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Hydrogeology and Water Quality of the Floridan Aquifer System and Effects of Lower Floridan Aquifer Pumping on the Upper Floridan Aquifer at Fort Stewart, Georgia

Scientific Investigations Report 2011–5065

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

Cover. Drill rig used to install Lower Floridan aquifer production well, Fort Stewart, Georgia. Photograph by O. Gary Holloway, USGS.

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U.S. Department of the Interior
KEN SALAZAR, Secretary

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

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

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Conversion Factors and Datums

Multiply	By	To obtain
	Length	
inch	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
acre	0.004047	square kilometer (km^2)
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)	3.785	liter (L)
gallon (gal)	0.003785	cubic meter (m^3)
gallon (gal)	3.785	cubic decimeter (dm^3)
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)
gallon per day (gal/d)	0.003785	cubic meter per day (m^3/d)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
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 Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F = (1.8 \times °C) + 32$$

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

$$°C = (°F - 32) / 1.8$$

Vertical coordinate information is referenced 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.

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

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

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

Acronyms

ASTM	American Society for Testing and Materials
GaEPD	Georgia Environmental Protection Division
HAAF	Hunter Army Airfield
K_h	hydraulic conductivity
K_v	vertical conductivity
LFA	Lower Floridan aquifer
LFCU	Lower Floridan confining unit
MCL	primary maximum contaminant levels
RMSE	root mean square error
SMCL	secondary maximum contaminant level
UFA	Upper Floridan aquifer
U.S. Army	U.S. Department of the Army
USEPA	U.S. Environmental Protection Agency
USGS	U.S. Geological Survey

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Hydrogeology and Water Quality of the Floridan Aquifer System and Effects of Lower Floridan Aquifer Pumping on the Upper Floridan Aquifer at Fort Stewart, Georgia

By John S. Clarke, Gregory C. Cherry, and Gerard J. Gonthier

Abstract

Test drilling, field investigations, and digital modeling were completed at Fort Stewart, GA, during 2009–2010, to assess the geologic, hydraulic, and water-quality characteristics of the Floridan aquifer system and evaluate the effect of Lower Floridan aquifer (LFA) pumping on the Upper Floridan aquifer (UFA). This work was performed pursuant to the Georgia Environmental Protection Division interim permitting strategy for new wells completed in the LFA that requires simulation to (1) quantify pumping-induced aquifer leakage from the UFA to LFA, and (2) identify the equivalent rate of UFA pumping that would produce the same maximum drawdown in the UFA that anticipated pumping from LFA well would induce. Field investigation activities included (1) constructing a 1,300-foot (ft) test boring and well completed in the LFA (well 33P028), (2) constructing an observation well in the UFA (well 33P029), (3) collecting drill cuttings and borehole geophysical logs, (4) collecting core samples for analysis of vertical hydraulic conductivity and porosity, (5) conducting flowmeter and packer tests in the open borehole within the UFA and LFA, (6) collecting depth-integrated water samples to assess basic ionic chemistry of various water-bearing zones, and (7) conducting aquifer tests in new LFA and UFA wells to determine hydraulic properties and assess interaquifer leakage. Using data collected at the site and in nearby areas, model simulation was used to assess the effects of LFA pumping on the UFA.

Borehole-geophysical and flowmeter data indicate the LFA at Fort Stewart consists of limestone and dolomitic limestone between depths of 912 and 1,250 ft. Flowmeter data indicate the presence of three permeable zones at depth intervals of 912–947, 1,090–1,139, and 1,211–1,250 ft. LFA well 33P028 received 50 percent of the pumped volume from the uppermost permeable zone, and about 18 and 32 percent of the pumped volume from the middle and lowest permeable zones, respectively. Chemical constituent concentrations increased with depth, and water from all permeable zones contained sulfate at concentrations that exceeded the U.S. Environmental Protection Agency secondary maximum contaminant level of 250 milligrams per liter.

A 72-hour aquifer test pumped LFA well 33P028 at 740 gallons per minute (gal/min), producing about 39 ft of drawdown in the pumped well and about 0.4 foot in nearby UFA well 33P029. Simulation using the U.S. Geological Survey finite-difference code MODFLOW was used to determine long-term, steady-state flow in the Floridan aquifer system, assuming the LFA well was pumped continuously at a rate of 740 gal/min. Simulated steady-state drawdown in the LFA was identical to that observed in pumped LFA well 33P028 at the end of the 72-hour test, with values larger than 1 ft extending 4.4 square miles symmetrically around the pumped well. Simulated steady-state drawdown in the UFA resulting from pumping in LFA well 33P028 exceeded 1 ft within a 1.4-square-mile circular area, and maximum drawdown in the UFA was 1.1 ft. Leakage from the UFA through the Lower Floridan confining unit contributed about 98 percent of the water to the well; lateral flow from specified-head model boundaries contributed about 2 percent. About 80 percent of the water supplied to LFA well 33P028 originated from within 1 mile of the well, and 49 percent was derived from within 0.5 mile of the well. Vertical hydraulic gradients and vertical leakage are progressively higher near the LFA pumped well which results in a correspondingly higher contribution of water from the UFA to the pumped well at distances closer to the pumped well.

Simulated pumping-induced interaquifer leakage from the UFA to the LFA totaled 725 gal/min (1.04 million gallons per day), whereas simulated pumping at 205 gal/min (0.3 million gallons per day) from UFA well 33P029 produced the equivalent maximum drawdown as pumping LFA well 33P028 at 740 gal/min during the aquifer test. This equivalent pumping rate in the UFA underpredicts the area affected by vertical leakage resulting from pumping the new LFA well, and therefore underpredicts the pumping offset (reduction) required in the UFA to produce no net hydrologic effect on the UFA from pumping at the new LFA well. Two simulations that decreased pumping rates in existing UFA wells at Fort Stewart by a total of 205 and 370 gal/min while simultaneously pumping LFA well 33P028 at 740 gal/min reduced the magnitude and extent of drawdown in the UFA when compared with a simulation of pumping from well 33P028 without adjusting withdrawals at UFA wells.

Introduction

Fort Stewart is located in the coastal area of Georgia near the city of Hinesville, Liberty County (fig. 1). Water supply at the facility is derived from groundwater withdrawal from wells completed in the Upper Floridan aquifer (UFA). Concern over saltwater intrusion at Hilton Head Island, South Carolina, has resulted in increased restrictions by the Georgia Environmental Protection Division (GaEPD) on permitted groundwater withdrawals from the UFA. To meet growing demands for water in the coastal Georgia area, GaEPD has encouraged use of alternative sources of water to the UFA, including wells completed in the Lower Floridan aquifer (LFA). The U.S. Department of the Army (U.S. Army) seeks to provide for projected increased demand using a well completed in the LFA.

Because pumping from the LFA may increase the head gradient locally between the UFA and LFA, lower water levels in the UFA, and induce leakage (groundwater flow) from the UFA to the LFA, the GaEPD requires an assessment of these effects as a permitting requirement. In January 2003, GaEPD released an interim strategy for permitting LFA groundwater withdrawals in the 24-county coastal Georgia area (Nolton Johnston, Georgia Environmental Protection Division, written commun., January 28, 2003; fig. 1). The GaEPD permitting strategy states:

> "The applicant must demonstrate, using detailed aquifer testing and standard hydrogeological methods, that their LF [Lower Floridan] aquifer withdrawal does not induce downward leakage from the UF [Upper Floridan] aquifer and will have no net negative impact on water levels in the UF aquifer, or:
>
> "If the aquifer tests do show that there is an impact on water levels in the UF aquifer because of production from the LF aquifer, the applicant must calculate, using an approved hydrologic analysis, the UF contribution to the LF well. Then, using the information from the hydrogeological studies, the applicant must reduce nearby current UF withdrawals in an amount equal to any induced leakage from the UF into the LF. In other words, the applicant must offset the impact of the LF pumping by reducing nearby UF permitted pumping in the same general area (within a 5 mile (mi) radius) by an amount equal to or greater than the determined UF leakage. This will assure continued protection of the UF aquifer under the no net negative impact policy."

As part of the interim permitting strategy, GaEPD provided a hydrogeologic study protocol that states:

> "The applicant must conduct site-specific hydrogeological testing to obtain the data needed for development of a groundwater model capable of determining the contribution from the UFA that would result from the proposed withdrawal from the LFA. This information would be used to develop a new groundwater model, which would be run 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., January 28, 2003).

To assess the water-supply potential of the LFA at Fort Stewart, GA, the U.S. Geological Survey (USGS), in cooperation with the U.S. Army, conducted an investigation during 2009–2010 to determine the hydrogeology and water quality of the Floridan aquifer system and the potential effect that pumping from the LFA would have on the UFA. The study included construction of a test well in the LFA, detailed site investigations, and groundwater-modeling analyses.

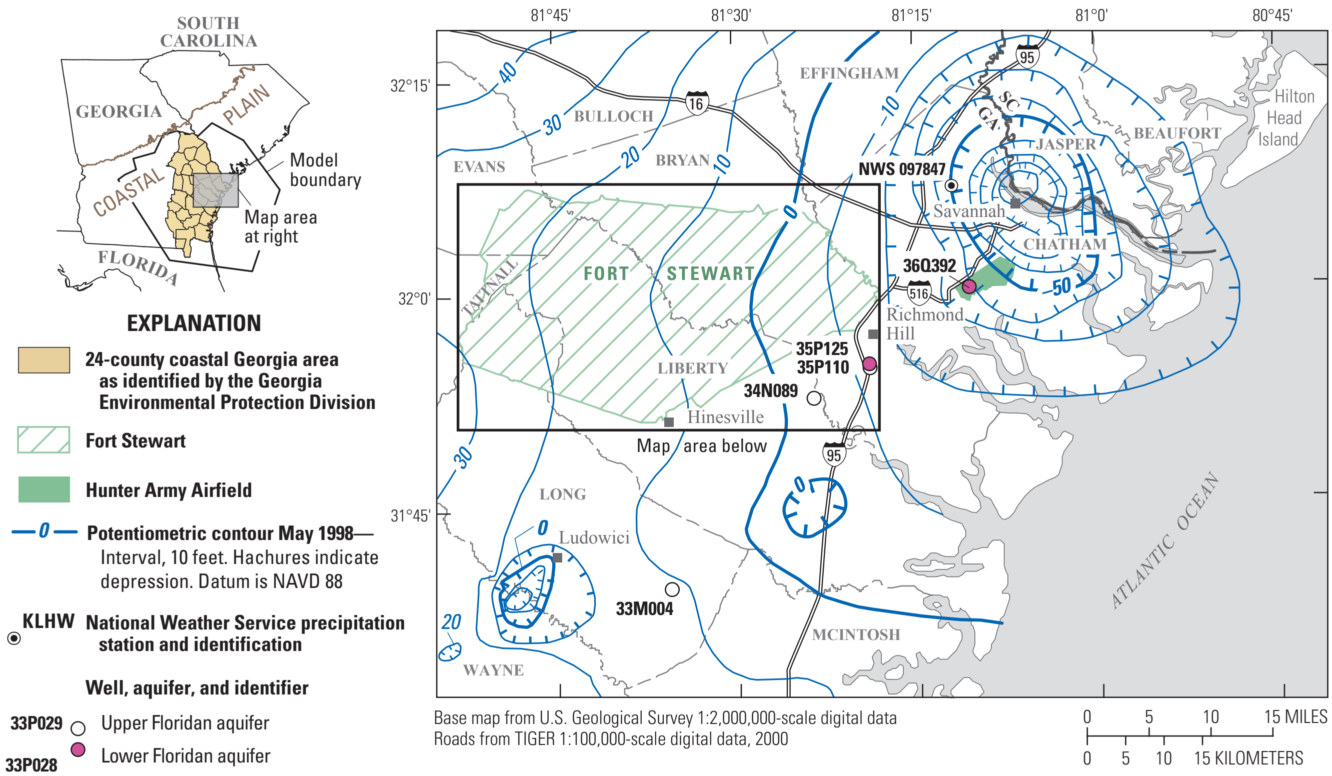
Purpose and Scope

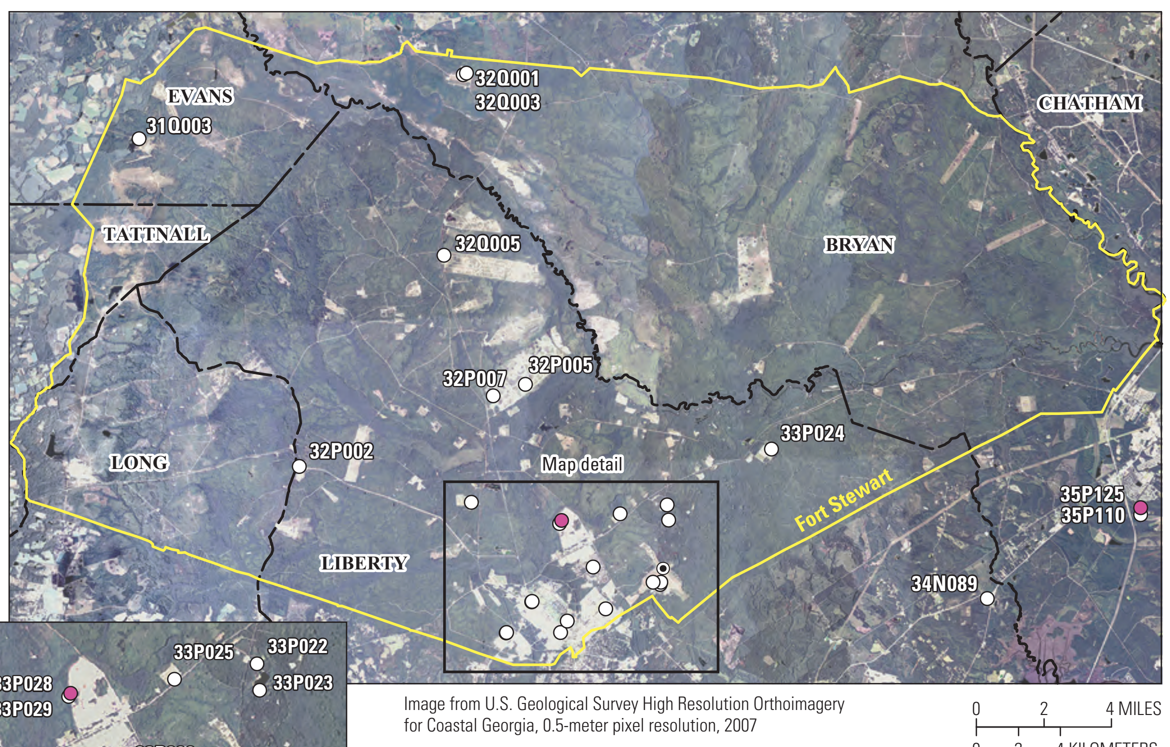
This report documents results of field investigations and groundwater-model simulations completed at Fort Stewart during 2009–2010 to determine the hydrogeology and water quality of the Floridan aquifer system and to provide data needed to assess the effect of LFA pumping on the UFA, specifically to

- Evaluate leakage response in a nearby well completed in the UFA to pumping from the LFA, and
- Quantify the amount of pumping reduction in the Upper Floridan well (or wells) required to offset pumping-induced leakage from the UFA into the LFA and mitigate drawdown in the UFA caused by pumping in the LFA.

Field investigations included:

- Boring a 1,300-foot (ft) test hole and constructing a 1,255-ft test well completed in the LFA;
- Collecting drill cuttings and borehole geophysical logs at the test well;
- Sampling core for analysis of vertical hydraulic conductivity and porosity;
- Performing flowmeter and packer tests in the open borehole within the UFA and LFA in the test well;
- Collecting depth-integrated water samples to assess chemistry of various water-bearing zones; and
- Testing the LFA at the test well and existing UFA wells to determine hydraulic properties and assess interaquifer leakage.





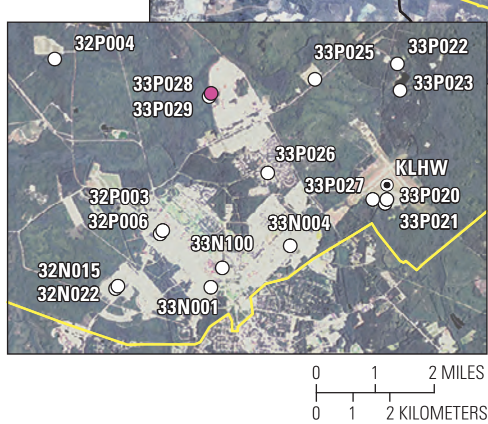


Figure 1. Location of study and model area, selected wells, and weather stations at Fort Stewart and vicinity, GA (potentiometric contours modified from Peck and others, 1999).

The effects of interaquifer leakage on the UFA were quantified through simulation using a modified groundwater-flow model of coastal Georgia (Payne and others, 2005). The groundwater model was used to quantify the amount of pumping reduction required in the UFA to offset drawdown and leakage resulting from pumping a new LFA well.

Previous Studies

The USGS, in cooperation with U.S. Army, investigated the Floridan aquifer system at Hunter Army Airfield in Chatham County, about 25 mi northeast of Fort Stewart (Clarke and others, 2010; Williams, 2010). The scope of that investigation, conducted during 2009, included field investigations and groundwater-model simulations to determine the hydrogeology and water quality of the Floridan aquifer system and to provide data needed to assess the effect of LFA pumping on the UFA. The scope of the current investigation at Fort Stewart is identical to the earlier investigation at Hunter Army Airfield.

Gonthier (2011) presented results of hydrologic testing of the Floridan aquifer system at Fort Stewart. This report included descriptions of data collection, results of the analysis of aquifer tests and packer-slug tests conducted during 2009–2010, and evaluation of drawdown response based on filtered water-level data. Data and information from the Gonthier (2011) report served as a basis for model simulations described in this report.

A revised hydrogeologic framework for the Floridan aquifer system was developed by Williams and Gill (2010) for eight northern coastal counties in Georgia and five coastal counties in South Carolina, including the area surrounding Fort Stewart, 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 Upper and Lower Floridan aquifers and of the individual permeable zones that compose these aquifers. These revised boundaries conform to those used at Fort Stewart for the current investigation.

Site Description

Fort Stewart and Hunter Army Airfield are home to the 3rd Infantry Division. Fort Stewart is the focus of this investigation, encompassing 280,000 acres including parts of Liberty, Long, Tattnall, Evans, and Bryan Counties (*http://www.stewart.army.mil/about/facts.asp*, accessed on September 3, 2010; fig. 1). The site is located in the Coastal Plain and is characterized by flat topography, with sandy topsoil typical of the Georgia coastal area. The test-drilling site is located at an altitude of about 82 ft (North American Vertical Datum of 1988; NAVD 88) in the south-central part of Fort Stewart in Liberty County. Here, static (non-pumping) water levels in the UFA exist at an altitude of about –5 ft (NAVD 88), or a depth of 85 ft below land surface.

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 (097847, fig. 1; Southeast Regional Climate Center, 2010). During 1971–2000, precipitation at station 097847 averaged about 49 inches per year (in/yr). Maximum monthly rainfall (exceeding 4 inches per month) generally occurs during 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 during April–August.

Water Use

Water supply at Fort Stewart is provided by 20 wells completed in the UFA, with a GaEPD permit limit of 5.5 million gallons per day (Mgal/d) as a monthly average and 4.5 Mgal/d as an annual average (William Frechette, Georgia Environmental Protection Division, written commun., February 11, 2010). Most of the production is derived from five wells located on the main post, with the remaining water withdrawn at scattered locations throughout the facility. During 2008, average monthly withdrawals ranged from 1.57 to 2.97 Mgal/d, with an annual average withdrawal of 2.14 Mgal/d (table 1). Average annual withdrawals during 1980–2008 ranged from a high of 4.10 Mgal/d in 1987, to a low of 1.99 Mgal/d in 2005.

Hydrogeologic Setting

The 24-county coastal Georgia area (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, in order of descending depth: the surficial aquifer system, the Brunswick aquifer system, and the Floridan aquifer system (fig. 2).

In the coastal area, the surficial aquifer system (fig. 2) consists of Miocene and younger interlayered sand, clay, and thin limestone beds (Clarke, 2003). At Fort Stewart, the surficial aquifer consists of an unconfined zone extending to depths between 20 and 40 ft, and a confined zone between depths of 50 and 90 ft. A supply well completed in a confined zone of the surficial aquifer at Fort Stewart was test pumped at rates of 500–550 gal/min in 2010. Elsewhere in coastal Georgia, the surficial aquifer system includes a water-table zone and two confined zones; however, the areal extent of the confined 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.

Table 1. Average daily groundwater withdrawal at Fort Stewart, Georgia, 1980–2008.

[Data from U.S. Geological Survey, unpublished data from Georgia Water Science Center files, 2010; —, no data]

Year	Average withdrawal, in million gallons per day												
	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual average
1980	1.75	2.04	1.85	2.38	2.98	3.19	3.55	3.23	2.65	2.24	2.07	1.88	2.48
1981	1.98	2.11	2.03	2.44	2.82	3.20	3.16	2.55	2.50	2.14	2.07	1.97	2.41
1982	2.25	2.23	2.26	2.58	3.54	3.46	2.98	3.02	2.76	2.30	2.19	1.95	2.63
1983	2.27	2.34	2.38	0.57	—	—	—	—	—	—	—	—	—
1984	—	—	—	—	—	—	—	—	—	2.79	2.81	2.62	—
1985	3.07	3.11	3.16	3.62	4.24	4.39	3.94	3.96	3.75	3.45	3.07	3.40	3.60
1986	3.48	3.53	3.49	3.98	4.78	4.95	4.98	4.41	4.03	4.06	3.61	3.34	4.05
1987	3.61	3.53	3.78	4.28	4.50	4.53	4.81	4.86	4.70	3.80	3.39	3.44	4.10
1988	3.38	3.58	3.64	3.55	3.99	4.39	4.20	3.87	3.67	3.14	3.05	2.58	3.59
1989	2.78	2.77	2.96	3.49	3.44	4.14	3.16	3.67	3.41	3.03	2.91	3.17	3.24
1990	2.94	2.64	2.89	3.03	3.88	4.33	4.06	3.65	3.56	2.86	2.63	2.43	3.24
1991	2.21	2.30	2.67	2.56	2.71	2.92	2.83	3.48	2.83	3.10	2.70	2.48	2.73
1992	2.88	2.90	2.71	2.45	3.06	2.97	3.13	2.78	2.66	—	—	—	2.84
1993	—	—	—	2.43	2.75	3.29	3.70	3.04	2.63	2.48	2.08	2.19	2.73
1994	2.29	2.24	2.41	—	—	—	—	—	—	2.32	2.17	2.30	—
1995	2.03	2.42	2.33	2.59	3.02	2.62	2.61	2.52	2.43	2.23	2.04	2.11	2.41
1996	2.25	2.50	2.37	2.46	3.01	2.93	2.65	2.65	2.63	2.55	2.28	2.42	2.56
1997	2.57	2.53	2.48	2.59	2.69	—	2.71	2.60	2.59	2.29	2.29	2.22	2.30
1998	2.19	2.16	2.33	2.25	2.67	3.43	3.19	2.92	3.02	2.44	2.33	2.13	2.59
1999	2.41	2.35	2.34	2.83	2.97	2.93	2.63	3.01	2.58	2.41	2.27	2.15	2.57
2000	2.28	2.46	2.36	2.32	3.12	3.06	2.59	2.66	2.56	2.23	1.78	2.06	2.46
2001	2.12	2.11	2.05	2.30	2.99	2.40	2.47	2.65	2.44	2.38	2.46	2.19	2.38
2002	2.39	2.31	2.41	2.48	2.91	2.86	2.86	2.74	2.58	2.18	1.93	1.82	2.46
2003	2.26	2.14	2.10	2.09	2.27	2.18	2.22	2.47	2.42	2.43	2.54	2.25	2.28
2004	2.42	2.28	2.07	2.33	2.63	2.48	2.51	2.49	2.32	2.40	2.27	2.15	2.36
2005	2.21	2.09	2.00	1.93	1.88	1.90	2.10	2.15	2.18	1.87	1.93	1.60	1.99
2006	1.80	1.82	2.20	2.78	2.97	3.00	3.03	3.07	2.69	2.65	2.37	2.26	2.55
2007	2.42	2.27	2.52	2.87	2.84	2.41	2.33	2.19	2.14	1.87	1.84	1.69	2.28
2008	1.82	1.57	1.69	2.07	2.69	2.97	2.41	2.22	2.39	2.30	1.85	1.65	2.14
Minimum	**1.75**	**1.57**	**1.69**	**0.57**	**1.88**	**1.90**	**2.10**	**2.15**	**2.14**	**1.87**	**1.78**	**1.60**	**1.99**
Average	**2.45**	**2.46**	**2.50**	**2.64**	**3.13**	**3.24**	**3.11**	**3.03**	**2.85**	**2.59**	**2.41**	**2.31**	**2.73**
Maximum	**3.61**	**3.58**	**3.78**	**4.28**	**4.78**	**4.95**	**4.98**	**4.86**	**4.70**	**4.06**	**3.61**	**3.44**	**4.10**

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

The Miocene Brunswick aquifer system (fig. 2) consists of two water-bearing zones—the upper Brunswick aquifer and the lower Brunswick aquifer (Clarke, 2003). The upper Brunswick aquifer consists of poorly sorted, fine to coarse, slightly phosphatic and dolomitic, quartz sand and dense, phosphatic limestone (Clarke and others, 1990). The lower Brunswick aquifer consists of poorly sorted, fine to coarse, phosphatic and dolomitic Oligocene and Miocene sand (Clarke and others, 1990). At the city of Ludowici, in Long County southwest of Fort Stewart, the upper Brunswick aquifer consists of about 40 ft of medium sand, whereas the lower Brunswick aquifer consists of about 85 ft of clayey sand (Priest and Cherry, 2007). The aquifers are separated by a 70-ft-thick confining unit consisting of clay and sand. A well completed in the upper and lower Brunswick aquifers yielded between 580 and 650 gal/min during a 24-hour test in July 2003 (Priest and Cherry, 2007). 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 water for all uses (excluding thermoelectric) in the coastal area of Georgia is the Floridan aquifer system. The Floridan aquifer system is composed of carbonate rocks of varying permeability that are separated into several water-bearing zones by layers of relatively dense limestone that act as semiconfining units. These semiconfining units allow some vertical leakage of groundwater between the permeable zones.

In the Savannah–Hilton Head Island area, McCollum and Counts (1964) identified five water-bearing zones in strata that would later be defined as part of the Floridan aquifer system. The two shallowest of these water-bearing zones are part of the UFA, and the deeper three are part of the LFA (Krause and Randolph, 1989; Williams and Gill, 2010). In Beaufort County, SC, the term *middle Floridan aquifer* is used by the State of South Carolina (Ransom and White, 1999) for a water-bearing zone approximately 250–550 ft below land surface that is equivalent to zones 3 and 4 of McCollum and Counts (1964). This zone is presently included in the Lower Floridan aquifer (Williams and Gill, 2010).

The UFA is overlain by a confining unit (fig. 2) consisting of layers of silty clay and dense phosphatic Oligocene dolomite that separate the aquifer from overlying permeable units of the Brunswick aquifer system. Reported vertical hydraulic conductivity of this confining unit, based on laboratory analysis of core, ranges from 2.3×10^{-4} to 3.0 feet per day (ft/d; Clarke and others, 2004).

The UFA (fig. 2) is highly productive and consists of Eocene to Oligocene limestone and dolomite. Williams and Gill (2010) reported ranges in aquifer thickness in Liberty County from 200 to 250 ft. Reported transmissivity of the UFA in Liberty County ranges from 124,000 to 160,000 feet squared per day (ft^2/d; Clarke and others, 2004). Zones of very high hydraulic conductivity exist within relatively thin intervals of the Floridan aquifer system, especially in the UFA (Clarke and others, 2004).

The UFA is underlain by the Lower Floridan confining unit (LFCU) consisting of dense, recrystallized middle Eocene limestone and dolomitic limestone that hydraulically separates, to varying degrees, the UFA from the LFA (fig. 2). Counts and Donsky (1963) reported that the vertical hydraulic conductivity of this confining unit was 6.7×10^{-4} ft/d on the basis of laboratory analysis of a single core. The position and thickness of the LFCU was recently remapped in the area on the basis of flowmeter and borehole geophysical logs (Williams and Gill, 2010). The middle confining unit is about 200 to 250 ft thick in Liberty County and lies at an altitude between about –550 and –700 ft NAVD 88.

