ of LFA, upper permeable zone of Lower Floridan aquifer; —, no data; µg/L, micrograms per liter; δD, delta deuterium; $\delta^{18}O$, delta oxygen-18; $\delta^{13}C$, delta carbon-13]

Sample number	Georgia well name, site name (fig. 1)	Calcium, dissolved (mg/L)	Magnesium, dissolved (mg/L)	Sodium, dissolved (mg/L)	Potassium, dissolved (mg/L)	Strontium, dissolved (mg/L)	Chloride, dissolved (mg/L)	Sulfate, dissolved (mg/L)	Fluoride, dissolved (mg/L)	Silica, dissolved (mg/L)	Alkalinity, as calcium carbonate (mg/L)	Hydrogen sulfide (mg/L)	Total organic carbon (mg/L)
10	33H188, Colonels Island	820	608	5,700	120	16.4	9,700	2,900	1.6	23	123	2.2	2.1
11	34G002, Brunswick Lanier Bridge	53	30	47	2.3	0.6	80	130	0.6	37	114	1.4	1.1
12	34H393, Brunswick USGS TW-17	200	148	1,200	29	3.1	2,100	610	0.6	34	119	1.6	1.1
13	34H495, Brunswick CSSI	36	23	19	2.1	0.5	26	89	0.6	32	103	<1.0	0.5
14	34H495, Brunswick CSSI	150	98	140	5.3	4.7	190	690	1.2	30	121	—	—
15	34H495, Brunswick CSSI	330	212	850	25	6.3	1,300	1,500	1.4	27	122	<1.0	2.1
16	34H495, Brunswick CSSI	1,100	842	9,800	260	18.7	18,000	3,400	1.4	14	130	<1.0	1.1
17	34H495, Brunswick CSSI	1,800	778	15,000	320	30.6	26,000	4,200	1.6	12	86	6	1.3
18	34H500, Brunswick CSSI	100	82	660	10	1.2	990	270	0.5	34	116	<1.0	1.5
19	34H500, Brunswick CSSI	54	40	160	4.6	0.7	300	140	0.6	34	104	<1.0	1.3

Table 8. Water-quality analyses of water samples collected from wells in Effingham, Glynn, and McIntosh Counties, Georgia, and modern seawater, 1999–2002.

[°C, degrees Celsius; µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; CSSI, Coastal Sound Science Initiative; <, less than; UFA, Upper Floridan aquifer; UPZ of LFA, upper permeable zone of Lower Floridan aquifer; FAS, Floridan aquifer system; —, no data; µg/L, micrograms per liter; δD, delta deuterium; $\delta^{18}O$, delta oxygen-18; $\delta^{13}C$, delta carbon-13; SJRWMD, data from St Johns River Water Management District, Palatka, Florida; USGS, U.S. Geological Survey]

Sample number	Georgia well name, site name (fig. 1)	Aquifer	Sample depth, in feet below land surface	Date of sample collection	Development/ sample collection method	Temperature (°C)	Field specific conductance (µS/cm)	Total dissolved solids (mg/L)	Field pH standard units	Hardness, total as calcium carbonate (mg/L)	Nitrogen, ammonia dissolved (mg/L)	Nitrogen, nitrate plus nitrite dissolved (mg/L)	Phosphorus, dissolved (mg/L)	Phosphorus, ortho dissolved (mg/L)
Effingham County														
20	34S011, Pineora CSSI	UFA	360	12/10/2001	Reverse-air purge/wireline sampler	25	199	204	8.3	78	0.60	<0.02	0.02	0.02
Glynn County														
21	35H070, St Simons Island	UFA	638–743	12/17/2002	Submersible pump/low-flow submersible pump	25	470	380	7.3	200	0.02	<0.02	<0.02	<0.01
22	35H068, St Simons Island	UPZ of LFA	1,391–1,591	6/11/2002	Reverse-air purge/wireline sampler	32	1,690	1,350	7.3	890	0.18	<0.02	<0.02	<0.01
23	35H068, St Simons Island Duplicate	UPZ of LFA	1,391–1,591	6/162002	Turbine pump (aquifer test)/ sample port on dishcarge line	32	1,560	1,250	7.5	—	—	—	—	—
McIntosh County														
24	35L085, Shellman Bluff CSSI	UPZ of LFA	1,144–1,422	2/15/2001	Reverse-air purge/wireline sampler	34	3,480	2,830	7.6	1,400	0.28	0.16	<0.02	<0.01
25	35L085, Shellman Bluff CSSI	near base of FAS	1,830	3/13/2001	Reverse-air purge/wireline sampler	39	4,360	4,600	7.3	1,200	0.72	0.09	<0.02	<0.01
North Atlantic Ocean														
26	Seawater (Hem, 1989; Phelps, 2001)	—	—	4/7/1998	—	—	41,800	34,600	7.8	—	—	—	0.09	—

Table 8. Water-quality analyses of water samples collected from wells in Effingham, Glynn, and McIntosh Counties, Georgia, and modern seawater, 1999–2002. — Continued

[°C, degrees Celsius; µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; CSSI, Coastal Sound Science Initiative; <, less than; UFA, Upper Floridan aquifer; UPZ of LFA, upper permeable zone of Lower Floridan aquifer; FAS, Floridan aquifer system; —, no data; µg/L, micrograms per liter; δD, delta deuterium; $\delta^{18}O$, delta oxygen-18; $\delta^{13}C$, delta carbon-13; SJRWMD, data from St Johns River Water Management District, Palatka, Florida; USGS, U.S. Geological Survey]

Sample number	Georgia well name, site name (fig. 1)	Calcium, dissolved (mg/L)	Magnesium, dissolved (mg/L)	Sodium, dissolved (mg/L)	Potassium, dissolved (mg/L)	Strontium, dissolved (mg/L)	Chloride, dissolved (mg/L)	Sulfate, dissolved (mg/L)	Fluoride, dissolved (mg/L)	Silica, dissolved (mg/L)	Alkalinity, as calcium carbonate (mg/L)	Hydrogen sulfide (mg/L)	Total organic carbon (mg/L)
						Effingham County							
20	34S011, Pineora CSSI	19	7.2	11	2.8	0.4	4.4	7.3	0.4	41	89	<1.0	1.4
						Glynn County							
21	35H070, St Simons Island	40	24	22	1.9	0.7	24	88	0.6	37	114	<1.0	0.4
22	35H068, St Simons Island	192	99	31	13	3.5	25	830	1.6	30	104	<1.0	0.7
23	35H068, St Simons Duplicate Island	179	94	29	13	3.2	25	750	1.7	32	99	—	—
						McIntosh County							
24	35L085, Shellman Bluff CSSI	300	150	330	15	4.6	260	1,600	1.7	29	111	<1.0	1.1
25	35L085, Shellman Bluff CSSI	250	140	620	25	7.8	430	1,700	2.3	25	124	<1.0	1.4
						North Atlantic Ocean							
26	Seawater (Hem,1989; Phelps, 2001)	410	1,350	10,500	390	8.0	19,000	2,700	1.3	6.4	116	—	0.1

Table 8. Water-quality analyses of water samples collected from wells in Effingham, Glynn, and McIntosh Counties, Georgia, and modern seawater, 1999–2002. — Continued

[°C, degrees Celsius; µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; CSSI, Coastal Sound Science Initiative; <, less than; UFA, Upper Floridan aquifer; UPZ of LFA, upper permeable zone of Lower Floridan aquifer; FAS, Floridan aquifer system; —, no data; µg/L, micrograms per liter; δD, delta deuterium; $\delta^{18}O$, delta oxygen-18; $\delta^{13}C$, delta carbon-13; SJRWMD, data from St Johns River Water Management District, Palatka, Florida; USGS, U.S. Geological Survey]

Sample number	Georgia well name, site name (fig. 1)	Iron, dissolved (µg/L)	Manganese, dissolved (µg/L)	Aluminum, dissolved (µg/L)	Lithium, dissolved (µg/L)	Bromide, dissolved (mg/L)	δD per mil (Vienna-Standard Mean Ocean Water)	$\delta^{18}O$ per mil (Vienna-Standard Mean Ocean Water)	Carbon-14, percent modern carbon	$\delta^{13}C$ per mil (Peedee Belemnite)	Tritium, tritium units	Strontium isotopes, ratio of strontium-87/strontium-86
Effingham County												
20	34S011, Pineora CSSI	17	6.5	5.9	11	<0.05	-17.3	-3.83	3.07	-3.66	—	0.70802
Glynn County												
21	35H070, St Simons Island	127	2.6	5.4	8.4	0.08	-14.9	-3.49	—	—	—	0.70800
22	35H068, St Simons Island	138	4.2	5.9	26	<1.0	-16.7	-3.55	1.54	-1.39	—	0.70775
23	35H068, St Simons Island Duplicate	—	2.5	5.0	23	<0.5	—	—	—	—	—	—
McIntosh County												
24	35L085, Shellman Bluff CSSI	306	13	17	41	1.1	-19.7	-3.76	2.06	-0.66	—	0.70788
25	35L085, Shellman Bluff CSSI	8,600	68	8.7	80	2.1	-20.1	-3.74	—	—	—	0.70783
North Atlantic Ocean												
26	Seawater (Hem, 1989; Phelps, 2001)	3	2	1.0	170	67	6.2	0.66	110	-1.75	—	0.70916

secondary drinking-water standard of 250 mg/L at these four sites (table 5).

Chloride concentrations in discharge-water samples collected from the upper permeable zone of the Lower Floridan aquifer ranged from 5 to 162 mg/L at Richmond Hill well 35P109 and from 180 to 310 mg/L at Shellman Bluff well 35L085 (table 5). Concentrations increased with depth in both wells. Chloride concentrations in samples collected from the Lower Floridan aquifer by a submersible pump in Richmond Hill well 35P109 and by wireline sampler in Shellman Bluff well 35L085 were 160 mg/L and 260 mg/L, respectively, and confirmed the chloride results from the reverse-air rotary discharge samples (tables 6, 8). Discharge-water samples from the Upper Floridan aquifer at the Richmond Hill and Shellman Bluff sites had chloride concentrations ranging from 4 to 5 mg/L and from 11 to 20 mg/L, respectively (table 5). Only the water samples from the Lower Floridan aquifer at Shellman Bluff had chloride concentrations that exceeded the secondary drinking-water standard of 250 mg/L.

Identification of the top of the freshwater interval of the upper permeable zone of the Lower Floridan aquifer at the Brunswick site was complicated by the presence of chloride contamination in the Upper Floridan aquifer. The Brunswick site is within the chloride-contamination plume in downtown Brunswick, and had chloride concentrations ranging from 1,500 to 2,900 mg/L in the Upper Floridan aquifer during the drilling of wells 34H495 and 34H500 (table 5; fig. 13). The highest chloride concentrations were near the base of the Upper Floridan aquifer at 1,143 ft in well 34H495 and 1,139 ft in well 34H500. As the drilling of the borehole progressed to include the freshwater interval of the Lower Floridan aquifer, the chloride concentrations of reverse-air rotary discharge samples collected from 1,206 to 1,405 ft in well 34H495 ranged from 2,000 to 2,400 mg/L and reflected the borehole dilution of chloride-contaminated water from the Upper Floridan aquifer with freshwater from the Lower Floridan aquifer but did not reflect the actual chloride concentration of the Lower Floridan aquifer (table 5). A wireline water sample collected near the bottom of the open borehole at a depth of 1,380 ft below land surface had a chloride concentration of 26 mg/L, which reflected the actual chloride concentration of the freshwater interval of the upper permeable zone of the Lower Floridan aquifer (table 7).

Based on the chloride analyses of reverse-air discharge water in well 34H495, the top of the freshwater interval of the upper permeable zone of the Lower Floridan aquifer was assumed to be at a depth of 1,249 ft. After setting 1,212 ft of casing in the borehole of well 34H500, the chloride concentration of reverse-air discharge samples decreased from 530 mg/L at 1,269 ft to 290 mg/L at 1,400 ft (table 5). Water flowing from well 34H500 had a chloride concentration of 300 mg/L. The chloride analysis indicates that the final open interval in well 34H500 was still receiving some chloride-contaminated water from the base of the Upper Floridan aquifer and did not represent the actual chloride concentration of the freshwater interval of the upper permeable zone of the Lower Floridan aquifer.

After setting 1,396 ft of casing in well 34H495 at the Brunswick site, the chloride concentrations of the reverse-air rotary discharge samples collected from the upper permeable zone of the Lower Floridan aquifer ranged from 12 to 36 mg/L in the interval from 1,426 to 1,648 ft and from 100 to 340 mg/L in the interval from 1,679 to 1,962 ft. The chloride concentrations declined to 180 mg/L at 2,057 ft before the borehole penetrated the dense dolomite at the base of the local confining unit. After penetrating the top of the Fernandina permeable zone at 2,087 ft, the chloride concentrations in well 34H495 increased in the reverse-air discharge samples from 1,100 mg/L at 2,089 ft to 2,000 mg/L in the discharge samples from 2,186 ft and then abruptly increased to 17,000 mg/L in the samples collected at 2,217 ft. Another abrupt increase to 27,000 mg/L was observed in the sample at 2,689 ft. The chloride concentrations in water samples from the Upper Floridan aquifer, the Lower Floridan aquifer from 1,869 to 1,962 ft, and the Fernandina permeable zone at the Brunswick site exceeded the secondary drinking-water standard of 250 mg/L.

Salinity

Salinity is based on TDS concentrations and, therefore, reflects all chemical constituents, not merely the dissolved chloride concentrations in water samples (Robinove and others, 1958). TDS concentrations are less than 1,000 mg/L in freshwater and range from 1,000 to 3,000 mg/L for slightly saline, 3,000 to 10,000 mg/L for moderately saline, and 10,000 to 35,000 mg/L for very saline. Seawater typically is very saline with TDS concentrations of approximately 35,000 mg/L (Hem, 1989). For this report, water from the Fernandina permeable zone with a TDS concentration of 48,400 mg/L is considered to be brine. TDS concentrations in samples analyzed for this report also were compared to the Federal secondary drinking-water standard of 500 mg/L (U.S. Environmental Protection Agency, 2000).

Except for chloride analyses of the reverse-air rotary discharge-water samples, water samples were not collected for analysis from the Upper Floridan aquifer in well 35L085 at Shellman Bluff or the Lower Floridan aquifer in well 34S011 at Pineora; however, field parameters were measured for the reverse-air discharge water in these two intervals (table 9). Based on the other freshwater concentrations reported in tables 6–8, the TDS concentration can be estimated as approximately equal to the measured specific conductance of the reverse-air rotary discharge samples with an uncertainty of plus or minus 100 mg/L; therefore, the TDS is estimated to be approximately 500 mg/L for the Upper Floridan aquifer at Shellman Bluff and 388 mg/L for the Lower Floridan aquifer at Pineora (table 9).

Freshwater is present in the Lower Floridan aquifer at the Pineora, Pembroke, and St Marys sites, and in the interval

Table 9. Temperature, specific conductance, and estimated concentration of total dissolved solids in discharge-water samples collected from the Lower Floridan aquifer in well 34S011 in Effingham County and the Upper Floridan aquifer in well 35L085 in McIntosh Counties, Georgia, 2001.

[°C, degrees Celsius; µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; CSSI, Coastal Sound Science Initiative; UPZ of LFA, upper permeable zone of Lower Floridan aquifer; UFA, Upper Floridan aquifer]

Georgia well name, site name (fig. 1)	Aquifer	Sample depth or depth interval, in feet below land surface	Sample collection date(s)	Development/ sample collection method	Temperature (°C), for sample depth interval	Field specific conductance (µS/cm), range for sample depth interval	Total dissolved solids (mg/L), estimated from specific conductance
Effingham County							
34S011, Pineora CSSI	UPZ of LFA	808	12/18/01	Reverse-air purge/ reverse-air discharge	24	388	388
McIntosh County							
35L085, Shellman Bluff CSSI	UFA	560–849	1/03/2001–1/05/2001	Reverse-air purge/ reverse-air discharge	25	367–604	500

from 1,259 to 1,648 ft in well 34H495 at the Brunswick site based on specific conductance (apps. 1, 2). TDS concentrations in water samples from the Lower Floridan aquifer were less than 1,000 mg/L at all four sites and less than the secondary drinking-water standard of 500 mg/L at the Pembroke, Pineora, and Brunswick sites. Slightly saline water was present in the Lower Floridan aquifer at Richmond Hill, Shellman Bluff, and St Simons Island, and in the interval from 1,679 to 1,970 ft in well 34H495 at the Brunswick site. Water samples collected from the Fernandina permeable zone in well 34H495 had TDS concentrations of 4,400 mg/L (moderately saline) in the interval from 2,087 to 2,200 ft, 33,700 mg/L (very saline) in the interval from 2,200 to 2,685 ft, and 48,400 mg/L (brine) in the interval from 2,685 ft to the total well depth of 2,720 ft (table 7).

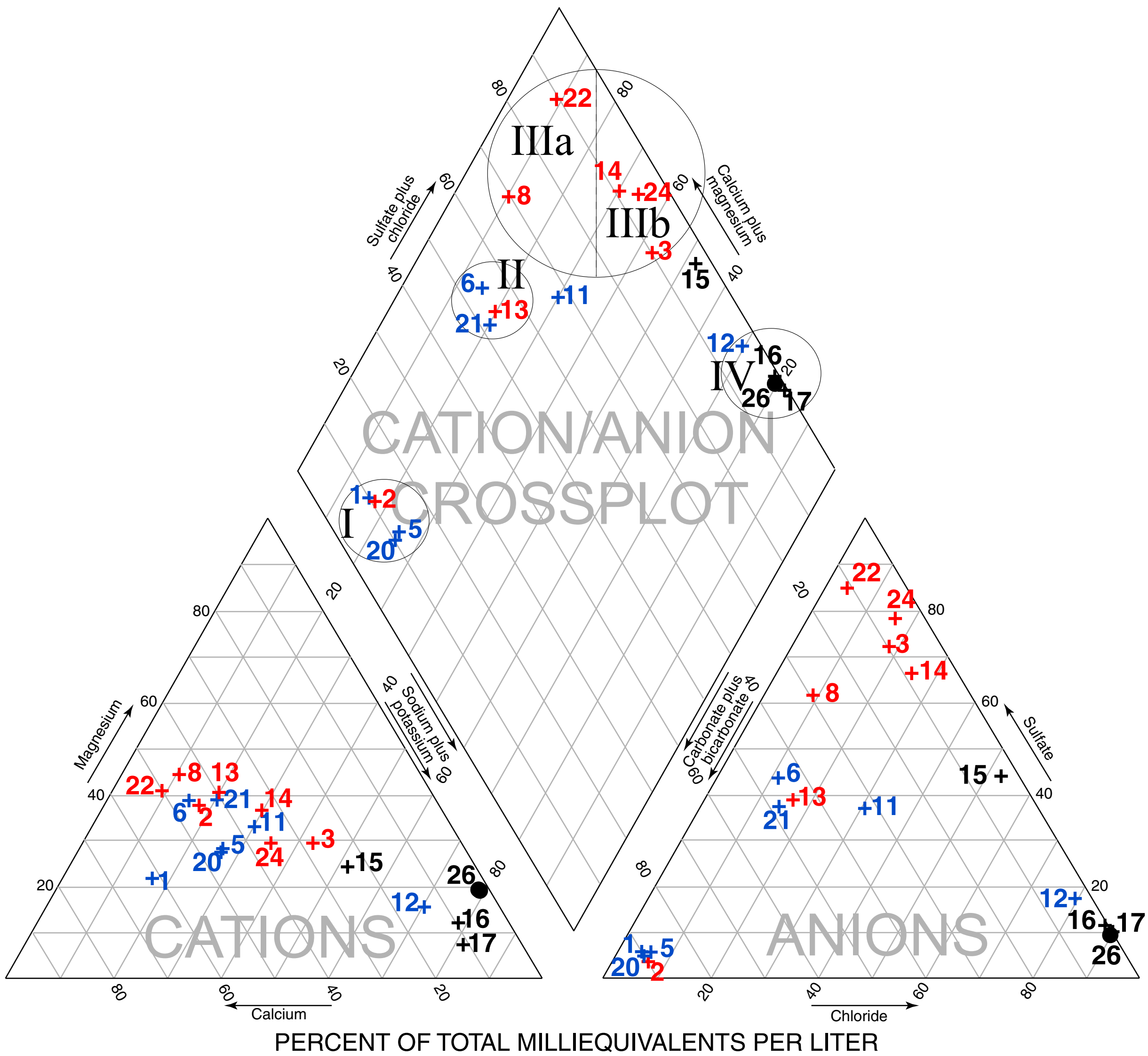
With the exception of the Brunswick site, the water samples collected from wells open to the Upper Floridan aquifer at and near the five other CSSI sites and the St Simons Island site had TDS concentrations less than 1,000 mg/L, and can be considered freshwater (tables 6, 8, 9). Of these samples, all had TDS concentrations less than the secondary drinking-water standard of 500 mg/L, except for the two samples collected from the Upper Floridan aquifer in well 33D054 at St Marys, which had TDS concentrations of 569 and 571 mg/L (table 6).

