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Simulated Effects of Lower Floridan Aquifer Pumping on the Upper Floridan Aquifer at Barbour Pointe, Chatham County, Georgia

Scientific Investigations Report 2017–5085

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

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By Gregory S. Cherry and John S. Clarke

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RYAN K. ZINKE, Secretary

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William H. Werkheiser, Acting Director

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Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
Length		
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
Area		
square foot (ft^2)	929.0	square centimeter (cm^2)
square foot (ft^2)	0.0929	square meter (m^2)
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
Volume		
gallon (gal)	0.003785	cubic meter (m^3)
Flow rate		
foot per day (ft/d)	0.3048	meter per day (m/d)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
Precipitation		
inch per month (in/mo)	25.4	millimeter per month (mm/mo)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)
Specific capacity		
gallon per minute per foot [(gal/min)/ft)]	0.207	liter per second per meter [(L/s)/m]
Hydraulic conductivity		
foot per day (ft/d)	0.3048	meter per day (m/d)
Transmissivity*		
foot squared per day (ft^2/d)	0.0929	meter squared per day (m^2/d)

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

°C = (°F – 32) / 1.8

Datum

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

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

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

Supplemental Information

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

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

Abbreviations

FAS	Floridan aquifer system
GaEPD	Georgia Environmental Protection Division
K_h	horizontal hydraulic conductivity
K_v	vertical hydraulic conductivity
LFA	Lower Floridan aquifer
LFCU	Lower Floridan semiconfining unit
RMSE	root-mean-square error
UFA	Upper Floridan aquifer
USGS	U.S. Geological Survey

Acknowledgments

Simulated Effects of Lower Floridan Aquifer Pumping on the Upper Floridan Aquifer at Barbour Pointe, Chatham County, Georgia

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Abstract

Steady-state simulations using a revised regional groundwater-flow model based on MODFLOW were run to assess the potential long-term effects on the Upper Floridan aquifer (UFA) of pumping the Lower Floridan aquifer (LFA) at well 36Q398, located at Barbour Pointe in coastal Georgia near Savannah. Simulated pumping of well 36Q398 at a rate of 750 gallons per minute (gal/min; or 1.08 million gallons per day [Mgal/d]) indicated a maximum drawdown of about 2.19 feet (ft) in the UFA directly above the pumped well and at least 1 ft of drawdown within a nearly 190-square-mile area (scenario A). Induced vertical leakage from the UFA provided about 98 percent of the water to the pumped well. Simulated pumping of well 36Q398 caused increased downward leakage in all layers above the LFA, decreased upward leakage in all layers above the LFA, increased inflow to and decreased outflow from lateral specified-head boundaries in the UFA and LFA, and an increase in the volume of induced inflow from the general-head boundary representing outcrop units. Water budgets for scenario A indicated that changes in inflows and outflows through general-head boundaries would compose about 45 percent of the simulated pumpage from well 36Q398, with the remaining 55 percent of the pumped water derived from flow across lateral specified-head boundaries.

Additional steady-state simulations were run to evaluate a pumping rate in the UFA of 240 gal/min (0.346 Mgal/d), which would produce an equivalent maximum drawdown in the UFA as pumping from well 36Q398 in the LFA at a rate of 750 gal/min (called the "drawdown offset"; scenario B). Simulated pumping in the UFA for the drawdown offset produced about 2.18 ft of drawdown, comparable to 2.19 ft of drawdown in the UFA simulated in scenario A. Water budgets for scenario B also provided favorable comparisons with scenario A, indicating that 42 percent of the drawdown-offset pumpage (0.346 Mgal/d) in the UFA originates as increased inflow and decreased outflow across general-head boundaries from overlying units in the surficial and Brunswick aquifer systems and that the remaining simulated pumpage originates as flow across general- and specified-head boundaries within the UFA and LFA.

The revised model was evaluated for sensitivity by first altering horizontal and vertical hydraulic conductivity in the Lower Floridan semiconfining unit and then adjusting horizontal and vertical hydraulic conductivity in the LFA to match the 35.6 ft of drawdown at pumping well 36Q398. These adjustments also affected the maximum simulated drawdown in the UFA and the equivalent offset pumping in the UFA that would produce the same amount of drawdown. The maximum drawdown in the UFA ranged from 1.82 to 2.57 ft and the equivalent offset pumping in the UFA ranged from 199 to 278 gal/min.

The revised model reasonably depicts changes in groundwater levels resulting from pumping the LFA at Barbour Pointe at a rate of 750 gal/min. Results are limited, however, by the same model assumptions and design as the original model, and placement of boundaries and type of boundary used exert the greatest control on overall groundwater flow and interaquifer leakage in the system. Simulation results have improved regional characterization of the Floridan aquifer system, which could be used by State officials in evaluating requests for groundwater withdrawal from the LFA.

Introduction

Barbour Pointe, one of several residential communities served by Consolidated Utilities LLC, in western Chatham County, Georgia (fig. 1), is experiencing increased demands on its limited freshwater resources. To alleviate the potential for saltwater intrusion in coastal Georgia, the Georgia Environmental Protection Division (GaEPD) has restricted further development of the Upper Floridan aquifer (UFA) in the Chatham County area and encouraged development of alternative water sources, such as the Lower Floridan aquifer (LFA; Georgia Department of Natural Resources, 2006).

Recent studies by the U.S. Geological Survey (USGS) at nearby Pooler, Ga., Hunter Army Airfield, Fort Stewart, and Rincon, Ga., evaluating the LFA as an alternate source of groundwater indicate that a strong interaquifer connection between the UFA and LFA exists in the Chatham County area and southern portion of Effingham County (Cherry and
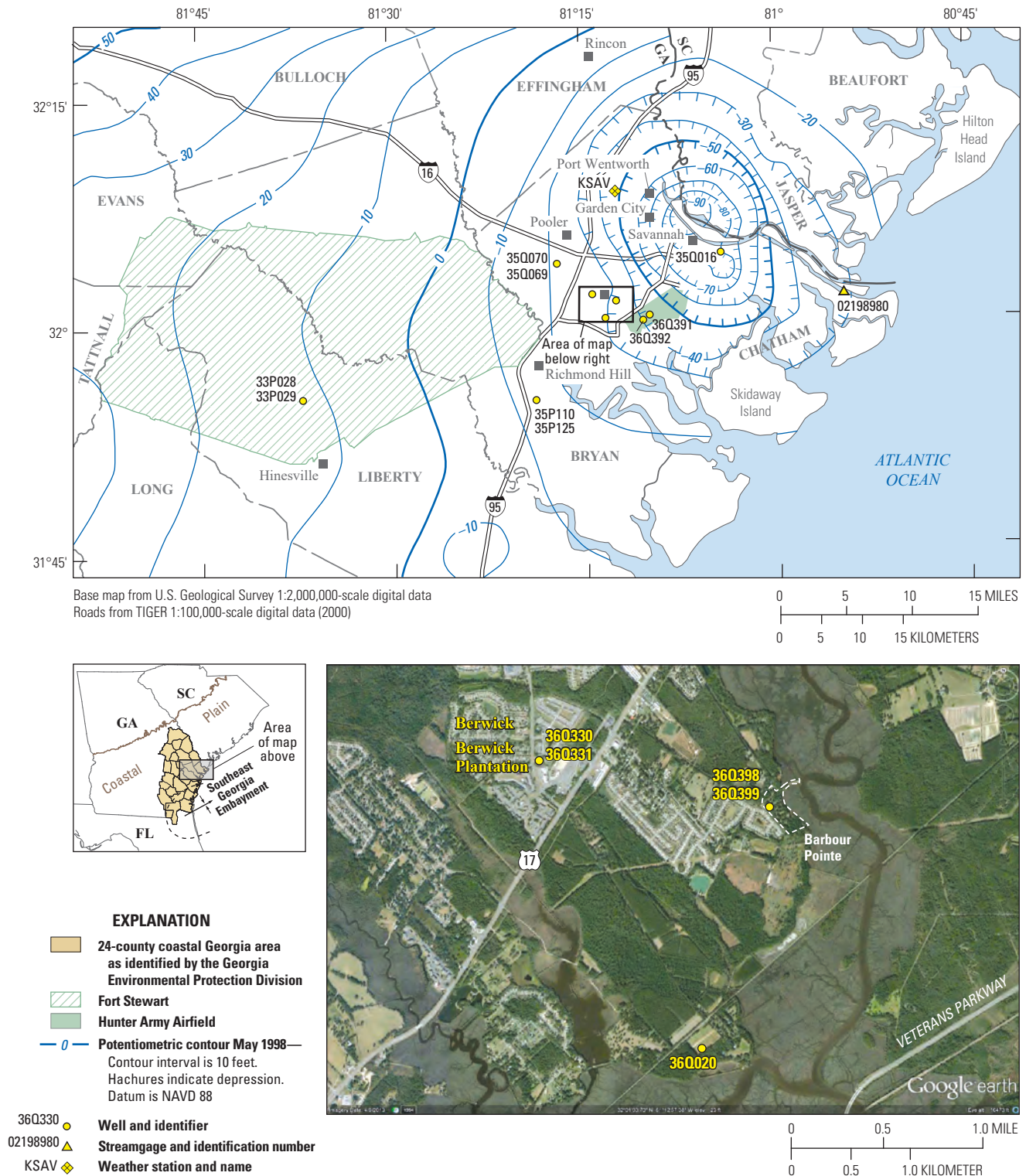
Figure 1.   Barbour Pointe test site (wells 36Q398 and 36Q399), Chatham County, Georgia, and potentiometric surface of the Upper Floridan aquifer in coastal Georgia, 1998.

Clarke, 2013, 2015; Clarke and others, 2010, 2011). As a result of these findings, GaEPD issued a policy statement on May 20, 2013, that stated the Floridan aquifer system (FAS) "is really one aquifer with hydraulically connected upper and lower permeable zones" (Georgia Department of Natural Resources, 2013). The lowermost of these zones has been designated the LFA by Williams and Gill (2010).

To assess the water-supply potential of the LFA, the USGS, in cooperation with Consolidated Utilities LLC, performed an investigation during 2013 to determine the hydrogeology and water quality of the FAS and the potential simulated interaquifer leakage from the UFA into the LFA caused by pumping from a new production well in the LFA. The study included construction of an LFA production well (36Q398) and UFA observation well (36Q399) and detailed site investigations (Gonthier and Clarke, 2016). Data from this investigation add to the USGS database of hydrogeologic information that collectively improves regional characterization of the FAS in the Southeast.

Purpose and Scope

This report documents the results of groundwater-model simulations completed at Barbour Pointe during 2013 to assess the effect of LFA pumping on the UFA, specifically, to

- evaluate the leakage response in a nearby well completed in the UFA (36Q399) to pumping from the LFA (36Q398), and

- quantify the reduction in pumping in a UFA well (or wells) that would offset leakage from the UFA into the LFA induced by pumping and mitigate drawdown in the UFA caused by pumping in the LFA.

Model simulations were completed using a modified version of a regional groundwater-flow model of coastal Georgia covering 42,155 square miles (mi^2) in Georgia and adjacent areas in South Carolina and Florida (fig. 1–1; Payne and others, 2005). The 2005 report includes maps showing drawdown response to pumping, ZONEBUDGET (Harbaugh, 1990) analysis of interaquifer and boundary flow, and a comparison of simulation results to the original model of Payne and others (2005). All data input files and corresponding output are provided in Cherry (2017).

Previous Studies

Jordan, Jones, and Goulding, Inc. (2002) completed detailed field studies at nearby Berwick Plantation at Berwick that included construction of an LFA test well (36Q330), collection of geophysical and flowmeter logs (by the USGS), water sampling, and completion of an 8-hour UFA test and 72-hour LFA test. The report included some preliminary groundwater model simulations.

The USGS completed several comprehensive field and modeling studies of the FAS in coastal Georgia. These include Hunter Army Airfield (Clarke and others, 2010; Williams, 2010), Fort Stewart (Clarke and others, 2011; Gonthier, 2011), Pooler (Cherry and Clarke, 2013; Gonthier, 2012), and Rincon (Cherry and Clarke, 2015; Carter and Sloope, 2004). The scope of these investigations included field testing and groundwater-model simulations to determine the hydrogeology and water quality of the FAS and to provide data needed to assess the effect of LFA pumping on the UFA. The method of study for the Barbour Pointe test site is similar to the earlier investigations at Hunter Army Airfield, Fort Stewart, and the city of Pooler. Field investigations consisted of

- boring a test hole and constructing a test well completed in the LFA,

- collecting drill cuttings and borehole geophysical logs at the test well,

- completing flowmeter surveys through the entire length of the FAS in the open test hole and in the completed LFA well,

- collecting depth-integrated water samples to assess water quality of various water-bearing zones,

- boring and constructing an observation well completed in the UFA, and

- completing a 72-hour aquifer test at the test well open to the LFA while monitoring water levels in both the LFA and UFA test wells.

The other three studies also included the collection of cores for hydraulic analysis and completing packer slug tests within the Lower Floridan semiconfining unit (LFCU); however, the current investigation did not complete these tests owing to cost limitations. Results of field investigations at the Barbour Pointe site are provided in Gonthier and Clarke (2016). In addition to field investigations, the method applied for model simulations at Hunter Army Airfield, Fort Stewart, Pooler, and Rincon was identical to that applied to the Barbour Pointe study, with modifications similar to those of the regional model of Payne and others (2005). Collectively, data obtained from these investigations add to the body of knowledge needed to characterize the FAS on a regional scale.

Miller (1986) developed a hydrogeologic framework for the FAS throughout its extent in Georgia, Florida, South Carolina, and Alabama. This framework was subsequently revised by Williams and Gill (2010) for 8 northern coastal counties in Georgia and 5 coastal counties in South Carolina, including the area of the Barbour Pointe test site and test sites at Hunter Army Airfield, Fort Stewart, Pooler, and Rincon. Williams and Kuniansky (2015) further revised the framework of the aquifer system in all four States. The Williams and Gill (2010) and Williams and Kuniansky (2015) studies used borehole geophysical and flowmeter log data collected since the original study of Miller

(1986) to shift the position of internal boundaries of the UFA and LFA and of the individual permeable zones that compose these aquifers. These revised boundaries, but not the nomenclature, were used to guide projected drilling depths at the Barbour Pointe site.

Site Description

Barbour Pointe is located in the Coastal Plain physiographic province in west-central Chatham County, Ga., near Interstate 95 (fig. 1). The site is characterized by low-altitude, flat topography and sandy topsoil, typical of the Georgia coastal area. A new LFA production well (36Q398) was constructed at the site, and a new UFA observation well (36Q399) was installed about 40 feet (ft) to the north. The LFA well 36Q398 is located at an altitude of about 5 ft above the North American Vertical Datum of 1988 (NAVD 88) with static (non-pumping) water levels in the UFA at an altitude of about –30 ft, or a depth of 35 ft below land surface during May 1998 (Peck and others, 1999).

The study area has a mild climate with warm, humid summers and mild winters. Long-term climatic patterns in the area are derived from records provided by the National Weather Service Station at Savannah International Airport (climatological station 097847, labeled "KSAV" on fig. 1; Southeast Regional Climate Center, 2011). During 1971–2000, precipitation at station 097847 averaged about 49.6 inches per year. Maximum monthly rainfall (exceeding 4 inches per month) generally occurs during January and June–September, with monthly rainfall totals averaging less than 4 inches during the rest of the year. Mean monthly pan evaporation at station 097847 during 1965–2003 ranged from 2.43 to 8.49 inches per month, with the greatest evaporation occurring during April–August (Southeast Regional Climate Center, 2011).

Water Use

Water supply for the nearby city of Berwick (Consolidated Utilities LLC) is provided by 4 wells completed in the UFA, 1 well completed in the LFA, and 3 wells completed in the Brunswick aquifer system. Because of concern about saltwater intrusion, the GaEPD has implemented restrictions on groundwater withdrawals from the UFA and designated management zones in coastal Georgia. Barbour Pointe is located in the GaEPD "red zone," where withdrawal from the UFA is capped at the 2004 pumping rate. The GaEPD water-withdrawal permit for the city of Berwick allows an annual daily average withdrawal of 0.309 million gallons per day (Mgal/d) for the UFA (Jeff Larson, Georgia Environmental Protection Division, written commun., 2008), 0.525 Mgal/d for the LFA (Christine Voudy, Georgia Environmental Protection Division, written commun., 2003), and 2 Mgal/d for the Brunswick aquifer system (William Frechette, Georgia Environmental Protection Division, written commun., 2013).

