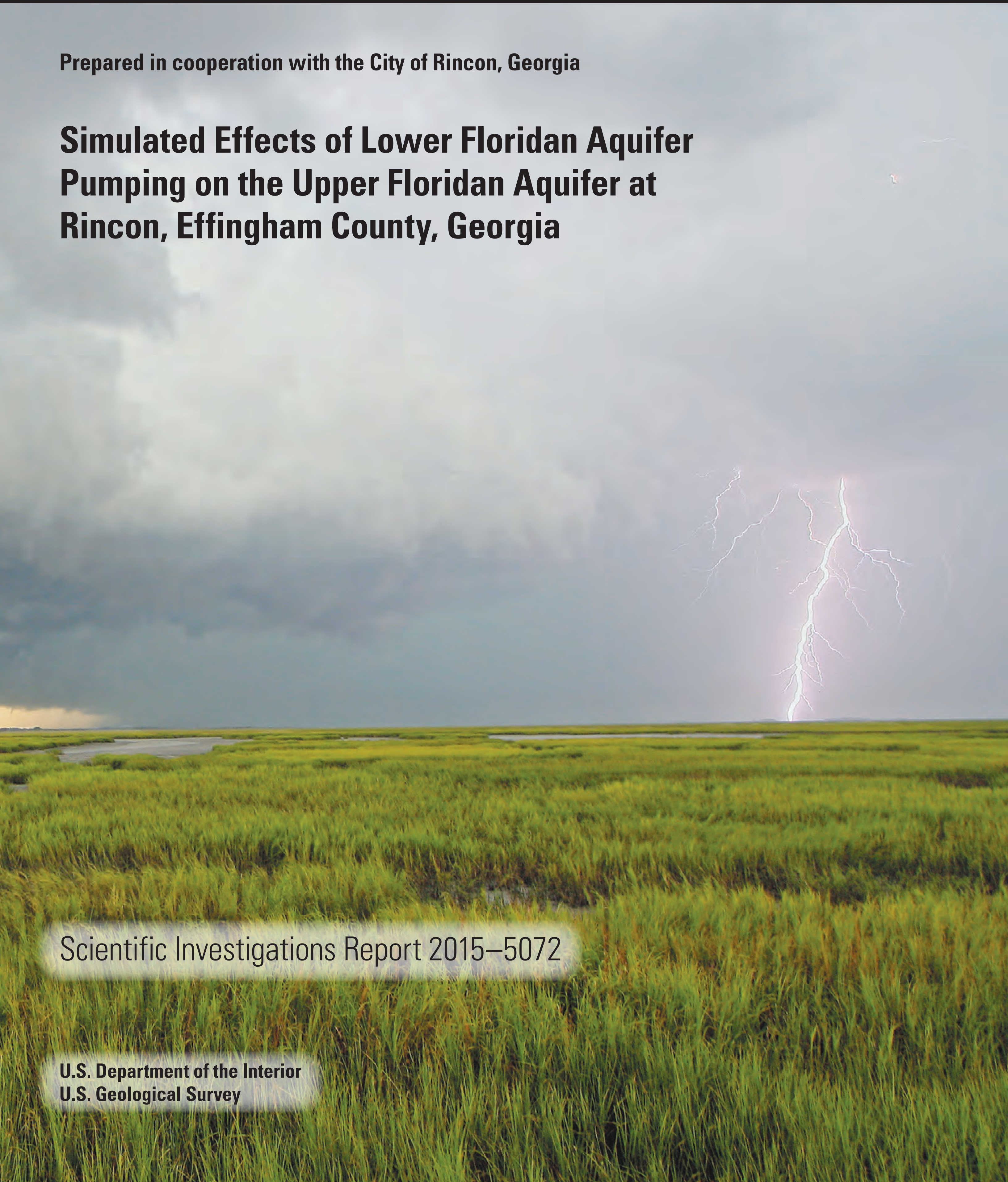
Prepared in cooperation with the City of Rincon, Georgia

Simulated Effects of Lower Floridan Aquifer Pumping on the Upper Floridan Aquifer at Rincon, Effingham County, Georgia



Scientific Investigations Report 2015–5072

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

Cover. Thunderstorm, over the Brunswick River Marsh, from Jekyll Island Causeway, Glynn County, Georgia (photograph by Alan M. Cressler, USGS).

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By Gregory S. Cherry and John S. Clarke

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SALLY JEWELL, Secretary

U.S. Geological Survey
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Suggested citation:
Cherry, G.S., and Clarke, J.S., 2015, Simulated effects of Lower Floridan aquifer pumping on the Upper Floridan aquifer at Rincon, Effingham County, Georgia: U.S. Geological Survey Scientific Investigations Report 2015–5072, 35 p., http://dx.doi.org/10.3133/sir20155072.

ISSN 2328–0328 (online)

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Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
Length		
inch	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
Area		
square foot (ft^2)	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		
million gallons (Mgal)	3,785	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)
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:

$$°C = (°F - 32) / 1.8$$

Datums

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.

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 confining unit
RMS	root mean square
UFA	Upper Floridan aquifer
USGS	U.S. Geological Survey

Acknowledgments

The authors thank Tim Baumgartner of EMC Engineering Services and Wesley Corbitt of the City of Rincon for helpful support throughout the study. Dr. Jim Kennedy, State Geologist, Georgia Environmental Protection Division (GaEPD), provided valuable feedback and comments during the review process.

Lynn J. Torak, Gerard J. Gonthier, and Bruce G. Campbell, U.S. Geological Survey (USGS), provided valuable technical reviews and suggestions to improve this report.

Simulated Effects of Lower Floridan Aquifer Pumping on the Upper Floridan Aquifer at Rincon, Effingham County, Georgia

By Gregory S. Cherry and John S. Clarke

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 (36S048) near the City of Rincon in coastal Georgia near Savannah. Simulated pumping of well 36S048 at a rate of 1,000 gallons per minute (gal/min; or 1.44 million gallons per day [Mgal/d]) indicated a maximum drawdown of about 6.8 feet (ft) in the UFA directly above the pumped well and at least 1 ft of drawdown within a nearly 400-square-mile area (scenario A). Induced vertical leakage from the UFA provided about 99 percent of the water to the pumped well. Simulated pumping of well 36S048 indicated 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 72 percent of the simulated pumpage from well 36S048, with the remaining 28 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 292 gal/min (0.42 Mgal/d), which would produce the equivalent maximum drawdown in the UFA as pumping from well 36S048 in the LFA at a rate of 1,000 gal/min (called the drawdown offset; scenario B). Simulated pumping in the UFA for the drawdown offset produced about 6.7 ft of drawdown, comparable to 6.8 ft of drawdown in the UFA simulated in scenario A. Water budgets for scenario B also provided favorable comparisons with scenario A, indicating that 69 percent of the drawdown-offset pumpage (0.42 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.

A steady-state simulation representing implementation of drawdown-offset-pumping reductions totaling 292 gal/min at Rincon UFA production wells 36S034 and 36S035 and pumping from the new LFA well 36S048 at 1,000 gal/min (scenario C) resulted in decreased magnitude and areal extent of drawdown in the UFA compared with scenario A. In the latter scenario, the LFA well was pumped without UFA drawdown-offset-pumping reductions. Water budgets for scenario C yielded percentage contributions from flow components that were consistent with those from scenario B. Specifically, 69 percent of the increased pumping in scenario C originated from general-head boundaries from overlying units of the surficial and Brunswick aquifer systems and the balance of flow was derived from general- and specified-head boundaries in the UFA. In all scenarios, the placement of model boundaries and type of boundary exerted the greatest control on overall groundwater flow and inter-aquifer leakage in the system.

Introduction

Increased pumping demands on limited freshwater resources available to the City of Rincon, Effingham County, Georgia (Ga.; fig. 1), primarily from the Upper Floridan aquifer (UFA), pose a threat of possible saltwater intrusion and lowering of groundwater levels (drawdown) in the area. To alleviate the potential for saltwater intrusion in coastal Georgia, the Georgia Environmental Protection Division (GaEPD) has restricted further development of the UFA in adjacent Chatham County and part of Effingham County and encouraged development of alternative water sources (Georgia Department of Natural Resources, 2006). On May 20, 2013, the GaEPD issued a policy statement with the determination that the Floridan aquifer system (FAS) "is really one aquifer with hydraulically connected upper and lower permeable zones" (Dr. Jim Kennedy, State Geologist, Georgia Environmental Protection Division, written commun., June 12, 2013).

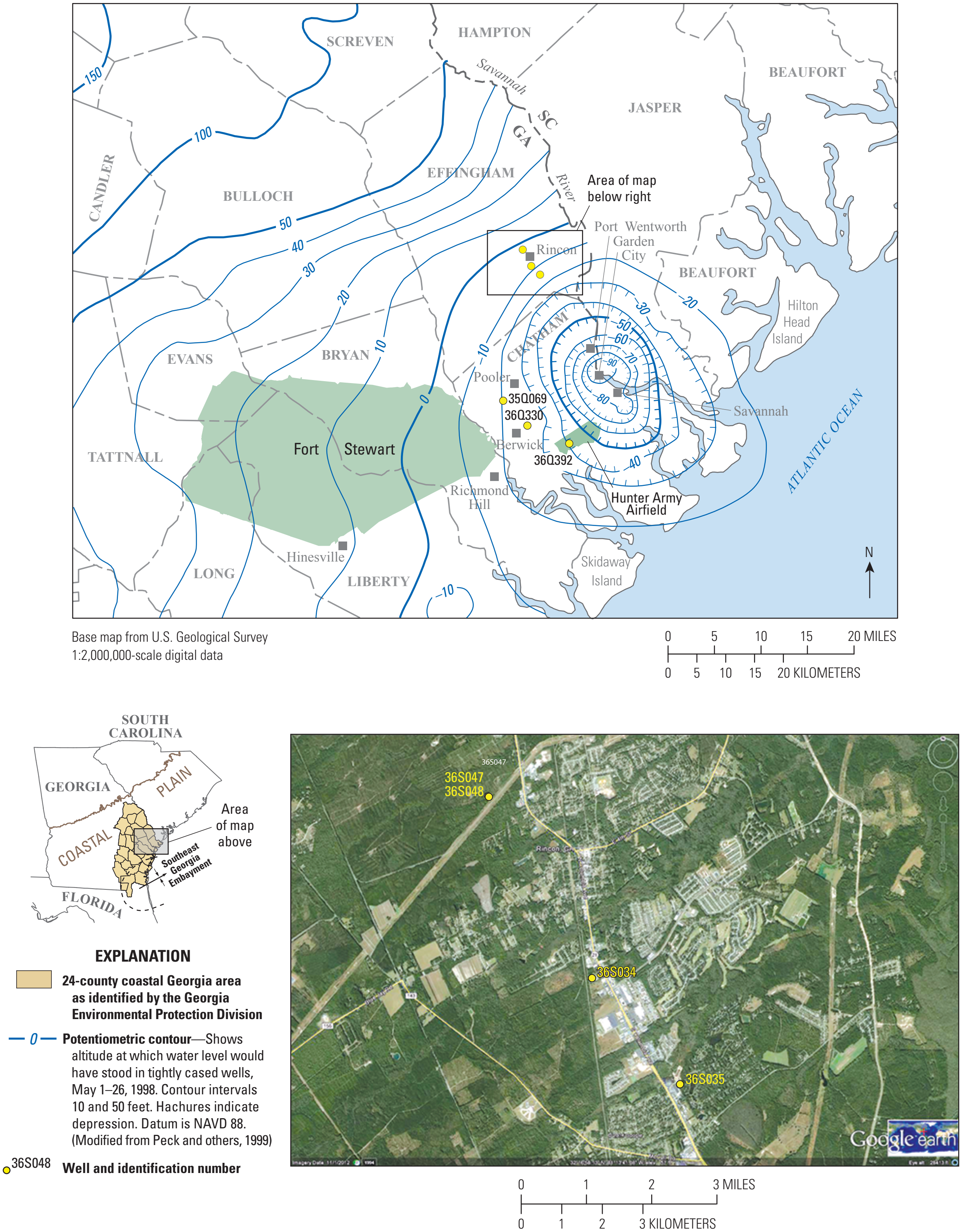


Figure 1. Location of Rincon test site (well 36S048), observation well (36S047), and production wells (34S034 and 34S035) south of Rincon, Georgia.

To assess the water-supply development potential of the Lower Floridan aquifer (LFA) at Rincon, Ga., the U.S. Geological Survey (USGS), in cooperation with the City of Rincon, performed steady-state model simulations during 2014 to determine the potential for long-term interaquifer leakage from the UFA into the LFA caused by pumping well 36S048 in the LFA.

Purpose and Scope

This report documents results of steady-state groundwater-model simulations at Rincon, Ga., completed during 2014 to assess the effect of LFA pumping on the UFA. The specific objectives were to

- evaluate downward leakage response in a nearby well completed in the UFA to pumping from a proposed new well completed in the LFA;
- quantify the reduction in pumping in the UFA that would offset drawdown (called drawdown offset) in the UFA caused by pumping well 36S048 in the LFA; and
- identify changes in vertical leakage and lateral flow in the UFA and LFA resulting from implementing the proposed new pumping in the LFA and drawdown-offset pumping reductions in the UFA.

The scope of the current investigation at Rincon, Ga., emphasizes model simulations because field-data collection was completed as part of a previous investigation by Carter and Sloope (2004). The focus of this report is to analyze simulated changes in groundwater levels (drawdown) and interaquifer leakage on the UFA and LFA resulting from pumping well 36S048 in the LFA and implementing drawdown-offset pumpage reductions in the UFA. This report contains maps showing drawdown in response to pumping, and tables that list water-budget components of interaquifer and boundary flows and compare simulation results of the revised model to the original model of Payne and others (2005).

Previous Studies

Carter and Sloope (2004) completed detailed field studies at Rincon that included construction of well 36S048, collection of geophysical and flowmeter logs (by USGS), water sampling, and completion of an 8-hour UFA test and 72-hour LFA test. Their report included some preliminary groundwater model simulations. A similar evaluation was completed at Berwick in western Chatham County by Jordan, Jones, and Goulding (2002).

The USGS completed several comprehensive field and modeling studies of the FAS in coastal Georgia. The simulated area is coincident with that used for a regional steady-state model developed by Payne and others (2005) that encompassed 42,155 square miles (mi^2) in Georgia and adjacent areas of South Carolina and Florida (fig. 1–1). Small-area studies at nearby Hunter Army Airfield (fig. 1; Clarke and others, 2010; Williams, 2010); Fort Stewart (Clarke and others, 2011; Gonthier, 2011), and Pooler, Ga. (Cherry and Clarke, 2013; Gonthier, 2012) involved field testing and groundwater-model simulations that evaluated the LFA as a possible alternative water source. Results of these studies, however, indicate a strong interaquifer connection between the UFA and LFA in the Chatham County area. These studies refined existing knowledge concerning the hydrogeology and water quality of the FAS in the Coastal Plain physiographic province and provided essential data and simulation results needed to assess the effect of LFA pumping on groundwater flow and water levels in the UFA.

