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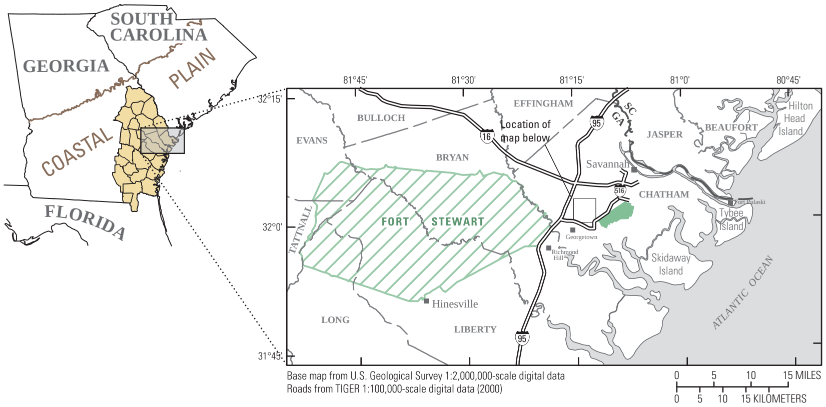
Prepared in cooperation with Consolidated Utilities LLC, Chatham County, Georgia

Hydrogeology and Water Quality of the Floridan Aquifer System and Effect of Lower Floridan Aquifer Withdrawals on the Upper Floridan Aquifer at Barbour Pointe Community, Chatham County, Georgia, 2013



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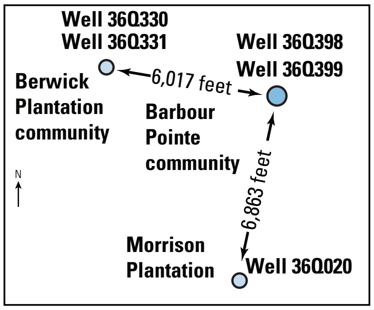
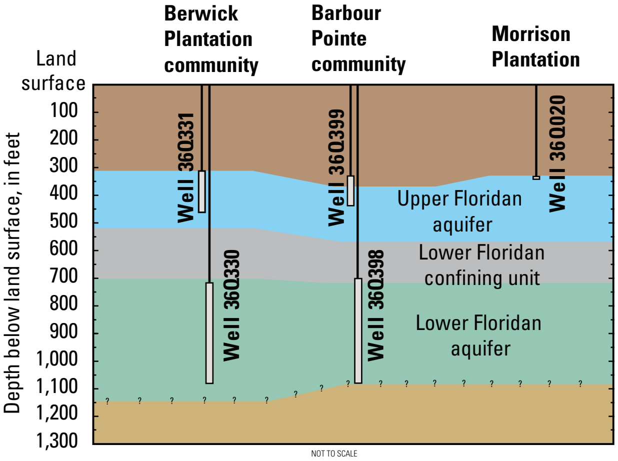
Roads from TIGER 1:100,000-scale digital data (2000)





Scientific Investigations Report 2016–5028

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

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By Gerard J. Gonthier and John S. Clarke

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U.S. Department of the Interior
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U.S. Department of the Interior
SALLY JEWELL, Secretary

U.S. Geological Survey
Suzette M. Kimball, Director

U.S. Geological Survey, Reston, Virginia: 2016

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Contents

Figures

Appendix Figures

Tables

Appendix Tables

Conversion Factors

[U.S. customary units to International System of Units]

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
inch (in.)	25,400	micrometer (mm)
	Area	
square foot (ft^2)	929.0	square centimeter (cm^2)
square foot (ft^2)	0.0929	square meter (m^2)
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	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)
inches per year (in/yr)	25.4	millimeters per year (mm/yr)
	Mass	
pound (lb)	453,600	milligram (mg)
	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)

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29) or the North American Vertical Datum of 1988 (NAVD 88).

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

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

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

Abbreviations

DD	Drawdown. Water-level change in a well in response to pumping water from the same well or another well.
EM	Electromagnetic
GaEPD	Georgia Environmental Protection Division
HAAF	Hunter Army Airfield
KSAV	Weather station located at Savannah/Hilton Head International Airport, climatological station 097847
LCU	Lower confining unit. Confining unit underlying the Lower Floridan aquifer.
LFA	Lower Floridan aquifer
LISAPCU	Lisbon-Avon Park composite unit
MSU	Middle semiconfining unit between the Upper Floridan and Lower Floridan aquifers
NWBL	Nonwater-bearing limestone above the Upper Floridan aquifer at the Barbour Pointe test site
RMS	Root mean square of the differences between a simulated and measured parameter values.
SI	Sample interval. Within an upward-flowing borehole, the vertical extent between two consecutive composite water-quality sample collection depths or the vertical extent between the deepest water-quality sample collection depth and the borehole bottom.
WLM	Water-level model. Using explanatory-variable time series to simulate a measured water-level time series, not to be confused with groundwater-flow modeling.
UFA	Upper Floridan aquifer
USGS	U.S. Geological Survey

Acknowledgments

The authors thank Tony Abbott of Consolidated Utilities LLC, Chatham County, for his support during this investigation. Ron Kolat of HK Engineering Group helped develop the plan of study and coordinated project drilling with testing activities completed by the U.S. Geological Survey (USGS) at the test site. Chris Matthews, also of HK Engineering Group, monitored onsite drilling activities, logged drill cuttings, and monitored specific conductance of drilling fluids.

Harold Gill with HK Engineering, and former USGS employee, provided guidance on the depths of boundaries between hydrogeologic units. Lester J. Williams, former USGS employee, collected borehole electromagnetic flowmeter-survey and water-level data.

Hydrogeology and Water Quality of the Floridan Aquifer System and Effect of Lower Floridan Aquifer Withdrawals on the Upper Floridan Aquifer at Barbour Pointe Community, Chatham County, Georgia, 2013

By Gerard J. Gonthier and John S. Clarke

Abstract

Two test wells were completed at the Barbour Pointe community in western Chatham County, near Savannah, Georgia, in 2013 to investigate the potential of using the Lower Floridan aquifer as a source of municipal water supply. One well was completed in the Lower Floridan aquifer at a depth of 1,080 feet (ft) below land surface; the other well was completed in the Upper Floridan aquifer at a depth of 440 ft below land surface. At the Barbour Pointe test site, the U.S. Geological Survey completed electromagnetic (EM) flowmeter surveys, collected and analyzed water samples from discrete depths, and completed a 72-hour aquifer test of the Floridan aquifer system withdrawing from the Lower Floridan aquifer.

Based on drill cuttings, geophysical logs, and borehole EM flowmeter surveys collected at the Barbour Pointe test site, the Upper Floridan aquifer extends 369 to 567 ft below land surface, the middle semiconfining unit, separating the two aquifers, extends 567 to 714 ft below land surface, and the Lower Floridan aquifer extends 714 to 1,056 ft below land surface.

A borehole EM flowmeter survey indicates that the Upper Floridan and Lower Floridan aquifers each contain four water-bearing zones. The EM flowmeter logs of the test hole open to the entire Floridan aquifer system indicated that the Upper Floridan aquifer contributed 91 percent of the total flow rate of 1,000 gallons per minute; the Lower Floridan aquifer contributed about 8 percent. Based on the transmissivity of the middle semiconfining unit and the Floridan aquifer system, the middle semiconfining unit probably contributed on the order of 1 percent of the total flow.

Hydraulic properties of the Upper Floridan and Lower Floridan aquifers were estimated based on results of the EM flowmeter survey and a 72-hour aquifer test completed in Lower Floridan aquifer well 36Q398. The EM flowmeter data were analyzed using an AnalyzeHOLE-generated model to simulate upward borehole flow and determine the transmissivity of water-bearing zones. Aquifer-test data were analyzed with a two-dimensional, axisymmetric, radial, transient, groundwater-flow model using MODFLOW–2005. The flowmeter-survey and aquifer-test simulations provided an estimated transmissivity of about 60,000 square feet per day for the Upper Floridan aquifer and about 5,000 square feet per day for the Lower Floridan aquifer.

Water in discrete-depth samples collected from the Upper Floridan aquifer, middle semiconfining unit, and Lower Floridan aquifer during the EM flowmeter survey in August 2013 was low in dissolved solids. Tested constituents were in concentrations within established U.S. Environmental Protection Agency drinking water-quality criteria. Concentrations of measured constituents in water samples from Lower Floridan aquifer well 36Q398 collected at the end of the 72-hour aquifer test in November 2013 were generally higher than in the discrete-depth samples collected during EM flowmeter testing in August 2013 but remained within established drinking water-quality criteria.

Water-level data for the aquifer test were filtered for external influences such as barometric pressure, earth-tide effects, and long-term trends to enable detection of small (less than 1 ft) water-level responses to aquifer-test withdrawal. During the 72-hour aquifer test, the Lower Floridan aquifer was pumped at a rate of 750 gallons per minute resulting in a drawdown response of 35.5 ft in the pumped well; 1.6 ft in the Lower Floridan aquifer observation well located about 6,000 ft west of the pumped well; and responses of 0.7, 0.6, and 0.4 ft in the Upper Floridan aquifer observation wells located about 36 ft, 6,000 ft, and 6,800 ft from the pumped well, respectively.

Introduction

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

Studies by the U.S. Geological Survey (USGS) since 2009 at nearby Pooler, Ga., and Hunter Army Airfield (HAAF; fig. 1) evaluated the LFA as an alternate supply of groundwater. There, aquifer-test results indicated that a strong interaquifer connection between the UFA and the LFA exists in the Chatham County area (Cherry and Clarke, 2013; Clarke and others, 2010). As a result of these findings, the GaEPD issued a policy release on May 20, 2013, stating that the Floridan aquifer system “is really one aquifer with hydraulically connected upper and lower permeable zones” (Georgia Department of Natural Resources, 2013).

To assess the water-supply potential of the LFA in the Barbour Pointe community, the USGS, in cooperation with Consolidated Utilities LLC, Chatham County, Georgia, investigated during 2013 to determine the hydrogeology and water quality of the Floridan aquifer system and any effect that withdrawals from the LFA would have on the UFA. The study included construction of a LFA production well (36Q398) and an UFA observation well (36Q399) (fig. 1), detailed site investigations, and hydraulic characterization of the Floridan aquifer system.

Purpose and Scope

The purpose of this report is to document results of field investigations completed at Barbour Pointe community, near Savannah, Ga. (fig. 1), during 2013 to determine the hydrogeology and water quality of the Floridan aquifer system and to provide data needed to assess the effect of LFA withdrawals on the overlying UFA. Specifically, this report does the following:

- Describes hydraulic and water-quality characteristics of the UFA, LFA, and intervening middle semiconfining unit (Lisbon-Avon Park composite unit or LISAPCU in Williams and Kuniansky, 2015; herein referred to as the MSU); and
- Identifies how withdrawals from the LFA affect water levels in the overlying UFA.

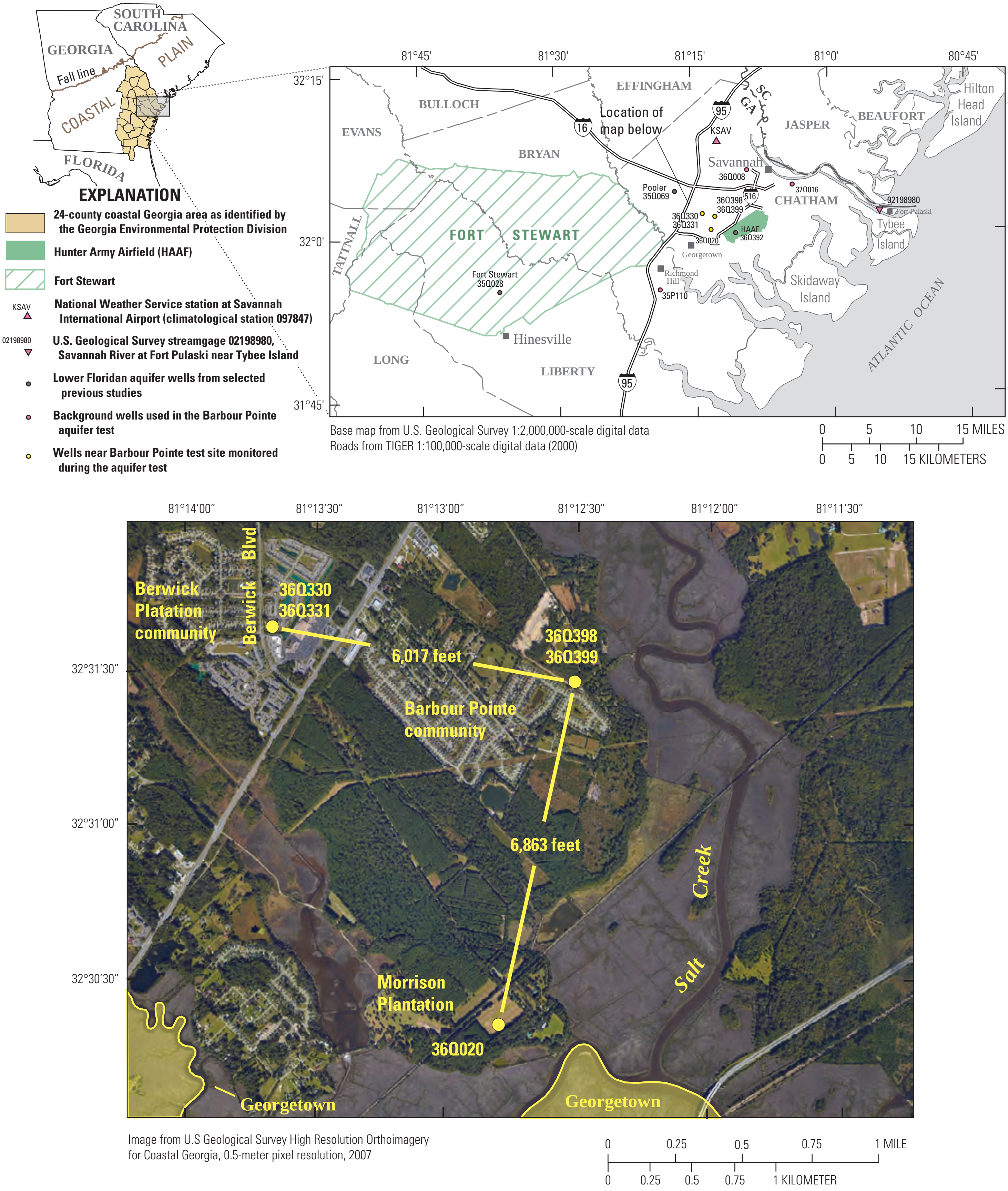
Field investigations included the following:

- Boring a 1,080-foot (ft)-deep test hole penetrating the UFA, MSU, and LFA (August 2013);
- Collecting drill cuttings and borehole geophysical logs at the test hole (August 2013);
- Completing electromagnetic (EM) flowmeter surveys of the Floridan aquifer system in the open test hole (August 2013);
- Collecting depth-integrated water samples to assess water quality of various water-bearing zones (August 2013);
- Constructing a production well completed in the LFA between depths of 700 and 1,080 ft (early November 2013);
- Constructing a 440-ft-deep observation well completed in the UFA (early November 2013);
- Completing a 72-hour aquifer test at the test well open to the LFA (November 2013); and
- Monitoring water levels in the two constructed wells, an UFA well 6,863 ft from the pumped LFA well, and a LFA and UFA well both 6,017 ft from the pumped LFA well (November–December 2013).