Groundwater use in Chatham County totaled 54.6 Mgal/d during 2010 (Steven J. Lawrence, U.S. Geological Survey, written commun., 2013). Nearly 60 percent of this use, or 32.0 Mgal/d, was for public supply. Most production wells are located in the city of Savannah; additional wells to the northwest serve Pooler and to the northeast serve Garden City and Port Wentworth (fig. 1; Fanning and Trent, 2009). Payne and others (2005) estimated that during 1980–2000, nearly 95 percent of groundwater withdrawn in Chatham County was pumped from the UFA; the remaining 5 percent was derived from the LFA. Groundwater withdrawals from the FAS in the county decreased from 68.2 Mgal/d in 2000 to 54.6 Mgal/d in 2010.

Hydrogeologic Setting

Chatham County (fig. 1) is underlain by Coastal Plain strata consisting of consolidated to unconsolidated layers of sand and clay and semiconsolidated to very dense layers of limestone and dolomite (Miller, 1986; Clarke and others, 1990; Williams and Gill, 2010; Williams and Kuniansky, 2015). These sediments constitute three major aquifer systems, which are, in descending order, the surficial aquifer system, Brunswick aquifer system, and FAS (fig. 2).

In coastal Georgia, the surficial aquifer system consists of Miocene and younger interlayered sand, clay, and thin limestone beds (Clarke, 2003). At Barbour Pointe, the surficial aquifer system consists of fine- to coarse-grained sand, clay, and marl at depths of less than 70 ft and largely is unconfined. Elsewhere in coastal Georgia, the surficial aquifer system includes a water-table zone and two confined water-bearing zones; however, the areal extent of the confined water-bearing zones is unknown (Clarke, 2003). The surficial aquifer system is separated from the underlying Brunswick aquifer system by a confining unit consisting of silty clay and dense, phosphatic Miocene limestone.

The Oligocene to Miocene Brunswick aquifer system consists of two water-bearing zones—the upper Brunswick aquifer and the lower Brunswick aquifer (Clarke, 2003). The upper Brunswick aquifer consists of poorly sorted, fine- to coarse-grained, slightly phosphatic and dolomitic quartz sand, and dense, phosphatic limestone (Clarke and others, 1990). The lower Brunswick aquifer consists of poorly sorted, fine- to coarse-grained, phosphatic and dolomitic Oligocene and Miocene sand (Clarke and others, 1990). At Barbour Pointe, Miocene sediments equivalent to the Brunswick aquifer system are present between depths of 67 and 280 ft, and consist largely of low permeability, clayey fine sand and silt, with slightly higher permeability between depths of 246 and 280 ft.

Series	Stage	Upper Coastal Plain[1]		Lower Coastal Plain[2]				Model layer
		Geologic unit	Hydrogeologic unit	Geologic unit[3]	Hydrogeologic unit Savannah Brunswick			
Post-Miocene		Undifferentiated	Upper Three Runs aquifer	Undifferentiated	Water-table zone		Surficial aquifer system	GHB (not modeled)
Miocene	Upper			Ebenezer Formation	Confining unit — Upper water-bearing zone; Lower water-bearing zone			1
	Middle			Coosawhatchie Formation	Confining unit — Upper Brunswick aquifer		Brunswick aquifer system	2
	Lower			Marks Head Formation				3
				Parachucla Formation				
				Tiger Leap Member of Parachucla Formation	Lower Brunswick aquifer			
Oligocene				Lazaretto Creek Formation	Upper Floridan confining unit		Floridan aquifer system	4
				Suwannee Limestone	Upper Floridan aquifer — Upper water-bearing zone			
Eocene	Upper	Barnwell Group		Ocala Limestone	Upper Floridian semi-confing unit; Lower water-bearing zone			5
	Middle	Santee Limestone	Confining unit	Avon Park Formation	Lower Floridan semiconfining unit[4]			6
	Lower	Congaree Formation	Gordon aquifer	Oldsmar Formation	Lower Floridan aquifer — Confining unit			7
Paleocene		Snapp Formation Ellenton Formation (undifferentiated)	Confining unit[5]	Cedar Keys Formation	Fernandina permeable zone			
Upper Cretaceous		Steel Creek Formation Black Creek Group (undifferentiated)	Upper Dublin aquifer	Undifferentiated	Confining unit			Not modeled

[1]Modified from Falls and others, 1997.

[2]Modified from Randolph and others, 1991; Clarke and Krause, 2000.

[3]Modified from Randolph and others, 1991; Weems and Edwards, 2001.

[4]Middle confining unit 1 in Miller (1986); middle confining unit in Williams and Gill (2010); Lisbon-Avon Park composite unit in Williams and Kuniansky (2015).

[5]In local areas includes Millers Pond aquifer.

Figure 2. Generalized correlation chart showing geologic and hydrogeologic units and model layers in the Coastal Plain of Georgia (modified from Payne and others, 2005). [GHB, general head boundary].

The principal source of water for all uses (excluding thermoelectric) in the coastal area of Georgia is the FAS, which is the subject of this report. The FAS is confined by overlying clay layers and is separated into several permeable, water-bearing zones by layers of dense limestone or dolomite that act as semiconfining units. In the coastal area, the system has been subdivided by the USGS into the UFA and LFA (Miller, 1986; Williams and Gill, 2010; Williams and Kuniansky, 2015).

Williams and Gill (2010) provided an updated hydrogeologic framework for the northern coastal area of Georgia and adjacent part of South Carolina. Using information from that report and new data collected at Barbour Pointe, the UFA and LFA, as defined by the USGS, are present at the following depths at the Barbour Pointe well site:

- Top UFA: 300 ft

- Base UFA: 567 ft

- Top LFA: 714 ft

- Base of LFA: 1,050 ft

Results of flowmeter testing in the Barbour Pointe well indicate there are three principal water-bearing zones in the UFA present at depths of: 364–400 ft, 421–456 ft, and 482–560 ft (fig. 3; Gonthier and Clarke, 2016). The calculated transmissivity from a 24-hour aquifer test of the UFA was 60,000 feet squared per day (ft^2/d; Gonthier and Clarke, 2016).

The UFA and LFA are separated by a leaky semiconfining unit consisting of chalky and glauconitic limestone in the uppermost part of the middle Eocene Avon Park Formation, extending from 567 to 714 ft at Barbour Pointe (fig. 3; Gonthier and Clarke, 2016). This leaky unit is called "middle confining unit I" in Miller (1986); "lower Floridan confining unit" in Payne and others (2005); "middle confining unit" in Williams and Gill (2010); and "Lisbon-Avon Park composite unit" in Williams and Kuniansky (2015). In this report, the leaky semiconfining unit is referred to as the "lower Floridan semiconfining unit" (LFCU). The thickness and hydraulic conductivity of the LFCU control the rate of interaquifer leakage between the UFA and LFA. Results of a flowmeter survey indicate that the LFCU contributes little to the overall flow in a test hole open to the entire FAS, and a single water-bearing zone is present between depths of 700 and 719 ft, yielding 7 gallons per minute (gal/min). Hydraulic properties of the LFCU were not measured at Barbour Pointe; however, they were characterized at the nearby Pooler and Hunter Army Airfield sites (Williams, 2010; Gonthier, 2012). Slug tests and core samples were analyzed for selected intervals within the LFCU at each of the two sites. At Hunter Army Airfield, the estimated vertical hydraulic conductivity (K_v) ranged from 0.02 to 0.36 foot per day (ft/d), with a median of 0.075 ft/d (Williams, 2010). At Pooler, estimated K_v ranged from 0.05 to 1.67 ft/d, with a median of 0.79 ft/d. The median of all values at the two sites was 0.33 ft/d, which indicates the LFCU is not fully confining.

The LFA consists of chalky and glauconitic limestone in the upper part of the middle Eocene Avon Park Formation, which is similar in lithology to overlying units. The depth interval of the LFA was generally consistent in the Barbour Pointe area with greater thickness towards the north near the Rincon area (table 1). The observed drawdown in the UFA resulting from pumping the LFA was 4.5 ft at Rincon (Carter and Sloope, 2004) and ranged from 0.37 to 0.8 ft at the other four sites, which includes Barbour Pointe. Results of flowmeter testing at Barbour Pointe identified four water-bearing depth intervals within the LFA: 753 to 770 ft, 783 to 796 ft, 870 to 940 ft, and 1,023 to 1,050 ft (fig. 3; Gonthier and Clarke, 2016). No flow was detected below a depth of 1,050 ft where the lower confining unit is present. The transmissivity of the LFA is 5,100 ft^2/d at Barbour Pointe (Gonthier and Clarke, 2016), compared to 4,000 ft^2/d at Pooler (Gonthier, 2012) and 10,700 ft^2/d at Hunter Army Airfield (Williams, 2010).

Groundwater Flow

Groundwater flow in the FAS is determined by the rate and distribution of recharge to and discharge from the system, the extent and effectiveness of confinement, and the ability of aquifers to transmit and store water (Krause and Randolph, 1989). The conceptualized predevelopment (no pumping) and modern-day (2000) groundwater-flow systems in coastal Georgia (fig. 4) receive water from precipitation and downward leakage through shallow geologic units that recharge the aquifers in the northern part of the coastal area where the units are exposed at or near land surface. Groundwater then flows mostly southeastward toward the coast, where it discharges into overlying units and surface-water bodies. Prior to development, the flow system was considered to be in dynamic equilibrium, where recharge balances discharge, and potentiometric surfaces were considered nearly static from year to year. Generally, predevelopment potentiometric surfaces were higher than current groundwater levels, and test wells tapping the FAS flowed at the surface along the coast (fig. 4*A*).

The modern-day (2000) flow system reflects changes that have occurred as a result of groundwater development (withdrawals; fig. 4*B*). Groundwater withdrawals have lowered potentiometric heads in the UFA, induced additional recharge from vertical leakage and regional flow, reduced natural discharge, and degraded the quality of water locally along the coast. Groundwater pumping has caused an extensive cone of depression to develop in the potentiometric surface of the UFA in the Savannah area (fig. 1). This feature has affected groundwater flow near Barbour Pointe, as evidenced by the shape of potentiometric contours, indicating groundwater flow is toward the center of the cone of depression.

Saltwater contamination restricts development of the groundwater supply in coastal Georgia and adjacent parts of South Carolina and Florida (Krause and Clarke, 2001). Pumping from the UFA has resulted in substantial groundwater-level decline and subsequent saltwater intrusion into the UFA at Brunswick, Ga., from underlying strata containing highly saline water and the encroachment of seawater into the UFA at the northern end of Hilton Head Island, S.C. Saltwater contamination at these locations has constrained further development of the UFA in the coastal area and has created competing demands for the limited supply of freshwater.
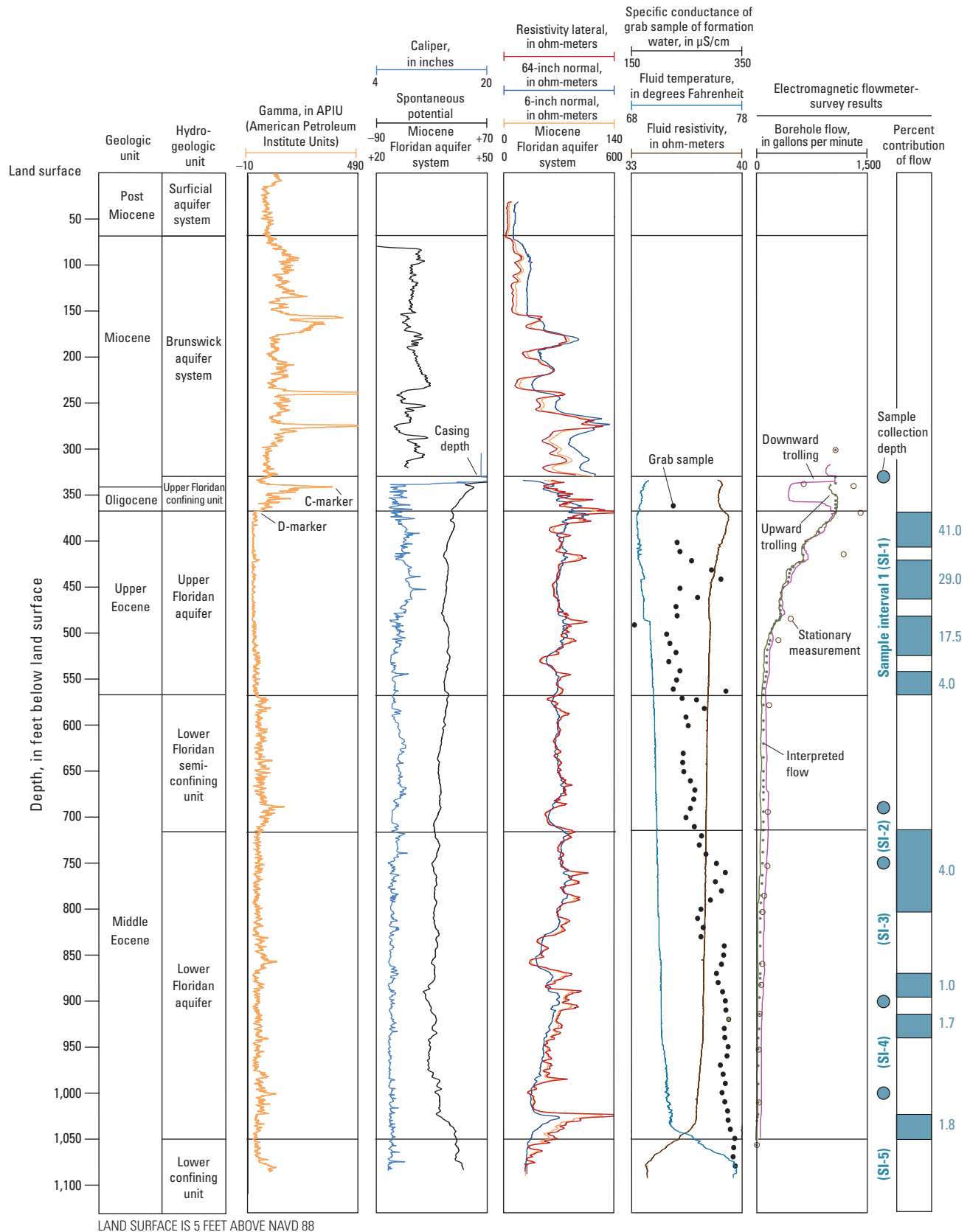
Figure 3.   Geophysical properties, electromagnetic flowmeter survey, and specific conductance of discharging formation water, test hole for Lower Floridan aquifer well 36Q398, Barbour Pointe, Chatham County, Georgia. [µS/cm, microsiemens per centimeter at 25 degrees Celsius].

Table 1.   Summary of data collected at sites in the Lower Floridan aquifer in coastal Georgia.