A revised hydrogeologic framework for the FAS was developed by Williams and Gill (2010) for eight northern coastal counties in Georgia and five coastal counties in South Carolina, including the area of Rincon, Ga. In this area, borehole geophysical and flowmeter log data collected during previous investigations were used 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 conform to those used at Rincon in the current investigation.

Site Description

Rincon, Ga., is located in the southeastern part of Effingham County, about 17 miles (mi) northwest of Savannah and 6.5 mi west of the Savannah River (fig. 1). During 2011, the City of Rincon had an estimated population of 8,865, representing a 100-percent increase since 2000 (City-data.com, 2015).

Because of concern about saltwater intrusion near the Savannah-Hilton Head Island, South Carolina, area (fig. 1), the GaEPD has implemented restrictions on groundwater withdrawal from the UFA and designated management zones in coastal Georgia. Rincon is located in the GaEPD “red zone,” where withdrawals from the UFA are capped at 2004 rates. In Chatham County, groundwater use has declined from 64.97 million gallons per day (Mgal/d) during 2005 to 55.89 Mgal/d during 2010 (Fanning and Trent, 2009; Steven J. Lawrence, U.S. Geological Survey, written commun., April 10, 2014).

The site is characterized by flat topography, with sandy topsoil that is typical of coastal Georgia. The site is underlain by geologic deposits consisting of sand, clay, limestone, and dolomite. The LFA well 36S048 is located at an altitude of about 70 feet (ft). Here, static (non-pumping) water levels in the UFA are at an altitude of about –5 ft, or a depth of 75 ft below land surface.

Water Use

Groundwater use in nearby Chatham County totaled 64.97 Mgal/d during 2005 (Fanning and Trent, 2009). About half of that, 33.52 Mgal/d, was for public supply. Most production wells are within the Savannah city limits; additional wells to the northwest serve Pooler, 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 from the county was pumped from the UFA and the remaining 5 percent was obtained from the LFA. Groundwater withdrawal from the FAS in Chatham County increased from 79.75 Mgal/d in 1980 to 85.54 Mgal/d in 1990 and decreased to 68.15 Mgal/d in 2000, 64.97 Mgal/d in 2005, and 55.89 Mgal/d in 2010 (Fanning and Trent, 2009; Steven J. Lawrence, U.S. Geological Survey, written commun., April 10, 2014).

The water supply for Rincon is provided by two wells (36S034 and 36S035) completed in the UFA located about 2.5 mi southeast of the test site, with a permitted annual withdrawal rate of 0.87 Mgal/d in 2012 (H&K Engineering Group, 2013). During 2005, total groundwater use in Effingham County was 5.96 Mgal/d, with a withdrawal rate of 0.73 Mgal/d from the two production wells (Fanning and Trent, 2009). This represents an increase in total groundwater use from 5.29 Mgal/d during 2000 with a withdrawal rate of 0.54 Mgal/d by the city of Rincon (Fanning, 2003).

Hydrogeologic Setting

Effingham 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). These sediments constitute three major aquifer systems, which are, in descending order, the surficial aquifer system, Brunswick aquifer system, and FAS. The Brunswick aquifer system near Rincon contains material having low permeability with no discernible water-bearing units (fig. 2).

In coastal Georgia, the surficial aquifer system consists of Miocene and younger interlayered sand, clay, and thin limestone beds (Clarke, 2003). At Rincon, the surficial aquifer system consists of fine-grained sands at depths of less than 50 ft and is largely unconfined, with typical yields ranging from 2 to 25 gallons per minute (gal/min; Peck and others, 2013). Elsewhere in coastal Georgia, the surficial aquifer system includes a water-table zone and two confined water-bearing zones; 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 Rincon, the Brunswick aquifer system consists of clayey, fine-grained sand and silt that has much lower permeability than areas within the Southeast Georgia Embayment and can largely be considered a confining unit. For this study, the upper and lower Brunswick aquifers are considered a single unit, and the combined thickness and composite hydraulic properties are used for model simulations.

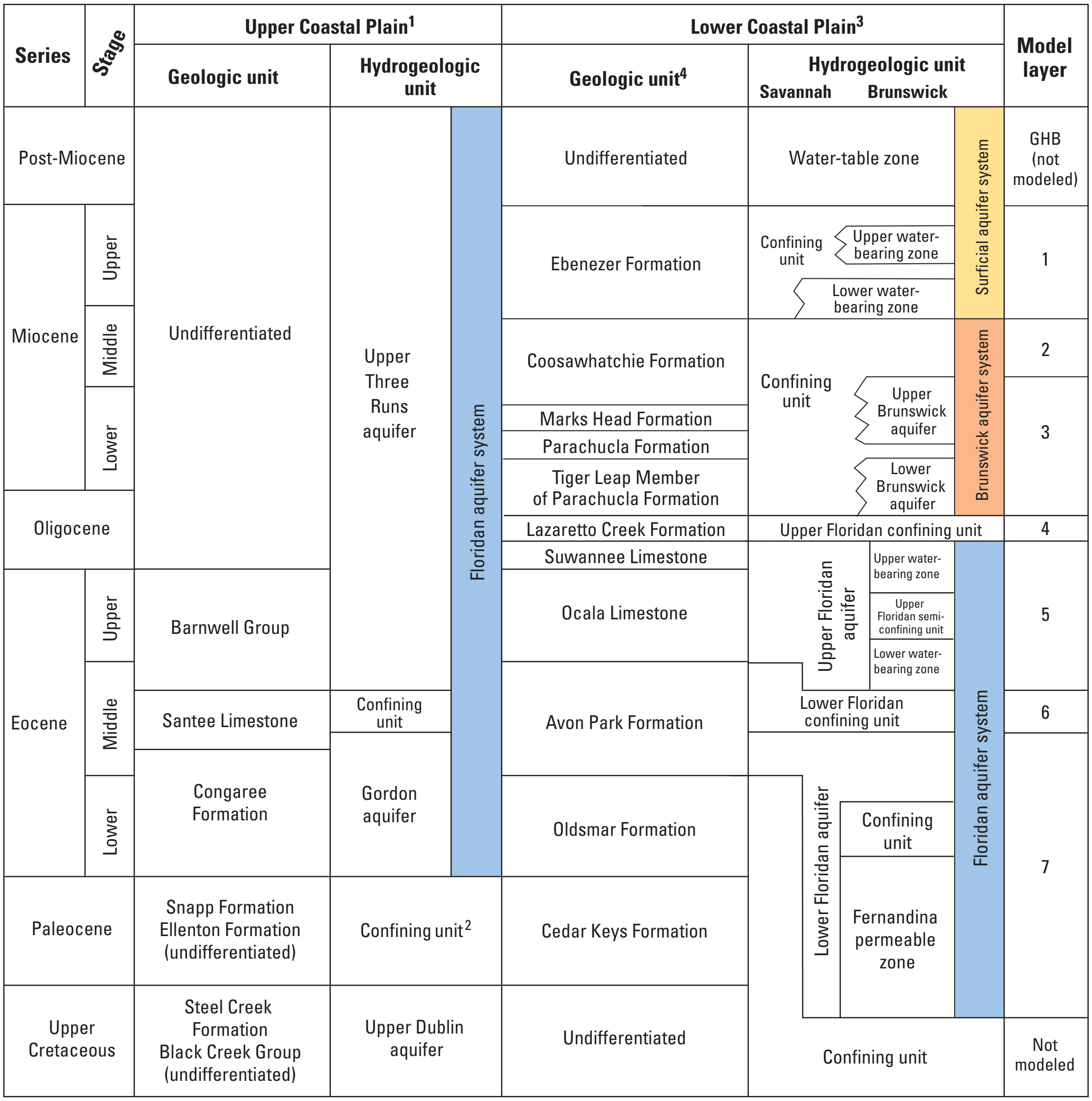
The principal source of groundwater for all uses in coastal Georgia is the FAS, composed of carbonate rocks of varying permeability. In the coastal area, the system has been subdivided by the USGS into the UFA and LFA (Miller, 1986; Williams and Gill, 2010).

The FAS is confined by overlying clay layers and is separated into several permeable water-bearing zones by layers of dense limestone or dolostone that act as semi-confining units that allow vertical leakage of groundwater into either the UFA or LFA, depending on the hydraulic conductivity and direction of the head gradient. According to Williams and Gill (2010), the UFA and LFA boundaries are at the following depths at the well 36S048 site:

- Top UFA: 290 ft
- Base UFA: 410 ft
- Top LFA: 565 ft
- Base of LFA: 1,000 ft

A detailed representation of the geophysical and flow-meter characteristics of the FAS at well 36S048 by Williams and Gill (2010) indicates five water-bearing zones within the FAS (fig. 3), which is similar to findings from an earlier study by McCollum and Counts (1964). The analysis of flowmeter data indicated zones 1 and 4 produce the majority of water, and zones 2, 3, and 5 produce lesser amounts. Zone 1 spans a 30-ft interval within the UFA and zone 4 is present within the uppermost 10 to 15 ft of the LFA. Water production diminishes in the LFA below zone 5 at depths greater than 750 ft.

The LFA is at a shallower depth at Rincon than at the other three sites (table 1). Well 36S048 was pumped at 1,000 gal/min, a higher rate than at the other three sites, resulting in larger drawdown in both the UFA and LFA at that well than at the other three sites. The observed drawdown in the UFA resulting from pumping the LFA was 4.5 ft at well 36S048 (Carter and Sloope, 2004) and ranged from 0.37 to 0.8 ft at the other sites.



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

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

Table 1. Summary of properties of 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)	HAAF (well 36Q392)
LFA depth interval (feet)	565–1,000	702–1,040	700–1,080	703–1,080
LFA test yield (gallons per minute)	1,000	782	718	748
LFA specific capacity (gallons per minute per foot of drawdown)	13.8	15	23.1	20.8
Maximum drawdown LFA (feet)	72.3	52	31	36
Maximum drawdown UFA (resulting from LFA pumping, in feet)	4.5	0.8	0.37	0.76

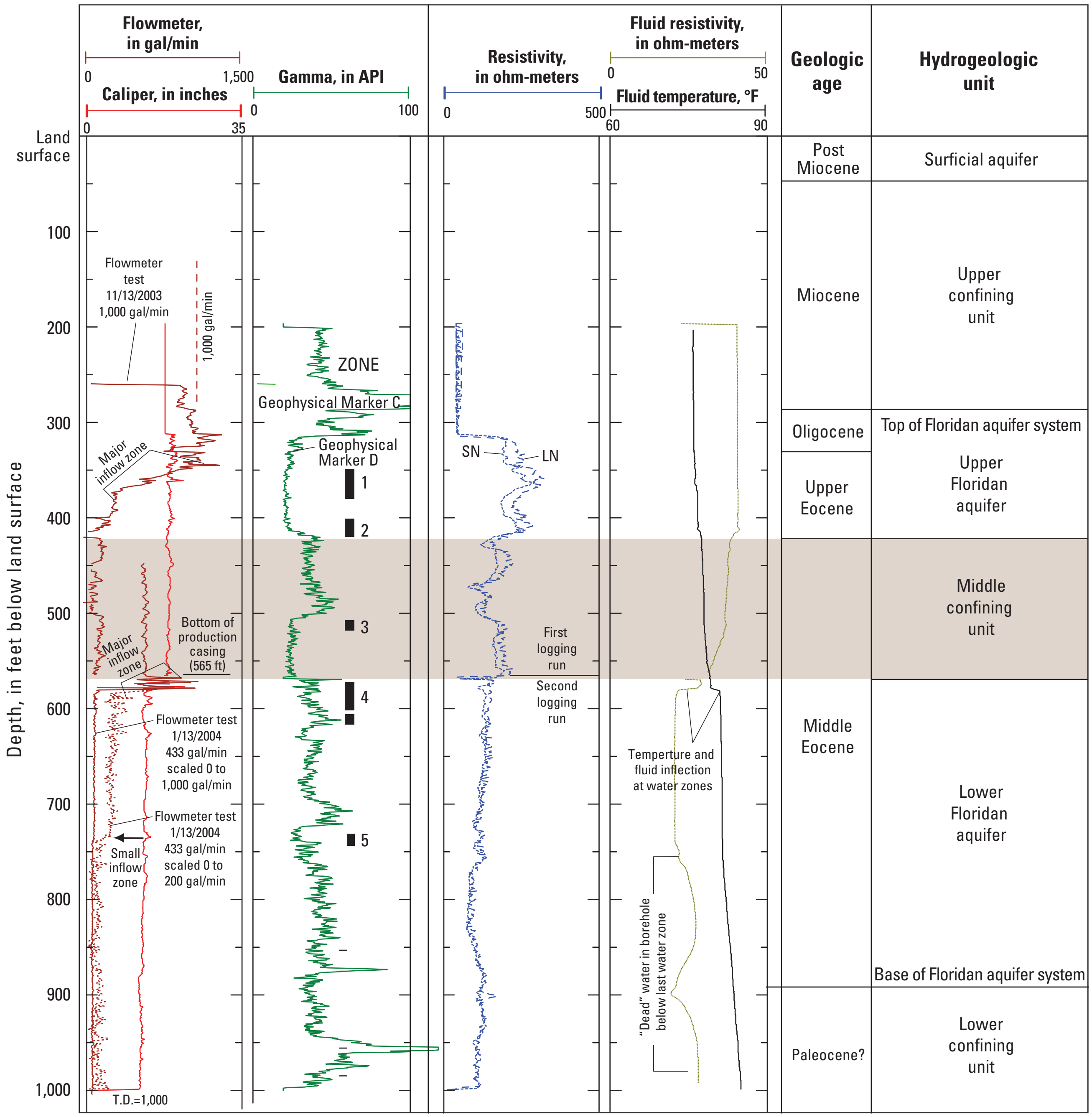


Figure 3. Borehole geophysical logs from test well 36S048 in the Lower Floridan aquifer at Rincon, Effingham County, Georgia. Black bars denote water-bearing zones. Zones 1 through 5 correlate to water-bearing zones previously defined in the area by McCollum and Counts (1964). [gal/min, gallon per minute; API, American Petroleum Institute; °F, degrees Fahrenheit; ft, foot; T.D., total depth; LN, long normal resistivity; SN, short normal resistivity]. From Williams and Gill (2010).

Groundwater Flow

Groundwater flow in the FAS is controlled 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. During the 1880s prior to development, the flow system was considered to be in dynamic equilibrium, with recharge balancing discharge, and potentiometric surfaces were considered nearly static from year to year with water-level altitudes of 30 to 40 ft at Savannah (Krause and Clarke, 2001). In general, 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*).