A hydrogeologic description of the subsurface at the test-well site was based on data and subsurface samples collected during field investigations by (1) determining the depth and thickness of hydrogeologic units, (2) identifying productive water-bearing zones, and (3) estimating hydraulic properties of the UFA and LFA. Digital simulation of aquifer response to pumping in the LFA can be used to answer two specific questions sought by regulators: How much must pumping the UFA be decreased to offset UFA drawdown in response to pumping in the LFA? And how much water being pumped from the LFA comes directly from the UFA? This information can be used by regulators to determine allowable permit limits for wells in the Floridan aquifer system at sites with new LFA wells. Results of this investigation add to the body of knowledge needed to characterize the Floridan aquifer system on a regional basis. Water-level information from 8 wells identified in this report, 5 observation wells used to monitor the 72-hour aquifer test at the Barbour Pointe test site and 3 background wells used to estimate drawdown in response to the aquifer-test pumping are stored in the USGS National Water Information System database, which can be accessed at http://waterdata.usgs.gov/nwis.

Previous Studies

Jordan, Jones, and Goulding, Inc. (2002) completed detailed field studies at nearby Berwick Plantation community that included construction of a LFA test well (36Q330; fig. 1), collection of geophysical and flow-meter logs (by the USGS), water sampling, and completion of an 8-hour UFA test and 72-hour LFA test. The report included some preliminary groundwater-model simulations.



Base map from U.S. Geological Survey 1:2,000,000-scale digital data
Roads from TIGER 1:100,000-scale digital data (2000)

Image from U.S Geological Survey High Resolution Orthoimagery for Coastal Georgia, 0.5-meter pixel resolution, 2007

Figure 1. Location of Barbour Pointe community test site, near Savannah, Chatham County, Georgia, 2013.

The USGS completed several comprehensive field and modeling studies of the Floridan aquifer system in coastal Georgia. These include, HAAF (Clarke and others, 2010; Williams, 2010), Fort Stewart (Clarke and others, 2011; Gonthier, 2011); and Pooler, Ga. (Cherry and Clarke, 2013; Gonthier, 2012). The scope of these investigations included field testing and groundwater-model simulations to determine the hydrogeology and water quality of the Floridan aquifer system, and provide data needed to assess the effect of LFA withdrawals on the UFA.

Miller (1986) developed a hydrogeologic framework for the Floridan aquifer system throughout its extent in Georgia, Florida, South Carolina, and Alabama. This framework was subsequently revised by Williams and Gill (2010) for eight northern coastal-plain counties in Georgia and five coastal-plain counties in South Carolina including the area of the Barbour Pointe community, HAAF, Fort Stewart, and Pooler, Ga., test sites. Williams and Kuniansky (2015) revised the framework from Miller (1986) for the entire extent of the Floridan aquifer system. The Williams and Gill (2010) study used borehole geophysical and EM flowmeter log data collected since the original study of Miller (1986) to shift the altitude of the tops and bottoms of the UFA and LFA, and of the individual permeable (water-bearing) zones that compose these aquifers; and to revise the top and thickness of the middle composite unit, herein for the Barbour Pointe study area referred to as the middle semiconfining unit (MSU). For the regional Floridan aquifer system, the MSU is part of what is named the Lisbon-Avon Park composite unit in Williams and Kuniansky (2015) as the units within the middle of the Floridan aquifer system, while often less permeable than the UFA are rarely confining and in many regions have hydraulic properties of the UFA or LFA. The term “composite” is used to indicate that the unit varies from confining to semiconfining. Clarke and Krause (2000) called what is currently referred to as the Lisbon-Avon Park composite unit the MSU throughout coastal Georgia. These revised boundaries from Williams and Gill (2010) were used to guide projected drilling depths at the Barbour Pointe test site and locally map the MSU.

Description of the Study Area

Barbour Pointe community is located in Chatham County, Ga., about 3.6 miles (mi) east of Interstate 95 (fig. 1). The study area is bounded on the north by the northern extent of the Barbour Pointe community, to the east by Salt Creek, to the west by Berwick Boulevard, and to the south by Morrison Plantation. The study area lies in the Barrier Island Sequence District of the Sea Island Section of the Coastal Plain physiographic province of Georgia (Clark and Zisa, 1976). The study site is characterized by low-altitude, flat topography, and sandy topsoil typical of the Georgia coastal area. A new LFA production well (36Q398) was constructed at the site within Barbour Pointe community roughly 0.3 mi west of Salt Creek. A new UFA observation well (36Q399) was installed about 36 ft to the northeast of the new LFA production well. Test drilling occurred at an altitude of about 5 ft (National Geodegic Vertical Datum of 1929 [NGVD 29]). Static (nonpumping) water levels in the UFA, at the study site, stood at an altitude of about -30 ft (NGVD 29) or a depth of 35 ft below land surface during May 1998 (Peck and others, 1999).

The study area has a mild climate with warm, humid summers and mild winters. Long-term climatic patterns in the area are derived from records provided by the National Weather Service Station at Savannah International Airport (climatological station 097847, labeled “KSAV” on fig. 1). During 1971–2000, precipitation at station 097847 averaged about 49.6 inches per year (in/yr). Maximum monthly rainfall (exceeding 4 inches per month) generally occurs during January and June–September; monthly rainfall totals generally average less than 4 inches during the rest of the year (Southeast Regional Climate Center, 2011). Mean monthly pan evaporation at station 097847 during 1965–2003 ranged from 2.43 to 8.49 inches per month with the greatest evaporation occurring during April–August (Clarke and others, 2010).

Water Use

Groundwater use in Chatham County (fig. 1) totaled 54.31 million gallons per day (Mgal/d) during 2010 (Lawrence, 2015). Nearly 60 percent of total groundwater use, or 32.03 Mgal/d, was for public supply. Most public supply wells are located in the city of Savannah, Ga., additional wells to the northwest serve Pooler, Ga., and other communities just north of Savannah, Ga. (Fanning and Trent, 2009). Payne and others (2005) estimated that during 1980–2000, nearly 95 percent of groundwater pumped from Chatham County was withdrawn from the UFA; the remaining 5 percent was derived from the LFA. Groundwater withdrawal from the Floridan aquifer system in Chatham County decreased from 68.15 Mgal/d in 2000 to 54.61 Mgal/d in 2010. Reasons for the decrease include the recession in 2008–9, conservation efforts, down time in changing a coal-fired power plant over to natural gas, and UFA pumping restrictions (Stephen J. Lawrence, U.S. Geological Survey, oral commun., May 4, 2015).

Consolidated Utilities LLC, Chatham County, Ga., supplies water to Barbour Pointe and Berwick communities with 4 wells completed in the UFA, 1 well completed in the LFA, and 3 wells completed in the Brunswick (Miocene) aquifer system. Because of concern about saltwater intrusion, the GaEPD has implemented restrictions on groundwater withdrawal from the UFA and designated management zones in coastal Georgia. Barbour Pointe community is located in the GaEPD “red zone,” where withdrawal from the UFA is capped at the 2004 rate (Georgia Department of Natural Resources, 2006). The GaEPD water-withdrawal permits for Consolidated Utilities LLC, Chatham County, Ga., allow an annual daily average of 0.309 Mgal/d for the UFA (Jeff Larson, Georgia Environmental Protection Division, written commun., December 31, 2008), 0.525 Mgal/d for the LFA (Christine Voudy, Georgia Environmental Protection Division, written commun., November 3, 2003), and 2 Mgal/d for the Brunswick aquifer system (William Frechette, Georgia Environmental Protection Division, written commun., March 20, 2013).

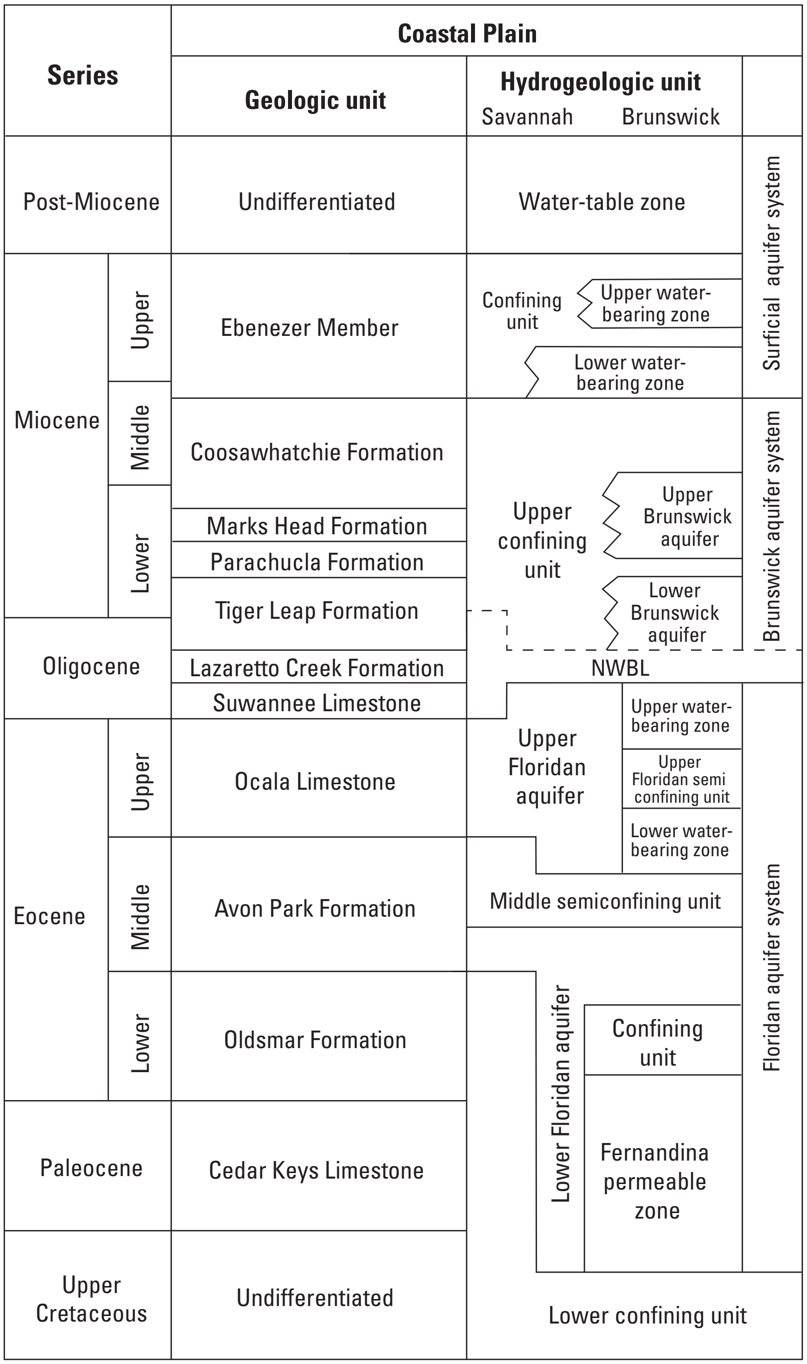
Hydrogeologic Setting

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

In the coastal area, the surficial aquifer system consists of Miocene and younger interlayered sand, clay, and thin limestone beds (Clarke, 2003). At Barbour Pointe community, the surficial aquifer system consists of fine sands at depths less than 67 ft and largely is unconfined. The surficial aquifer system is separated from the underlying Brunswick aquifer system by a confining unit consisting of silty clay and dense, phosphatic Miocene limestone.

The Oligocene to Miocene Brunswick aquifer system consists of two water-bearing zones: the upper Brunswick aquifer and the lower Brunswick aquifer (Clarke, 2003). The upper Brunswick aquifer is Miocene and 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 is Oligocene to Miocene and consists of poorly sorted, fine to coarse, phosphatic and dolomitic sand (Clarke and others, 1990). The Brunswick aquifer system is centered about Brunswick, Ga. Williams and Kuniansky (2015) classify the sediments between the base of the surficial aquifer system and the top of the UFA (including the Brunswick aquifer system) as the upper confining unit to the Floridan aquifer system. At Barbour Pointe community, Miocene sediments at the stratigraphic level of the Brunswick aquifer system are between depths of 67 and 280 ft, and consist largely of low permeability clayey fine sand and silt with slightly higher permeability between depths of 246 and 280 ft. The test site is located near the mapped extent of the Brunswick aquifer as delineated by Williams and Kuniansky (2015).

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 confined by overlying clay, below the Brunswick aquifer system (fig. 2), and separated into several permeable water-bearing zones by layers of dense limestone or dolostone that act as semiconfining units. In the coastal area, the system has been subdivided by the USGS into the UFA and LFA,



Modified from Williams and Gill, 2010; Gonthier, 2012; Cherry and Clarke, 2013; and Williams and Kuniansky, 2015

NWBL, nonwater-bearing limestone above the Upper Floridan aquifer; The Lisbon-Avon Park composite unit is referred to as the middle semiconfining unit at Barbour Pointe

Figure 2. Generalized correlation of geologic and hydrogeologic units in the Coastal Plain of Georgia.

which interact with each other (Miller, 1986; Williams and Gill, 2010; Williams and Kuniansky, 2015). Williams and Kuniansky (2015) abandoned naming confining units within the Floridan aquifer system, owing to the fact that many of the discontinuous numbered middle confining units of Miller (1986) are not low permeability confining units and are very leaky over large areas; however, there are some subregional confining units and generally the Upper Floridan is more permeable than the Lower Floridan within Georgia. For this reason, the GaEPD considers the Floridan aquifer system as one aquifer for the purpose of water resource management (Georgia Department of Natural Resources, 2013).

The UFA mostly consists of Oligocene and upper Eocene carbonate units 198 ft thick at Barbour Pointe community. Previous studies at nearby Berwick Plantation community (Faye and Gill, 2005) indicated that the transmissivity of the UFA was about 46,000 square feet per day (ft^2/d), and the storage coefficient was about 1.0×10^{-4}.

The UFA is underlain by the MSU, which consists of chalky and glauconitic limestone in the uppermost part of the middle Eocene Avon Park Formation, and is nearly 147 ft thick at Barbour Pointe community. Thickness and vertical hydraulic conductivity of the semiconfining unit control the rate of interaquifer leakage between the UFA and LFA. An EM flowmeter survey at nearby Berwick Plantation community (Williams and Gill, 2010) indicated that the MSU contributed little to the overall flow in a test hole open to the entire Floridan aquifer system. Hydraulic properties of the MSU were not measured at Berwick Plantation community or Barbour Pointe community; however, they were characterized at the nearby Pooler, Ga., and HAAF sites (fig. 1) (Williams, 2010; Clarke and others, 2010; and Gonthier, 2012). Slug tests and core samples were analyzed for selected intervals within the MSU at each of the two sites. At the HAAF, the estimated vertical hydraulic conductivity (K_v) of core samples ranged from 0.13 to 0.34 foot per day (ft/d) (Clarke and others, 2010). At Pooler, Ga., estimated K_v of core samples ranged from 0.57 to 1.67 ft/d (Gonthier, 2012). The median K_v for all values at the two sites was 0.46 ft/d.

The LFA consists of chalky and glauconitic limestone in the lower part of the middle Eocene Avon Park Formation with a thickness of 342 ft at Barbour Pointe community. Previous studies at nearby Berwick Plantation community (Faye and Gill, 2005) indicated that the transmissivity of the LFA was about 8,200 ft^2/d.