[HAAF, Hunter Army Airfield; LFA, Lower Floridan aquifer; UFA, Upper Floridan aquifer]

Property	Rincon (well 36S048)	Pooler (well 35Q069)	Berwick (well 36Q330)	Barbour Pointe (well 36Q398)	HAAF (well 36Q392)
LFA depth interval (feet)	565–1,000	702–1,040	700–1,080	714–1,050	703–1,080
LFA test yield (gallons per minute)	1,000	782	718	750	748
LFA specific capacity (gallons per minute per foot of drawdown)	13.8	15	23.1	21.1	20.8
Maximum drawdown LFA (feet)	72.3	52	31	35.6	36
Maximum drawdown UFA (resulting from LFA pumping, in feet)	4.5	0.8	0.37	0.71	0.76
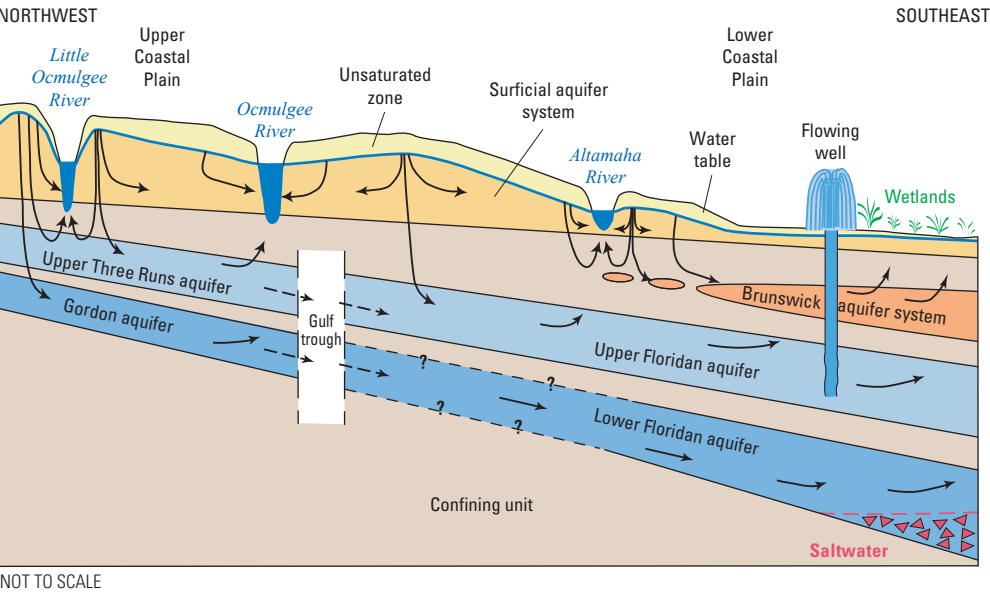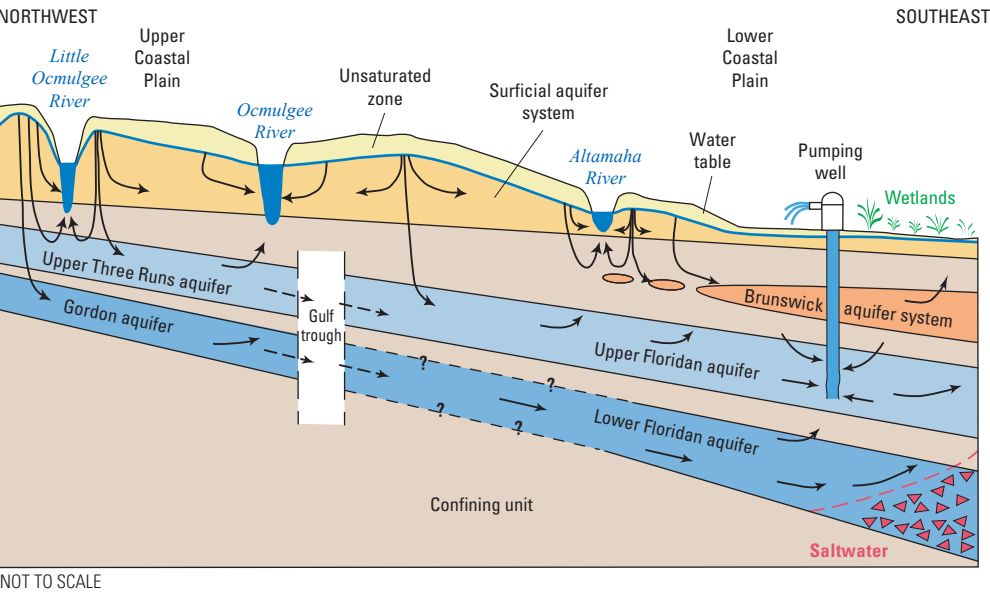
Figure 4.   Schematic diagram showing conceptual model of, *A*, predevelopment and, *B*, modern-day (2000) flow system. Arrows indicate general direction of groundwater flow (modified from Priest, 2004; Payne and others, 2005).

Well Identification

In this report, wells are named by means of a local USGS numbering system that is based on the index of USGS topographic maps (such as 36Q398). In Georgia, each 7.5-minute topographic quadrangle map has been given a number and letter designation beginning at the southwestern corner of the State. Numbers increase eastward through 39, and letters increase alphabetically northward through "Z" and then become double-letter designations "AA" through "PP." The letters "I" and "O" are not used. Wells inventoried in each quadrangle are numbered sequentially beginning with "1." For example, well 36Q398 is the 398th well inventoried in the Garden City quadrangle (map 36Q).

Simulated Effect of Lower Floridan Aquifer Pumping on the Upper Floridan Aquifer

The potential effects of pumping the LFA on water levels in the UFA were evaluated by monitoring drawdown response in nearby UFA wells and through model simulation. Observed water-level response in the UFA as a result of pumping the LFA was determined by using water-level data that were filtered for tidal, barometric, and pumping interferences (Gonthier and Clarke, 2016). These measured drawdowns provided a basis for evaluating the accuracy of model simulations. These simulations were used to determine long-term (steady-state) leakage response of the UFA to pumping from the LFA, and to estimate the equivalent amount of UFA pumping that would produce similar drawdown.

Observed Water-Level Response

The LFA well 36Q398 was pumped at a rate of 750 gal/min for a 72-hour period during November 19–22, 2013. In this study, the same pumping rate of 750 gal/min was used to simulate drawdown in the UFA and LFA. Filtering of water-level data using the spreadsheet procedure of Halford (2006) isolated the drawdown response from unrelated natural and anthropogenic controls, such as tidal, barometric, and regional pumping influences (Gonthier and Clarke, 2016). The filtering yielded synthesized water levels that presumably reflect drawdown caused only by pumping of LFA well 36Q398 (fig. 5*A*, *B*). These synthesized water levels indicated drawdown was 0.7 ft in UFA well 36Q399 (fig. 6*B*) and 35.5 ft in LFA well 36Q398 (fig. 5*B*; Gonthier and Clarke, 2016).

Drawdown in the LFA was nearly stable, whereas drawdown in the UFA continued to decline at the end of the 72-hour test period (figs. 5 and 6). Hypothetical water levels using the Theis solution provide a relatively good fit to the estimated drawdown in both wells. Because test pumping at LFA well 36Q398 was discontinued before drawdown had stabilized in the UFA, model simulation was used to determine long-term, steady-state effects on the FAS beyond the aquifer-test period. Simulations by Payne and others (2005) in coastal Georgia indicate that it could take 5 years or more to reach a steady-state condition in the Chatham County area. Because a 5-year-long aquifer test is impractical, model simulation provided a means to estimate the long-term steady-state condition.

Model Simulation

The groundwater-flow model was used to simulate requirements described in the GaEPD interim strategy for permitting LFA groundwater withdrawals in the 24-county coastal Georgia area (fig. 1; Nolton Johnston, Georgia Environmental Protection Division, written commun., 2003). Stipulations include (1) quantifying interaquifer leakage from the UFA to the LFA resulting from pumping the new LFA well and (2) calculating "the equivalent Upper Floridan pumping that induces the identical maximum drawdown in the Upper Floridan that would be expected as a result of pumping the Lower Floridan."

To comply with the GaEPD stipulations, the regional groundwater-flow model of Payne and others (2005) was modified to increase the spatial resolution and incorporate hydrogeologic information obtained from field investigations at Barbour Pointe (described earlier) and from nearby existing wells, as described in appendix 1. Simulations to evaluate the effects of pumping LFA well 36Q398 on groundwater levels and interaquifer leakage in the FAS were run using the revised model, which incorporated average pumping rates during 2010 in the city of Berwick wells and pumping rates during 2000 elsewhere as a base case for the evaluations.

Simulations of the following groundwater-model scenarios were used to quantify the long-term response of the FAS to changes in groundwater pumping in both the UFA and LFA (table 2):

- Scenario A—Steady-state simulation with LFA well 36Q398 pumping at a rate of 750 gal/min, approximately same rate used during the 72-hour aquifer test.

- Scenario B—Steady-state simulation with UFA well 36Q399 pumping at a rate 240 gal/min, which would produce the same amount of drawdown as that resulting from pumping LFA well 36Q398 at a rate of 750 gal/min (simulated for scenario A). Several model runs were performed on a trial-and-error basis to achieve a drawdown match.

Figure 5.   Fit of synthetic water levels to measured water levels for Lower Floridan aquifer pumped well 36Q398, Barbour Pointe, Georgia, November 16–December 1, 2013. *A*, Synthetic and measured water levels, and *B*, Sum of Theis transforms, estimated drawdown, and synthetic water level minus the measured water level. Modified from Gonthier and Clarke (2016).

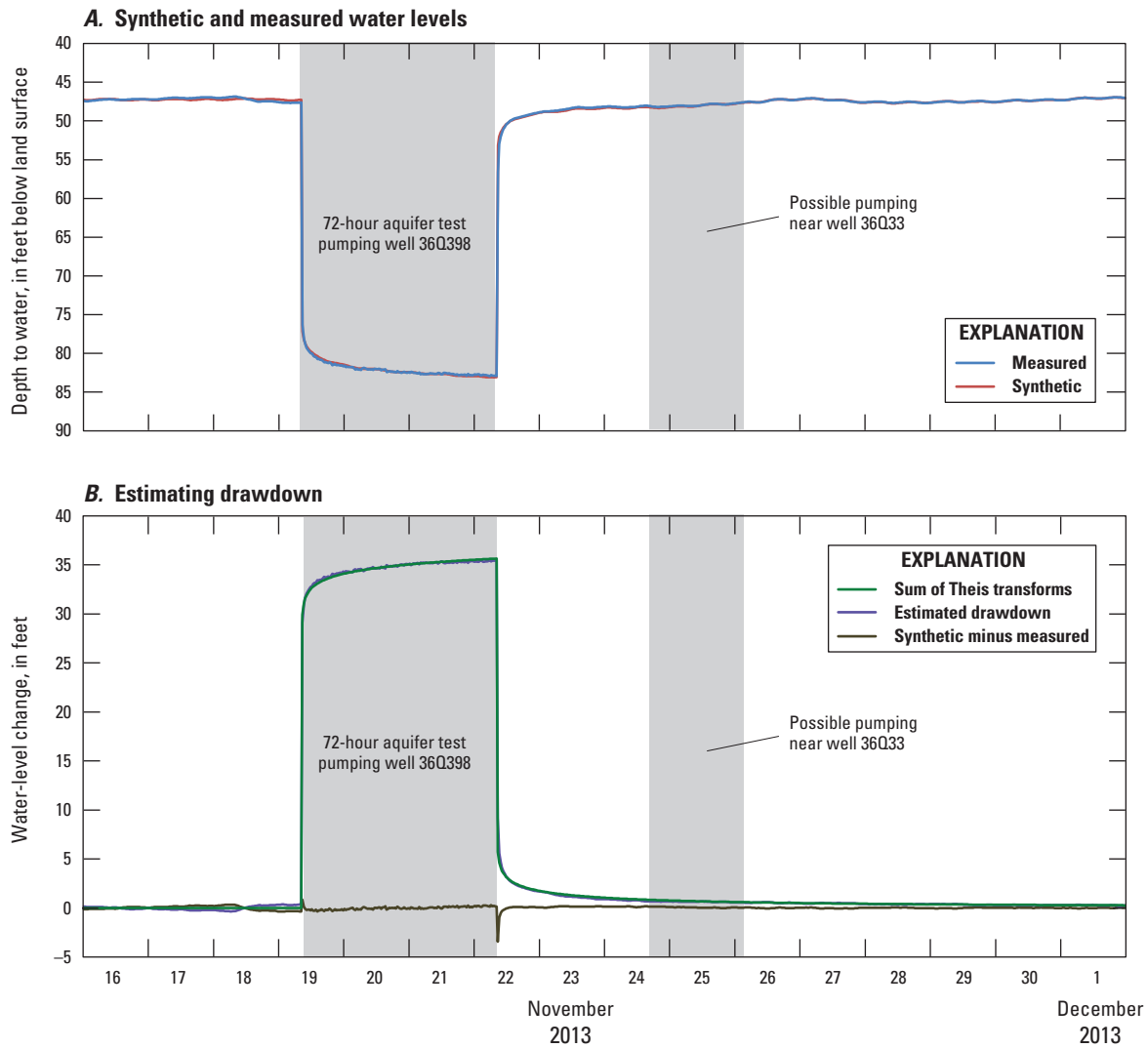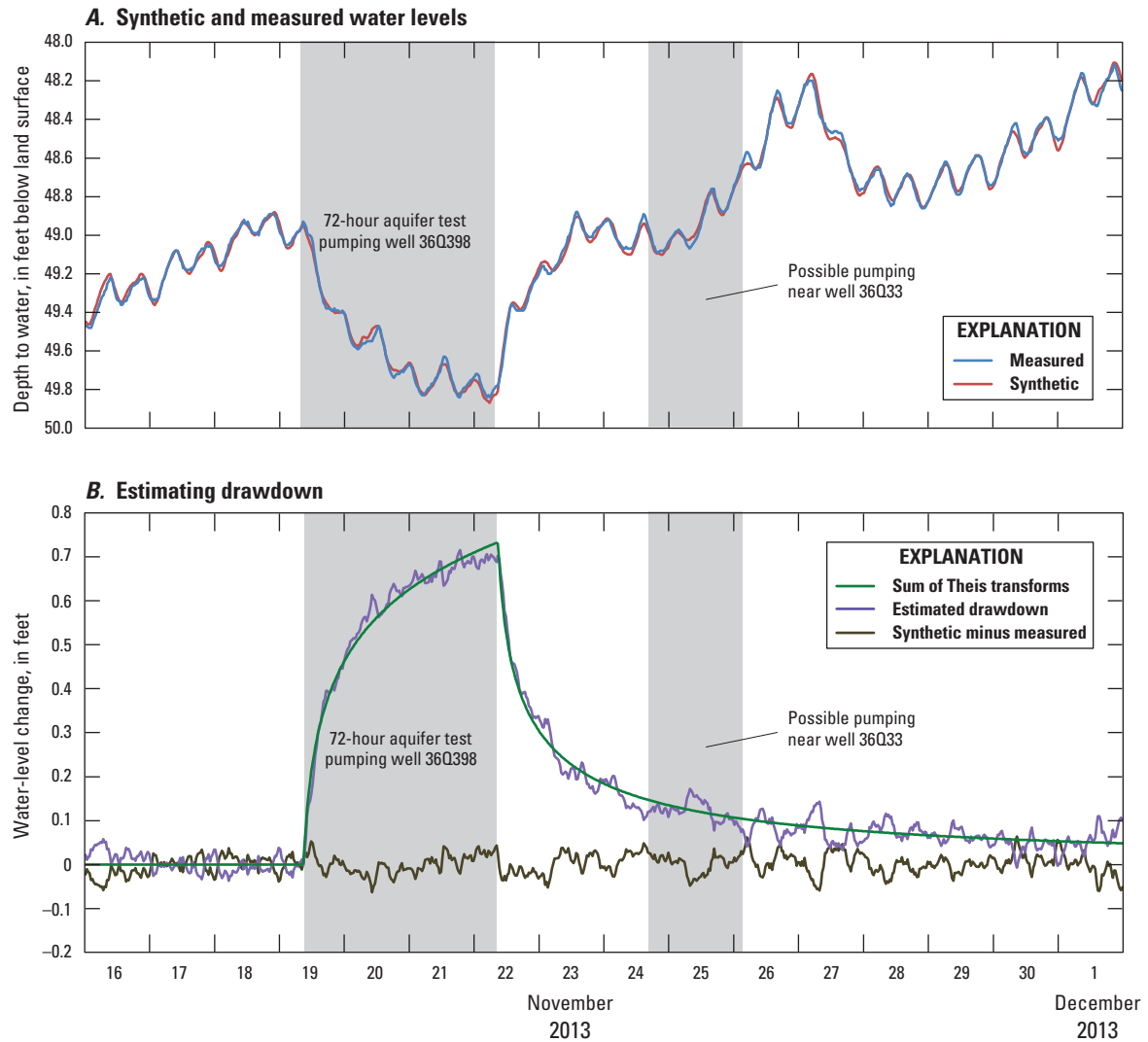**Figure 6.**   Fit of synthetic water levels to measured water levels for Upper Floridan aquifer well 36Q399, Barbour Pointe, Georgia, November 16–December 1, 2013. *A*, Synthetic and measured water levels, and *B*, Sum of Theis transforms, estimated drawdown, and the synthetic water level minus the measured water level. Modified from Gonthier and Clarke (2016).

Table 2.   Description of model scenarios and simulated drawdown in the Upper and Lower Floridan aquifers for various pumping distributions at Barbour Pointe, Georgia.