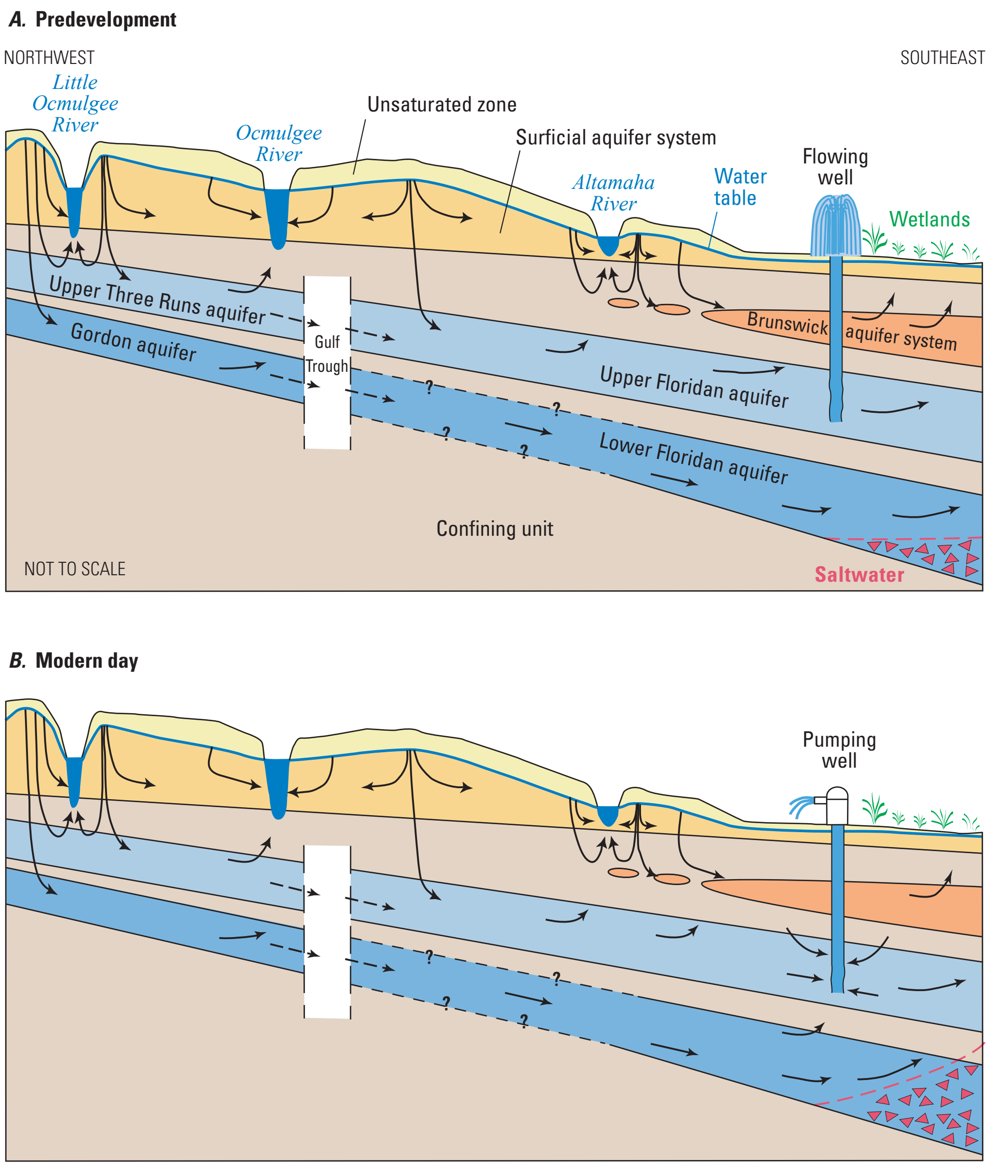


Figure 4. Schematic diagram showing conceptual model of *A*, predevelopment, and *B*, modern-day (2000) flow system. Arrows indicate general direction of groundwater flow (modified from Priest, 2004; Payne and others, 2005).

The modern-day (2000) flow system reflects changes that have occurred as a result of groundwater pumping (fig. 4*B*). Groundwater withdrawals have lowered water levels, induced additional recharge from vertical leakage and regional flow, reduced natural discharge, and allowed seawater to migrate into the UFA in places 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 cone of depression has affected groundwater flow near Rincon, as evidenced by the shape of potentiometric contours, indicating groundwater flow is toward the center of the cone of depression at Savannah.

Saltwater contamination restricts the development of groundwater supply in coastal Georgia and adjacent parts of South Carolina and Florida (Krause and Clarke, 2001). Pumping from the UFA has resulted in (1) substantial groundwater-level decline and subsequent saltwater intrusion into the UFA at Brunswick, Ga., from underlying strata containing highly saline water and (2) seawater encroachment into the UFA at the northern end of Hilton Head Island, S.C. (fig. 1–4). Saltwater contamination at these locations has constrained further development of the UFA in the coastal area and has increased the competition for limited freshwater resources.

Well Identification

In this report, wells are identified by means of a USGS numbering system based on the index of USGS topographic maps (such as 36S048). In Georgia, each 7-1/2-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 36S048 is the 48th well inventoried in the Rincon quadrangle (map 36S).

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

Numerical simulation of groundwater flow within the study area provides a quantitative estimate of the long-term (steady-state) leakage and drawdown response of the UFA to pumping from the LFA. Estimates of the amount of UFA pumpage that would produce the equivalent drawdown in the UFA as that caused by pumping in the LFA can be determined through simulation to obtain the drawdown-offset pumping rate for the UFA. Aquifer testing at Rincon, Ga., provided (1) the basis to simulate drawdown response in nearby UFA wells to pumping in the LFA and (2) a dataset of hydrologic conditions that were used to estimate hydraulic properties and assess simulation accuracy. Drawdown response in the UFA to pumping the LFA was evaluated by the simulation of several hypothetical pumping scenarios in the UFA and LFA.

Observed Water-Level Response

LFA well 36S048 was pumped at a rate of 1,000 gal/min during a 72-hour period beginning on January 20, 2004. During the 72-hour test, 72.3 ft of drawdown was observed in pumped well 36S048, and 4.5 ft of drawdown was observed in UFA well 36S047. The wells are located within 100 ft of each other (Carter and Sloope, 2004) but their screened intervals are separated vertically by about 155 ft of fine-grained material identified as the Lower Floridan confining unit (LFCU). Model simulation was used to determine long-term, steady-state drawdown and leakage 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 aquifer test period is impractical, model simulation provided a practical means to estimate the long-term steady-state drawdown and leakage conditions in the FAS resulting from pumping in the LFA.

Model Simulation

A 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). These requirements are to (1) quantify the aquifer leakage from the UFA to LFA resulting from pumping LFA well 36S048 and (2) calculate “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., January 28, 2003).

The regional groundwater-flow model of Payne and others (2005) was modified so that steady-state model simulations would comply with the requirements of the GaEPD interim strategy for permitting LFA groundwater withdrawal. The spatial resolution of the model was increased and model inputs integrated recently acquired local hydrogeologic information obtained from field investigations at Rincon (described earlier) and from nearby existing wells, as described in appendix 1. Simulations to evaluate drawdown and leakage in the FAS resulting from pumping LFA well 36S048 were performed using the revised model, which incorporated average pumping rates for 2012 (0.87 Mgal/d) at Rincon wells and pumping rates for 2000 elsewhere as a base case for the evaluations. For the revised model, general- and specified-head boundaries were not modified from those used in the original regional groundwater-flow model of Payne and others (2005). General-head boundaries represent aquifer outcrop areas in model layers 1, 2, and 5, allowing recharge to enter into the groundwater-flow system. Specified-head boundaries represent lateral boundaries for model layers 5, 6, and 7, located along the southwest edge of the model domain where the FAS extends beyond the domain boundary.

Steady-state simulations of the following groundwater-withdrawal conditions were used to quantify the long-term response of the FAS to changes in pumpage in both the UFA and LFA (table 2).

- Scenario A—LFA well 36S048 was pumped at a rate of 1,000 gal/min, approximately the same rate used during the 72-hour aquifer test of Carter and Sloope (2004).
- Scenario B—UFA well 36S047 was pumped at a rate 292 gal/min, which would produce a UFA drawdown equivalent to that simulated by pumping LFA well 36S048 at a rate of 1,000 gal/min (simulated in scenario A). Several trial-and-error simulations were performed to obtain a drawdown-offset pumping rate (292 gal/min) for the UFA that achieved a drawdown equivalent to that obtained by the simulation of LFA well 36S048 pumping at a rate of 1,000 gal/min.
- Scenario C—LFA well 36S048 was pumped at 1,000 gal/min, and total pumpage from existing UFA wells at Rincon was reduced by a drawdown-offset pumping rate of 292 gal/min. The reduction in UFA pumpage represents the amount of UFA pumping that would produce a maximum drawdown in the UFA equivalent to that resulting from pumping the LFA at 1,000 gal/min (results of scenario B).

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

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

Scenario	Pumping change, in gallons per minute		UFA drawdown			LFA 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	+1,000	6.78	396	1,156	72.0	395	1,156	Pumping LFA well 36S048 at approximate rate used during the 72-hour aquifer test (1,000 gal/min)
B	+292	0	6.73	8.35	105	—	—	—	Pumping UFA well 36S047 at a rate that would replicate the amount of UFA drawdown simulated as the result of pumping LFA well 36S048 at a rate of 1,000 gal/min (as was simulated in scenario A). Note that several model runs were completed until a drawdown match was obtained.
C	–292	+1,000	5.99	190	733	71.2	190	732	Pumping LFA well 36S048 at approximate rate used during the 72-hour aquifer test (1,000 gal/min) and reducing flow from existing Rincon UFA wells by 292 gal/min. The UFA reduction represents the results of scenario B—the equivalent amount of UFA pumping that would produce an equivalent drawdown in the UFA as that resulting from pumping the LFA at 1,000 gal/min.

Scenario A—Interaquifer Leakage and Drawdown Response

For scenario A, simulated pumping of LFA well 36S048 at a rate of 1,000 gal/min resulted in a maximum steady-state drawdown of 72.0 ft (table 2, fig. 5), which is nearly identical to the 72.3-ft maximum drawdown observed during the 72-hour aquifer test (table 1; Carter and Sloope, 2004). Because changes in water levels over time were approaching zero by the end of the 72-hour test, the steady-state simulation provided a reasonable representation of field conditions in the LFA during the Carter and Sloope (2004) aquifer test. Simulated steady-state drawdown in the LFA of at least 1 ft occurred within 396-mi^2 area for scenario A (fig. 5, table 2).

Simulated pumping of LFA well 36S048 at a rate of 1,000 gal/min (scenario A) caused leakage through the LFCU, which resulted in drawdown in the overlying UFA (fig. 6). Because water levels in the UFA had not stabilized by the end of the 72-hour test, observed drawdown in well 36S047 represented a lower limit for steady-state model calibration. Comparison of simulated drawdown and drawdown determined from water-level data at the end of the 72-hour aquifer test in LFA well 36S048 (Carter and Sloope, 2004) indicated that the simulated steady-state UFA drawdown near well 36S047 of about 6.8 ft exceeded the observed value of 4.5 ft by about 2.3 ft. This difference is expected because the long-term steady-state response to pumping simulated by the model represents an aquifer condition that contains no time-varying changes in groundwater level in response to hydrologic stress; that is, all hydrologic stresses on the aquifer (such as pumping) are allowed to operate on the flow system for enough time until no further changes to groundwater levels occur. Simulations by Payne and others (2005) indicated steady state conditions were reached in about 5 years. If groundwater-level decline (drawdown) in response to pumping is measured only 72 hours following the inception of pumping in well 36S048, the observed drawdown is 2.3 ft less than the 6.8 ft maximum observed during steady-state conditions. Model results for scenario A indicate that drawdown in the UFA exceeded 1 ft over a 396-mi^2 area (table 2, fig. 6).

Steady-state water budgets derived from simulations of 2000 conditions with and without pumping at well 36S048 were compared to compute the difference in groundwater flows in the UFA and LFA resulting from additional pumping in the LFA (table 3). Although rounding errors in values for water-budget components prevents an exact accounting of flows in the FAS, comparison of component values for the two simulations provides some insight into the relative contribution of groundwater flow to LFA well 36S048. Pumping 1.44 Mgal/d (1,000 gal/min) at well 36S048 caused small changes to the 2000 regional water budget and resulted in the following redistribution of groundwater flow among model layers:

- Layer 1 (surficial aquifer)—a 0.79-Mgal/d gain in inflow from, and a 0.12-Mgal/d reduction in outflow to, the general-head boundary for a net inflow of +0.91 Mgal/d.
- Layer 2 (Brunswick aquifer system confining unit)—a 0.058-Mgal/d-gain in inflow from, and a 0.005-Mgal/d reduction in outflow to, the general-head boundary for a net inflow of +0.063 Mgal/d.
- Layer 5 (UFA)—a 0.045-Mgal/d gain in inflow from, and a 0.026-Mgal/d reduction in outflow to, the general-head boundary and a 0.30-Mgal/d gain in inflow from, and 0.097-Mgal/d reduction in outflow to, lateral specified-head boundaries for a net inflow of +0.468 Mgal/d.
- Layer 7 (LFA)—a 0.009-Mgal/d gain in inflow from, and a 0.008-Mgal/d reduction in outflow to, lateral specified-head boundaries for a net inflow of +0.017 Mgal/d.

For scenario A, 9 percent of the simulated 1.44-Mgal/d pumping rate in well 36S048 was supplied by increased leakage from overlying layers, and 1 percent was derived from the lateral specified-head boundary of the LFA (layer 7) (table 3). A combined 90.8 percent of the inflow to well 36S048 from overlying layers was derived from general-head boundaries in the surficial aquifer (layer 1, 63.2 percent) and from the specified-head boundary in the UFA (layer 5, 27.6 percent). The remainder of flow from overlying layers (9.3 percent) was contributed from the general-head boundary in the Brunswick aquifer system confining unit (layer 2, 4.4 percent) and in the UFA (layer 5, 4.9 percent).