Well 34G002 and the Brunswick site are in two areas of Brunswick that have chloride contamination in the Upper Floridan aquifer (fig. 13). Water collected from the Upper Floridan aquifer in well 34G002—the smaller of the two chloride-contaminated areas—was freshwater with a TDS concentration of 522 mg/L, which exceeds the secondary drinking-water standard. The Brunswick site inside the larger chloride-contaminated area in downtown Brunswick had slightly saline water with a TDS concentration of 2,300 mg/L in the interval of the Upper Floridan aquifer of well 34H500.

Major Ions, Other Constituents, and Saturation Indices

For the following discussion, 16 of 18 water samples were grouped into four water types, which reflect the dominant major anion(s) for each water type. The four water types include bicarbonate, sulfate-bicarbonate, sulfate, and chloride waters and are assigned roman numerals I, II, III, and IV, respectively (fig. 14). The water samples collected from the Upper Floridan aquifer at well 34G002 and the moderately saline water zone at the top of the Fernandina permeable zone in well 34H495 at the Brunswick site have major ion compositions that are subtly different from water types II and IV, respectively, but are included in the discussion of these two water types.

A trilinear plot was used to classify the four water types based on major cation and anion compositions (Piper, 1944). The major ion compositions were plotted as a percentage of the total milliequivalents per liter for the major cations and anions for 18 water samples, including 7 samples from the Upper Floridan aquifer, 7 samples from the Lower Floridan aquifer, 3 samples from the Fernandina permeable zone, and 1 seawater sample (fig. 14).



EXPLANATION

Ground-water samples from the Upper Floridan aquifer and a seawater sample (sample numbers and depths from tables 6-8):

- + 6 St Marys, 33D054
- + 11 Brunswick, 34G002
- + 12 Brunswick, 34H393
- + 21 St Simons, 35H070
- + 5 Richmond Hill, 35P110
- + 1 Pembroke, 33R045, 395 ft
- + 20 Pineora, 34S011, 360 ft
- ● 26 Seawater (Hem, 1989)

Ground-water samples from the Lower Floridan aquifer (sample numbers and depths from tables 6-8):

Upper permeable zone:

- + 8 St Marys, 33D073
- + 13 Brunswick, 34H495, 1,380 ft
- + 14 Brunswick, 34H495, 1,675 ft
- + 22 St Simons, 35H068
- + 24 Shellman Bluff, 35L085
- + 3 Richmond Hill, 35P109
- + 2 Pembroke, 33R045, 800 ft

Fernandina permeable zone:

- + 15 Brunswick, 34H495, 2,084 ft
- + 16 Brunswick, 34H495, 2,243 ft
- + 17 Brunswick, 34H495, 2,720 ft

Water type:

- I Bicarbonate
- II Bicarbonate-Sulfate
- IIIa Calcium-Magnesium-Sulfate
- IIIb Calcium-Magnesium-Sodium-Sulfate
- IV Chloride

Figure 14. Major cation and anion compositions of water samples from the Upper Floridan aquifer, and the upper permeable and Fernandina permeable zones of the Lower Floridan aquifer at the Coastal Sound Science Initiative wells, and at Upper Floridan aquifer monitoring wells in Brunswick and St Marys, Georgia, and for a modern seawater sample (Hem, 1989).

Not all laboratory results, particularly several trace constituents and nutrients, are discussed in this report; however, all results are presented in tables 6–8. In addition to major ions, the water samples were analyzed for strontium, bromide, hydrogen sulfide, and total organic carbon, which are important constituents used to characterize the four water types relative to freshwater and saltwater. For hydrogen sulfide, a concentration of less than 1 mg/L means the concentration was below the laboratory analytical limit of 1 mg/L and does not mean that hydrogen sulfide was absent.

Concentrations also were compared to Federal secondary drinking-water standards of 500 mg/L for TDS, 250 mg/L for chloride, and 250 mg/L for sulfate (U.S. Environmental Protection Agency, 2000). All water samples had fluoride concentrations less than 2.0 mg/L and pH values ranging from 6.5 to 8.5, which are also Federal secondary drinking-water standards, (U.S. Environmental Protection Agency, 2000), except for the sample with a fluoride concentration of 2.3 mg/L collected near the base of the Floridan aquifer system in Shellman Bluff well 35L085 (tables 6–8).

Dissolved-oxygen concentration is not presented in tables 6–8, but was measured in all samples and was found to be less than 0.2 mg/L. This concentration was the lower reporting limit of the meter used in the field to measure dissolved oxygen, and is assumed to indicate anaerobic conditions in the Floridan aquifer system at the well sites that were sampled.

Saturation indices were calculated for each sample using the geochemical modeling program, WATEQ4F (Ball and Nordstrom, 1991). Saturation indices were calculated and discussed for calcite, aragonite, dolomite, gypsum, and anhydrite, which are mineral phases observed in drill cuttings and associated with the carbonate rocks of the Floridan aquifer system (table 10). A saturation index for a particular mineral phase is approximately equal to zero when the water composition is at equilibrium with the mineral phase. A saturation index less than zero indicates that the water is undersaturated with the mineral phase and favors dissolution; a saturation index greater than zero indicates oversaturation and favors precipitation of the mineral phase.

Water Type I—Bicarbonate

Water type I is bicarbonate and includes samples from the Upper Floridan aquifer at Pineora, Pembroke, and Richmond Hill, and the Lower Floridan aquifer at Pembroke (fig. 14). These samples are from CSSI wells at the three northernmost sites in the study area in Bryan and Effingham Counties, GA (fig. 1). Bicarbonate was the dominant anion and represented greater than 85 percent of the anion composition of the four water samples (fig. 14). Calcium and magnesium were the dominant cations, relative to sodium and potassium, and represented greater than 70 percent of the cation composition of these samples. The major ion composition of the water in these four samples can be classified as calcium-magnesium-bicarbonate.

The ion concentrations in these waters did not exceed Federal secondary drinking-water standards for TDS, chloride, and sulfate (U.S. Environmental Protection agency, 2000). These four water samples had TDS concentrations of less than 300 mg/L, making these four samples fresh, and had the four lowest ionic strengths of the 18 ground-water samples analyzed. These samples had concentrations less than or equal to 6 mg/L for chloride, 7.3 mg/L for sulfate, 0.4 mg/L for strontium, 0.05 mg/L for bromide, and less than 1.0 mg/L for hydrogen sulfide (tables 6, 8). The concentration of total organic carbon ranged from 0.9 to 1.4 mg/L. Specific conductance in all four bicarbonate samples ranged from 199 to 269 μS/cm. The water from the Lower Floridan aquifer at the Pineora site had a specific conductance of 388 μS/cm (table 9).

The four samples were saturated with respect to calcite and dolomite, and undersaturated with respect to gypsum and anhydrite (table 10). The saturation indices for aragonite were greater than zero in the samples from the Upper Floridan aquifer at Pembroke and Pineora and from the Lower Floridan aquifer at Pembroke, and slightly less than zero in the sample from the Upper Floridan aquifer at Richmond Hill, indicating saturation or close to saturation with respect to aragonite.

Water Type II—Sulfate-Bicarbonate

Found only in the southern sites, water type II is sulfate-bicarbonate and includes samples from the Upper Floridan aquifer at the St Marys and St Simons Island sites, and from the upper permeable zone of the Lower Floridan aquifer at 1,380 ft in well 34H495 at the Brunswick site. Well 34G002 is within a small plume of chloride contamination in the Upper Floridan aquifer in downtown Brunswick and is included in the discussion of this water type because water from this well has most of the characteristics of the other water samples of type II, except for its sodium and chloride concentrations (figs. 13, 14). Except for the chloride-contaminated sample from well 34G002 in downtown Brunswick, sulfate and bicarbonate represented about 38 to 48 percent and 44 to 48 percent, respectively, of the major anion composition of the three type II samples. Chloride was less than 20 percent in these samples. Calcium and magnesium were the dominant cations, relative to sodium and potassium, and represented greater than 80 percent of the cation composition. The major ion composition of the three samples can be classified as calcium-magnesium-sulfate-bicarbonate water. The ratio of calcium to sodium was approximately 2 to 1 or greater.

The ion concentrations of the three sulfate-bicarbonate water samples did not exceed secondary drinking-water standards for TDS, chloride, and sulfate, except for the sample from the Upper Floridan aquifer in well 33D054 at St Marys with a TDS concentration of 571 mg/L. All three samples were fresh, ranging in TDS concentrations from 355 to 571 mg/L, chloride concentrations from 24 to 32 mg/L, sulfate concentrations from 88 to 160 mg/L, strontium concentrations from 0.5 to 0.7, and bromide concentrations from 0.08 to 0.1 (tables 6–8). The water sample from the Upper Floridan

Table 10. Calculated saturation indices of water samples from wells in the Coastal Sound Science Initiative study area with respect to selected carbonate and evaporite minerals.

[CSSI, Coastal Sound Science Initiative; shading, negative values indicate undersaturated conditions. Water types: I, bicarbonate; II, sulfate-bicarbonate; III, sulfate; IV, chloride; C, contaminated zone]

Sample number (tables 6–8; fig. 14), Georgia well name, site name, county name	Sample depth, in feet below land surface	Water type	Calcite	Aragonite	Dolomite	Gypsum	Anhydrite
Upper Floridan aquifer							
(1) 33R045, Pembroke CSSI, Bryan	395	I	0.230	0.086	0.151	-3.051	-3.275
(5) 35P110, Richmond Hill CSSI, Bryan	320–440	I	0.045	-0.100	0.016	-3.133	-3.363
(6) 33D054, St Marys #2, Camden	563–1,001	II	0.098	-0.046	0.262	-1.481	-1.701
(20) 34S011, Pineora CSSI, Effingham	360	I	0.233	0.091	0.420	-3.127	-3.339
(11) 34G002, Brunswick Lanier Bridge, Glynn	585–750	II–III	-0.086	-0.231	-0.099	-1.652	-1.879
(12) 34H393, USGS Test Well-17 Brunswick, Glynn	615–723	IV	-0.015	-0.157	0.226	-0.941	-1.144
(18) 34H500, Brunswick CSSI, Glynn	1,185	C	0.096	-0.045	0.493	-1.387	-3.478
(21) 35H070, St Simons, Glynn	638–743	II	-0.423	-0.567	-0.724	-1.880	-2.100
Lower Floridan aquifer							
(2) 33R045, Pembroke CSSI, Bryan	800	I	0.258	0.113	0.571	-3.192	-3.416
(3) 35P109, Richmond Hill CSSI, Bryan	1,010–1,275	III	0.201	0.061	0.597	-0.757	-0.957
(8) 33D073, St Marys CSSI, Camden	1,365–1,500	III	0.170	0.029	0.512	-1.189	-1.390
(13) 34H495, Brunswick CSSI, Glynn	1,380	II	0.121	-0.021	0.429	-1.916	-2.121
(14) 34H495, Brunswick CSSI, Glynn	1,675	III	0.004	-0.135	0.218	-0.798	-0.986
(22) 35H068, St Simons, Glynn	1,391–1,591	III	0.057	-0.082	0.218	-0.629	-0.815
(24) 35L085, Shellman Bluff CSSI, McIntosh	1,144–1,422	III	0.458	0.321	1.011	-0.348	-0.524
Fernandina permeable zone							
(15) 34H495, Brunswick CSSI, Glynn	2,084–2,091	III–IV	1.073	0.936	2.371	-0.429	-0.599
(16) 34H495, Brunswick CSSI, Glynn	2,243	IV	0.600	0.464	1.561	-0.127	-0.280
(17) 34H495, Brunswick CSSI, Glynn	2,720	IV	0.310	0.174	0.747	0.092	-0.053

aquifer in St Marys well 33D054 had a hydrogen sulfide concentration of 4.3 mg/L and a total organic carbon concentration of 3.4 mg/L, the highest concentrations for both constituents in the samples from the Upper Floridan aquifer collected during this study.

The chloride-contaminated sample collected from Upper Floridan aquifer well 34G002 in downtown Brunswick plotted to the right of the water type II on the trilinear diagram and is distinguished from the composition of sulfate-bicarbonate water samples by having nearly equal percentages of sulfate, bicarbonate, and chloride in the anion composition and calcium, magnesium, and sodium in the cation composition (fig. 14). The calcium to sodium ratio is less than 2 to 1. Similar to the sulfate-bicarbonate water of the St Marys sample, the ion composition of the sample from the Upper Floridan aquifer in well 34G002 in downtown Brunswick did not exceed standards for chloride and sulfate, but did exceed the standard for TDS concentration. The sample had minor chloride contamination (80 mg/L) compared to sulfate-bicarbonate water samples from the Upper Floridan aquifer in CSSI wells 34H495 and 34H500 at the Brunswick site and well 34H393 just south of the Brunswick site. The chloride concentration in the sample from well 34G002, however, was more than twice the concentration in the sulfate-bicarbonate water samples (fig. 14). The water sample from well 34G002 was freshwater, with a TDS concentration of 522 mg/L and concentrations of sulfate, strontium, and bromide that are within the range of concentrations in the type II water samples (table 7). The ratio of calcium to sodium is approximately 1 to 1. The sample had concentrations of 1.4 mg/L for hydrogen sulfide and 1.1 mg/L for total organic carbon.

The specific conductance of the three sulfate-bicarbonate water samples ranged from 470 to 732 µS/cm. The reverse-air rotary discharge-water samples collected in the Upper Floridan aquifer at Shellman Bluff had a specific conductance of approximately 500 µS/cm and probably was bicarbonate or sulfate-bicarbonate water similar to water types I or II, respectively.

All four water samples were undersaturated relative to gypsum and anhydrite (table 10). The samples from the Upper Floridan aquifer at St Marys and the upper permeable zone of the Lower Floridan aquifer in well 34H495 at the Brunswick site were saturated relative to calcite and dolomite, and had negative saturation indices almost equal to zero (saturation) for aragonite. The sulfate-bicarbonate samples from the Upper Floridan aquifer at St Simons Island and the chloride contaminated sample from the Upper Floridan aquifer in downtown Brunswick were undersaturated relative to all three carbonate minerals.

Water Type III—Sulfate

Water type III is sulfate and includes the five water samples from the upper permeable zone of the Lower Floridan aquifer at the St Marys, St Simons Island, Brunswick, Shellman Bluff, and Richmond Hill sites (fig. 14). The Brunswick sample collected at 1,675 ft below land surface in CSSI well 34H495 represents the high-chloride interval of the Lower Floridan aquifer from 1,657 to 2,030 ft below land surface, in contrast to the low-chloride interval of the Lower Floridan aquifer represented by the sulfate-bicarbonate water in the sample collected at 1,380 ft.

Sulfate is the dominant anion for water samples of this type and represents 62 to 86 percent of the major anion composition of these five samples. The major cation compositions separate the five samples into two subtypes (fig. 14). The compositions of the samples from St Marys and St Simons Island were calcium-magnesium-sulfate waters and had calcium to sodium ratios of 4 to 1 and 6 to 1, respectively. The compositions of the samples from Shellman Bluff, Richmond Hill, and Brunswick were calcium-magnesium-sodium-sulfate waters and had calcium to sodium ratios equal to or less than 1 to 1.

The ion concentrations for TDS and sulfate for all five samples exceeded the Federal secondary drinking-water standards for these constituents. The sample from Shellman Bluff had a chloride concentration of 260 mg/L and was the only type III sample of the five to exceed the Federal secondary drinking-water standard for chloride. All of the samples had TDS concentrations between 1,000 and 3,000 mg/L and were slightly saline, except for the St Marys sample, which had a TDS concentration of 722 mg/L and was fresh.

The calcium-magnesium-sulfate waters from the upper permeable zone of the Lower Floridan aquifer at St Marys and St Simons Island had sulfate, strontium, and bromide concentrations that generally were greater than the bicarbonate and sulfate-bicarbonate waters. The chloride concentrations were in the same range as the sulfate-bicarbonate waters. The water sample from the Lower Floridan aquifer at St Marys had the highest concentration of hydrogen sulfide (3.4 mg/L) and total organic carbon (3.3 mg/L) for the Lower Floridan aquifer wells sampled, just as the sample from the Upper Floridan aquifer at the St Marys site had the highest concentrations of those two constituents observed in the Upper Floridan aquifer. The St Simons Island water sample had a concentration of less than 1.0 mg/L for hydrogen sulfide and 0.7 mg/L for total organic carbon.

The calcium-magnesium-sodium-sulfate waters from the upper permeable zone of the Lower Floridan aquifer at Richmond Hill, Shellman Bluff, and Brunswick had chloride, sulfate, strontium, and bromide greater than the bicarbonate, sulfate-bicarbonate, and calcium-magnesium-sulfate waters, except for the bromide concentrations. Concentrations were less than 1.0 mg/L for hydrogen sulfide and approximately 1.0 mg/L for total organic carbon in these samples, except in Brunswick well 34H495 at 1,675 ft where these constituents were not measured.

All five samples were saturated to slightly oversaturated relative to the carbonate minerals. This includes the saturation index –0.08 for aragonite in the St Simons Island samples, which is nearly zero (table 10). These water samples had saturation indices for gypsum and anhydrite ranging from

-0.3 to -1.4, and were undersaturated but not as undersaturated as the type I and type II samples, with saturation indices ranging from -1.5 to -3.4.

Water Type IV—Chloride

Water type IV is chloride and includes three ground-water samples and a seawater sample (fig. 14). The three ground-water samples were collected from a chloride-contaminated interval of the Upper Floridan aquifer in well 34H393 and from depths of 2,243 and 2,720 ft below land surface in the Fernandina permeable zone of CSSI well 34H495 in downtown Brunswick (table 7). These three samples were sodium-chloride waters with chloride and sodium making up more than 75 and 70 percent of the major anion and cation compositions, respectively (fig. 14). The calcium to sodium ratios for these samples decreased to less than 1 to 5, relative to the type III samples.

The anion composition of the ground-water sample collected at 2,084 ft from the upper part of the Fernandina permeable zone in well 34H495 was a sulfate-chloride water. The composition of this sample was transitional between water types III and IV, but is included in this section. Because sodium constitutes 52 percent of the cation composition, the ionic composition of this sample was classified as sodium-sulfate-chloride water.

During the drilling of the Fernandina permeable zone in CSSI well 34H495, the salinity of the water was moderately saline in the interval from 2,087 to 2,186 ft, very saline from 2,186 to 2,685 ft, and brine from 2,685 ft to the bottom of the borehole at 2,720 ft (table 5). Similar changes in salinity also were documented in the Fernandina permeable zone at well 33H188 on Colonels Island, GA (Jones and others, 2002). Ground-water samples were collected from each of the three high salinity intervals in well 34H495 and from the water flowing from well 33H188. The ion concentrations of TDS, sulfate, and chloride in these four ground-water samples exceeded the Federal secondary drinking-water standards for these constituents. The sodium-sulfate-chloride water type from the moderately saline interval had TDS concentrations of 4,400 mg/L; the two sodium-chloride waters collected from the very saline and brine intervals had increasing concentrations of TDS of 33,700 and 48,400 mg/L. The increase in TDS concentration with depth in the Fernandina permeable zone of well 34H495 paralleled similar increases in concentrations with depth for chloride, sulfate, strontium, and bromide (table 7). Based on these three samples, concentrations of TDS and chloride in the very saline water of the Fernandina permeable zone were most similar to modern seawater; however, the very saline ground-water sample had a higher sulfate concentration and a calcium-to-sodium ratio of 1 to 9 compared with 1 to 22 for the seawater sample. The higher sulfate and calcium-to-sodium ratio indicate that the composition of the ground-water sample was affected by the dissolution of minerals—anhydrite, gypsum, and carbonate minerals—in the aquifer. Concentrations were greater than 1.0 mg/L for total organic carbon in these three ground-water samples, but only exceeded 1.0 mg/L for hydrogen sulfide in the brine sample. The sodium-chloride water collected from well 33H188 at Colonels Island was a mixture of waters from the Fernandina permeable zone and, therefore, had concentrations of TDS, chloride, sulfate, strontium, and bromide that were between the moderately saline concentrations and very saline interval in well 34H495 (table 7).

The saline water from the Fernandina permeable zone beneath Brunswick has been described as the most probable source of saltwater contamination observed in the Upper Floridan aquifer in downtown Brunswick (Krause and Randolph, 1989). The sodium-chloride type sample collected from the Upper Floridan aquifer in well 34H393 is assumed to be a mixture of original freshwater from the Upper Floridan aquifer and water from the Fernandina permeable zone. This sample was moderately saline with concentrations of TDS, chloride, and sulfate that exceeded Federal secondary drinking-water standards for these constituents. Concentrations of total organic carbon and hydrogen sulfide were 1.1 and 1.6 mg/L, respectively (table 7).

The three samples collected from the Fernandina permeable zone in well 34H495 were saturated to oversaturated relative to calcite, aragonite, and dolomite and had saturation indices that ranged from 0.2 to 2.4. The water collected from the Upper Floridan aquifer in well 34H393 and the Fernandina permeable zone in well 33H188 probably resulted from mixing at least two waters in the borehole and, therefore, was not representative of a particular zone or aquifer. Compared with the 18 ground-water samples discussed in this report, the very saline and brine waters from the Fernandina permeable zone in well 34H495 and the water collected from the Colonels Island well had the lowest saturation indices for gypsum and anhydrite and were undersaturated to saturated with these two minerals (table 10). Drill cuttings of gypsum and anhydrite were most commonly observed in the stratigraphic interval of the very saline and brine water of the Fernandina permeable zone in wells 34H495 and 33H188, where the water was saturated or approached saturation with gypsum and anhydrite and did not result in dissolution of these two minerals (Jones and others, 2002).