[LFA, Lower Floridan aquifer ; UFA, Upper Floridan aquifer; gal/min, gallon per minute; —, not applicable]

Scenario	Pumping change, in gallons per minute		Upper Floridan aquifer drawdown			Lower Floridan aquifer drawdown			Remarks
	Upper Floridan aquifer	Lower Floridan aquifer	Maximum, in feet	Area of 1-foot contour, in square miles	Area of 0.5-foot contour, in square miles	Maximum, in feet	Area of 1-foot contour, in square miles	Area of 0.5-foot contour, in square miles	
A	0	+750	2.19	115	760	35.6	116	761	Pumping LFA well 36Q398 at approximate rate used during the 72-hour aquifer test (750 gal/min).
B	+240	0	2.18	0.012	8.57	—	—	—	Pumping UFA well 36Q399 at a rate that would replicate the amount of UFA drawdown simulated as the result of pumping LFA well 36Q398 at a rate of 750 gal/min (as was simulated in scenario A). Note that several model runs were completed until a drawdown match was obtained.

Interaquifer Leakage and Drawdown Response

For scenario A, simulated pumping of LFA well 36Q398 at a rate of 750 gal/min resulted in a maximum steady-state drawdown of 35.6 ft (table 2, fig. 7), which is nearly identical to the 35.5-ft maximum drawdown observed during the test (fig. 5). Because changes in water levels over time were approaching zero by the end of the 72-hour test, the steady-state simulation seems to be a reasonable estimate of field conditions in the LFA. Simulated steady-state drawdown in the LFA for scenario A exceeded 1 ft over a 116-mi^2 area (fig. 7, table 2).

Simulated pumping of LFA well 36Q398 at 750 gal/min (scenario A) caused interaquifer leakage through the LFCU, which resulted in drawdown in the overlying UFA (fig. 8). Because water levels in the UFA had not stabilized by the end of the 72-hour test, observed drawdown in well 36Q399 was considered a lower limit for steady-state model calibration. At the end of the 72-hour aquifer test, drawdown in well 36Q399 was 0.7 ft, compared to the simulated steady-state drawdown of 2.19 ft. This difference is expected because field data represent a short-term, transient condition in which drawdown in the UFA was still accumulating at the end of the 72-hour test, whereas the model simulated the long-term steady-state response. Model results for scenario A indicate that drawdown in the UFA exceeded 1 ft over a 115-mi^2 area (table 2).

Simulated potentiometric surface for the UFA from scenario A resulted in no noticeable changes in the regional configuration of implied groundwater-flow directions for the UFA when compared with a base case representing year 2000 conditions (fig. 9). Groundwater flow in the region remained dominated by a large cone of depression centered over the Savannah, Ga., area.

To assess the amount of interaquifer leakage resulting from pumping in the LFA, the steady-state water budgets before and after pumping at well 36Q398 were compared (table 3). Because of independent rounding, the water budget values listed may not add to totals; however, comparison of values provides some insight into the relative contribution of flow to LFA well 36Q398. Pumping 1.08 Mgal/d (750 gal/min) at well 36Q398 resulted in small changes to the regional water budget and the following redistribution of flow among model layers (table 3):

- Layer 1 (surficial aquifer)—a 0.36-Mgal/d gain in inflow from, and a 0.08-Mgal/d reduction in outflow to, the general-head boundary for a net inflow of 0.44 Mgal/d.

- Layer 2 (Brunswick aquifer confining unit)—a 0.018-Mgal/d gain in inflow from, and a 0.002-Mgal/d reduction in outflow to, the general-head boundary for a net inflow of 0.020 Mgal/d.

- Layer 5 (UFA)—a 0.01-Mgal/d gain in inflow from, and a 0.006-Mgal/d reduction in outflow to, the general-head boundary and a 0.38-Mgal/d gain in inflow from, and 0.16-Mgal/d reduction in outflow to, lateral specified-head boundaries for a net inflow of 0.556 Mgal/d.

- Layer 7 (LFA)—a 0.014-Mgal/d gain in inflow from, and a 0.011-Mgal/d reduction in outflow to, lateral specified-head boundaries for a net inflow of 0.025 Mgal/d.

For scenario A, of the 1.08-Mgal/d pumping rate in well 36Q398, an estimated 97.5 percent of the flow was derived from increased leakage from overlying layers, and 2.5 percent

was from the lateral specified-head boundary for the LFA (layer 7). Most of the flow from overlying layers was from the general-head boundary in the surficial aquifer (layer 1, 41.6 percent) and lateral specified-head boundaries in the UFA (layer 5, 49.9 percent). The remainder of flow from overlying layers was contributed from the general-head boundary in layers 2 and 5.
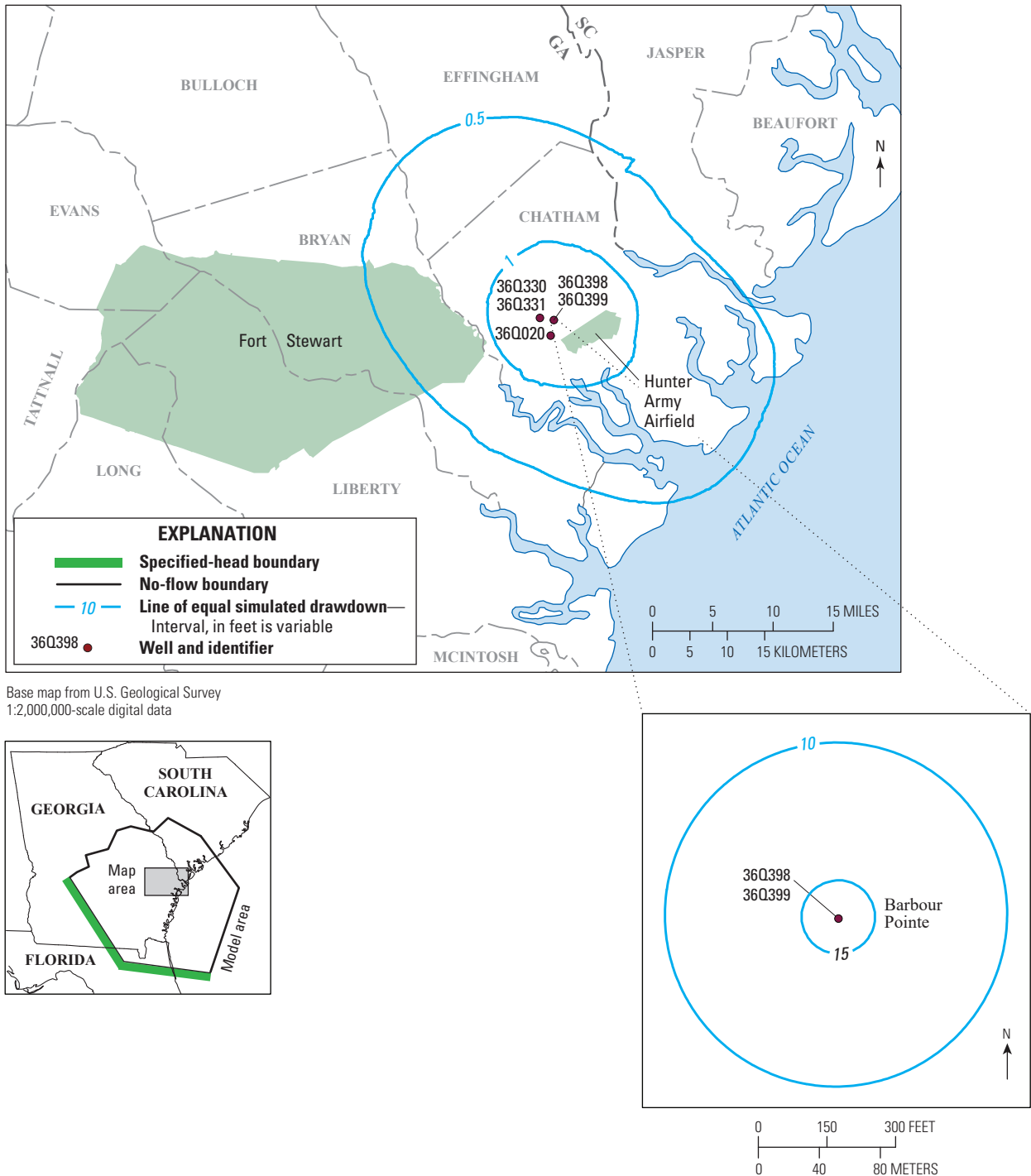
Figure 7.   Simulated steady-state drawdown in the Lower Floridan aquifer for scenario A—pumping Lower Floridan aquifer well 36Q398 at 750 gallons per minute, Barbour Pointe, Georgia, and vicinity. Maximum drawdown in well 36Q398 is 35.6 feet.

Figure 8.   Simulated steady-state drawdown in the Upper Floridan aquifer for scenario A—pumping Lower Floridan aquifer well 36Q398 at 750 gallons per minute, Barbour Pointe, Georgia, and vicinity. Maximum drawdown in well 36Q399 is 2.19 feet.
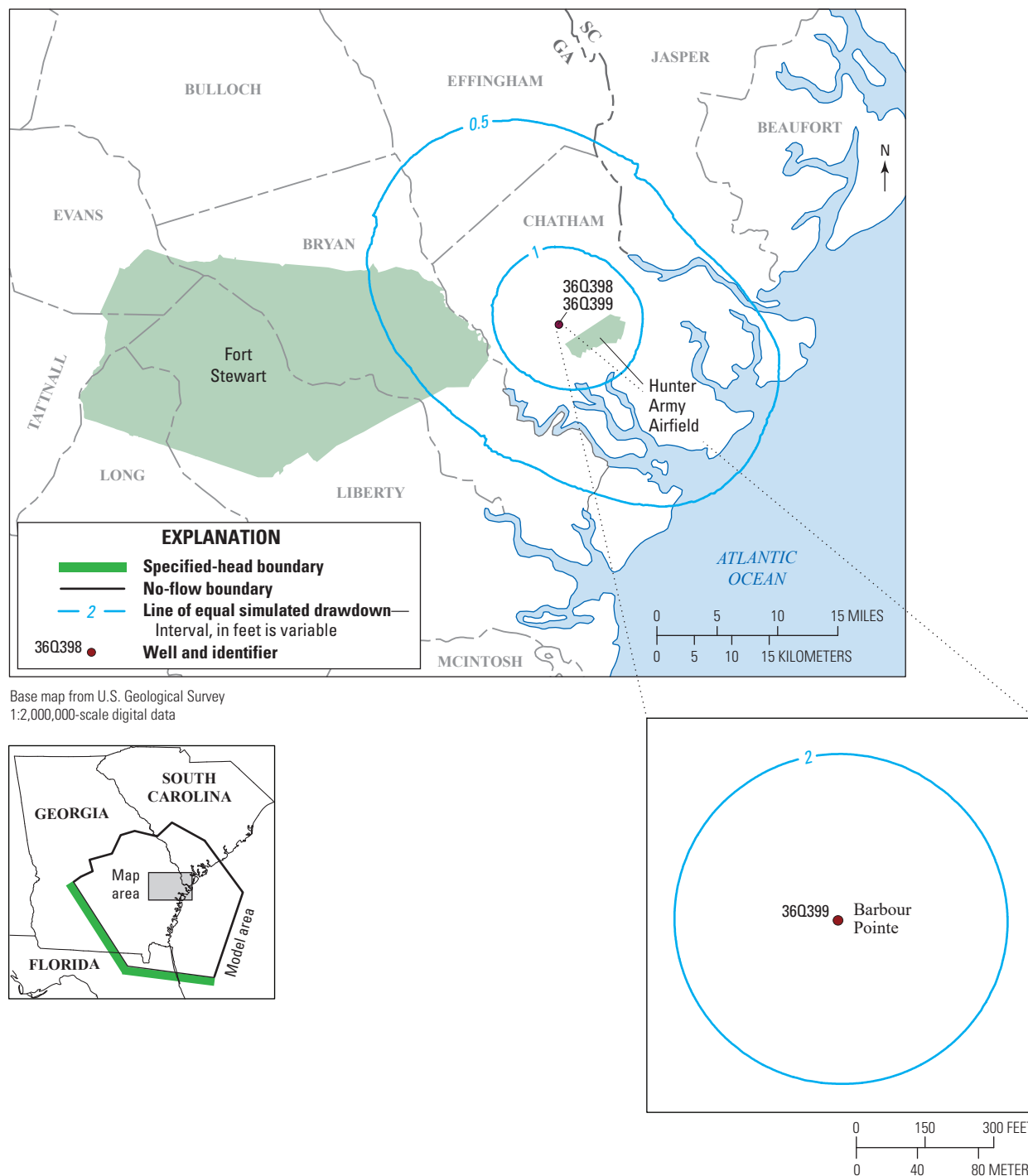
Base Case
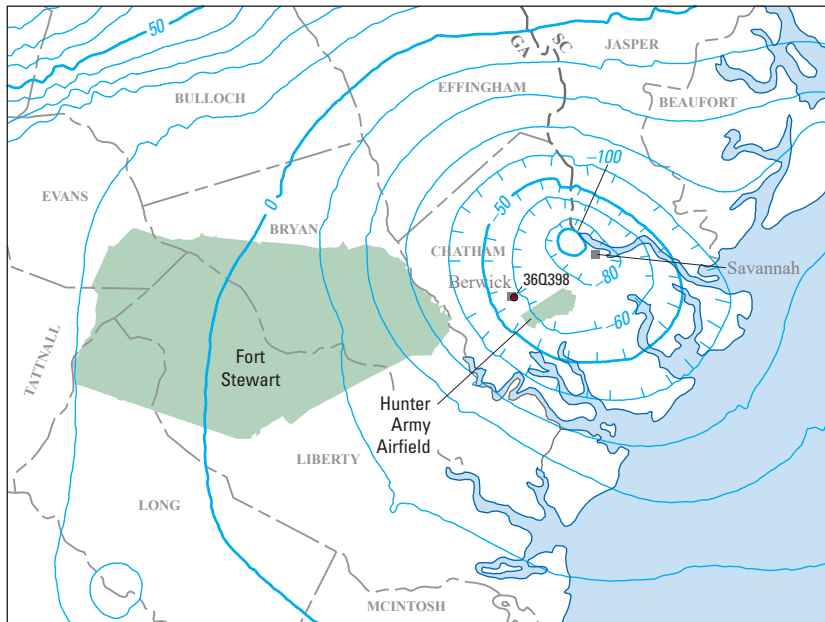
Scenario A
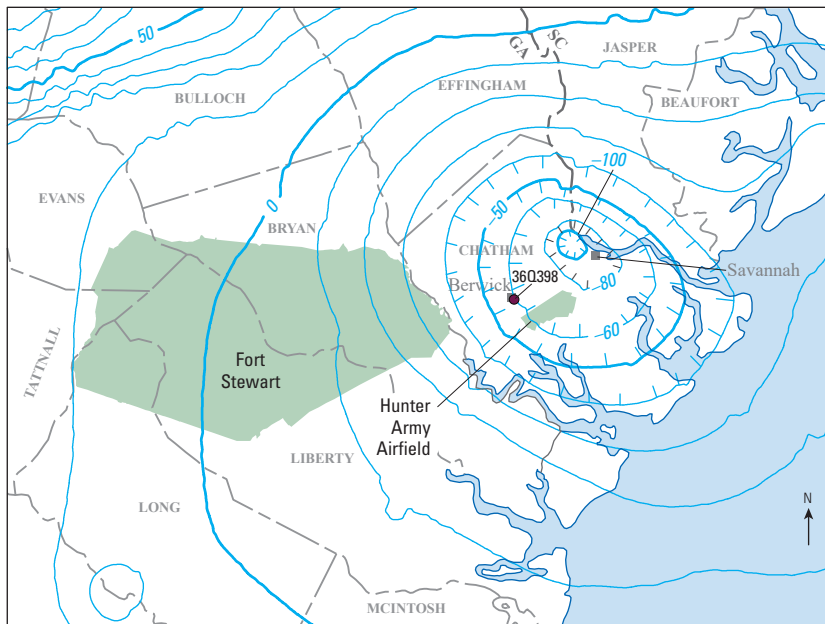
Base map from U.S. Geological Survey
1:2,000,000-scale digital data

0   5   10   15 MILES

0   5   10   15 KILOMETERS
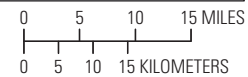
EXPLANATION

— *50* —   **Simulated potentiometric contour**—Intervals 10 and 20 feet.
                Hachures indicate depression. Datum is NAVD 88

36Q398 ●   **Well and identifier**

Figure 9.   Simulated Upper Floridan aquifer potentiometric surface for the year 2000 base case and scenario A, Barbour Pointe, Georgia, and vicinity.

Table 3.   Simulated steady-state water budgets for 2000 and for scenario A, after pumping 750 gallons per minute (1.08 million gallons per day) at Lower Floridan aquifer well 36Q398, Barbour Pointe, Chatham County, Georgia.