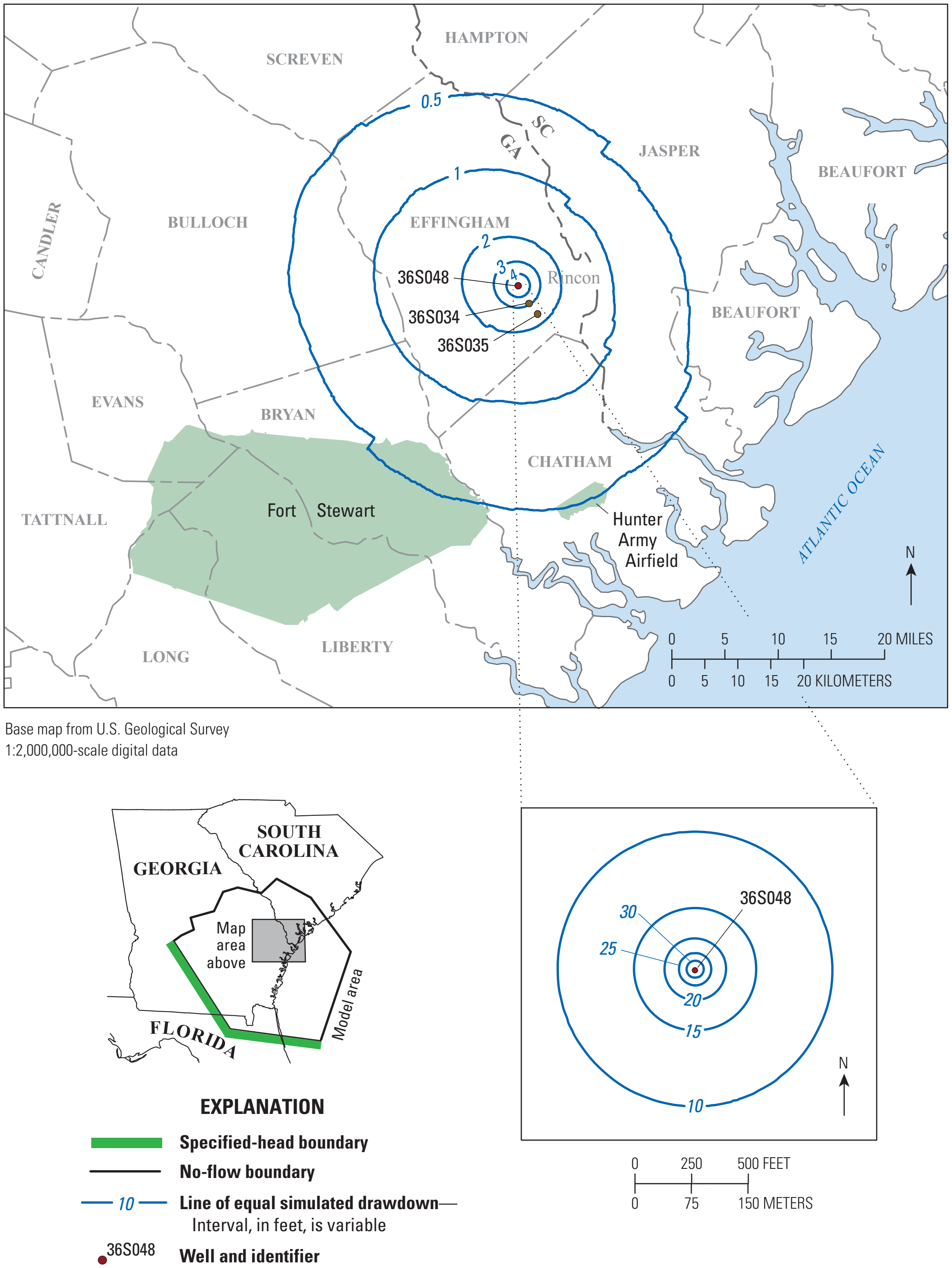


Figure 5. Simulated steady-state drawdown in the Lower Floridan aquifer (LFA) for scenario A—pumping LFA well 36S048 at 1,000 gallons per minute, Rincon and vicinity, Georgia. Maximum drawdown in well 36S048 is 72.0 feet.

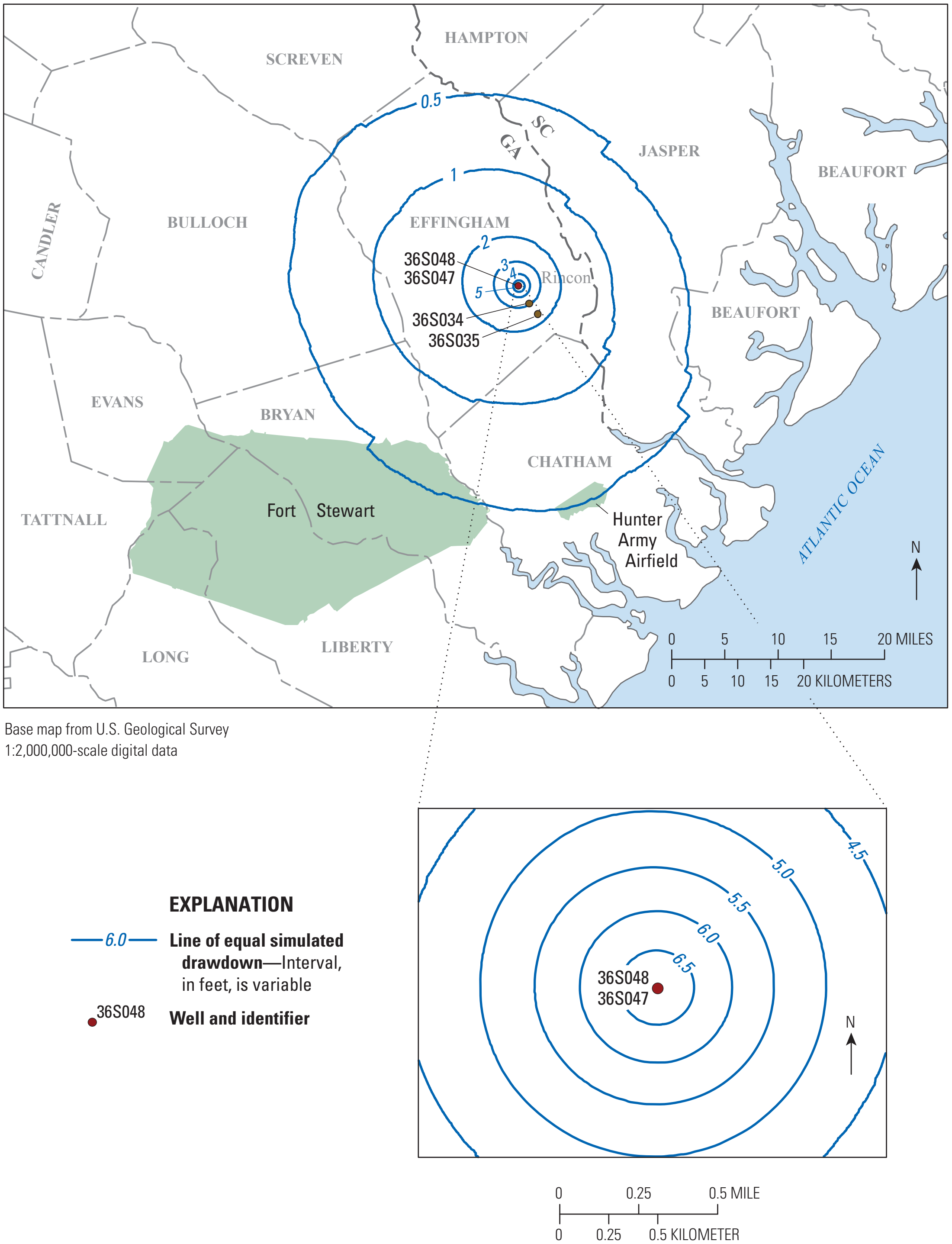


Figure 6. Simulated steady-state drawdown in the Upper Floridan aquifer for scenario A—pumping Lower Floridan aquifer well 36S048 at 1,000 gallons per minute, Rincon and vicinity, Georgia. Maximum drawdown in well 36S047 is 6.78 feet.

Table 3. Simulated steady-state water budgets for base case (year 2000) and for scenario A, after pumping 1,000 gallons per minute (1.44 million gallons per day) at Lower Floridan aquifer well 36S048, Rincon, Georgia.

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

Hydrogeologic unit	Model layer	Simulated flow, in million gallons per day														
		Pumpage			Inflow from general-head boundary			Outflow to general-head boundary			Inflow along lateral boundary			Outflow along lateral boundary		
		2000	Well 36S048 added	Difference	2000	Well 36S048 added	Difference	2000	Well 36S048 added	Difference	2000	Well 36S048 added	Difference	2000	Well 36S048 added	Difference
Surficial aquifer system	1	<0.001	<0.001	<0.001	278.25	279.04	0.79	100.13	100.01	–0.12	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Confining unit	2	<0.001	<0.001	<0.001	32.880	32.938	0.058	2.049	2.043	–0.005	<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	674.45	674.45	0.00	147.34	147.38	0.045	19.568	19.542	–0.026	843.11	843.41	0.30	385.64	385.54	–0.097
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	132.02	133.45	1.44	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	15.094	15.103	0.009	2.607	2.600	–0.008
Total all layers		**806.71**	**808.14**	**1.44**	**458.47**	**459.36**	**0.888**	**121.75**	**121.60**	**–0.151**	**858.21**	**858.52**	**0.309**	**388.25**	**388.14**	**–0.108**

Scenario B—Upper Floridan Aquifer Drawdown Offset

The amount of equivalent UFA pumping to offset the drawdown effect in the UFA of pumping LFA well 36S048 was obtained by simulating pumping reductions at existing UFA production wells located within a 5-mi radius of well 36S048. Simulations to determine the pumping rate in the UFA that would produce the equivalent maximum drawdown in the UFA as pumping from the LFA (drawdown offset), constituted scenario B. For this scenario, various pumping rates were assigned to a hypothetical UFA well positioned above the model location that simulated pumping in LFA well 36S048 until the amount of UFA drawdown matched that simulated for the UFA by scenario A (table 2, fig. 7). Simulations indicated that pumping at a rate of 292 gal/min approximated the 6.8-ft drawdown in the UFA simulated by scenario A.

The drawdown offset for the UFA produces an identical maximum drawdown above LFA well 36S048 as that produced by pumping LFA well 36S048. The drawdown-offset pumping rates for wells in the UFA, however, do not produce the same areal drawdown pattern in the UFA as produced by pumping the LFA well and deriving UFA drawdown from induced leakage to the pumped LFA well. For example, the 1-ft water-level contour in the UFA corresponding to scenario B (simulating drawdown-offset pumping in UFA wells) encompassed an area of about 8.4 mi^2 (fig. 7), whereas the 1-ft contour encompassed 396 mi^2 in the UFA when the LFA was pumped (scenario A, fig. 6). The large difference in affected area between scenarios involving pumping UFA and LFA wells results from differences in (1) the hydraulic properties of the aquifers and (2) the manner by which ground-water flow to the simulated wells in either the UFA or LFA as leakage and from lateral boundaries contributes to the pumped volumes. Drawdown in the LFA resulting from pumping well 36S048 occurs over a large area that induces leakage from (and drawdown within) an equally large area of the UFA. In contrast, drawdown resulting from offset-pumping wells located in the UFA occurs within a steep cone of depression that is smaller in area than the broad cone of depression generated in the LFA from pumping LFA well 36S048.

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 36S047 (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 0.23-Mgal/d gain in inflow from, and a 0.04-Mgal/d reduction in outflow to, the general-head boundary for a net inflow of +0.27 Mgal/d.
- Layer 2 (Brunswick aquifer system confining unit)—a 0.017-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 +0.019 Mgal/d.
- Layer 5 (UFA)—a 0.015-Mgal/d gain in inflow from, and a 0.008-Mgal/d reduction in outflow to, the general-head boundary and a 0.07-Mgal/d gain in flow from, and 0.022-Mgal/d reduction in outflow to, lateral specified-head boundaries for a net inflow of +0.115 Mgal/d.
- Layer 7 (LFA)—a 0.003-Mgal/d gain in inflow from, and a 0.002-Mgal/d reduction in outflow to, lateral specified-head boundaries for a net inflow of +0.005 Mgal/d.

For scenario B, 69 percent of the 0.42-Mgal/d pumping rate in well 36S047 was derived from increased leakage from overlying layers, and 27 percent was derived from general- and specified-head boundaries for the UFA (layer 5; table 4). About 64 percent of the inflow to the pumped UFA well from overlying layers was derived from the general-head boundary in the surficial aquifer (0.27 Mgal/d; layer 1); the remaining inflow to well 36S047 from overlying layers was contributed by the general-head boundary in the Brunswick aquifer system confining unit (layer 2).

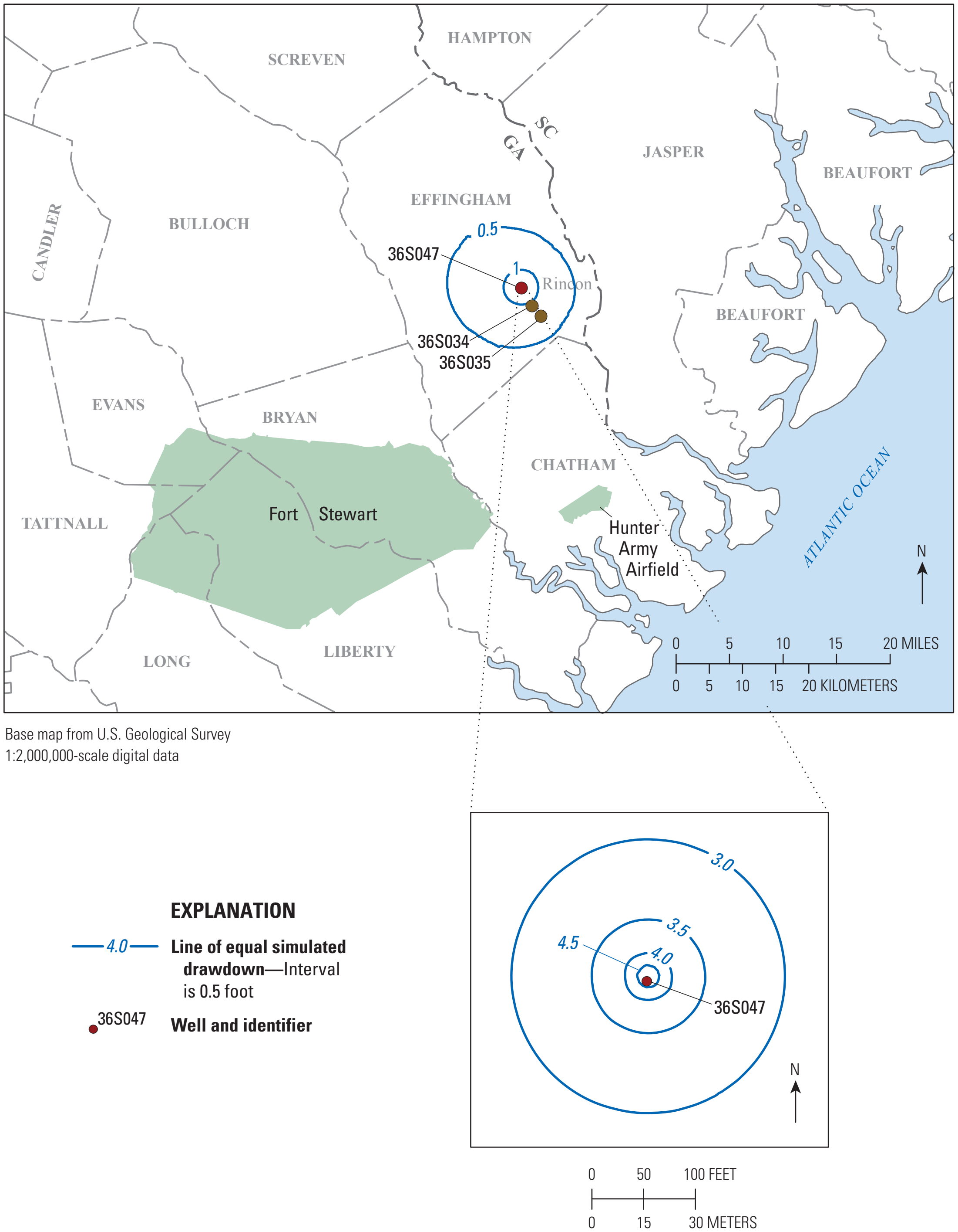


Figure 7. Simulated steady-state drawdown in the Upper Floridan aquifer (UFA) for scenario B—pumping UFA well 36S047 at 292 gallons per minute, Rincon and vicinity, Georgia. Maximum drawdown in well 36S047 is 6.74 feet.