Well Identification

In this report, wells are identified by a USGS numbering system based on the index of USGS topographic maps (such as 36Q398). 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 36Q398 is the 398th well inventoried in the Garden City quadrangle (map 36Q).

Hydrogeology and Water Quality of the Floridan Aquifer System

To assess the hydrogeology and water quality of the Floridan aquifer system at the Barbour Pointe test site, multidiscipline site investigations were completed during 2013 to collect and analyze geologic, geophysical, hydrologic, meteorological, and water-chemistry data. Analysis of these data provided a basis for refining the depth, thickness, hydraulic properties, and water quality of hydrogeologic units that compose the Floridan aquifer system in Chatham County, Ga. (fig. 1).

Methods of Investigation

Hydrogeology and water quality of the Floridan aquifer system at the Barbour Pointe test site were assessed by installing two wells (a production well in the LFA and a nearby observation well in the UFA) and completing geophysical logging, EM flowmeter surveys, water-quality sample collection and analyses, and a 72-hour aquifer test of the LFA. Well installation included drilling a 1,080-ft-deep test hole, and completing well (36Q398; fig. 3) in the LFA and an observation well (36Q399, fig 4) in the UFA 36 ft northeast of the new LFA well. Well construction information for all wells used during this study is listed in table 1.

The method of study for the Barbour Pointe test site is similar to that used in the three earlier investigations at HAAF, Fort Stewart, and Pooler, Ga. The three previous investigations also included collection of core for hydraulic analysis targeting the MSU, EM flowmeter surveying in the completed test well open to the LFA, completing packer slug tests within the MSU, and a 24-hour aquifer test at a nearby well open to the UFA; however, the current investigation at the Barbour Pointe test site did not include these tests because of cost limitations.

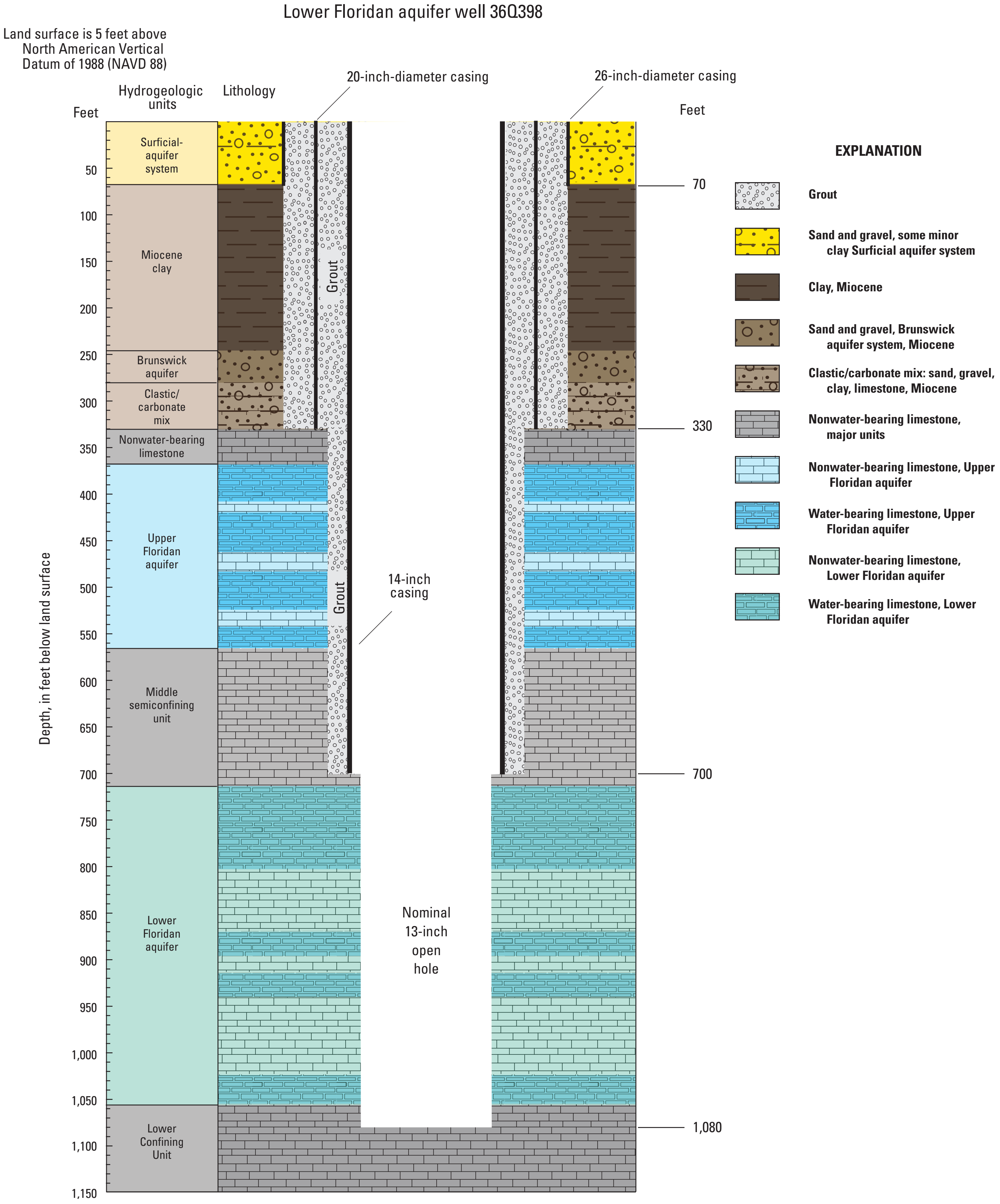


Figure 3. Hydrogeologic units and well completion diagram for Lower Floridan aquifer well 36Q398, Barbour Pointe community, near Savannah, Georgia.

Table 1. Location and open intervals of wells used in the aquifer-test analyses, Barbour Point community, near Savannah, Georgia, November 19–22, 2013.

[USGS, U.S. Geological Survey; LFA, Lower Floridan aquifer; PUMP, pumped well; OBS, observation well that was monitored for drawdown in response to the aquifer test; UFA, Upper Floridan aquifer; Background, well with background water levels used to estimate drawdown of observation wells]

USGS site identifier (fig. 1)	USGS site number	Depth (foot below land surface)		Aquifer	Role in aquifer test	Remarks
		Top of open interval	Bottom of open interval			
36Q398	320126081120001	700	1,056	LFA	PUMP/OBS	Production well constructed for Barbour Pointe Study.
36Q399	320126081122901	330	440	UFA	OBS	Observation well constructed for Barbour Pointe Study.
36Q330	320139081134002	718	1,080	LFA	OBS	Berwick Plantation Community (Faye and Gill, 2005).
36Q331	320139081134003	318	460	UFA	OBS	Berwick Plantation Community (Faye and Gill, 2005).
36Q020	320021081124801	330	336	UFA	OBS	USGS continuous water-level monitoring site, Morrison Plantation.
36Q008	320530081085001	250	406	UFA	Background	USGS continuous water-level monitoring site, Savannah, Ga.
37Q016	320433081042701	260	500	UFA	Background	USGS continuous water-level monitoring site, Savannah, Ga.
35P110	315443081185902	315	441	UFA	Background	USGS continuous water-level monitoring site, Richmond Hill, Ga.

Test Drilling and Well Installation

To assess the hydrogeology of the Floridan aquifer system at Barbour Pointe community (fig. 1), onsite investigations were completed during 2013. A 1,080-ft-deep test boring was completed (fig. 3) in the Floridan aquifer system during June 2013 using the following procedures:

- A pilot hole was first drilled through the unconsolidated surficial aquifer system, and a 26-in.-diameter casing was installed to a depth of about 70 ft.
- A pilot hole was then advanced using mud-rotary methods and a bentonite-based drilling fluid through unconsolidated Miocene and younger sediments to a depth of about 330 ft.
- Before setting an upper well casing, a set of geophysical logs was collected in the pilot hole followed by installation of a 20-in.-diameter well casing to a depth of about 330 ft.
- Reverse-air-rotary methods then were used to drill a nominal 13-in.-diameter boring through consolidated limestone of the Floridan aquifer system to a depth of 1,080 ft. A second set of geophysical logs then was collected in the 330–1,080 ft interval. The specific conductance of outgoing formation water was monitored at 10-ft intervals to evaluate the quality of formation water while drilling.

Based on results of the EM flowmeter survey and geophysical logging, the top of the MSU was identified at a depth of about 567 ft. The bottom of the MSU was first identified at a depth of about 700 ft, but was later confirmed to be at a depth of about 714 ft. Construction of well 36Q398 was completed by installing a 14-in.-diameter well casing from land surface to a depth of about 700 ft, which sealed off the UFA and most of the MSU, leaving the LFA exposed in the open interval between about 714 and 1,056 ft (fig. 3). The interval between about 1,056 and 1,080 ft was open to a nonwater-bearing zone that is either part of the LFA or the lower confining unit beneath the Floridan aquifer system.

An observation well, 36Q399, was completed in the UFA about 36 ft northeast of the pumped well. A 6-in.-diameter casing was installed from land surface to a depth of about 330 ft. Well 36Q399 was completed open to the upper one-third of the UFA from approximately 330 to 440 ft below land surface (fig. 4).

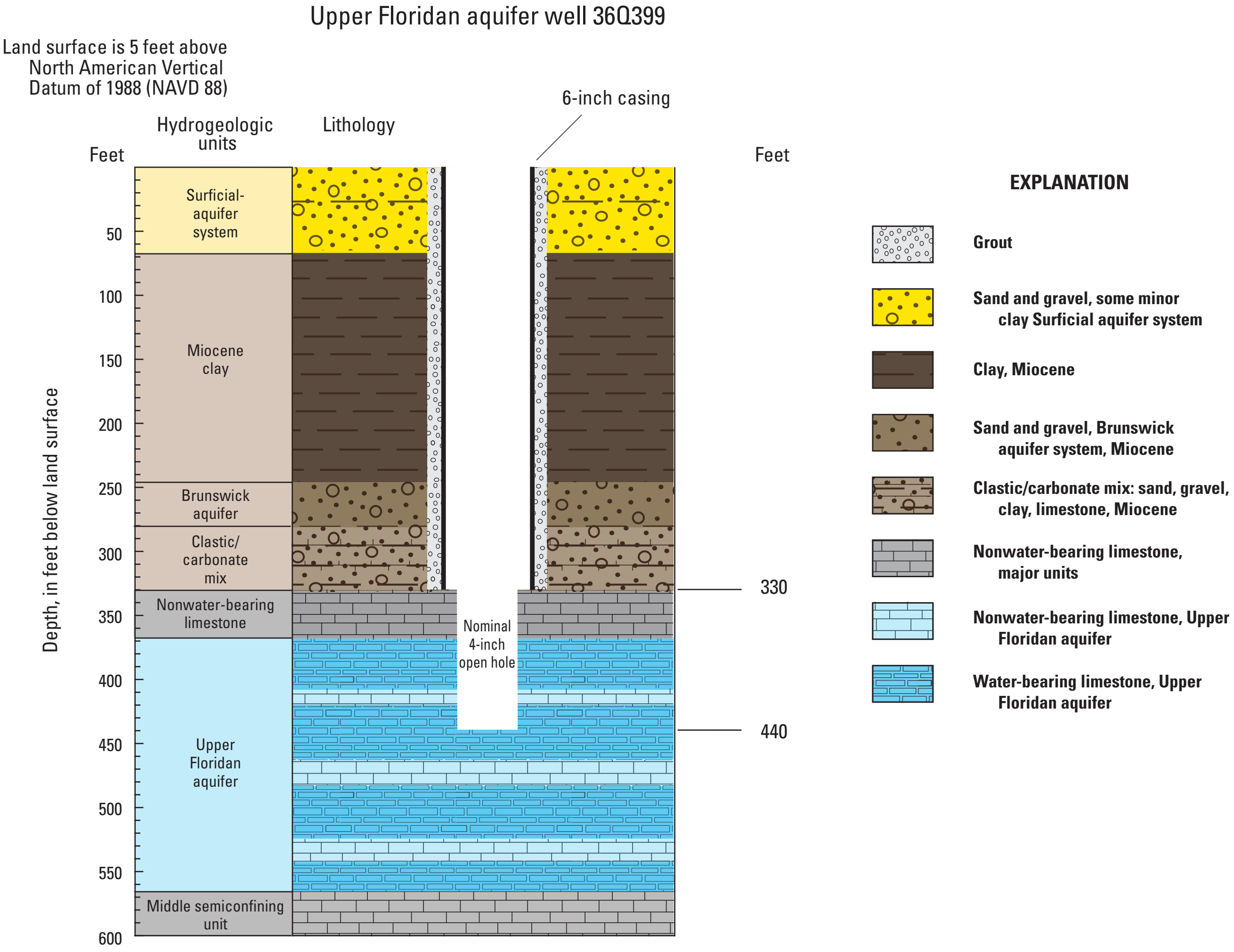


Figure 4. Hydrogeologic units and well completion diagram for Upper Floridan aquifer well 36Q399, Barbour Pointe community, near Savannah, Georgia.

Lithologic and Borehole Geophysical Logs

Drill cuttings collected every 10 ft from well 36Q398 were identified for general lithology in the 330–1,080 ft interval representing the Floridan aquifer system. Borehole geophysical logs were collected at various stages of drilling well 36Q398 to characterize the physical properties of penetrated sediments, rock, and interstitial fluid (fig. 5). The first set of logs was collected in the 0–330 ft interval where mud-rotary drilling penetrated clastic sediments overlying the Floridan aquifer system. The second set of logs was collected in the 330–1,080 ft interval where reverse-air-rotary drilling was used to penetrate the carbonates of the Floridan aquifer system. In both intervals, the following logs were collected: caliper; natural gamma; spontaneous potential, and single-point lateral, long- and short-normal resistivity. In the deeper carbonate interval within the Floridan aquifer system, borehole-fluid resistivity and temperature, and an EM flowmeter survey also were run.

Water-Level Measurements

Continuous and intermittent groundwater-level measurements were made at the borehole and wells during the study according to USGS standard procedures (Stallman, 1971; and Cunningham and Schalk, 2011). Manual, intermittent water-level measurements were made for calibration of groundwater-level recorder readings. Manual measurements were accurate to the nearest 0.01 ft using an electric tape and following procedures described in Cunningham and Schalk (2011). Water levels in five wells (36Q398, 36Q399, 36Q330, 36Q331, and 36Q020; fig. 1) were recorded every 15 minutes using submerged, vented pressure transducers.