Isotopes

Water samples were collected and analyzed for the stable isotopes of oxygen, hydrogen, and carbon, radiogenic isotopes of carbon-14 and tritium, and the ratio of strontium-87 to strontium-86 (tables 6–8). Isotopic results also are included for a modern seawater sample collected off the northeast coast of Florida for comparison with results from the Floridan aquifer system in Georgia (Phelps, 2001).

The stable oxygen, hydrogen, and carbon isotopic results are reported from the laboratory in delta notation, which is defined as the per mil (parts per thousand) difference between the isotopic ratio of the sample relative to the isotopic ratio of a standard (Faure, 1977). The isotopic ratios used are oxygen-18/oxygen-16 of water, deuterium/hydrogen of water, and carbon-13/carbon-12 of the dissolved inorganic carbon (DIC) in the water. Therefore, sample results are more positive or more negative when the sample is more enriched or more depleted, respectively, in the heavier isotope in each ratio. The standards are Peedee Belemnite (PDB) for stable carbon isotopes of the DIC in the water and Vienna-Standard Mean Ocean Water (V-SMOW) for the stable hydrogen and oxygen isotopes of water (Gonfiantini, 1984; Coplen, 1994). The 2-sigma (two standard deviations) analytical precision of the laboratory is 0.2 per mil for oxygen, 1.5 per mil for deuterium, and 0.2 per mil for carbon isotopes.

Carbon-14 results are reported in percent modern carbon. Analytical precision for carbon-14 results is less than 0.1 percent modern carbon (pmc). Tritium results are reported in tritium units (TU). The lower analytical limit for tritium results is 0.3 TU. Results for strontium isotopes are presented as the ratio of strontium-87 to strontium-86 and have a precision of plus or minus 0.00003.

Stable Hydrogen and Oxygen Isotopes

Stable hydrogen and oxygen isotopes commonly are used as conservative environmental tracers to determine source, movement, and proportional mixing of water masses. In this report, these isotopes are used for assessment of water source and movement in the aquifers of the Floridan aquifer system and for estimating proportional mixing of freshwater in the Upper Floridan aquifer with higher-chloride waters of the Fernandina permeable zone.

The stable oxygen isotopic compositions for 16 groundwater samples and a modern seawater sample were plotted relative to the stable hydrogen isotopic compositions (fig. 15). The Global Meteoric Line is an average of the stable oxygen and hydrogen isotopes for freshwater samples collected worldwide (Craig, 1961). A linear regression line is plotted through the Brunswick water samples for the discussion of mixing (Helsel and Hirsch, 1992).

The freshwater, slightly saline, and moderately saline samples collected from the Upper Floridan aquifer, the upper permeable zone of the Lower Floridan aquifer, and the uppermost interval of the Fernandina permeable zone plotted close to the Global Meteoric Line and ranged in composition from -2.7 to -4.0 per mil for stable oxygen isotopes and from -10.6 to -19.7 for stable hydrogen isotopes (fig. 15). For this dataset, the compositions of the Upper and Lower Floridan aquifer samples ranged from more negative or isotopically depleted at the northern well sites to more positive or isotopically enriched at the southern well sites. The geographic distribution of these compositions indicates that water in the Floridan aquifer system at different locations in coastal Georgia either entered the recharge areas to the west of the study area under different climatic conditions or followed flowpaths of different lengths from the recharge area to specific sites. Samples collected from the upper permeable zone of the Lower Floridan aquifer at the St Marys, St Simons Island, Richmond Hill, and Pembroke sites had compositions similar to samples collected in the Upper Floridan aquifer at these four sites, respectively. The similarities in composition indicate that waters at a specific site in coastal Georgia entered the recharge area under similar climatic conditions and followed fairly similar flowpaths from the recharge area to the Upper and Lower Floridan aquifers at the sites discussed in this report.

The water samples collected from wells in Glynn County had a larger range in stable oxygen and hydrogen isotopic compositions compared with water samples from the counties to the north and St Marys to the south (fig. 15). Samples from the Upper and Lower Floridan aquifers at the St Simons Island site and at 1,380 ft in the upper permeable zone of the Lower Floridan aquifer at the Brunswick site had lower chloride concentrations and depleted stable oxygen and hydrogen isotopic compositions, relative to the higher-chloride and isotopically enriched water samples in the downtown Brunswick wells 34G002 and 34H393 and at 2,084 ft in well 34H495 (fig. 15).

The sample from 2,084 ft in well 34H495 is moderately saline water at the top of the Fernandina permeable zone and represents a transitional mixing zone between the slightly saline sulfate water from the upper permeable zone of the Lower Floridan aquifer collected at 1,675 ft and the very saline water of the Fernandina permeable zone collected at 2,243 ft. Proportional mixing, based on the chloride concentrations of samples collected at 1,675 and 2,243 ft in well 34H495, would require a water mixture of approximately 93 percent from the sulfate water of the upper permeable zone of the Lower Floridan aquifer and 7 percent from the saltwater of the Fernandina permeable zone. Assuming similar mixing proportions for the stable isotopes in these samples, the stable oxygen and hydrogen isotopic compositions of the sulfate water of the upper permeable zone of the Lower Floridan aquifer can be estimated to be approximately -3.53 and -15.3 per mil, respectively, and are represented by a red diamond in figure 15.

Wells 34G002 and 34H393 have intervals open to the high-chloride plumes in downtown Brunswick, where saline water from beneath the Upper Floridan aquifer has intruded the freshwater of the Upper Floridan aquifer. If the freshwaters of the Upper and Lower Floridan aquifers in Brunswick can be assumed to have similar stable oxygen and hydrogen isotopic compositions, as was documented at the St Marys, St Simons Island, Richmond Hill, and Pembroke sites, then prior to intrusion, the uncontaminated freshwater in the Upper Floridan aquifer in downtown Brunswick probably had stable oxygen and hydrogen isotopic compositions of -3.4 and -16.7 per mil, respectively, and a chloride concentration of 26 mg/L, similar to the Lower Floridan aquifer. The chloride-contaminated water in well 34H393 had stable oxygen and hydrogen isotopic compositions of -2.9 and -12.9 per mil, respectively; therefore, the stable isotopic compositions of the chloride-contaminated water in the Upper Floridan aquifer could not have resulted from the intrusion of waters from only the upper permeable zone of the Lower Floridan aquifer, which ranged

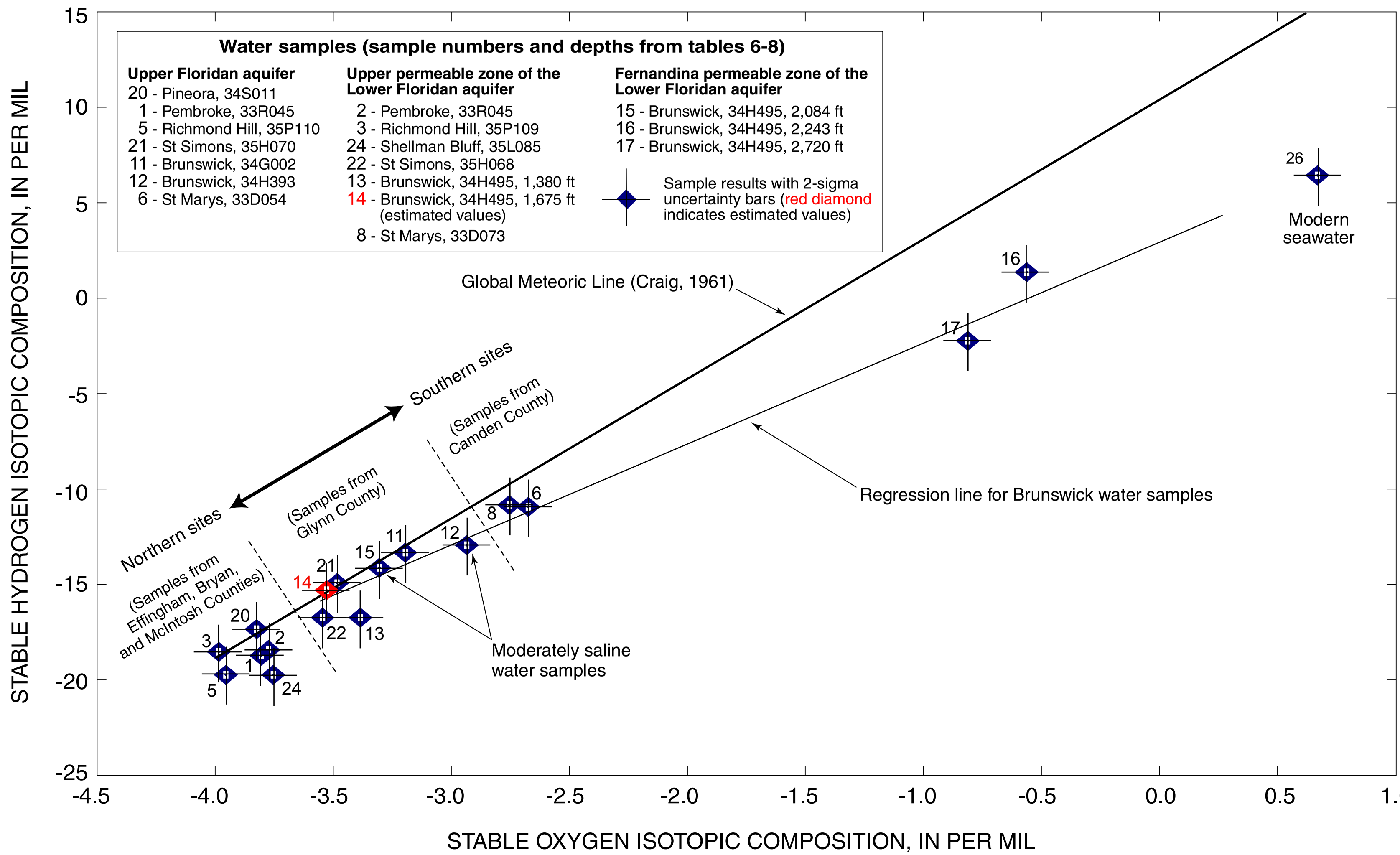


Figure 15. Stable oxygen and hydrogen isotopic compositions of borehole-water samples collected from wells open to the Upper Floridan aquifer and the upper permeable and Fernandina permeable zones of the Lower Floridan aquifer in the Coastal Sound Science Initiative study area, and a modern seawater sample (Phelps, 2001), relative to Vienna-Standard Mean Ocean Water.

from -3.4 to -3.5 per mil and -15.3 to -16.7 per mil for stable oxygen and hydrogen isotopes, respectively (table 7).

The intrusion of some water from the saltwater interval of the Fernandina permeable zone, however, could account for the chemical and isotopic composition of the water in well 34H393 in downtown Brunswick. Proportional mixing would require at least 12 to 20 percent of the water to be from saltwater of the Fernandina permeable zone. It also is assumed, however, that saltwater from the Fernandina permeable zone would mix with waters from the overlying moderately saline-water interval and from the upper permeable zone of the Lower Floridan aquifer as it moves up to the Upper Floridan aquifer. The range of 12 to 20 percent for the volume of saltwater, therefore, is the minimum needed to produce the chloride concentrations and stable isotopic compositions in the water at well 34H393.

The stable oxygen and hydrogen values for the very saline and brine samples collected from 2,243 and 2,720 ft in Brunswick well 34H495 are enriched relative to the freshwater and moderately saline water samples by at least 2.0 and 8.0 per mil, respectively (fig. 15). The saltwater and brine samples, however, have a distinctly different isotopic composition relative to the modern seawater sample and are assumed to be the result of relict seawater interacting with the minerals of the Paleocene strata. Like the modern seawater sample, saltwater and brine from the Fernandina permeable zone plot below the Global Meteoric Line.

Carbon Isotopes

Water samples were collected and analyzed for carbon-14 and stable carbon isotopes of the DIC in 18 ground-water samples from the Floridan aquifer system, including one duplicate sample (tables 6–8). Stable carbon isotopes are commonly used as environmental tracers of carbon sources contributing to the DIC in the water and the physiochemical processes that affect water chemistry. In previous studies, carbon-14 and the stable carbon isotopic compositions of the DIC in water samples have been presented and used to interpret the relative and absolute ages of water samples from the Upper Floridan aquifer beneath coastal Georgia and South Carolina (Plummer, 1993; Landmeyer and Stone, 1995; Landmeyer and Belval, 1996; U.S. Army Corps of Engineers, 1998).

In the hydrologic cycle, the natural source of carbon-14 is the atmosphere. The DIC in recharge water is assumed to be in equilibrium with the atmospheric reservoir of carbon-14 of approximately 100 percent modern carbon (pmc) or greater, and to have a stable carbon isotopic composition in equilibrium with carbon dioxide from soil zone respiration of plants and oxidation of organic matter of approximately -21 to -25 per mil. Marine-derived calcitic and aragonitic rock components in the Floridan aquifer system have stable carbon isotopic compositions of approximately 1 per mil and contain no carbon-14.

As water flows from the recharge area into the confined ground-water system and becomes isolated from the atmospheric source of carbon-14, the concentration of carbon-14, which has a half-life of 5,730 years, decreases in the confined ground-water flow system by radioactive decay as a function of time. Therefore, carbon-14 concentration is partially an indication of the residence time of ground water in an aquifer. The carbon-14 concentration of ground water, however, can also be diluted with "radioactively dead" carbon derived from the dissolution of carbonate minerals and reduction of organic carbon in the aquifer, which complicates the calculation of ground-water age. If the dominant geochemical process is carbonate dissolution driven by carbon dioxide (CO_2), and the carbonate minerals have a stable carbon isotopic composition of 1.0 per mil, then the stable isotopic composition of the DIC (-21 to -25 per mil) becomes isotopically enriched or more positive relative to the DIC in the water in the recharge area. Other geochemical processes, however, including sulfate reduction in the aquifer, can produce isotopically depleted CO_2 and, therefore, DIC with a relatively depleted stable carbon isotopic composition.

The concentration of carbon-14 in ground-water samples was used in this investigation to estimate the relative age of ground-water samples. Therefore, the presence of high concentrations (50 to 100 pmc) of carbon-14 indicates that relatively modern freshwater or saltwater has recharged the aquifer. Conversely, low concentrations of carbon-14 (less than 5 pmc) indicate long residence times and geochemical conditions that favor dilution of the percent modern carbon of the water in the aquifer.

Stable Carbon Isotopes and Water Types With Respect to Geochemical Processes

The stable carbon isotopic compositions of most of the water samples were related to water type and concentrations of sulfate and hydrogen sulfide in the water (fig. 16). Water type and concentrations of these constituents indicated the geochemical processes that were active or dominant in specific hydrogeologic units and in specific parts of coastal Georgia. This relation between stable carbon isotopic composition and water type also was observed in results for the Floridan aquifer system in Duval County, FL (Phelps, 2001). All of the samples collected from the Floridan aquifer system during this investigation had stable carbon isotopic compositions that ranged from -0.2 to -9.4 per mil.

Water type I from the Upper Floridan aquifer at Pineora well 34S011, Pembroke well 33R045, and Richmond Hill well 35P110, and from the Lower Floridan aquifer at Pembroke well 33R045 had concentrations of sulfate equal to or less than 7.3 mg/L, concentrations of hydrogen sulfide of less than 1.0 mg/L, and stable carbon isotopic compositions ranging from -3.7 to -6.6 per mil (fig. 16; tables 6, 8). Calcium-carbonate dissolution was the dominant geochemical process resulting in the calcium-magnesium-bicarbonate composition and the range of stable isotopic compositions in these samples.

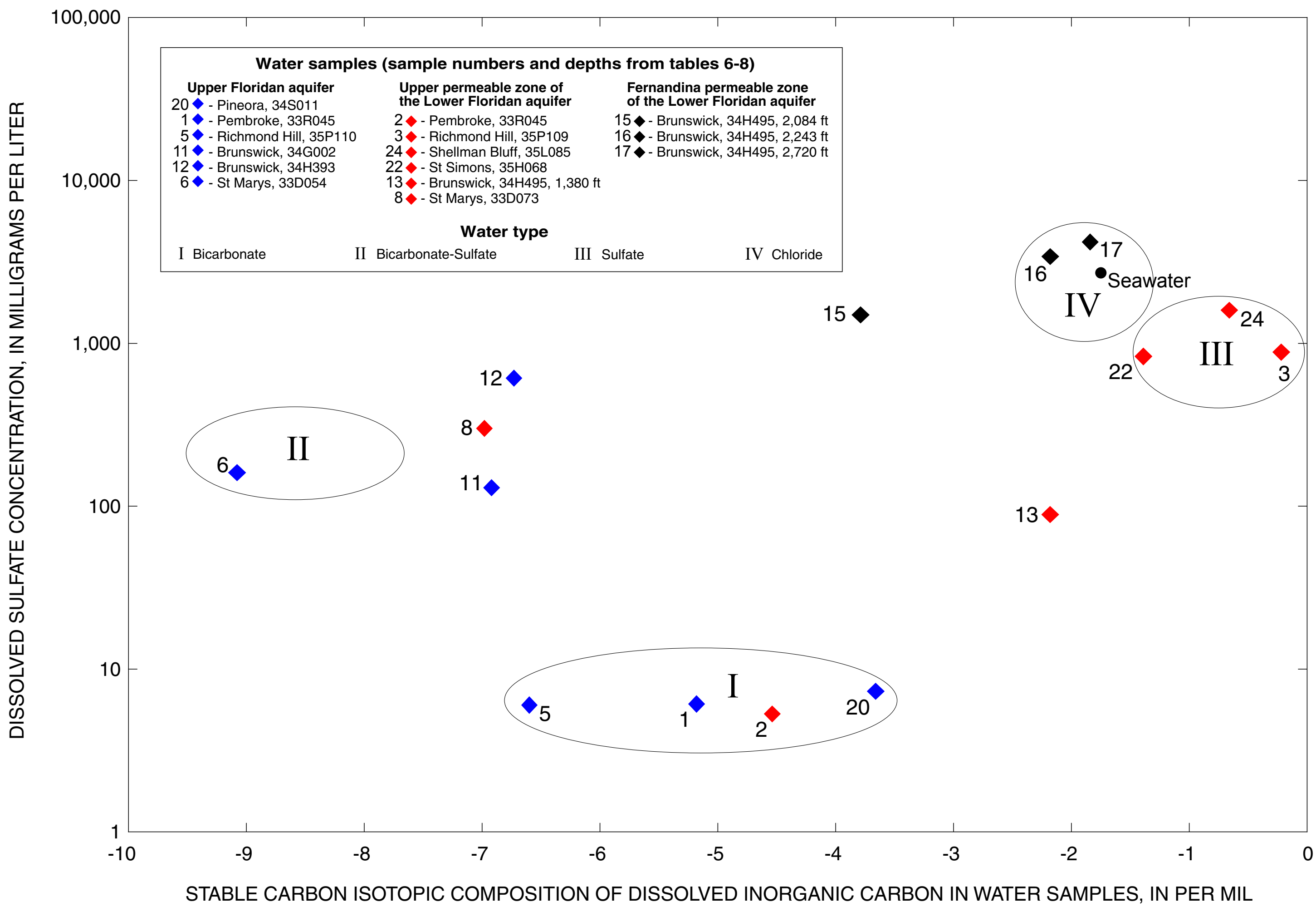


Figure 16. Relation of stable carbon isotopic composition, relative to Peedee Belemnite, and dissolved sulfate with water types in samples collected from the Floridan aquifer system in the Coastal Sound Science Initiative study area, Georgia.

Sulfate concentrations are low enough to limit the effects of sulfate reduction at these sites.

Four water samples had stable carbon isotopic compositions more depleted (more negative) than the samples of water type I (fig. 16). These four samples had concentrations of sulfate ranging from 130 to 610 mg/L, hydrogen sulfide ranging from 1.4 to 4.3 mg/L, total organic carbon ranging from 1.1 to 3.4 mg/L and stable carbon isotopic compositions ranging from -6.7 to -9.4 per mil (tables 6, 7). The four samples were water type II from the Upper Floridan aquifer in St Marys well 33D054, water type III from the upper permeable zone of the Lower Floridan aquifer in St Marys well 33D073, and the two chloride-contaminated samples from the Upper Floridan aquifer in downtown Brunswick, which include transitional water type II–III in well 34G002 and type IV in well 34H393. Relative to water type I, sulfate reduction produced the higher concentrations of hydrogen sulfide and more isotopically depleted stable carbon isotopic compositions of the DIC in water type II and these other samples.

Six water samples had stable carbon isotopic compositions more enriched (more positive) than the samples of water type I. These water samples include four samples from the upper permeable zone and two samples from the Fernandina permeable zone of the Lower Floridan aquifer.