Table 4. Simulated steady-state water budgets for base case (year 2000) and for scenario B, after pumping 292 gallons per minute (0.42 million gallons per day) at Upper Floridan aquifer well 36S047, Rincon, Georgia.

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

Hydrogeologic unit	Model layer	Simulated flow, in million gallons per day														
		Pumpage			Inflow from general-head boundary			Outflow to general-head boundary			Inflow along lateral boundary			Outflow along lateral boundary		
		2000	Well 36S047 added	Difference	2000	Well 36S047 added	Difference	2000	Well 36S047 added	Difference	2000	Well 36S047 added	Difference	2000	Well 36S047 added	Difference
Surficial aquifer system	1	<0.001	<0.001	<0.001	278.25	278.48	0.23	100.13	100.09	–0.04	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Confining unit	2	<0.001	<0.001	<0.001	32.880	32.897	0.017	2.049	2.047	–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	674.45	674.87	0.42	147.34	147.35	0.015	19.568	19.560	–0.008	843.11	843.18	0.07	385.64	385.62	–0.022
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	132.02	132.02	0.000	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	15.094	15.097	0.003	2.607	2.605	–0.002
Total all layers		**806.71**	**807.13**	**0.42**	**458.47**	**458.73**	**0.262**	**121.75**	**121.70**	**–0.050**	**858.21**	**858.28**	**0.073**	**388.25**	**388.22**	**–0.024**

Scenario C—Effects of Pumping Offsets on Groundwater Levels at Rincon, Ga.

Scenario C evaluated the combined effect of simulating pumping at 1,000 gal/min (1.44 Mgal/d) from LFA well 36S048 and simultaneously decreasing pumping in existing UFA wells (36S034 and 36S035) at Rincon by the drawdown-offset pumping rate of 292 gal/min (0.42 Mgal/d, scenario B) (table 2, fig. 8). Maximum simulated drawdown totaled 71.2 ft at LFA well 36S048 (fig. 8) and 5.99 ft near well 36S047 in the UFA (fig. 9).

Applying the drawdown offset at Rincon reduced the magnitude and areal extent of simulated drawdown in the UFA (scenario C) relative to scenario A, which did not simulate drawdown offsets for the existing UFA wells at Rincon (table 2). For scenario A, pumping LFA well 36S048 at a rate of 1,000 gal/min without drawdown offsets in the UFA resulted in UFA drawdown that exceeded 1 ft over a 395-mi^2 area, with a maximum drawdown of 6.8 ft near well 36S048 (fig. 6). The drawdown offset simulated by scenario C resulted in UFA drawdown exceeded 1 ft over a 190 mi^2 area, with a maximum drawdown of 5.99 ft near well 36S047 (fig. 9; table 2).

The simulated potentiometric surface of the UFA for scenarios A and C differed slightly from the year-2000 base case in the regional configuration of implied groundwater-flow directions in the UFA (fig. 10). The −20- and −30-ft potentiometric contours moved slightly to the northwest, upgradient from their base case positions, indicating lowering of the potentiometric surface because of pumping of well 36S048. The −20-ft contour contains a distinctive bend toward well 36S048, indicating slight convergence of flow toward the well. Groundwater flow in the region, however, remained dominated by a large cone of depression centered over the Savannah, Ga., area.

Comparing simulated water-budget components from scenario C to that obtained from base case conditions for 2000 indicated that (table 5) adjustments to UFA pumping rates for the drawdown offset resulted in small changes to the base-case water budget, with the following redistribution of groundwater flow among model layers:

- Layer 1 (surficial aquifer)—a 0.56-Mgal/d gain in inflow from, and a 0.09-Mgal/d reduction in outflow to, the general-head boundary for a net inflow of +0.65 Mgal/d.
- Layer 2 (Brunswick aquifer system confining unit)—a 0.044-Mgal/d gain in inflow from, and a 0.005-Mgal/d reduction in outflow to, the general-head boundary for a net inflow of +0.049 Mgal/d.
- Layer 5 (UFA)—a 0.03-Mgal/d gain in inflow from, and a 0.02-Mgal/d reduction in outflow to, the general-head boundary and a 0.22-Mgal/d gain in inflow from, and 0.07-Mgal/d reduction in outflow to, lateral specified-head boundaries for a net inflow of +0.34 Mgal/d.
- Layer 7 (LFA)—a 0.003-Mgal/d gain in inflow from, and a 0.005-Mgal/d reduction in outflow to, lateral specified-head boundaries for a net inflow of +0.008 Mgal/d.

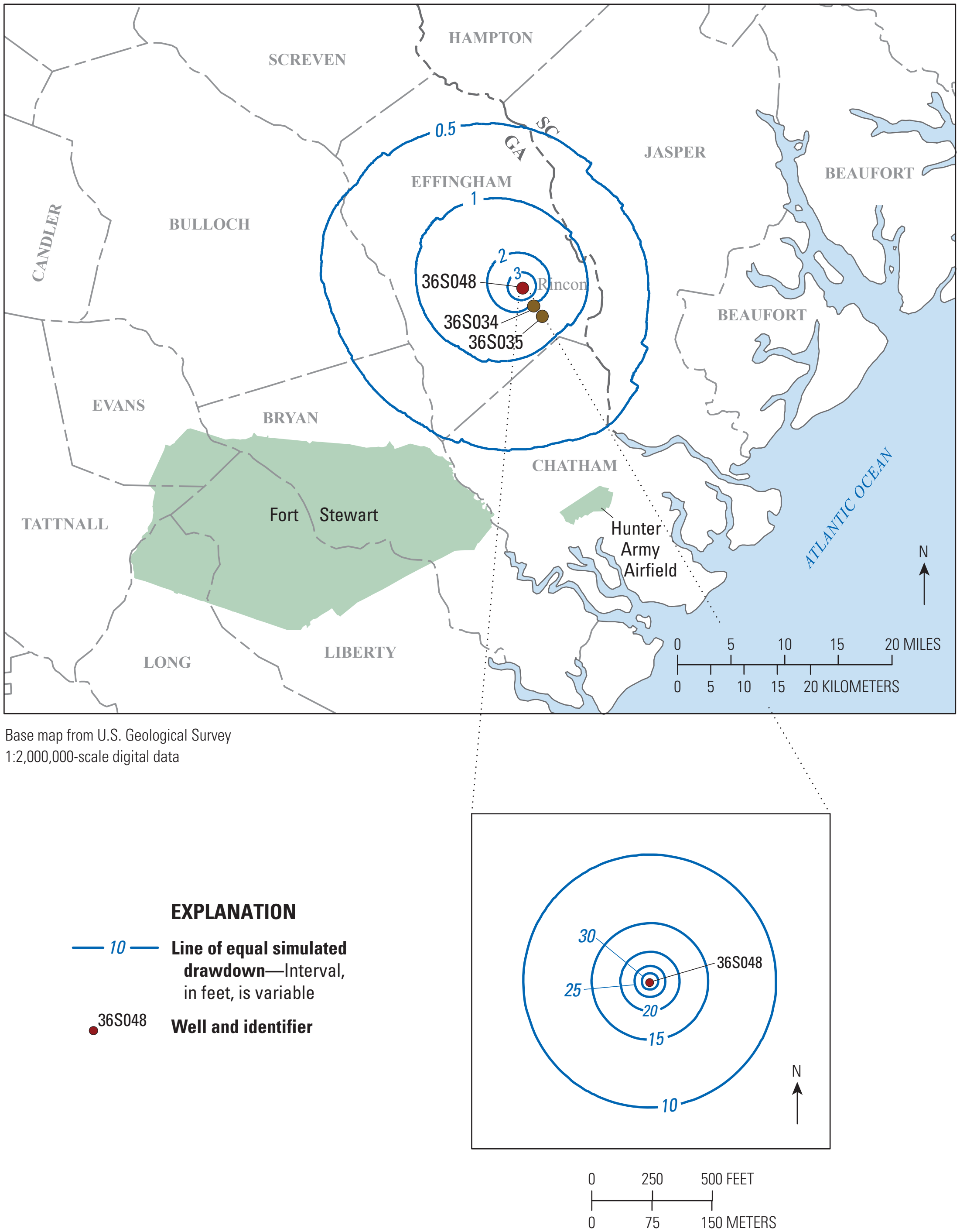
As a result of the 1.02-Mgal/d net increase in the FAS pumping rate simulated in scenario C, increased leakage from overlying layers supplied about 69 percent of the flow to LFA well 36S048, and general- and specified-head boundaries for the UFA supplied about 30 percent (layer 5). The general-head boundary in the surficial aquifer (layer 1) contributed most of the inflow to the pumped well (about 0.65 Mgal/d) from overlying layers. The remainder of inflow from overlying layers was contributed by the general-head boundary in the Brunswick aquifer system confining unit (layer 2).

Limitations of Analysis

Analyses of the effects of pumping the LFA on water levels in the UFA are limited by the accuracy of field data, including possible errors and uncertainty in water-level measurements, hydraulic properties, and groundwater-use estimates based on 2000 pumping rates (not quantified in this report). For example, available water-level data were not adjusted to minimize or eliminate effects of local interferences, such as tides, barometric pressure, and pumping, which could affect recorded water levels and the computed hydraulic properties based upon them.

Model results are limited by the same model assumptions and design as described by Payne and others (2005). Potential errors are inherent in (1) the conceptual model of groundwater flow; (2) approximations made in representing the physical properties of the flow system and spatial distribution of these properties; (3) approximations made in the formulation and application of model boundary and initial conditions; (4) numerical approximation and solution of the mathematical model of the flow system; and (5) 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. Although the revised groundwater-flow model reasonably simulates steady-state conditions, use of transient simulation would provide insight into drawdown and groundwater leakage over time.

The variably spaced grid used in the revised model contains aspect ratios (relative lengths between row and column dimensions) as large as 1,011:1, which can lead to inaccurate representation of hydraulic gradients parallel to the long axis of the grid cell (de Marsily, 1986, p. 351). Fortunately, these large-aspect-ratio grid cells are only in areas distant from Rincon and have little effect on simulated results in the area, as indicated by the calibration results in appendix 1. Although the vertical hydraulic conductance of the LFCU was held constant at the highest measured value in the area, 1.67 feet per day (ft/d), it is likely that this parameter had little effect on simulation results because of low sensitivity, as indicated by the sensitivity analysis performed as part of a study for the City of Pooler, Ga. (Cherry and Clarke, 2013).



Base map from U.S. Geological Survey
1:2,000,000-scale digital data

Figure 8. Simulated steady-state drawdown in the Lower Floridan aquifer (LFA) for scenario C—pumping LFA well 36S048 at 1,000 gallons per minute (gal/min) and reducing pumping at Upper Floridan aquifer wells 36S034 and 36S035 by 292 gal/min, Rincon and vicinity, Georgia. Maximum drawdown in well 36S048 is 71.2 feet.

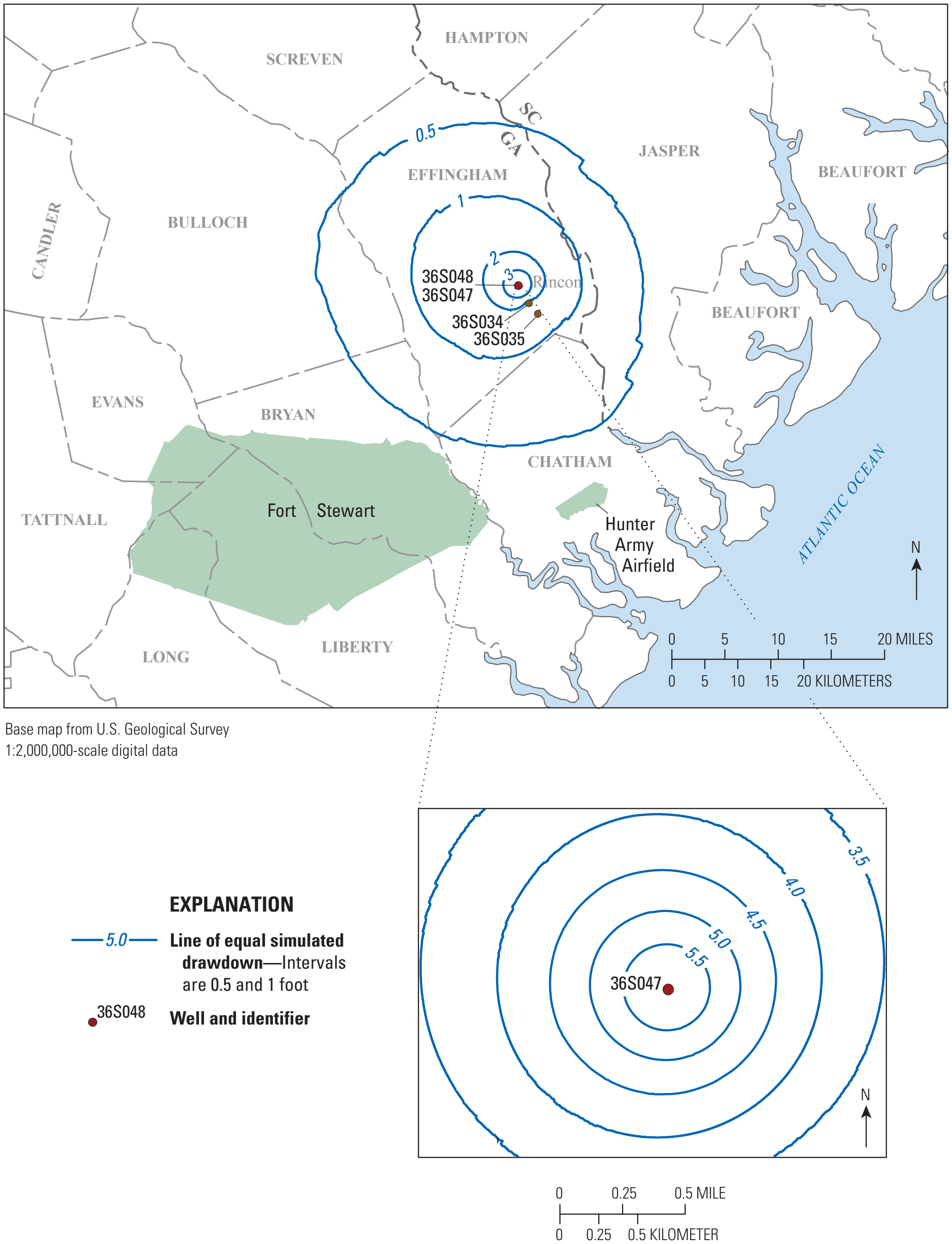


Figure 9. Simulated steady-state drawdown in the Upper Floridan aquifer (UFA) for scenario C—pumping Lower Floridan aquifer well 36S048 at 1,000 gallons per minute (gal/min) and reducing pumping at UFA wells 36S034 and 36S035 by 292 gal/min, Rincon and vicinity, Georgia. Maximum drawdown in well 36S047 is 5.99 feet.