Estimation of Hydraulic Properties and Drawdown Response

Hydraulic properties of the UFA, MSU, and LFA were estimated based on results of the EM flowmeter survey at

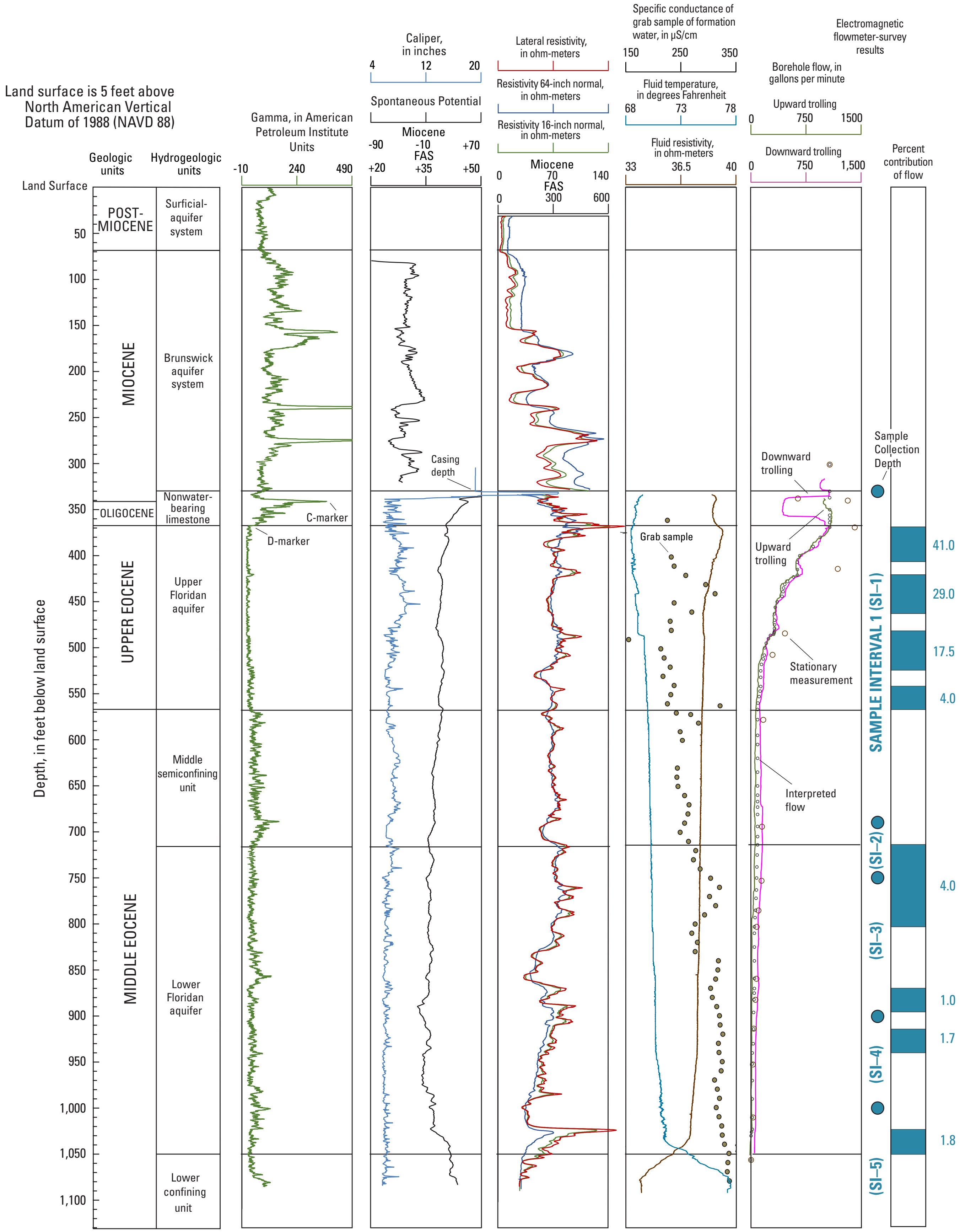


Figure 5. Geophysical properties, electromagnetic flowmeter survey, and specific conductance of discharging formation water of test hole for well 36Q398, Barbour Pointe community, near Savannah, Georgia.

test hole 36Q398 open to the Floridan aquifer system, and on results of a 72-hour aquifer test completed in LFA well 36Q398 (fig. 1). Electromagnetic flowmeter data were analyzed using AnalyzeHOLE (Halford, 2009) to simulate upward borehole flow and to determine the transmissivity of water-bearing zones. Drawdown in response to the 72-hour aquifer test was estimated using SeriesSEE, an Excel add-in (Halford and others, 2012). Aquifer-test data were analyzed using a two-dimensional, axisymmetric, radial, transient, groundwater-flow model using MODFLOW–2005 (Harbaugh, 2005) to simulate drawdown within wells and estimate hydraulic properties of hydrogeologic units within the Floridan aquifer system. Estimated hydraulic properties and maximum drawdown are summarized in table 2. The simulations are discussed in more detail in the appendix.

Electromagnetic Flowmeter Survey

An EM flowmeter survey was completed in test hole 36Q398 on August 21, 2013, in the open interval between 330 and 1,080 ft, to quantify the relative contributions of flow from water-bearing zones within the Floridan aquifer system (fig. 5). Flow rates from this EM flowmeter survey (1) helped to determine the position of the semiconfining unit between the UFA and LFA, (2) were used to calculate the concentrations of constituents in water from intervals between composite grab samples, and (3) were simulated to estimate values of transmissivity for the UFA and LFA. AnalyzeHOLE (Halford, 2009) was used to estimate transmissivity of hydrogeologic units by simulating upward borehole flow (see appendix).

Table 2. Summary of hydraulic properties and drawdown estimated from electromagnetic flowmeter survey and 72-hour aquifer test, Barbour Pointe community, near Savannah, Georgia, 2013.

[Numbers in brackets were fixed values within the model. EM, electromagnetic; –, not applicable; gal/min, gallon per minute; LFA, Lower Floridan aquifer; ±, plus or minus; UFA, Upper Floridan aquifer; ft^2/d, square foot per day; FAS, Floridan aquifer system; MSU, Middle semiconfining unit; K_v/K_h, vertical hydraulic conductivity divided by horizontal hydraulic conductivity]

Test information	Hydrogeologic unit	Distance from pumping well 36Q398 (foot)	EM flowmeter survey	72-hour aquifer test	Concluded value
Interval tested (feet below land surface)	–	–	330–1080	700–1,080	–
Test date	–	–	August 21, 2013	November 19–22, 2013	–
Pumping rate (gal/min)	–	–	1,000	750	–
Analysis method	–	–	AnalyzeHOLE (Halford, 2009)	Two-dimensional, axisymmetric, radial, transient groundwater-flow model using the numerical model MODFLOW-2005 (Harbaugh, 2005)	
Well information			Maximum (72-hour) drawdown (foot)		
Well 36Q398	LFA	At pumping source	–	35.5 ± 0.18	35.5
Well 36Q399	UFA	36	–	0.71 ± 0.02	0.7
Well 36Q330	LFA	6,017	–	1.62 ± 0.02	1.6
Well 36Q331	UFA	6,017	–	0.62 ± 0.06	0.6
Well 36Q020	UFA	6,863	–	0.35 ± 0.06	0.4
Hydraulic Properties					
			Model calibration values		
Transmissivity (ft^2/d)	FAS	–	65,324	65,466	65,000
Specific storage per foot	FAS	–	[1.16×10^{-6}]	1.16×10^{-6}	1.16×10^{-6}
Storage coefficient (dimensionless)	FAS	–	–	7.97×10^{-4}	8.00×10^{-4}
Transmissivity (ft^2/d)	UFA	–	60,288	59,875	60,000
Transmissivity (ft^2/d)	MSU	–	[441]	441	450
Transmissivity (ft^2/d)	LFA	–	4,595	5,150	5,000
Anisotropy (K_v/K_h)	FAS	–	[0.14]	0.14	0.14

To complete the EM flowmeter survey, a pump was installed to a depth of 75 ft in the cased part of the test hole and pumped at a rate of 1,000 gallons per minute (gal/min). The well was pumped while three traverses were made in the open borehole with an EM flowmeter that measured accumulated flow as it was trolled downward, then upward, and finally held stationary so that measurements at 20 different depths were made. Hole-diameter measurements from caliper logs were used to convert EM flowmeter-survey values of velocity to discharge rates of upward borehole flow. Electromagnetic flowmeter-survey results (values of upward borehole flow with depth) mostly were based on the up-troll measurement series as it had the least noise of the three measurement series (fig. 5). Upward borehole flow ranged from no flow at the bottom of the test hole at 1,080 ft depth (fig. 3) to 1,000 gal/min at the base of the casing at the 330 ft depth. With decreasing depth, upward borehole flow either increased or did not change. Zones where upward borehole flow increased with decreasing depth were considered to be water-bearing zones. Zones where upward borehole flow did not change with decreasing depth were considered to be nonwater-bearing zones. The amount of flow being contributed from a given depth interval is the upward borehole flow at the top of the interval minus the upward borehole flow at the bottom of the interval. The proportion of flow contributed by a given depth interval is the amount of flow being contributed by the depth interval divided by the total flow from the well (1,000 gal/min).

Aquifer Test

A 72-hour aquifer test was completed at the Barbour Pointe test site during November 19–22, 2013, to estimate the transmissivity of the LFA and UFA, the K_v of the MSU, and storage coefficient of the Floridan aquifer system; and determine the amount of drawdown in the UFA. The test involved pumping LFA well 36Q398 at a rate of 750 gal/min (fig. 6, table 1). Background water levels before, response during, and recovery after the aquifer test were monitored in two LFA wells and three UFA wells from November 18 to December 02, 2013. Wells 36Q398 (LFA) and 36Q399 (UFA) composed a well pair at Barbour Pointe community. Wells 36Q330 (LFA) and 36Q331 (UFA) composed a well pair at the Berwick Plantation community approximately 6,017 ft west of the Barbour Pointe wells. Well 36Q020 (UFA) was located at Morrison Plantation approximately 6,863 ft south of the Barbour Pointe wells (figs. 1 and 6).

Drawdown response to the 72-hour aquifer test was simulated using a two-dimensional, axisymmetric, radial, transient, groundwater-flow model using MODFLOW–2005 (Harbaugh, 2005). Aquifer test analyses and results are discussed in detail in the appendix.

Drawdown Estimation

Water levels fluctuate in response to a number of influences including ocean tides near the coast, earth tides, barometric-pressure fluctuations, precipitation events, and regional stress-induced long-term trends. These fluctuations may obscure minor changes in water levels in a well in response to aquifer-test pumping and require filtering away to enable quantitative assessment of drawdown response.

Values of drawdown were estimated using SeriesSEE spreadsheets that model water-level response to environmental and pumping influences (Halford and others, 2012). The amount of water-level change that is caused by pumping is taken as the estimate of drawdown. Input time series used by SeriesSEE include barometric pressure, gravity (a surrogate for earth tides), ocean tides, water levels of background wells, and pump schedules for pumped wells that affect water levels of wells at the aquifer-test site. Drawdown-estimation methods and results are discussed in detail in the appendix. Drawdown in LFA wells 36Q398 (pumped well) and 36Q330 (about 6,017 ft west of the pumped well; fig. 6), in response to 72 hours of pumping at a rate of 750 gal/min, was 35.5 and 1.6 ft, respectively. Drawdown in the UFA wells was moderate, but geographically extensive. Drawdown in UFA wells 36Q399 (36 ft northeast of the pumped well), 36Q331 (about 6,017 ft west of the pumped well), and 36Q020 (about 6,863 ft south of the pumped well) was 0.7, 0.6, and 0.4 ft, respectively (table 2).

Water-Quality Sampling and Analysis

To assess vertical distribution of water quality, the specific conductance of formation water was measured at 10-ft intervals during reverse-air-rotary drilling from 330 to 1,080 ft in the test hole (fig. 5). The measurement procedure consisted of capturing a sample of formation water 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 hydrogeologic units exposed within the test hole above a given depth, variations in specific conductance may provide an indication of changes in water quality with depth in the test hole. Freshwater, having a specific conductance lower than the return formation water, was added to assist drilling in several depth intervals, which resulted in lower values (dilution of inflowing groundwater) of specific conductance at that interval. As a result, data for these intervals are not used and are not shown in figure 5.

Water samples were collected in the test hole for well 36Q398 (fig. 1) on August 22, 2013, following a borehole, EM flowmeter survey using a wireline grab sampler at five distinct depths: 330, 690, 750, 900, and 1,000 ft (table 3, fig. 5). The test hole was pumped for at least 1 hour before water samples were collected. These grab samples were collected with the pump set within the casing above all water-bearing zones and pumping at a rate of 1,000 gal/min; therefore, each of these samples represents a composite of the water entering the test hole beneath its sampling depth. This is in contrast with sampling formation water for specific conductance during drilling where the sample collection at the surface is a composite of all water entering the well above the concurrent drill depth. Water was transferred from the grab sampler to sample bottles using a peristaltic pump. Samples were analyzed for pH, alkalinity reported as calcium carbonate, total hardness, total dissolved solids, and selected major ions (table 4).

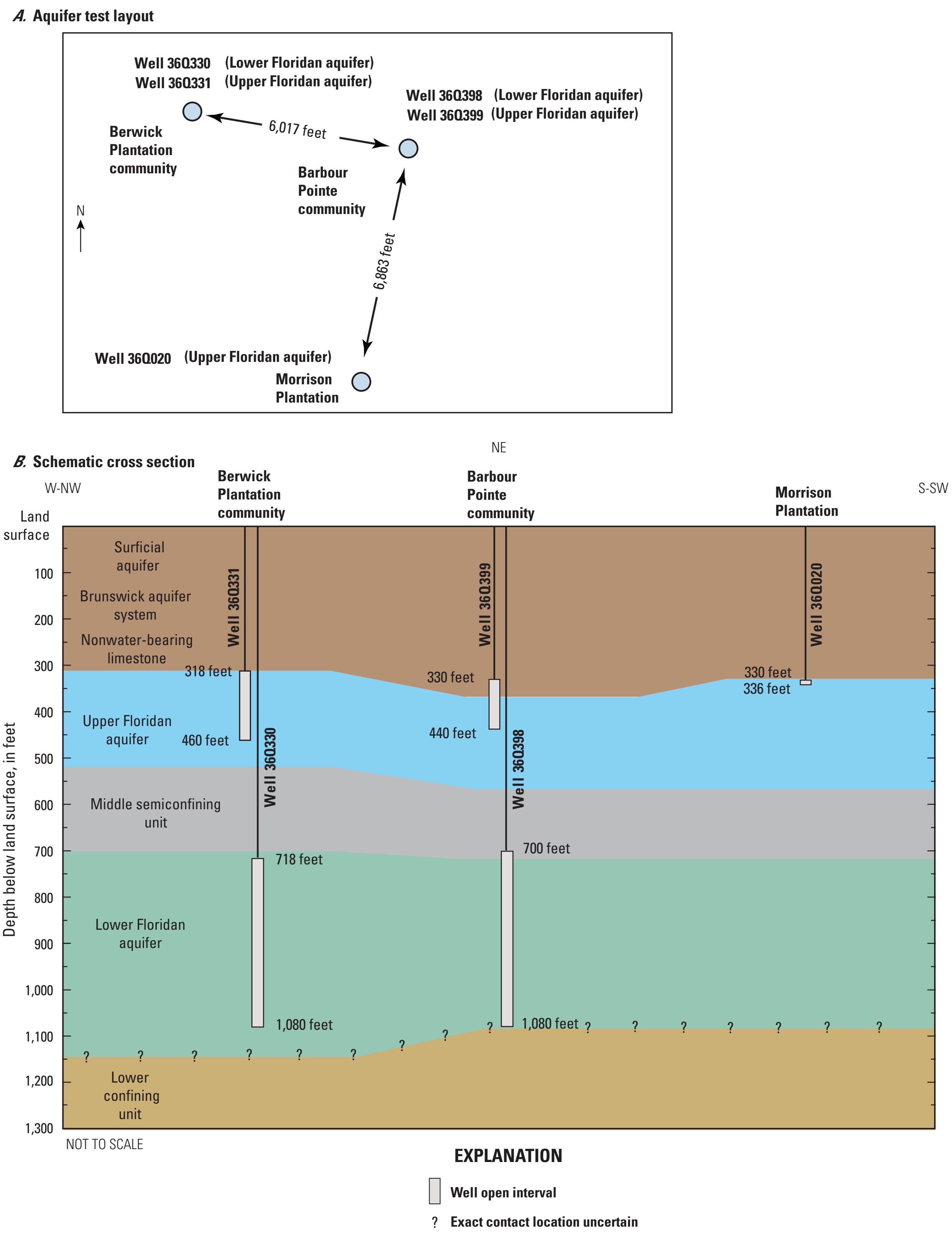


Figure 6. Location and open interval of wells used for the 72-hour aquifer test at Barbour Pointe community, near Savannah, Georgia, November 19–22, 2013. *A*, diagram showing aquifer-test layout; and, *B*, schematic cross section showing major hydrogeologic units.