The LFA is composed of middle Eocene limestone and dolomitic limestone. In Liberty County, the LFA occurs at altitudes ranging from about –700 to –950 ft NAVD 88, and has a reported thickness of 450 to 600 ft (Williams and Gill, 2010). Reported transmissivity of the LFA at sites in Chatham, Bryan, and McIntosh Counties, GA, ranged from 6,000 to 8,300 ft^2/d (Clarke and others, 2004). A well completed in the LFA at Hunter Army Airfield in Chatham County had a transmissivity of 11,000 ft^2/d (Williams, 2010).

The LFA is underlain by lower Eocene marl of low permeability (Williams and Gill, 2010), which Falls and others (2005) describe as a semi-indurated, fine-grained mixture of carbonate, clay, silt, and sand that generally is dominated by clay and silt. In parts of the coastal area, the base of the Floridan aquifer system and the underlying marl is recognized on natural-gamma logs by a sharp increase in counts per second from carbonate strata to the marl (Falls and others, 2005).

The permeability of the Floridan aquifer system is reduced in the vicinity of the Gulf Trough (fig. 3)—a zone of relatively thick accumulations of fine-grained clastic sediments and clay-bearing carbonates where the permeability of early Tertiary through Miocene Coastal Plain deposits decreases. In this area, groundwater flow is partially impeded by the juxtaposition of rocks of higher permeability updip and downdip from the Trough, with rocks of lower permeability within the Trough (Krause and Randolph, 1989).

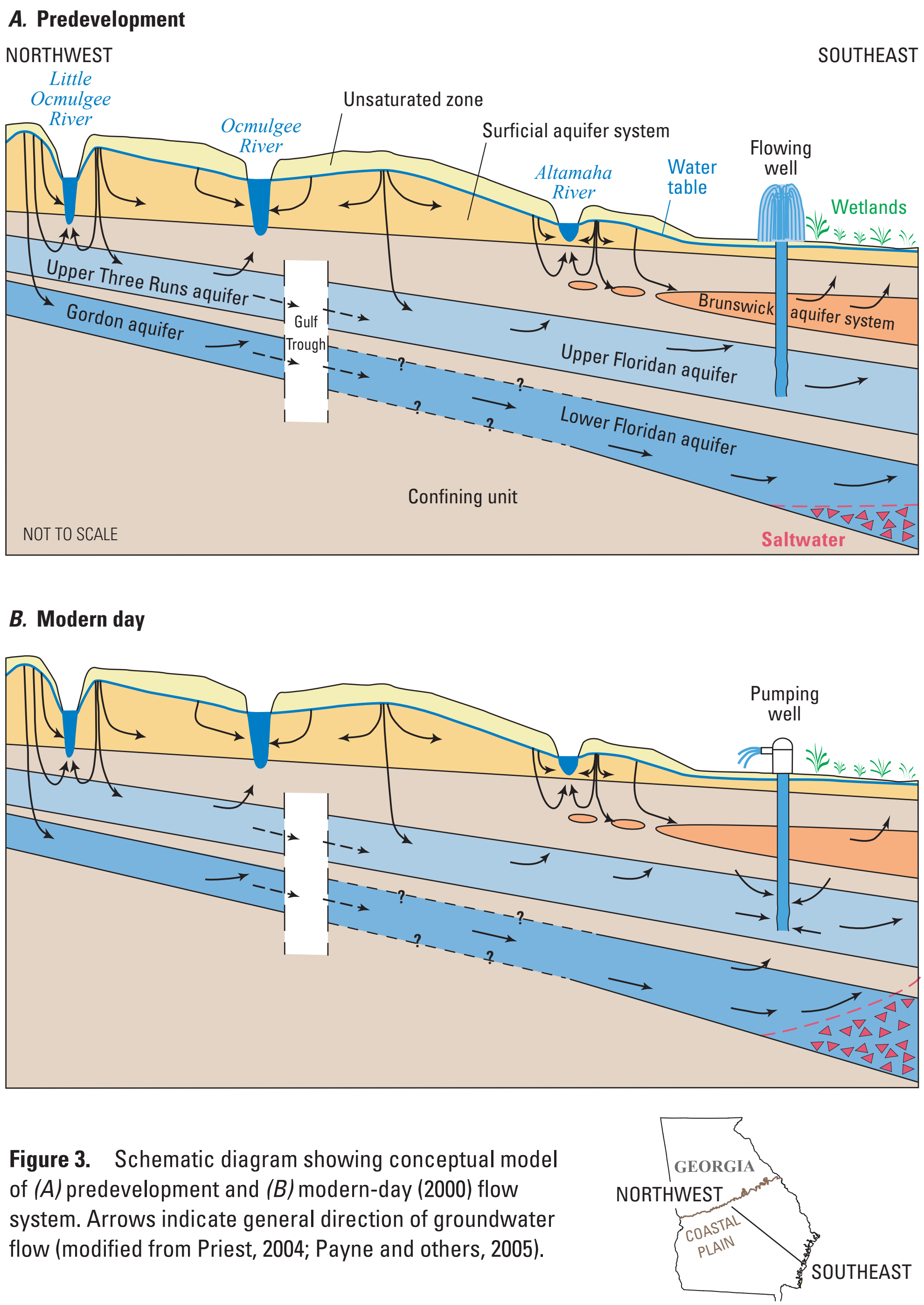


Figure 3. Schematic diagram showing conceptual model of *(A)* predevelopment and *(B)* modern-day (2000) flow system. Arrows indicate general direction of groundwater flow (modified from Priest, 2004; Payne and others, 2005).

Groundwater Flow

Groundwater flow in the Floridan aquifer system mainly is controlled by rates 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) flow systems in coastal Georgia (fig. 3) 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 balanced discharge and potentiometric surfaces were considered nearly static from year to year.

The modern-day flow system reflects changes that have occurred as a result of groundwater development (withdrawal; fig. 3*B*). Groundwater withdrawal has lowered water levels, induced additional recharge from vertical leakage and regional flow, reduced natural discharge, and degraded the quality of water in places along the coast. An extensive cone of depression has developed in the potentiometric surface of the UFA in the Savannah area (fig. 1). This cone of depression has affected groundwater flow at Fort Stewart, as evidenced by the arcuate shape of potentiometric contours indicating groundwater flow toward the center of the cone of depression.

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 substantial groundwater-level decline and subsequent saltwater intrusion into the UFA at Brunswick, GA, from underlying strata containing highly saline water, and encroachment of seawater into the UFA at the northern end of Hilton Head Island, SC. 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.

Well Identification

In this report, wells are identified by a USGS numbering system based on the index of USGS topographic maps (such as 33PQ028). 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 33P028 is the 28th well inventoried in the Trinity quadrangle (map 33P).

Hydrogeology and Water Quality of the Floridan Aquifer System

To assess the hydrogeology and water quality of the Floridan aquifer system at Fort Stewart, multidiscipline site investigations were performed during 2009–2010 to collect and analyze geologic, geophysical, hydrologic, climatological, and water-chemistry data. Analysis of these data provided a basis for refining prior conceptualization of the flow system and for developing model inputs for simulating interaquifer flow within the Floridan aquifer system.

Methods of Data Collection and Analysis

To assess the hydrogeology and water quality of the Floridan aquifer system at Fort Stewart, site investigations were completed during 2009–2010, including drilling a 1,300-ft test boring followed by construction of a new 1,255-ft well (33P028) completed in the LFA (fig. 1). An observation well was constructed in the UFA (33P029) adjacent to the new LFA well. Well construction and location information for all wells used during this study are listed in table 2. Data collection in the new test wells included borehole geophysical logs, flowmeter testing, water-quality sampling and analysis, core hydraulic analysis, packer-slug tests, and aquifer tests. These data were synthesized into a modified regional groundwater model used to simulate effects of LFA pumping on the UFA.

Test Drilling and Well Installation

An LFA test well (33P028) was drilled and installed at Fort Stewart during October 2009–January 2010 (table 3). Drilling occurred in several stages to accommodate collecting core, conducting geophysical logging, and completing various hydraulic tests. A test borehole was drilled using (1) hydraulic mud-rotary methods and a bentonite-based drilling fluid through unconsolidated sediments to a depth of 460 ft, and (2) reverse-air rotary methods through consolidated limestone of the UFA and LFA to a depth of 1,300 ft.

Table 2. Well-construction and location information for selected wells at Fort Stewart and vicinity, Georgia.

[—, data not available; UFA, Upper Floridan aquifer; LFA, Lower Floridan aquifer]

County	Well identifier	Well name	Latitude	Longitude	Altitude, in feet above NAVD 88	Open interval, in feet below land surface		Year drilled	Aquifer	Reported yield, in gallons per minute
			Decimal degrees (NAD 83)			Top	Bottom			
Bryan	32Q001	Ft. Stewart 9 Tac X	32.102344	–81.657119	81	403	570	—	UFA	165
Bryan	35P110	Richmond Hill UF TW	31.911944	–81.316389	9.52	315	441.25	2000	UFA	—
Bryan	35P125	CSSI Richmond Hill modified LF well	31.912000	–81.316278	11	1,010	1,095	2006	LFA	—
Chatham	36Q392	U.S. Army HAAF 11	32.001400	–81.172500	19	703	1,112	2009	LFA	750
Evans	31Q003	Ft. Stewart 08 Camp Oliver (T15003)	32.077420	–81.822059	124.24	451	706	1979	UFA	300
Liberty	33N001	Ft. Stewart 01 (P00933)	31.862987	–81.613446	88.08	451	816	1940	UFA	2,000
Liberty	32P003	Ft. Stewart 3 (P01325)	31.876289	–81.627775	67	436	750	—	UFA	863
Liberty	33N100	Ft. Stewart 02 (bldg 456)	31.867709	–81.610112	85.04	436	762	1942	UFA	—
Liberty	33N004	Ft. Stewart 04 (bldg 9961)	31.872709	–81.590390	77.06	439	805	1942	UFA	1,317
Liberty	32N015	Ft. Stewart 05 (bldg 4524)	31.863144	–81.640989	68	560	779	—	UFA	—
Liberty	32P002	Ft. Stewart 07 Taylors Creek (T16009)	31.936039	–81.744003	94	360	468	1955	UFA	500
Liberty	33P024	Ft. Stewart 10 Evans Army Heliport (T19107)	31.939486	–81.504950	30	404	600	—	UFA	118
Liberty	33P025	Ft. Stewart 14 Bravo–Clifford Range	31.913150	–81.582269	88	420	520	1999	UFA	90
Liberty	33P020	USA Ft. Stewart 6A Wright Airfield E Lowe Cir (T07731)	31.882603	–81.562736	42	374	472	—	UFA	500
Liberty	33P021	USA Ft Stewart 6B Wright Airfield W Lowe Cir (T07732)	31.883669	–81.566353	42	393	508	—	UFA	435
Liberty	32P004	Ft. Stewart 11 Ammo Supply Point	31.919002	–81.657861	60	—	500	—	UFA	75
Liberty	33P022	Ft. Stewart 12b Holbrook Pond Skeet Range	31.910566	–81.557616	42	—	605	—	UFA	80
Liberty	33P023	Ft. Stewart 12a Holbrook Pond Campground	31.916813	–81.558422	45	—	605	—	UFA	80
Liberty	32P007	Ft. Stewart 13 DMPRC	31.964719	–81.645269	65	400	505	2009	UFA	275
Liberty	32P005	Ft. Stewart 15 Red Cloud Golf (abandoned)	31.969453	–81.628720	61	—	—	—	UFA	—
Liberty	33P026	Ft. Stewart 16 Brittin Elem School (abandoned)	31.890572	–81.598150	82	—	—	—	UFA	—
Liberty	32Q005	Ft. Stewart 17 Red Cloud Alpha	32.041516	–81.667514	70	—	—	—	UFA	—
Liberty	33P028	Ft. Stewart IBCT Lower Floridan Production well	31.909531	–81.612939	81.76	895	1,255[a]	2010	LFA	740
Liberty	33P029	Ft. Stewart IBCT Upper Floridan	31.909461	–81.612931	80.41	460	560	2010	UFA	387
Liberty	34N089	U.S. Geological Survey, test well 1	31.870767	–81.397887	16.01	410	789	1967	UFA	—
Long	33M004	U.S. Geological Survey, test well 3	31.648550	–81.600944	60.3	538	870	1967	UFA	—

[a] Original borehole depth 1,300 feet; backfilled to 1,255 feet.

Table 3. Drilling stage, logging, and testing procedures for Lower Floridan aquifer well 33P028, Fort Stewart, Georgia, 2009–2010.

Drilling stage	Testing/remarks
Stage 1: drilled a 32-inch-diameter hole with mud-rotary methods to 150 feet; set and grouted 26-inch-diameter steel casing to 150 feet	No logs collected in this interval.
Stage 2: drilled a 25-inch-diameter hole with mud-rotary methods to 460 feet; set and grouted 20-inch-diameter steel casing to 460 feet	Caliper and electric logs collected in mud-rotary hole prior to setting casing.
Stage 3: drilled 12.25-inch-diameter pilot hole with reverse air-rotary methods to 1,300 feet	Caliper, electric, acoustic, and optical televiewer, and full-wave sonic logs collected in water-filled hole; ambient and pumping flowmeter traverses were run to determine the depth and yield of water-bearing zones and identify confining bed; packer tests completed in the confining bed; spot core samples collected at selected intervals during drilling; drilling fluids monitored for specific conductance changes.
Stage 4: reamed pilot hole to 19-inch diameter to a depth of 895 feet and set and grouted 14-inch-diameter steel casing to 895 feet	Casing set to occlude Upper Floridan aquifer and Lower Floridan confining unit; no logs collected during this stage.
Stage 5: cleaned out bottom part of hole from 895 to 1,300 feet	Removed cuttings from bottom part of hole for final development and well completion; ambient and pumping flowmeter traverses were run to confirm depth and yield of water-bearing zones in the completed well.
Stage 6: backfilled borehole from 1,300 to 1,255 feet	Conducted 72-hour aquifer test and collected final water sample following emplacement of backfill.

During drilling, rock cuttings were collected every 10 ft from land surface to the bottom of the borehole, and changes in drill-bit-penetration rates and the specific conductance of drilling fluids were monitored and recorded. Changes in drill-bit-penetration rates were compared to lithologic changes observed in cuttings to assist in determining the depth intervals of contacts between rock units and voids, including solution cavities. In the open borehole, packer tests and ambient/pumping flowmeter traverses were conducted, and grab water samples were collected. These data were critical in determining depths of the confining unit and water-bearing zones, and groundwater quality. Using this information, casing was installed to a depth of 895 ft, and the well was backfilled to a total depth of 1,255 ft, leaving an open-hole interval of 895–1,255 ft (fig. 4*A*).

A second well (33P029) was completed in the UFA at the test site during January–February 2010 (table 2; fig. 4*B*). Data collected from this well provided information on the hydraulic characteristics of the UFA, and was used as an observation well to monitor any leakage response during a 72-hour aquifer test conducted in the LFA well.

Borehole Geophysical Logs

Borehole-geophysical logs were collected at various stages of drilling well 33P028 to characterize the physical properties of sediments and rock penetrated (fig. 5). The first set of logs was collected in the 0–460 ft interval where mud-rotary drilling was used to penetrate clastic sediments. The second set of logs was collected in the carbonate 460–1,300 ft interval, following installation of 20-inch-diameter casing to a depth of 460 ft. In both intervals, the following logs were collected: caliper (not shown for 0–460 ft interval); natural gamma; spontaneous potential; single-point, lateral, long- and short-normal resistivity; borehole-fluid resistivity, and temperature. In the deeper carbonate interval, full-waveform-sonic, acoustic-televiewer, and optical-televiewer logs were collected but are not shown in this report. Locations of permeable zones in the hydrogeologic units were indicated by sharp signal increases on formation resistivity logs (single-point, lateral, and long- and short-normal resistivity) which were verified later through flowmeter testing.

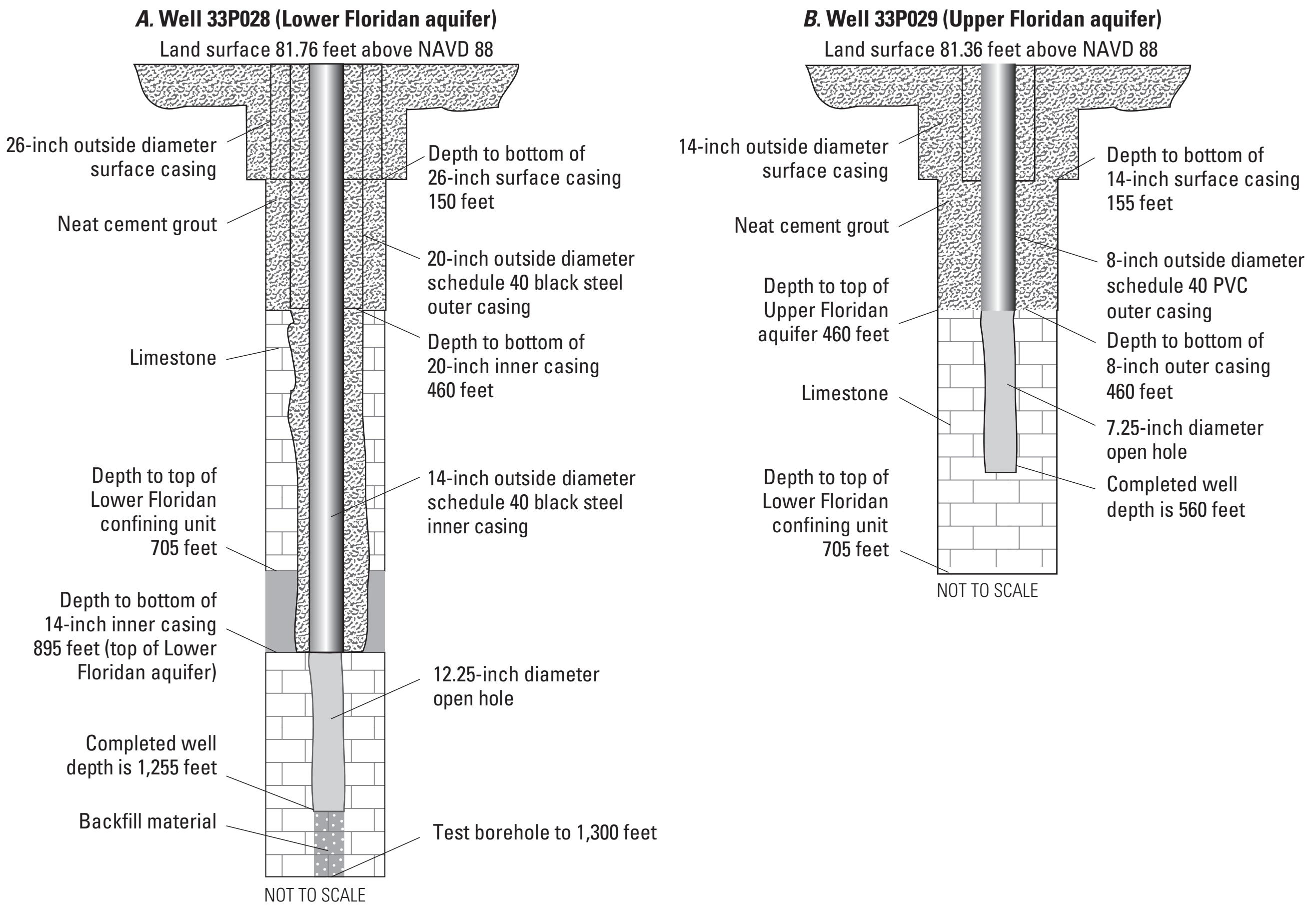


Figure 4. Well-construction diagrams for wells *(A)* 33P028 and *(B)* 33P029, Fort Stewart, GA, 2010.

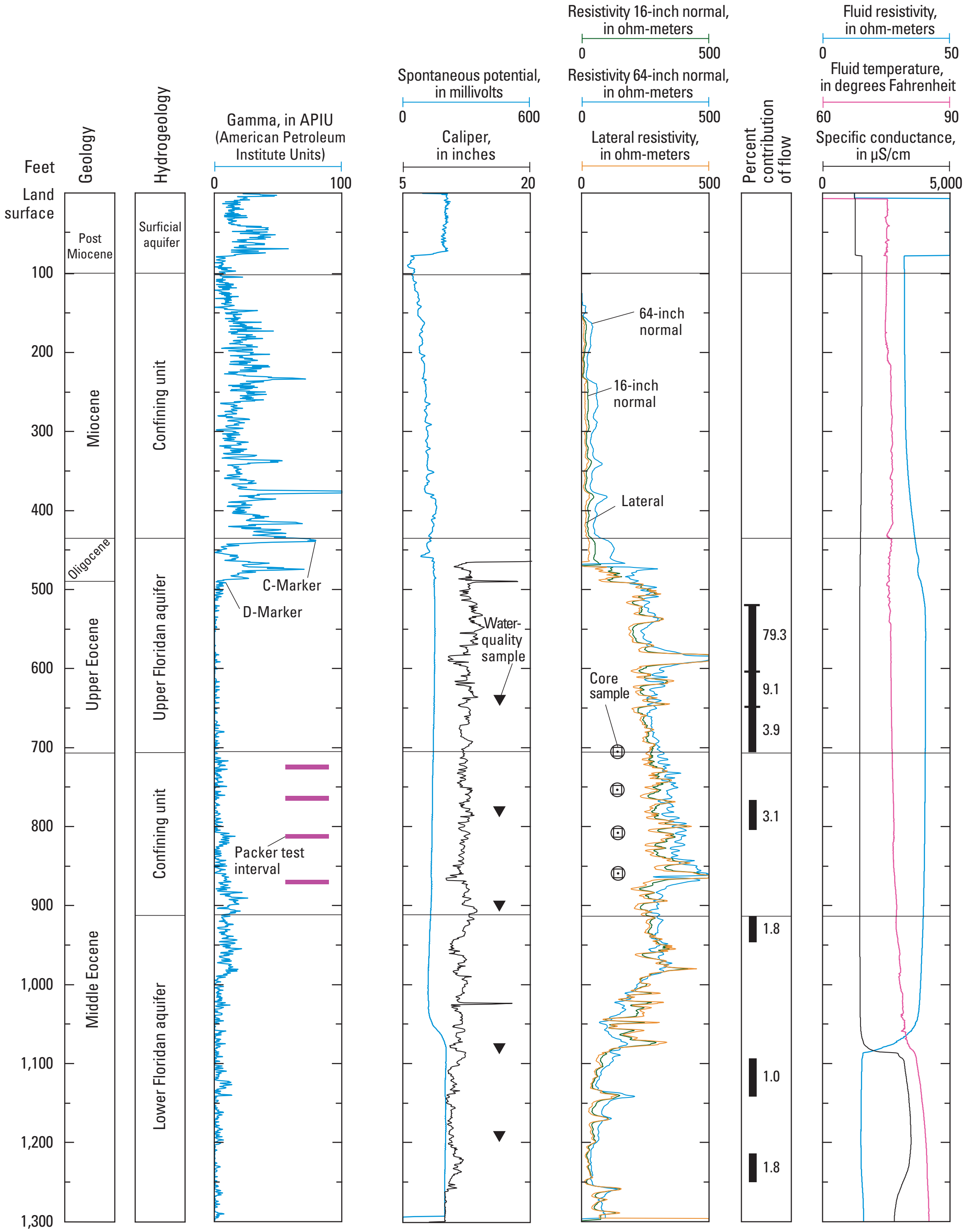


Figure 5. Selected borehole geophysical data and percent flow contribution from permeable zones at well 33P028. Percent flow contribution was determined from flowmeter survey in open borehole, 460–1,300 feet (see figure 6*A*). [µS/cm, microsiemens per centimeter at 25 degrees Celsius]

Flowmeter Testing

Electromagnetic flowmeter testing was performed during two stages of well installation to identify relative contribution of flow from water-bearing zones in the Floridan aquifer system, identify the position of the intervening confining unit, and ensure accurate placement of well casing. A test pump was installed in the casing to a depth of 215 ft, and the well was pumped while several traverses were made in the open borehole with an electromagnetic (EM) flowmeter to measure accumulated flow up the borehole (fig. 6*A*, *B*). Tests were conducted during two stages of casing installation: (1) upon completion of drilling to a total depth of 1,300 ft and prior to installation of the 14-inch-diameter casing, November 19–20, 2009, which tested flow in the entire 460–1,300 ft interval (UFA and LFA, figs. 5, 6*A*); and (2) after installation of the 895 ft of 14-inch-diameter casing, January 26, 2010, to test flow in the 895–1,300 ft open interval (LFA only, fig. 6*B*). Flowmeter tests measured borehole flow under initial static or ambient conditions, followed by pumping at a rate of 772 gal/min during the first stage, and 740 gal/min during the second stage.

Water-Quality Sampling and Analysis

To assess vertical distribution of water quality, the specific conductance of drilling fluids was measured at 10-ft depth intervals during air-reverse drilling of the 524–1,300 ft interval in the test borehole (fig. 7). The measurement procedure consisted of capturing a sample of drilling fluid as it emerged at land surface and measuring the specific conductance after every 10 ft of drilling progression. Although discharge water is a composite of all units exposed above a given depth, changes in specific conductance provide an indication of changes in water quality with depth in the borehole. The average specific conductance of drilling fluids was 258 microsiemens per centimeter at 25 degrees Celsius (µS/cm) in the upper part of the borehole between 524 and 1,150 ft, and a sharp increase to 826 µS/cm was observed in the 1,160-ft sample. The observed increase in specific conductance with depth indicates that water quality had degraded from fresh to brackish. Specific conductance averaged 414 µS/cm in the lower interval (1,160–1,300 ft), so drilling was terminated at a depth of 1,300 ft.

A wireline water sampler was used during borehole flowmeter testing to collect water samples at five distinct depth intervals in the open borehole (table 4; fig. 8). These grab samples were collected with the pump set at a depth of 215 ft within the casing and above all water-bearing intervals, with pumping at a rate of 772 gal/min; therefore, the samples represent a composite of water entering the borehole beneath that depth. For example, the sample at 1,080 ft represents the composite of water entering the borehole between 1,080 ft and the total borehole depth of 1,300 ft. Water samples were removed from the wireline sampler as it emerged from the borehole by using a peristaltic pump to transfer the water into sample bottles. Water samples representing a composite of all water-bearing zones of the completed well (895–1,255 ft) were collected from pump discharge at land surface near the end of the 72-hour aquifer test on March 11, 2010, and later on March 24, 2010.

Grab and composite water samples were analyzed for major ions, including chloride and sulfate, for pH, and for alkalinity as calcium carbonate, which is an indicator of hardness (table 4; fig. 8). Water samples for ion analysis were filtered using 0.45-micrometer capsule filters and analyzed at Test America Laboratories, Savannah, GA. A trilinear diagram showing the relative composition of major ions in water from the various depth intervals is shown in figure 9. In general, constituent concentrations increase with depth of sampled interval.