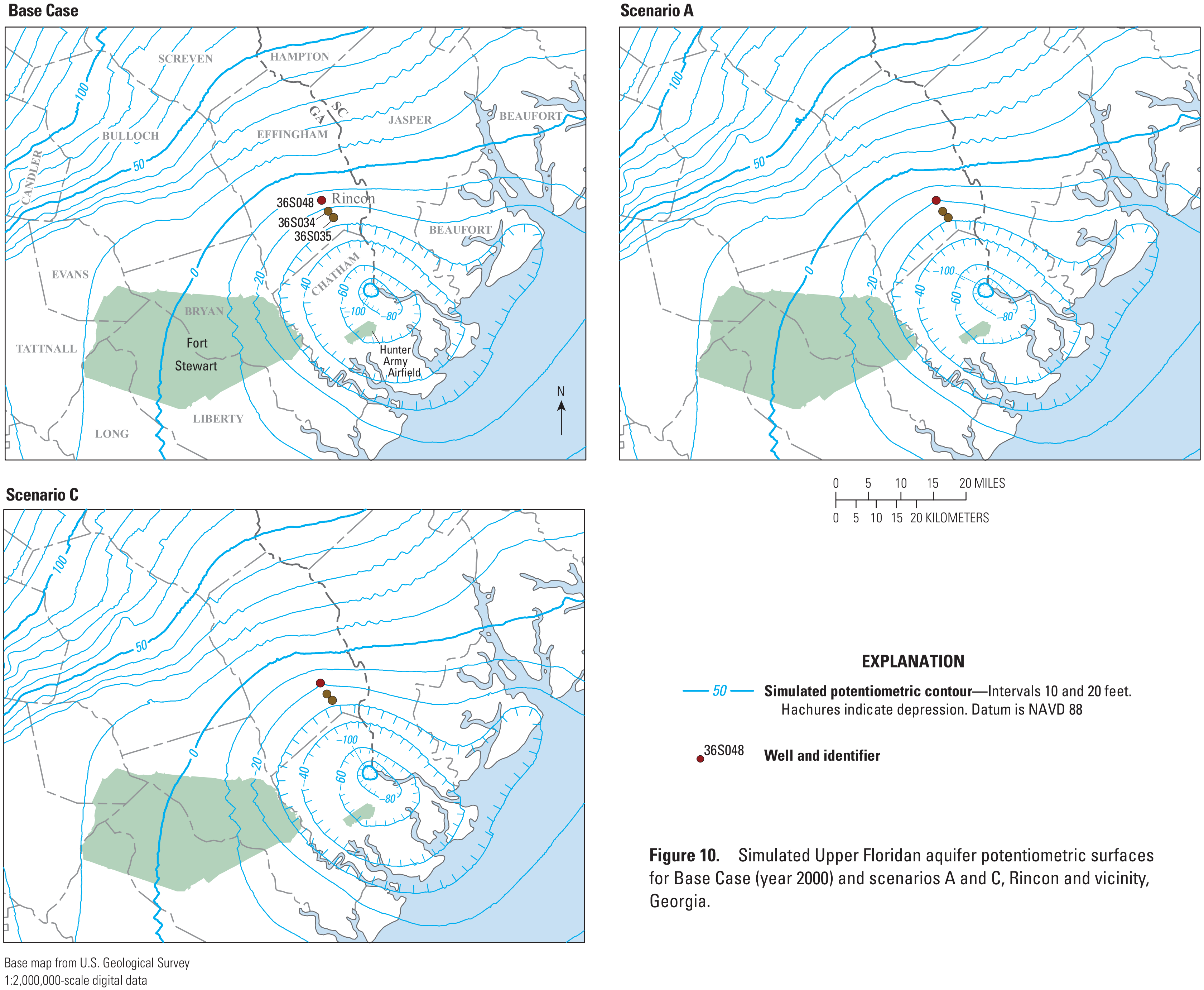


Figure 10. Simulated Upper Floridan aquifer potentiometric surfaces for Base Case (year 2000) and scenarios A and C, Rincon and vicinity, Georgia.

Table 5. Simulated steady-state water budgets for base case (year 2000) and for scenario C, after pumping 1,000 gallons per minute (1.44 million gallons per day) at Lower Floridan aquifer well 36S048 and reducing pumping at Upper Floridan aquifer wells 36S034 and 36S035 by 292 gallons per minute (0.42 million gallons per day), Rincon, Georgia.

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

Hydrogeologic unit	Model layer	Simulated flow, in million gallons per day														
		Pumpage			Inflow from general-head boundary			Outflow to general-head boundary			Inflow along lateral boundary			Outflow along lateral boundary		
		2000	Well 36S048 added	Difference	2000	Well 36S048 added	Difference	2000	Well 36S048 added	Difference	2000	Well 36S048 added	Difference	2000	Well 36S048 added	Difference
Surficial aquifer system	1	<0.001	<0.001	<0.001	278.25	278.81	0.56	100.13	100.04	–0.09	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Confining unit	2	<0.001	<0.001	<0.001	32.880	32.924	0.044	2.049	2.044	–0.005	<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	674.45	674.03	–0.42	147.34	147.37	0.030	19.568	19.548	–0.020	843.11	843.33	0.22	385.64	385.57	–0.070
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	132.02	133.45	1.440	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	15.094	15.100	0.003	2.607	2.602	–0.005
Total all layers		**806.71**	**807.72**	**1.02**	**458.47**	**459.10**	**0.634**	**121.75**	**121.63**	**–0.115**	**858.21**	**858.43**	**0.225**	**388.25**	**388.17**	**–0.075**

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

Summary

- Simulation of long-term pumping at a rate of 1,000 gallons per minute (gal/min) from the Lower Floridan aquifer (LFA) (scenario A) caused a maximum drawdown of about 6.8 feet in the Upper Floridan aquifer (UFA), with drawdown exceeding 1 foot over a 396-square-mile area. Induced vertical leakage from the UFA supplied about 99 percent of the pumped water to the LFA. Simulated drawdown in the UFA, although slight with regard to drawdown in the LFA, extended into the Coastal Plain beyond Rincon because of the relatively large (about 4:1) contrast in the water-transmitting ability, or transmissivity, of the UFA compared with the LFA.

- Simulated pumping changed regional water-budget components and redistributed flow among model layers, specifically increasing inflow to, and decreasing outflow from, lateral boundaries in the UFA and LFA, and increasing inflow (recharge) from the general-head boundary to outcrop areas in the surficial aquifer, underlying semiconfining unit, and UFA.

- Simulations that addressed the leakage offset (scenario A) or drawdown offset (scenario B) of the Georgia Environmental Protection Division interim permitting strategy identified widely varying pumping offsets for the UFA, depending on whether the leakage or the drawdown offset for UFA pumping was evaluated. For example, when pumping the LFA at a rate of 1,000 gal/min, the drawdown offset (292 gal/min) was three times less than the leakage offset (990 gal/min).

- Simulating pumping of LFA well 36S048 at a rate of 1,000 gal/min and simultaneously pumping existing Rincon UFA supply wells according to the reduced UFA drawdown offset of 292 gal/min resulted in decreased magnitude and extent of drawdown in the UFA relative to scenario A, which did not contain drawdown offsets for pumping the UFA wells at Rincon.

- Simulated rates of interaquifer leakage and drawdown in the UFA can differ from actual rates because the model-imposed specified-head and general-head boundaries that contributed flow to these leakage and drawdown conditions are controlled by the hydraulic head and gradients computed in the model area near these boundaries. As actual hydrologic stresses change the head and gradient conditions near these boundaries, leakage and drawdown in the UFA will vary from that simulated by the model. In addition, these model boundaries can simulate an unlimited supply of water to the groundwater system—water that may not be available to meet actual, additional pumping demand from the LFA.

- Simulations with the revised regional model of Payne and others (2005) developed for this study, have contributed toward improving regional characterization of the Floridan aquifer system. Model results could be improved, however, by (1) replacing lateral specified-head boundaries with a natural boundary, such as a groundwater divide, which would imply expanding the model area; and, (2) actively simulating the surficial aquifer with a model layer that would contain hydrologic stresses and horizontal flow.

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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 (LFA) at Rincon, Georgia. The regional model is described in detail in Payne and others (2005); a brief description 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 (fig. 1–1).

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 confining unit.
- Layer 5: Upper Floridan aquifer (UFA).
- Layer 6: Lower Floridan confining unit (LFCU).
- Layer 7: 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 range from approximately 4,000×5,000 feet (ft; 0.7 mi^2) to 16,500×16,500 ft (9.8 mi^2). At Rincon, the mesh resolution was 14,900×16,100 ft, requiring 10×10-ft 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, LFA, and intervening confining unit), 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 with 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, because 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 non-site-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 Rincon was within the same range of calibrated pumping conditions as the regional model.

Revisions to Regional Model

The regional model of Payne and others (2005) was modified using hydrogeologic information obtained from field investigations at Rincon (Carter and Sloope, 2004) and from existing wells in the vicinity of Pooler, Ga. (Gonthier, 2012), Hunter Army Airfield (Clarke and others, 2010), and Fort Stewart (fig. 1; Clarke and others, 2011). These modifications involved adding new hydraulic-property zones for vertical and horizontal hydraulic conductivity in the UFA and LFA and intervening confining unit. 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), and at 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 layering and boundary conditions of the original regional model.

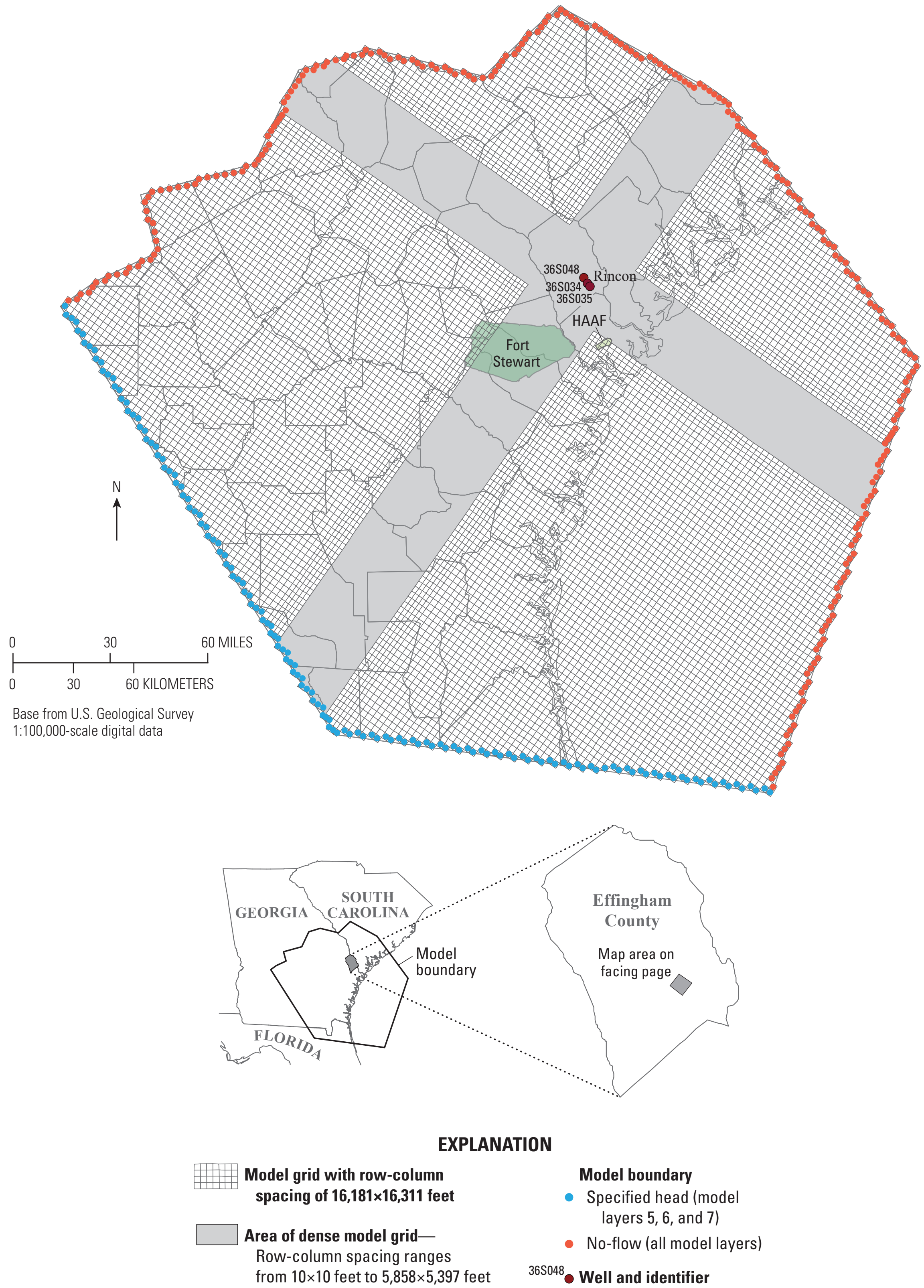

Figure 1–1. Location of selected wells, regional groundwater model and boundary conditions, and revised model grid, City of Rincon, Fort Stewart, and vicinity, Georgia. [HAAF, Hunter Army Airfield]