Water collected for analysis of major ions was filtered using a capsule filter with a 0.45-micrometer (µm) pore medium. Samples for cations were preserved using nitric acid. Samples were analyzed at Avery Laboratories & Environmental Services, LLC, Savannah, Ga., or one of two subcontract laboratories: TestAmerica Laboratories, Inc., or Analytical Environmental Services, Inc., both in Savannah, Ga. Test methods used for each analyte are listed in table 5.

A simple mixing equation and the flow contribution from water-bearing zones from the borehole EM flowmeter survey were used to convert composite water-sample concentrations into concentrations of individual sample intervals between sample-collection points. Water was assumed to be flowing from adjacent hydrogeologic units and completely mixing before reaching the collection point. Sample intervals, hydrogeologic units, and percentage flow contribution associated

Table 3. Sample intervals between water-sample collection depths and composite-sample intervals in pumped test hole for well 36Q398 following an electromagnetic flowmeter survey, Barbour Pointe community, near Savannah, Georgia, August 21–22, 2013

[UFA, Upper Floridan aquifer; MSU, Middle semiconfining unit; LFA, Lower Floridan aquifer; LCU, Lower confining unit]

Sample interval (SI) number	Depth of sample interval (foot below land surface)		Hydrogeologic unit(s) to which the sample interval is open	Percent contribution of flow
	Top (also depth of grab sample)	Bottom (also depth of grab sample for the lower sample interval)		
SI–1	330	690	UFA, MSU	91.5
SI–2	690	750	MSU, LFA	1.2
SI–3	750	900	LFA	3.8
SI–4	900	1,000	LFA	1.7
SI–5	1,000	1,080	LFA, LCU	1.8

Composite sample depth	Depth of sample interval (feet below land surface)		Hydrogeologic unit(s) to which the sample interval is open	Percent contribution of flow
	Top (also depth of grab sample)	Bottom (also depth of bottom of well)		
330	330	1,080	UFA, MSU, LFA, LCU	100
690	690	1,080	MSU, LFA, LCU	8.5
750	750	1,080	LFA, LCU	7.3
900	900	1,080	LFA, LCU	3.5
1,000	1,000	1,080	LFA, LCU	1.8

Table 4. Water quality of composite samples and sample intervals following an electromagnetic flowmeter survey of the Floridan aquifer system at a test hole for well 36Q398, Barbour Pointe community, near Savannah, Georgia, August 22, 2013.

[Composite samples represent quality of water from top of interval to depth of well. Significant figures are reported as final results from the lab. Borehole flow corrected values reflect water quality of sampled interval. Water quality of the Upper Floridan aquifer is highlighted in blue. Water quality of the Lower Floridan aquifer is highlighted in green. ft, foot; gal/min, gallon per minute; UFA, Upper Floridan aquifer; MSU, Middle semiconfining unit; <, less than; BRL, below reporting limit; LFA, Lower Floridan aquifer; LCU, lower confining unit; n/a, not applicable]

Hydrogeologic unit(s)	Constituent			Manganese		Chloride		Fluoride		Sulfate	
	Units			Milligrams per liter							
	U.S. Environmental Protection Agency (2011) secondary drinking-water regulation			0.05		250		2		250	
	Sample interval	Interval depth (ft)	Interval flow (gal/min)	Composite	Borehole flow corrected	Composite	Borehole flow corrected	Composite	Borehole flow corrected	Composite	Borehole flow corrected
UFA, MSU	1	330-690	915	<0.005	BRL	6.56	6.51	0.31	0.30	4.71	4.60
MSU, LFA	2	690-750	12	0.008	0.014	7.13	10.48	0.39	0.21	5.88	6.12
LFA	3	750-900	38	0.007	0.005	6.58	6.14	0.42	0.43	5.84	5.50
LFA	4	900-1,000	17	0.009	0.006	7.06	7.90	0.41	0.45	6.21	7.39
LFA, LCU	5	1,000-1,080	18	0.012	0.012	6.27	6.27	0.37	0.37	5.10	5.10

Hydrogeologic unit(s)	Constituent			Alkalinity		Total Hardness		Total Dissolved Solids		pH	
	Units			Milligrams per liter						Standard units	
	U.S. Environmental Protection Agency (2011) secondary drinking water regulation			n/a		n/a		500		6.5-8.5	
	Sample interval	Interval depth (ft)	Interval flow (gal/min)	Composite	Borehole flow corrected	Composite	Borehole flow corrected	Composite	Borehole flow corrected	Composite	Borehole flow corrected
UFA, MSU	1	330-750	915	113	113	101	102	180	180	7.71	7.70
MSU, LFA	2	690-750	12	113	131	95	65	182	200	7.86	8.24
LFA	3	750-900	38	110	107	100	99	179	174	7.82	7.85
LFA	4	900-1,000	17	113	117	101	99	184	183	7.79	7.74
LFA, LCU	5	1,000-1,080	18	109	109	103	103	185	185	7.84	7.84

Table 5. Test Methods used to analyze water-quality data.

[Test method numbers are as reported by the laboratory. Avery Laboratories & Environmental Services, LLC was the lead lab. Analytical Environmental Services, Inc., and TestAmerica Laboratories, Inc. were contract labs. $CaCO_3$, calcium carbonate; EPA, U.S. Environmental Protection Agency; SM, standard method; ASTM, American Society for Testing and Materials; SW, solid waste]

Analyte	Sample date	Lab	Method
Alkalinity as $CaCO_3$	2013 Aug 22	Avery Laboratories & Environmental Services, LLC	EPA 310.2
Chloride	2013 Aug 22	Avery Laboratories & Environmental Services, LLC	SM 4500-CL e
Total hardness	2013 Aug 22	Avery Laboratories & Environmental Services, LLC	SM 2340b
Iron	2013 Aug 22	Avery Laboratories & Environmental Services, LLC	EPA 200.7
Manganese	2013 Aug 22	Avery Laboratories & Environmental Services, LLC	EPA 200.7
Zinc	2013 Aug 22	Avery Laboratories & Environmental Services, LLC	EPA 200.7
Nitrate as Nitrogen	2013 Aug 22	Avery Laboratories & Environmental Services, LLC	SM 4500-NO3 h
Nitrite as Nitrogen	2013 Aug 22	Avery Laboratories & Environmental Services, LLC	SM 4500-NO2 b
pH	2013 Aug 22	Avery Laboratories & Environmental Services, LLC	SM 4500-H b
Total dissolved solids	2013 Aug 22	Avery Laboratories & Environmental Services, LLC	SM 2540c
Sulfate	2013 Aug 22	Avery Laboratories & Environmental Services, LLC	ASTM D516-90
Turbidity	2013 Aug 22	Avery Laboratories & Environmental Services, LLC	EPA 180.1
Fluoride	2013 Aug 22	Analytical Environmental Services, Inc.	SW 9056A
Color	2013 Aug 22	Analytical Environmental Services, Inc.	EPA 110.2 / SM 2120 B
Total carbon dioxide	2013 Aug 22	Analytical Environmental Services, Inc.	SM 4500-CO2
Nitrate as Nitrogen	2013 Nov 22	TestAmerica Laboratories, Inc.	EPA 300.0
Sulfate	2013 Nov 22	TestAmerica Laboratories, Inc.	EPA 300.0
Fluoride	2013 Nov 22	TestAmerica Laboratories, Inc.	EPA 300.0
Nitrate plus Nitrite as Nitrogen	2013 Nov 22	TestAmerica Laboratories, Inc.	EPA 300.0
Chloride	2013 Nov 22	TestAmerica Laboratories, Inc.	EPA 300.0
Nitrite as Nitrogen	2013 Nov 22	TestAmerica Laboratories, Inc.	EPA 300.0
Iron	2013 Nov 22	TestAmerica Laboratories, Inc.	EPA 200.7 Rev. 4.4

Table 5. Test Methods used to analyze water-quality data.—Continued

[Test method numbers are as reported by the laboratory. Avery Laboratories & Environmental Services, LLC was the lead lab. Analytical Environmental Services, Inc., and TestAmerica Laboratories, Inc. were contract labs. EPA, U.S. Environmental Protection Agency; SM, standard method; ASTM, American Society for Testing and Materials; SW, solid waste.]

Analyte	Sample date	Lab	Method
Manganese	2013 Nov 22	TestAmerica Laboratories, Inc.	EPA 200.7 Rev. 4.4
Zinc	2013 Nov 22	TestAmerica Laboratories, Inc.	EPA 200.7 Rev. 4.4
Hardness as calcium carbonate	2013 Nov 22	TestAmerica Laboratories, Inc.	SM 2340B
pH	2013 Nov 22	TestAmerica Laboratories, Inc.	EPA 150.1
Turbidity	2013 Nov 22	TestAmerica Laboratories, Inc.	2130B-2011
Color	2013 Nov 22	TestAmerica Laboratories, Inc.	SM 2120B
Alkalinity	2013 Nov 22	TestAmerica Laboratories, Inc.	SM 2320B
Carbon dioxide, free	2013 Nov 22	TestAmerica Laboratories, Inc.	no report
Total dissolved solids	2013 Nov 22	TestAmerica Laboratories, Inc.	SM 2540C

with them are listed in table 3. The mixing equation adopted from Kendall and Caldwell (1998, p. 80) was applied to sample intervals in the test hole as follows:

$$Q_{T,n}C_{T,n} = Q_{T,n-1}C_{T,n-1} + Q_{I,n}C_{I,n}\ , \qquad (1)$$

where

$Q_{T,n}$ is the composite discharge at sample-collection point, n, contributed to or flowing up the borehole from all water-bearing zones below n in gallons per minute;

$C_{T,n}$ is the concentration of a specific conservative constituent in discharge water, $Q_{T,n}$, expressed in a linear-unit value that varies with constituent, but represents the mass of the constituent per volume of water;

$Q_{T,n-1}$ is the composite discharge at sample-collection point, n –1, contributed to or flowing up the borehole from all water-bearing zones below n –1 in gallons per minute;

$C_{T,n-1}$ is the concentration of a specific conservative constituent in discharge water, $Q_{T,n-1}$, expressed in a linear-unit value that varies with constituent, but represents the mass of the constituent per volume of water;

$Q_{I,n}$ is the discharge entering the well from the interval between sample-collection points n and n –1 in gallons per minute; and

$C_{I,n}$ is the concentration of a specific conservative constituent in discharge, $Q_{I,n}$, expressed in a linear-unit value that varies with constituent, but represents the mass of the constituent per volume of water.

Discharge rates are known from the borehole EM flowmeter survey, and the composite water-sample concentrations at sample-collection points are known from sampling and analysis; therefore, equation 1 can be rearranged to solve for the concentration, $C_{I,n}$, of the specific conservative constituent in discharge water ($Q_{I,n}$) entering the well between the two sample-collection points n and n–1:

$$C_{I,n} = \frac{Q_{T,n}C_{T,n} - Q_{T,n-1}C_{T,n-1}}{Q_{I,n}} \qquad (2)$$

Results of water analysis before and after flow rate corrections (composite and sample interval, respectively) are listed in table 4, and corrected values (sample intervals) are plotted in figure 7; for example, calculating the chloride concentration from sample interval 3 using composite concentration values from table 4; $Q_{T,n}$ =18+17+38=73 gal/min, $C_{T,n}$ =6.58 milligrams per liter (mg/L), $Q_{T,n-1}$ =18+17=35 gal/min, $C_{T,n-1}$ =7.06 mg/L, and $Q_{I,n}$ =38 gal/min. Entering these numbers into equation 2 produces a chloride concentration ($C_{I,n}$) of 6.14 mg/L.

In addition to the grab water samples collected in the test borehole at specific depths, a composite water sample was collected from LFA well 36Q398 after 71 hours of pumping during the 72-hour aquifer test on November 22, 2013. The water sample was analyzed for pH, total dissolved solids, color, dissolved carbon dioxide, turbidity, hardness as calcium carbonate, iron, manganese, zinc, sulfate, chloride, fluoride, and nitrate plus nitrite as nitrogen (table 6). Samples were analyzed at TestAmerica Laboratories, Inc., Savannah, Ga. As with the August 2013 samples, test methods for analytes are listed in table 5.

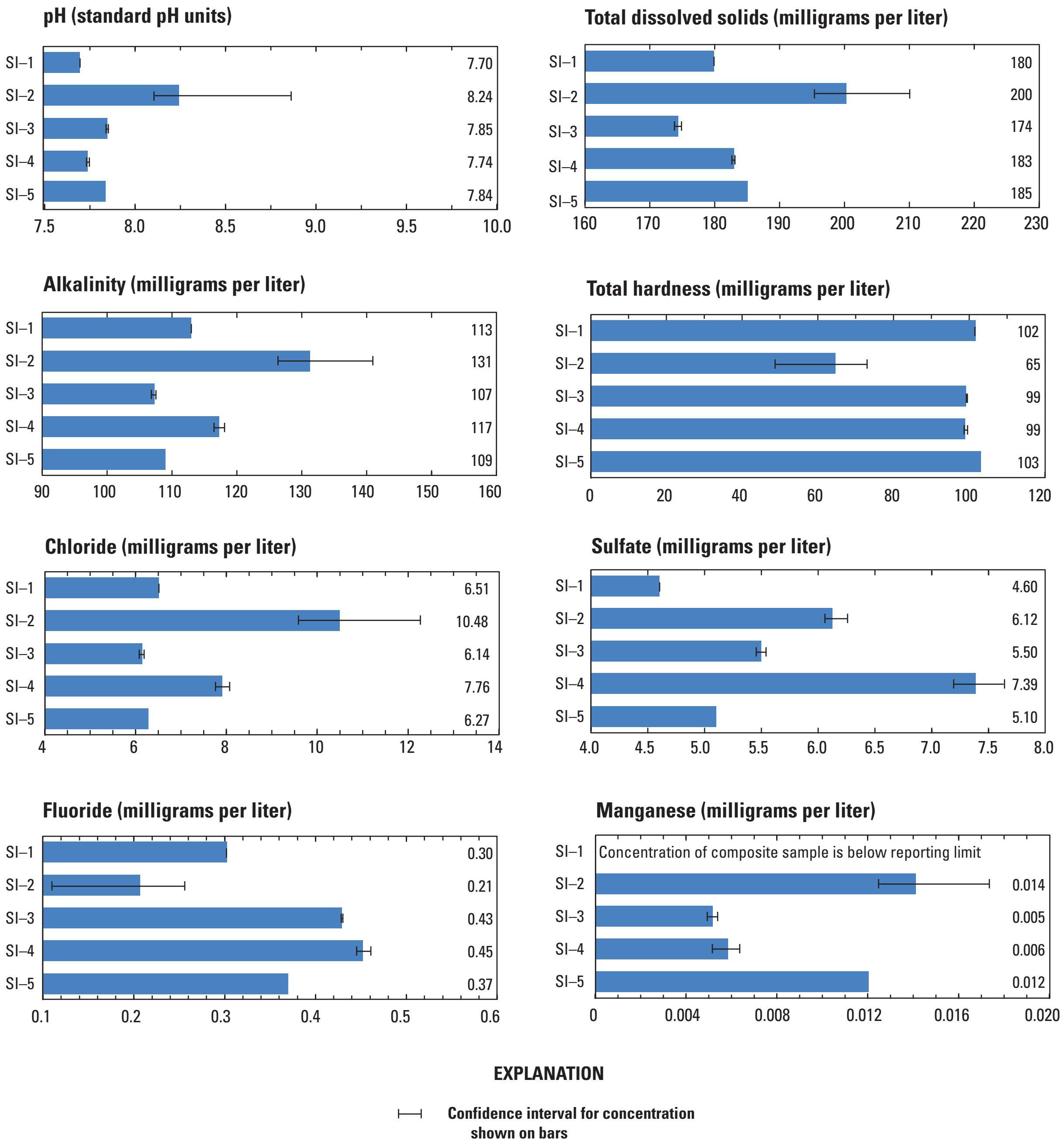


Figure 7. Borehole-flow corrected water quality by sample interval in test hole for well 36Q398, Barbour Pointe community, near Savannah, Georgia, August 22, 2013.