The four samples from the upper permeable zone of the Lower Floridan aquifer were a sample of water type II from well 34H495 at the Brunswick site and three samples of water type III from Richmond Hill well 35P109, Shellman Bluff well 35L085, and St Simons Island well 35H068. The four samples had concentrations of hydrogen sulfide less than 1.0 mg/L, total organic carbon ranging from 0.5 to 1.1 mg/L, and stable carbon isotopic compositions ranging from -0.2 to -2.2 per mil (tables 6–8). The sample of water type II has a concentration of sulfate of 89 mg/L, considerably lower than the samples of water type III that had sulfate concentrations ranging from 830 to 1,600 mg/L. The higher percentage of sodium, relative to calcium and magnesium, in samples of water type III from the Lower Floridan aquifer at Richmond Hill and Shellman Bluff may be the result of minor quantities of saltwater retained in the fine-grained carbonate and marl beneath the Lower Floridan aquifer and calcium-sodium exchange between the ground water and the matrix of the aquifer and underlying confining unit. Cation exchange of calcium for sodium would allow additional carbonate to be dissolved, which would result in an enriched, stable carbon isotopic composition of the DIC, relative to water type I (Pearson and Swarzenki, 1974).

The two water samples from the Fernandina permeable zone were water type IV from a depth of 2,243 and 2,720 ft in well 34H495 at the Brunswick site, with concentrations of sulfate of 3,400 and 4,200 mg/L, and total organic carbon of 1.1 and 1.3 mg/L, respectively (fig. 16; table 7). The saltwater sample from 2,243 ft had a hydrogen sulfide concentration less than 1.0 mg/L, similar to the other samples with enriched stable carbon isotopic compositions; however, the brine sample from 2,720 ft had a hydrogen sulfide concentration of 6.0 mg/L, which was the highest concentrations for this constituent in this study (table 7). The saltwater and the brine in the Fernandina permeable zone are interpreted as relict marine waters buried in these strata after deposition with stable carbon isotopic compositions of approximately -2.0 per mil, which is close to the -1.8 per mil of the modern seawater sample. Mineralization, including the dissolution of sulfate minerals and sulfate reduction, has altered the chemical composition of the brine, relative to the saltwater, but has not resulted in a large difference between the stable isotopic compositions of these two samples.

Carbon-14

Carbon-14 concentrations in samples collected from the Lower Floridan aquifer were similar to those collected from the overlying Upper Floridan aquifer and the underlying Fernandina permeable zone. The water samples collected from the Floridan aquifer system during this investigation had carbon-14 concentrations ranging from 0.66 to 5.07 pmc in samples from the Upper Floridan aquifer, 0.91 to 2.79 pmc in samples from the upper permeable zone of the Lower Floridan aquifer, and 1 to 3.15 pmc in samples from the Fernandina permeable zone of the Lower Floridan aquifer (tables 6–8).

The ages of water samples in the Upper and Lower Floridan aquifers at a specific site, however, cannot be assumed to be the same just because the carbon-14 concentrations are the same. As discussed in the section on stable carbon isotopes, the stable carbon isotopic compositions and the water types were not similar in the Upper and Lower Floridan aquifers at the St Marys, Brunswick, and Richmond Hill sites. As a result, dilution of carbon-14 concentrations by geochemical processes in the Lower Floridan aquifer could differ from those in the Upper Floridan aquifer. The site-specific similarities in the stable oxygen and hydrogen isotopic compositions of waters in the Upper and Lower Floridan aquifer at the St Marys, Brunswick, Richmond Hill, and Pembroke sites indicated that the waters in both aquifers at a specific well site in the study area probably entered the recharge area under similar climatic conditions and, therefore, could have similar ages.

In this usage, the term “similar ages” has an accuracy of plus or minus 2,000 to 5,000 years. Preparation of water samples processed for carbon-14 analysis by the accelerator-mass-spectrometer (AMS) method has resulted in an error of plus or minus 4,000 years for age calculations in previous investigations (Phelps, 2001). Therefore, the fresh or slightly saline waters in the Lower Floridan aquifer at a specific site in coastal Georgia may have had a different geochemical history compared to the freshwater in the Upper Floridan aquifer; however, the ages of the waters in both aquifers at a specific site were probably similar within an accuracy of plus or minus a few thousand years.

In addition to the effects of carbon-14 dilution by aquifer-specific and site-specific geochemical processes, the potential for contamination of water samples with modern atmospheric carbon-14 must be considered. It seems unrealistic to assume modern recharge of freshwater or saltwater to the brine in the Fernandina permeable zone at the Brunswick site, given that the brine is buried more than 2,680 ft below downtown Brunswick and is overlain by saltwater in the Fernandina permeable zone with a carbon-14 concentration of 1 pmc. Therefore, the carbon-14 concentration of 3.2 pmc for the brine sample seems unrealistic. The brine and saltwater were collected with a wireline sampler, but the transfer of water from the sampler to the sample bottle likely resulted in contamination of the brine sample with a minor amount of modern atmospheric carbon-14 and likely resulted in minor contamination of other samples collected with the wireline sampler. Of the water samples collected in Camden, McIntosh, Bryan, and Effingham Counties, carbon-14 concentrations ranged from 1.5 to 5.1 pmc in the five samples collected by wireline sampler and from 0.7 to 1.7 pmc in the five samples collected from the discharge of submersible or turbine pumps. In Brunswick, the carbon-14 concentrations for both sampling techniques ranged from 1 to 4 pmc.

Based on low carbon-14 concentrations of these water samples, water collected from the Floridan aquifer system during this investigation is thousands of years old and probably greater than 10,000 years old. Most of the sampled wells are at the downgradient end of ground-water flowpaths in coastal Georgia, and the depth and confinement of the Floridan aquifer system at these sites is consistent with low measured carbon-14 concentrations in the samples. Given the sample-preparation error for the AMS method, the potential for contamination with the wireline-sampling technique, and the complex geochemical history of the water in the Floridan aquifer system, absolute ages were not calculated from these carbon-14 results.

Tritium

Results for tritium are limited to 5 of the 24 water samples. The presence of tritium at concentrations above the minimum laboratory reporting limit indicates the presence or the influence of modern water (less than 50 years) or possible contamination of a ground-water sample with modern atmospheric water vapor during sampling.

Four water samples were collected from existing production or monitoring wells open to the Upper Floridan aquifer and Fernandina permeable zone in Glynn County and the Upper Floridan aquifer in Camden County, GA, to test the integrity of the wells and sampling procedures at the CSSI wells. The three Upper Floridan samples had tritium concentrations less than 0.3 TU. The sample from the Fernandina permeable zone in well 33H188 had a concentration of 0.5 TU. Given the low carbon-14 concentration of 2.99 pmc in this sample, the tritium probably is the result of a small amount of atmospheric contamination during sample collection (table 7). Subsequently, a water sample was collected in CSSI well 34H495 in downtown Brunswick in the interval from 2,084 to 2,091 ft from the moderately saline-water interval at the top of the Fernandina permeable zone, which had a tritium concentration of less than 0.3 TU. These tritium results, and the carbon-14 concentration of 1.42 pmc in the sample from 2,084 to 2,091 in well 34H495, indicated the absence of modern freshwater or saltwater recharge to the Floridan aquifer system in these wells in Glynn and Camden Counties, GA.

Strontium Isotopes of Water

The strontium isotope ratio in marine carbonate strata is presumed to be in equilibrium with the strontium isotope ratio of the seawater of its origin (Hess and others, 1986). For example, marine carbonate that formed during the Eocene should have a strontium isotope ratio similar to Eocene seawater. With a long residence time in the aquifer, the strontium isotope ratio of ground water will equilibrate with the strontium-bearing carbonate minerals in the carbonate strata. Therefore, the strontium isotope ratio of ground-water samples cannot be used to determine the relative or absolute age of ground water, as in the case of tritium or carbon-14, but can be used to determine the ground-water source strata. The original strontium isotope ratio of marine carbonate, however, can be altered during the geochemical processes involved in the formation of dolomite.

The ratios of the absolute proportions of strontium-87 to strontium-86 were measured in 11 ground-water samples collected in coastal Georgia and compared with published strontium isotope ratios for limestone from the Floridan aquifer system in Duval County, FL (Phelps, 2001). One of the 11 ground-water samples, not previously discussed, is from well 33D074 in St Marys, GA, which was drilled by the SJRWMD. The sample from well 33D074 was collected from the Lower Floridan aquifer in the interval from 1,840 to 2,045 ft. The strontium isotope ratios of the 11 ground-water samples were plotted on a scatter diagram as a function of inverse strontium concentration in liters per milligram (fig. 17). Not included in this figure is the strontium isotope ratio of 0.70916 for the modern seawater sample given in Phelps (2001).

The five freshwater samples from the Upper Floridan aquifer at the Pineora, Pembroke, Richmond Hill, St Marys, and St Simons Island sites and the two freshwater samples from the Lower Floridan aquifer at the Pembroke and St Marys sites had inverse strontium concentrations greater than 1 and strontium isotope ratios that fall in the range of Oligocene or Miocene seawaters (fig. 17). Oligocene strata were porous at Pineora, Pembroke, and Richmond Hill and were included as part of the Upper Floridan aquifer at these sites. Conversely, the Oligocene strata were nonporous at St Simons Island and absent at St Marys, and definitely not present in the Lower Floridan aquifer at Pembroke and CSSI well 33D073 at St Marys.

Three possible explanations are proposed for the occurrence of Oligocene and Miocene strontium isotope ratios in the fresh ground-water samples—dolomitization, mixing, and residence time. Dolomitization could have altered the strontium ratio of carbonate strata in the Lower Floridan aquifer at St Marys and resulted in a ratio that falls in the range of Oligocene seawater samples. Downward leakage of porewaters from the upper confining unit probably occurred with ground-water withdrawals from the Upper Floridan aquifer. If the residence time of the mixed water has not been long enough to allow for re-equilibration with the Eocene strata, then the mixing of porewater from the Miocene strata of the upper confining unit with the water of the Upper Floridan aquifer could result in a strontium isotope ratio similar to that of the Oligocene strata.

The four ground-water samples from the Lower Floridan aquifer at Shellman Bluff, Richmond Hill, and St Simons Island, and well 33D074 at St Marys were slightly saline and had inverse strontium concentrations less than 1 liter per milligram (fig. 17). The strontium isotope ratios in these samples were similar to Eocene seawater and are assumed, therefore, to be at equilibrium with the strontium isotope ratio of the Eocene strata of the Lower Floridan aquifer.

Water-Supply Potential of the Lower Floridan Aquifer

Transmissivity and water quality are two potential limitations of using the upper permeable zone of the Lower Floridan aquifer as an alternative water supply to the Upper Floridan aquifer. The Fernandina permeable zone of the Lower Floridan aquifer, with its saltwater and brine, would require extensive water treatment to be considered for most water-supply needs and, therefore, is not discussed as a potential alternative water supply to the Upper Floridan aquifer.

Transmissivity is a measure of an aquifer's ability to transmit water. The transmissivities of the upper permeable zone of the Lower Floridan aquifer at the Richmond Hill, Shellman Bluff, and St Marys sites were as much as one to two orders of magnitude less than published transmissivities and measured transmissivities of the Upper Floridan aquifer (Harrelson and Falls, 2003); however, these transmissivities for the Lower Floridan aquifer are in the same range as

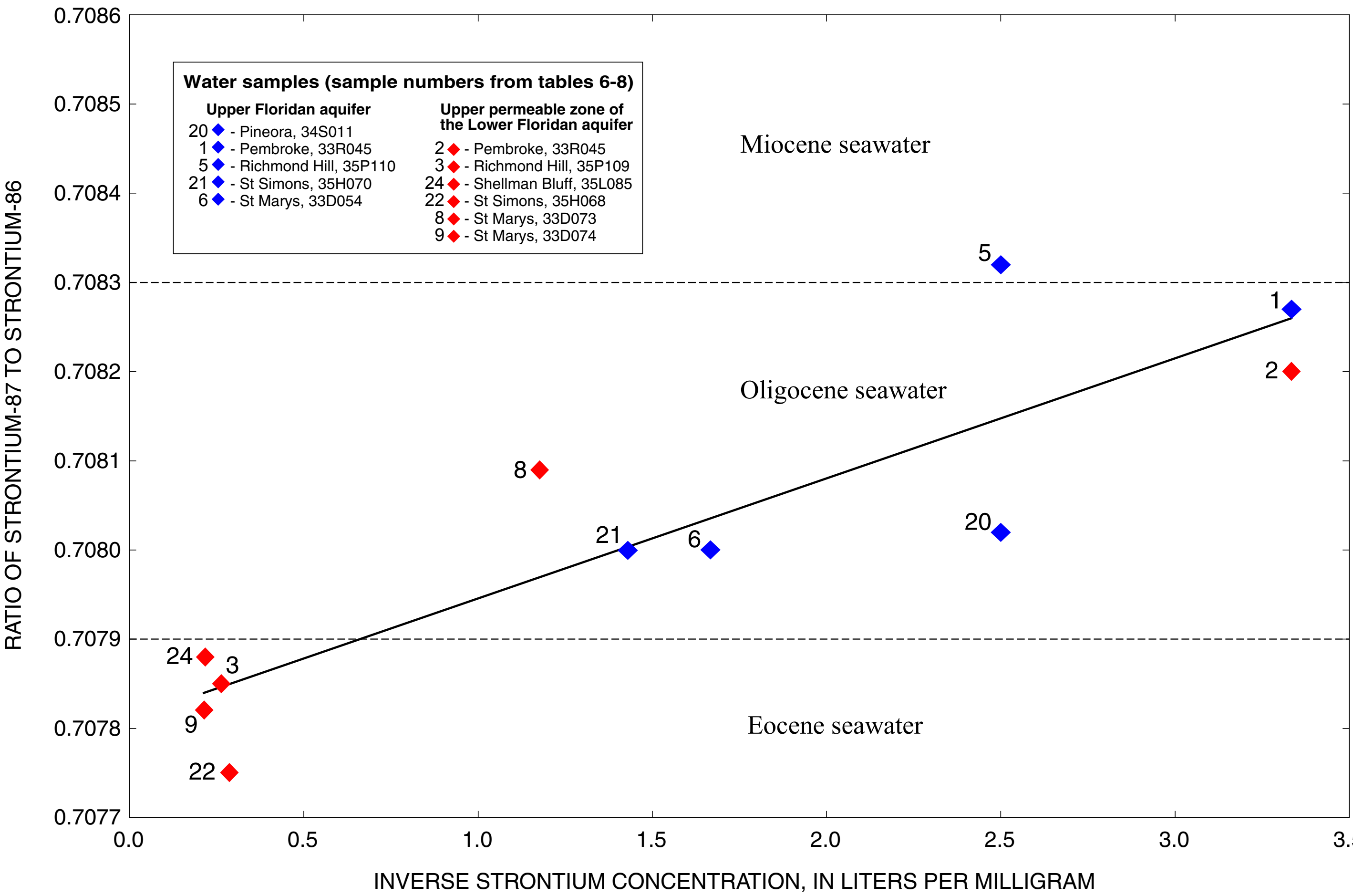


Figure 17. Relation of strontium isotope ratio with the inverse of strontium concentration in water samples collected from wells open to the Upper and Lower Floridan aquifers in the Coastal Sound Science Initiative study area, Georgia.

other water-supply aquifers in Georgia and South Carolina, including the sand aquifers in the Tertiary and Cretaceous strata of the Upper Coastal Plain in both States (Brooks and others, 1985; Clarke and others, 1985; Newcome, 1993). Transmissivities of 6,000 to 8,300 feet squared per day (ft^2/d) at the Shellman Bluff and Richmond Hill sites, respectively, and 13,000 ft^2/d at the St Marys site may not yield enough water to efficiently meet the demand of industrial water supply, as seen in Chatham, Glynn, Camden, and Wayne Counties, GA, but a well in the Lower Floridan aquifer could meet the more moderate needs of public supply in small communities and large municipalities, as well as seasonal agricultural needs. The low yield of water during the drilling at the Pineora site and the estimated transmissivity of 500 ft^2/d at the St Simons Island site indicate that the Lower Floridan aquifer may have limited use as an alternative water supply to the Upper Floridan aquifer at these two sites.

The water quality of the upper permeable zone exceeded secondary drinking-water standards for sulfate and total dissolved solids more frequently and had higher chloride concentrations at several sites, relative to the Upper Floridan aquifer. Water in the upper permeable zone of the Lower Floridan aquifer would need to be treated or diluted at most coastal Georgia sites to meet the Federal secondary drinking-water standards for sulfate and TDS. Sulfate and TDS concentrations did not exceed the Federal secondary drinking-water standards at the Pembroke and Brunswick sites. Given the sulfate concentrations of the upper permeable zone at most coastal sites, the construction of wells combining permeable zones of the Upper and Lower Floridan aquifers potentially would allow borehole mixing of waters from both aquifers and could result in undesirable geochemical reactions, including the production of hydrogen sulfide.

Chloride concentrations in the upper permeable zone of the Lower Floridan aquifer were not as common a problem as sulfate and TDS concentrations. Chloride concentrations slightly exceeded the Federal secondary drinking-water standard only at the Shellman Bluff site. Production of water from a combined interval of the Upper and Lower Floridan aquifers at Richmond Hill or Shellman Bluff, however, would result in higher chloride concentrations than in a well open only to the Upper Floridan aquifer. As with sulfate and TDS, water from the Lower Floridan aquifer at these two sites would require treatment or dilution to meet the secondary drinking-water standard.

Summary

For more than a century, the abundant yield of good-quality water from the Upper Floridan aquifer has provided most of the water-supply wells in the coastal counties of Georgia and, until the late 1990s, generally limited the need to explore the Lower Floridan aquifer as a water supply. This report documents the results of a hydrogeologic and water-quality field investigation of the upper permeable and Fernandina permeable zones of the Lower Floridan aquifer in the 24-county study area of the Georgia Coastal Sound Science Initiative with data collected from wells drilled at Pineora, Pembroke, Richmond Hill, Shellman Bluff, St Simons Island, Brunswick, and St Marys, Georgia. Based on the hydrogeologic characteristics, these seven sites are divided into the northern sites at Shellman Bluff, Richmond Hill, Pembroke, and Pineora; and southern sites at St Marys, Brunswick, and St Simons Island. The top of the Lower Floridan aquifer correlates within 50 feet of the previously reported top of the Lower Floridan aquifer, except at the St Simons Island site where the top is more than 80 feet higher.

At the northern sites, the Lower Floridan aquifer is thinner than the Upper Floridan aquifer and consists of strata of the middle Eocene Avon Park Formation. The Lower Floridan aquifer is 157 feet thick at Pineora with three beds of dolomite, and at least 310 feet thick at Pembroke with four beds of dolomite. The Lower Floridan aquifer is 310 feet of porous and nonporous dolomitic limestone at Richmond Hill, and 228 feet of porous and nonporous limestone at Shellman Bluff. Transmissivities in the Lower Floridan aquifer are 8,300 feet squared per day at Richmond Hill and 6,000 feet squared per day at Shellman Bluff.

At the southern sites, the upper permeable zone of the Lower Floridan aquifer is thicker than the Upper Floridan aquifer, and consists of porous limestone and dolomite interbedded with nonporous strata of the middle Eocene Avon Park and early Eocene Oldsmar Formations. The porous strata are 19, 28, and 22 percent of the total thickness of the Lower Floridan aquifer at St Marys, Brunswick, and St Simons Island, respectively. Intercrystalline and moldic porosity in the dolomite varies from 10 to 35 percent. Interparticle porosity in the limestone is generally 5 to 10 percent. Fractures and solution cavities were detected during drilling at Brunswick, St Marys, and St Simons Island. Estimated transmissivities are 13,000 and 500 feet squared per day at St Marys and St Simons Island, respectively. The Fernandina permeable zone of the Lower Floridan aquifer was present at only St Marys and Brunswick.

Hydrographs for Coastal Sound Science Initiative wells and other nearby wells open to the Upper Floridan aquifers, and the upper permeable and Fernandina permeable zones of the Lower Floridan aquifer have similar water-level trends. Wells open to the Upper and Lower Floridan aquifers at the northern sites (through January 1, 2004) had measured water levels below land surface. At Brunswick, measured water levels for the upper permeable and Fernandina permeable zones of the Lower Floridan aquifer are above land surface and greater than the Upper Floridan aquifer. At the St Marys site, ground-water levels in the Upper and Lower Floridan aquifer have similar trends; water levels increased by over 19 feet after the closure of a paper mill in October 2002.

Freshwater is present in the Lower Floridan aquifer at Pineora, Pembroke, and St Marys, and from 1,259 to 1,648 feet below land surface at Brunswick. Slightly saline water is present in the Lower Floridan aquifer at Richmond Hill, Shellman Bluff, St Simons Island, and from 1,679 to 1,970 feet below land surface in well 34H495 at Brunswick. The Fernandina permeable zone in well 34H495 includes moderately saline water, very saline water, and brine.