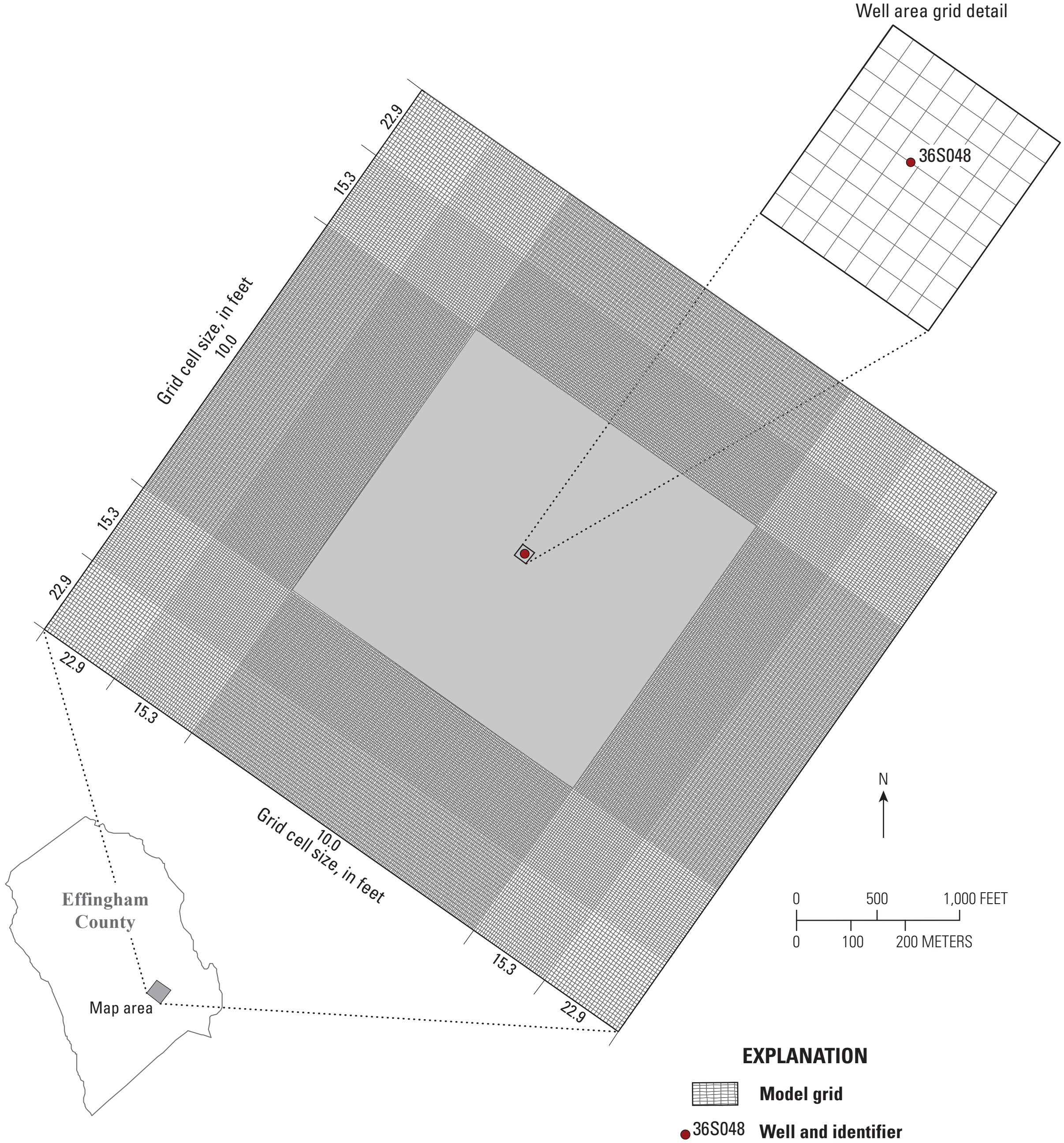

Figure 1–1. Location of selected wells, regional groundwater model and boundary conditions, and revised model grid, City of Rincon, Fort Stewart, and vicinity, Georgia. [HAAF, Hunter Army Airfield]—Continued

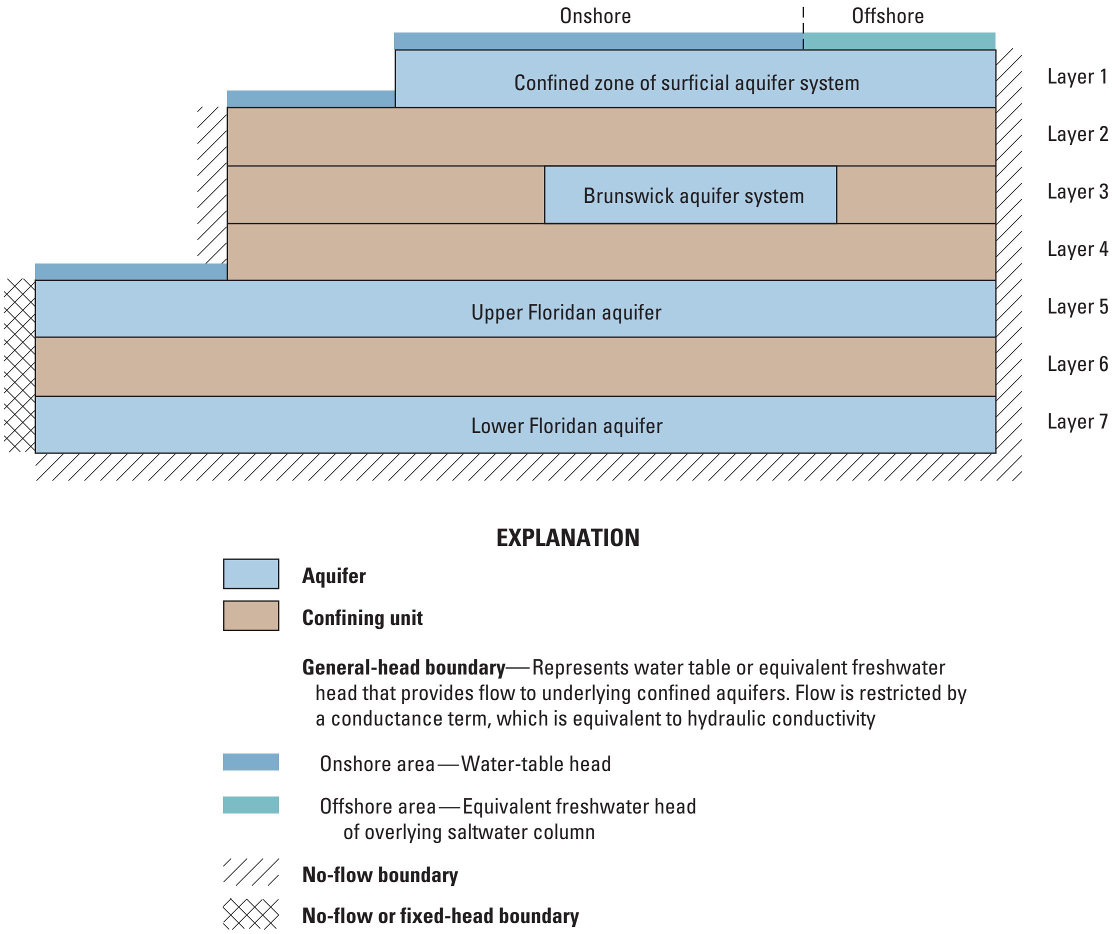

Figure 1–2. Schematic diagram showing model layers and boundary conditions (from Payne and others, 2005).

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 36S048 to a maximum size of about 10,113 ft in the row direction and 10,128 ft in the column direction. The grid orientation was rotated 325 degrees counterclockwise to accommodate the finer mesh in the Rincon area. The revised model consists of 590 rows and 649 columns. The variably spaced grid used in the revised model contains aspect ratios between row and column dimensions as large as 1,011:1, which can lead to numerical errors (de Marsily, 1986, p. 351). Fortunately, these large-aspect-ratio grid cells are only in areas distant from Rincon and have little effect on simulation results in the study area.

Refinement of Hydraulic Conductivity Distribution

Previous studies at Rincon, Pooler, Hunter Army Airfield and Fort Stewart 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 Rincon, 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 Rincon (Carter and Sloope, 2004) 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 overlying UFA, which guided revisions to K_v and K_h values from previous calibrated values near Rincon. Hydraulic conductivity of the LFCU was not measured during previous studies at Rincon, so results from core analyses and packer-slug tests at Hunter Army Airfield and Pooler were applied to the model (Williams, 2010; Gonthier, 2012).

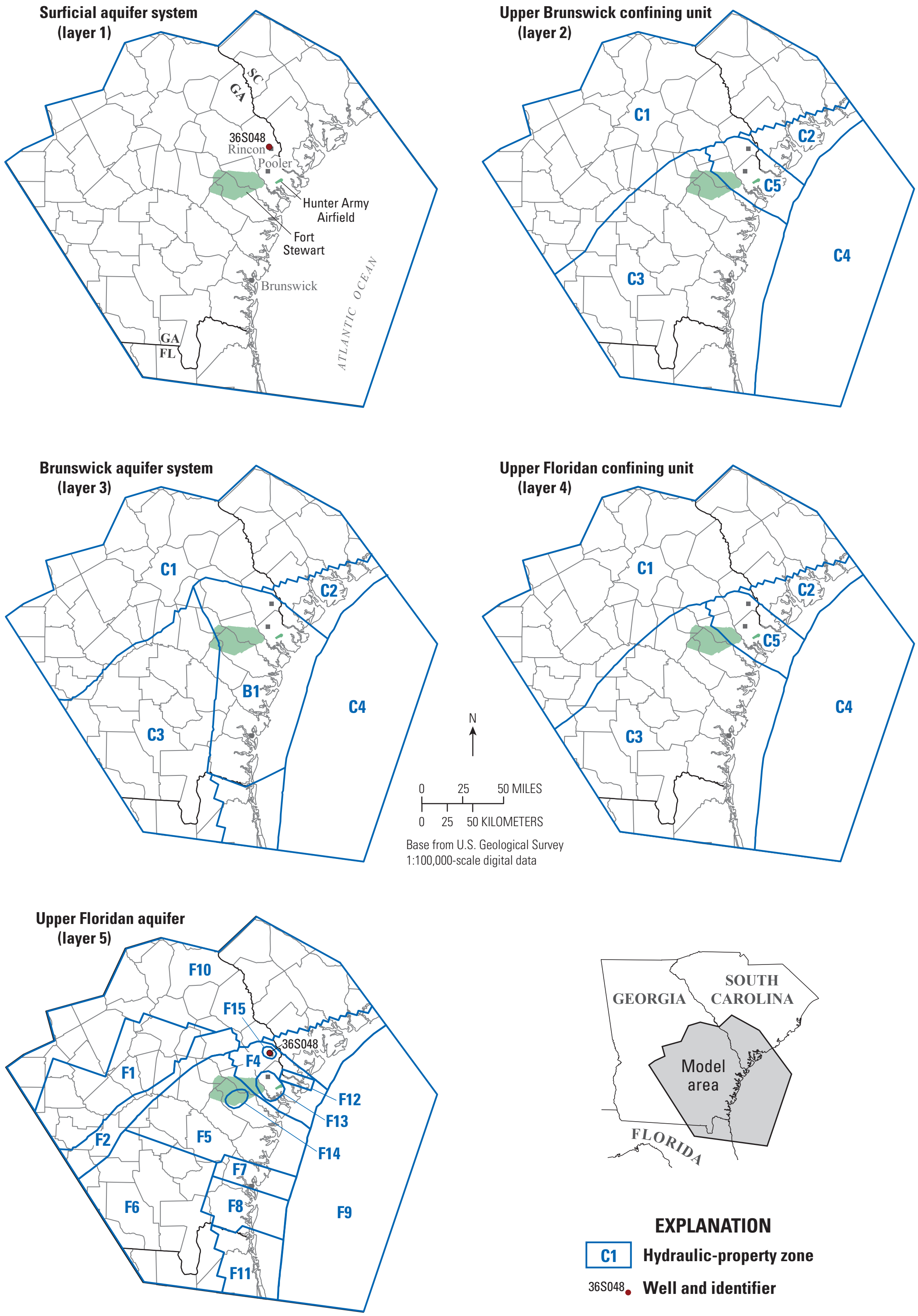

Figure 1–3. Simulated hydraulic property zones by model layer. Table 1–1 lists hydraulic conductivity values assigned to zones.

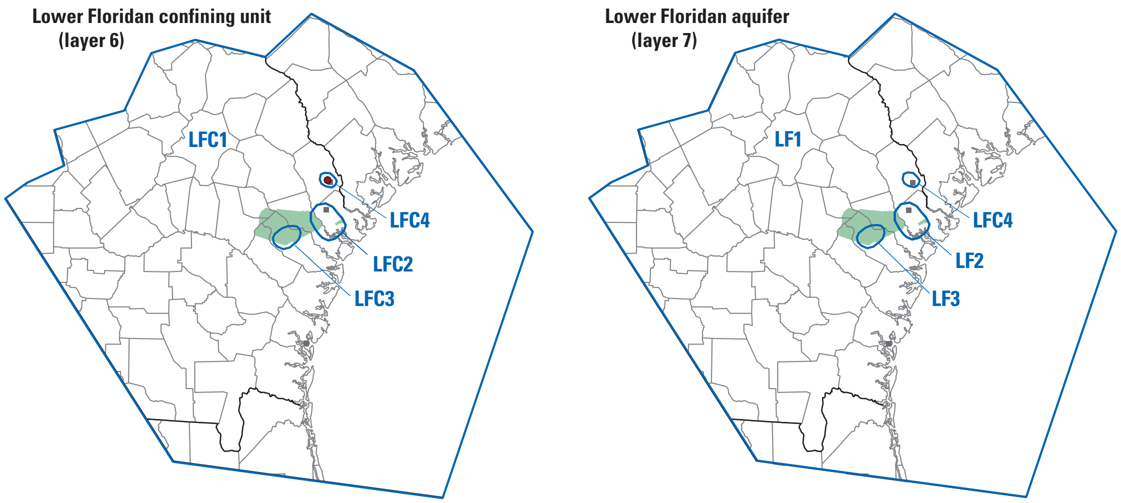

Figure 1–3. Simulated hydraulic property zones by model layer. Table 1–1 lists hydraulic conductivity values assigned to zones.—Continued

New hydraulic-property zones were developed for the study on the basis of field data collected by Carter and Sloope (2004), Gonthier (2012), and Clarke and others (2010, 2011), as described previously. Zones were added as follows (fig. 1–3; table 1–1):

- UFA (layer 5)—zone F13 added at Hunter Army Airfield and expanded outward to include Pooler, zone F14 added at Fort Stewart, and zone F15 added at Rincon.
- LFCU (layer 6)—zone LFC2 added at Hunter Army Airfield and expanded outward to include Pooler, zone LFC3 added at Fort Stewart, and zone LFC4 added at Rincon.
- LFA (layer 7)—zone LF2 added at Hunter Army Airfield and expanded outward to include Pooler, zone LF3 added at Fort Stewart, and zone LF4 added at Rincon.