Table 6. Water-quality analysis of completed Lower Floridan aquifer well 36Q398, 71 hours into a 72-hour aquifer test, November 22, 2013, and select samples from the test hole for well 36Q398, August 22, 2013, Barbour Pointe community, near Savannah, Georgia

[Water-quality analysis from the Lower Floridan aquifer at the test hole for well 36Q398 on August 22, 2013, is shown for comparison. LFA, Lower Floridan aquifer; UFA, Upper Floridan aquifer; ft, foot; gal/min, gallon per minute; µg/L, microgram per liter; <, less than; –, not available; BRL, below reporting limit; NTU, nephelometric turbidity unit; n/a, not applicable; mg/L, milligram per liter; MCL, maximum contaminant level; PCU, platinum-cobalt unit]

Sample information			
Aquifer	LFA	LFA	UFA
Sample type	Out flow from completed well	Composite sample 690 to 1,080 ft depth	Sample interval from 330 to 690 ft depth
Sample date	2013 November 22	2013 August 22	2013 August 22
Pumping rate (gal/min)	750	1,000	1,000
Approximate pumping time before sampling (hours)	71	3	3

Water-quality sample results

Constituent parameter	LFA completed well	LFA composite 690 ft	UFA sample interval	U.S. Environmental Protection Agency (2011) secondary drinking-water regulation
pH (standard pH units)	7.99	7.86	7.70	6.5-8.5
Iron (µg/L)	<50	–	–	300
Manganese (µg/L)	<10	8	BRL	50
Zinc (µg/L)	<20	–	–	5,000
Turbidity (NTU)	<0.1	–	–	n/a
Nitrate plus Nitrite as Nitrogen (mg/L)	<0.05	–	–	1 (MCL)
Chloride (mg/L)	37	7.13	6.51	250
Fluoride (mg/L)	1	0.39	0.30	2
Sulfate (mg/L)	30	5.88	4.60	250
Color (PCU)	15	–	–	15
Alkalinity	–	113	113	n/a
Carbon dioxide, free (mg/L)	<5	–	–	n/a
Hardness as calcium carbonate (mg/L)	86	95	102	n/a
Total dissolved solids (mg/L)	270	182	180	500

Hydrogeology and Water Quality

Hydrogeologic units of the Floridan aquifer system in the Barbour Pointe community study area were distinguished by differences in flow contribution, lithology, geophysical characteristics, and water quality. The following sections describe the depths and hydraulic characteristics of hydrogeologic units that form the Floridan aquifer system at the Barbour Pointe test site.

Drilling activity and geophysical logs of test hole for well 36Q398 (fig. 1) indicate that clastic sediments consisting of clay, sand, and some gravel are present from land surface to a depth of 280 ft. This clastic sequence represents a combination of the surficial and Brunswick aquifer systems (fig. 3). The interval between 280 and 330 ft consists of a Miocene mix of clastic and carbonate sediments of low permeability considered to be the base of the Brunswick aquifer system. Beneath the mixed clastic and carbonate sediments extends limestone mostly of the Floridan aquifer system from 330 ft to the total depth of the borehole (1,080 ft; fig. 3). The top of the Oligocene corresponds to a spike in the natural-gamma log called the “C-marker” associated with deposits of phosphate-rich glauconite (fig. 5; Wait, 1965; Gregg and Zimmerman, 1974; Clarke and others, 1990). At the study site, the uppermost several feet of the carbonate sequence is above the C-marker; therefore, the carbonate sequence extends several feet into the overlying Miocene. Nonwater-bearing limestone (NWBL) extends from the top of the carbonate rock at 330 ft to the top of the first water-bearing zone at 369 ft. The NWBL includes the lower part of the Miocene Tiger Leap Formation, the lower Oligocene Lazaretto Creek Formation, and may include the lower Oligocene Suwanee Formation. Based on an EM flowmeter survey, drill cuttings, and geophysical logs, major hydrogeologic units of the Floridan aquifer system extend from 330 to 1,056 ft and include the following units:

- NWBL, 330–369 ft
- UFA, 369–567 ft
- MSU, 567–714 ft
- LFA, 714–1,056 ft

At the study site, the bottom of the LFA is based on the bottom of the lowest water-bearing zone at 1,056 ft. Carbonate rock extending below this depth may be the upper part of the lower confining unit provided that there are no more water-bearing zones below 1,056 ft. The driller’s log indicates a slight change in color or “green tint” in limestone below 1,060 ft depth, which may be an indication of a change in the carbonate rock, which may in turn represent a lack of water-bearing zones below this depth. Early Eocene clay beneath the carbonate sequence and below the bottom of the well bore generally comprises the lower confining unit (Miller, 1986; Williams and Gill, 2010). The depth of the top of this clay is not known at the site and is not represented in figures 3 or 4.

Upper Floridan Aquifer

The top of the UFA in well 36Q398 begins at the top of the uppermost water-bearing zone at a depth of about 369 ft. This depth also coincides with the top of a long interval of low natural-gamma radiation called the “D-marker” (fig. 5), which is the top of the upper Eocene Ocala Limestone (Wait, 1965; Gregg and Zimmerman, 1974; Clarke and others, 1990). The base of the UFA (at a depth of about 567 ft) is close to the contact between the upper Eocene Ocala Limestone and middle Eocene Avon Park Formation, and corresponds to the base of a thin, porous limestone. The thin, porous limestone is associated with a main water-bearing zone as determined by the EM-flowmeter-survey results. Total thickness of the UFA at the Barbour Pointe test site is 198 ft compared to 242 ft at Berwick Plantation (Williams and Gill, 2010), 182 ft at Pooler, Ga. (Gonthier, 2012), and 275 ft at HAAF (Williams, 2010).

Electromagnetic Flowmeter Survey

On August 21, 2013, a borehole EM flowmeter survey was completed in the test hole for well 36Q398 (fig. 1) within the 330 to 1,080 ft depth interval while pumping at a rate of 1,000 gal/min. The borehole EM flowmeter survey indicated that 91.5 percent (915 gal/min) of the total flow originated from the UFA, and the remaining 8.5 percent (85 gal/min) was derived from the underlying MSU and the LFA (fig. 5). Four major water-bearing zones provided flow in the UFA:

- 369–407 ft (41.0 percent)
- 421–463 ft (29.0 percent)
- 482–525 ft (17.5 percent)
- 542–567 ft (4.0 percent).

The extent of the UFA water-bearing zones corresponded closely to the vertical extent of low natural-gamma-log values from the D-marker of the top of the upper Eocene down to the base of the upper Eocene (fig. 5). The dominance of water-bearing potential in the UFA also was found at HAAF (Williams, 2010), Pooler, Ga. (Gonthier, 2012), and Fort Stewart (Gonthier, 2011). At all four sites, the majority of flow is located below the D-marker within the Ocala Limestone.

Hydraulic Properties

Estimated transmissivity for the UFA based on the simulations of the EM flowmeter survey and aquifer-test drawdown was about 60,000 ft^2/d, which is higher than that reported at Berwick Plantation (46,000 ft^2/d), Pooler, Ga. (44,000 ft^2/d), and HAAF (39,700 ft^2/d) sites (Faye and Gill, 2005; Gonthier, 2012; Williams, 2010). Dividing the estimated transmissivity by the thickness of the UFA (198 ft) results in an estimated horizontal hydraulic conductivity (K_h) of about 300 ft/d.

Simulation of the aquifer test using the axisymmetric model involved matching drawdown response (table 2) in wells located at Barbour Pointe community (LFA well 36Q398 and UFA well 36Q399), Berwick Plantation community

(LFA well 36Q330 and UFA well 36Q331) located 6,017 ft to the west, and at Morrison Plantation (UFA well 36Q020) located 6,863 ft to the south (fig. 6). Model calibration resulted in a good match at Barbour Pointe wells and at Morrison Plantation UFA well 36Q020, but simulated drawdown for the two Berwick wells (LFA well 36Q330 and UFA well 36Q331) was consistently much less than observed drawdown (75 and 42 percent less, respectively). The underestimation in drawdown in the Berwick wells probably is because of heterogeneity of hydrogeologic units that the axisymmetric model does not adequately represent.

Water Quality

Values of specific conductance of formation water in the UFA in the 369–567-ft interval ranged from 155–311 microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25°C) and had a median specific conductance of 232 µS/cm at 25°C (fig. 5). As mentioned in the previous section “Water-Quality Sampling and Analysis”, water collected during drilling is a composite of all water entering the borehole above the concurrent drill depth. For that reason, the bottom three samples in the vertical extent of the UFA (depths 540, 550, and 560) best represent the water from the UFA. Water from these samples had a median specific conductance of 231 µS/cm at 25°C. Water quality in the UFA was determined from sample interval one (SI–1; sample collection after the EM flowmeter survey), which is the interval between two composite grab samples taken at a depth of 330 and 690 ft (tables 3 and 4, figs. 5 and 7). The SI–1 spans all of the UFA and the upper part of the MSU. More than 90 percent of the flow during the EM flowmeter survey was from this interval; virtually all flow originated from the UFA.

Water from SI–1 had low total dissolved solids concentration of 180 mg/L (tables 4 and 6). Concentrations of all measured constituents were below water-quality criteria established by the U.S. Environmental Protection Agency for drinking water and health advisories (tables 4 and 6; U.S. Environmental Protection Agency, 2011).

Middle Semiconfining Unit

The MSU at well 36Q398 consists of chalky and glauconitic limestone in the uppermost part of the middle Eocene Avon Park Formation between depths of 567 and 714 ft (figs. 2 and 5). Thickness and K_v of the MSU control the rate of interaquifer leakage between the UFA and LFA.

The MSU is 147 ft thick at the Barbour Pointe test site compared to 156 ft at Berwick Plantation (Williams and Gill, 2010), 187 ft at Pooler, Ga. (Gonthier, 2012), and 143 ft at HAAF (Williams, 2010). The MSU contains carbonate sediments of slightly lower permeability than those of the LFA. This unit is similar in lithology to overlying and underlying rock units. The lithologic similarity between rock units precluded identification of the MSU unit during drilling. Following construction of the test hole for well 36Q398, the thickness and depths of the MSU were assessed by using borehole geophysical logs and results of an EM flowmeter survey.

Electromagnetic Flowmeter Survey

The vertical extent of the MSU at test hole for well 36Q398 was assessed by using EM-flowmeter-survey results, which indicated that there were no notable water-bearing zones between depths of 567 and 714 ft (fig. 5). Although the EM flowmeter survey was unable to detect flow being contributed from the MSU, a small amount of diffuse flow is expected to be produced in the MSU. Such flow from the MSU roughly can be estimated as the proportion of the transmissivity of the Floridan aquifer system that is attributed to the MSU. Based on slug tests in previous studies at Pooler, Ga., and HAAF (Gonthier, 2012; William, 2010), and axisymmetric model results, the K_h of the MSU at the Barbour Pointe test site is estimated to be about 3 ft/d. Thickness of the MSU of about 147 ft would indicate transmissivity of the MSU of about 441 ft^2/d. Based on the Floridan aquifer system having a transmissivity of about 65,000 ft^2/d (table 2), the proportion of that transmissivity attributed to the MSU would be about 0.7 percent.

Hydraulic Properties

Values of K_h and K_v of the MSU were not measured at the Barbour Pointe test site; however, these hydraulic properties were characterized at the nearby Pooler, Ga., and HAAF sites by completing packer-isolated slug tests within the MSU, and analyzing core samples from the MSU (Williams 2010; Clarke and others, 2010; and Gonthier, 2012). At HAAF (fig. 1), the estimated K_h within the LFCU ranged from 0.16 to 3.1 ft/d and had a median K_h of 0.65 ft/d (Williams, 2010). At Pooler, Ga., the estimated K_h ranged from 0.5 to 10 ft/d and had a median K_h of 3 ft/d (Gonthier, 2012). At HAAF, the estimated K_v ranged from 0.13 to 0.34 ft/d and had a median K_v of 0.20 ft/d (Williams, 2010). At Pooler, Ga., estimated K_v ranged from 0.57 to 1.67 ft/d and had a median K_v of 1.08 ft/d (Gonthier, 2012). The median K_h and K_v for all values at the two sites was 1.1 and 0.46 ft/d, respectively.

Water Quality

Because of a lack of water-bearing zones, water-quality information generally is unavailable for the MSU. From sample depths of 570 to 710, specific conductance within the MSU increases from about 241 to 263 µS/cm at 25 °C (fig. 5). This increase indicates that conductance and, most likely, total dissolved solids were slightly increasing during the drilling operation. The increase may be attributable to higher salinity in groundwater with depth or possible dissolution of drilled material into recirculating formation water over time.

A grab sample for sample interval two (SI–2) was collected 24 ft above the base of the MSU (table 4 and fig. 5). The water from this interval is mostly from the uppermost zone near the top of the LFA and is not a representative part of the MSU.

Lower Floridan Aquifer

The LFA at well 36Q398 consists of chalky and glauconitic limestone in the upper part of the middle Eocene Avon Park Formation that is similar in lithology to overlying units (figs. 2 and 5). At well 36Q398, the top of the LFA is at a depth of 714 ft and extends to a depth of 1,056 ft. The LFA is 342 ft thick at the Barbour Pointe test site compared to 338 ft at Pooler, Ga. (Gonthier, 2012), and 377 ft at HAAF (Williams, 2010).

Electromagnetic Flowmeter Survey

Water-bearing zones were identified in the LFA using results of EM flowmeter testing in the test hole for well 36Q398 (fig. 1) completed on August 21, 2013. The LFA contributed about 85 gal/min or 8.5 percent of the total 1,000 gal/min flow rate. Four major water-bearing zones provided measurable flow in the LFA within the test hole (fig. 5):

- 714–803 ft (4.0 percent)
- 870–896 ft (1.0 percent)
- 914–940 ft (1.7 percent)
- 1,023–1,056 (1.8 percent)

No flow was detected below a depth of 1,056 ft, indicating that this may be the top of the lower confining unit to the Floridan aquifer system.