[Values may not sum to totals because of independent rounding; <, less than]

Hydro-geologic unit	Model layer	Pumpage			Inflow from general-head boundary			Outflow from general-head boundary			Inflow along lateral boundary			Outflow along lateral boundary		
		2000	Well 36Q398 added	Difference	2000	Well 36Q398 added	Difference	2000	Well 36Q398 added	Difference	2000	Well 36Q398 added	Difference	2000	Well 36Q398 added	Difference
Surficial aquifer system	1	<0.001	<0.001	<0.001	276.52	276.88	0.36	100.08	100.00	−0.08	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Confining unit	2	<0.001	<0.001	<0.001	32.703	32.721	0.018	2.006	2.004	−0.002	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Brunswick aquifer system	3	0.241	0.241	0.000	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Confining unit	4	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Upper Floridan aquifer	5	674.13	674.13	0.00	148.79	148.80	0.01	20.319	20.313	−0.006	821.36	821.74	0.38	364.32	364.16	−0.16
Semi-confining unit	6	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.004	0.004	0.000	<0.001	<0.001	<0.001
Lower Floridan aquifer	7	131.03	132.11	1.08	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	15.140	15.154	0.014	2.362	2.351	−0.011
Total, all layers		**805.40**	**806.48**	**1.08**	**458.01**	**458.40**	**0.388**	**122.40**	**122.32**	**−0.088**	**836.50**	**837.90**	**0.394**	**366.68**	**366.51**	**−0.171**

Simulated flow, in million gallons per day

Upper Floridan Aquifer Drawdown Offset

As part of the interim permitting strategy for the LFA, GaEPD established a hydrogeologic-study protocol, which states that a groundwater model shall be used ". . . to simulate the equivalent Upper Floridan pumping that induces the identical maximum drawdown in the Upper Floridan that would be expected as a result of pumping the Lower Floridan." (Nolton Johnston, Georgia Environmental Protection Division, written commun., 2003). The amount of equivalent UFA pumping required to offset the effect of anticipated LFA pumping would be derived from pumping reductions at existing production wells within a 5-mile radius of the LFA well.

Scenario B was designed to determine the pumping rate in the UFA that would produce the identical maximum drawdown in the UFA as pumping from the LFA (herein called "drawdown offsets"). Scenario B is a series of steady-state simulations, applying various pumping rates to UFA well 36Q399, that were completed to match UFA drawdown as simulated by scenario A (table 2). Simulated pumping of UFA well 36Q399 at a rate of 240 gal/min approximated the 2.19-ft maximum drawdown in the UFA resulting from pumping LFA well 36Q398 at 750 gal/min (scenario A, table 2). A map showing drawdown in the UFA resulting from scenario B is not shown because of the small area affected by pumping.

Although it is possible to derive a drawdown offset for the UFA that produces the same maximum drawdown as that induced by leakage caused by pumping the LFA, that resultant UFA pumping will not produce the same overall drawdown pattern in the UFA as that produced by pumping the LFA. Pumping LFA well 36Q398 (scenario A; table 2) produced a larger drawdown area in the UFA than scenario B in which UFA well 36Q399 was pumped to offset the maximum UFA drawdown. For example, the 1-ft drawdown contour in the UFA corresponding to scenario B (pumping the UFA) encompassed an area of 0.012 mi^2, whereas the 1-ft contour encompassed 115 mi^2 in the UFA when the LFA was pumped (scenario A).

The large difference in affected area between scenarios involving pumping UFA and LFA wells is a consequence of the differences in hydraulic properties between the aquifers and the manner in which water flows to the simulated wells as leakage and from lateral boundaries. Drawdown in the UFA resulting from pumping the LFA has a more gradual lateral gradient and covers a wider area, whereas drawdown resulting from a well pumping directly from the UFA results in a steeper cone of depression covering a smaller area.

Pumping from the LFA produces a steep hydraulic gradient in that aquifer in the vicinity of the pumped well, progressively decreasing away from the well. Drawdown resulting from pumping LFA well 36Q398 extends to lateral specified-head boundaries in both the UFA and LFA, with boundaries in the UFA contributing relatively more flow than boundaries in the LFA for scenario A (table 2). The tenfold greater transmissivity of the UFA relative to the LFA enables drawdown to propagate over larger areas.

Comparison of water-budget values for components derived from simulating 2000 conditions without LFA pumpage with similar component values corresponding to drawdown-offset pumpage at UFA well 36Q399 (scenario B; table 4) indicated small changes to the 2000 regional water budget and the following redistribution of groundwater flow among model layers:

- Layer 1 (surficial aquifer)—a 0.12-Mgal/d gain in inflow from, and a 0.02-Mgal/d reduction in outflow to, the general-head boundary for a net inflow of 0.14 Mgal/d.

- Layer 2 (Brunswick aquifer system confining unit)—a 0.006-Mgal/d gain in inflow from the general-head boundary.

- Layer 5 (UFA)—a 0.002-Mgal/d reduction in outflow to the general-head boundary and a 0.08-Mgal/d gain in flow from, and 0.05-Mgal/d reduction in outflow to, lateral specified-head boundaries for a net inflow of 0.132 Mgal/d.

- Layer 7 (LFA)—a 0.004-Mgal/d in inflow from, and a 0.004-Mgal/d reduction in outflow to, lateral specified-head boundaries for a net inflow of 0.008 Mgal/d.

For scenario B, 42 percent of the 0.346-Mgal/d pumping rate in well 36Q399 was derived from increased leakage from overlying layers, and 38 percent was derived from general- and specified-head boundaries for the UFA (layer 5; table 4). About 40 percent of the inflow to the pumped UFA well from overlying layers was derived from the general-head boundary in the surficial aquifer (0.14 Mgal/d; layer 1); the remaining inflow to well 36Q399 from overlying layers was contributed by the general-head boundary in the Brunswick aquifer system confining unit (layer 2).

Model Sensitivity

To assess the relative importance of model parameters to groundwater levels and flow rates, Payne and others (2005) provided a comprehensive sensitivity analysis of the original regional model for both 1980 and 2000 simulations. Their evaluation included determination of composite-scaled sensitivities for pumping rate, horizontal and vertical hydraulic conductivity (K_h and K_v, respectively) for each hydraulic-property zone, and the conductance of the general-head boundary using procedures described by Hill (1998). Results of this analysis indicate that the model is most sensitive, by a wide margin, to pumping variations, followed by K_h of several zones in layer 5 (UFA). The K_v of the LFCU (layer 6) was ranked near last (20 of 23 parameters). Additional model sensitivity analysis was performed using the modified regional model for the city of Pooler (Cherry and Clarke, 2013). The hydraulic-property zones established for the analysis at Pooler include Barbour Pointe and coincide with those used for the current modified regional model. According to Cherry and Clarke (2013), increases in K_h and K_v of the LFA in hydraulic-property zone LF2 (see appendix 1 for locations

Table 4.   Simulated steady-state water budgets for base case (year 2000) and for scenario B, after pumping 240 gallons per minute (0.346 million gallons per day) at Upper Floridan aquifer well 36Q399, Barbour Pointe, Chatham County, Georgia.

[Values may not sum to totals because of independent rounding; <, less than]

Hydro-geologic unit	Model layer	Simulated flow, in million gallons per day														
		Pumpage			Inflow from general-head boundary			Outflow from general-head boundary			Inflow along lateral boundary			Outflow along lateral boundary		
		2000	Well 36Q399 added	Difference	2000	Well 36Q399 added	Difference	2000	Well 36Q399 added	Difference	2000	Well 36Q399 added	Difference	2000	Well 36Q399 added	Difference
Surficial aquifer system	1	<0.001	<0.001	<0.001	276.52	276.64	0.12	100.08	100.06	−0.02	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Confining unit	2	<0.001	<0.001	<0.001	32.703	32.709	0.006	2.006	2.006	0.000	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Brunswick aquifer system	3	0.241	0.241	0.000	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Confining unit	4	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Upper Floridan aquifer	5	674.13	674.47	0.346	148.79	148.79	0.00	20.319	20.317	−0.002	821.36	821.44	0.08	364.32	364.27	−0.05
Semi-confining unit	6	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.004	0.004	0.000	<0.001	<0.001	<0.001
Lower Floridan aquifer	7	131.03	131.03	0.00	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	15.140	15.144	0.004	2.362	2.358	−0.004
Total, all layers		**805.40**	**806.74**	**0.346**	**458.01**	**458.14**	**0.126**	**122.40**	**122.38**	**−0.022**	**836.50**	**836.59**	**0.084**	**366.68**	**366.63**	**−0.054**

of hydraulic-property zones) resulted in lower drawdown in both the UFA and LFA, a slight decrease in flow from model general-head boundaries (recharge), and a slight increase in flow from lateral specified-head boundaries in the UFA and LFA. Increases in K_h and K_v of the UFA in zone F13 (see appendix 1) resulted in lower drawdown in both the UFA and LFA, decreased flow from the general-head boundaries, and increased flow from lateral specified-head boundaries in the UFA and LFA. Changing K_h and K_v of the LFA and UFA had virtually no effect on downward flow (leakage) from the LFCU to the LFA.

The same sensitivity analysis performed for the Pooler study indicated increases in K_h and K_v of the LFCU in zone LFC2 (see appendix 1) resulted in decreased maximum drawdown in the LFA and increased maximum drawdown in the UFA. The sensitivity analysis for the Barbour Pointe study focused on changes to K_h and K_v of the LFCU in zone LFC2 and the use of values considered to be the upper and lower endpoints in a range of values obtained from analysis of core samples at Hunter Army Airfield (Clarke and others, 2010). The nearly 10:1 ratio of horizontal to vertical hydraulic conductivity was also obtained from the core analysis and incorporated in the values used for the simulations. Hydraulic conductivity values of K_h of 14.2 ft/d and K_v of 1.67 ft/d were assigned as the higher endpoints based on the Rincon study where the 72-hour aquifer test indicated a strong interaquifer connection between the UFA and the LFA (Cherry and Clarke, 2015; table 1). Hydraulic conductivity values of 0.2 ft/d for K_h and 0.02 ft/d for K_v were assigned as the lower endpoints because of a more delayed response in the UFA to pumping in the LFA at Hunter Army Airfield (Clarke and others, 2010). Hydraulic conductivity values of 2 ft/d for K_h and 0.2 ft/d for K_v were assigned for the Pooler study and the current analysis for Barbour Pointe because the vertical hydraulic conductivity approximates the median value from the core analysis at Hunter Army Airfield (Cherry and Clarke, 2013; Clarke and others 2010). These changes in the hydraulic conductivity values assigned to the LFCU in zone LFC2 also required adjustments to hydraulic properties of the LFA in zone LF2 in order for simulated drawdown to match the observed drawdown in LFA pumping well 36Q398 after 72 hours.

Zone LF2 in layer 7 was expanded northwestward from an area of 114 mi^2 in the Hunter Army Airfield model to 221 mi^2 in the Pooler and Barbour Pointe models. Zone LF2 in layer 7 covers an area identical to zones F13 in layer 5 and LFC2 in layer 6, with a calibrated K_h value of 114 ft/d, compared to 88 ft/d for the calibrated Pooler model (Cherry and Clarke, 2013). Multiplying the K_h value by the simulated thickness of the aquifer yields an estimated transmissivity of 5,647 ft^2/d, which is slightly greater than the 5,100-ft^2/d value derived from field testing at Barbour Pointe (Gonthier and Clarke, 2016). Using higher hydraulic conductivities for LFC2 in layer 6 (K_h = 14.2 ft/d, K_v = 1.67 ft/d) resulted in a calibrated K_h of 102 ft/d in zone LF2 in layer 7 that, when multiplied by the simulated thickness of the aquifer, yields an estimated transmissivity of 5,052 ft^2/d. Using lower

hydraulic conductivities for LFC2 in layer 6 (K_h = 0.2 ft/d, K_v = 0.02 ft/d) resulted in a calibrated K_h of 123 ft/d in zone LF2 in layer 7 that, when multiplied by the simulated thickness of the aquifer, gives an estimated transmissivity of 6,093 ft^2/d.

The changes to the hydraulic conductivities of LFC2 in layer 6 required recalibration of the horizontal hydraulic conductivity of zone LF2 in layer 7 and altered the maximum drawdown in the UFA directly above the LFA pumping well 36Q398. This, in turn, changes the determination of the pumping rate in the UFA that would produce an identical maximum drawdown in the UFA as pumping from the LFA (scenario B). Scenario B is a series of steady-state simulations, each applying a given pumping rate to UFA well 36Q399, that were completed to match UFA drawdown as simulated by scenario A (table 2). Simulated pumping of UFA well 36Q399 at a rate of 240 gal/min approximated the 2.19-ft maximum drawdown in the UFA resulting from pumping LFA well 36Q398 at 750 gal/min (scenario A, table 2). Using higher hydraulic conductivities for LFC2 in layer 6 (K_h = 14.2 ft/d, K_v = 1.67 ft/d) resulted in a maximum drawdown in the UFA of 2.57 ft, which required simulated pumping of UFA well 36Q399 at a rate of 278 gal/min to produce identical drawdown. Using lower hydraulic conductivities for LFC2 in layer 6 (K_h = 0.2 ft/d, K_v = 0.02 ft/d) resulted in a maximum drawdown in the UFA of 1.82 ft, which required simulated pumping of UFA well 36Q399 at a rate of 199 gal/min to produce identical drawdown. This sensitivity analysis indicates the simulated offset pumping in the UFA ranges from 199 to 278 gal/min, which represents 26.5 to 37 percent of the 750 gal/min pumping rate in LFA well 36Q398.

Additional model validation is provided by results from a transient simulation, which can be compared to the observed drawdown of 0.71 ft at UFA well 36Q399 at the completion of the 72-hour aquifer test. The calibrated simulation of scenario A provided the best match, with a simulated drawdown after 72 hours of 0.87 ft at UFA well 36Q399. Using higher hydraulic conductivities for LFC2 in layer 6 simulated a quicker response, with a simulated drawdown after 72 hours of 1.28 ft at UFA well 36Q399. Using lower hydraulic conductivities for LFC2 in layer 6 simulated a delayed response, with a simulated drawdown after 72 hours of 0.46 ft at UFA well 36Q399.

Limitations of Analysis

Analysis of the effects of pumping the LFA on water levels in the UFA is limited by the accuracy of field data, including possible errors and uncertainty in water-level measurements, hydraulic properties, and pumping (not quantified in this report). Although water-level data were filtered to minimize or eliminate the effects of local interferences, such as tides, barometric pressure, and pumping (Gonthier and Clarke, 2016), some interferences could remain and affect recorded levels to some degree and, thus, affect computed hydraulic properties.

The revised model of Payne and others (2005) reasonably depicts changes in groundwater levels resulting from pumping the LFA at Barbour Pointe at a rate of 750 gal/min. Results are limited by the same model assumptions and design as described by Payne and others (2005). These limitations include inaccuracies in the conceptual model of groundwater flow; approximations made in representing the physical properties of the flow system and errors inherent in estimating the spatial distribution of these properties; approximations made in the formulation and application of model boundary and initial conditions; errors associated with numerical approximation and solution of the mathematical model of the flow system; and assumptions made in using the models to predict the future behavior of the flow system, such as no variations in recharge rates or boundary heads.

The variably spaced grid used in the revised model contains aspect ratios between row and column dimensions as large as 1,013:1, which can lead to numerical errors (de Marsily, 1986, p. 351). Fortunately, these large aspect ratio grid cells are only in areas distant from Barbour Pointe and have little effect on simulated results in the area (see calibration results in appendix 1).

Sensitivity analysis was completed for a model constructed to simulate flow in the FAS at the nearby city of Pooler (Cherry and Clarke, 2013). Because the Pooler model has similar model layering, boundary conditions, hydraulic properties, and hydrologic conditions as the Barbour Pointe model, results of sensitivity analysis are probably similar to what would be expected at Barbour Pointe. Simulation results at Pooler indicated that drawdown in the UFA and LFA is most sensitive to variations in K_h and K_v of the UFA and LFA in hydraulic-property zones F13 and LF2, respectively (Cherry and Clarke, 2013). Errors in computation of these values would affect simulated maximum drawdown and associated drawdown offset computations.