The hydraulic-property zones surrounding Rincon in layers 5 through 7 each encompass a 34-mi^2 area that includes the area of highest grid resolution and wells evaluated by model simulations (fig. 1–3). Each zone was initially assigned a K_h and K_v value on the basis of results of field testing at or near each site. With the exception of K_v for the LFCU, values were adjusted slightly to calibrate to water-level changes in the UFA and LFA observed during 72-hour aquifer tests at the two sites. The highest value for K_v of the LFCU that was determined during a previous investigation at Hunter Army Airfield, 1.67 feet per day (ft/d; Williams, 2010), was assigned to this model parameter for layer 6, zone LFC4, located at Rincon. This value is about two orders of magnitude larger than the previous value of K_v (0.02 ft/d) used in the regional model by Payne and others (2005) for the Rincon area. The new K_v value was held constant at the request of the Georgia Environmental Protection Division to ensure simulation of conservative leakage rates; that is, rates that would yield the highest possible leakage, because K_v was not measured at Rincon. Areal hydraulic conductivity in and near Rincon for zone LFC4 was assigned a value of 14.2 ft/d, which was obtained by applying the 8.5:1 ratio of areal to vertical hydraulic conductivity reported at Hunter Army Airfield to the K_v value.

For the UFA (layer 5), a value of 45 ft/d was assigned to the areal hydraulic conductivity of zone 15. This value is slightly lower than the 70-ft/d value assigned in the original regional model; however, the product of this value and the simulated thickness of the aquifer yielded an estimated transmissivity of 15,500 feet squared per day (ft^2/d) at Rincon, which is 6.9 percent greater than the 14,500 ft^2/d value obtained from field testing by Carter and Sloope (2004).

Hydraulic properties for model layer 7, which represents the LFA, were represented with a single zone in the regional model of Payne and others (2005) having uniform K_h and K_v values of 10 ft/d. At Rincon, zone LF4 was assigned a K_h value of 20 ft/d and a K_v value of 2.4 ft/d. Multiplying the K_h value by the simulated thickness of the aquifer yields an estimated transmissivity of 3,830 ft^2/d, 55 percent greater than the 2,470-ft^2/d value derived from field testing at Rincon (Carter and Sloope, 2004).

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 model.

[—, not applicable]

Unit	Model 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 unit	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
		—	—	—	F15	45	45
Confining unit	6	—	0.02000	0.02000	LFC1	0.02000	0.02000
		—	—	—	LFC2	2.00000	0.2
		—	—	—	LFC3	10.00000	0.2
		—	—	—	LFC4	14.20000	1.67
Lower Floridan aquifer	7	—	10.0000	1	LF1	10	10
		—	—	—	LF2	87	10
		—	—	—	LF3	15.80000	1.6
		—	—	—	LF4	20	2.4

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 36S048 because the area of the grid cell containing the pumped well (10 square feet [ft^2]) is much larger than the area defined by the 12-inch well diameter (0.78 ft^2). Simulated drawdown at the pumped well can be adjusted on the basis of the proportional increase in area attributed to the grid cell relative to the area of the pumped well using the following equation (Peaceman, 1983):

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

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 (192,499);
- 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 (3,826); and
- T_{yy} is transmissivity in the *y* direction, in feet squared per day (3,826).

Results obtained using this equation indicated that simulated values of drawdown at the center of the grid cell containing pumped well 35S048 would under-represent the observed drawdown in the well by 18.4 ft for a pumping rate of 1,000 gallons per minute (gal/min). A similar analysis of a UFA well pumped at a rate of 292 gal/min, having the same radius as well 35S048 but with a value of 15,500 ft^2/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 1.33 ft. Simulated drawdown for the UFA and LFA were adjusted using these correction factors and compared with observed data 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 Rincon, a favorable 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 those for 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 areas covering 114.5 mi^2 at Fort Stewart, 221-mi^2 at Hunter Army Airfield and Pooler, and 34 mi^2 at Rincon, representing less than 1 percent of the model area.

The 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 (–2.59 ft), as shown on the residuals map and graphs (table 1–2, figs. 1–4*A*, 1–5). For layer 5 (UFA), the mean residual remained negative in the revised model, changing from –0.84 ft to –3.55 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 ft to 3.05 ft. The root mean square (RMS) of residuals for layer 5 was similar for the original (9.94 ft) and revised (10.5 ft) models. For layer 7, the RMS of residuals decreased from 9.15 ft in the regional model to 8.87 ft in the revised model.

The RMS of water-level residuals for layer 3 (11.1 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 RMS of residuals for layer 3 can be attributed to two wells in the Brunswick aquifer system that contained water-level residuals of nearly –19 ft each (figs. 1–4*A*, 1–5). These wells are located adjacent to one another in the same model cell and 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. This relatively large grid size and corresponding large water-level residuals were distant from the area of high grid resolution and the focus of the study at Rincon, and are assumed to only slightly influence simulated heads in the Rincon area. In the Rincon area, the revised model simulated groundwater levels for the Brunswick aquifer that were within 5 ft of measured water levels (fig. 1–4*A*), attesting to the relatively high accuracy of the revised model in the area of interest to this study.

Simulated water budgets for the regional and revised models compared favorably with most variation occurring in layers 1, 2, and 5 (table 1–3). The revised model showed a decrease in recharge from, and discharge to, the overlying general-head boundary in the surficial aquifer and Brunswick aquifer system confining unit (layers 1 and 2). In the UFA (layer 5), the revised model showed an increase in recharge from, and decrease in discharge to, the general-head boundary, and increased outflow and inflow along lateral specified-head boundaries. In the LFA (layer 7), inflow from the lateral specified-head boundary was slightly lower, and outflow to the lateral specified-head boundary was slightly higher.

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]

Aquifer	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	–18.5	13.3	14.4	1.79	–2.59	5.91	11.1
Upper Floridan aquifer	5	155	–44.4	–33.9	36.4	28.0	–0.84	–3.55	9.94	10.5
Lower Floridan aquifer	7	11	–3.62	–5.10	21.5	25.0	5.2	3.05	9.15	8.87

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 reported to three significant digits and 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	278	132	100	<0.001	<0.001	<0.001	<0.001
Confining unit	2	<0.001	<0.001	46.6	32.9	3.62	2.05	<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	147	22.3	19.6	712	843	268	386
Confining unit	6	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.004	0.005	<0.001	<0.001
Lower Floridan aquifer	7	129	129	<0.001	<0.001	<0.001	<0.001	15.5	15.1	2.32	2.62
Total all layers		**798**	**798**	**498**	**458**	**158**	**122**	**728**	**858**	**270**	**389**

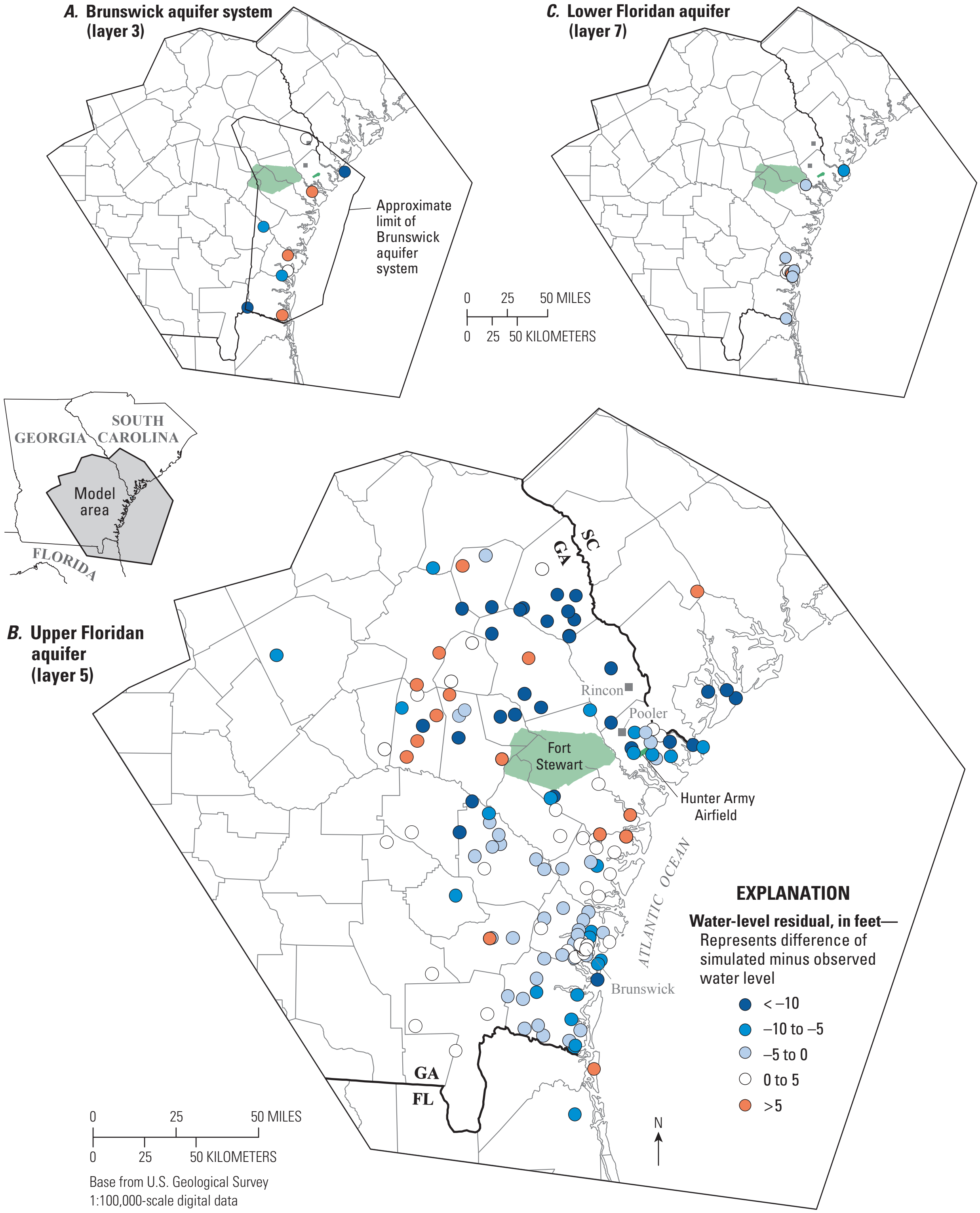

Figure 1–4. Difference between simulated and observed water levels (residuals) by model layer for 2000, revised regional flow model. *A*, Brunswick aquifer system (layer 3), *B*, Upper Floridan aquifer (layer 5), and *C*, Lower Floridan aquifer (layer 7).

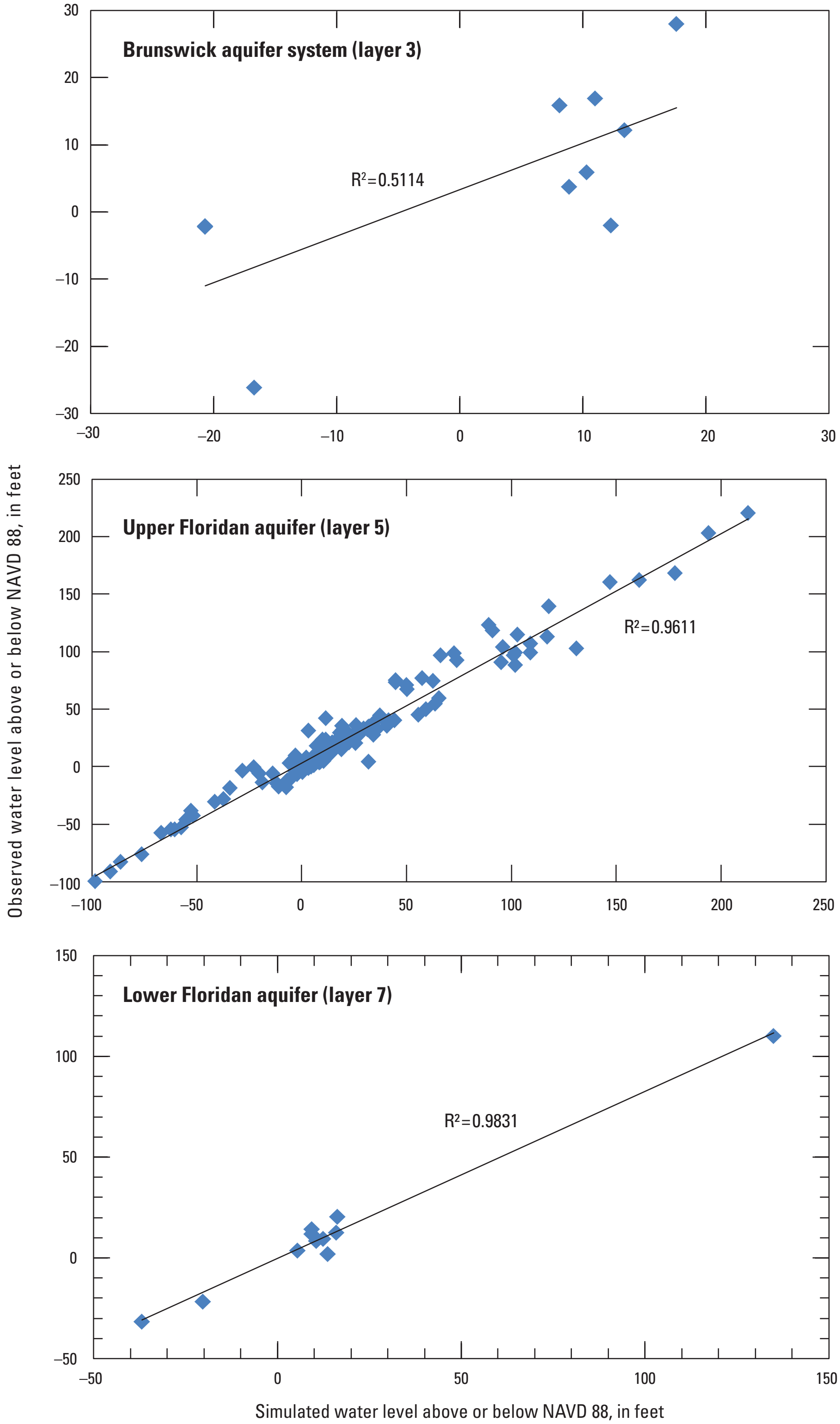

Figure 1–5. Observed and simulated water levels in model layers 3, 5, and 7, revised groundwater model.

Manuscript approved May 11, 2015

Prepared by the USGS Science Publishing Network
Raleigh Publishing Service Center
Edited by Michael Deacon
Illustrations and layout by Caryl J. Wipperfurth

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Cherry and Clarke—**Simulated Effects of Lower Floridan Aquifer Pumping on the Upper Floridan Aquifer at Rincon, Effingham County, Ga.**—Scientific Investigations Report 2015–5072

ISSN 2328–0328 (online)
http://dx.doi.org/10.3133/sir20155072