Hydraulic Properties

Estimated transmissivity of the LFA, based on the simulations of the EM flowmeter survey and aquifer-test drawdown, ranged from about 4,600 to 5,200 ft^2/d. This is consistent with the reported value of 5,200 ft^2/d at Pooler, Ga. (Gonthier, 2012), and is less than the 8,200 ft^2/d value reported at Berwick Plantation community (Faye and Gill, 2005) and 11,000 ft^2/d value reported at HAAF (Williams, 2010). Dividing the estimated transmissivity at the Barbour Pointe test site by the thickness of the LFA (342 ft) gives an average K_h of the LFA ranging from 13 to 15 ft/d.

Water Quality

The quality of water in the LFA was initially evaluated during drilling of the test hole for well 36Q398 (fig. 1) by measuring specific conductance of reverse-air-rotary formation water within the Floridan aquifer system (fig. 5). Specific conductance values of drilling fluid in the LFA in the open borehole between depths of 714 and 1,056 ft generally increased with depth. There is an abrupt change in specific conductance at about 840 ft. Above this depth, specific conductance smoothly varies plus or minus ± 60 µS/cm at 25°C in conductance while a base line value increases from 230 to 275 µS/cm at 25°C. Below 840 ft, specific conductance values become more stable with depth increasing from roughly 305 to 335 µS/cm at 25°C. The abrupt conductance change at 840 ft is not within a measureable water-bearing zone indicating that the trend break may not be attributed to inflow of higher groundwater conductance with depth. The overall increase in specific conductance values with depth may be attributed to higher total dissolved solids within the lower water-bearing zones of the LFA, but may also be attributed to an introduction of dissolved solids into recirculating formation water.

More detailed water quality of the LFA was determined by collecting composite grab samples during EM flowmeter testing of the test borehole for well 36Q398 and correcting for flow between sample depths (table 4, fig. 7). Samples were collected at depths of 690, 750, 900, and 1,000 ft representing the lower boundaries of SI–2, sample interval three (SI–3), and sample interval four (SI–4); and upper boundary of sample interval five (SI–5), respectively. All four lowest sample intervals are representative of the LFA. The composite sample collected at 690 ft is a collection of the water produced from the LFA and a thin part of the MSU, and, therefore, best represents the water quality of the LFA.

Overall, water quality between the LFA and UFA was similar. Measured constituents had low concentrations that were all below the U.S. Environmental Protection Agency secondary drinking-water standard (table 4; U.S. Environmental Protection Agency, 2011). Water in the UFA as represented by SI–1 was similar to water in the LFA as represented by the composite sample from 690 ft (table 4). Water from the LFA had slightly higher concentrations of total dissolved solids, manganese, chloride, fluoride, sulfate, total dissolved solids, and pH than water from the UFA. Water from the UFA was slightly harder than water from the LFA.

Water-quality variation within the LFA is mainly attributed to SI–2, which had the greatest concentrations of total dissolved solids, alkalinity, chloride and manganese; the highest value of pH; and the lowest concentrations of total hardness and fluoride (fig. 7). Water from SI–4 had a slightly higher sulfate concentration compared to water from all other sample intervals. Overall water quality within the LFA sample intervals was similar, and measured constituents had low concentrations that were all below the U.S. Environmental Protection Agency secondary drinking-water standard (table 4; U.S. Environmental Protection Agency, 2011).

A composite water sample collected from completed LFA well 36Q398 near the end of the 72-hour aquifer test on November 22, 2013, was tested for a limited number of analytes (table 6). Comparisons of results from this analysis to concentrations of composite samples collected at 690 ft after the EM flowmeter survey on August 22, 2013, indicate that concentrations in the completed LFA well were different from those measured in the open borehole. Concentrations of chloride, fluoride, and sulfate were up to five times greater in the completed well than in the composite sample at 690 ft, but still below the secondary drinking-water standards (tables 6; U.S. Environmental Protection Agency, 2011). Total dissolved solids concentration was 270 mg/L, which was higher than measured concentrations in each of the grab samples collected on August 22, 2013, but still within the 500-mg/L secondary drinking-water standard (U.S. Environmental Protection Agency, 2011).

The reason for the higher concentrations of chloride, fluoride, and sulfate in completed LFA well 36Q398 in November 2013 compared to the test hole for well 36Q398 in August 2013 is unknown. The difference could be related to a longer pumping period leading to a larger sampling radius of the aquifer compared to that for the grab samples collected after the EM flowmeter testing in August 2013.

The color of the water sample collected in completed LFA well 36Q398 in November 2013 was at the secondary drinking-water standard of 15 platinum cobalt (color) units. Color was not analyzed in the grab samples collected in August 2013. Color may be indicative of dissolved organic material or the presence of inorganic constituents such as metals (U.S. Environmental Protection Agency, 2011). Color is not a health hazard, but rather an aesthetic measure that may indicate water is undesirable, but not harmful. According to the U.S. Environmental Protection Agency (2011), the point of consumer complaint is variable over a range from 5 to 30 color units, though most people find color objectionable over 15 color units.

Effect of Lower Floridan Aquifer Withdrawals on the Upper Floridan Aquifer

The effect of withdrawing water from the LFA by pumping LFA well 36Q398 at a rate of about 750 gal/min during the November 19–22, 2013, aquifer test was evaluated in UFA observation wells 36Q399, 36Q331, and 36Q020; and in LFA wells 36Q398 and 36Q330 (figs. 1 and 6). Drawdown in the UFA was moderate, but geographically extensive. Water levels in LFA well 36Q398 declined 35.5 ft at the end of the 72-hour pumping period on November 22, 2013 (table 2). This pumping caused a water-level decline of 0.7 ft in UFA well 36Q399 36 ft from the pumped well. Drawdown at UFA wells located farther from the pumped well was only slightly lower: 0.6 ft at well 36Q331 located 6,017 ft west, and 0.4 ft at well 36Q020 located 6,863 ft south of the pumped well. This moderate, but broad drawdown response in the UFA to withdrawals in the LFA was similar to the responses at HAAF, Fort Stewart, and Pooler, Ga. (Williams 2010; Clarke and others, 2010; Gonthier, 2011; and Gonthier, 2012).

Summary and Conclusions

To assess the water-supply potential of the Lower Floridan aquifer (LFA) at Barbour Pointe community in western Chatham County, Georgia, the U.S. Geological Survey (USGS), in cooperation with the Consolidated Utilities, LLC, Chatham County, Ga., completed an investigation during 2013 to determine the hydrogeology and water quality of the Floridan aquifer system, and the potential effect that withdrawals from the LFA would have on the Upper Floridan aquifer (UFA). The study included construction of a test well in the LFA (36Q398) and one in the UFA (36Q399), detailed site investigations, and hydraulic and water-quality characterization of the Floridan aquifer system. Drill cuttings, geophysical logs, and borehole electromagnetic (EM) flowmeter surveys indicated that the UFA extends from about 369 to 567 feet (ft) below land surface, the middle semiconfining unit (MSU), which separates the UFA and the LFA, extends from about 567 to 714 ft below land surface, and the LFA extends from about 714 to 1,056 ft below land surface.

A borehole EM flowmeter survey completed in the test hole for well 36Q398 open to the entire Floridan aquifer system indicates that the UFA contains four water-bearing zones at depth intervals of 369–407, 421–463, 482–525, and 542–567 ft; and the LFA contains four water-bearing zones at depth intervals of 714–803, 870–896, 914–940, and 1,023–1,056 ft. No water-bearing zones were detected in the MSU. Borehole EM flowmeter survey of the test hole open to the entire Floridan aquifer system indicated that the UFA contributed 91 percent of the total flow rate of 1,000 gallons per minute (gal/min), and the LFA contributed 8 percent. Based on horizontal hydraulic conductivity from nearby studies at Pooler, Ga., and HAAF, the MSU probably contributed a diffuse flow of about 1 percent.

Hydraulic properties of the UFA, MSU, and LFA were estimated based on results of the EM flowmeter survey and a 72-hour aquifer test completed in LFA well 36Q398. Electromagnetic flowmeter data were analyzed using AnalyzeHOLE to simulate upward borehole flow and determine the transmissivity of water-bearing zones. Aquifer-test data were analyzed using a two-dimensional, axisymmetric, radial, transient, groundwater-flow model using MODFLOW–2005. The flowmeter-survey and aquifer-test simulations provided an estimated transmissivity of about 60,000 feet squared per day (ft^2/d) for the UFA, 50–450 ft^2/d for the MSU, and about 5,000 ft^2/d for the LFA.

Simulation of the aquifer test using the axisymmetric model involved matching drawdown response in wells located at Barbour Pointe community, Berwick Plantation community located 6,017 ft to the west, and at Morrison Plantation well located 6,863 ft to the south. Model calibration resulted in a good match at the Barbour Pointe wells and the Morrison Plantation well to the south, but simulated drawdown for wells located at Berwick Plantation community was consistently much less than observed drawdown. The underestimation in simulated drawdown in the Berwick wells probably is because of heterogeneity of hydrogeologic units, which the axisymmetric model does not adequately represent.

The quality of water in discrete-depth samples from the UFA, MSU, and LFA collected during the EM flowmeter survey in August 2013 was low in dissolved solids; all samples were within established U.S. Environmental Protection Agency water-quality criteria. Total dissolved solids concentrations ranged from 174 to 200 milligrams per liter. Concentrations of measured constituents in completed LFA well 36Q398 collected at the end of the 72-hour aquifer test in November 2013 generally were higher than in the discrete-depth samples collected during EM flowmeter testing in August 2013, but still within established water-quality criteria. The explanation for higher concentrations in November is unknown, but could be related to a longer pumping period during the aquifer test leading to a larger sample radius of the aquifer compared to that for the discrete-depth samples collected after the EM flowmeter testing in August 2013.

The effect of withdrawing water from the LFA by pumping the LFA well 36Q398 on water levels in three UFA wells and one LFA well was evaluated by monitoring drawdown response during the 72-hour aquifer test. Drawdown in the UFA was moderate, but geographically extensive. Observed water-level responses in the UFA and LFA wells as a result of withdrawing water from the LFA were determined by using water-level data that were filtered for tidal, barometric, and long-term regional trends. Total drawdown at the end of the 72-hour aquifer test was 35.5 ft in the pumped LFA well. This pumping caused a water-level decline of 0.7 ft in the UFA observation well located 36 ft northeast of the pumped well. Drawdown at the UFA wells located farther from the pumped well was only slightly lower (0.6 ft at well 36Q331 located 6,017 ft west and 0.4 ft at well 36Q020 located 6,863 ft south of the pumped well).

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Appendix 1—Estimation of Hydraulic Properties and Drawdown Response

Hydraulic properties of the Floridan aquifer system were estimated at the Barbour Pointe test site based on results of an electromagnetic (EM) flowmeter survey in a test hole for well 36Q398 open to the Floridan aquifer system and a 72-hour aquifer test completed in Lower Floridan aquifer (LFA) well 36Q398 (see "Introduction" section, fig. 1 for well location). Electromagnetic flowmeter data were analyzed using AnalyzeHOLE (Halford, 2009) to simulate upward borehole flow and determine the transmissivity of water-bearing zones. AnalyzeHOLE simulates flow within the wellbore and surrounding hydrogeologic units using a two-dimensional, axisymmetric, radial transient, groundwater-flow model using MODFLOW–2000 (Harbaugh and others, 2000). Aquifer-test data were analyzed with a two-dimensional, axisymmetric, radial, transient, groundwater-flow model, similar to the AnalyzeHOLE model, using MODFLOW–2005 (Harbaugh, 2005). Drawdown response to the 72-hour aquifer test was determined by filtering water-level data from five monitored wells for effects of barometric pressure, earth tide, ocean tide, long-term trends on the order of a couple of weeks, and regional trends using procedures developed by Halford and others (2012).

Electromagnetic Flowmeter Analysis

The EM flowmeter log in the test hole for well 36Q398 (see "Introduction" section, fig. 1 for well location) was used with AnalyzeHOLE (Halford, 2009) to determine the horizontal hydraulic conductivity (K_h) of the Floridan aquifer system as a function of depth. AnalyzeHOLE is an integrated analysis tool for simulating flow and transport in a pumped well. Electromagnetic flowmeter-survey data are input into the model. Parameter-estimation program PEST (Doherty, 2005) estimates the K_h of hydrogeologic units to match simulated flow to measured flow. Full descriptions of the derivation of two-dimensional radial models using a single layer or multiple layers are provided in the following references: Rutledge (1991), Reilly and Harbaugh (1993), Langevin (2008), and Halford (2009). The method to compute flow observations for parameter estimation with radial models is described in Clemo (2002).

For model simulation and parameter estimation, initial single values of specific storage, porosity, and vertical anisotropy (the ratio of vertical hydraulic conductivity [K_v] to K_h) were entered for all hydrogeologic units. An initial value of composite (or target) transmissivity was entered for the entire hydrogeologic column.

The model of the EM flowmeter survey is made up of 53 columns, 200 rows, and 1 traditional model layer (fig. 1–1). The columns represented lateral distance away from the pumped test hole; the rows represented horizontal hydrogeologic units in the way that normal three-dimensional models would use traditional model layers to represent horizontal units (fig. 1–1). The model radially extends 200,000 feet (ft) from the test hole for LFA well 36Q398. The left-most column represents the wellbore radius with high values of hydraulic conductivity and specific storage. Two columns just to the right of the wellbore represent the well casing and annular space, respectively. Above the open interval of the borehole, the cell representing both the casing and annular space were inactive. The fourth column from the left is 0.3181 ft wide and represents the aquifer adjacent to the annular space. Each column beyond that increases in width by a factor 1.2726 to a maximum width of 42,836 ft. Each row represents a height of 5.175 ft. The sides and bottom of the model are no-flow boundaries. The top row of the model is a no-flow boundary representing the water table. The initial head in the model is set to 0 ft. Rather than pumping from the model, water was injected into the model at the same rate that water was withdrawn from the LFA at the pumped well. This procedure allowed the simulated increase in water level to be directly taken as simulated drawdown. Also, injecting water in the model prevents the possibility of dewatering within model cells.

One limitation of AnalyzeHOLE is that PEST does not estimate the specific storage or K_v/K_h of any parts of the aquifer system within the model. Only one value of specific storage was used for the model, 1.16×10^{-6} ft^{-1}, which is equivalent to a storage coefficient of 7.97×10^{-4} for the Floridan aquifer system with a 687-ft thickness at the Barbour Pointe test site. The value of K_v/K_h used in the model was 0.14. The specific storage and K_v/K_h used in the AnalyzeHOLE model were from the aquifer-test model results described below.

A second limitation of the model originates from the EM flowmeter data. Due to noise in the counts per second with depth, no contribution of flow was recognized in many of the less permeable zones including the middle semiconfining unit (MSU). As a result, K_h values determined from model simulations were close to 0.3 ft/d or about an order of magnitude less than values determined from slug tests in previous investigations in nearby sites (Williams, 2010; Gonthier, 2011; Gonthier, 2012).