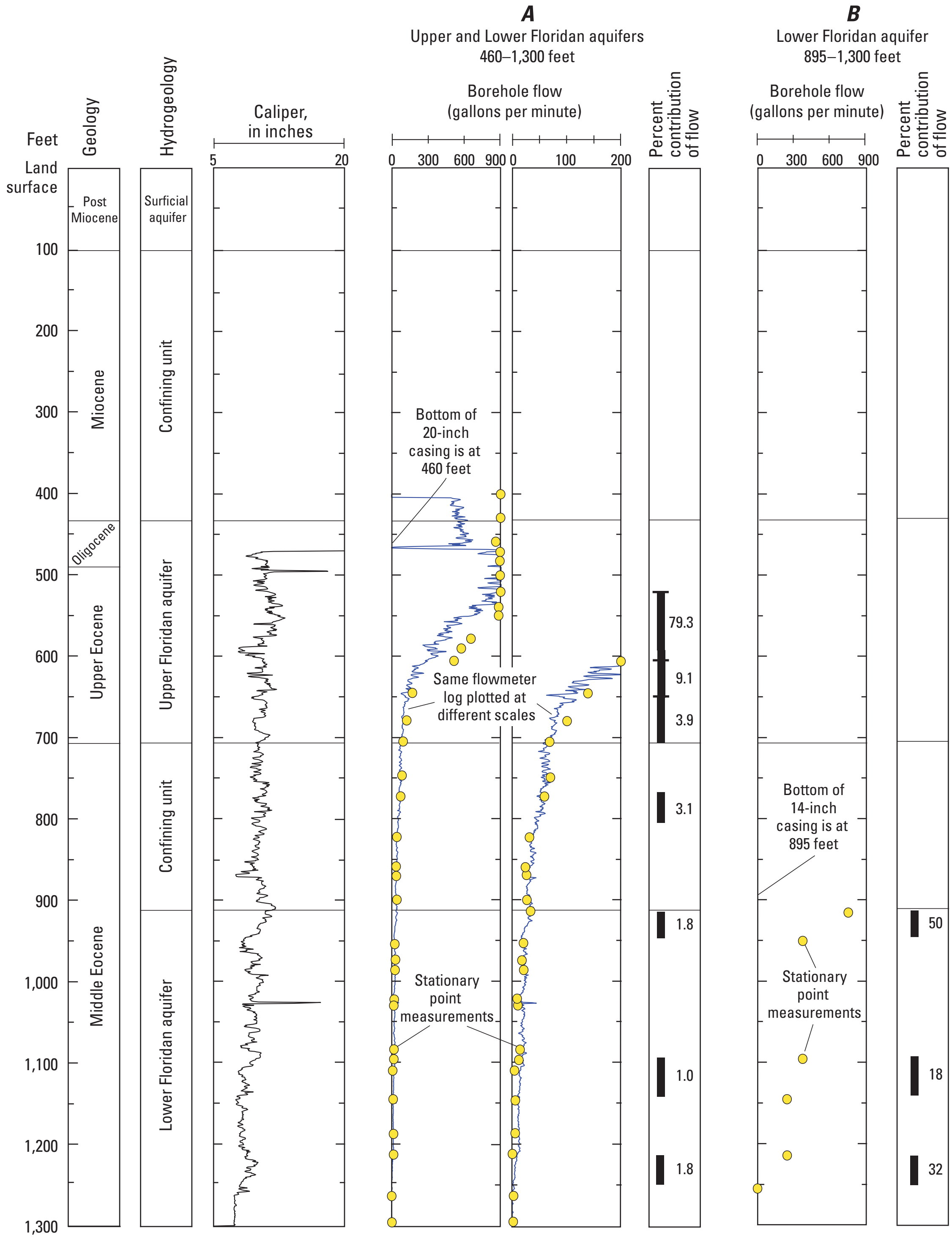


Figure 6. Borehole flowmeter data from well 33P028, Fort Stewart, GA: *(A)* pumping flowmeter survey of Upper and Lower Floridan aquifers prior to installation of 14-inch casing, *(B)* pumping flowmeter survey of the Lower Floridan aquifer after installation of 14-inch casing.

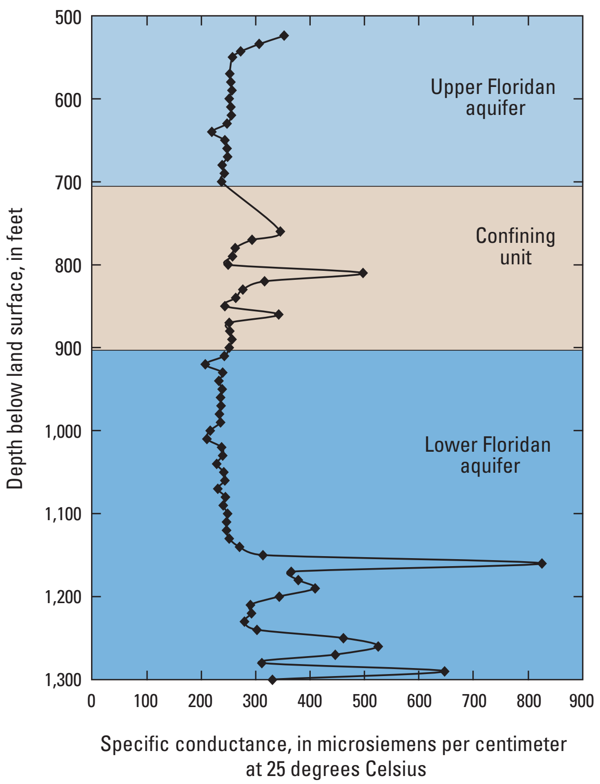


Figure 7. Specific conductance of drilling fluids with depth while drilling well 33P028, Fort Stewart, GA, 2009.

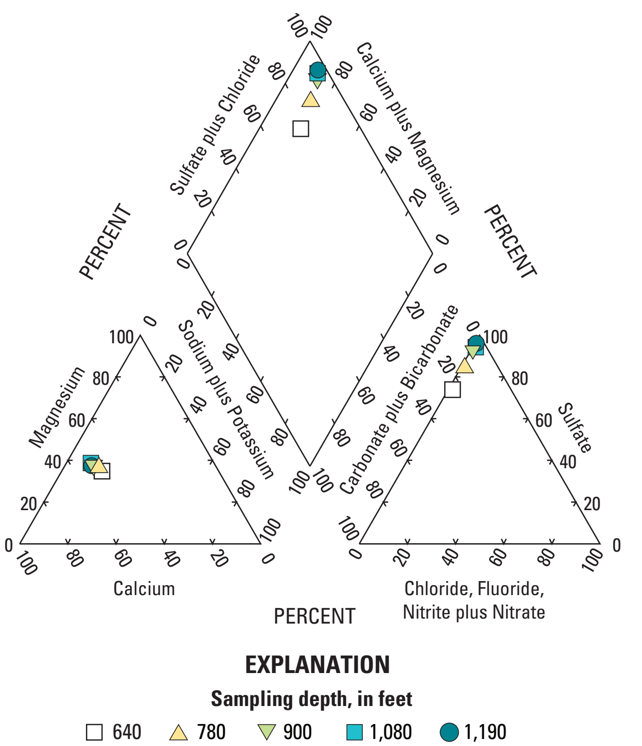


Figure 9. Trilinear diagram showing composition of major ions at various depths at well 33P028, Fort Stewart, GA, November 2009. [Percentages are based on milliequivalents per liter]

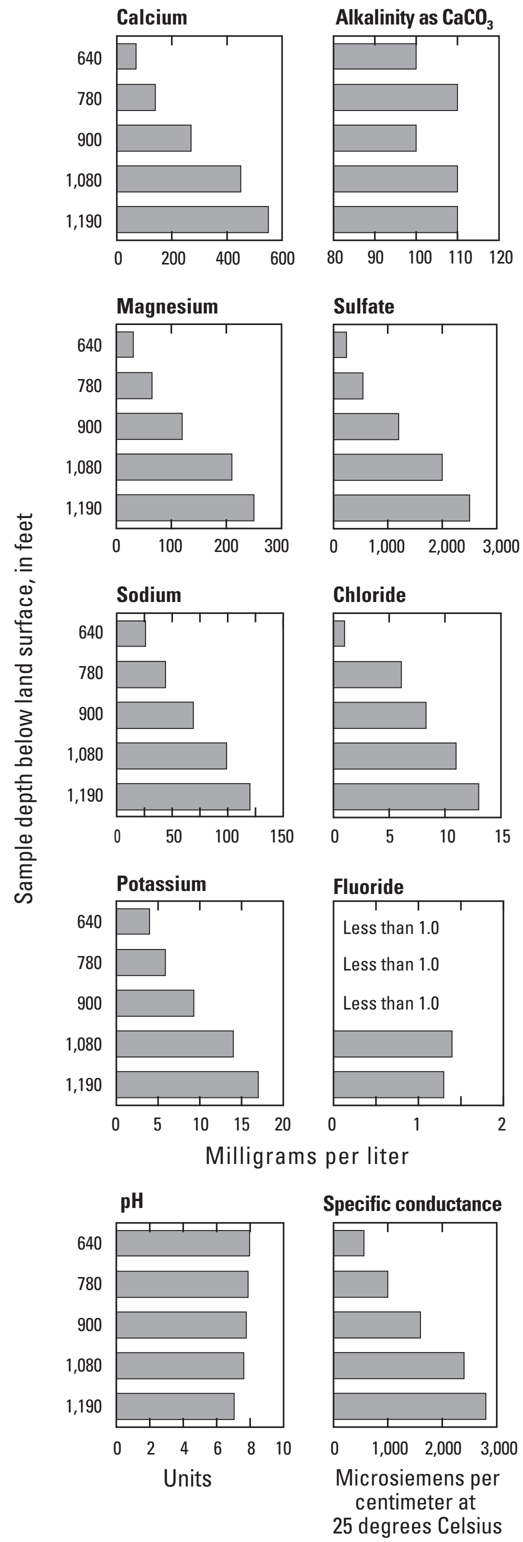


Figure 8. Distribution of selected chemical properties and constituent concentrations by sampled depth at well 33P028, Fort Stewart, GA, November 21, 2009.

Table 4. Water-quality analysis at selected depths in well 33P028, Fort Stewart, Georgia, November 2009 and March 2010.

[NS, no standard; —, not analyzed ; <, less than]

Collection date	Sample depth, in feet	pH laboratory	Laboratory specific conductance, in microsiemens per centimeter at 25 degrees Celsius	Dissolved concentration												
				Milligrams per liter											Micrograms per liter	
				Calcium	Magnesium	Sodium	Potassium	Hardness as calcium carbonate	Alkalinity as $CaCO_3$	Sulfate	Bromide	Chloride	Fluoride	Dissolved solids, residue on evaporation	Iron	Manganese
U.S. Environmental Protection Agency Secondary Maximum Contaminant Level[a]				NS	NS	NS	NS	NS	NS	250	NS	250	4[b]	NS	300	50
11/21/2009[c]	640	7.97	560	70	31	26	4	—	100	240	—	<5	<1	480	<50	<10
11/21/2009[c]	780	7.88	1,000	140	65	44	5.9	—	110	540	<5	6.1	<1	940	<50	<10
11/21/2009[c]	900	7.77	1,600	270	120	69	9.3	—	100	1,200	<5	8.3	<1	1,800	58	<10
11/21/2009[c]	1,080	7.62	2,400	450	210	99	14	—	110	2,000	<5	11	1.4	2,900	<50	<10
11/21/2009[c]	1,190	7.04	2,800	550	250	120	17	—	110	2,500	<5	13	1.3	3,600	<50	11
3/11/2010[c]	895–1,255[d]	7.67	—	250	—	—	—	1,100	—	1,100	<5	8.4	1.3	1,700	140	<3
3/24/2010[e]	895–1,255[d]	7.7	1,816	238	106	53	7.9	1,032	—	1,116	—	8.1	1.7	—	70	<0.02

[a] *http://www.epa.gov/safewater/contaminants/index.html#mcls*, accessed July 14, 2009.

[b] Primary standard.

[c] Analysis by Test America Laboratories, Inc., Savannah, GA.

[d] Completed well.

[e] Analysis by Culligan Analytical Laboratory, Rosemont, IL.

Core Hydraulic Analysis and Packer-Slug Tests

Core samples were collected and analyzed for vertical hydraulic properties at a testing laboratory, and packer-slug tests were completed in the borehole to estimate horizontal hydraulic properties. Relatively undisturbed core samples were collected at depths of 702.9–703.8, 750.9–751.4, 803.5–804.4, and 854.0–854.8 ft and submitted to Geotechnics, Inc., East Pittsburgh, PA, for hydraulic testing of vertical hydraulic conductivity (K_v) and porosity (table 5). To retain the undisturbed nature of these largely consolidated core samples, the samples were preserved onsite using procedures described in American Society for Testing and Materials (ASTM) D5079 and analyzed using a flexible wall permeameter following procedures described in ASTM D5084.

Packer-slug tests at selected intervals—726.5–733.5, 766.5–773.5, 816.5–823.5, and 876.5–883.5 ft (fig. 5)—during December 5–6, 2009, were performed to determine horizontal hydraulic conductivity (K_h) of the LFCU (Gonthier, 2011; table 6). Each depth interval was isolated using straddle packers; a slug of water was injected into the interval, and the rate of head decline was recorded. Pressure above and below the test interval was monitored to ensure no leakage of the packer seals during the tests. A description of the techniques used to deploy and test the integrity of the packer system is provided in Holloway and Waddell (2008). With the exception of the 766.5–773.5 ft depth interval, data were analyzed for K_h using the Bouwer and Rice (1976) method contained in a spreadsheet developed by Halford and Kuniansky (2002). The Bouwer and Rice (1976) method assumes that (1) the aquifer has an infinite areal extent, (2) the aquifer is homogeneous with a uniform thickness, (3) the test well is fully or partially penetrating, (4) effects of storage are negligible, (5) flow to the well is quasi-steady-state, and (6) the slug is introduced into the well instantaneously. An oscillatory water-level response in the permeable 766.5–773.5 ft interval, required application of the van der Kamp (1976) method also contained in the spreadsheet developed by Halford and Kuniansky (2002). The van der Kamp method assumes that the aquifer is homogeneous, the well is fully penetrating, and the frequency of oscillation remains constant.

Table 5. Estimated vertical hydraulic conductivity and porosity of core samples collected from the Lower Floridan confining unit at well 33P028, Fort Stewart, Georgia.

[Analyses by Geotechnics, Inc., East Pittsburgh, PA]

Interval (feet below land surface)	Vertical hydraulic conductivity (feet per day)	Porosity (percent)
702.9–703.8	0.26	0.37
750.9–751.4	0.37	0.25
803.5–804.4	0.40	0.26
854.0–854.8	0.79	0.38
Average	**0.45**	**0.32**

Table 6. Horizontal hydraulic conductivity of the Lower Floridan confining unit determined from packer-slug tests and estimated vertical hydraulic conductivity at well 33P028, Fort Stewart, Georgia.

[Data from Gonthier, 2011; BR, Bouwer and Rice, 1976; VK, van der Kamp, 1976. Both methods were analyzed using spreadsheet developed by Halford and Kuniansky, 2002]

Interval, in feet below land surface	Horizontal hydraulic conductivity, in feet per day	Estimated vertical hydraulic conductivity, in feet per day[a]	Method
726.5–733.5	20	2.4	BR
766.5–773.5	70	12	VK
816.5–823.5	20	2.4	BR
876.5–883.5	2	0.24	BR

[a]Derived from approximate 8.5:1 ratio of vertical to horizontal hydraulic conductivity estimated at well 36Q392 at Hunter Army Airfield (Clarke and others, 2010).

Aquifer Tests

Two aquifer tests were completed at Fort Stewart to evaluate hydraulic properties of the UFA and LFA and to assess whether pumping in the LFA produced a drawdown response in the UFA. During the first test, UFA well 33P029 was pumped for 24 hours, and during the second test, LFA well 33P028 was pumped for 72 hours. Aquifer test site layout is shown in figure 10. A detailed description of the aquifer tests and subsequent analysis are provided in Gonthier (2011); a brief discussion is included here.

Pressure transducers and manual water-level measurements were used to monitor water levels during the aquifer tests. Monitoring at well 33P028 began on January 27, 2010, and at observation wells 33P029 and 33P025 on February 25, 2010. The testing consisted of a pre-test background period of slightly more than 3½ days, the 24-hour aquifer test in the UFA, a recovery period of about 4 days, a 72-hour aquifer test in the LFA, and a post-test period of approximately 4 days. Raw, unfiltered water-level data for onsite and offsite background wells before, during, and after the 24-hour and 72-hour aquifer tests are shown in figure 11.

A single well 24-hour aquifer test was completed at well 33P029 on March 3–4, 2010, to determine transmissivity of the UFA. For this test, well 33P029 was pumped at an average rate of 387 gal/min, and drawdown response was observed in the pumped well and in adjacent LFA well 33P028, located about 40 ft away (fig. 10). An additional UFA well (33P025), located 1.8 mi east of well 33P029, also was monitored during the test. A similar 72-hour test was conducted March 8–11, 2010, in well 33P028 to determine

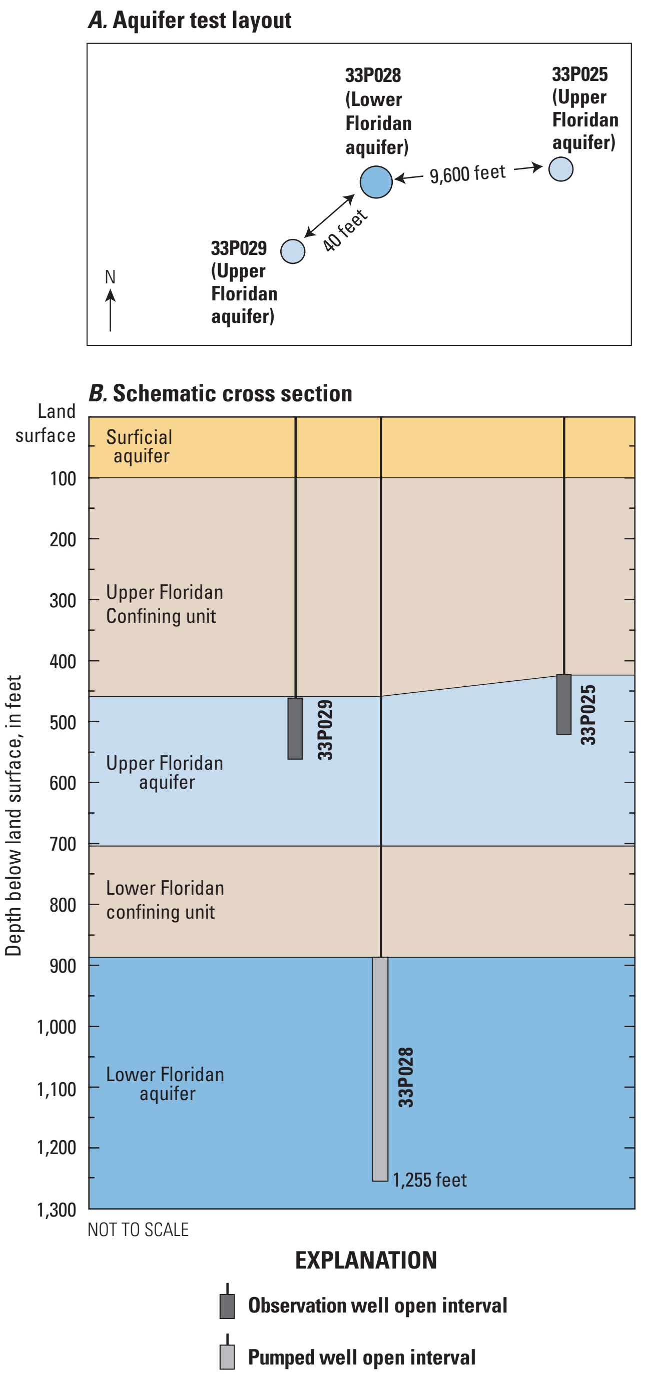


Figure 10. Location and construction characteristics of wells used for aquifer tests at Fort Stewart, GA: *(A)* diagram showing aquifer test layout and *(B)* schematic cross section showing the open intervals of the wells in relation to major hydrogeologic units.

the transmissivity of the LFA. For this test, well 33P028 was pumped at an average rate of 740 gal/min, and water levels were recorded in the pumped well and in UFA wells 33P025 and 33P029 to assess interaquifer leakage response.

For each test, data were collected and analyzed using the following procedures.

- Prior, during, and after each aquifer test, water levels were monitored to identify static and pumping water levels and ambient water-level fluctuations and trends.
- Upon completion of the pumping period, water-level recovery was monitored for a minimum period equal in length to the pumping period.
- Test data (water levels) were corrected (filtered) to remove influences caused by barometric-pressure fluctuations, gravity and earth tides, and regional pumping trends.

Aquifer test drawdown data were evaluated for local hydraulic properties by using the Cooper-Jacob (1946) analytical method at UFA well 33P029 and by using a combined simulation and optimization approach at LFA well 33P028; these methods are discussed in detail in Gonthier (2011).

The Cooper-Jacob method (1946) is a simplification of the Theis (1935) solution for flow to a fully penetrating well in a confined aquifer and may be used to analyze data from a single pumping well. This solution has the same assumptions as the Theis (1935) solution, including: (1) the aquifer is infinite in areal extent, homogeneous, and isotropic; (2) the pumping well is fully penetrating, and flow to the pumping well is horizontal and laminar; (3) the aquifer has uniform thickness and is horizontal; (4) the potentiometric surface is horizontal initially; and (5) the aquifer is fully confined, and discharge is derived exclusively from storage in the aquifer.

At well 33P028, transmissivity of the UFA and LFA was estimated by simulating aquifer-test response using a two-dimensional, radial, transient, groundwater-flow model that incorporated pumped well 33P028 and observation wells 33P029 and 33P025 (Gonthier, 2011). Flow was simulated using MODFLOW-96 (McDonald and Harbaugh, 1988; Harbaugh and McDonald, 1996) and calibrated using MODOPTIM (Halford, 2006b). For these simulations, (1) horizontal hydraulic conductivity was assumed to be laterally homogenous within each hydrogeologic unit, (2) lateral anisotropy was assumed to be uniform, and (3) specific storage and vertical anisotropy (vertical hydraulic conductivity divided by the horizontal hydraulic conductivity) were assumed to be homogeneous through the entire aquifer system (Gonthier, 2011).

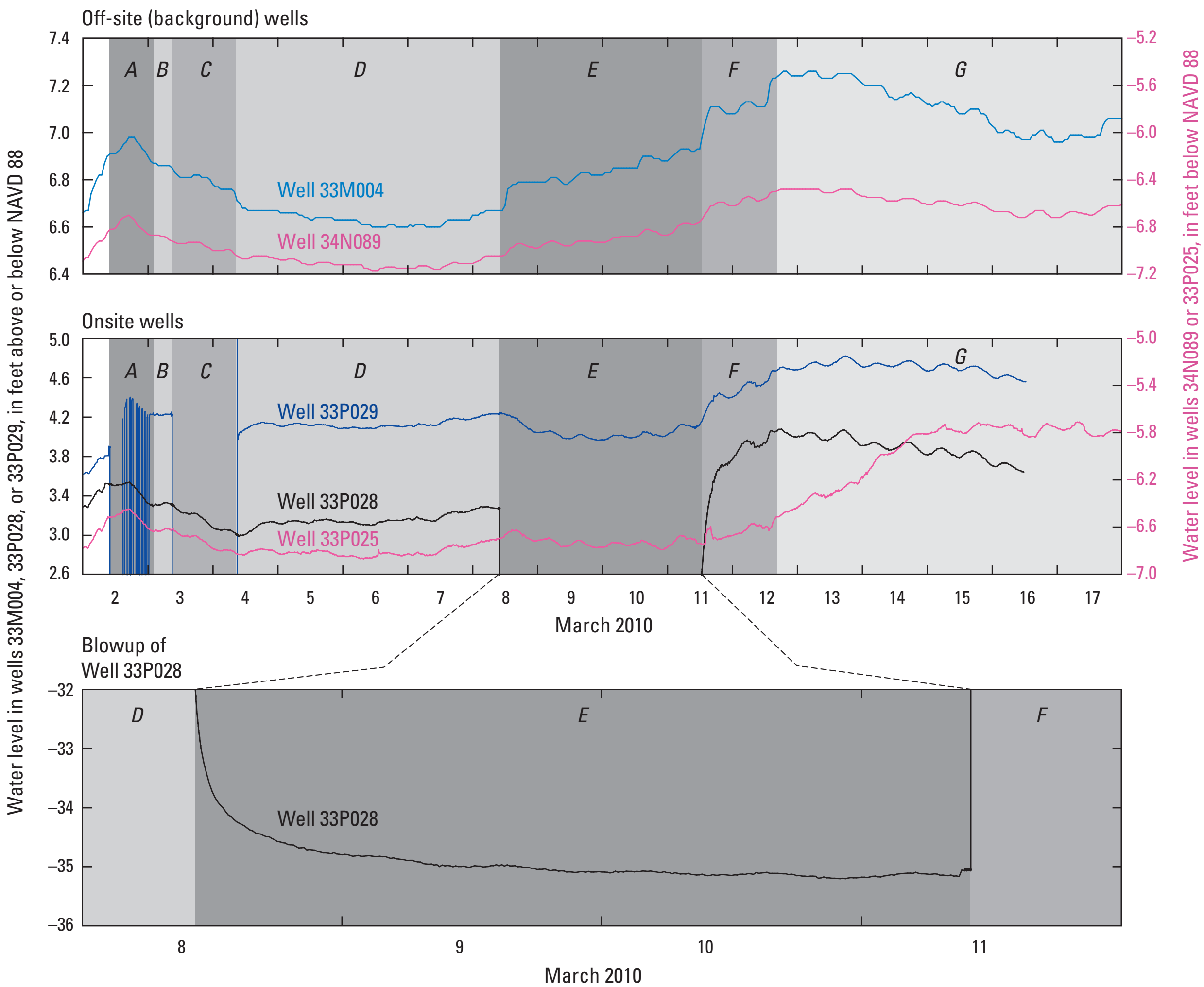


Figure 11. Raw, unfiltered water levels in selected wells during 24-hour Upper Floridan aquifer test and 72-hour Lower Floridan aquifer test, Fort Stewart, GA and vicinity, March 2–17, 2010: *(A)* period of well development and pumping variations prior to Upper Floridan aquifer test conducted in well 33P029, *(B)* recovery following well development and pumping variations in well 33P029, *(C)* drawdown during Upper Floridan aquifer test in well 33P029, *(D)* recovery following Upper Floridan aquifer test in well 33P029, *(E)* drawdown during Lower Floridan aquifer test in well 33P028, (F) recovery following Lower Floridan aquifer test conducted in well 33P028, and *(G)* regional water-level decline following Lower Floridan aquifer test conducted in well 33P028.

Filtering of Water-Level Data

Major influences on groundwater levels in the Fort Stewart area include earth-tide and barometric-pressure changes and regional pumping trends as indicated at background monitoring wells 33M004 and 34N089 (fig. 12). These external influences were filtered out of water-level data for each aquifer test using a spreadsheet procedure developed by Halford (2006a) and are explained in detail in Gonthier (2011). Filtering enabled quantification of the pumping response (drawdown) in each observation well. Negligible modification of the observed drawdown by filtering occurred at the pumped wells, owing to the large magnitude of the drawdown, which obscured signals derived from non-pumping influences.

Water levels in onsite UFA wells 33P029 and 33P025 and in LFA well 33P028 demonstrate nearly identical responses to hydrologic stresses and are similar to background monitoring wells 33M004 and 34N089 (fig. 12). Because the water-level record for well 33P028 begins in January 2010, whereas data for the other two wells were not available until late February 2010, data from 33P028 provided the basis for evaluation of nonpump-test influences and for filtering of water levels in all three wells during the aquifer tests.

Using the filtering spreadsheet provided by Halford (2006), the amplitude and phase of each time series (barometric pressure, gravity tide, earth tide, and water levels in background monitoring wells) were adjusted, and an offset and slope were applied to synthesize water levels for well 33P028 to match measured water levels during the pre-aquifer-test fitting period, January 31 to March 2, 2010 (fig. 13). The root mean square error (RMSE) was used to ascertain the "goodness of fit" of synthetic water levels to measured water levels. When visual examination indicated the fit was functional, the same phase shifts and multipliers were used to synthesize water levels during the aquifer-test period for pumped well 33P028 and observation wells 33P029 and 33P025. Following application of phase shifts and multipliers determined at well 33P028 to each of the three wells, the offset and slope of the synthetic water level was manually adjusted for each well to initialize the estimated drawdown to zero just prior to the start of the aquifer test (figs. 14 and 15). The RMSE of 0.0068 for well 33P028 was computed based on a fitting period of January 31–March 2, 2010, whereas the RMSEs of 0.0062 and 0.012 for wells 33P029 and 33P025, respectively, were computed based on a fitting period of February 25–March 2, 2010.