Bicarbonate water (water type I) was present in the Upper Floridan aquifer at Pineora, Pembroke, and Richmond Hill, and in the Lower Floridan aquifer at Pembroke. Sulfate-bicarbonate water (water type II) was present in the Upper Floridan aquifer at St Marys and St Simons Island, and in the upper permeable zone of the Lower Floridan aquifer at 1,380 feet in Brunswick well 34H495. Sulfate water (water type III) was present in the Upper Floridan aquifer and the upper permeable zone of the Lower Floridan aquifer at St Marys and St Simons Island, respectively. Water type III also was present in the upper permeable zone of the Lower Floridan aquifer at Shellman Bluff, Richmond Hill, and Brunswick. The bicarbonate, sulfate-bicarbonate, and sulfate waters are saturated with calcite and dolomite, and undersaturated with gypsum and anhydrite. In the upper permeable zone of the Lower Floridan aquifer, Federal secondary drinking-water standards were exceeded for total dissolved solids and sulfate, except at Pineora and Pembroke, and for chloride at only Shellman Bluff.

Chloride water (water type IV) was present in the chloride-contaminated interval of the Upper Floridan aquifer and the Fernandina permeable zone of the Lower Floridan aquifer beneath downtown Brunswick. Concentrations of total dissolved solids, sulfate, and chloride exceeded the Federal secondary drinking-water standards. The very saline and brine waters from the Fernandina permeable zone are slightly undersaturated to saturated with gypsum and anhydrite. Based on chloride and stable isotope results for Brunswick well 34H393, the chloride-contaminated plumes in the Upper Floridan aquifer beneath downtown Brunswick would require at least a 12- to 20-percent contribution of very saline water from the Fernandina permeable zone.

Water from the upper permeable zone of the Lower Floridan aquifer at the St Marys, Brunswick, Richmond Hill, and Pembroke sites had carbon-14 concentrations and stable oxygen and hydrogen isotopic compositions that were similar to water from the Upper Floridan aquifer at these respective sites. The site-specific similarities in the stable oxygen and hydrogen isotopic compositions of water indicate that waters in both aquifers at a specific well site probably entered the recharge area under similar climatic conditions and, therefore, could have similar ages within an accuracy of plus or minus a few thousand years.

Five samples from the Upper Floridan aquifer at Pineora, Pembroke, Richmond Hill, St Marys, and St Simons Island and two freshwater samples from the upper permeable zone of the Lower Floridan aquifer at Pembroke and St Marys have strontium isotope ratios that fall in the range of Oligocene or Miocene seawaters. Four ground-water samples from the upper permeable zone of the Lower Floridan aquifer at Shellman Bluff, Richmond Hill, and St Simons Island, and St Marys well 33D074 have strontium isotope ratios in the range of Eocene seawater.

Transmissivities for the Lower Floridan aquifer are in the same range as other water-supply aquifers in Georgia and South Carolina and could meet the needs of public supply in small communities and large municipalities, as well as seasonal agricultural needs. Water of the upper permeable zone of the Lower Floridan aquifer exceeded the Federal secondary drinking-water standards for sulfate and total dissolved solids at most coastal Georgia sites and for chloride at the Shellman Bluff site.

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Appendix 1. Lithology, bit penetration rate, water quality, and well construction for Coastal Sound Science Initiative well 33D073 at the St Marys site, Georgia.

[ft, feet; µS/cm, microsiemens per centimeters at 25 degrees Celsius; mg/L, milligrams per liter; °C, degrees Celsius; %, percent; <, less than]

Sample interval depth, in ft below land surface	Lithology, dominant clastic grain size or Folk (1962) carbonate classification; grain type or allochem, color (Geological Society of America color chart, 1991); porosity estimated	Drill bit penetration rate, in ft/min	Specific conductance of reverse-air discharge water, in µS/cm (chloride/sulfate in mg/L)	Temperature of reverse-air discharge water, in °C	Observations during drilling
0–10	Landfill sand to depth of 3 ft, very fine to fine, subangular, 5–10 % organic, sampled from wall of mudpit; sand (wetland), very fine to fine, clayey, organic, dark gray (N3) to light olive gray (5Y6/1), intergranular porosity.	0.59			Stage 1 — mud rotary drilling with a 21-inch bit. Installed 16-inch (nominal) surface casing.
10–20	Sand, very fine to fine and silty clay, modern cypress roots, dark greenish gray (5G4/1).	0.59			
20–30	Sand, as above.	1.11			
30–40	Clay from 31–33 ft, silty, greenish gray (5G6/1) sampled from bit; sand, fine to coarse, clayey, abundant shell material, phosphate, greenish gray (5GY6/1) to light olive gray (5Y6/1).	0.05			
40–50	Sand, as above.	1.11			
50–60	Sand, as above.	2			
60–65	Sand, as above; limestone from 63–64 ft, micrite with fine to coarse sand, pelecypods, phosphate <5%, light gray (N7).	0.42			
65–70	Limestone, as above.	1			
70–80	Limestone, as above, to depth of 74 ft; fine to coarse sand, silty, calcareous, light olive gray (5Y6/1).	0.11			
80–90	Dolomite and limestone, sandy and silty, pelecypods, phosphatic, light gray (N7) to greenish gray (5GY6/1).	1			Stage 2 — mud rotary drilling with a 15.25-inch bit. Installed 12-inch (nominal) casing.
90–100	Limestone, as above, to depth of 93 ft; clay, silty, fine sand, phosphatic, greenish gray (5GY5/1).	1			
100–110	Clay, as above.	0.4			
110–120	Clay, as above.	0.67			
120–127	Clay, as above; hard, white clay nodules.	0.7			
130–140	Clay, as above with hard gray clay.	0.7			
140–150	Sand, medium to coarse, and clay, pelecypods, phosphatic, greenish gray (5GY5/1).	0.7			
150–160	Clay, with fine to coarse sand, pelecypods, phosphatic, greenish gray (5GY5/1).	0.7			
160–170	Clay, as above.	0.5			

Appendix 1. Lithology, bit penetration rate, water quality, and well construction for Coastal Sound Science Initiative well 33D073 at the St Marys site, Georgia. — Continued

[ft, feet; µS/cm, microsiemens per centimeters at 25 degrees Celsius; mg/L, milligrams per liter; °C, degrees Celsius; %, percent; <, less than]

Sample interval depth, in ft below land surface	Lithology, dominant clastic grain size or Folk (1962) carbonate classification; grain type or allochem, color (Geological Society of America color chart, 1991); porosity estimated	Drill bit penetration rate, in ft/min	Specific conductance of reverse-air discharge water, in µS/cm (chloride/sulfate in mg/L)	Temperature of reverse-air discharge water, in °C	Observations during drilling
170–180	Clay, as above.	0.33			
180–190	Clay, as above.	0.32			
190–200	Sand, fine to coarse, clayey, phosphatic, pelecypods, pale olive (10Y6/2).	0.67			
200–210	Sand, as above, with clay, pale olive (10Y6/2).	0.4			
210–220	Sand, silty, clayey, pelecypods, sharks teeth observed, phosphatic, greenish gray (5GY6/1).	0.4			
220–230	Clayey sand to sandy clay, fine to medium, subrounded, pelecypods, phosphatic, greenish gray (5GY5/1).	1			
230–240	Clay, with fine to coarse sand, pelecypods, phosphatic, greenish gray (5GY5/1).	0.33			
245–250	Clay, with fine to coarse sand, and calcareous sandstone, pale olive (10Y6/2) to grayish olive (10Y4/2).	0.2			
255–260	Clay, minor sand and phosphate, greenish gray (5GY6/1) to grayish olive green (5GY4/2).	0.2			
265–270	Clay, as above, dusky yellow green (5GY5/2).	0.2			
275–280	Clay, as above.	0.2			
285–290	Clay, as above.	0.23			
295–300	Clay, as above.	0.4			
305–310	Clay, as above.	1.43			
310–318	Clay, slightly silty, noncalcareous, dark greenish gray (5GY4/1).	0.44			
318–324	Dolomite, sandy, phosphatic, pelecypods, yellow gray (5Y8/1).	0.35			
324–334	Clay, silty, dark greenish gray 5GY4/1).	0.72			
334–344	Clay, as above.	0.67			
344–354	Clay, as above.	0.73			
354–364	Clay, with fine to medium sand, phosphatic, dark greenish gray (5GY4/1); limestone nodules or thin beds at 360 and 361.5 ft.	0.26			

Appendix 1. Lithology, bit penetration rate, water quality, and well construction for Coastal Sound Science Initiative well 33D073 at the St Marys site, Georgia. — Continued

[ft, feet; µS/cm, microsiemens per centimeters at 25 degrees Celsius; mg/L, milligrams per liter; °C, degrees Celsius; %, percent; <, less than]

Sample interval depth, in ft below land surface	Lithology, dominant clastic grain size or Folk (1962) carbonate classification; grain type or allochem, color (Geological Society of America color chart, 1991); porosity estimated	Drill bit penetration rate, in ft/min	Specific conductance of reverse-air discharge water, in µS/cm (chloride/sulfate in mg/L)	Temperature of reverse-air discharge water, in °C	Observations during drilling
364–374	Clay, as above, sand content increasing downward to very fine to medium sand at 373 ft; no limestone.	0.4			
374–384	Clay silty, dense, dark greenish gray (5GY4/1).	0.38			
384–394	Clay, as above.	0.3			
394–404	Clay, as above.	0.25			
404–414	Clay, as above.	0.3			
414–424	Clay, as above; very fine to fine sand starting at 418 ft, clayey, phosphate 2–3%, light olive gray (5Y6/1) to dark greenish gary (5GY6/1).	0.39			
424–432	Sand, as above.	0.31			
432–438	Limestone and dolomite, nodules or thin beds from 432–434 ft; very fine to medium sand, clayey, light olive gray (5Y6/1), subrounded; silty clay, dark greenish gray (5GY4/1).	0.42			
438–448	Sand, very fine to coarse, clayey, subrounded to rounded, phosphate up to 20%, dark greenish gray (5GY4/1); thin interbeds of dolomite and limestone, sandy, fossiliferous, yellow gray (5Y5/2).	0.4			
448–458	Sand, as above from 448–454 ft; limestone, with very fine to medium quartz sand, phosphate 20%, pelecypods <5%.	0.25			
458–463	Limestone, as above, phosphate 20–30%.	0.45			
463–468	Limestone, as above, plus bryozoans.	1.25			
468–473	Clay, calcareous, minor sandy, very fine-grained, minor phosphate, light olive gray (5Y5/2).	1.25			
473–483	Clay, with very fine sand and minor phosphate, light olive gray (5Y5/2).	0.26			
483–493	Clay, as above.	0.45			
493–503	Clay, as above.	0.8			
503–513	Clay, as above.	0.5			

Appendix 1. Lithology, bit penetration rate, water quality, and well construction for Coastal Sound Science Initiative well 33D073 at the St Marys site, Georgia. — Continued

[ft, feet; µS/cm, microsiemens per centimeters at 25 degrees Celsius; mg/L, milligrams per liter; °C, degrees Celsius; %, percent; <, less than]

Sample interval depth, in ft below land surface	Lithology, dominant clastic grain size or Folk (1962) carbonate classification; grain type or allochem, color (Geological Society of America color chart, 1991); porosity estimated	Drill bit penetration rate, in ft/min	Specific conductance of reverse-air discharge water, in µS/cm (chloride/sulfate in mg/L)	Temperature of reverse-air discharge water, in °C	Observations during drilling
513–523	Limestone, biosparite/biomicrite with bryozoans, echinoids, pelecypods, oysters, subrounded granules of phosphate, light gray (N7) to light olive gray (5Y6/1), intra/interparticle porosity <5%.	0.4			
523–533	Limestone, as above.	0.67			
533–543	Limestone, as above, yellow gray (5Y8/1), phosphate <1%.	0.18	410	24	
543–553	Limestone, as above.	0.24			
553–563	Limestone, as above.	0.17			
565–575	Limestone, as above.	1.25			11-inch bit/8-inch (nominal) casing.
575–585	Limestone, as above.	0.63			
585–594	Limestone, biosparite/biomicrite with bryozoans, echinoids, oysters, foraminifera, yellow gray (5Y7/2), intra/interparticle porosity 5–10%.	0.71			
594–603	Limestone, biosparite/biomicrite with bryozoans, echinoids, plicated pelecypods, foraminifera, yellow gray (5Y8/1), intra/interparticle pores 5–10%, biomoldic pores <5%.	0.47	706	26	Air rotary begins.
603–613	Limestone, as above, no biomoldic pores; clay, yellow green at depth 604 ft.	0.42			
613–623	Limestone, biopelsparite, as above, yellow gray (5Y7/2) with intra/interparticle pores 10–20%, biopelmicrite with pores <5%.	0.29	727 (624/175)	24.5	
627–637	Limestone, as above, intra/interparticle pores 10–15%.	0.35			
637–647	Limestone, as above, intra/interparticle pores <10%.	0.32			
647–654	Limestone, biopelsparite/biopelmicrite, bryozoans, foraminifera, pelecypods, echinoids, yellow gray (5Y8/1), interparticle pores 5–15%.	0.27	727	24.5	
654–663	Limestone, as above.	0.5			
663–673	Limestone, as above, biopelsparite with intra/interparticle pores 5–15%, biopelmicrite, very light gray (N8), vuggy pore <5%.	0.4			
673–683	Limestone, as above.	0.29			

Appendix 1. Lithology, bit penetration rate, water quality, and well construction for Coastal Sound Science Initiative well 33D073 at the St Marys site, Georgia. — Continued

[ft, feet; µS/cm, microsiemens per centimeters at 25 degrees Celsius; mg/L, milligrams per liter; °C, degrees Celsius; %, percent; <, less than]

Sample interval depth, in ft below land surface	Lithology, dominant clastic grain size or Folk (1962) carbonate classification; grain type or allochem, color (Geological Society of America color chart, 1991); porosity estimated	Drill bit penetration rate, in ft/min	Specific conductance of reverse-air discharge water, in µS/cm (chloride/sulfate in mg/L)	Temperature of reverse-air discharge water, in °C	Observations during drilling
683–693	Limestone, as above.	0.34	717	24.5	Water level below land surface = 13.56 ft, 10/20/99, 7:18 a.m.
695–705	Limestone, biopelmicrite, pelecypods, foraminifera, yellow gray (5Y8/1) and very light gray (N8), interparticle pores <5%.	0.29			
705–715	Limestone, as above.	0.29			
715–725	Limestone, biopelsparite with abundant foraminifera, pelecypods, echinoids, yellow gray (5Y8/1), interparticle pore 5–15%, and biopelmicrite, yellow gray (5Y8/1), interparticle pores <5%.	0.33	717	24.5	
725–735	Limestone, biopelmicrite, pores <5%, glauconite <1%; biopelsparite, fine-grained with foraminifera, pelecypods, minor echinoids, yellow gray (5Y8/1), interparticle pores 10–15%.	0.33			
735–745	Limestone, primarily biopelmicrite, as above.	0.33			
745–757	Limestone, premarily biopelmicrite, as above, interparticle pores <5%.	0.29	717 (34/173)	24.5	
757–767	Limestone, primarily biopelmicrite, as above; biopelsparite, fine-grained, foraminifera, pelecypods, minor echinoids, yellow gray (5Y8/1), interparticle pores 5–10%.	0.24			
767–777	Limestone, biopelmicrite/biopelsparite as above.	0.29			
777–784	Limestone, as above, pyrite <1%.	0.5	710	25	
784–794	Limestone, biopelmicrite, foraminifera, bryozoan, pellets, pyrite <1%, yellow gray (5Y8/1), pores <5%.	0.26			
794–804	Limestone, as above, biopelsparite, interparticle pore 5–15%, biopelmicrite, pore <5%.	0.21			
804–812	Limestone, pelsparite/pelmicrite, foraminifera less common than above, yellow gray (5Y8/1), interparticle pore 5–10%.	0.16	710	25	Water level below land surface = 13.16 ft, 10/21/99, 7:30 a.m.
812–818	Limestone, pelmicrite with foraminifera, yellow gray (5Y8/1), biomoldic pore <5%, with dolomite from 814–815 ft, moderate yellow brown (10YR5/4), intercrystalline pores 10–20%, vuggy/biomoldic pores 5%.	0.13			

Appendix 1. Lithology, bit penetration rate, water quality, and well construction for Coastal Sound Science Initiative well 33D073 at the St Marys site, Georgia. — Continued

[ft, feet; µS/cm, microsiemens per centimeters at 25 degrees Celsius; mg/L, milligrams per liter; °C, degrees Celsius; %, percent; <, less than]

Sample interval depth, in ft below land surface	Lithology, dominant clastic grain size or Folk (1962) carbonate classification; grain type or allochem, color (Geological Society of America color chart, 1991); porosity estimated	Drill bit penetration rate, in ft/min	Specific conductance of reverse-air discharge water, in µS/cm (chloride/sulfate in mg/L)	Temperature of reverse-air discharge water, in °C	Observations during drilling
818–829	Dolomite, as above, vuggy pores 5–10%; and limestone, pelmicrite, very pale orange (10YR8/2), pores <2%.	0.13			
829–839	Dolomite and limestone, as above.	0.2			
839–849	Dolomite, as above.	0.09	710	25	
849–859	Dolomite and limestone, as above.	0.24			
859–869	Dolomite, as above.	0.08			Water level below land surface = 12.86 ft, 10/22/99, 7:20 a.m.
869–879	Limestone, biopelmicrite/biopelsparite, with pellets and disk-shaped foraminifera, yellow gray (5Y8/1), pores <2%.	0.42	710 (35/175)	25	
879–889	Limestone, as above.	0.25			
889–899	Limestone, biopelsparite with pellets and pelecypods, yellow gray (5Y8/1), porosity <5%.	0.18			
899–909	Limestone, biopelsparite with pellets, bryozoans, echinoids, pelecypods, foraminifera, white (N9) to yellow gray (5Y8/1), interparticle pores 5–10%.	0.2	670 (35/173)	28	
909–919	Limestone, biopelsparite, as above; pelbiomicrite, very light gray (N8), pores <2%.	0.29			
919–929	Dolomitic limestone and calcareous dolomite, biopelmicrite with pellets, echinoids, bryozoans, yellow gray (5Y8/1), intercrystalline porosity 5–10%.	0.19			
929–939	Limestone, biopelmicrite, foraminifera, bryozoans, pellets, spicules, yellow gray (5Y8/1), pores <2%.	0.19	686	26	Water level below land surface = 15.04 ft, 10/25/99, 7:18 a.m.
939–949	Limestone, dolomitic, micrite; and dolomite, gray orange (10YR7/4), intercrystalline pores <5%.	0.33			
949–959	Limestone, biopelsparite, foraminifera, echinoids, bryozoans, yellow gray (5Y8/1), interparticle pores 5–10%.	0.33	684	26	
959–969	Limestone, as above.	0.36	683	26	
969–979	Limestone, as above, abundant echinoid spines, yellow gray (5Y8/1), interparticle pores 5–15%.	0.4			
979–989	Limestone, as above.	0.26	684	26	
989–999	Limestone, as above, plus biopelmicrite.	0.22			

Appendix 1. Lithology, bit penetration rate, water quality, and well construction for Coastal Sound Science Initiative well 33D073 at the St Marys site, Georgia. — Continued

[ft, feet; µS/cm, microsiemens per centimeters at 25 degrees Celsius; mg/L, milligrams per liter; °C, degrees Celsius; %, percent; <, less than]

Sample interval depth, in ft below land surface	Lithology, dominant clastic grain size or Folk (1962) carbonate classification; grain type or allochem, color (Geological Society of America color chart, 1991); porosity estimated	Drill bit penetration rate, in ft/min	Specific conductance of reverse-air discharge water, in µS/cm (chloride/sulfate in mg/L)	Temperature of reverse-air discharge water, in °C	Observations during drilling
999–1,009	Limestone, as above; plus calcareous dolomite, moderate yellow brown (10YR5/4), intercrystalline pores 10–15%.	0.36			
1,009–1,019	Limestone, as above to a depth of 1,018 ft; then dolomite, moderate yellow brown (10YR5/4), intercrystalline pores 15–25%, vuggy/biomoldic pores 5–10%.	0.17	686 (32/165)	26	
1,019–1,029	Dolomite, as above to a depth of 1,026 ft, intercrystalline pores 15–30%; then limestone, dolomitic matrix 10–15%, biopelmicrite, yellow gray (5Y8/1), pores <2%.	0.1	686	26	Water level below land surface = 14.92 ft, 10/26/99, 7:05 a.m.
1,029–1,039	Limestone, biopelsparite/micrite, and calcareous dolomite, pores <5%.	0.28			
1,039–1,048	Limestone, as above, no dolomite.	0.31	660 (34/169)	28	
1,049–1,061	Limestone, micrite, minor fossils, mainly foraminifera, yellow gray (5Y8/1), pores <2%.	0.17	686	28	
1,061–1,069	Dolomite, yellow gray (5Y7/2), intercrystalline pores 20%, vuggy pores 5%.	0.27			
1,069–1,079	Dolomite, no observed porosity.	0.23	670 (31/162)	28	
1,079–1,089	Limestone, micrite, sparsely fossiliferous, gastropods and foraminifera, pellets, yellow gray (5Y8/1), pores <2%.	0.24			
1,089–1,099	Limestone, biopelsparite, calcareous algal grains (?) and foraminifera, yellow gray (5Y8/1), interparticle porosity <5%.	0.21			
1,099–1,109	Limestone, micrite, sparsely fossiliferous, foraminifera, yellow gray (5Y8/1); dolomite from 1,103–1,105 ft, intercrystalline pores 10–20%.	0.2	735 (31/165)	26	
1,109–1,119	Limestone, micrite, very sparsely fossiliferous, echinoid spines, yellow gray (5Y8/1), vugs <2%.	0.22	696	26	
1,119–1,129	Limestone, oobiosparite with echinoid fragments and spines, foraminifera, pellets and ooids, very pale orange (10YR8/2), interparticle pores 5–10%.	0.21			
1,129–1,139	Limestone, as above.	0.19	696	26	
1,139–1,149	Limestone, as above.	0.22	686 (36/165)	27.5	Water level below land surface = 13.52 ft, 10/27/99, 7:15 a.m.
1,149–1,159	Limestone, as above, interparticle pores 10–15%.	0.26			