Simulated rates of interaquifer leakage and drawdown in the UFA can differ from actual rates because of the influence of specified-head and general-head boundaries, which allow an unlimited amount of water exchange between the model and the aquifer region that extends beyond the model grid. This unlimited supply can affect simulated drawdown and rates of interaquifer leakage. Lastly, although the revised groundwater flow model reasonably simulates steady-state conditions, additional analysis using a transient simulation would provide insight into drawdown and groundwater leakage over time.

Summary

Model simulation was used to assess the potential effects on the Upper Floridan aquifer (UFA) of pumping at a new well, completed in the Lower Floridan aquifer (LFA) and located at Barbour Pointe, in western Chatham County, Georgia. An existing regional groundwater-flow model that simulated steady-state flow in the Floridan aquifer system (FAS) was modified with a fine spatial resolution and detailed hydrogeologic information resulting from field investigations at Barbour Pointe and existing wells in the area. Model scenarios were completed whereby

- the LFA was pumped at a rate of 750 gallons per minute (gal/min), the approximate rate of a 72-hour aquifer test (scenario A); and

- the UFA was pumped at a rate of 240 gal/min (scenario B), the amount of pumping required to produce an identical drawdown response in the UFA as scenario A (drawdown offset).

The major findings are summarized as follows:

- Long-term pumping at a rate of 750 gal/min from the LFA would cause a simulated maximum drawdown of about 2.19 feet in the UFA, with drawdown exceeding 1 foot over a 115-square-mile area. This pumping resulted in no discernible change in the configuration of the simulated UFA potentiometric surface.

- Induced vertical interaquifer leakage from the UFA provided about 98 percent of the water to the LFA, with the remainder from lateral specified-head boundaries in the LFA. The effects of this interaquifer leakage on the UFA, although slight with regard to drawdown in the UFA, extend into the Coastal Plain beyond Barbour Pointe because of the relatively large (about 10:1) contrast in the water-transmitting ability, or transmissivity, of the UFA compared with that of the LFA.

- Simulated pumping changed regional water-budget components slightly and redistributed flow among model layers; namely increasing inflow to, and decreasing outflow from, lateral specified-head boundaries in the UFA and LFA, and increasing inflow (recharge) from the general-head boundary to outcrop areas in model layers 1, 2, and 5 (surficial aquifer system, Brunswick aquifer system confining unit, and UFA, respectively).

- Simulations run to address the interaquifer leakage or drawdown offset of the Georgia Environmental Protection Division (GaEPD) interim permitting strategy identified widely varying pumping offsets for the UFA, depending on whether the interaquifer leakage or the drawdown offset for UFA pumping was evaluated. When pumping the LFA for scenario A, interaquifer leakage from overlying layers accounted for about 98 percent of flow to the well. When pumping the UFA to replicate the simulated maximum drawdown resulting from pumping the LFA (scenario B, drawdown offset), leakage accounted for 32 percent of the LFA pumping rate.

- Simulated rates of interaquifer leakage and drawdown offset in the UFA can differ from actual rates because of the influence of specified- and general-head boundaries, which supply an unlimited amount of water to the groundwater system. This unlimited supply may result in differences in simulated drawdown offset and rates of interaquifer leakage. Simulation results could be improved by replacing lateral specified-head boundaries with a natural boundary, such as a groundwater divide, and by using active simulation of the surficial aquifer. Simulation results have improved regional characterization of the FAS, which may be used by State officials in evaluating requests for groundwater withdrawals from the LFA.

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Appendix 1.   Regional Groundwater Model

A regional groundwater flow model (herein referred to as "regional model") developed by Payne and others (2005) for the coastal region of Georgia and adjacent parts of South Carolina and Florida was modified and used to simulate the effects of pumping from the Lower Floridan aquifer at Barbour Pointe, in Chatham County, Georgia. The regional model is described in detail in Payne and others (2005); a brief description of the model follows.

The regional model uses MODFLOW–2000 (Harbaugh and others, 2000) to simulate flow in the surficial, Brunswick, and Floridan aquifer systems. To account for natural hydrologic boundaries, the model encompasses a 42,155-square-mile (mi^2) area that includes the Coastal Plain of Georgia, northeastern Florida, southwestern South Carolina, and the adjacent offshore area (see fig. 1–1). All data input files and corresponding output are provided in Cherry (2017).

The regional model consists of the following seven model layers and corresponding hydrogeologic units (fig. 1–2) in descending order:

- Layer 1: Confined upper and lower water-bearing zones of the surficial aquifer system.

- Layer 2: Brunswick aquifer system confining unit.

- Layer 3: Upper and lower Brunswick aquifers, composing the Brunswick aquifer system.

- Layer 4: Upper Floridan aquifer confining unit.

- Layer 5: Upper Floridan aquifer (UFA).

- Layer 6: Lower Floridan semiconfining unit (LFCU).

- Layer 7: Lower Floridan aquifer (LFA).

These units crop out to the northwest of the study area and generally dip and thicken to the southeast. The thickness, extent, and other hydraulic properties of these units, as well as the model development process, are described in detail in Payne and others (2005).

The regional model was discretized in the areal dimensions using a variably spaced grid and cell sizes ranging from approximately 4,000×5,000 feet (ft; 0.7 mi^2) to 16,500×16,500 ft (9.8 mi^2). At Barbour Pointe, the mesh resolution was 14,900×16,100 ft, requiring refinement for the current model application. Each hydrogeologic unit was represented by one layer of grid cells in the vertical dimension.

Lateral boundaries for all layers of the regional model were designated as no-flow, with the exception of the southern and southwestern sides of layers 5, 6, and 7 (UFA, LFCU, and LFA, respectively), which were set as specified-head cells. Values assigned to specified-head cells were based on estimates of UFA head derived from the potentiometric-surface map for 1998 developed by Peck and others (1999).

The lowermost boundary of the regional model was designated as no-flow, corresponding to the lower confining unit of the Floridan aquifer system; the uppermost boundary was set as a head-dependent flow (or general-head) boundary representing the confined zone of the surficial aquifer system (fig. 1–2). The general-head boundary required a controlling specified-head and a conductance term to regulate groundwater flow between the top two layers of the model. The controlling head represented the water table in the onshore area and the freshwater equivalent of the saltwater head in the offshore area. In the onshore area, the conductance was set to limit the amount of recharge entering the system in any given grid cell for the 1980 and 2000 simulation periods to less-than-maximum recharge derived from base-flow estimates (Priest, 2004). The conductance established in the offshore area was set arbitrarily large, posing minimal resistance to flow in or out of the system, as little is known about hydraulic properties in this area.

Estimates of average annual pumpage were assigned in the regional model on the basis of county-aggregate and site-specific data. These data were used to develop pumpage distributions for the assumed steady-state conditions of 1980 and 2000 used for calibration. Pumpage was assigned to model layers 3 (Brunswick aquifer system), 5 (UFA), and 7 (LFA) on the basis of the open interval of wells. Pumping rates within a model cell were obtained by summing site-specific and nonsite-specific pumping rates corresponding to that model cell. Pumpage simulated by the model totaled 692 million gallons per day (Mgal/d) for 1980 and 798 Mgal/d for 2000. Because pumpage during 2010 (799 Mgal/d) was about the same as during 2000, the revised model used to evaluate groundwater flow near Barbour Pointe was within the same range of calibrated pumping conditions as the regional model.

Figure 1–1A.   Location of selected wells, regional groundwater model and boundary conditions, and revised model grid, city of Berwick, Fort Stewart, Barbour Pointe, Georgia, and vicinity.
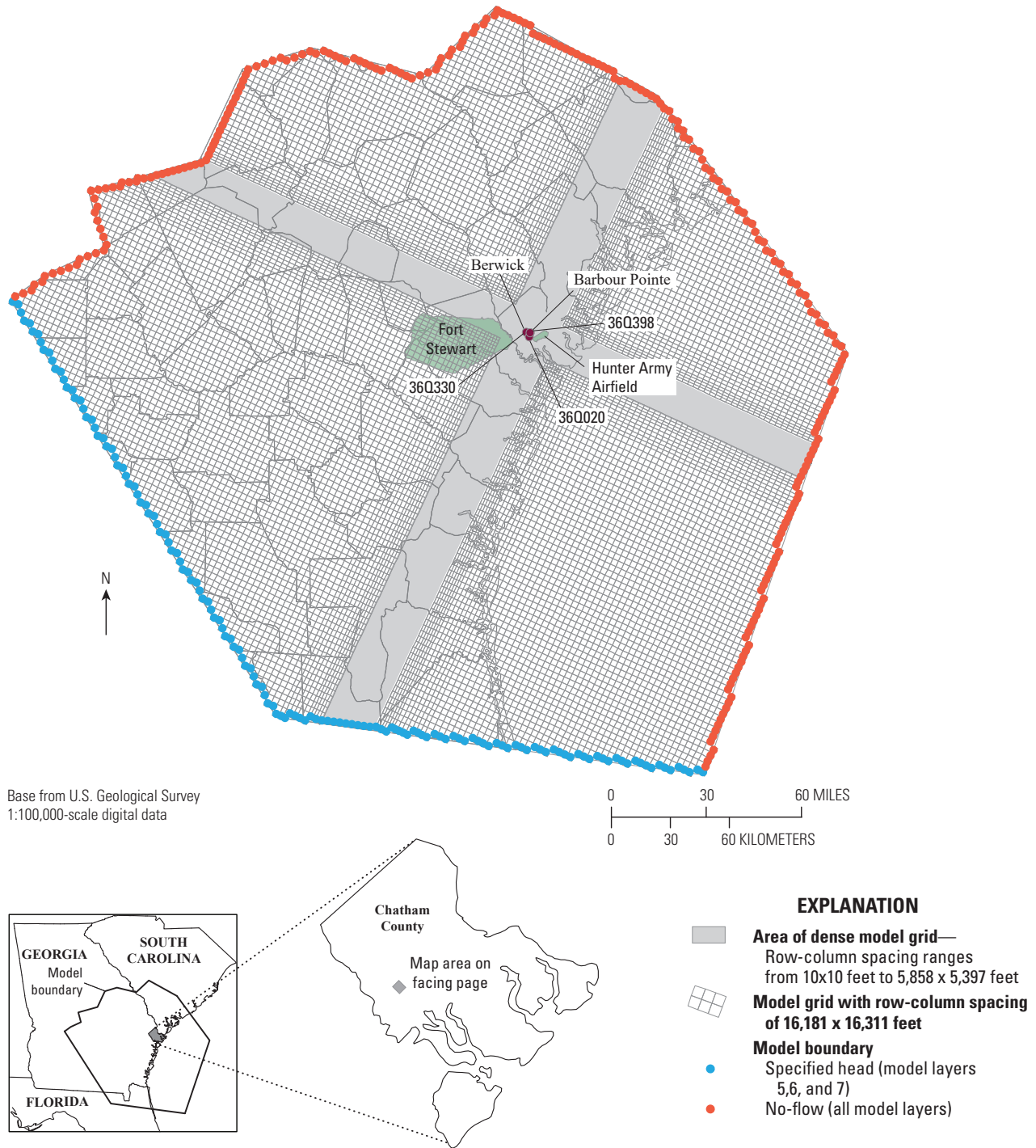
Figure 1–1B. Location of selected wells, regional groundwater model and boundary conditions, and revised model grid, city of Berwick, Fort Stewart, Barbour Pointe, Georgia, and vicinity.
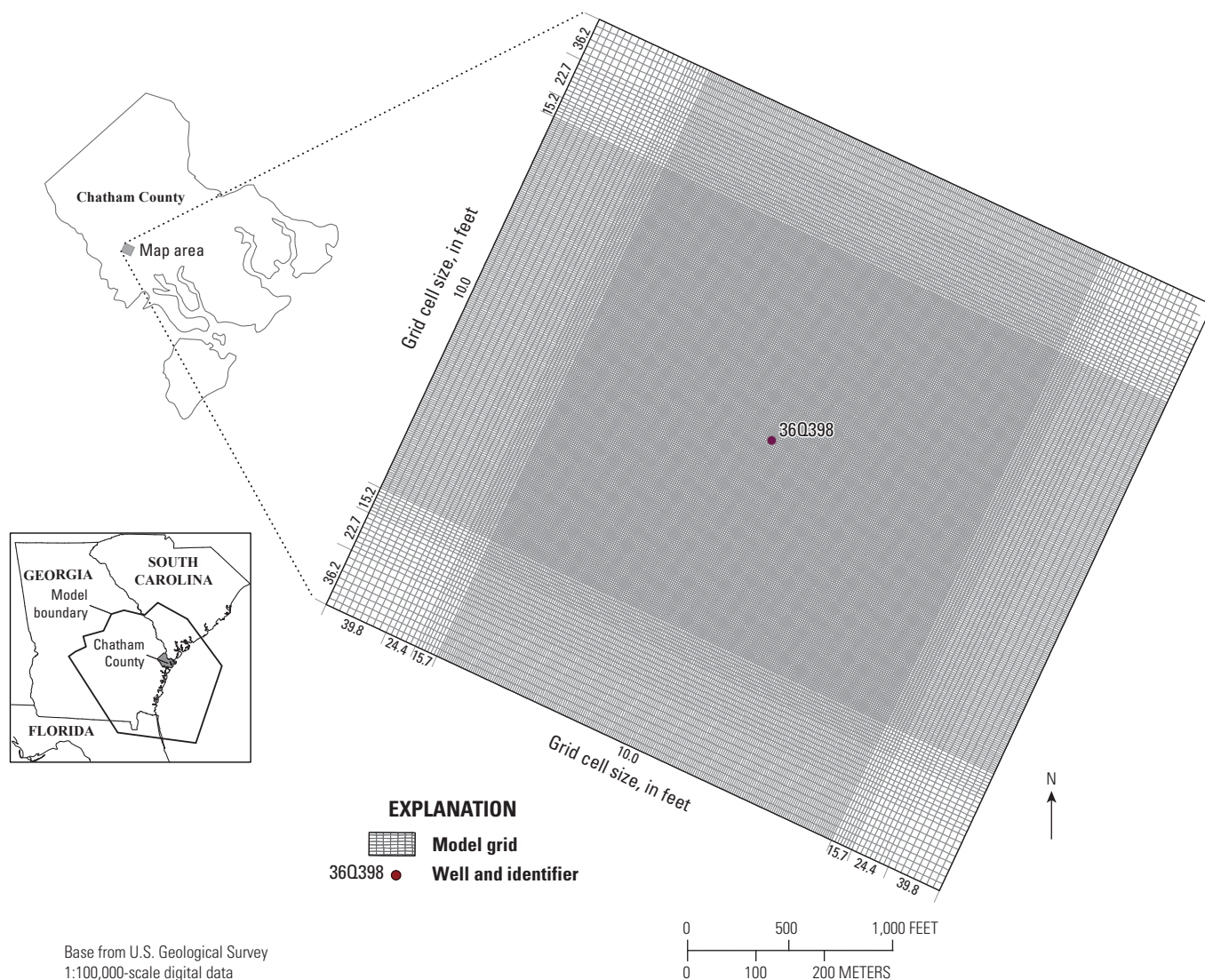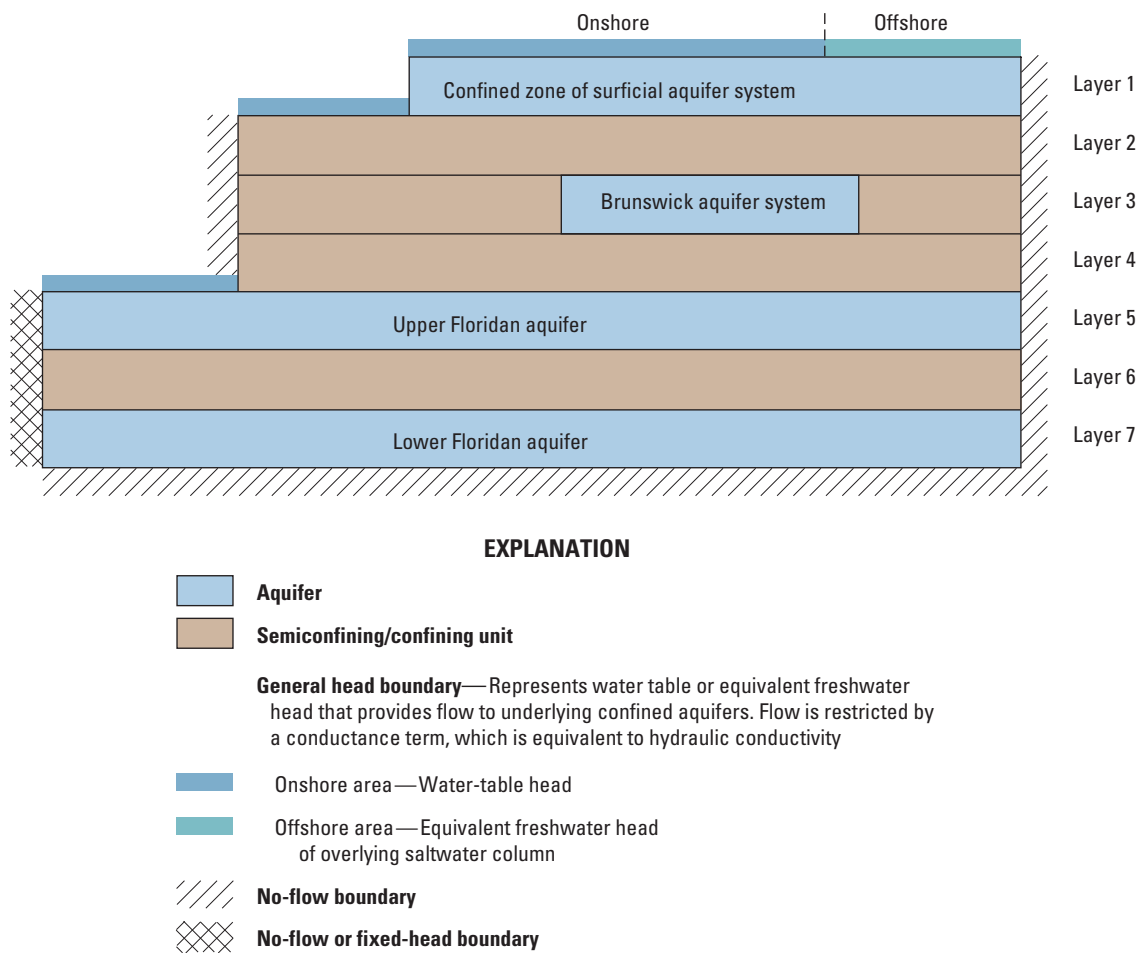
Figure 1–2.   Schematic diagram showing model layers and boundary conditions (from Payne and others, 2005).