Groundwater-Flow Model

A groundwater-flow model previously developed by the USGS (Payne and others, 2005; Clarke and others, 2010) was modified for finer spatial resolution and site-specific data to assess (1) the amount of induced interaquifer leakage and drawdown in the UFA resulting from pumping LFA well 33P028 at a rate of 740 gal/min, and (2) the equivalent amount of pumping from the UFA that would replicate simulated drawdown in the UFA (that resulted from pumping the LFA) adjacent to well 33P028. The revised model also was used to simulate groundwater-pumping scenarios that evaluated the effect of various redistributions of pumping on groundwater conditions at Fort Stewart. Modifications to the groundwater model are described in the appendix.

Hydrogeology and Water Quality

Hydrogeologic units of the Floridan aquifer system were distinguished by differences in flow contribution, lithology, geophysical characteristics, and water quality. Miller (1986) provided a regional definition of the Floridan aquifer system on the basis of widely spaced stratigraphic and borehole geophysical data in the coastal area of Georgia and South Carolina. New hydrogeologic and water-quality data collected at Fort Stewart were used to help refine Miller's (1986) regional definition of the Floridan aquifer system (Williams and Gill, 2010). The following sections describe the depths of occurrence and hydraulic characteristics of hydrogeologic units that constitute the Floridan aquifer system at Fort Stewart.

Upper Floridan Aquifer

The UFA at well 33P028 consists of Oligocene and upper Eocene carbonate units that include several high permeability zones (fig. 5). The top of the aquifer is composed of the Oligocene Suwannee Limestone and corresponds to a spike in the natural-gamma log called the "C-marker" (Wait, 1965; Gregg and Zimmerman, 1974; Clarke and others, 1990). The thickest part of the aquifer is composed of upper Eocene Ocala Limestone, which is characterized by a very low natural-gamma radiation, the top of which is called the "D-marker" (Wait, 1965; Gregg and Zimmerman, 1974; Clarke and others, 1990). The uppermost part of middle Eocene limestone (Avon Park Formation) represents the base of the aquifer (at a depth of 705 ft) and was designated on the basis of flowmeter data that indicated a large reduction in borehole flow at that depth.

Regional maps showing the depth and thickness of geologic units constituting the Floridan aquifer system (Miller, 1986) indicated that the UFA is between depths of 420 and 750 ft below land surface at Fort Stewart. Geophysical and flowmeter data collected from well 33P028 (figs. 5 and 6) were used to refine this depth interval to a range of 440 to 705 ft.

Flowmeter Survey

On November 19–20, 2009, a borehole flowmeter survey was completed in well 33P028 in the interval between 460 and 1,300 ft while pumping at a rate of 772 gal/min. The survey indicated that 92.3 percent (682 gal/min) of the total flow came from the UFA, and the remaining 7.7 percent (56 gal/min) came from the underlying confining unit and the LFA (fig. 6). The water-producing zones of the UFA at Fort Stewart differ from than those observed at Hunter Army Airfield. At Hunter Army Airfield, five water-bearing intervals in the UFA appeared to coincide with the development of secondary permeability (Clarke and others, 2010; Williams, 2010), whereas at Fort Stewart, the UFA appears to have three principal water-bearing zones. Of the 682 gal/min contributed by the UFA, 79.3 percent of the flow was produced in the 520–590 ft interval, 9.1 percent in the 590–650 ft interval, and 3.9 percent in the 650–705 ft interval (fig. 6*A*). The uppermost part of the UFA (440–460 ft) consists of Oligocene deposits of lower permeability than the lower part of the aquifer, and was not tested because the uppermost part was isolated by well casing set at 460 ft. The base of the UFA, which is the top of LFCU, was designated at a depth of 705 ft, where no contribution to borehole flow was detected during the flowmeter survey. An ambient flowmeter survey completed prior to pumping indicated that flow in the 460–1,300 ft interval was generally downward, reflecting a general downward head gradient. There was little change in flow in the 450–550 ft and 1,112–1,267 ft intervals, which may indicate relatively flat vertical gradients in these intervals.

Water Quality

Water from the UFA can be distinguished from that of the LFA by lower specific conductance and concentrations of dissolved constituents, and by differences in the relative percentage of constituents (water type). Specific conductance of reverse-air drilling fluids (formation water) indicates that water from the UFA had an average specific conductance of 257 µS/cm compared to 287 µS/cm for the LFCU and 307 µS/cm for the LFA (fig. 7).

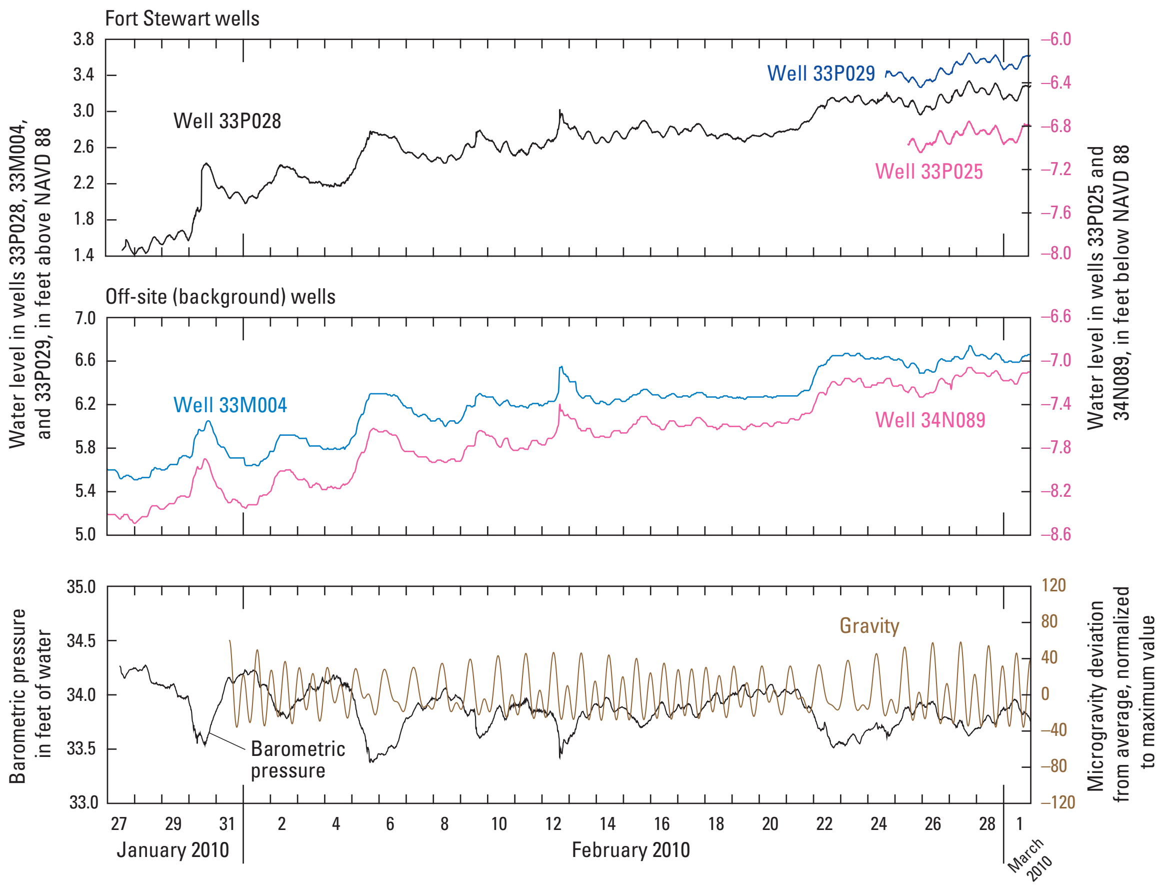


Figure 12. Water-level fluctuations in selected Fort Stewart and off-site wells and fluctuations in barometric pressure and gravity, January 27–March 1, 2010.

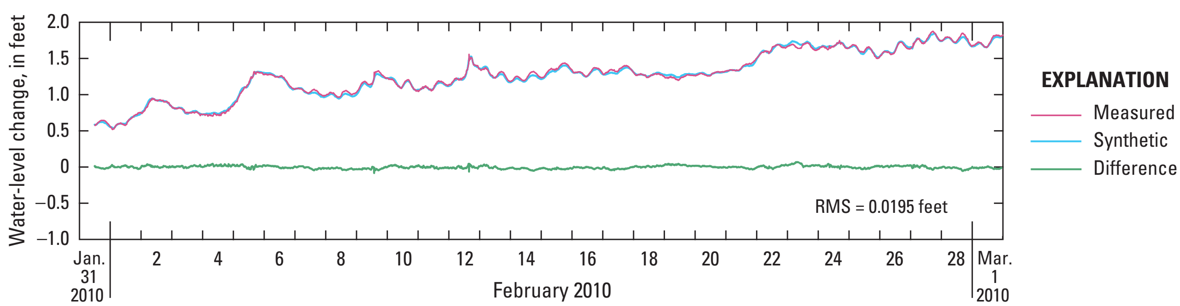


Figure 13. Measured and synthetic water levels for well 33P028 during background matching period, January 31–March 1, 2010, Fort Stewart, GA. Water-level data were synthesized using barometric, earth-tide, and gravity data, and water-level data from background wells using the spreadsheet procedure of Halford (2006b). Differences are shown on graph as synthetic minus measured water levels. [RMS, root mean square of differences between measured and synthetic water levels]

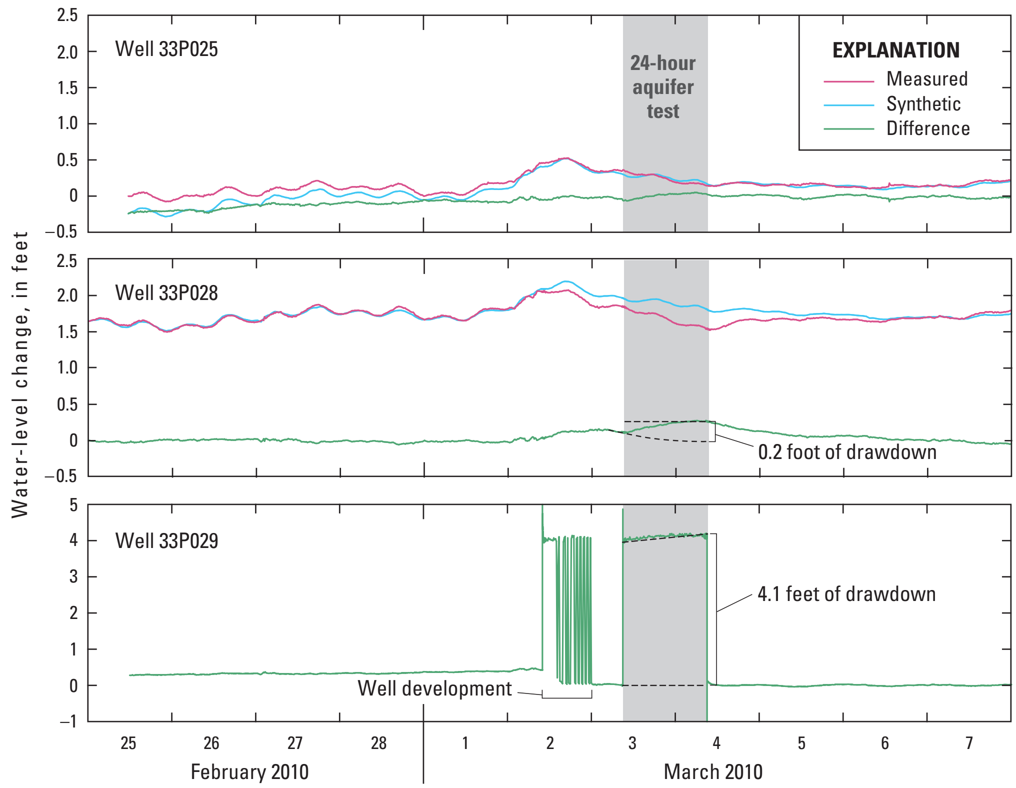


Figure 14. Measured and synthetic water levels and estimated drawdown in wells 33P025 and 33P028 before, during, and after a 24-hour aquifer test conducted in Upper Floridan aquifer well 33P029, Fort Stewart, GA, February 25–March 7, 2010.

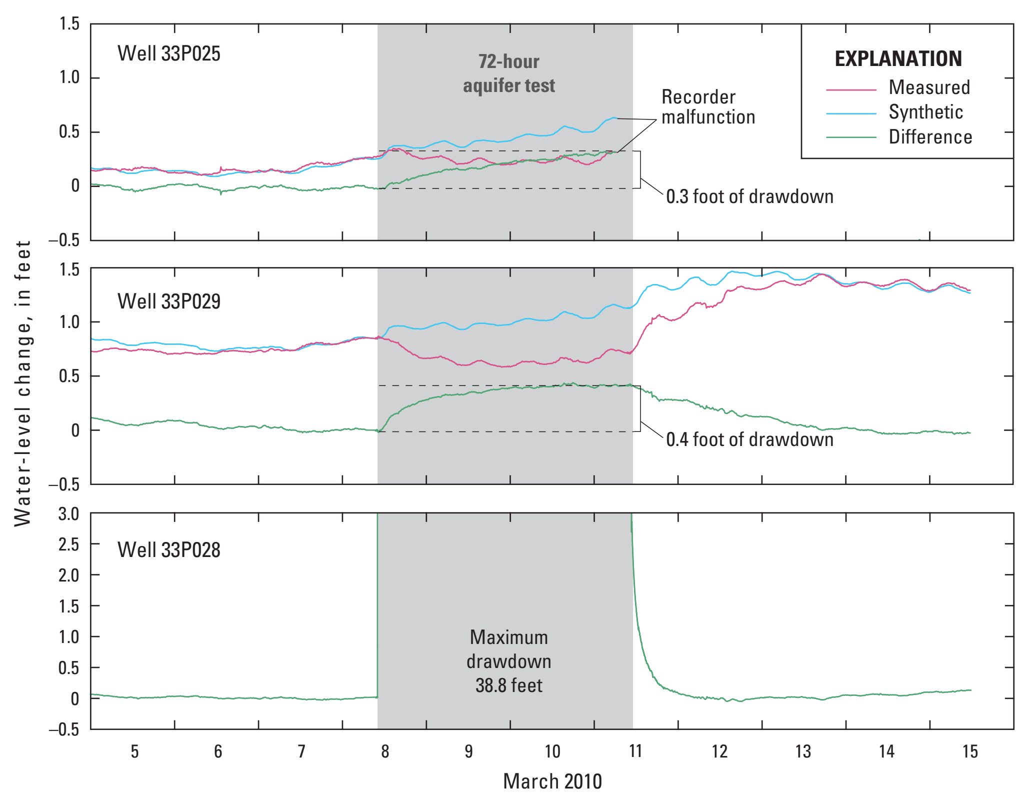


Figure 15. Measured and synthetic water levels and estimated drawdown in wells 33P025 and 33P029 before, during, and after a 72-hour aquifer test conducted in Lower Floridan aquifer well 33P028, Fort Stewart, GA, March 5–15, 2010.

A water-quality sample was collected from the UFA at a depth of 640 ft in the open borehole during flowmeter testing using a wireline sampler and analyzed for major ions (table 4; figs. 8, 9). Water from this depth represents a composite sample of water contributed to the borehole from the water-bearing zones located below 640 ft to the bottom of the bore-hole at 1,300 ft. The specific conductance of the grab sample (560 µS/cm) is higher than that of drilling fluids in the UFA (average 257 µS/cm). The grab sample represents a composite of the water quality between 640 ft and 1,300 ft where the water contains higher concentrations of dissolved constituents; the drilling fluids represent a composite of water between 460 and 640 ft where the water contains lower concentrations of dissolved constituents. Despite this difference, because of the relatively higher percent-flow contribution from the UFA (92.3 percent) compared with the LFCU (3.1 percent) and LFA (4.6 percent; fig. 5), the grab sample most likely is representa-tive of chemical constituents in the UFA. Each constituent analyzed in the 640-ft sample was within U.S. Environmental Protection Agency (USEPA) primary maximum contaminant levels (MCL; U.S. Environmental Protection Agency, 2009). Water from the 640-ft sample is hard with an alkalinity of 100 milligrams per liter (mg/L), contains a low concentration of chloride (less than 5 mg/L), and contains a sulfate concen-tration of 240 mg/L, which is slightly below the 250-mg/L USEPA secondary maximum contaminant level (SMCL; U.S. Environmental Protection Agency, 2009). Water from the 640-ft sample appears to be a calcium-magnesium-sulfate type (fig. 9), with increased percentages of these constituents in deeper parts of the borehole.

Hydraulic Properties

A 24-hour aquifer test was conducted March 3–4, 2010, to determine the transmissivity of the UFA. For this test, well 33P029 was pumped at an average rate of 387 gal/min, while drawdown response was observed (1) in the pumped well, (2) in LFA well 33P028, which is located about 40 ft away, and (3) in UFA well 33P025, located 9,600 ft east of the pumped well (table 2; fig. 1). Well 33P028 is completed in the LFA between depths of 895 and 1,255 ft below land surface. Wells 33P029 and 33P025 are open to the uppermost part of the Upper Floridan aquifer with depths below land surface of 460–560 ft and 420–520 ft, respectively (fig. 10). Pumping well 33P029 at an average rate of 387 gal/min resulted in a maximum drawdown of 4.1 ft during the 24-hr aquifer test (fig. 14). Drawdown at well 33P025 in response to the aquifer test at well 33P029 was less than 0.1 ft and was considered insufficient for computation of hydraulic properties using an analytical method. A transmissivity estimate of 100,000 ft^2/d (table 7) was computed at well 33P029 (Gonthier, 2011) by applying the Cooper-Jacob straight-line method (Cooper and Jacob, 1946) using a spreadsheet from Halford and Kuniansky (2002).

Transmissivity of the UFA was also estimated by simulating aquifer-test response using a two-dimensional, radial, transient, groundwater-flow model that incorporated pumped well 33P028 and observation wells 33P029 and 33P025. Flow was simulated using MODFLOW-96 (McDon-ald and Harbaugh, 1988; Harbaugh and McDonald, 1996) and calibrated using MODOPTIM (Halford, 2006). Simulated transmissivity of the UFA was 90,000 ft^2/d (Gonthier, 2011).

Table 7. Summary of aquifer tests conducted in Upper and Lower Floridan aquifer wells at Fort Stewart, Georgia, 2010.

[Data from Gonthier, 2011]

Pumping well	Aquifer	Testing period	Test duration, in hours	Average pumping rate, in gallons per minute	Transmissivity, in feet squared per day	Remarks
33P029	Upper Floridan aquifer	March 3–4, 2010	24	387	100,000	Single well test computed using a spread-sheet from Halford and Kuniansky (2002) that applies the Cooper-Jacob straight-line method (Cooper and Jacob, 1946).
33P029	Upper Floridan aquifer	March 8–11, 2010	72	740	90,000	Gonthier (2011) estimated transmissivity by simulating aquifer-test response using a two-dimensional, radial, transient, groundwater-flow model. Flow was simulated using MODFLOW-96 (McDonald and Harbaugh, 1988; Harbaugh and McDonald, 1996) and calibrated using MODOPTIM (Halford, 2006b).
33P028	Lower Floridan aquifer	March 8–11, 2010	72	740	7,000	

Estimated transmissivity values of 100,000 ft^2/d derived using the Cooper-Jacob (1946) method, and 90,000 ft^2/d derived using simulation (Gonthier, 2011), are consistent with a previously reported value of transmissivity of 124,000 ft^2/d derived using the Theis non-equilibrium method (1935) at well 33N001 at Fort Stewart (Warren, 1944).

Lower Floridan Confining Unit

The LFCU at well 33P028 consists of chalky and glauconitic limestone in the uppermost part of the middle Eocene Avon Park Formation between depths of 705 and 912 ft (figs. 2, 5). The thickness and hydraulic conductivity of the confining unit control the rate of interaquifer leakage between the UFA and LFA.

The LFCU is about 207 ft thick at Fort Stewart, compared with a thickness of 143 ft at Hunter Army Airfield, which is about 25 mi northeast of Fort Stewart (fig. 1). The LFCU contains slightly lower permeability carbonate sediments than the LFA. This unit is similar in lithology to overlying and underlying rock units, which precluded identification of the confining unit during drilling. Following completion of the pilot boring, the thickness and location of the confining unit were assessed by using borehole geophysical logs and the results of a flowmeter survey.

Flowmeter Survey

Borehole flowmeter testing in well 33P028 (fig. 6*A*) of the 460–1,300 ft open interval indicated that the LFCU contributed little to the overall flow in the borehole. In particular, continuous vertical sections of limestone at 705–793 and 822–912 ft contributed no detectable amounts of water during the 772 gal/min flowmeter survey. Within the confining unit, a single water-bearing zone at 793–822 ft yielded 34 gal/min, or 3.1 percent of the total borehole flow, during the flowmeter survey. This water-bearing zone corresponded to an increase in the specific conductance of drilling fluids at that depth (fig. 7).

Water Quality

Water in the LFCU has a similar specific conductance to water from the LFA as indicated by drilling fluids monitored while completing the test borehole in well 33P028. The specific conductance of drilling fluids from the 760–910 ft interval of the LFCU averaged 287 µS/cm, compared with 307 µS/cm for the LFA (fig. 7).

A water-quality grab sample was collected at a depth of 780 ft from a water-bearing zone within the LFCU in the open borehole during flowmeter testing using a wireline sampler and was analyzed for major ions (table 4; figs. 8, 9). Water from this interval represents a composite sample of water contributed to the borehole from the water-bearing zones located below 780 ft to the bottom of the borehole at 1,300 ft. The specific conductance of the grab sample (1,000 µS/cm) is higher than that of drilling fluids in the LFCU (average 287 µS/cm) because the grab sample represents a composite of the water quality between 780 and 1,300 ft that contains higher concentrations of dissolved constituents, whereas the drilling fluids represent a composite of water between 460 and 780 ft that contains lower concentrations of dissolved constituents. Each constituent analyzed in the 780-ft sample was within the USEPA primary MCL (U.S. Environmental Protection Agency, 2009). Water from the 780-ft sample is hard with an alkalinity of 110 mg/L, contains a low concentration of chloride (6.1 mg/L), and contains a sulfate concentration of 540 mg/L, which is greater than the 250-mg/L USEPA SMCL (U.S. Environmental Protection Agency, 2009). Water from the 780-ft sample appears to be a calcium-magnesium-sulfate type (fig. 9), with increased percentages of these constituents in deeper parts of the borehole.

Hydraulic Properties

The K_v and porosity of the LFCU were determined by analyzing core for hydraulic analysis at four intervals: 702.9–703.8, 750.9–751.4, 803.5–804.4, and 854.0–854.8 ft (table 5). Values of K_v ranged from 0.26 to 0.79 ft/d, averaged 0.45 ft/d, and are consistent with reported ranges for carbonate rocks and silty sand (Heath, 1983). Porosity values ranged from 0.25 to 0.38, averaging 0.32, and are within reported ranges for limestone and sandy clay (Heath, 1983). K_v of the cores may not fully represent the K_v of the confining unit because of the small volumes that the cores represent.

The K_h of the LFCU was determined by completing packer-slug tests at four separate intervals—726.5–733.5, 766.5–773.5, 816.5–823.5, and 876.5–883.5 ft (fig. 5)—prior to installation of 14-inch-diameter casing (table 6; Gonthier, 2011). K_h values for three of the intervals ranged between 2 and 20 ft/d, with a value of 70 ft/d obtained for the 766.5–773.5 ft interval. The 766.5–773.5 ft interval is a few feet above a water-bearing zone within the confining unit that produced 34 gal/min during flowmeter testing.

An approximation of the K_v of the LFCU was derived from an approximate 8.5:1 ratio of K_h to K_v reported based on core and slug test data collected at Hunter Army Airfield by Clarke and others (2010). Using this relation, the estimated K_v of the confining unit generally ranges from 0.24 to 2.4 ft/d, with one sample having a value of 12 ft/d (table 6). These values are consistent with K_v values derived using ranges of K_h reported by Heath (1983) for carbonate rocks.

Lower Floridan Aquifer

Williams and Gill (2010) reported that, in Liberty County, the LFA is between about –625 and –850 ft NAVD 88, with thickness ranging between 400 and 650 ft. The LFA at well 33P028 was encountered at a depth of about 912 ft (–835 NAVD 88) and extends to a depth of at least 1,300 ft. The aquifer consists of chalky and glauconitic limestone in the uppermost part of the middle Eocene Avon Park Formation that is similar in lithology to overlying units (fig. 2). The LFA is at least 395 ft thick at Fort Stewart, compared with a thickness of 143 ft at Hunter Army Airfield, which is about 25 mi northeast of Fort Stewart (fig. 1).

Flowmeter Survey

Results of flowmeter testing in the interval between 895 and 1,300 ft identified the following three water-producing depth intervals in the LFA: 912–947, 1,090–1,139, and 1,211–1,250 ft (fig. 6*B*). Flowmeter-test data (fig. 6*B*) indicated that when pumping at a rate of 740 gal/min, the upper water-bearing zone produced 50 percent of the total flow (370 gal/min), the middle zone produced 18 percent of the flow (134 gal/min), and the lowermost zone produced 32 percent of the flow (236 gal/min). Flow was not detected by the flowmeter beneath a depth of 1,250 ft.

Fluid Temperature Logs

Fluid temperature logs collected under static conditions in well 33P028 indicate an anomalous increase in temperature with depth, which is larger than can be attributed to the geothermal gradient (fig. 5). This temperature increase occurs in the lower 250 ft of the open borehole, at approximately the same depth as a change in fluid resistivity and specific conductance. According to Freeze and Cherry (1979, p. 508), anomalous temperature distributions may be caused by the redistribution of heat by moving groundwater. Under natural unstressed conditions, groundwater temperature increases with depth at a constant rate of 1 degree Celsius (°C) per 100 ft of depth in response to a natural geothermal gradient resulting from higher rock temperatures toward the earth's core. Wait and Gregg (1974) reported the normal gradient in coastal Georgia as 0.8 °C per 100 ft of depth. At well 33P028, between depths of 100 and 1,050 ft, fluid temperature increases from 22.6 to 24.3 °C for a gradient of 0.18 °C per 100 ft of depth, which is lower than the gradient reported by Wait and Gregg (1974). In the lower part of the borehole at well 33P028, the temperature gradient increases from 24.3 °C at a depth of 1,050 ft, to 28.7 °C at a depth of 1,300 ft, for a gradient of 1.76 °C per 100 ft of depth. The lower gradient in the upper part of the borehole indicates that cool water from shallower depths may be contributing to borehole flow, whereas the anomalously high gradient below the 1,050-ft depth indicates warm water from depths below 1,300 ft may be contributing to borehole flow.

Water Quality

The quality of water in the LFA was evaluated during drilling of well 33P028 by measuring specific conductance of reverse-air drilling fluids, and by analyzing (1) grab water samples collected during flowmeter testing, and (2) composite water samples collected from the completed well. The specific conductance of drilling fluids averaged 307 µS/cm between depths of 920 and 1,150 ft, increased abruptly to 826 µS/cm at a depth of 1,160 ft, and averaged 414 µS/cm for the 1,160–1,300 ft interval (fig. 7). Specific conductance decreased to about 300 µS/cm in the 1,210–1,240 ft interval reflecting contribution from the deepest water-bearing zone (fig. 6*B*) and ranged from 311–647 µS/cm in the 1,250–1,300 ft interval. The increased specific conductance with depth indicates an increase in dissolved solids concentration that could affect the suitability of the water for water supply. Drilling was halted at a depth of 1,300 ft to avoid further penetration into zones containing water with a high total dissolved solids concentration.

Grab samples from the LFA were collected on November 21, 2010, in the open borehole at depths of 900, 1,080, and 1,190 ft during flowmeter testing using a wireline sampler and were analyzed for major ions (table 4; figs. 8, 9). Data indicate that water is generally a calcium-magnesium-sulfate type with increasing percentages of constituents with depth. Water from each interval represents a composite sample of water contributed to the borehole from the depth of the water-bearing zone to the bottom of the borehole at 1,300 ft. The specific conductance of each grab sample (1,600–2,800 µS/cm) is greater than that of drilling fluids in the LFA (average 307 µS/cm) because each grab sample represents a composite of the water between sample depth and the bottom of the borehole at 1,300 ft, which contains higher concentrations of dissolved constituents; however, the drilling fluids represent a composite of water between 460 ft and the sampled interval, which contains lower concentrations of dissolved constituents.