Appendix 1. Lithology, bit penetration rate, water quality, and well construction for Coastal Sound Science Initiative well 33D073 at the St Marys site, Georgia. — Continued

[ft, feet; µS/cm, microsiemens per centimeters at 25 degrees Celsius; mg/L, milligrams per liter; °C, degrees Celsius; %, percent; <, less than]

Sample interval depth, in ft below land surface	Lithology, dominant clastic grain size or Folk (1962) carbonate classification; grain type or allochem, color (Geological Society of America color chart, 1991); porosity estimated	Drill bit penetration rate, in ft/min	Specific conductance of reverse-air discharge water, in µS/cm (chloride/sulfate in mg/L)	Temperature of reverse-air discharge water, in °C	Observations during drilling
1,159–1,169	Limestone, as above.	0.23			
1,169–1,179	Limestone, biopelsparite/micrite, echinoids, foraminiferas, calcareous algal grains, pellets, yellow gray (5Y8/1), interparticle pores <10%.	0.13	670	28	
1,179–1,189	Limestone as above from 1,179–1,185 ft; then dolomite, calcareous (5–15%), minor calcite fossils including echinoids, olive black (5Y8/1) to moderate yellow brown (10YR5/4), intercrystalline pores 15–25%.	0.1			
1,189–1,199	Dolomite, slightly calcareous, moderate yellow brown (10YR5/4), intercrystalline pores 10–20%.	0.05	689	26.5	Water level below land surface = 13.10 ft, 10/28/99, 7:05 a.m.
1,199–1,209	Dolomite, slightly calcareous, dark yellow brown (10YR4/2), intercrystalline pores 15–25%, vuggy pores 2–5%, to a depth of 1,204; then limestone, biopelsparite/micrite, foraminifera, calcareous algal grains, pellets, echinoids, yellow gray (5Y8/1), intregranular pores 5–10%.	0.13	708	28	
1,209–1,219	Limestone, as above.	0.4			
1,219–1,229	Limestone, as above, echinoids, gastropods, bryozoans, foraminifera.	0.26	708 (40/163)	28	
1,229–1,239	Limestone, biomicrite, sparse to common fossils, echinoids, foraminifera, yellow gray (5Y8/1) to very light gray (N8), pores <2%.	0.23	708	28	
1,239–1,249	Limestone, biomicrite to biopelmicrite, fossiliferous, foraminifera, echinoids, calcareous algal grains, yellow gray (5Y8/1), pores <2%.	0.26			
1,249–1,259	Limestone, as above.	0.42	708	28	
1,259–1,269	Limestone, biopelsparite, foraminifera, echinoids, yellow gray (5Y8/1), interparticle pores 5%.	0.3			
1,269–1,279	Dolomite, moderate yellow brown (10YR5/4), intercrystalline pores 15–25%.	0.1	673 (34/163)	27	Water level below land surface = 12.28 ft, 10/29/99, 7:20 a.m.
1,279–1,289	Dolomite, as above.	0.07	708	28	
1,289–1,299	Dolomite, as above.	0.1			

Appendix 1. Lithology, bit penetration rate, water quality, and well construction for Coastal Sound Science Initiative well 33D073 at the St Marys site, Georgia. — Continued

[ft, feet; µS/cm, microsiemens per centimeters at 25 degrees Celsius; mg/L, milligrams per liter; °C, degrees Celsius; %, percent; <, less than]

Sample interval depth, in ft below land surface	Lithology, dominant clastic grain size or Folk (1962) carbonate classification; grain type or allochem, color (Geological Society of America color chart, 1991); porosity estimated	Drill bit penetration rate, in ft/min	Specific conductance of reverse-air discharge water, in µS/cm (chloride/sulfate in mg/L)	Temperature of reverse-air discharge water, in °C	Observations during drilling
1,299–1,309	Dolomite, as above.	0.13	708 (34/160)	28	Water level below land surface = 10.7 ft, 11/1/99, 11:30 a.m.
1,309–1,319	Dolomite, as above, plus vuggy pores 5%.	0.11	724 (35/159)	27.5	
1,319–1,326	Dolomite, as above, plus vuggy pores 5–10%.	0.13			
1,326–1,334	Dolomite, as above, with bryozoans, intercrystalline pores 15–25%, biomoldic pores 5%.	0.23	750 (34/162)	27	Water level below land surface = 9.18 ft, 11/2/99, 7:04 a.m.
1,334–1,344	Limestone, biosparite/micrite, foraminifera, pelecypods, echinoids, yellow gray (5Y8/1) to very light gray (N8), interparticle pores <5%.	0.24			
1,344–1,354	Limestone, biomicrite/sparite with foraminifera, echinoids, yellow gray (5Y8/1) to very light gray (N8), interparticle pores <5%; dolomite, calcareous, moderate yellow brown (10YR5/4), intercrystalline pores <10%.	0.16	712 (35/164)	27	
1,354–1,365	Limestone, foraminifera, pelecypods, echinoids, bryozoans, pellets, yellow gray (5Y6/1), interparticle pores 5–15%.	0.26	705 (33/164)	28.5	Water level below land surface = 10.04 ft, 11/3/99, 7:04 a.m.; = 9.86 ft, 11/5/99 7:15 a.m.
1,365–1,375	Limestone, as above.	0.26			7-inch bit/open hole 1,365–1,500 ft
1,375–1,385	Limestone, as above.	0.37	759 (32/183)	26	
1,385–1,395	Limestone, as above; dolomite at 1,388 ft, moderate yellow brown (10YR5/4), intercrystalline pores 10–20%.	0.19			
1,395–1,405	Dolomite, calcareous, with echinoids and bryozoans, dark yellow brown (10YR4/2), intercrystalline pores 10–20%.	0.2	776 (32/183)	26.5	
1,405–1,415	Limestone, biosparite/micrite, foraminifera, pyrite 1%, glauconite 1%, light olive gray (5Y6/1), pores <2%.	0.17			Water level below land surface = 0.56 ft, 12/3/99, 7:10 a.m.
1,415–1,425	Limestone, biomicrite, gastropods, bryozoans, foraminifera, echinoids, light olive gray (5Y8/1), biomoldic pores 2%.	0.17			
1,425–1,435	Limestone, biomicrite, bryozoans, foraminifera, very light gray (N8), pores <2%; dolomite from 1,429–1,431 ft, medium gray (N5) to olive gray (5Y4/1), intercrystalline pores 10–20%, biomoldic pores <5%.	0.26	769 (33/194)	27	
1,435–1,445	Limestone, biosparite, bryozoans, foraminifera, pyrite 1–3%, yellow gray (5Y8/1), interparticle pores 10–15%.	0.31			

Appendix 1. Lithology, bit penetration rate, water quality, and well construction for Coastal Sound Science Initiative well 33D073 at the St Marys site, Georgia. — Continued

[ft, feet; µS/cm, microsiemens per centimeters at 25 degrees Celsius; mg/L, milligrams per liter; °C, degrees Celsius; %, percent; <, less than]

Sample interval depth, in ft below land surface	Lithology, dominant clastic grain size or Folk (1962) carbonate classification; grain type or allochem, color (Geological Society of America color chart, 1991); porosity estimated	Drill bit penetration rate, in ft/min	Specific conductance of reverse-air discharge water, in µS/cm (chloride/sulfate in mg/L)	Temperature of reverse-air discharge water, in °C	Observations during drilling
1,445–1,455	Limestone, biomicrite, bryozoans, foraminifera, dolimitic 5%, pyrite 1–3%, yellow gray (5Y8/1) to very light gray (N8), pores <5%.	0.22			
1,455–1,465	Limestone as above, pyrite 2–5%, plus echinoids.	0.25	745 (31/216)	29	
1,465–1,475	Limestone, as above, glauconite 1%, pores <5%.	0.29			
1,475–1,485	Limestone, as above, biomicrite/sparite.	0.33			
1,485–1,500	Limestone, biosparite, foraminifera, bryozoans, echinoids, interparticle pores 5–15%.	0.32	850 (31/254)	28.5	Water level above land surface = 0.74 ft at 6:45 a.m., 12/6-/99 and 1.56 ft at 7:00 a.m., 12/7/99
					Total depth = 1,500.36 ft below land surface

Appendix 2. Lithology, bit penetration rate, water quality, and well construction for Coastal Sound Science Initiative wells 34H495 and 34H500 at the Brunswick site, Georgia.

[%, percent; <, less than; ft, feet; psi, pounds per square inch; µS/cm, microsiemens per centimeters at 25 degrees Celsius; mg/L, milligrams per liter; °C, degrees Celsius; QW, water quality]

Sample interval depth, in ft below land surface (well 34H495)	Lithology, dominant clastic grain size or Folk (1962) carbonate classification; grain type or allochem, color (Geological Society of America color chart, 1991); porosity estimated	Drill bit penetration rate, in ft/min	Well 34H495 Specific conductance of reverse-air discharge water in µS/cm (chloride in mg/L)	Temperature of reverse-air discharge water, in °C	Well 34H500 Specific conductance of reverse-air discharge water in µS/cm (and chloride in mg/L)	Observations during drilling
0–10	Sand, very fine to medium, moderate to poor sorting, subangular to subrounded, dark yellowish brown (10YR4/2) to light olive gray (5Y5/2), shell fragments and phosphate.					30-inch bit.
10–20	Sand, as above.					
20–30	Sand, as above, and clay, dark greenish gray (5GY4/1).					
30–37	Clay, dark greenish gray (5GY4/1).					
37–47	Sand, very fine to medium, some granules, moderate to poor sorting, subangular to subrounded, light olive gray (5Y5/2), shell fragments, phosphate.					
47–57	Clay, pale olive (10Y6/2), sandy.					
57–67	Sand, very fine to medium, moderate to poor sorting, subangular to subrounded, light olive gray (5Y5/2) with clay, subrounded granules, shell fragments.					
67–79	Sand with clay, as above.					
79–89	Sand with clay, as above, more granules and phosphate, with some sandy limestone, pale olive (10Y6/2) at 84–85 ft depth.					
89–100	Sand and clay with sandy limestone, as above.					
100–103	Sand and granules as above, very poor sorting.					103 ft of 24-inch (nominal) steel casing.
103–110	Clay to sandy clay, pale olive (10Y6/2) to grayish olive (10Y4/2).					
110–120	Clay to sandy clay, as above, sandy at top of interval.					30-inch diameter hole to 120 ft.

Appendix 2. Lithology, bit penetration rate, water quality, and well construction for Coastal Sound Science Initiative wells 34H495 and 34H500 at the Brunswick site, Georgia. — Continued

[%, percent; <, less than; ft, feet; psi, pounds per square inch; µS/cm, microsiemens per centimeters at 25 degrees Celsius; mg/L, milligrams per liter; °C, degrees Celsius; QW, water quality]

Sample interval depth, in ft below land surface (well 34H495)	Lithology, dominant clastic grain size or Folk (1962) carbonate classification; grain type or allochem, color (Geological Society of America color chart, 1991); porosity estimated	Drill bit penetration rate, in ft/min	Well 34H495 Specific conductance of reverse-air discharge water in µS/cm (chloride in mg/L)	Temperature of reverse-air discharge water, in °C	Well 34H500 Specific conductance of reverse-air discharge water in µS/cm (and chloride in mg/L)	Observations during drilling
120–130	Sand, fine to very coarse, with quartz and phosphate granules, subangular to subrounded, yellowish gray (5Y7/2), shell fragments and interbedded sandy clay, light olive gray (5Y6/1) to olive gray (5Y4/1).	1.5				
130–140	As above.	0.7				
140–150	Clay, sandy, as above.	1.23				
150–160	Sand and sandy clay, as above.	0.4				
160–171	Clay, sandy, as above.	1.1				
171–181	Sand, as above.	1.2				
181–192	Sand, as above.	1.2				
192–203	Clay, sandy, as above.	5.5				
203–213	Sand, as above.	3.3				
213–223	Clay, grayish olive (10Y4/2), some fine to coarse sand interbeds with granule and small shell fragments.	0.8				
223–235	Clay, as above.	0.7				
235–245	Clay, as above.	0.8				
245–255	Clay, as above.	1				
255–267	Clay, as above.	1.2				
267–277	Clay, as above.	2				
277–287	Clay, as above.	1.4				
287–298	Sand, fine to very coarse, clayey with granules, subrounded, yellowish gray (5Y7/2) and sandy limestone, pale olive (10Y6/2), minor phosphatic, and silty clay, grayish olive green (5GY3/2).	1				
298–308	Sand, as above.	0.8				
308–318	Sand, as above, sharks teeth observed.	2.5				

Appendix 2. Lithology, bit penetration rate, water quality, and well construction for Coastal Sound Science Initiative wells 34H495 and 34H500 at the Brunswick site, Georgia. — Continued

[%, percent; <, less than; ft, feet; psi, pounds per square inch; µS/cm, microsiemens per centimeters at 25 degrees Celsius; mg/L, milligrams per liter; °C, degrees Celsius; QW, water quality]

Sample interval depth, in ft below land surface (well 34H495)	Lithology, dominant clastic grain size or Folk (1962) carbonate classification; grain type or allochem, color (Geological Society of America color chart, 1991); porosity estimated	Drill bit penetration rate, in ft/min	Well 34H495 Specific conductance of reverse-air discharge water in µS/cm (chloride in mg/L)	Temperature of reverse-air discharge water, in °C	Well 34H500 Specific conductance of reverse-air discharge water in µS/cm (and chloride in mg/L)	Observations during drilling
318–329	Sand as above with clay from 320–325 ft, grayish olive (10Y4/2).	0.8				
329–339	Sand, as above, oyster fragments, phosphatic.	0.6				
339–349	Sand, as above.	0.8				
349–361	Clay, sandy and silty, pale olive (10Y6/2), phosphate granules, shell fragments, sandy limestone.	1.1				
361–371	Clay, as above, less phosphate and shells.	0.7				
371–381	Clay, as above.	0.8				
381–393	Silt, clayey, with sand-size quartz and phosphate, minor shell fragments, pale olive (10Y6/2).	1.2				
393–403	Silt, calcareous with very fine to fine quartz and phosphate sand, minor shell fragments, pale olive (10Y6/2).	2.5				
403–413	Silt, as above.	2.5				
413–424	Silt, as above, with calcareous sandstone, very fine to medium, shell fragments, phosphatic, greenish gray (5GY6/1) near base of interval.	1.6				
424–434	Sand, silty to calcareous, very fine to coarse, rounded to subrounded phosphate granules.	1.7				
434–444	Sand, as above with calcareous sandstone interval from 437–444 ft.	0.8				
444–456	Sand, as above.	0.9				
456–466	Sand, as above.	3.3				
466–476	Sand, as above with calcareous sandstone interval from 474–479 ft, pelecypods and oysters.	3.3				
476–488	Sand, as above with addition of echinoid spines, less phosphate.	1.3				
488–498	Sand, as above.	1.7				

Appendix 2. Lithology, bit penetration rate, water quality, and well construction for Coastal Sound Science Initiative wells 34H495 and 34H500 at the Brunswick site, Georgia. — Continued

[%, percent; <, less than; ft, feet; psi, pounds per square inch; µS/cm, microsiemens per centimeters at 25 degrees Celsius; mg/L, milligrams per liter; °C, degrees Celsius; QW, water quality]

Sample interval depth, in ft below land surface (well 34H495)	Lithology, dominant clastic grain size or Folk (1962) carbonate classification; grain type or allochem, color (Geological Society of America color chart, 1991); porosity estimated	Drill bit penetration rate, in ft/min	Well 34H495 Specific conductance of reverse-air discharge water in µS/cm (chloride in mg/L)	Temperature of reverse-air discharge water, in °C	Well 34H500 Specific conductance of reverse-air discharge water in µS/cm (and chloride in mg/L)	Observations during drilling
498–508	Sand, as above.	2				
508–520	Sand, as above to 515 ft, then clay with very fine sand, minor phosphate and shell fragments.	1.5				
520–530	Clay, sandy, as above.	0.9				
530–540	Sand, very fine to fine, phosphate granules, dark greenish gray (5GY4/1), hardens at 535 ft to calcareous sandstone, fine to very coarse, pale greenish yellow (10Y8/2), phosphate granules, interparticle pores, gastropod moldic pores.	0.3				
540–552	Sandstone, as above to 545 ft, then sand, calcareous, very fine to coarse with granules and phosphate, subrounded to rounded, interparticle pores.	0.3				
552–562	Sand, calcareous as above to 557ft, then limestone, fine-grained biosparite with very fine to fine sand, pelecypods and glauconite, light olive gray (5GY8/1), moldic pores in hardened intervals, interparticle pores.	0.5				
562–572	Limestone, sandy, as above.	0.4				
572–578	Limestone, sandy, as above with glauconite and oyster fragment.	0.5				
578–584	Limestone, not sandy, biosparite, minor biomicrite, very little to no glauconite, light gray (N7), pelecypods, bryozoans, and foraminifera.	0.5				584 ft of 16-inch (nominal) steel casing in 604 ft of 21-inch hole.
584–594	Limestone, as above, interparticle porosity <5%.	0.4				
594–605	Limestone, as above.	0.6				
605–617	Limestone, as above.					
617–627	Limestone, as above.					
627–637	Limestone, as above					

Appendix 2. Lithology, bit penetration rate, water quality, and well construction for Coastal Sound Science Initiative wells 34H495 and 34H500 at the Brunswick site, Georgia. — Continued

[%, percent; <, less than; ft, feet; psi, pounds per square inch; µS/cm, microsiemens per centimeters at 25 degrees Celsius; mg/L, milligrams per liter; °C, degrees Celsius; QW, water quality]

Sample interval depth, in ft below land surface (well 34H495)	Lithology, dominant clastic grain size or Folk (1962) carbonate classification; grain type or allochem, color (Geological Society of America color chart, 1991); porosity estimated	Drill bit penetration rate, in ft/min	Well 34H495 Specific conductance of reverse-air discharge water in µS/cm (chloride in mg/L)	Temperature of reverse-air discharge water, in °C	Well 34H500 Specific conductance of reverse-air discharge water in µS/cm (and chloride in mg/L)	Observations during drilling
637–648	Limestone, biosparite to biomicrite, bryozoan, pelecypods, very light gray (N8), interparticle porosity <5%.	0.4	5,000	25		
648–658	Limestone, as above.	0.5				
658–668	Limestone, as above.	0.3	5,882 (1,500)	26		
668–679	Limestone, biosparite to biomicrite, bryozoan, pelecypods, echinoids, foraminifera, very light gray (N8) to yellow gray (5Y8/1), minor silicification, interparticle porosity <5%.	0.1				
679–690	Limestone, as above.	0.2				
690–700	Limestone, as above.	0.3	5,865 (1,600)	27	6,050 (1,600)	
700–712	Limestone, as above, interparticle pores 5 to 10%.	0.2				
712–722	Limestone, as above.	0.3			6,130 (1,700)	
722–732	Limestone, pelbiosparite to biomicrite, bryozoans, foraminifera, echinoids, very light gray (N8), interparticle pores <5%.	0.5	6,666 (1,700)	26	6,100 (1,700)	
732–743	Limestone, as above.	0.6				
743–753	Limestone, as above.	0.6				
753–763	Limestone, as above.	0.5	6,635 (1,700)	27	6,130 (1,700)	
763–775	Limestone, biosparite to biomicrite as above, glauconite increases from here down to 835 ft, interparticle pores <5%.	0.3				
775–785	Limestone, as above.	0.3				
785–795	Limestone, biomicrite, very fine fossils including bryozaon, pelecypod, echinoid, and foraminifera (lepidocyclids), glauconite 1–3%, very light gray (N8) to light greenish gray (5GY8/1), interparticle pores <5%.	0.4	6,863 (1,700)	26	6,010 (1,700)	
795–807	Limestone, as above.	0.3				
807–817	Limestone, as above.	0.4				

Appendix 2. Lithology, bit penetration rate, water quality, and well construction for Coastal Sound Science Initiative wells 34H495 and 34H500 at the Brunswick site, Georgia. — Continued

[%, percent; <, less than; ft, feet; psi, pounds per square inch; µS/cm, microsiemens per centimeters at 25 degrees Celsius; mg/L, milligrams per liter; °C, degrees Celsius; QW, water quality]