Revisions to Regional Model

The regional model of Payne and others (2005) was modified using hydrogeologic information obtained from field investigations at Barbour Pointe (Gonthier and Clarke, 2016), and from existing wells in the vicinity of Berwick Plantation near Berwick (Jordan, Jones, and Goulding, Inc., 2002), Pooler (Gonthier, 2012), Hunter Army Airfield (Williams, 2010), Rincon (Carter and Sloope, 2004), and Fort Stewart (Gonthier, 2011). These modifications involved addition of new hydraulic-property zones for vertical and horizontal hydraulic conductivity in the UFA and LFA and intervening semiconfining unit (LFCU). Modifications to the regional model that were made during previous investigations at Pooler (Cherry and Clarke, 2013) and Hunter Army Airfield in Chatham County (Clarke and others, 2010), Rincon in Effingham County (Cherry and Clarke, 2015), and Fort Stewart in Liberty County (Clarke and others, 2011) also were applied to the model developed for the current study. The revised model retained the original model layering and boundary conditions.

Refinement of Grid Resolution

Grid-cell dimensions were modified to variably spaced dimensions (fig. 1–1) that increase from the smallest cell size of 10×10 ft near well 36Q398 to a maximum size of about 16,181 ft in the row direction and 16,311 ft in the column direction. The orientation of the grid was rotated slightly in a clockwise manner to accommodate the finer mesh in the Barbour Pointe area. The revised model consists of 440 rows and 424 columns. The variably spaced grid used in the revised model contains aspect ratios between row and column dimensions as large as 1,013:1, which can lead to numerical errors (de Marsily, 1986, p. 351). Fortunately, these large aspect ratio grid cells are only in areas distant from Barbour Pointe and have little effect on simulation results in the area.

Refinement of Hydraulic Conductivity Distribution

Packer-slug tests and core analyses performed at Barbour Pointe during the course of this study and in previous studies at Hunter Army Airfield, Fort Stewart, and Pooler provided the basis for revising hydraulic-conductivity values assigned to these areas in the regional model (Payne and others, 2005). In the area outside of Barbour Pointe, values of vertical and horizontal hydraulic conductivity (K_v and K_h, respectively) correspond to values used (1) in the regional model (Payne and others, 2005); (2) in the area of Hunter Army Airfield, as simulated by Clarke and others (2010); (3) in the area of Fort Stewart, as simulated by Clarke and others (2011); and (4) in the area of Pooler, as simulated by Cherry and Clarke (2013) (fig. 1–3, table 1–1). Field testing

at Barbour Pointe (Gonthier and Clarke, 2016) provided new information about the hydraulic properties of the UFA (layer 5) and LFA (layer 7) and enabled refinement of values that were used in the regional model. In addition, results of a 72-hour aquifer test conducted in the LFA provided information about drawdown in the LFA and in the overlying UFA, which guided revisions to K_v and K_h values from previous calibrated values near Barbour Pointe. Hydraulic conductivity of the LFCU was not measured at Barbour Pointe, so results from core analysis and packer-slug tests at Hunter Army Airfield and Pooler were applied to the model (Williams, 2010; Gonthier, 2012).

New hydraulic-property zones were developed for this study on the basis of field data collected at Berwick Plantation near Berwick (Faye and Gill, 2005), Barbour Pointe (Gonthier and Clarke, 2016), Hunter Army Airfield (Williams, 2010), Fort Stewart (Gonthier, 2011), and Pooler (Gonthier, 2012). Hydraulic-property zones were added as follows (fig. 1–3, table 1–1):

- UFA (layer 5): Zone F13 added at Hunter Army Airfield and expanded northwestward to include Pooler and Barbour Pointe; zone F14 added at Fort Stewart.

- LFCU (layer 6): Zone LFC2 added at Hunter Army Airfield and expanded northwestward to include Pooler and Barbour Pointe; zone LFC3 added at Fort Stewart.

- LFA (layer 7): Zone LF2 added at Hunter Army Airfield and expanded northwestward to include Pooler and Barbour Pointe; zone LF3 added at Fort Stewart.

Each hydraulic-property zone was initially assigned a K_h and K_v value on the basis of results of field testing at each site. With the exception of K_v for the LFCU, values were adjusted slightly to calibrate water-level changes in the UFA and LFA observed during 72-hour aquifer tests at the two sites. Values for K_v of the LFCU were assigned the median value measured during previous studies, 0.2 foot per day (ft/d), measured at Hunter Army Airfield (Williams, 2010). This value was held constant to ensure computed leakage simulations were conservative, that is, similar to Hunter Army Airfield and Pooler, because K_v was not measured at the Barbour Pointe site.

For the UFA (layer 5), zone F13 for the Hunter Army Airfield study (Clarke and others, 2010) was expanded from a 114-mi^2 area in the Hunter Army Airfield model, to 221 mi^2 in the Pooler and Barbour Pointe models. Here, the UFA was assigned K_h and K_v values of 90 ft/d each (table 1–1), which is slightly higher than the 70-ft/d value assigned in the original regional model. Multiplying 90 ft/d by the thickness of the aquifer gives an estimated transmissivity of 50,755 feet squared per day (ft^2/d) at Barbour Pointe, which is about 85 percent of the 60,000-ft^2/d value reported by aquifer testing (Gonthier and Clarke, 2016).
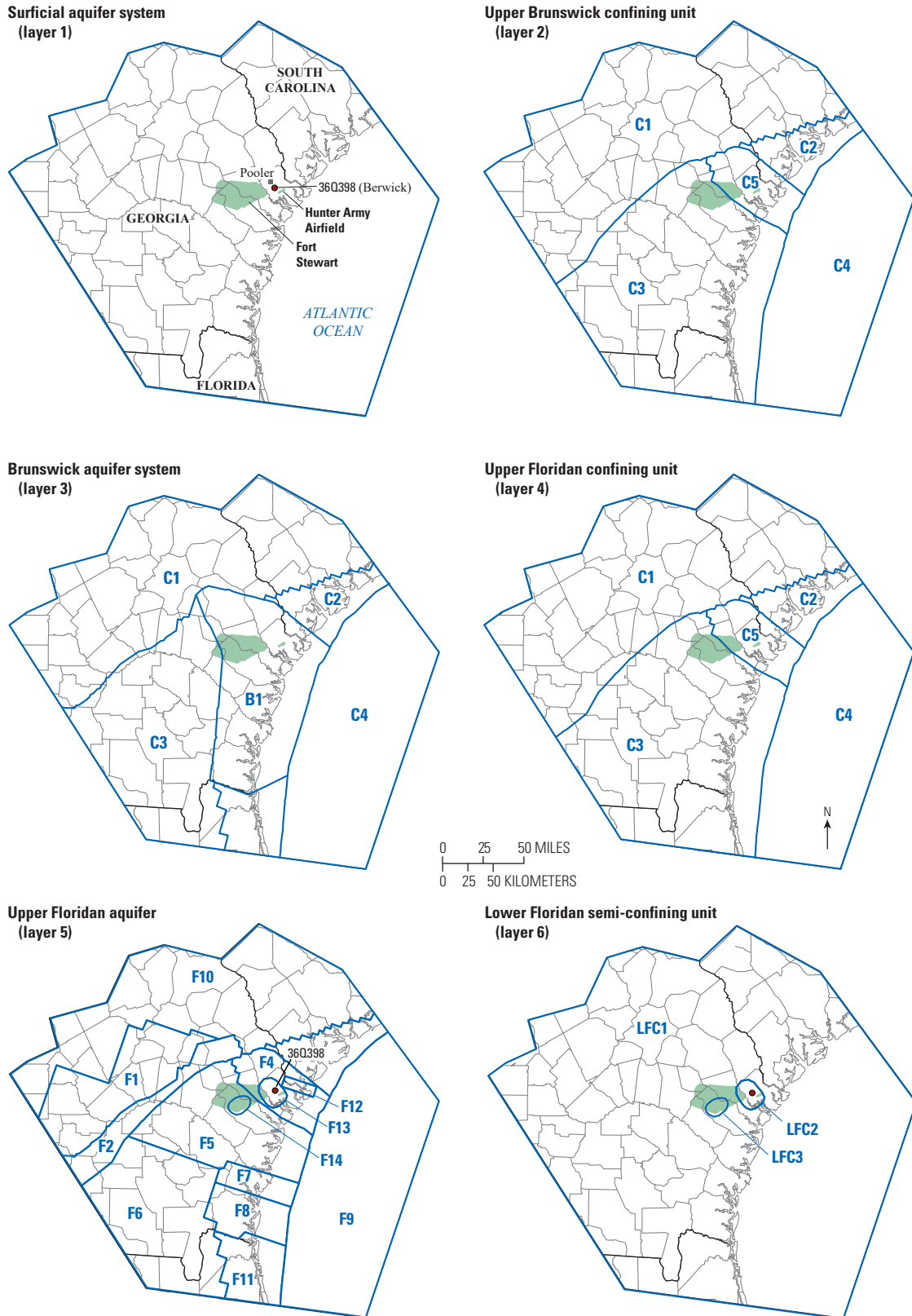
Figure 1–3 (pages 28 and 29).   Simulated hydraulic-property zones by model layer. Table 1–1 lists hydraulic conductivity values assigned to zones.

Table 1–1.   Horizontal and vertical hydraulic conductivity values assigned to hydraulic-property zones for the original (Payne and others, 2005) and revised groundwater-flow models.

[—, not applicable]

Unit	Layer	Payne and others (2005)			Revised model		
		Hydraulic property zone	Hydraulic conductivity, in feet per day		Hydraulic property zone	Hydraulic conductivity, in feet per day	
			Horizontal	Vertical		Horizontal	Vertical
Surficial aquifer	1	—	70	70	1	70	70
Confining unitr	2	C1	0.00002	0.00002	C1	0.00002	0.00002
		C2	0.20000	0.20000	C2	0.20000	0.20000
		C3	0.00001	0.00001	C3	0.00001	0.00001
		C4	0.00010	0.00010	C4	0.00010	0.00010
		C5	0.00010	0.00010	C5	0.00010	0.00010
Brunswick aquifer system	3	B1	50	50	B1	50	50
		C1	0.00002	0.00002	C1	0.00002	0.00002
		C2	0.20000	0.20000	C2	0.20000	0.20000
		C3	0.00001	0.00001	C3	0.00001	0.00001
		C4	0.00010	0.00010	C4	0.00010	0.00010
Confining unit	4	C1	0.00002	0.00002	C1	0.00002	0.00002
		C2	0.20000	0.20000	C2	0.20000	0.20000
		C3	0.00001	0.00001	C3	0.00001	0.00001
		C4	0.00010	0.00010	C4	0.00010	0.00010
		C5	0.00010	0.00010	C5	0.00010	0.00010
Upper Floridan aquifer	5	F1	34	34	F1	34	34
		F2	2	2	F2	2	2
		F3	100	100	F3	100	100
		F4	70	70	F4	70	70
		F5	394	394	F5	394	394
		F6	2,819	2,819	F6	2,819	2,819
		F7	150	150	F7	150	150
		F8	2,727	2,727	F8	2,727	2,727
		F9	100	100	F9	100	100
		F10	56	56	F10	56	56
		F11	94	94	F11	94	94
		F12	25	25	F12	25	25
		—	—	—	F13	90	90
		—	—	—	F14	398	398
Semiconfining unit	6	—	0.020000	0.020000	LFC1	0.02000	0.02000
		—	—	—	LFC2	2.0	0.2
		—	—	—	LFC3	10.00000	0.2
Lower Floridan aquifer	7	—	10.00000	1	LF1	10	10
		—	—	—	LF2	114	13.4
		—	—	—	LF3	15.80000	1.6

Lower Floridan aquifer (layer 7)

LF1

LF2

LF3

GEORGIA   SOUTH CAROLINA

Model area

FLORIDA
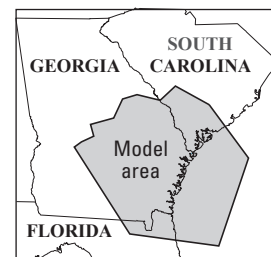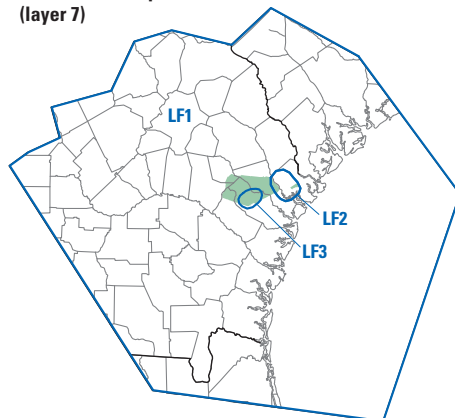
EXPLANATION

C1   Hydraulic-property zone

36Q398 ●   Well and identifier

For the revised model in the Fort Stewart area, zone F14 was subdivided from regional model zone F5 and assigned slightly higher K_h and K_v values of 398 ft/d each, which is based on results of aquifer testing (table 1–1). The new zone value of 398 ft/d represents a 1-percent increase from the 394-ft/d value assigned to zone F5 in the regional model (Payne and others, 2005). Multiplying 398 ft/d by the thickness of the aquifer gives an estimated transmissivity of 100,000 ft²/d, which matches the results of field testing (Gonthier, 2011).

In the regional model (Payne and others, 2005), the Lower Floridan semiconfining unit (LFCU; layer 6) was assigned a single K_h and K_v value of 0.02 ft/d (table 1–1). Field data were used as a basis to delineate one additional zone in the vicinity of Hunter Army Airfield (LFC2) and one additional zone at Fort Stewart (LFC3). At Fort Stewart, zone LFC3 in layer 6 covers an area identical to that of zone F14 in layer 5, with a calibrated K_h value of 10 and a K_v value of 0.2; these values are within the range of field testing (Gonthier, 2011). Zone LFC2 was expanded northwestward from an area of 114 mi² in the Hunter Army Airfield model, to 221 mi² in the Pooler and Barbour Pointe models. Within zone LFC2 in the revised model, the LFCU was assigned a K_v value of 0.2 ft/d, which approximates the median reported value of previous investigations completed in the area, based on results at Hunter Army Airfield (Clarke and others, 2010). A K_h value of 2 ft/d was assigned to the LFCU in zone LFC2 based on a reported K_h / K_v ratio of 8.5:1 at the Hunter Army Airfield site.