Water from the LFA is very hard with hardness as calcium carbonate of 1,032–1,100 mg/L in the composite well samples collected on March 11 and 24, 2010 (table 4). Data indicate that constituent concentrations increase with depth (fig. 8). Water samples from all depth intervals of the LFA have sulfate concentrations that exceed the USEPA SMCL of 250 mg/L (U.S. Environmental Protection Agency, 2009). Sulfate, often associated with a "rotten egg" odor in water, is a naturally occurring constituent that is dissolved from rocks containing gypsum, iron sulfides, or other sulfur compounds. Sulfate minerals can cause scale buildup in water pipes, may be associated with a bitter taste in water, and can have a laxative effect on humans and young livestock (Odom, 2010). Sulfate concentration can be lowered to within acceptable levels through treatment such as reverse osmosis prior to distribution as drinking water.

Comparison of data from analysis of samples from completed LFA well 33P028 collected on March 11 and 24, 2010, and grab samples from depths of 900, 1,080, and 1,190 ft collected on November 21, 2010, indicate that concentrations of chemical constituents in the grab samples were generally higher than concentrations in water from the completed well (table 4). Sulfate concentration of the completed well water was between 1,100 and 1,116 mg/L, which is greater than the 250-mg/L SMCL (U.S. Environmental Protection Agency, 2009).

Hydraulic Properties

A 72-hour aquifer test was conducted March 8–11, 2010, to determine the transmissivity of the LFA. For this test, well 33P028 was pumped at an average rate of 740 gal/min, and drawdown response was observed in the pumped well and observation wells 33P029 and 33P025 completed in the UFA to assess interaquifer leakage response. Pumping well 33P028 at an average rate of 740 gal/min resulted in a maximum drawdown of 38.8 ft at the end of the 72-hr aquifer test (fig. 15). Transmissivity of the LFA was estimated by simulating aquifer-test response using a two-dimensional, radial, transient, groundwater-flow model that incorporated pumped well 33P028 and observation wells 33P029 and 33P025. Flow was simulated using MODFLOW-96 (McDonald and Harbaugh, 1988; Harbaugh and McDonald, 1996) and calibrated using MODOPTIM (Halford, 2006). Simulated transmissivity of the LFA was 7,000 ft^2/d (Gonthier, 2011), which is slightly less than the 11,000 ft^2/d average transmissivity reported at Hunter Army Airfield, which is about 25 mi northeast of Fort Stewart (Clarke and others, 2010; Williams, 2010).

Effects of Lower Floridan Aquifer Pumping on the Upper Floridan Aquifer

Potential effects on water levels in the UFA caused by pumping the LFA were evaluated by monitoring drawdown response in nearby UFA wells during aquifer testing and by simulation. The resulting water-level response (drawdown) in the UFA from pumping the LFA was obtained after filtering water-level data to remove tidal, barometric, and regional pumping influences, discussed previously in the Methods of Data Collection and Analysis section. These drawdown values provided a basis for assessing the accuracy of model simulations. Simulation quantified the long-term (steady-state) leakage response of the UFA to pumping from the LFA and provided the means to estimate the equivalent amount of UFA pumping that would produce similar drawdown to that resulting from leakage.

Observed Water-Level Response

During the 72-hour LFA aquifer test, drawdown of 38.8 ft was observed in pumped well 33P028, and small amounts of drawdown were recorded in UFA wells 33P029 (located 40 ft from the pumped well) and 33P025 (located 9,600 ft from the pumped well; fig. 10). Raw, unfiltered water-level data (fig. 11) indicate distinct water-level declines in UFA wells 33P029 and 33P025, and in pumped LFA well 33P028 (fig. 11). Filtering of water-level data using the spreadsheet procedure of Halford (2006a) isolated the drawdown response from unrelated natural and anthropogenic influences to produce synthesized water levels that presumably contain only drawdown resulting from pumping well 33P028 (fig. 15). The synthesized water levels indicated drawdown in the UFA of 0.4 ft in well 33P029 and 0.3 ft in well 33P025, caused by pumping in LFA well 33P028.

Model Simulation

The GaEPD interim strategy for permitting LFA groundwater withdrawals in the 24-county coastal Georgia area (Nolton Johnston, Georgia Environmental Protection Division, written commun., January 28, 2003) stipulates that an applicant must: (1) quantify aquifer leakage from the UFA to LFA resulting from pumping the new LFA well, 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." To meet these requirements, model simulation was applied.

Although LFA well 33P028 was pumped for only 72 hours, model simulation was used to determine long-term, steady-state effects on the Floridan aquifer system. A revised version of a regional groundwater-flow model (Payne and others, 2005) simulated water-level response in the UFA to pumping from LFA well 33P028 at the identical rate used during the 72-hour aquifer test until steady state was reached (scenario A, fig. 16, table 8). The revised model also was used to simulate the equivalent pumping rate required by UFA well 33P029 (located 40 ft from well 33P028) that would produce a comparable drawdown response as that resulting from pumping LFA well 33P028. Pumping rates and drawdown simulated for all model simulations presented in this report are listed in table 8.

Revisions to the regional model (Payne and others, 2005) incorporated hydrogeologic information obtained from field investigations (described earlier) and from existing wells in the area into model inputs. The model grid was modified to a 10- by-10-ft cell size near well 33P028 to provide more detailed simulations than could be provided by the regional-scale grid. Revisions to the regional model of Payne and others (2005) are described in the appendix.

The revised model simulated average pumping rates for 2010 in Fort Stewart wells, and pumping rates for 2000 elsewhere, to compute drawdown and water-budget components in response to pumping LFA well 33P028. Simulated pumping of LFA well 33P028 at the same rate that the well was pumped during the 72-hour aquifer test (740 gal/min) resulted in a maximum steady-state drawdown of 38.6 ft at the well, which is nearly identical to the 38.8-ft maximum drawdown observed during the test (fig. 11). Because changes in water levels over time were approaching zero by the end of the 72-hour test, the steady-state simulation appears to be a reasonable estimate of field conditions in the LFA. Simulated steady-state drawdown in the LFA for scenario A exceeded 1 ft for an area of 4.4 mi^2 (fig. 16, table 8).

Table 8. Simulated drawdown in the Upper and Lower Floridan aquifers for various pumping distributions at Fort Stewart, Georgia.

[NA, 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	+740	1.1	1.4	256.1	38.6	4.4	258.4	Pumping change at Lower Floridan aquifer well 33P028
B	+740	0	3.1	1.86	254.1	1.1	1.4	258.1	Pumping change at Upper Floridan aquifer well 33P029
C	+205	0	1.1	NA	1.35×10^{-5}	0.31	NA	NA	Pumping change at Upper Floridan aquifer well 33P029
D	–205	+740	0.92	NA	38.4	38.4	2.6	39.3	Upper Floridan aquifer pumping change at wells within 5 miles of well 33P028 and at Lower Floridan aquifer well 33P028
E	–370	+740	0.78	NA	8.7	38.3	2.0	9.6	Upper Floridan aquifer pumping change at wells within 5 miles of well 33P028 and at Lower Floridan aquifer well 33P028

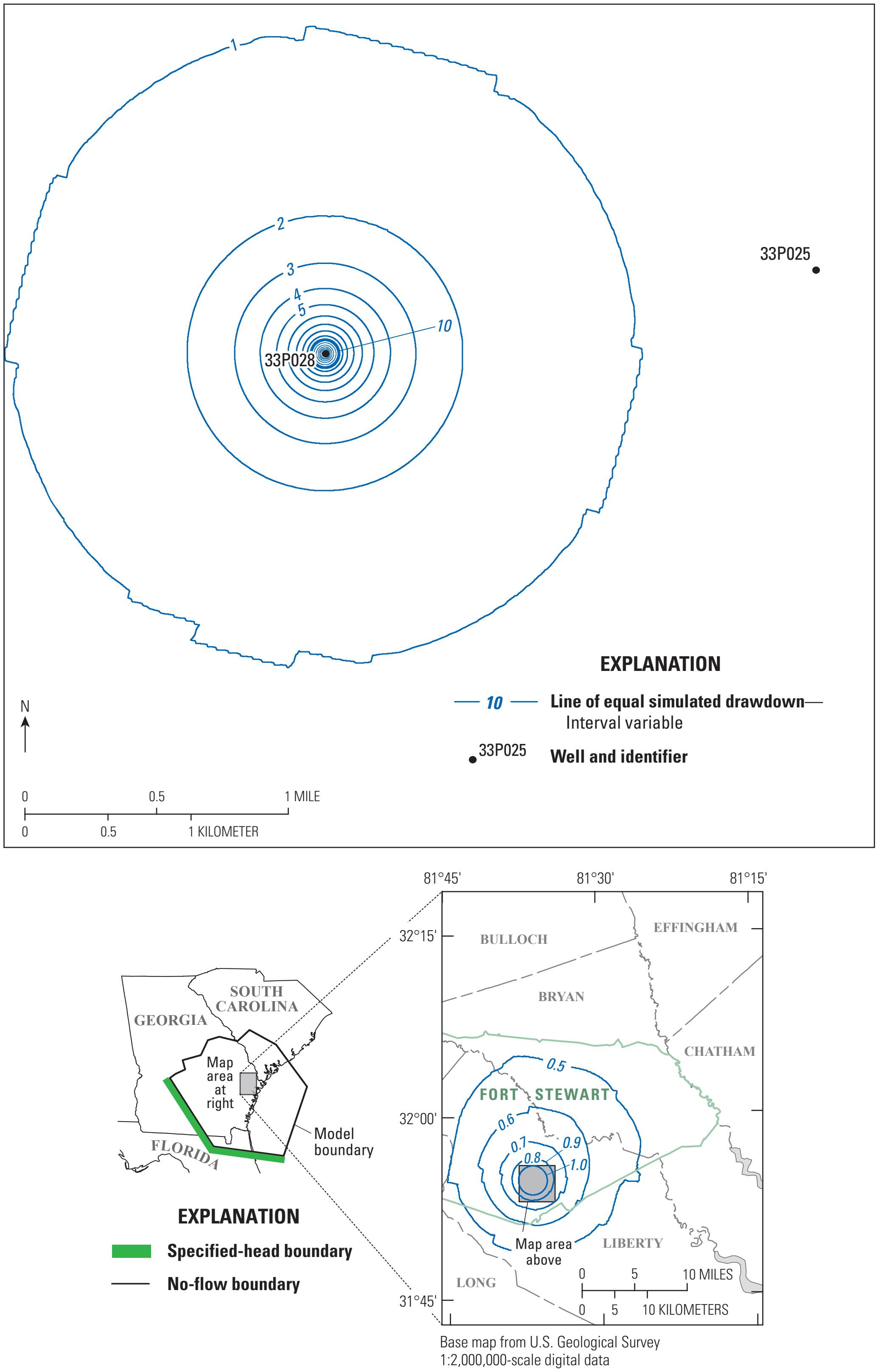


Figure 16. Simulated steady-state drawdown in the Lower Floridan aquifer for scenario A—pumping Lower Floridan aquifer well 33P028 at 740 gallons per minute, Fort Stewart and vicinity, GA. Maximum drawdown in well 33P028 is 38.6 feet.

Interaquifer Leakage and Drawdown Response

Simulated pumping (scenario A) of the LFA at well 33P028 caused leakage through the LFCU, which resulted in drawdown in the overlying UFA (fig. 17). Observed drawdown in the UFA was used as a guide for model calibration. Because drawdown in the UFA had not reached steady state at the end of the 72-hour test, observed water levels were considered a lower limit for evaluation of model simulations.

Model results indicate that steady-state drawdown in the UFA exceeded 1 ft over a 1.4-mi^2 area, was 0.81 ft at well 33P025, and had a maximum drawdown of 1.1 ft near well 33P029 (table 8). Comparison of simulated values to filtered water-level data at the end of the 72-hour aquifer test conducted in LFA well 33P028 indicates that simulated UFA drawdown was greater than the observed values of 0.4 ft in well 33P029 and 0.3 ft in well 33P025. This difference in drawdown is expected because the simulations represent long-term steady-state conditions and field data represent a transient condition whereby drawdown in the UFA had not stabilized at the end of the 72-hour test.

To assess the amount of leakage resulting from pumping in the LFA, the steady-state water budgets before and after pumping at well 33P028 were compared (table 9; fig. 18). Although pumping 1 Mgal/d (740 gal/min) at well 33P028 resulted in small changes to the regional water budget, it did result in a redistribution of flow among model layers, including:

- increased downward leakage in all layers,
- decreased upward leakage in layers 1–6,
- increased upward leakage in layer 7,
- increased inflow and decreased outflow from lateral boundaries in layers 5 and 7, and
- increased inflow (recharge) from the general head boundary to layers 1, 2, and 5.

Flow to well 33P028 was derived from net increases in leakage through the LFCU (layer 6, 98 percent) and contribution from the lateral specified head boundary for the LFA (layer 7, 2 percent). Of the 98 percent contribution (1.05 Mgal/d) from leakage through layer 6, 78 percent was derived from the UFA (layer 5)—by either induced inflow from (58 percent) or reduced outflow to (20 percent) lateral specified-head boundaries. These specified head cells are located along the western and southern boundary of the model (see model boundaries, figure 17), so lateral flow to layers 5 and 7 is derived from these areas. The remaining 22 percent was contributed by leakage from layers above layer 5 (21 percent) and from the general head boundary (1 percent).

Simulation results were processed using ZONEBUDGET (Harbaugh, 1990) to obtain the percentage of total interaquifer leakage from the UFA to the LFA that contributed to the pumped LFA well from within designated zones centered at the pumped LFA well (fig. 19). Three concentric zones centered at well 33P028 were designated—0 to 0.5 mi, 0.5 to 1 mi, and greater than 1 mi. About 80 percent of the interaquifer leakage from the UFA that contributed water to well 33P028 came from within 1 mi of the pumped well, of which 49 percent came from within 0.5 mi of the pumped well. The larger contribution of water at locations near well 33P028 resulted from a larger vertical head gradient between the pumped well and the overlying UFA in areas near the pumped well.

To verify the interconnection between the UFA and LFA, model scenario B was run, in which UFA well 33P029, which is located about 40 ft away from LFA well 33P028 (fig. 10), was pumped at the same rate (740 gal/min) as was used to pump well 33P028 during the 72-hour aquifer test. Simulated drawdown for scenario B indicated a nearly identical response in the UFA when LFA well 33P028 was pumped (fig. 20), verifying the vertical hydraulic connection between the UFA and LFA. The simulated 1-ft drawdown contour for the UFA covered a slightly larger area (1.86 mi^2) with pumping derived from the UFA (scenario B, fig. 20, table 8) than with pumping derived from the LFA (1.4 mi^2) (scenario A, fig. 20, table 8).

Simulated maximum drawdown in the LFA was greater for scenario A, which included pumping 740 gal/min from LFA well 33P028, than for scenario B, which included pumping 740 gal/min from UFA well 33P029 (table 8). A steeper cone of depression was formed in the LFA when LFA well 33P028 was pumped than when UFA well 33P029 was pumped (fig. 21). Maximum simulated LFA drawdown resulting from pumping LFA well 33P028 equaled 38.6 ft at the well, and drawdown exceeded 0.5 ft over a 258.4-mi^2 area (table 8). Pumping at UFA well 33P029 caused a maximum simulated drawdown of 1.1 ft in the LFA, with drawdown exceeding 0.5 ft over a 258.1-mi^2 area. Although pumping from LFA well 33P028 or UFA well 33P029 at a rate of 740 gal/min had a local effect on groundwater levels, pumping had little effect on the regional configuration of the simulated potentiometric surface and related groundwater-flow directions for the UFA (fig. 22).

To assess the amount of leakage resulting from pumping in the UFA (layer 5), steady-state water budgets before and after pumping at well 33P029 (scenario B) were compared (table 10; fig. 23). Pumping from this well resulted in:

- increased downward leakage in all layers,
- decreased upward leakage in layers 1–3,
- increased upward leakage in layers 6 and 7,
- increased inflow and decreased outflow from lateral boundaries in layers 5 and 7, and
- increased inflow (recharge) from the general head boundary to layers 1, 2, and 5.

Table 9. Simulated steady-state water budgets for 2000 and for scenario A, after pumping 740 gallons per minute (1.07 million gallons per day) at Lower Floridan aquifer well 33P028, Fort Stewart, Georgia.

[Values reported to three significant digits and may not sum to totals because of independent rounding; <, less than; NA, not applicable]

Hydrogeologic unit	Layer	Simulated flow, in million gallons per day									
		Pumpage		Recharge from general head boundary		Discharge to general head boundary		Inflow along specified head boundary		Outflow along specified head boundary	
		Year 2000	Well 33P028 added	Year 2000	Well 33P028 added	Year 2000	Well 33P028 added	Year 2000	Well 33P028 added	Year 2000	Well 33P028 added
Surficial aquifer system	1	<0.001	<0.001	280	280	105	105	<0.001	<0.001	<0.001	<0.001
Confining unit	2	<0.001	<0.001	44.6	44.6	5.59	5.59	<0.001	<0.001	<0.001	<0.001
Brunswick aquifer system	3	0.241	0.241	NA	NA	NA	NA	<0.001	<0.001	<0.001	<0.001
Confining unit	4	<0.001	<0.001	NA	NA	NA	NA	<0.001	<0.001	<0.001	<0.001
Upper Floridan aquifer	5	670	670	142	142	20.2	20.2	676	676	228	228
Confining unit	6	<0.001	<0.001	NA	NA	NA	NA	0.004	0.004	<0.001	<0.001
Lower Floridan aquifer	7	128	129	NA	NA	NA	NA	16.6	16.6	1.72	1.71
Total all layers		**798**	**799**	**467**	**467**	**131**	**131**	**693**	**693**	**230**	**230**

Table 10. Simulated steady-state water budgets for 2000 and for Scenario B, after pumping 740 gallons per minute (1.07 million gallons per day) at Upper Floridan aquifer well 33P029, Fort Stewart, Georgia.

[Values reported to three significant digits and may not sum to totals because of independent rounding; <, less than; NA, not applicable]

Hydrogeologic unit	Layer	Simulated flow, in million gallons per day									
		Pumpage		Recharge from general head boundary		Discharge to general head boundary		Inflow along specified head boundary		Outflow along specified head boundary	
		Year 2000	Well 33P029 added	Year 2000	Well 33P029 added	Year 2000	Well 33P029 added	Year 2000	Well 33P029 added	Year 2000	Well 33P029 added
Surficial aquifer system	1	<0.001	<0.001	280	280	105	105	<0.001	<0.001	<0.001	<0.001
Confining unit	2	<0.001	<0.001	44.6	44.6	5.59	5.59	<0.001	<0.001	<0.001	<0.001
Brunswick aquifer system	3	0.241	0.241	NA	NA	NA	NA	<0.001	<0.001	<0.001	<0.001
Confining unit	4	<0.001	<0.001	NA	NA	NA	NA	<0.001	<0.001	<0.001	<0.001
Upper Floridan aquifer	5	670	671	142	142	20.2	20.2	676	676	228	228
Confining unit	6	<0.001	<0.001	NA	NA	NA	NA	0.004	0.004	<0.001	<0.001
Lower Floridan aquifer	7	128	128	NA	NA	NA	NA	16.6	16.6	1.72	1.71
Total all layers		**798**	**799**	**467**	**467**	**131**	**131**	**693**	**693**	**230**	**230**

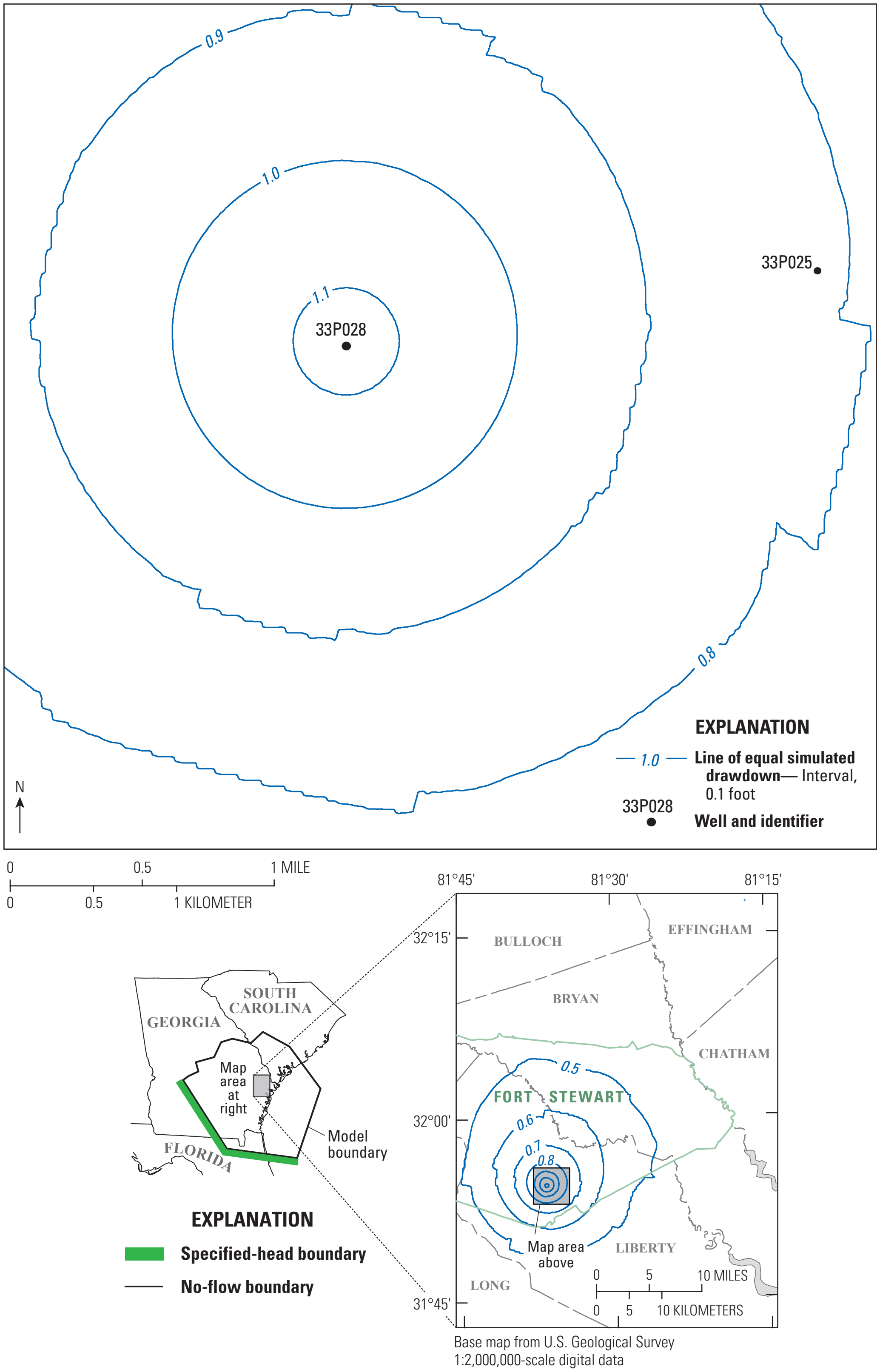


Figure 17. Simulated steady-state drawdown in the Upper Floridan aquifer for scenario A—pumping Lower Floridan aquifer well 33P028 at 740 gallons per minute, Fort Stewart and vicinity, GA.

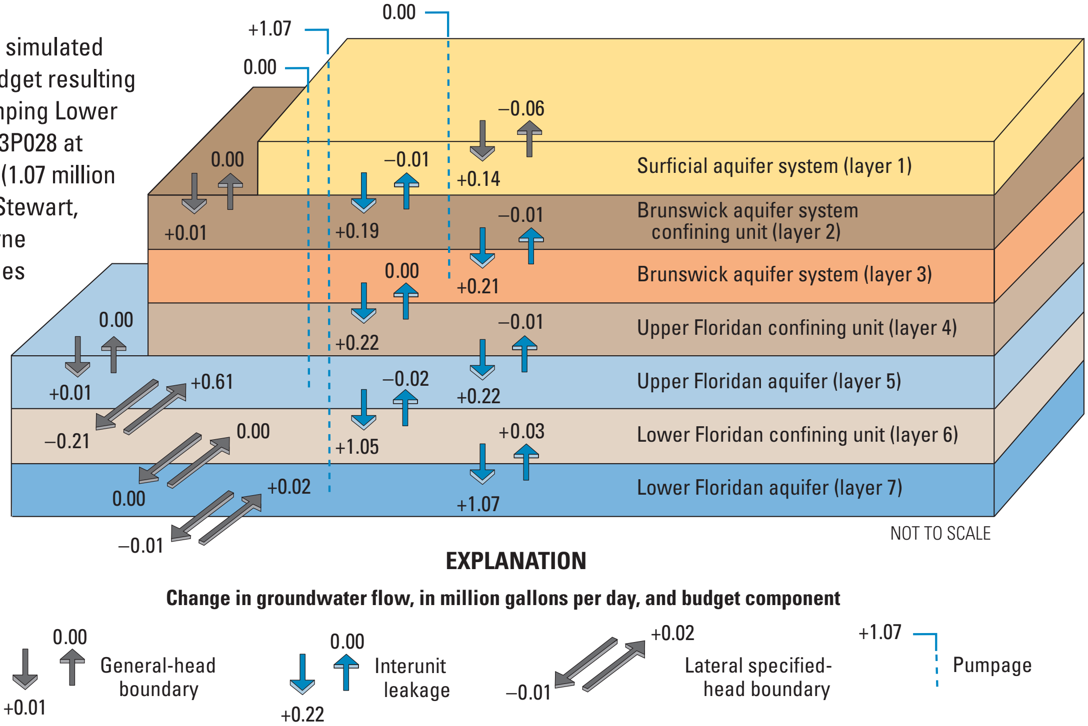


Figure 18. Change in simulated steady-state water budget resulting from scenario A—pumping Lower Floridan aquifer well 33P028 at 740 gallons per minute (1.07 million gallons per day), Fort Stewart, GA (modified from Payne and others, 2005). Values rounded to three significant figures.

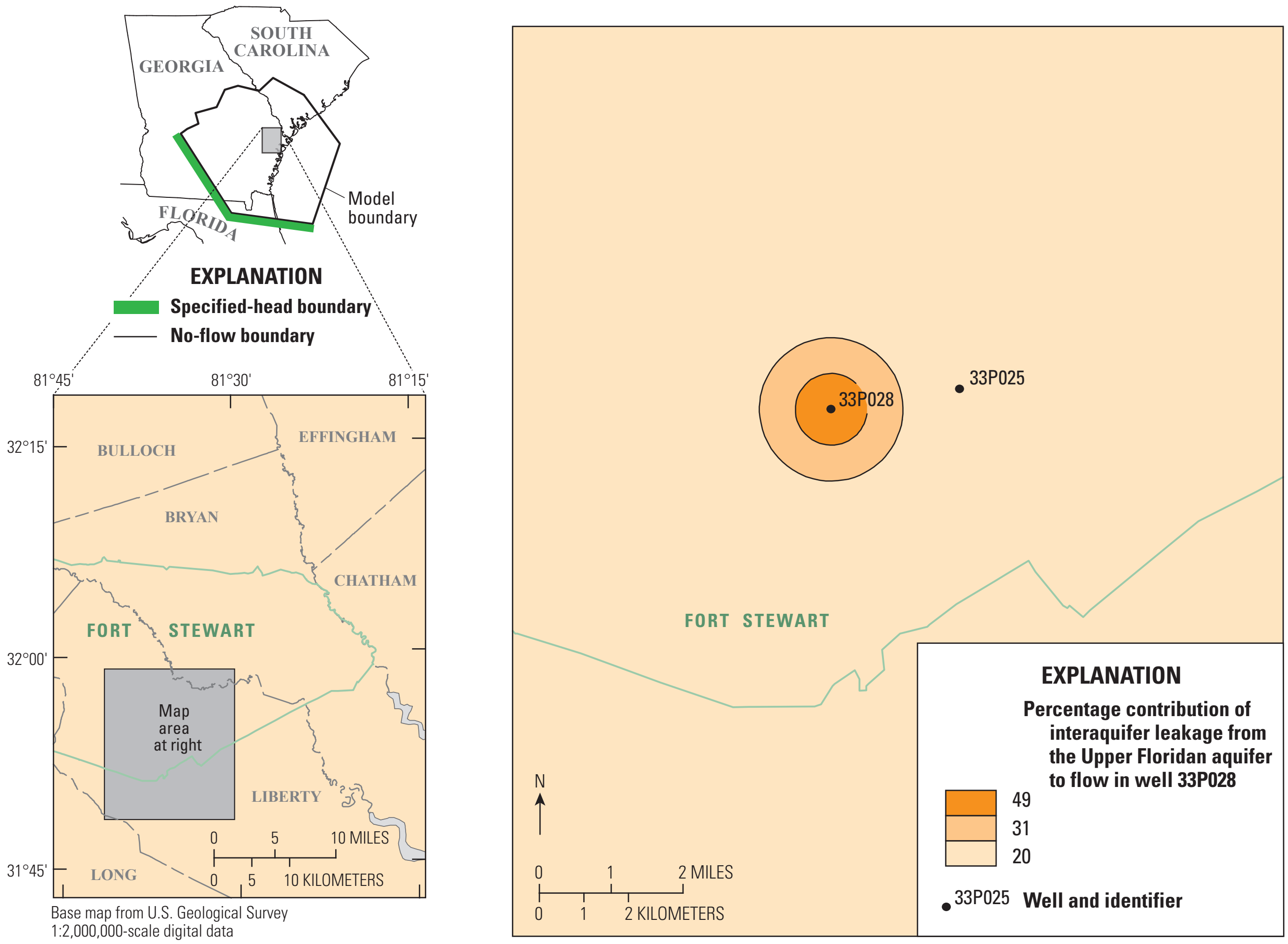
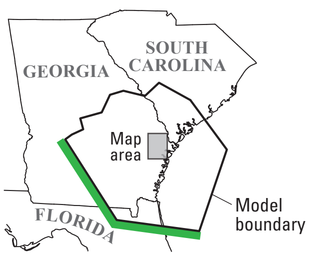


Figure 19. Distribution of interaquifer leakage from the Upper Floridan aquifer for scenario A—lower Floridan aquifer well 33P028 pumping at a rate of 740 gallons per minute, Fort Stewart and vicinity, GA.