Sample interval depth, in ft below land surface (well 34H495)	Lithology, dominant clastic grain size or Folk (1962) carbonate classification; grain type or allochem, color (Geological Society of America color chart, 1991); porosity estimated	Drill bit penetration rate, in ft/min	Well 34H495 Specific conductance of reverse-air discharge water in µS/cm (chloride in mg/L)	Temperature of reverse-air discharge water, in °C	Well 34H500 Specific conductance of reverse-air discharge water in µS/cm (and chloride in mg/L)	Observations during drilling
817–827	Limestone, as above.	0.7	6,765 (1,700)	26	5,910 (1,600)	
827–839	Limestone, as above to 835 ft, then sand-sized fragments of foraminifera (lepidocyclids), echinoids, bryozoan, and pelecypods, glauconite <1%, yellowish gray (5Y8/1), interparticle pores.	0.5				
839–849	Limestone, as above.	0.3				
849–859	Limestone, as above.	0.4	6,863 (1,700)	26	5,920 (1,700)	
859–870	Limestone, as above.	0.4				
870–880	Limestone, as above, biosparite to biomicrite with pellets and lepidocyclids, large pieces with interparticle pores <5%.	0.5				
880–890	Limestone, as above to 883 ft, then dolomite, some calcitic foraminifera preserved, dusky yellow (5Y6/4), moldic pores and intercrystalline pores 10–20%.	0.4	6,863 (1,800)	26	5,770 (1,700)	
890–902	Dolomite, as above to 895 ft, then limestone, dolomitic, biopelsparite, lepidocyclids, yellow gray (5Y7/2), interparticle pores <5% down to 900 ft, then dolomite, as above.	0.4				
902–912	Dolomite, subhedral to euhedral crystals, dark yellow brown (10YR4/2), some cuttings are dense with a few moldic pores, others have intercrystalline pores 10–20%.	0.4				
912–922	Dolomite, as above, dusky yellow brown (10YR2/2), most cuttings are dense with moldic pores 5%.	0.1	6,730 (1,700)	27	5,760 (1,600)	
922–933	Dolomite, subhedral to euhedral crystals, moderate yellow brown (10YR4/2), moldic pores 5%, intercrystalline pores 10–20%.	0.3				

Appendix 2. Lithology, bit penetration rate, water quality, and well construction for Coastal Sound Science Initiative wells 34H495 and 34H500 at the Brunswick site, Georgia. — Continued

[%, percent; <, less than; ft, feet; psi, pounds per square inch; µS/cm, microsiemens per centimeters at 25 degrees Celsius; mg/L, milligrams per liter; °C, degrees Celsius; QW, water quality]

Sample interval depth, in ft below land surface (well 34H495)	Lithology, dominant clastic grain size or Folk (1962) carbonate classification; grain type or allochem, color (Geological Society of America color chart, 1991); porosity estimated	Drill bit penetration rate, in ft/min	Well 34H495 Specific conductance of reverse-air discharge water in µS/cm (chloride in mg/L)	Temperature of reverse-air discharge water, in °C	Well 34H500 Specific conductance of reverse-air discharge water in µS/cm (and chloride in mg/L)	Observations during drilling
933–943	Limestone, dolomitic, biosparite with peloids, foraminifera, echinoids, intercrystalline pores 5–10%.	0.3				
943–953	Limestone, as above, dolomitic to nondolomitic, pelbiosparite, lepidocyclids and peloids, glauconitic from 945–949 ft, intercrystalline to interparticle porosity 5–10%.	0.5	6,730 (1,700)	27	5,900 (1,700)	
953–964	Limestone, as above, glauconitic down to 961 ft, then dolomitic to 964 ft, moderate yellow brown (10YR4/2) to yellow gray (5Y8/1), interparticle to intercrystalline pores 5–10%.	0.4				
964–974	Limestone, pelbiosparite, nondolomitic to dolomitic, foraminifera dominate the fauna, some peloidal grains, yellow gray (5Y8/1) to moderate yellow brown (10YR4/2), intercrystalline to interparticle pores 5%.	0.5				
974–984	Limestone, as above, interparticle pores 5–10%.	0.4	6,863 (1,800)	26	6 040 (1,700)	
984–996	Limestone, biosparite, foraminifera, bryozoan, echinoids, yellow gray (5Y8/1), interparticle pores 5–10%.	0.4				
996–1,006	Limestone, biosparite, nondolomitic to dolomitic, foraminifera, bryozoan, echinoid, yellow gray (5Y8/1), interparticle to intercrystalline pores 5–10%.	0.4				
1,006–1,016	Dolomite, noncalcareous to calcareous, subhedral to euhedral crystals, olive gray (5Y4/1) to yellow gray (5Y7/2), dense to porous with intercrystalline and moldic pores 0–25%.	0.2	6,604 (1,700)	28	6,150 (1,700)	
1,016–1,027	Dolomite, as above, less calcareous dolomite than above.	0.3				

Appendix 2. Lithology, bit penetration rate, water quality, and well construction for Coastal Sound Science Initiative wells 34H495 and 34H500 at the Brunswick site, Georgia. — Continued

[%, percent; <, less than; ft, feet; psi, pounds per square inch; µS/cm, microsiemens per centimeters at 25 degrees Celsius; mg/L, milligrams per liter; °C, degrees Celsius; QW, water quality]

Sample interval depth, in ft below land surface (well 34H495)	Lithology, dominant clastic grain size or Folk (1962) carbonate classification; grain type or allochem, color (Geological Society of America color chart, 1991); porosity estimated	Drill bit penetration rate, in ft/min	Well 34H495 Specific conductance of reverse-air discharge water in µS/cm (chloride in mg/L)	Temperature of reverse-air discharge water, in °C	Well 34H500 Specific conductance of reverse-air discharge water in µS/cm (and chloride in mg/L)	Observations during drilling
1,027–1,037	Dolomite, as above, calcareous fossils, dusky yellow brown (10YR2/2), most cuttings are dense with moldic pores 5%.	0.3				
1,037–1,047	Dolomite, as above, noncalcareous, subhedral to euhedral crystals, olive gray (5Y4/1), dense, low porosity.	0.3	6,000 (1,500)	27	6,100 (1,700)	
1,047–1,059	Dolomite, as above.	0.2				
1,059–1,069	Dolomite, as above	0.06				
1,069–1,079	Dolomite, as above, chert nodules.	0.2	5,392 (1,400)	26	6,130 (1,700)	
1,079–1,091	Dolomite, as above, chert nodules, moldic pores 5–10%.	0.03				
1,091–1,101	Dolomite, as above, some glauconite.	0.06				
1,101–1,111	Limestone, biomicrite to biosparite, bryozaon, pelecypods, foraminifera and echinoids, glauconite, very light gray (N8) to yellowish gray (5Y8/1), interparticle pores <5%.	0.3	9,528 (2,800)	28	9,300 (2,700)	
1,111–1,123	Limestone, as above, biosparite dominates.	0.2				
1,123–1,133	Limestone, as above, biomicrite dominates, minor dolomite, porosity very low.	0.2				
1,133–1,143	Limestone, as above, biomicrite dominates.	0.4	10,480 (2,900)	27	10,000 (2,900)	
1,143–1,154	Dolomite, noncalcareous to calcareous, subhedral to euhedral crystals, pale yellowish brown (10YR6/2) to dark yellow brown (10YR4/2), predominantly dense with porosity <5% to porous with intercrystalline and moldic (vuggy) pores 5–25%.	0.2				
1,154–1,164	Dolomite, as above with minor chert.	0.1				
1,164–1,174	Dolomite, as above with minor chert.	0.04	9,615 (2,800)	27		
1,174–1,186	Dolomite, as above.	0.15				
1,186–1,196	Dolomite, as above.	0.09				

Appendix 2. Lithology, bit penetration rate, water quality, and well construction for Coastal Sound Science Initiative wells 34H495 and 34H500 at the Brunswick site, Georgia. — Continued

[%, percent; <, less than; ft, feet; psi, pounds per square inch; µS/cm, microsiemens per centimeters at 25 degrees Celsius; mg/L, milligrams per liter; °C, degrees Celsius; QW, water quality]

Sample interval depth, in ft below land surface (well 34H495)	Lithology, dominant clastic grain size or Folk (1962) carbonate classification; grain type or allochem, color (Geological Society of America color chart, 1991); porosity estimated	Drill bit penetration rate, in ft/min	Well 34H495 Specific conductance of reverse-air discharge water in µS/cm (chloride in mg/L)	Temperature of reverse-air discharge water, in °C	Well 34H500 Specific conductance of reverse-air discharge water in µS/cm (and chloride in mg/L)	Observations during drilling
1,196–1,206	Limestone, biomicrite to biosparite, predominantly foraminifera with minor pelecypods and bryozoans, very light gray (N8) to very pale orange (10YR8/2), interparticle pores <5%.	0.3	7,692 (2,200)	27		
1,206–1,217	Limestone, as above.	0.3				
1,217–1,227	Limestone, as above.	0.2				
1,227–1,237	Limestone, as above, with echinoids, a few cuttings are glauconitic, interparticle porosity 5–10% in biosparite, biomicrite has porosity of <5%.	0.2	8,823 (2,400)	26	3,350 (850)	
1,237–1,249	Limestone, as above, grading downward to dolomitic limestone and calcareous dolomite, subhedral to euhedral crystals, interparticle to intercrystalline porosity 5–10%.	0.2				
1,249–1,259	Dolomite, noncalcareous to calcareous, recognizable calcitic foraminifera, subhedral to euhedral crystals, pale yellowish brown (10YR6/2) to dark yellow brown (10YR4/2), predominantly dense with porosity <5% to porous with intercrystalline and moldic (vuggy) pores 5–25%.	0.1				
1,259–1,269	Dolomite, as above; and limestine, biomicrite, foraminifera, very light gray (N8) to very pale orange (10YR8/2), porosity <5%.	0.1	7,843 (2,200)	26	2,150 (530)	
1,269–1,281	Limestone to dolomitic limestone, pelbiomicrite, foraminifera, small pelecypods, bryozoan, echinoid spines, peloids, very pale orange (10YR8/2) to yellowish gray (5Y7/2), interparticle or intercrystalline porosity <5%.	0.3				
1,281–1,291	Limestone, as above.	0.3				
1,291–1,301	Limestone, as above, non-dolomitic.	0.1	8,018 (2,300)	28	2,000 (470)	

Appendix 2. Lithology, bit penetration rate, water quality, and well construction for Coastal Sound Science Initiative wells 34H495 and 34H500 at the Brunswick site, Georgia. — Continued

[%, percent; <, less than; ft, feet; psi, pounds per square inch; µS/cm, microsiemens per centimeters at 25 degrees Celsius; mg/L, milligrams per liter; °C, degrees Celsius; QW, water quality]

Sample interval depth, in ft below land surface (well 34H495)	Lithology, dominant clastic grain size or Folk (1962) carbonate classification; grain type or allochem, color (Geological Society of America color chart, 1991); porosity estimated	Drill bit penetration rate, in ft/min	Well 34H495 Specific conductance of reverse-air discharge water in µS/cm (chloride in mg/L)	Temperature of reverse-air discharge water, in °C	Well 34H500 Specific conductance of reverse-air discharge water in µS/cm (and chloride in mg/L)	Observations during drilling
1,301–1,313	Dolomite, and dolomitic limestone, moderate yellowish brown (10YR5/4) to dark yellowish brown (10YR4/2), dense, vuggy porosity <5%, intercrystalline porosity <5%.	0.08				
1,313–1,323	Dolomite and dolomitic limestone, as above	0.08				
1,323–1,333	Dolomite, as above to 1,325 ft, then limestone and dolomitic limestone, pelbiomicrite to biosparite, foraminifera, pelecypods, bryozoans, echinoids, peloids, yellowish gray (5Y8/1), interparticle and intercrystalline porosity <5%.	0.2	7,905 (2,200)	27.5	1,950 (460)	Flowing well. Sample collected from 34H500, 1,212 to 1,400 ft: specific conductance of 1,425 µS/cm, chloride concentration of 300 mg/L.
1,333–1,343	Dolomite, calcareous, and dolomitic limestone, foraminifera, bryozoans, and pelecypods, yellowish gray (5Y7/2) to yellowish gray (5Y8/1), intercrystalline and moldic porosity <5%.	0.1				
1,343–1,353	Dolimite calcareous, and dolomitic limestone, as above.	0.2				
1,353–1,363	Limestone, dolomitic, pelbiomicrite to biosparite with peloids, foraminifera, bryozoans, and echinoids, yellowish gray (5Y8/1), interparticle and intercrystalline pores 5–10%.	0.2	8,019 (2,300)	28		
1,363–1,373	Limestone and dolomitic limestone, biomicrite and biosparite, as above.	0.1			1,900 (440)	
1,373–1,383	Dolomite, moderate yellowish brown (10YR5/4) to dark yellowish brown (10YR4/2), moldic and intercrystalline porosity 15–25%.	0.1				Wireline sample collected after drilling. Specific conductance of 488 µS/cm.
1,383–1,393	Dolomite, dark yellowish brown (10YR4/2), intercrystalline and moldic porosity 20–25%, and calcareous dolomite, foraminifera and bryozoans, yellowish gray (5Y8/1), interparticle and intercrystalline pores <5%.	0.09	7,196	28.5		QW sample collected at 1,380 ft.

Appendix 2. Lithology, bit penetration rate, water quality, and well construction for Coastal Sound Science Initiative wells 34H495 and 34H500 at the Brunswick site, Georgia. — Continued

[%, percent; <, less than; ft, feet; psi, pounds per square inch; µS/cm, microsiemens per centimeters at 25 degrees Celsius; mg/L, milligrams per liter; °C, degrees Celsius; QW, water quality]

Sample interval depth, in ft below land surface (well 34H495)	Lithology, dominant clastic grain size or Folk (1962) carbonate classification; grain type or allochem, color (Geological Society of America color chart, 1991); porosity estimated	Drill bit penetration rate, in ft/min	Well 34H495 Specific conductance of reverse-air discharge water in µS/cm (chloride in mg/L)	Temperature of reverse-air discharge water, in °C	Well 34H500 Specific conductance of reverse-air discharge water in µS/cm (and chloride in mg/L)	Observations during drilling
1,393–1,405	Dolomite, as above to 1,395 ft, then slightly dolomitic limestone, biomicrite to biosparite, bryozoan, foraminifera, and pelecypods, yellowish gray (5Y8/1), interparticle porosity <5%.	0.1	7,103 (2,000)	28.5	1,700 (280) at 1,396 ft 1,650 (290) at 1,400 ft	1,396 ft of 12-inch casing, continue with 11-inch bit.
1,405–1,426	Dolomite, as above.					
1,418–1,426	Dolomite, noncalcareous to calcareous dolomite, calcitic foraminifera and bryozoans, yellowish gray (5Y7/2) to light olive gray (5Y5/2), dense, minor intercrystalline porosity <5%.		425 (36)	29		Water level, 39.8 ft above land surface.
1,427–1,437	Limestone, biosparite, bryozoans, pelecypods, and foraminifera, yellowish gray (5Y8/1), interparticle pores <5%.	0.2				
1,437–1,447	Dolomite, noncalcareous, yellowish gray (5Y7/2) to light olive gray (5Y5/2), dense to porous, intercrystalline 5%, moldic 5%.	0.2	425 (14)	28		
1,447–1,457	Dolomite, as above.	0.2				
1,457–1,467	Dolomite, as above to 1,463 ft, then dolomitic to nondolomitic limestone, biomicrite, yellowish gray (5Y8/1), dense, porosity <2%.	0.2				
1,467–1,477	Limestone, dense biomicrite to biosparite, bryozoans, echinoids, foraminifera, yellowish gray (5Y8/1), intraparticle porosity <2%.	0.3				
1,477–1,487	Limestone, as above, interbedded with porous dolomite (small cuttings), light olive gray (5Y5/2), moldic and intercrystalline porosity 10–20%.	0.3				Water level, 46.7 ft above land surface.
1,487–1,497	Dolomite, as above.	0.2	419 (13)	28.5		
1,497–1,507	Dolomite, as above, dense to porous, moldic and intercrystalline 0–20%.	0.2				
1,507–1,517	Dolomite, as above, interbedded with dense limestone, biomicrite to biosparite.	0.2				

Appendix 2. Lithology, bit penetration rate, water quality, and well construction for Coastal Sound Science Initiative wells 34H495 and 34H500 at the Brunswick site, Georgia. — Continued

[%, percent; <, less than; ft, feet; psi, pounds per square inch; µS/cm, microsiemens per centimeters at 25 degrees Celsius; mg/L, milligrams per liter; °C, degrees Celsius; QW, water quality]

Sample interval depth, in ft below land surface (well 34H495)	Lithology, dominant clastic grain size or Folk (1962) carbonate classification; grain type or allochem, color (Geological Society of America color chart, 1991); porosity estimated	Drill bit penetration rate, in ft/min	Well 34H495 Specific conductance of reverse-air discharge water in µS/cm (chloride in mg/L)	Temperature of reverse-air discharge water, in °C	Well 34H500 Specific conductance of reverse-air discharge water in µS/cm (and chloride in mg/L)	Observations during drilling
1,517–1,527	As above, predominantly limestone.	0.2	410 (13)	32		
1,527–1,537	Limestone, biosparite to biomicrite, slightly dolomitic to nondolomitic, bryozoan, formainifera, yellowish gray (5Y8/1), interparticle porosity 0–5%.	0.2				
1,537–1,547	Limestone, as above.	0.2				
1,547–1,557	Limestone, nondolomitic to dolomitic, biomicrite to biosparite, foraminifera, bryozoans, echionoids, yellowish gray (5Y8/1), interparticle porosity 0–5%.	0.2	418 (13)	31		Water level, 51.3 ft above land surface.
1,557–1,567	Limestone, as above, interparticle porosity 0–10%.	0.5				
1,567–1,577	Limestone, as above, interparticle porosity 0–5%.	0.3				
1,577–1,587	Limestone, as above, abundant disk-shaped foraminifera, interparticle porosity 0–10%.	0.5	516 (12)	30		Flow increased.
1,587–1,597	Limestone, as above, interparticle and intraparticle porosity 0–5%.	0.3				
1,597–1,607	Limestone, as above.	0.5				
1,607–1,617	Limestone, as above, interparticle porosity 0–10%.	0.3	540 (12)	31		Specific conductance of 446 µS/cm from wellhead.
1,617–1,627	Dolomite, calcareous, and dense noncalcareous dolomite, calcareous bryozoans and pelecypods, yellowish gray (5Y7/2) to yellowish gray (5Y8/1), intercrystalline and moldic porosity <5%.	0.2				
1,627–1,637	Dolomite, dense, noncalcareous, as above, porosity <5%.	0.4				
1,637–1,647	Limestone, biosparite to biomicrite, bryozoans, foraminifera, echinoids, yellowish gray (5Y8/1), interparticle porosity <5%.	0.3				

Appendix 2. Lithology, bit penetration rate, water quality, and well construction for Coastal Sound Science Initiative wells 34H495 and 34H500 at the Brunswick site, Georgia. — Continued

[%, percent; <, less than; ft, feet; psi, pounds per square inch; µS/cm, microsiemens per centimeters at 25 degrees Celsius; mg/L, milligrams per liter; °C, degrees Celsius; QW, water quality]

Sample interval depth, in ft below land surface (well 34H495)	Lithology, dominant clastic grain size or Folk (1962) carbonate classification; grain type or allochem, color (Geological Society of America color chart, 1991); porosity estimated	Drill bit penetration rate, in ft/min	Well 34H495 Specific conductance of reverse-air discharge water in µS/cm (chloride in mg/L)	Temperature of reverse-air discharge water, in °C	Well 34H500 Specific conductance of reverse-air discharge water in µS/cm (and chloride in mg/L)	Observations during drilling
1,647–1,657	Limestone, biomicrite, as above, plus pelecypods, interparticle porosity <5%.	0.3	614 (12)	32.3		Water level, 42.1 ft above land surface. QW sample at 1,650 ft by wireline.
1,657–1,667	Dolomite, pale yellowish borwn (10YR6/2), intercrystalline porosity 5–10%, generally <5%.	0.2				
1667–1,677	Dolomite, as above, some of the cuttings have intercrystalline porosity 10–20%, other <5%. Porous dolomite on curved surface of dense dolomite cuttings suggest cavity linings.	0.1				Void 1,673–1,676 ft. QW changed. Wireline sample collected at 1,675 ft with specific conductance of 2,810 µS/cm and chloride concentration of 190 mg/L.
1,677–1,687	Dolomite, as above to 1,683 ft, then limestone, biosparite, yellowish gray (5Y7/2), bryozoans, echinoids, foraminifera, interparticle porosity 5–10%.	0.2	1,295 (12)	31		
1,687–1,697	Limestone, as above.	0.3				
1,697–1,707	Limestone to dolomitic limestone, biomicrite to biosparite, foraminifera, small pelecypods, bryozoans, echinoids, yellowish gray (5Y7/2), interparticle or intercrystalline porosity 5–10%.	0.2				
1,707–1,717	Dolomitic (10–40%) limestone to calcareous (20–40%) dolomite, as above, porosity generally <5%.	0.3	1,228 (100)	32		
1,717–1,727	As above.	0.3				
1,727–1,737	As above to 1,734 ft, then dolomite, dense to porous, very pale orange (10YR8/2) to dark yellowish brown (10YR4/2), intercrystalline with some moldic porosity 0–10%.	0.2				
1,737–1,747	Dolomite, as above to 1,742 ft, then limestone as below.	0.3	1,027 (140)	30.8		