Hydraulic properties for model layer 7, which represents the LFA, were designated as a single zone in the regional model of Payne and others (2005), having uniform K_h and K_v values of 10 ft/d each (table 1–1). Additional zones for the LFA were designated on the basis of field studies at Pooler, Hunter Army Airfield, Fort Stewart, and Barbour Pointe. At Fort Stewart, zone LF3 covers an area identical to zones F14 and LFC3, containing a calibrated K_h value of 15.8 ft/d and a K_v value of 1.6 ft/d. Multiplying the K_h value by the simulated thickness of the aquifer gives an estimated transmissivity of 5,200 ft²/d at Fort Stewart, which is similar to results of field testing (Gonthier, 2011).

Zone LF2 in layer 7 was expanded northwestward from an area of 114 mi² in the Hunter Army Airfield model, to 221 mi² in the Pooler and Barbour Pointe models. Zone LF2 in layer 7 covers an area identical to zones F13 in layer 5 and LFC2 in layer 6 with a calibrated K_h value of 114 ft/d, compared to 88 ft/d in the calibrated Pooler model (Cherry and Clarke, 2013). Multiplying the K_h value by the simulated thickness of the aquifer gives an estimated transmissivity of 5,647 ft²/d, which is slightly greater than the 5,100-ft²/d value derived from field testing at Barbour Pointe (Gonthier and Clarke, 2016). A K_h value of 13.4 ft/d was assigned to the LFA in zone LF2 based on a reported K_h / K_v ratio of 8.5:1 at the Hunter Army Airfield site (table 1–1).

Simulation of Observed Drawdown in Pumped Well

Drawdown calculated by the revised model represents the average drawdown for a node located at the areal center of the grid cell containing the pumped well. This average drawdown under-represents the observed drawdown in the actual pumped well 36Q398. Because the area of the grid cell containing the pumped well (10 square feet [ft²]) is much larger than the area defined by the 8-inch (in.) well diameter (0.35 ft²), drawdown at the pumped well can be adjusted on the basis of the proportional increase in area attributed to the grid cell in comparison with the area of the pumped well using the following equation (Peaceman, 1983):

$$S_p = S_b + [Q * \ln(r_e/r_w) / 2\pi(T_{xx}T_{yy})^{0.5}], \quad (1)$$

where

S_p is adjusted drawdown in the pumped well, in feet;

S_b is simulated drawdown in the pumped well, in feet;

Q is pump discharge, in cubic feet per day (144,375);

r_e is equivalent well block radius, in feet (5);

r_w is well radius, in feet (0.5);

T_{xx} is transmissivity in the x direction, in feet squared per day (5,647); and

T_{yy} is transmissivity in the y direction, in feet squared per day (5,647).

Results of this equation indicated that simulated values of drawdown at the center of the grid cell containing pumped well 36Q398 would under-represent the observed drawdown by 9.37 ft for a pumping rate of 750 gallons per minute (gal/min). A similar analysis of an UFA well pumped at a rate of 240 gal/min, having a well radius of 3 in. and a value of 50,755 ft²/d for transmissivity indicates that the simulated drawdown in the grid cell containing the pumped well under-represents the observed drawdown at the pumped well by about 0.33 ft. Simulated drawdown for the UFA and LFA were adjusted using these correction factors and compared with field observations for model calibration.

Comparison of Revised to Original Regional Model

Because the regional model of Payne and others (2005) was modified by changing grid cell sizes and assigning different hydraulic properties in and near Barbour Pointe, a comparison of results from the two models ensures that the revised model is an accurate representation of groundwater flow. Simulation results indicate that water-level residuals and the water budget for the revised regional model are similar to the original model of Payne and others (2005), and thus, both

models provide similar simulation of the hydrologic system (tables 1–2, 1–3). These results were expected because model revisions were limited to 114- and 221-mi² areas representing less than 1 percent of the model area.

Mean water-level residual for layer 3 (Brunswick aquifer system) shifted from a positive bias in the original model (1.79 ft) to a negative bias in the revised model (–2.97 ft), as shown on the residuals map and graphs (table 1–2, figs. 1–4, 1–5). For layer 5 (UFA), the mean residual remained negative in the revised model, changing from –0.84 to –3.59 ft. The mean residual for layer 7 (LFA) remained positive in the revised model but was closer to zero than the value from the original model, changing from 5.2 to 2.35 ft.

The root-mean-square error (RMSE) of water-level residuals for layer 3 (11.2 ft) in the revised model is nearly double that of the original regional model (5.91 ft) but is considered acceptable for the purpose of the modified model, which is to simulate flow in the UFA and LFA. Most of the increase in the RMSE for layer 3 can be attributed to two wells in the Brunswick aquifer system that had water-level residuals of about –19 ft each (figs. 1–4, 1–5). These wells are adjacent to one another in the same model cell, in an area where the grid size of the revised model is more than four times larger than in the original regional model. This larger grid size reduced the capability of the model to simulate steep gradients in the vicinity of the Savannah-area cone of depression and resulted in a large residual. Because the relatively large grid size and related increase in RMSE for layer 3 occurred away from the area of high grid resolution in the vicinity of Barbour Pointe, simulated heads in the Barbour Pointe area were only slightly affected.

The RMSE of residuals for layer 5 was similar for the original (9.94 ft) and revised (9.90 ft) models. For layer 7, the RMSE of residuals decreased from 9.15 ft in the regional model to 8.75 ft in the revised model.

Simulated water budgets for the regional and revised models were similar, with most variation occurring in layers 1 and 5 (table 1–3). The revised model showed

- decreased recharge from the general-head boundary in layers 1 and 2;

- decreased discharge to the general-head boundary in layers 1, 2, and 5; and

- increased inflow and outflow along lateral specified-head boundaries in layer 5.

Table 1–2. Water-level calibration statistics for the original (Payne and others, 2005) and revised regional models, base case (year 2000) simulation.

[Residual equals simulated minus observed head]

Hydro-geologic unit	Model layer	Number of observations	Minimum residual, in feet		Maximum residual, in feet		Mean of residuals, in feet		Root mean square of residuals, in feet	
			Original model	Revised model	Original model	Revised model	Original model	Revised model	Original model	Revised model
Brunswick aquifer system	3	10	−7.67	−19.0	13.3	14.3	1.79	−2.97	5.91	11.2
Upper Floridan aquifer	5	155	−44.4	−30.2	36.4	27.1	−0.84	−3.59	9.94	9.90
Lower Floridan aquifer	7	11	−3.62	−5.10	21.5	25.0	5.20	2.35	9.15	8.75

Table 1–3.   Comparison of simulated water budget by model layer between the original (Payne and others, 2005) and revised regional models, base case (year 2000) simulation.

[Values may not sum to totals because of independent rounding. <, less than]

Hydro-geologic unit	Model layer	Simulated flow, in million gallons per day									
		Pumpage		Recharge from general-head boundary		Discharge to general-head boundary		Inflow along lateral boundary		Outflow along lateral boundary	
		Original model	Revised model	Original model	Revised model	Original model	Revised model	Original model	Revised model	Original model	Revised model
Surficial aquifer system	1	<0.001	<0.001	310	277	132	100	<0.001	<0.001	<0.001	<0.001
Confining unit	2	<0.001	<0.001	46.6	32.7	3.62	2.00	<0.001	<0.001	<0.001	<0.001
Brunswick aquifer system	3	0.241	0.241	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Confining unit	4	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Upper Floridan aquifer	5	669	669	141	149	22.3	20.3	712	821	268	364
Semi-confining unit	6	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.004	0.004	<0.001	<0.001
Lower Floridan aquifer	7	129	129	<0.001	<0.001	<0.001	<0.001	15.5	15.1	2.32	2.36
Total, all layers		**798**	**798**	**498**	**459**	**158**	**122**	**728**	**836**	**270**	**366**

A. Brunswick aquifer system (layer 3)

Approximate limit of Brunswick aquifer system

C. Lower Floridan aquifer (layer 7)

Berwick

Fort Stewart

Hunter Army Airfield

0   25   50 MILES

0   25   50 KILOMETERS

N

GEORGIA   SOUTH CAROLINA

Model boundary

FLORIDA

B. Upper Floridan aquifer (layer 5)

SOUTH CAROLINA

GEORGIA

ATLANTIC OCEAN

0   25   50 MILES

0   25   50 KILOMETERS

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

FLORIDA

EXPLANATION

Water-level residual, in feet— Represents difference of simulated minus observed water level
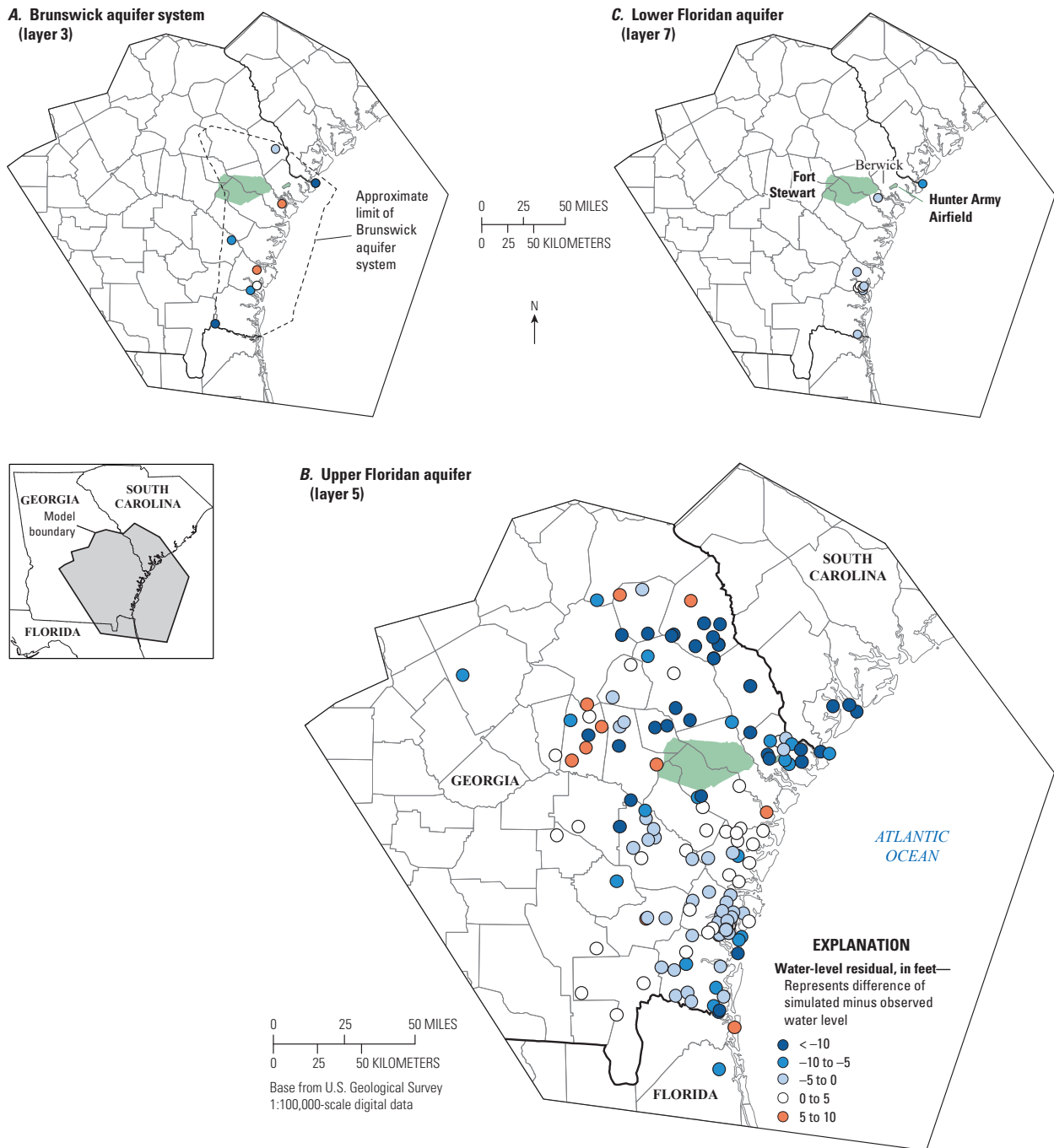
● < −10
● −10 to −5
● −5 to 0
○ 0 to 5
● 5 to 10

Figure 1–4.   Difference between simulated and observed water levels (residuals) by model layer for 2000, revised regional flow model. *A*, Brunswick aquifer system (layer 3), *B*, Upper Floridan aquifer (layer 5), and *C*, Lower Floridan aquifer (layer 7). Residuals by model layer for 2000.
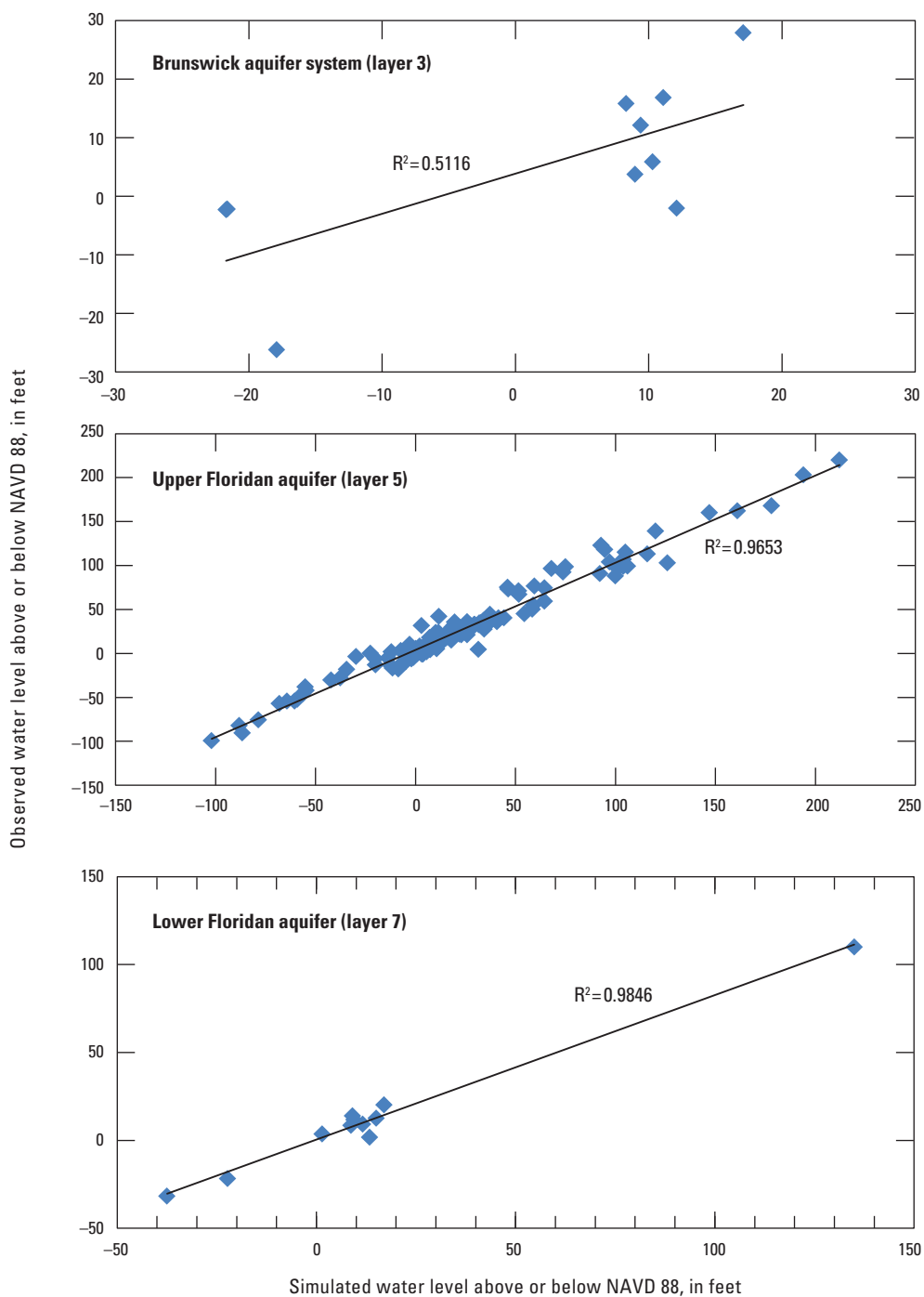
Figure 1–5.   Observed and simulated water levels in model layers 3, 5, and 7, revised groundwater model.

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