Figure 20. Simulated drawdown in the Upper Floridan aquifer for scenario A (pumping Lower Floridan aquifer well 33P028 at a rate of 740 gallons per minute) and scenario B (pumping Upper Floridan aquifer well 33P029 at a rate of 740 gallons per minute), Fort Stewart and vicinity, GA.



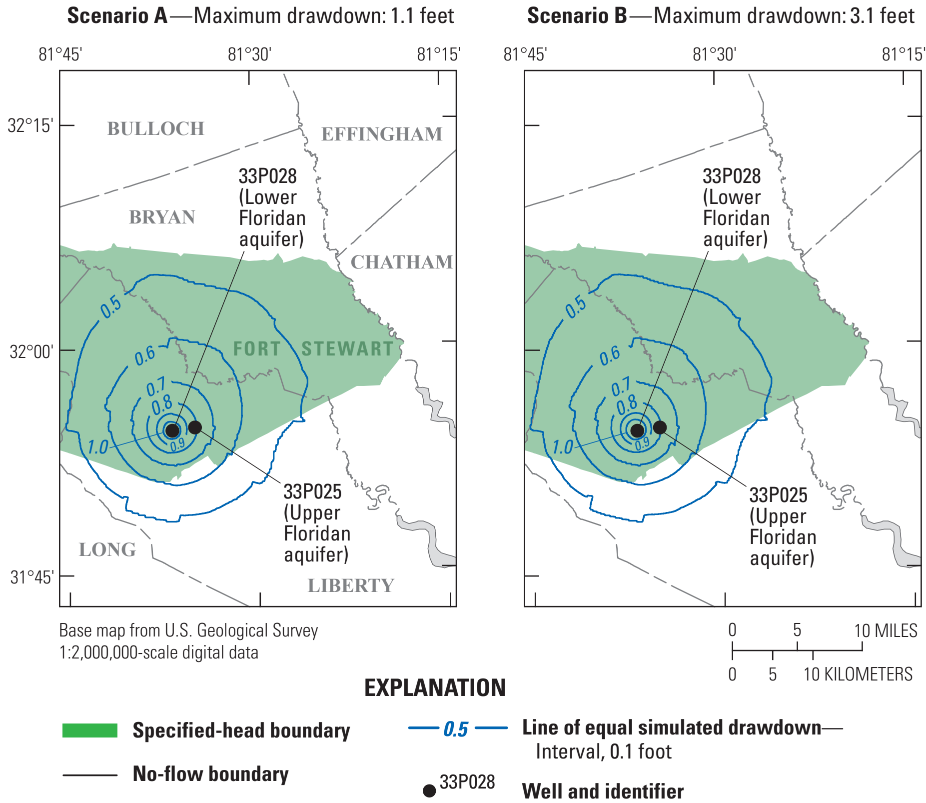
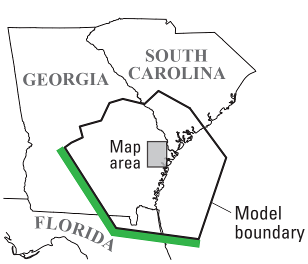
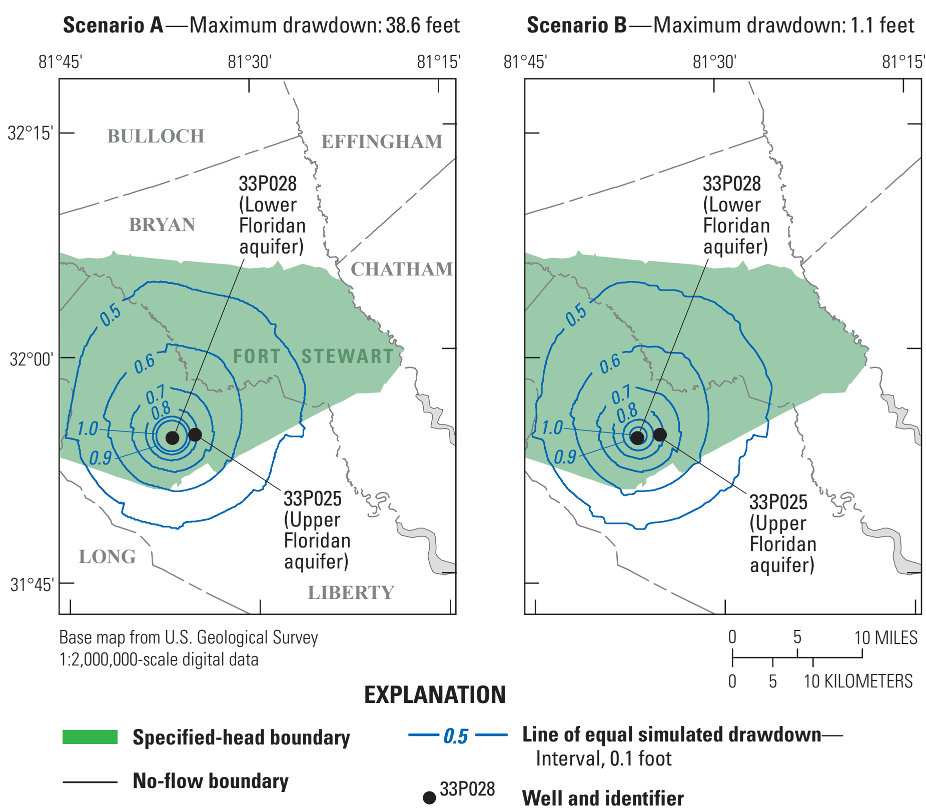
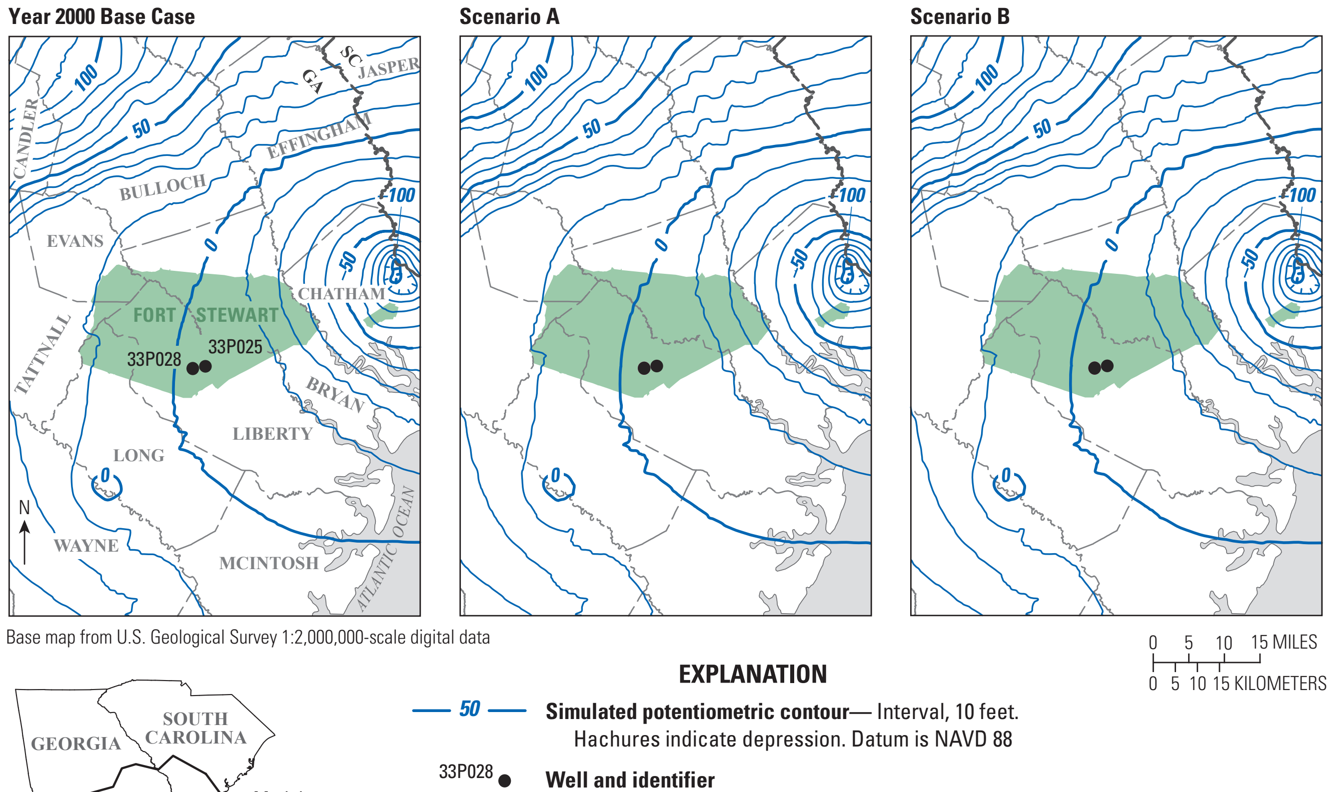


Figure 21. Simulated drawdown in the Lower Floridan aquifer for scenario A (pumping Lower Floridan aquifer well 33P028 at a rate of 740 gallons per minute) and scenario B (pumping Upper Floridan aquifer well 33P029 at a rate of 740 gallons per minute), Fort Stewart and vicinity, GA.







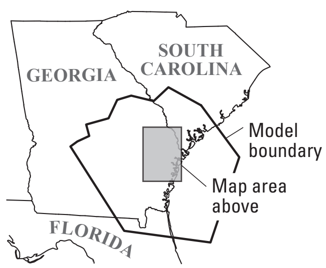
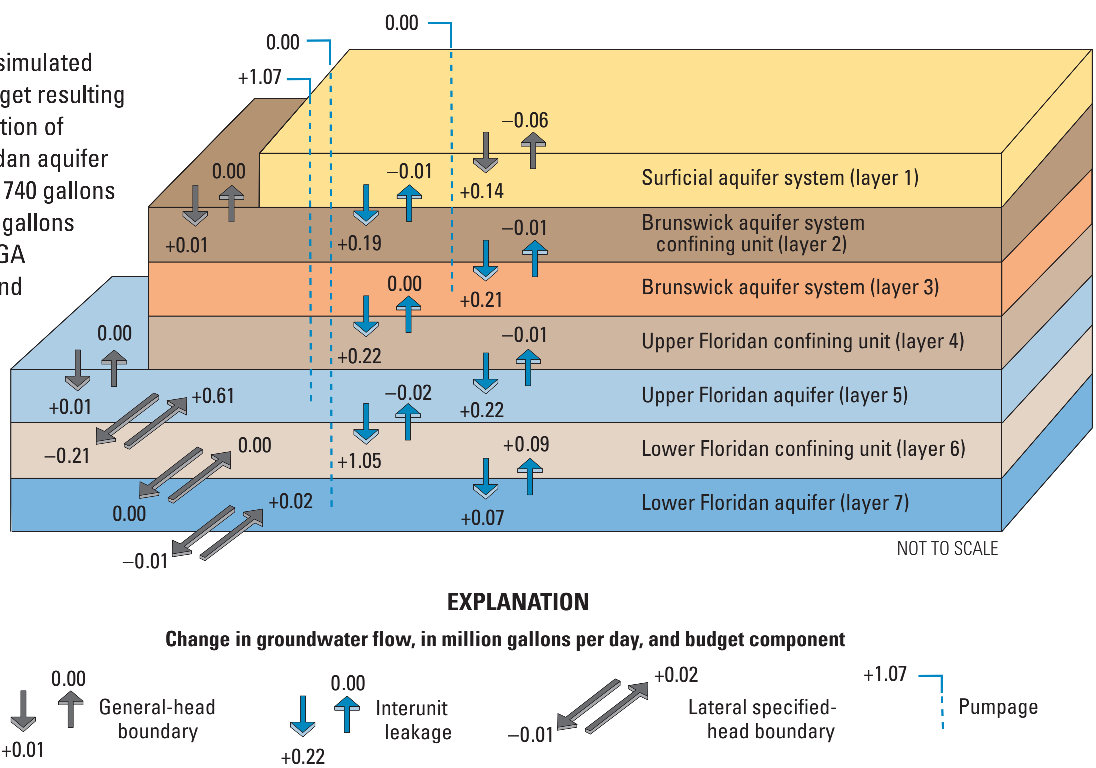


Figure 22. Simulated Upper Floridan aquifer potentiometric surfaces for the year 2000 base case and for scenario A (pumping Lower Floridan aquifer well 33P028 at a rate of 740 gallons per minute) and scenario B (pumping Upper Floridan aquifer well 33P029 at a rate of 740 gallons per minute), Fort Stewart and vicinity, GA.

Figure 23. Change in simulated steady-state water budget resulting from scenario B—initiation of pumping at Upper Floridan aquifer well 33P029 at a rate of 740 gallons per minute (1.07 million gallons per day), Fort Stewart, GA (modified from Payne and others, 2005). Values rounded to three significant figures.



The flow of water within layers 1–3 (fig. 23) is identical to that simulated when pumping LFA well 33P028 (fig. 18); however, some differences exist owing to the change in pumping from layer 7 (well 33P028) to layer 5 (well 33P029, fig. 23) that affected layers 5–7, namely,

- increased upward leakage into layer 5 from layers 6 and 7, and
- decreased downward leakage from layer 5 into layers 6 and 7.

Most of the flow to UFA well 33P029 (77 percent) for scenario B was derived from the lateral specified head boundary, with the remaining water coming from leakage from layer 4 (21 percent) and layer 6 (2 percent). Lateral flow in layer 5 contributes most of the flow to LFA well 33P028 and UFA well 33P029 during scenarios A and B (figs. 18 and 23) for the following reasons:

- The relatively high K_v of the LFCU permits the UFA to supply 98 percent (1.05 Mgal/d) of the water pumped from LFA well 33P028 by leakage. This leakage creates a drawdown response in the UFA that is nearly identical to the response obtained by pumping the UFA directly.
- The nearly 13:1 aquifer transmissivity contrast between the UFA and LFA causes a larger area in the UFA than in the LFA to supply water to the drawdown pattern established in the UFA by pumping from either aquifer. The relatively broad drawdown pattern established in the UFA indicates that a larger area contributes water to the pumped well by lateral flow than the relative small but deep drawdown pattern created near pumped LFA well 33P028.
- This larger area contributing water to the pumped well by the UFA than the LFA extends well beyond the model boundaries, as evidenced by the large amount (77 percent) of water contributed to the pumped well from arbitrary model boundaries representing lateral specified-head and general-head inflow and outflow in the UFA. These boundaries in the LFA supply about 3 percent of the pumped water, regardless of which aquifer is pumped.
- Water-budget components of lateral flow to or from specified-head or general-head boundaries indicate the identical response to pumping regardless of which aquifer is pumped; thus, pumping the LFA is essentially the same, hydrologically, as pumping the UFA.

Upper Floridan Aquifer Drawdown Offset

As part of the interim permitting strategy, GaEPD provided a hydrogeologic-study protocol, which states that a groundwater model shall be used (Nolton Johnston, Georgia Environmental Protection Division, written commun., January 28, 2003) ". . . 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." This amount of equivalent UFA pumping will be the amount of UFA pumping reduction required within a 5-mi radius to offset the effect of any new LFA pumping.

To determine the equivalent pumping rate in the UFA that would produce the identical maximum drawdown in the UFA as pumping from the LFA, a series of steady-state simulations were completed based on the revised regional model of Payne and others (2005). Each simulation involved applying a different pumping rate to UFA well 33P029, located adjacent to LFA well 33P028 (fig. 10). Model simulations indicated that pumping UFA well 33P029 at a rate of 205 gal/min approximates the 1-ft maximum drawdown in the UFA resulting from pumping LFA well 33P028 (scenario C, table 8).

The area in which UFA drawdown exceeds 0.5 ft for scenario C is 377 ft^2 (1.35×10^{-5} mi^2), compared to an area of 256.1 mi^2 when simulating pumping of LFA well 33P028 (scenario A). A map is not included for this scenario because of the small area affected by pumping. The large difference in affected area results from differences in the hydraulic properties of the aquifers and how water flows to the simulated well in the form of leakage and well pumping. Leakage stress in the UFA (caused by pumping the LFA, scenario A) occurs over a wide area, not at a localized position as is the case with an individual pumping well in the UFA (scenario B). Drawdown resulting from leakage shows 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 (fig. 24). The 13:1 transmissivity contrast between the UFA and LFA, and the 8.5:1 anisotropy ratio of K_h to K_v in the LFCU allows water to flow laterally in the UFA into the region where high vertical hydraulic gradients are established between the LFA and UFA near the pumped LFA well. Preferential flow is lateral until high vertical hydraulic gradients in close proximity to the pumped well direct flow downward into the LFA by vertical leakage. The relatively high transmissivity of the UFA causes water to flow laterally under relatively small horizontal hydraulic gradient to the region of large vertical leakage. Although vertical leakage seems localized in the UFA (centered around the pumped LFA well), the source of this leaking water from the UFA is lateral flow under much smaller horizontal gradients than the vertical gradients that induce leakage into the LFA from the UFA.

A pumping rate in the UFA that would provide the equivalent drawdown as pumping in the LFA will not produce the same leakage distribution because the drawdown exhibited by the UFA from pumping in the LFA was not derived from a point sink (well) located in the UFA; pumping in the LFA at a point sink (well) creates a focused drawdown pattern in the UFA that has a finite area. This area of focused drawdown is

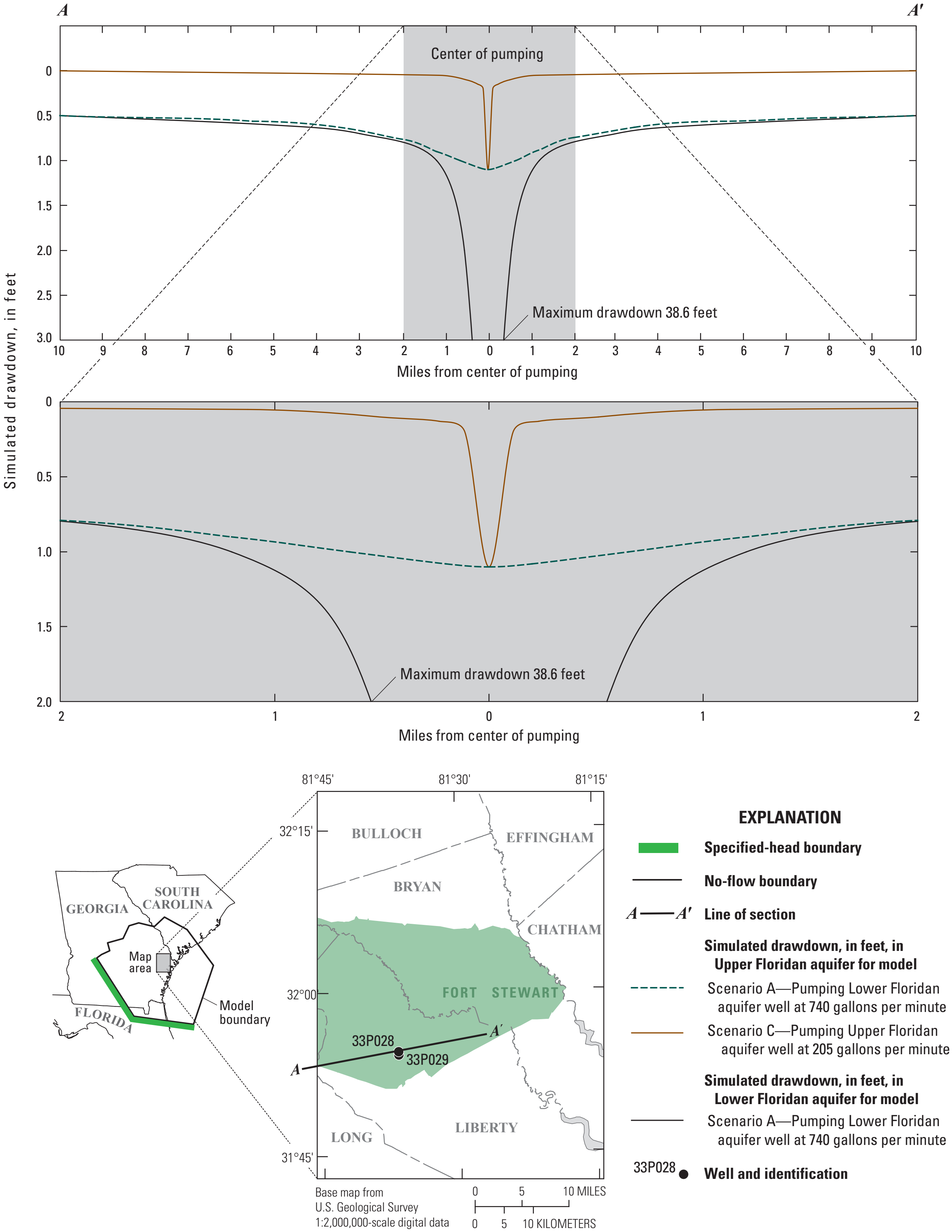


Figure 24. Simulated drawdown in the Upper Floridan aquifer for scenarios A and C, and in the Lower Floridan aquifer for scenario A, Fort Stewart and vicinity, GA.

the steep drawdown cone that establishes an area containing a high vertical hydraulic gradient that induces leakage from the UFA. The UFA responds to leakage from a focused area of high vertical hydraulic gradient instead of from a point sink as if a well were located in the UFA, and because of its higher transmissivity compared with the LFA, the UFA establishes a broad drawdown pattern over a larger area than the area defined by the focused drawdown pattern in the LFA (fig. 24). Lateral hydraulic gradients in the UFA are lessened by the relatively high transmissivity contrast between the UFA and LFA and the areally distributed vertical leakage pattern caused by the vertical hydraulic gradient distribution between the LFA and UFA. Although it is possible to derive an equivalent pumping rate in the UFA that produces the same leakage rate or volume as pumping in the LFA, that resultant UFA pumping will not produce the same drawdown pattern in the UFA as produced with pumping from the LFA; the equivalent pumping rate would have to be distributed over the area created by the vertical hydraulic gradient distribution caused by pumping the LFA.

Effect of Pumping Offsets on Groundwater Levels at Fort Stewart

To assess the effect of pumping redistribution on current groundwater conditions at Fort Stewart, two model scenarios were run.

- Scenario D—Effect of pumping LFA well 33P028, 24 hours per day at a rate of 740 gal/min (1.07 Mgal/d), and reducing pumping in existing UFA Fort Stewart supply wells by 205 gal/min (0.3 Mgal/d) or 28 percent of the pumping rate at LFA well 33P028. The reduction in withdrawals from the UFA represents the rate required to match the maximum UFA drawdown simulated near LFA well 33P028 for Scenario A.

- Scenario E—Effect of pumping the LFA at well 33P028 at a rate of 740 gal/min (1.07 Mgal/d), and reducing pumping in existing UFA Fort Stewart supply wells by 370 gal/min (0.53 Mgal/d) or 50 percent of the pumping rate at well 33P028.

Because offsetting existing UFA pumping by 98 percent of the LFA pumping rate (representing UFA leakage to the LFA) would result in only a small gain in production at Fort Stewart (0.02 Mgal/d), a scenario was not run to assess the effects of such a pumping change.

For scenarios D and E, permitted UFA withdrawals at Fort Stewart during 2010 were reduced at wells located within a 5-mi radius of new LFA well 33P028 and withdrawal from LFA well 33P028 was held constant at 1.07 Mgal/d (740 gal/min). Pumping changes for the two scenarios are summarized in table 11; maps showing water-level changes in the UFA resulting from scenarios D and E are provided in figures 25 and 26, respectively.

For each scenario, pumping reductions in the existing Fort Stewart UFA wells resulted in decreased magnitude and extent of drawdown when compared to a scenario in which a well in the LFA was pumped without reducing withdrawals in the UFA (fig. 16, table 8). For scenario A, pumping at LFA well 33P028 without reducing pumping in the UFA resulted in UFA drawdown that exceeded 0.5 ft over a 256.1-mi^2 area, and equaled 1.1 ft near wells 33P028 and 33P029. For scenario D, simulated maximum UFA drawdown equaled 0.92 ft near well 33P028, and the area in which drawdown exceeded 0.5 ft covered 38.4 mi^2 (fig. 25; table 8). Simulated maximum drawdown in the UFA for scenario E equaled 0.78 ft near well 33P028, and the simulated 0.5-ft drawdown contour covered an area of 8.7 mi^2 (fig. 26; table 8). None of the scenarios resulted in noticeable changes in the regional configuration of the simulated potentiometric surface and related groundwater-flow directions for the UFA (fig. 27).

Effect of Pumping Offsets on Water Supply at Fort Stewart

Results of model simulations used to evaluate the GaEPD interim permit strategy indicated that attempting to satisfy leakage and drawdown requirements results in distinctly different simulated pumping offsets for the UFA. Simulated interaquifer leakage from the UFA through the LFCU into the LFA totaled 725 gal/min (1.04 Mgal/d), whereas the pumping rate in UFA well 33P029 needed to match (offset) simulated maximum drawdown in the UFA resulting from interaquifer leakage totaled only 205 gal/min (0.3 Mgal/d). The simulated pumping rate needed to match (offset) the maximum drawdown in the UFA underpredicts the amount of pumping needed to offset leakage from the UFA to the LFA because the cone of depression formed in the UFA by the offset pumping is steeper near the pumped well and covers a smaller area than the drawdown simulated in the UFA in response to interaquifer leakage resulting from LFA pumping (fig. 24).

Model scenarios D and E were simulated to provide an assessment of the effects of pumping LFA well 33P028 at a rate of 740 gal/min while reducing UFA pumping by 205 and 370 gal/min, respectively (table 11, figs. 25–27). To assess possible net gains in water capacity at Fort Stewart, pumping offsets and net gain in water-production capacity were computed for pumping reductions of 205, 370, and 725 gal/min in the Upper Floridan aquifer for a variety of pumping periods (table 12). For a 12-hour daily pumping period, the net gain in capacity would range from 0.01 Mgal/d (to meet the leakage offset of 725 gal/min) to 0.39 Mgal/d (to meet the maximum drawdown offset of 205 gal/min). For a 24-hour pumping period, the net gain in capacity would range from 0.02 Mgal/d (to meet the leakage requirement) to 0.77 Mgal/d (to meet the maximum drawdown requirement).