Appendix 2. Lithology, bit penetration rate, water quality, and well construction for Coastal Sound Science Initiative wells 34H495 and 34H500 at the Brunswick site, Georgia. — Continued

[%, percent; <, less than; ft, feet; psi, pounds per square inch; µS/cm, microsiemens per centimeters at 25 degrees Celsius; mg/L, milligrams per liter; °C, degrees Celsius; QW, water quality]

Sample interval depth, in ft below land surface (well 34H495)	Lithology, dominant clastic grain size or Folk (1962) carbonate classification; grain type or allochem, color (Geological Society of America color chart, 1991); porosity estimated	Drill bit penetration rate, in ft/min	Well 34H495 Specific conductance of reverse-air discharge water in µS/cm (chloride in mg/L)	Temperature of reverse-air discharge water, in °C	Well 34H500 Specific conductance of reverse-air discharge water in µS/cm (and chloride in mg/L)	Observations during drilling
1,747–1,757	Limestone, biosparite, pelecypods, bryozoans, echinoids, disk-shaped foraminifera, yellowish gray (5Y8/1), interparticle porosity <5%.	0.3				
1,757–1,767	Limestone, as above. Interparticle porosity 0–10%, generally <5%.	0.4				
1,767–1,777	Limestone, as above.	0.4	1,038 (not collected)	34		
1,777–1,787	Limestone, biopelsparite to biopelmicrite, bryozoans, foraminifera, echinoids, pellets, yellowish gray (5Y8/1), interparticle porosity generally <5%.	0.3				
1,787–1,797	Limestone interparticle porosity 5–10%, as above to 1,795 ft, then dolomite as below.	0.3				
1,797–1,807	Dolomite, porous to dense, moderate yellow brown (10YR5/4), intercrystalline porosity 0–15%, porous dolomite could be cavity linings.	0.2				Appears to be a fracture zone or cavity at 1803 ft. No bit drop observed, but chlorides increasing downward.
1,805–1,815	Dolomite, as above, low porosity <5%, with abundant chert beds or nodules with recognizable spicules.	0.2	1,755 (170)	32		Water level, 56 ft above land surface.
1,815–1,820	Dolomite and chert as above, moldic porosity <3%.	0.1				
1,820–1,830	Limestone, very fine, biosparite to biomicrite, recognizable foraminifera and echinoid fragments, yellowish gray (5Y8/1), glauconite 1–2%, very small interparticle pores 5–10%, and chert, olive gray (5Y4/1) to medium dark gray (N4).	0.5				
1,830–1,840	Limestone and chert, as above.	0.5	2,088 (220)	32		
1,840–1,850	Limestone and chert, as above.	0.5				
1,850–1,860	Limestone and chert, as above.	0.4				

Appendix 2. Lithology, bit penetration rate, water quality, and well construction for Coastal Sound Science Initiative wells 34H495 and 34H500 at the Brunswick site, Georgia. — Continued

[%, percent; <, less than; ft, feet; psi, pounds per square inch; µS/cm, microsiemens per centimeters at 25 degrees Celsius; mg/L, milligrams per liter; °C, degrees Celsius; QW, water quality]

Sample interval depth, in ft below land surface (well 34H495)	Lithology, dominant clastic grain size or Folk (1962) carbonate classification; grain type or allochem, color (Geological Society of America color chart, 1991); porosity estimated	Drill bit penetration rate, in ft/min	Well 34H495 Specific conductance of reverse-air discharge water in µS/cm (chloride in mg/L)	Temperature of reverse-air discharge water, in °C	Well 34H500 Specific conductance of reverse-air discharge water in µS/cm (and chloride in mg/L)	Observations during drilling
1,860–1,870	Limestone, dolomitic (20–30%), biosparite to biomicrite, slighltly coarser than above, foraminifera, echinoids, and bryozoans, glauconite 1–2%, yellowish gray (5Y7/2), interparticle porosity 5–10%, and chert as above.	0.5	2,482 (310)	32		
1,870–1,880	Limestone, very fine, biosparite to biomicrite, recognizable foraminifera and echinoid fragments, yellowish gray (5Y8/1) to very light gray (N8), glauconite 2–20%, very small interparticle pores 0–10%; dolomite below 1,877ft, calcareous, very glauconitic (10–25%), light olive gray (5Y5/2) to dark greenish gary (5GY4/1), intercrystalline porosity 5–10% and chert, olive gray (5Y4/1) to medium dark gray (N4).	0.3				
1,880–1,890	Dolomite, as above, with gypsum nodules, cavity linings, and fracture fill.	0.2				
1,890–1,900	Dolomite, as above, intercrystalline porosity 5–10%; limestone below 1,898 ft, very fine biosparite to biomicrite, foraminifera, echinoids, glauconite 2–3%, yellowish gray (5Y8/1), interparticle porosity 0–10%,	0.5	2,518 (320)	32		Water level, 25.7 ft above land surface.
1,900–1,910	Limestone, as above with pelecypod fragments and pellets (peloids) for pelbiosparite.	0.5				
1,910–1,920	Limestone, as above, pelbiosparite, gastropods observed.	0.4				
1,920–1,930	Limestone, as above.	0.5	2,632 (340)	32		
1,930–1,940	Limestone, as above.	0.4				
1,940–1,950	Limestone, as above.	0.3				
1,950–1,960	Limestone, as above, more pelbiomicrite than above.	0.3				
1,960–1,970	Dolomite, light olive gray (5Y5/2), dense to porous, intercrystalline porosity 0–20%.	0.1	2,640 (340)	32		1,965–1,966.5 ft, bit dropped.

Appendix 2. Lithology, bit penetration rate, water quality, and well construction for Coastal Sound Science Initiative wells 34H495 and 34H500 at the Brunswick site, Georgia. — Continued

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Sample interval depth, in ft below land surface (well 34H495)	Lithology, dominant clastic grain size or Folk (1962) carbonate classification; grain type or allochem, color (Geological Society of America color chart, 1991); porosity estimated	Drill bit penetration rate, in ft/min	Well 34H495 Specific conductance of reverse-air discharge water in µS/cm (chloride in mg/L)	Temperature of reverse-air discharge water, in °C	Well 34H500 Specific conductance of reverse-air discharge water in µS/cm (and chloride in mg/L)	Observations during drilling
1,970–1,980	Limestone, dense biomicrite to biosparite, bryozoans, echinoids, foraminifera, yellowish gray (5Y8/1) to light gray (N7), intraparticle porosity <2%, also individual skeletal and pelletal grains.	0.3				
1,980–1,990	Limestone, as above, some biosparite cuttings with interparticle porosity 0–5%.	0.3				
1,990–2,000	Limestone, as above.	0.4	2,105 (220)	32		
2,000–2,010	Limestone, as above.	0.3				
2,010–2,020	Limestone, dolomitic (5–10%), predominantly pelbiomicrite, interparticle porosity <5%.	0.3				
2,020–2,030	Limestone, dolomitic (10–35%), biomicrite, pelecypods, light olive gray (5Y8/1), interparticle porosity <5%.	0.3	2,018 (210)	32		
2,030–2,040	Limestone, as above.	0.3				
2,040–2,050	Limestone, dolomitic (10–35%), biomicrite to biosparite, disk-shaped foraminifera, bryozoans, pelecypods, light olive gray (5Y6/1) to yellowish gray (5Y8/1), interparticle porosity <5%.	0.3				
2,050–2,060	Dolomite, dense to porous, light olive gray (5Y5/2) to pale yellowish brown (10YR6/2), intercrystalline and vuggy porosity 0–20%.	0.2	1,908 (180)	32		Water level, 23–29 ft above land surface.
2,060–2,070	Dolomite, as above.	0.2				
2,070–2,079	Limestone, dolomitic (10–25%), biomicrite to biosparite, foraminifera, pelecypods, yellowish gray (5Y8/1), interparticle porosity 0–10%, generally <5%; below 2,077 ft, dolomite,dense to porous, intercrystalline and some moldic porosity (0–20%).	0.7		34		Water level, 35 ft above land surface.

Appendix 2. Lithology, bit penetration rate, water quality, and well construction for Coastal Sound Science Initiative wells 34H495 and 34H500 at the Brunswick site, Georgia. — Continued

[%, percent; <, less than; ft, feet; psi, pounds per square inch; µS/cm, microsiemens per centimeters at 25 degrees Celsius; mg/L, milligrams per liter; °C, degrees Celsius; QW, water quality]

Sample interval depth, in ft below land surface (well 34H495)	Lithology, dominant clastic grain size or Folk (1962) carbonate classification; grain type or allochem, color (Geological Society of America color chart, 1991); porosity estimated	Drill bit penetration rate, in ft/min	Well 34H495 Specific conductance of reverse-air discharge water in µS/cm (chloride in mg/L)	Temperature of reverse-air discharge water, in °C	Well 34H500 Specific conductance of reverse-air discharge water in µS/cm (and chloride in mg/L)	Observations during drilling
2,079–2,089	Limestone, as above to 2,087 ft, then dolomite, as above.	0.2				Flow and pressure increased and chemistry changed. Set 2,084 ft of 8-inch casing. 7.875-inch bit from here to 2,720 ft.
2,089–2,091.5	Dolomite, as above.	0.1	5,932 (1,100)	34.7		
2,091.5–2,101.5	Dolomite, as above, yellowish gray (5Y5/2) to dark yellowish brown (10YR4/2), dense and porous, intercrystalline (0–20%).	0.1	5,870 (1,100)	34.5		
2,101.5–2,111.5	Dolomite, as above, cavity linings of porous dolomite on dense dolomite.	0.8				
2,111.5–2,121.5	Dolomite, as above.	0.5				
2,121.5–2,123	Limestone, pelbiosparite, nondolomitic to dolomitic, foraminifera dominate the fauna, some peloidal grains appear to be ooids, yellow gray (5Y8/1), interparticle porosity 0–10%, generally <5%.	0.4	6,300 (1,200)	35		
2,123–2,133	Limestone, nondolomitic, pelbiosparite, as above.	0.6				
2,133–2,143	Limestone, as above.	0.9				
2,143–2,153	Limestone, as above.	0.7	7,020 (1,400)	35		
2,153–2,163	Limestone, as above.	0.5				
2,163–2,173	Limestone, as above.	0.4				
2,173–2,186	Limestone, as above.	0.5	9,060 (2,000)	32		
2,186–2,197	Limestone, as above, several pieces of tightly cemented pelbiosparite in this bag.	0.4				
2,197–2,207	Limestone, as above to 2,200 ft, then dolomite, dense and porous,yellowish gray (5Y7/2) to light gray (N7), intercrystalline and moldic or honeycomb vugs 0–25%.	0.2				

Appendix 2. Lithology, bit penetration rate, water quality, and well construction for Coastal Sound Science Initiative wells 34H495 and 34H500 at the Brunswick site, Georgia. — Continued

[%, percent; <, less than; ft, feet; psi, pounds per square inch; µS/cm, microsiemens per centimeters at 25 degrees Celsius; mg/L, milligrams per liter; °C, degrees Celsius; QW, water quality]

Sample interval depth, in ft below land surface (well 34H495)	Lithology, dominant clastic grain size or Folk (1962) carbonate classification; grain type or allochem, color (Geological Society of America color chart, 1991); porosity estimated	Drill bit penetration rate, in ft/min	Well 34H495 Specific conductance of reverse-air discharge water in µS/cm (chloride in mg/L)	Temperature of reverse-air discharge water, in °C	Well 34H500 Specific conductance of reverse-air discharge water in µS/cm (and chloride in mg/L)	Observations during drilling
2,207–2,217	Dolimite, as above, some porous, mostly dense with vuggy pores and dark staining around some vugs.	0.3	45,560 (17,000)	35		
2,217–2,229	Dolomite, generally dense with some vuggy pores and dark staining around vugs.	0.2				
2,229–2,239	Dolomite, as above, dense to porous, pale yellowish brown (10YR6/2) to moderate yellowish brown (10YR5/4), intercrystalline porosity generally <5%, 10–20% in some cuttings with vuggy pores.	0.2	47,080 (17,000)	34		
2,239–2,249	Dolomite, as above.	0.3	46,980 (17,000)	34		Fine dolomite cuttings raining into borehole, possible fracture or fault zone at 2,240 ft. Wireline sample at 2,243 ft with specific conductance of 49,080 µS/cm and chloride concentration of 18,000 mg/L.
2,249–2,261	Dolomite, very coarse sand-sized cuttings of dolomite from fault or fracture zone.	0.5				
2,261–2,271	Dolomite, dense and porous, pale yellowish brown (10YR6/2) to medium light gray (N6), intercrystalline, generally <5%, 10–20%, some vuggy.	0.5				
2,271–2,281	Dolomite, as above, more of the porous (intercrystalline) cuttings than above.	0.3	47,010 (17,000)	35		
2,281–2,291	Dolomite, as above, sand-sized and large, dense, porous.	0.1				Bit dropped 1 ft at 2,281 ft. Continuous fine dolomite cuttings, possible fracture/ fault zone.
2,291–2,301	Dolomite, as above.	0.6				
2,301–2,311	Dolomite, as above.	0.6	47,220 (17,000)	35		

Appendix 2. Lithology, bit penetration rate, water quality, and well construction for Coastal Sound Science Initiative wells 34H495 and 34H500 at the Brunswick site, Georgia. — Continued

[%, percent; <, less than; ft, feet; psi, pounds per square inch; µS/cm, microsiemens per centimeters at 25 degrees Celsius; mg/L, milligrams per liter; °C, degrees Celsius; QW, water quality]

Sample interval depth, in ft below land surface (well 34H495)	Lithology, dominant clastic grain size or Folk (1962) carbonate classification; grain type or allochem, color (Geological Society of America color chart, 1991); porosity estimated	Drill bit penetration rate, in ft/min	Well 34H495 Specific conductance of reverse-air discharge water in µS/cm (chloride in mg/L)	Temperature of reverse-air discharge water, in °C	Well 34H500 Specific conductance of reverse-air discharge water in µS/cm (and chloride in mg/L)	Observations during drilling
2,311–2,323	Dolomite, as above, mostly porous dolomite cuttings, pale yellowish brown (10YR6/2), intercrystalline and vuggy porosity 10–25%.	0.2				
2,323–2,333	Dolomite, as above, dense with some porous cuttings.	0.3				
2,333–2,343	Dolomite, as above plus very finely crystalline, dense, yellowish gray (5Y7/2) to pale yellowish brown (10YR6/2), porosity 0–5%, mostly small vugs.	0.2	47,210 (17,000)	35		Water level, 18 ft above land surface.
2,343–2,353	Dolomite, as above, mostly dense, crystal-lined fracture or cavity surfaces, porosity 0–5%.	0.3				Bit dropped from 2,351 to 2,352 ft.
2,353–2,363	Dolomite, as above,	0.5	48,340 (17,000)	35		
2,363–2,375	Dolomite, as above, very pale orange (10YR8/2).	0.3	48,730 (17,000)	35		
2,375–2,385	Dolomite, as above, crystal-lined fracture surfaces.	0.2				
2,385–2,395	Dolomite, as above, dense, yellowish gray (5Y8/1), vuggy porosity <5%. Fracture surfaces not as apparent.	0.2				
2,395–2,405	Dolomite, as above, pale yellowish brown, fractured surfaces, vuggy porosity <5%.	0.3				
2,405–2,415	Dolomite, unusual striated texture on a few cuttings, otherwise, as above, dense.	0.4	48,210 (17,000)	35.3		
2,415–2,425	Dolomite, as above, yellowish gray (5Y8/1), intercrystalline porosity, some cuttings 10–20%, generally 0–5%, vuggy pores, crystal-lined fracture surface.	0.4				
2,425–2,435	Dolomite, as above, replacement of bryozoans structure by dolomite.	0.5				
2,435–2,445	Dolomite, as above.	0.5	48,540 (17,000)	35.5		

Appendix 2. Lithology, bit penetration rate, water quality, and well construction for Coastal Sound Science Initiative wells 34H495 and 34H500 at the Brunswick site, Georgia. — Continued

[%, percent; <, less than; ft, feet; psi, pounds per square inch; µS/cm, microsiemens per centimeters at 25 degrees Celsius; mg/L, milligrams per liter; °C, degrees Celsius; QW, water quality]

Sample interval depth, in ft below land surface (well 34H495)	Lithology, dominant clastic grain size or Folk (1962) carbonate classification; grain type or allochem, color (Geological Society of America color chart, 1991); porosity estimated	Drill bit penetration rate, in ft/min	Well 34H495 Specific conductance of reverse-air discharge water in µS/cm (chloride in mg/L)	Temperature of reverse-air discharge water, in °C	Well 34H500 Specific conductance of reverse-air discharge water in µS/cm (and chloride in mg/L)	Observations during drilling
2,445–2,455	Dolomite, as above, dense, very fine to fine crystalline texture with coarse crystalline texture lining vugs and fracture surfaces.	0.7				Full extension of caliper arms (21-inch borehole diameter, at least) from 2,444 down to 2,450 ft, which was the deepest tool would go.
2,455–2,465	Dolomite, more crystal-lined and some vuggy cuttings, generally dense, yellowish gray (5Y8/1); based on bit drop, open cavity from 2,460–2,464 ft.	0.4	48,840 (17,000)	35		Bit dropped 2,460 to 2,464 ft.
2,465–2,470	Dolomite, as above, more of the porous, coarsely crystalline cuttings with intercrystalline porosity 0–30%.	1.3	48,550 (17,000)	35		
2,470–2,480	Dolomite, abundant sand-sized cuttings of crystalline dolomite and dense dolomite with vuggy pores.	2.5				
2,480–2,490	Dolomite, porous to dense, as above, intercrystalline and vuggy porosity 0–30%.	0.9				
2,490–2,501	Dolomite, as above.	0.7	48,680 (17,000)	35.5		
2,501–2,511	Dolomite, as above, hard drilling begins at 2,503 ft.	0.4				
2,511–2,521	Dolomite, as above, dense at 2,515 ft, gypsum and anhydrite pieces and fracture filling in a few cutting.	0.09				Dense dolomite at 2,515 ft.
2,521–2,531	Dolomite, mostly dense with some vuggy pores <5%, still some coarsely crystalline cuttings with intercrystalline porosity (10–25%), yellowish gray (5Y8/1).	0.07				Water level, 17 ft above land surface.
2,531–2,541	Dolomite, as above.	0.1	47,630 (17,000)	34		
2,541–2,551	Dolomite, as above, some gypsum pieces.	0.2				
2,551–2,561	Dolomite, as above.	0.2				

Appendix 2. Lithology, bit penetration rate, water quality, and well construction for Coastal Sound Science Initiative wells 34H495 and 34H500 at the Brunswick site, Georgia. — Continued

[%, percent; <, less than; ft, feet; psi, pounds per square inch; µS/cm, microsiemens per centimeters at 25 degrees Celsius; mg/L, milligrams per liter; °C, degrees Celsius; QW, water quality]

Sample interval depth, in ft below land surface (well 34H495)	Lithology, dominant clastic grain size or Folk (1962) carbonate classification; grain type or allochem, color (Geological Society of America color chart, 1991); porosity estimated	Drill bit penetration rate, in ft/min	Well 34H495 Specific conductance of reverse-air discharge water in µS/cm (chloride in mg/L)	Temperature of reverse-air discharge water, in °C	Well 34H500 Specific conductance of reverse-air discharge water in µS/cm (and chloride in mg/L)	Observations during drilling
2,561–2,571	Dolomite, mostly dense with some intercrystalline and vuggy pores, yellowish gray (5Y8/1) to very light gray (N8).	0.1	48,680 (17,000)	35		Water level, 17 ft above land surface.
2,571–2,581	Dolomite, as above, gypsum fracture fill or nodules.	0.1	47,620 (17,000)	35		
2,581–2,591	Dolomite, as above, gypsum fracture fill or nodules.	0.3				
2,591–2,601	Dolomite and gypsum, as above, dense with vuggy pores, some intercrystalline porosity.	0.3	47,580 (17,000)	35		
2,601–2,611	Dolomite, as above.	0.2				
2,611–2,621	Dolomite, as above.	0.3				
2,621–2,631	Dolomite, as above.	0.3	47,440 (17,000)	35		Flow from wellhead has specific conductance of 13,350 µS/cm.
2,631–2,641	Dolomite and gypsum, yellowish gray (5Y8/1), dense with vuggy pores, more cuttings with intercrystalline porosity than above.	0.2				2,637 to 2,639 ft, drilling with no resistance from formation.
2,641–2,651	Dolomite and gypsum, as above.	0.3				
2,651–2,661	Dolomite and gypsum, as above.	0.3	48,070 (17,000)	35		
2,661–2,671	Dolomite, as above, dense with vuggy pores <5%, and porous with intercrystalline pores 10–25%.	0.2	47,860 (17,000)	35		
2,671–2,681	Dolomite, dense with vuggy pores as above.	0.3				Bit dropped from 2,675–2,677 ft.
2,681–2,689	Dolomite, as above.	0.3	68,370 (27,000)	35		
2,689–2,699	Dolomite, as above, sand-sized and large, dense and porous.	0.3				
2,699–2,709	Dolomite, as above.	0.2	68,390 (27,000)	35		
2,709–2,720	Dolomite, as above.	0.2	67,440 (27,000)	35		Total drill depth. Water level, 19.55 ft above land surface.

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