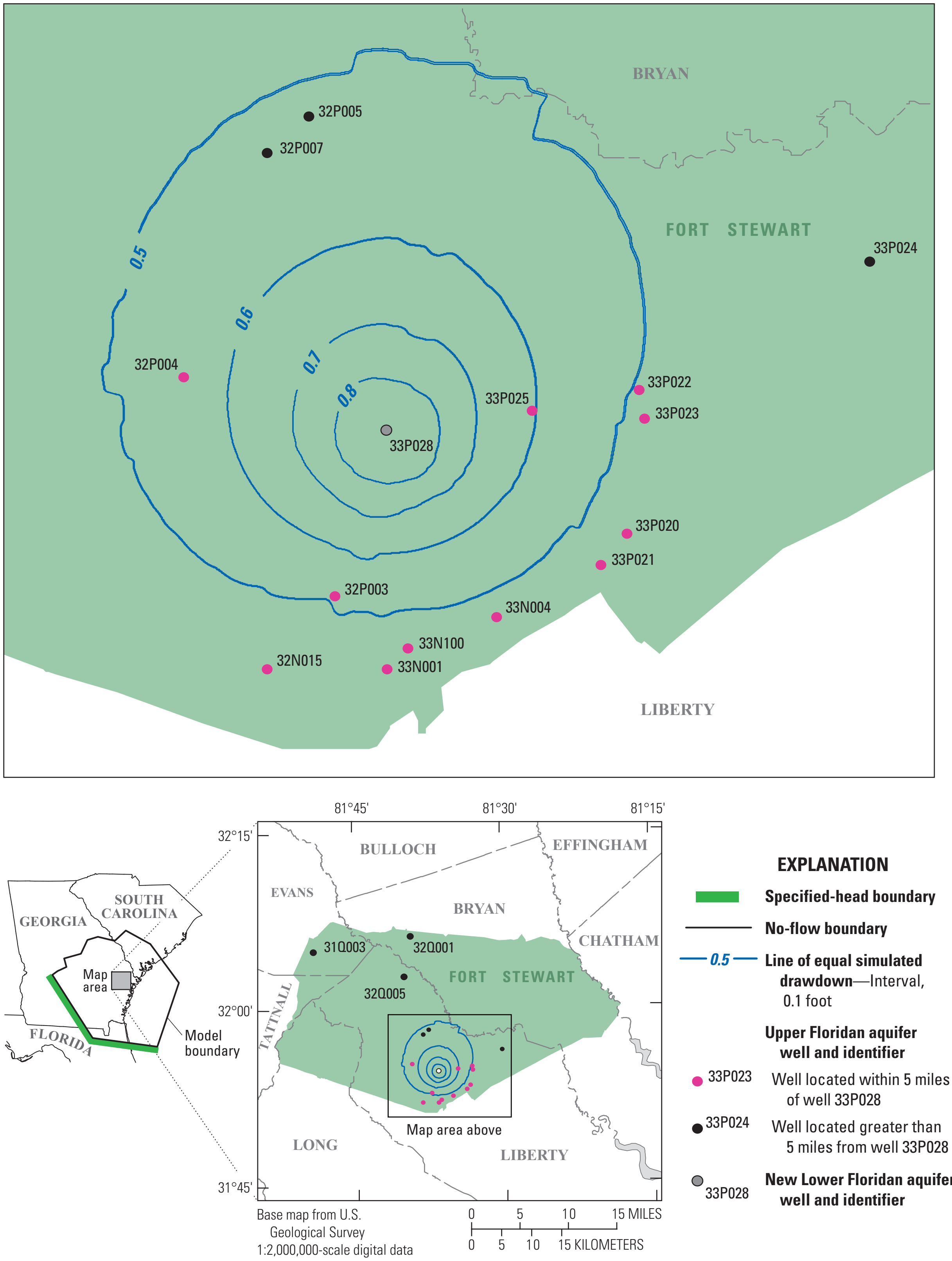


Figure 25. Simulated drawdown in the Upper Floridan aquifer for scenario D—effect of pumping Lower Floridan aquifer well 33P028 at a rate of 740 gallons per minute, and reducing pumping in the existing Upper Floridan aquifer supply wells by 205 gallons per minute, Fort Stewart and vicinity, GA.

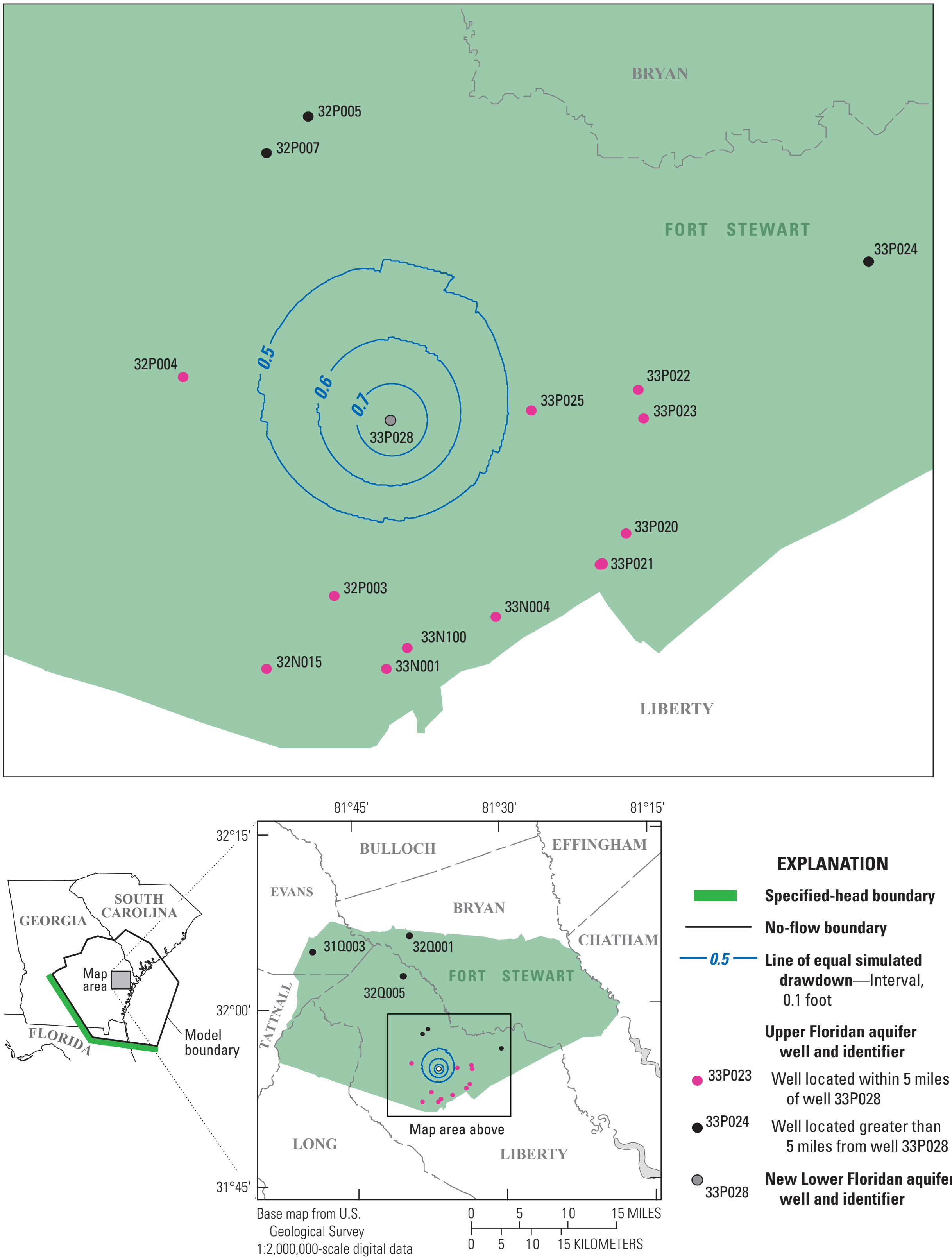


Figure 26. Simulated drawdown in the Upper Floridan aquifer for scenario E—effect of pumping Lower Floridan aquifer well 33P028 at a rate of 740 gallons per minute, and reducing pumping in the existing Upper Floridan aquifer supply wells by 370 gallons per minute, Fort Stewart and vicinity, GA.

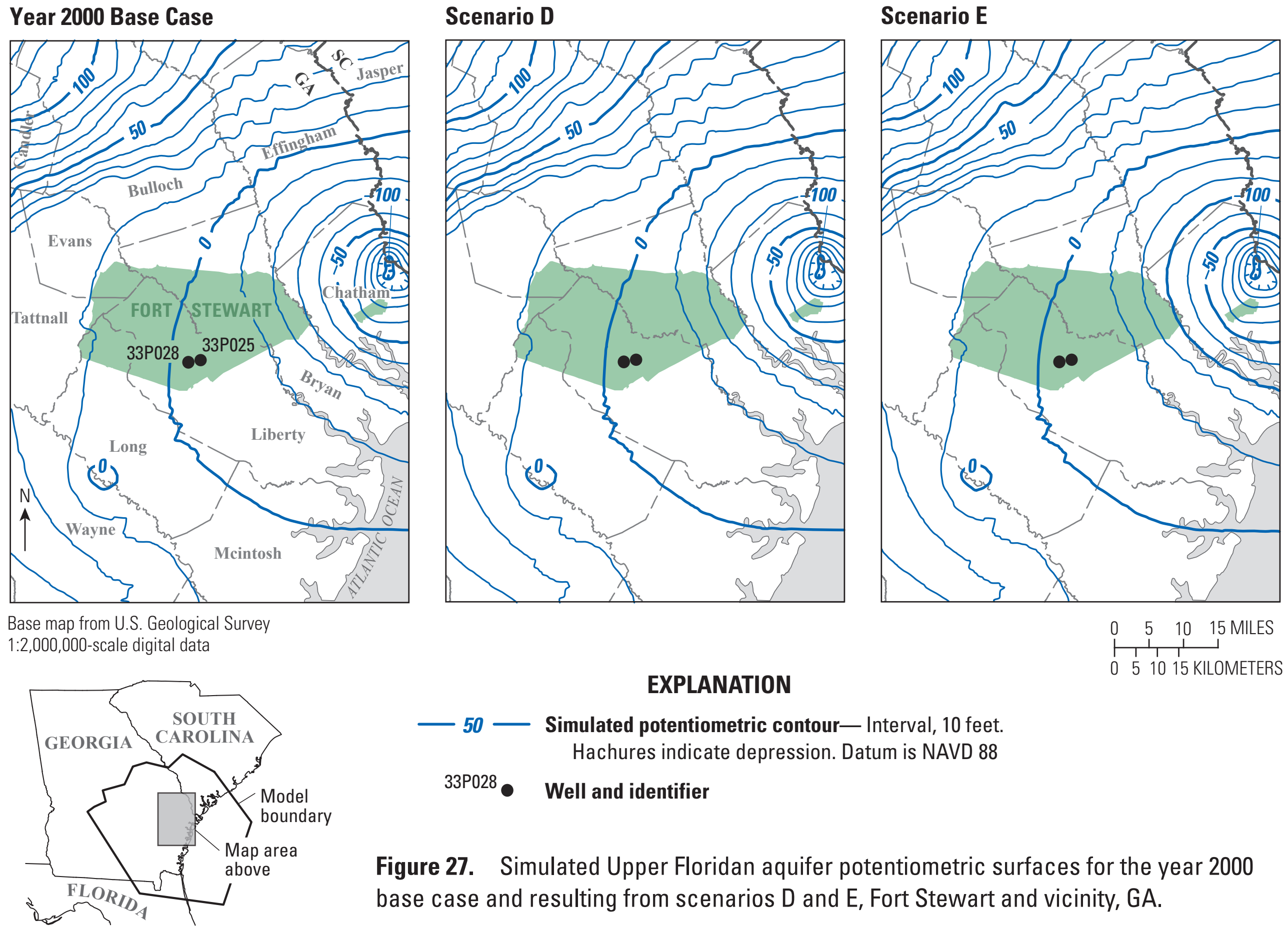


Figure 27. Simulated Upper Floridan aquifer potentiometric surfaces for the year 2000 base case and resulting from scenarios D and E, Fort Stewart and vicinity, GA.

Table 11. Simulated pumping for the year 2010 permitted pumping rate and model scenarios D and E.

[Mgal/d, million gallons per day; —, not applicable]

Well identifier	Well name	Simulated pumping rate, in million gallons per day		
		2010 permitted	Scenario D	Scenario E
Upper Floridan aquifer wells located within 5-mile radius of well 33P028				
33N001	Ft. Stewart 01 (P00933)	0.30	0.26	0.23
32P003	Ft. Stewart 3 (P01325)	0.30	0.26	0.23
33N100	Ft. Stewart 02 (bldg 456)	0.30	0.26	0.23
33N004	Ft. Stewart 04 (bldg 9961)	0.30	0.26	0.23
32N015	Ft. Stewart 05 (bldg 4524)	0.30	0.26	0.23
33P020	Ft. Stewart 6A Wright Airfield E Lowe Cir (T07731)	0.30	0.26	0.23
33P021	Ft. Stewart 6B Wright Airfield W Lowe Cir (T07732)	0.30	0.26	0.23
32P004	Ft. Stewart 11 Ammo Supply Point	0.10	0.09	0.09
33P022	Ft. Stewart 12b Holbrook Pond Skeet Range	0.10	0.09	0.09
33P023	Ft. Stewart 12a Holbrook Pond Campground	0.10	0.09	0.09
	Subtotal	**2.40**	**2.10**	**1.87**
Upper Floridan aquifer wells located outside 5-mile radius of well 33P028				
32Q001	Ft. Stewart 9 Tac X	0.30	0.30	0.30
31Q003	Ft. Stewart 08 Camp Oliver (T15003)	0.30	0.30	0.30
33P024	Ft. Stewart 10 Evans Army Heliport (T19107)	0.30	0.30	0.30
32P005	Ft. Stewart 15 Red Cloud Golf (abandoned)	0.30	0.30	0.30
32Q005	Ft. Stewart 17 Red Cloud Alpha	0.30	0.30	0.30
33P025	Ft. Stewart 14 Bravo-Clifford Range	0.30	0.30	0.30
32P007	Ft. Stewart 13 DMPRC	0.30	0.30	0.30
	Subtotal	**2.10**	**2.10**	**2.10**
	Total Upper Floridan aquifer	**4.50**	**4.20**	**3.97**
Lower Floridan aquifer				
33P028	Ft. Stewart IBCT Lower Floridan Production well	—	1.07	1.07
	Total Upper and Lower Floridan aquifers	**4.50**	**5.27**	**5.04**

Table 12. Projected reductions in Upper Floridan aquifer permitted capacity and net gain in total water capacity for various pumping periods, well 33P028, Fort Stewart, Georgia.

[gal/min, gallon per minute; Mgal/d, million gallons per day]

Lower Floridan pumping (well 33P028)			Estimated Upper Floridan aquifer pumping reduction to offset Lower Floridan aquifer pumping effects		January 2010 permitted Upper Floridan aquifer withdrawal rate	Revised Upper Floridan aquifer withdrawal rate (accounting for pumping reduction)	Total pumping capacity (Upper and Lower Floridan aquifers combined)	Net increase in pumping capacity (Upper and Lower Floridan aquifers combined)	Remarks
Daily pumping period, in hours	Gal/min	Mgal/d	Gal/min	Mgal/d	Mgal/d	Mgal/d	Mgal/d	Mgal/d	
725-gal/min reduction in Upper Floridan aquifer pumping to offset simulated interaquifer leakage response									
8	740	0.36	725	0.35	4.50	4.15	4.51	0.01	
12	740	0.53	725	0.52	4.50	3.98	4.51	0.01	
16	740	0.71	725	0.70	4.50	3.80	4.51	0.01	
24	740	1.07	725	1.04	4.50	3.46	4.52	0.02	
205-gal/min reduction in Upper Floridan pumping to offset simulated maximum drawdown in Upper Floridan aquifer									
8	740	0.36	205	0.10	4.50	4.40	4.76	0.26	
12	740	0.53	205	0.15	4.50	4.35	4.89	0.39	
16	740	0.71	205	0.20	4.50	4.30	5.01	0.51	
24	740	1.07	205	0.30	4.50	4.20	5.27	0.77	See model scenario A
370-gal/min reduction in Upper Floridan aquifer pumping to offset 50 percent of the simulated leakage rate									
8	740	0.36	370	0.18	4.50	4.32	4.68	0.18	
12	740	0.53	370	0.27	4.50	4.23	4.77	0.27	
16	740	0.71	370	0.36	4.50	4.14	4.86	0.36	
24	740	1.07	370	0.53	4.50	3.97	5.03	0.53	See model scenario B

Limitations of Analysis

Analysis 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 pumping. Although water-level data were filtered to minimize or eliminate local interferences, such as tidal and pumping effects (Halford, 2006), these interferences still could affect recorded levels to some degree and, thus, affect computed hydraulic properties and measured drawdown response.

Use of a revised, steady-state, regional flow model limits the analysis to evaluate long-term (steady-state) changes in groundwater flow. Additional insight into changes in water levels over time could be gained by using transient simulation. The revised model reasonably depicts changes in groundwater levels resulting from pumping the LFA at Fort Stewart at a rate of 740 gal/min. Results are limited by the same model assumptions and design as described by Payne and others (2005). In addition to limitations of field data accuracy as described above, the revised model may have 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. The variably spaced grid used in the revised model contains aspect ratios between row and column dimensions as large as 1,640:1, which can lead to numerical errors (de Marsily, 1986, p. 351). Fortunately, these large aspect ratio grid cells occur only in areas distant from Fort Stewart and will have little effect on simulated results in the area.

Simulated rates of interaquifer leakage and drawdown in the UFA may be less than actual because of the influence of specified head and general-head boundaries, which supply an unlimited amount of water to the groundwater system. This unlimited supply may result in lower simulated drawdown and related rates of interaquifer leakage. Model simulations were conducted to evaluate the effect on drawdown of changing the lateral specified head boundary in layers 5–7 to no-flow boundaries (table 13). Scenario F simulated drawdown resulting from pumping the LFA under the new boundary conditions (similar to scenario A), and scenario G simulated drawdown resulting from pumping the UFA under the new boundary conditions (similar to scenario B). Each of the two scenarios applied a pumping rate of 740 gal/min. Results of the simulations indicate that changing to no-flow boundaries resulted in slightly greater maximum drawdown in the UFA and LFA. Pumping the LFA resulted in an increase in maximum drawdown in the LFA from 38.6 ft for scenario A to 39.5 ft for scenario F and in the UFA from 1.1 ft for scenario A to 2.0 ft for scenario F. Similarly, pumping the UFA resulted in an increase in maximum drawdown in the UFA from 3.1 ft for scenario B to 4.0 ft for scenario G, and in the LFA from 1.1 for scenario B to 2.0 ft for scenario G. The higher drawdown values for scenarios F and G also would result in more simulated leakage because of increased head gradients between the UFA and LFA. 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.

Table 13. Effects of lateral boundary conditions on simulated maximum drawdown in the Upper and Lower Floridan aquifers, Fort Stewart, Georgia.

Scenario	Upper Floridan aquifer pumping rate, gallons per minute	Lower Floridan aquifer pumping rate, gallons per minute	Maximum drawdown in the Upper Floridan aquifer, feet	Maximum drawdown in the Lower Floridan aquifer, feet	Lateral model boundary in layers 5, 6, and 7
A	0	+740	1.1	38.6	Specified head
F	0	+740	2.0	39.5	No-flow
B	+740	0	3.1	1.1	Specified head
G	+740	0	4.0	2.0	No-flow

Summary and Conclusions

To assess the hydrogeology and water quality of the Floridan aquifer system and the potential effect of Lower Floridan aquifer (LFA) pumping on the Upper Floridan aquifer (UFA), the U.S. Geological Survey, in cooperation with the U.S. Department of the Army, conducted an investigation at Fort Stewart, GA, during 2009–2010. The study included construction of test wells completed in the UFA and LFA, aquifer-performance testing, packer-slug tests, core hydraulic analysis, geophysical logging, flowmeter testing, water-quality sampling and analysis, and digital groundwater modeling.

Results of test drilling and field tests indicate that the LFA at Fort Stewart consists of limestone and dolomitic limestone that extend to depths ranging from 912 to at least 1,300 feet (ft). Three major permeable zones were identified through borehole-geophysical logging and flowmeter testing: 912–947, 1,090–1,139, and 1,211–1,250 ft. These zones respectively contribute 50, 18, and 32 percent, respectively, to the total flow of 740 gal/min.

Analysis of grab water samples collected during flowmeter testing in the UFA and LFA indicates that concentrations of major constituents increased with depth. Water samples from all intervals of the LFA contained sulfate concentrations that exceeded the U.S. Environmental Protection Agency (USEPA) secondary maximum contaminant level (SMCL) of 250 milligrams per liter (mg/L). Sulfate concentration of water from the completed LFA well (33P028) equaled 1,100 mg/L, which would require treatment such as reverse osmosis to lower sulfate concentration to within acceptable levels prior to distribution as drinking water.

Pumping in the LFA caused minimal water-level decline (drawdown) in the UFA. Pumping LFA well 33P028 at a rate of about 1 million gallons per day (Mgal/d) for 72 hours caused nearly 39 ft of water-level decline (drawdown) in the LFA and 0.4 and 0.3 ft of drawdown, respectively, in UFA wells 33P029 and 33P025. Results from simulation of regional groundwater flow indicated that long-term pumping from the LFA would result in drawdown of about 1.1 ft in the UFA in the vicinity of well 33P028.

Model simulation results indicate that most of the water withdrawn from LFA well 33P028 is induced vertical leakage from the UFA (98 percent) with the remaining inflow (2 percent) provided from lateral flow boundaries. The area within 1 mile (mi) of the pumped well supplied about 80 percent of the water pumped; about half of the water pumped was derived from within 0.5 mi of the well. The effects of this leakage on the UFA, although slight with regard to drawdown in the UFA, extend into the Coastal Plain beyond Fort Stewart because of the relatively large, about 13:1, contrast in the water-transmitting ability, or transmissivity, of the UFA compared with that of the LFA.

Additional simulations addressed the two stipulations of the interim permitting strategy promulgated by the Georgia Environmental Protection Division (GaEPD), which are (1) to quantify aquifer leakage from the UFA to LFA resulting from pumping the new LFA well, and (2) to 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." Simulation results identified widely varying pumping offsets for the UFA depending on whether the leakage (stipulation 1) or the pumping equivalent (stipulation 2) was evaluated. The equivalent pumping rate necessary to match the maximum drawdown in the UFA for stipulation 2 (205 Mgal/d) underpredicts the pumping offset in the UFA equivalent to the rate of water supplied by vertical leakage from the UFA (725 Mgal/d) to the LFA well (to satisfy stipulation 1).

Factoring the pumping offsets resulting from the leakage requirement (stipulation 2) or the pumping requirement (stipulation 1) of the GaEPD interim permitting strategy with new pumping from LFA well 33P028 results in a range of net gain in total permitted capacity at Fort Stewart. For a 12-hour daily pumping period, the net gain in capacity would range from 0.01 Mgal/d (to meet the leakage offset of 725 gal/min, stipulation 2) to 0.39 Mgal/d (to meet the maximum drawdown offset of 205 gal/min, stipulation 1). For a 24-hour pumping period, the net gain in capacity would range from 0.02 Mgal/d (to meet the leakage requirement) to 0.77 Mgal/d (to meet the maximum-drawdown requirement).

Simulated rates of interaquifer leakage and drawdown in the UFA may be less than actual rates because of the influence of specified head and general-head boundaries which supply an unlimited amount of water to the groundwater system. This unlimited supply may result in lower simulated drawdown and related 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.

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Appendix. Regional Groundwater Model

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Regional Groundwater Model

A regional groundwater flow 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 Fort Stewart, Georgia. The regional model is described in detail in Payne and others (2005); a brief description is included below.

The regional model (Payne and others, 2005) 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. A–1).

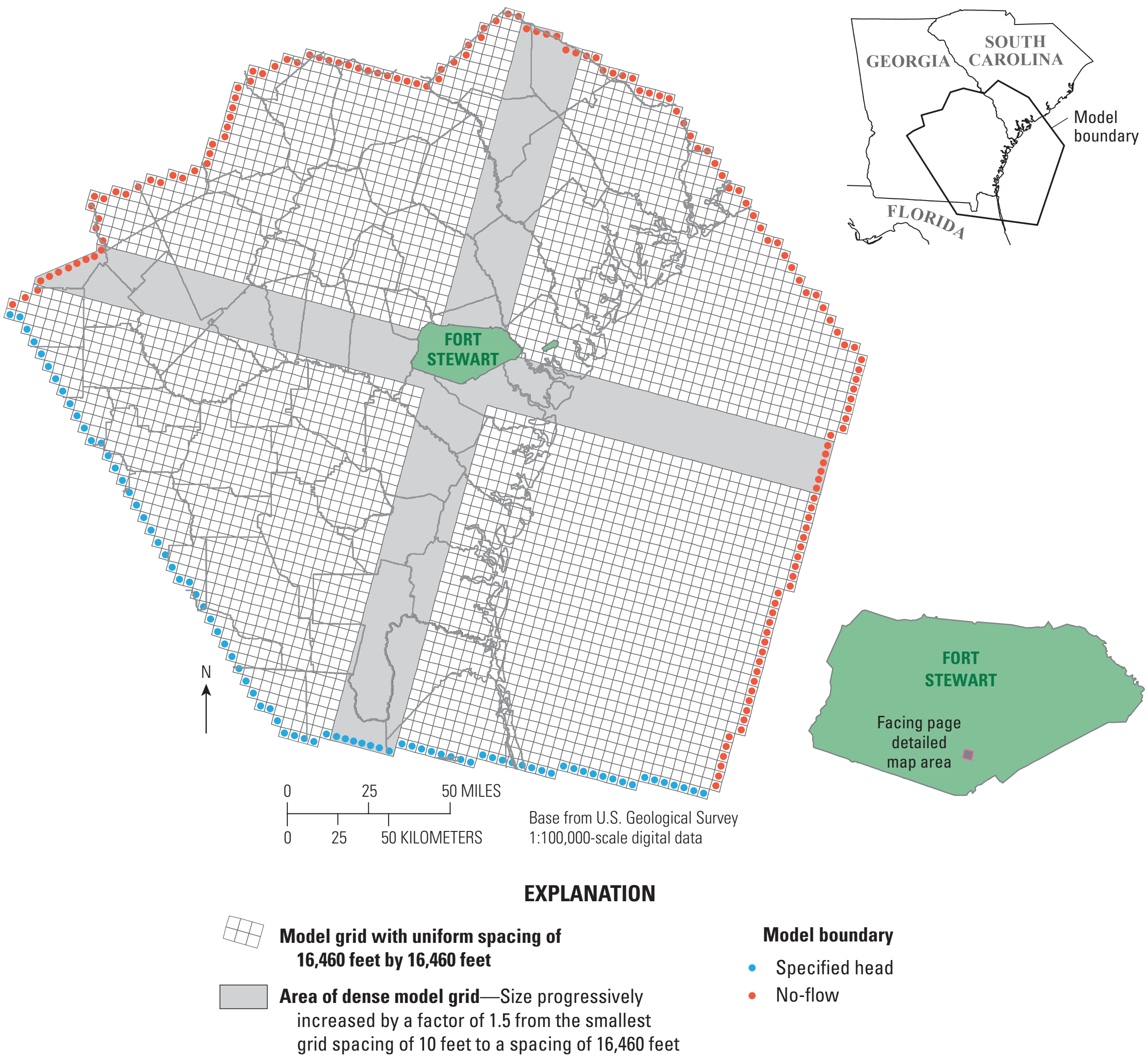

Figure A–1. Location of selected wells, regional groundwater model and boundary conditions, and revised model grid, Fort Stewart and vicinity, GA.

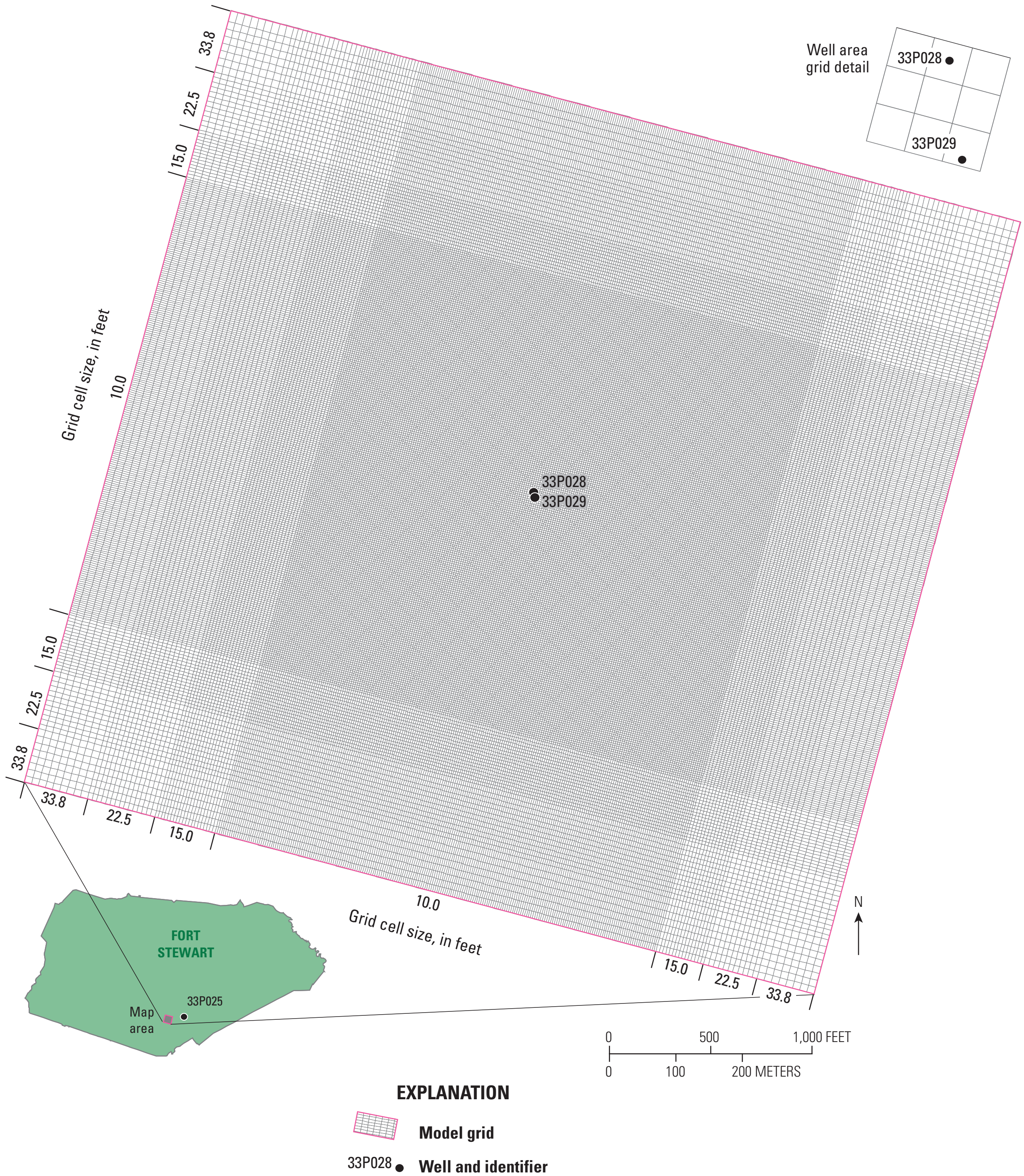

Figure A–1. Location of selected wells, regional groundwater model and boundary conditions, and revised model grid, Fort Stewart and vicinity, GA.—Continued

The regional model (Payne and others, 2005) consists of the following seven model layers and corresponding hydrogeologic units (fig. A–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, comprising the Brunswick aquifer system;
- Layer 4: Upper Floridan confining unit;
- Layer 5: Upper Floridan aquifer (UFA);
- Layer 6: Lower Floridan confining unit; and
- 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 (Payne and others, 2005) 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 Fort Stewart, the mesh resolution was 14,900 × 16,100 ft, requiring refinement for the current model application. Each hydrogeologic unit was represented with one layer of grid cells in the vertical dimension.

Lateral boundaries for all layers of the regional model (Payne and others, 2005) were designated as no flow, with the exception of the southern and southwestern sides of layers 5, 6, and 7 (Upper and Lower Floridan aquifers and intervening confining unit), which were set as specified head. 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 (Payne and others, 2005) 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. A–2). The general-head boundary

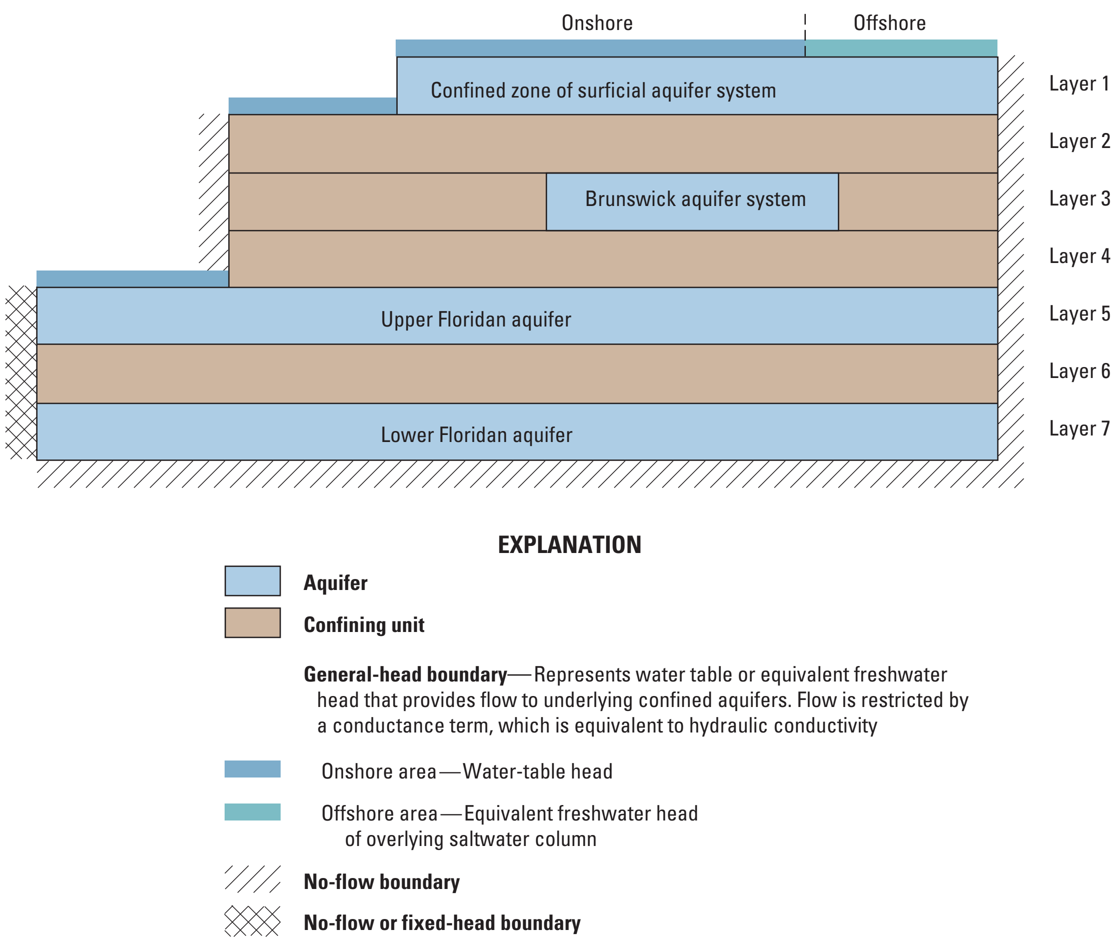

Figure A–2. Schematic diagram showing model layers and boundary conditions (from Payne and others, 2005).

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 to less-than-maximum recharge derived from baseflow 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 was assigned in the regional model (Payne and others, 2005) based on 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) based on 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. Total pumpage simulated by the model during 1980 was 692 million gallons per day (Mgal/d), and 798 Mgal/d during 2000. Because pumpage during 2010 (799 Mgal/d) was about the same as in 2000, the revised model was within calibration parameters for evaluation of groundwater flow at Fort Stewart.

Revisions to Regional Model

The existing U.S. Geological Survey regional ground-water-flow model (herein termed “regional model”) of Payne and others (2005) was modified using hydrogeological information obtained from field investigations and from existing wells in the vicinity of Hunter Army Airfield (HAAF; Clarke and others, 2010) and at Fort Stewart to simulate pumping from the newly constructed LFA well 33P028 and the effect of pumping on the UFA. Grid-cell dimensions were modified to a variably spaced grid (fig. A–1) that progressively increases by a factor of 1.5 from the smallest cell size of 10 ft by 10 ft near well 33P028 to a maximum size of about 16,400 ft by 16,400 ft. The revised model consisted of 449 rows and 474 columns. Model layering and boundary conditions were unchanged from the original regional model.

Some of the modifications to the regional model that were made during a previous investigation at HAAF in Chatham County (Clarke and others, 2010) also were applied to the model developed for the current study. These modifications involved addition of new hydraulic property zones for vertical and horizontal hydraulic conductivity in the Upper and Lower Floridan aquifers and intervening confining unit based on new field data collected at the HAAF.

Refinement of Hydraulic Conductivity Distribution

Packer-slug tests and core analyses performed at HAAF and Fort Stewart provided the basis for revising hydraulic-conductivity values assigned to these areas in the regional model (Payne and others, 2005) to values used in the revised model. For the revised model, values of vertical and horizontal hydraulic conductivity (K_v and K_h, respectively) in the area outside of Fort Stewart corresponded to values used (1) in the regional model (Payne and others, 2005), and (2) in the area of HAAF as simulated by Clarke and others (2010) (fig. A–3; table A–1). Field testing at Fort Stewart provided new information on the hydraulic properties of the UFA (layer 5), Lower Floridan confining unit (layer 6), and LFA (layer 7), and enabled refinement of values from that used in the regional model. In addition, results of a 72-hour aquifer test conducted in the LFA provided information on drawdown in the LFA and in the overlying UFA, which guided revisions to K_v and K_h values from previous calibrated values near Fort Stewart.

To incorporate refined hydraulic-property information, new hydraulic-property zones were developed on the basis of field data collected at HAAF (Clarke and others, 2010) and at Fort Stewart. Zones were added as follows:

- UFA (layer 5)—zone F13 added at HAAF and zone F14 added at Fort Stewart,
- Lower Floridan confining unit (layer 6)—zone LFC2 added at HAAF and zone LFC3 added at Fort Stewart,
- LFA (layer 7)—zone LF2 added at HAAF and zone LF3 added at Fort Stewart.

Each of the new hydraulic-property zones encompasses a 114-mi^2 common area that includes the area of highest grid resolution simulated during the HAAF and Fort Stewart studies and includes all wells evaluated by model simulations (fig. A–3). Each zone was initially assigned a K_h and K_y value based on results of field testing at each site. These values were adjusted slightly to calibrate water-level changes in the UFA and LFA observed during 72-hour aquifer tests conducted at the two sites.

For the UFA (layer 5), zone F13 for the HAAF study (Clarke and others, 2010) was subdivided from regional model zone F4 and assigned a K_h and K_y value of 76 feet per day (ft/d), which is slightly higher than the 70 ft/d value assigned in the original regional model. For the revised model in the Fort Stewart area, zone F14 was subdivided from regional model zone F5, and assigned a slightly higher K_h and K_v value of 398 ft/d, based on results of aquifer testing (table A–1). The new zone value of 398 ft/d represents a 1-percent increase from the 394 ft/d value assigned in the regional model (Payne and others, 2005) to zone F5. Multiplying the K_h value by the thickness of the aquifer gives an estimated transmissivity of 40,000 feet squared per day (ft^2/d), at HAAF, and 100,000 ft^2/d at Fort Stewart, matching results of field testing.

Figure A–3. Simulated hydraulic property zones by model layer. See table A–1 for hydraulic conductivity values assigned to zones.

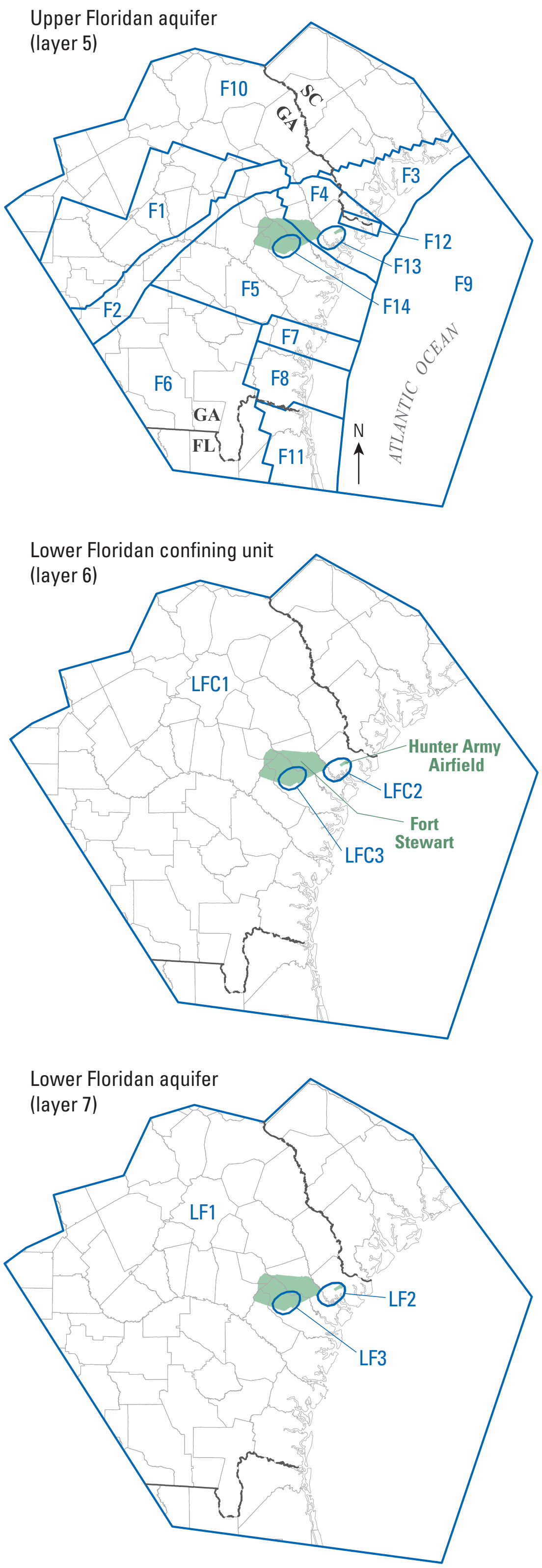

Figure A–3. Simulated hydraulic property zones by model layer. See table 1–1 for hydraulic conductivity values assigned to zones.—Continued

Table A–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): Hydraulic property zone	Payne and others (2005): Hydraulic conductivity, in feet per day: Horizontal	Payne and others (2005): Hydraulic conductivity, in feet per day: Vertical	Revised model: Hydraulic property zone (fig. A–3)	Revised model: Hydraulic conductivity, in feet per day: Horizontal	Revised model: Hydraulic conductivity, in feet per day: 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	76	76
		—	—	—	F14	398	398
Confining unit	6	—	0.02000	0.02000	LFC1	0.02000	0.02000
		—	—	—	LFC2	0.20000	0.02
		—	—	—	LFC3	10.00000	0.2
Lower Floridan aquifer	7	—	10.0000	1	LF1	10	10
		—	—	—	LF2	100	10
		—	—	—	LF3	15.80000	1.6

In the regional model (Payne and others, 2005), the Lower Floridan confining unit (layer 6) was assigned a single K_h and K_v value of 0.02 ft/d. Field data were used as a basis to delineate one additional zone at HAAF and one additional zone at Fort Stewart. At HAAF, zone LFC2, covering an identical area as zone F13, was assigned a K_h value of 0.2 ft/d and a K_v value of 0.02 ft/d (fig. A–3). At Fort Stewart, zone LFC3, covers an identical area as zone F14, and was assigned a K_h value of 10 and a K_v value of 0.2. Values at each of the sites were based on adjustments made during model calibration and are about an order of magnitude less than the lower end of the range of estimated values derived from packer-slug tests and core analysis. At Fort Stewart, results of packer-slug tests and core analysis for the Lower Floridan confining unit indicate that K_v ranged from 0.26 to 12 ft/d and K_h ranged from 2 to 80 ft/d, whereas calibrated K_v was 0.02 ft/d and calibrated K_h was 0.2 ft/d.

Hydraulic properties for model layer 7, which represents the LFA, were designated as a single zone in the regional model having a uniform K_h and K_v value of 10 ft/d (Payne and others, 2005). At HAAF, zone LF2 covers an identical area as zones F13 and LFC2 and was assigned a K_h value of 100 ft/d and a K_v value of 10 ft/d. At Fort Stewart, zone LF3 covers an identical area as zones F14 and LFC3 and was assigned a 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 7,000 ft^2/d, at HAAF, and 5,200 ft^2/d at Fort Stewart, similar to results of field testing (11,000 ft^2/d at HAAF; 7,000 ft^2/d at Fort Stewart).

Simulation of Observed Drawdown in Pumped Well

Drawdown calculated by the revised model using MODFLOW represents the average drawdown for a node located at the areal center of the grid cell containing the pumped well, and this average drawdown undercomputes the observed drawdown in the actual pumped well 33P028. Because the area of the grid cell containing the pumped well (10 ft^2) is much larger than the area defined by the well diameter (0.33 ft), drawdown at the pumped well should be based on 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):

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

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 (142,449);
- r_e is equivalent well block radius, in feet (5);
- r_w is well radius in feet (0.33);
- T_{xx} is transmissivity in the x direction, in feet squared per day (5,200); and
- T_{yy} is transmissivity in the y direction, in feet squared per day (5,200).

Use of this equation indicated that simulated values in the grid cell containing pumped well 33P028, completed in the LFA, would be 7.06 ft less than the observed drawdown for a pumping rate of 740 gallons per minute (gal/min). A similar analysis of an UFA well pumped at a rate of 205 gal/min having the same well radius as above but with a value of 100,000 ft^2/d for transmissivity indicates that the grid cell containing the pumped well undercomputes drawdown at the pumped well by about 0.365 ft. Simulated values for the UFA and LFA were adjusted using these correction factors and compared to 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 Fort Stewart, a comparison of the two models is provided to ensure that the revised model is an accurate representation of groundwater flow. Summaries of water-level residuals (simulated minus observed head) and simulated water budgets for the two models are presented (tables A–2 and A–3). Water-level residuals for the Upper and Lower Floridan aquifers are shown on maps plotted in figure A–4 and on graphs in figure A–5.

Model results indicate that the current (revised regional) model has water-level residuals and a simulated water budget similar to the original model of Payne and others (2005), and thus, both models provide similar simulation of the hydrologic system (tables A–2, A–3). These results are expected because model revisions are limited to a 114-mi^2 area representing less than 1 percent of the model area.

In the revised model, mean water-level residual for layer 3 shifted from a positive skew in the original model (1.79 ft) to a negative skew in the revised model (–3.43 ft, table A–2). For layer 5, the mean residual remained negative in the revised model, changing from –0.84 ft to –3.17 ft. The mean residual for layer 7 remained positive in the revised model but was closer to zero than the original model, changing from 5.2 ft to 1.01 ft. , The root mean square (RMS) of residuals for layer 5 was similar for the original (9.94 ft) and revised (10.0 ft) models. Eighty percent of the residuals for layer 5 derived from the revised model were within –5.4 to 0.19 ft of the original model residuals. For layer 7, the RMS of residuals decreased from 9.15 ft in the regional model to 7.74 ft in the revised model.

The RMS of water-level residuals for layer 3 (13.8 ft) in the revised model was more than double that in the original

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

[Residual equals simulated minus observed head]

Aquifer	Model layer	Number of observations	Minimum residual (feet)		Maximum residual (feet)		Mean of residuals (feet)		Root mean square of residuals (feet)	
			Original model (Payne and others, 2005)	Revised model	Original model (Payne and others, 2005)	Revised model	Original model (Payne and others, 2005)	Revised model	Original model (Payne and others, 2005)	Revised model
Brunswick aquifer system	3	10	–7.67	–27	13.3	14.4	1.79	–3.43	5.91	13.8
Upper Floridan aquifer	5	155	–44.4	–29.5	36.4	35	–0.84	–3.17	9.94	10
Lower Floridan aquifer	7	11	–3.62	–6.7	21.5	21	5.2	1.01	9.15	7.74

Table A–3. Comparison of simulated water budget by model layer between the original (Payne and others, 2005) and revised regional models, 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 (Payne and others, 2005)	Revised model	Original model (Payne and others, 2005)	Revised model	Original model (Payne and others, 2005)	Revised model	Original model (Payne and others, 2005)	Revised model	Original model (Payne and others, 2005)	Revised model
Surficial aquifer system	1	<0.001	<0.001	310	280	132	105	<0.001	<0.001	<0.001	<0.001
Confining unit	2	<0.001	<0.001	46.6	44.6	3.62	5.59	<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	142	22.3	20.2	712	676	268	228
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	16.6	2.32	1.72
Total all layers		**798**	**798**	**498**	**467**	**158**	**131**	**728**	**693**	**270**	**230**

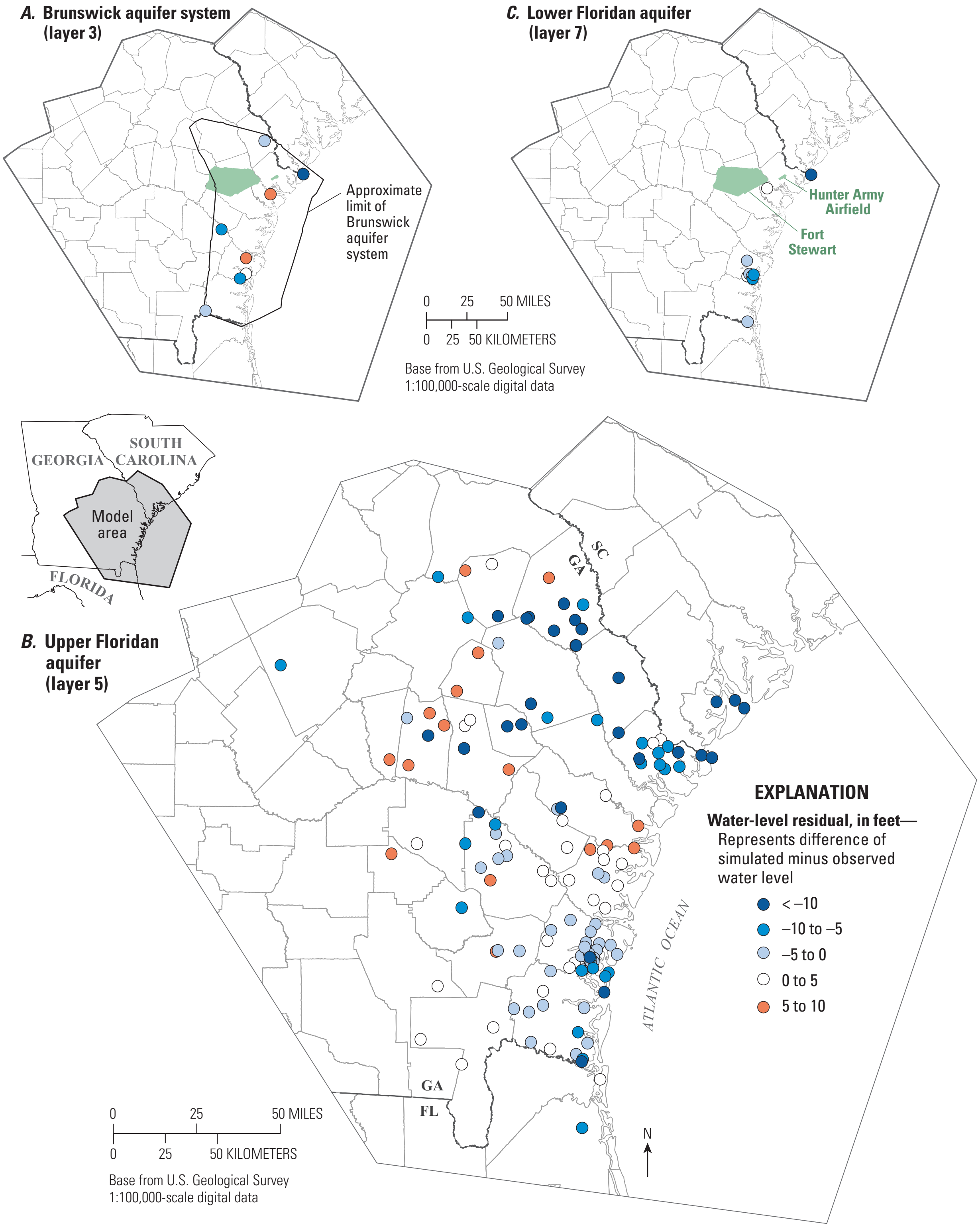

Figure A–4. Difference between simulated and observed water levels (residuals) by model layer for 2000, revised regional flow model: *(A)* Brunswick aquifer system (layer 3), *(B)* Upper Floridan aquifer (layer 5), and *(C)* Lower Floridan aquifer (layer 7).

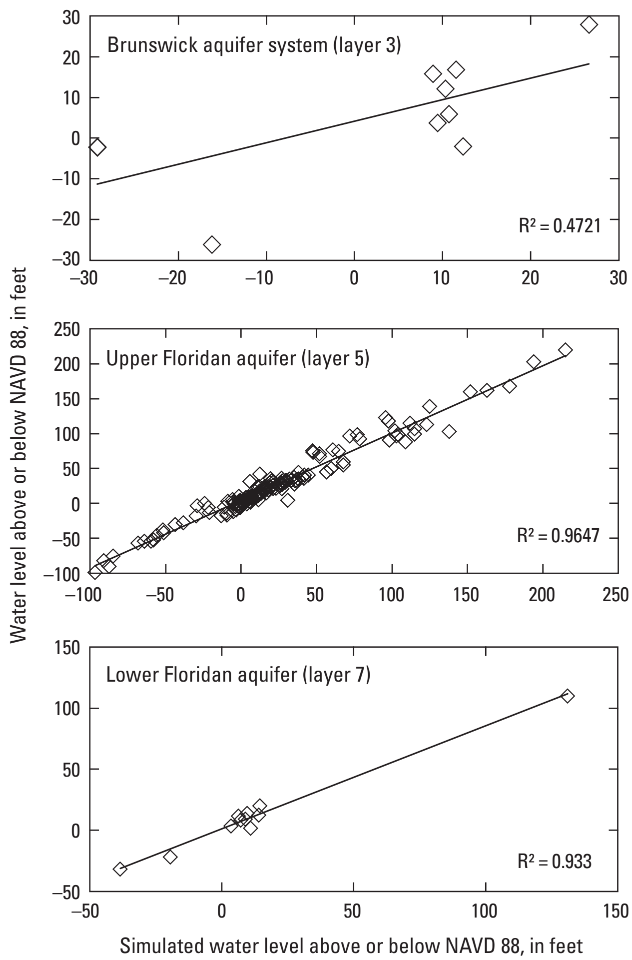

Figure A–5. Observed and simulated water levels in model layer, 3, 5, and 7 revised groundwater model.

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. Simulated water levels in 8 of 10 wells in layer 3 showed residuals that increased by 0.63 to 7.51 ft when compared to the original regional model. Most of the increase in the RMS for layer 3 can be attributed to two wells that had water-level residuals of –25 ft each (figs. A–4, A–5). These wells are located adjacent to one another in the same model cell, in an area where the grid size of the revised model was more than four times greater 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 RMS for layer 3 occurred away from the area of high grid resolution in the vicinity of Fort Stewart, model simulations at Fort Stewart were not affected.

Simulated water budgets for the regional and revised models were similar, with most variation occurring in layers 1 and 5 (table A–3). The revised model showed a decrease in recharge from and discharge to the overlying general-head boundary in layer 1, and decreased outflow and increased inflow along lateral specified-head boundaries in layer 5.

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