Because water levels were not monitored in any wells during the EM flowmeter survey, the model simulation was limited to matching EM flowmeter data. Parameter estimation for model calibration using PEST (Doherty, 2005) achieved a close match to EM flowmeter data (fig. 1–2, table 1–1). The model output includes estimated transmissivity for 57 subunits (table 1–2). The best match to EM flowmeter data was simulated using the following transmissivity values: Upper Floridan aquifer (UFA), 60,326 square feet per day (ft^2/d); MSU, 50 ft^2/d; and LFA, 4,460 ft^2/d.

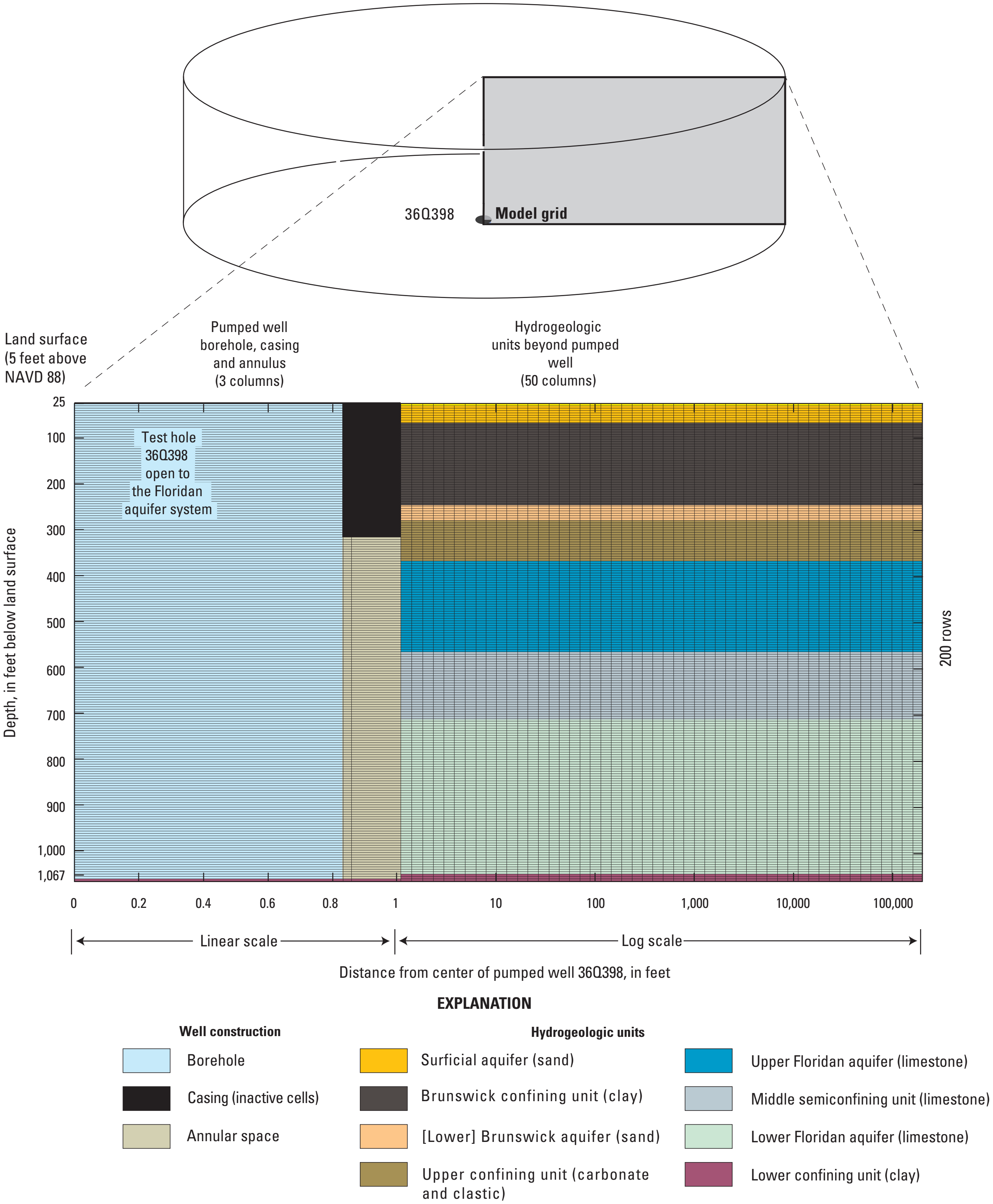

Figure 1–1. Axisymmetric model for electromagnetic flowmeter survey at pumped test hole for well 36Q398 when open to the Floridan aquifer system, Barbour Pointe community, near Savannah, Georgia, August 21, 2013.

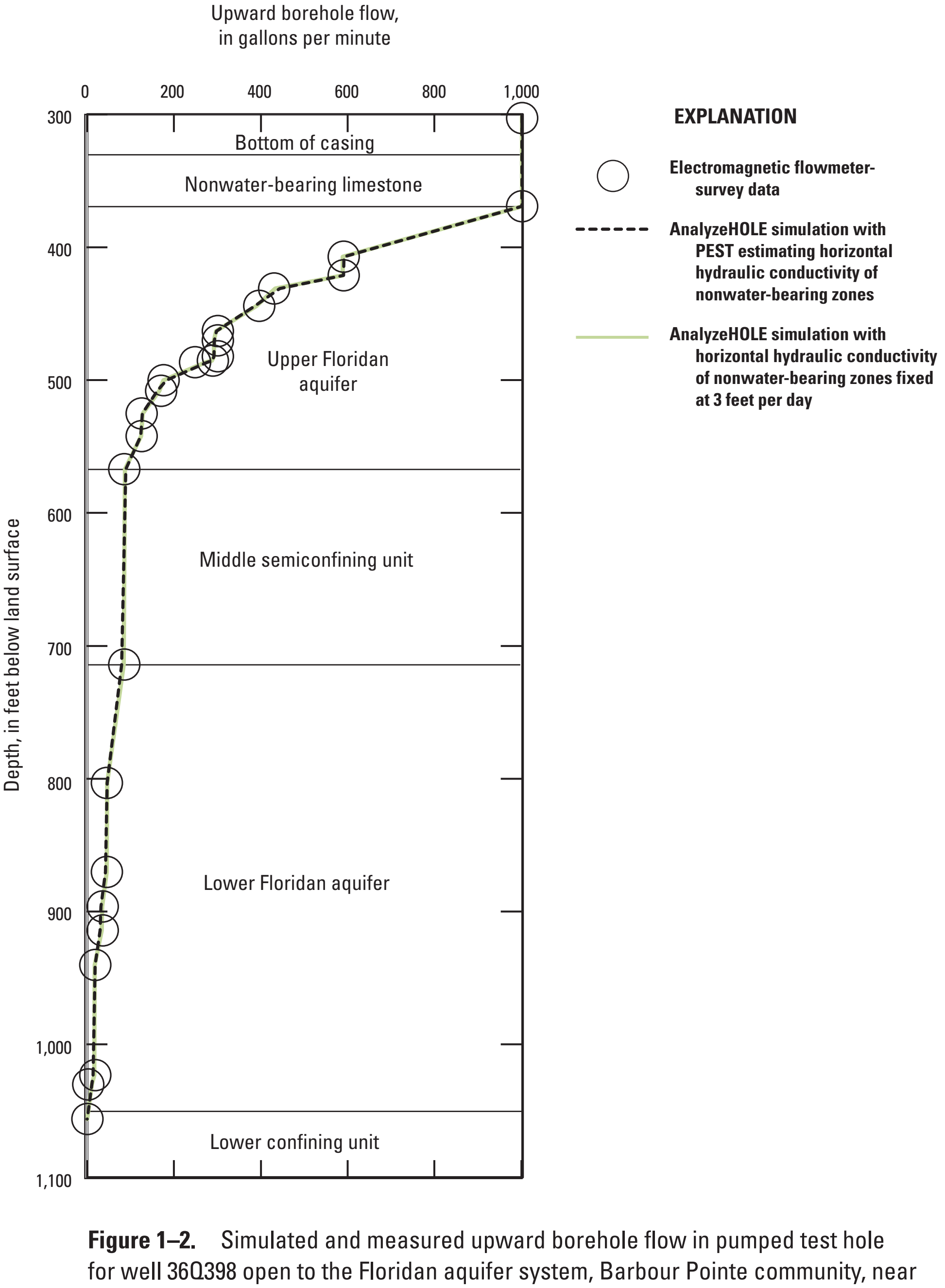

Figure 1–2. Simulated and measured upward borehole flow in pumped test hole for well 36Q398 open to the Floridan aquifer system, Barbour Pointe community, near Savannah, Georgia, August 21, 2013

Table 1–1. Measured and simulated electromagetic flowmeter-survey values with depth and by major hydrogeologic unit of the test hole for well 36Q398 open to the Floridan aquifer system, Barbour Pointe community, near Savannah, Georgia, 2013 August 21.

[Simulations were performed using AnalyzeHOLE. In one simulation, Parameter estimation (PEST) adjusted the horizontal hydraulic conductivity (K_h) of the middle semiconfining unit (MSU); in another simulation the K_h of the LFCU was fixed to 3 feet per day (ft/d).]

Depth, in feet below land surface	Flow profile: Upward borehole flow, in gallons per minute: Measured	Simulated: MSU K_h estimated using PEST	Simulated: MSU K_h fixed at 3 ft/d	Hydrogeologic unit	Percent contributed flow: Measured	Simulated: MSU K_h estimated using PEST	Simulated: MSU K_h fixed at 3 ft/d
70.0	1,000	1,000	1,000	Upper Floridan aquifer	91.5	91.3	91.0
301.0	1,000	1,000	1,000				
369.0	1,000	1,000	1,000				
407.0	590	588	591				
421.0	590	587	590				
431.0	430	433	443				
444.0	395	390	386				
463.0	300	296	297				
470.0	300	291	293				
482.0	300	291	292				
485.2	289	287	288				
486.5	248	273	276				
500.0	175	175	182				
508.0	170	166	161				
525.0	125	128	127				
542.0	125	124	123				
567.0	85	87	89	Middle semiconfining unit	Not detected	0.3	1.0
714.0	85	84	80				
803.0	45	46	45	Lower Floridan aquifer	8.5	8.4	8.0
870.0	45	45	42				
896.0	35	35	32				
914.0	35	33	30				
940.0	18	17	18				
1,023.0	18	17	14				
1,030.0	2	10	11				
1,056.2	0	0	0				

Table 1–2. Hydraulic parameters and hydrogeologic subunits used to simulate electromagnetic flowmeter-survey results, test hole for well 36Q398 open to the Floridan aquifer system, Barbour Pointe community, near Savannah, Georgia, August 21, 2013.

[Hydrogeologic units are subdivided by depth according to varying flow rates or lithology. Rows for the Upper Floridan aquifer are highlighted in blue. Rows for the Lower Floridan aquifer are highlighted in green. ft, foot; K_h, horizontal hydraulic conductivity; ft/d, foot per day; ft^2/d, square foot per day; *, K_h was fixed to this value; –, not applicable]

Depth to top of unit, in feet	Depth to bottom of unit, in feet	Hydrogeologic unit	Lithology and water-bearing properties	Number of subunits related to flow	Thickness (ft)	PEST adjusted K_h for nonwater-bearing zones		K_h for nonwater-bearing zones was fixed at 3 ft/d	
						Horizontal hydraulic conductivity (ft/d)	Transmissivity (ft^2/d)	Horizontal hydraulic conductivity (ft/d)	Transmissivity (ft^2/d)
25	67	Surficial aquifer system (sand)	Water-bearing sand	4	42	*10.00	420.0	*10.00	420.0
67	246	Brunswick confining unit (clay)	Tight clay	6	179	0.11	19.2	0.11	19.2
246	280	Lower Brunswick aquifer (sand)	Water-bearing sand	3	34	*10.00	340.0	*10.00	340.0
280	369	Upper Floridan confining unit (clay)	Tight clay	5	89	0.11	9.5	0.11	9.5
369	407	Upper Floridan aquifer	Water-bearing limestone	2	38	743.84	28,265.9	737.45	28,023.1
407	421	Upper Floridan aquifer	Nonwater-bearing limestone	1	14	0.42	5.9	*3.00	42.0
421	463	Upper Floridan aquifer	Water-bearing limestone	3	42	451.41	18,959.2	450.97	18,940.6
463	483	Upper Floridan aquifer	Nonwater-bearing limestone	1	20	0.41	8.1	*3.00	60.0
483	525	Upper Floridan aquifer	Water-bearing limestone	3	42	262.71	11,034.0	266.95	11,212.1
525	542	Upper Floridan aquifer	Nonwater-bearing limestone	1	17	0.35	6.0	*3.00	51.0
542	567	Upper Floridan aquifer	Water-bearing limestone	1	25	81.89	2,047.3	78.36	1,959.0
369	**567**	**Upper Floridan aquifer**	**Unit total**	**12**	**198**	**–**	**60,326.4**	**–**	**60,287.7**

Table 1–2. Hydraulic parameters and hydrogeologic subunits used to simulate electromagnetic flowmeter-survey results, test hole for well 36Q398 open to the Floridan aquifer system, Barbour Pointe community, near Savannah, Georgia, August 21, 2013.—Continued

[Hydrogeologic units are subdivided by depth according to varying flow rates or lithology. Rows for the Upper Floridan aquifer are highlighted in blue. Rows for the Lower Floridan aquifer are highlighted in green. ft, foot; K_h, horizontal hydraulic conductivity; ft/d, foot per day; ft²/d, square foot per day; *, K_h was fixed to this value; –, not applicable]

Depth to top of unit, in feet	Depth to bottom of unit, in feet	Hydrogeologic unit	Lithology and water-bearing properties	Number of subunits related to flow	Thickness (ft)	PEST adjusted Kh for nonwater-bearing zones		Kh for nonwater-bearing zones was fixed at 3 ft/d	
						Horizontal hydraulic conductivity (ft/d)	Transmissivity (ft²/d)	Horizontal hydraulic conductivity (ft/d)	Transmissivity (ft²/d)
157	714	Middle semi-confining unit	Nonwater-bearing limeston	3	147	0.34	49.9	*3.00	441
714	803	Lower Floridan aquifer	Water-bearing limestone	6	89	22.61	2012.5	22.11	1968.0
803	870	Lower Floridan aquifer	Nonwater-bearing limestone	4	67	0.36	23.9	*3.00	201.0
870	896	Lower Floridan aquifer	Water-bearing limestone	2	26	23.08	600.0	23.51	611.3
896	914	Lower Floridan aquifer	Nonwater-bearing limestone	1	18	0.40	7.2	*3.00	54
914	940	Lower Floridan aquifer	Water-bearing limestone	2	26	33.64	874.7	26.13	679.4
940	1023	Lower Floridan aquifer	Nonwater-bearing limestone	5	83	0.36	30.2	*3.00	249.0
1023	1056	Lower Floridan aquifer	Water-bearing limestone	3	27	27.64	912.1	25.23	832.5
714	**1056**	**Lower Floridan aquifer**	**Unit total**	**23**	**342**	–	**4460.5**	–	**4595.1**
1056	1070	Lower confining unit	Nonwater-bearing limestone	1	14	0.11	1.5	0.11	1.5

AnalyzeHOLE was also run to match the EM flowmeter-survey results with all nonwater-bearing zones, including the MSU, set with a constant K_h of 3 ft/d, which is a value similar to slug-test results in previous investigations in nearby sites (Williams, 2010; Gonthier, 2012). This fixed the transmissivity of the MSU to 441 ft^2/d. The upward borehole flow and estimated transmissivity of the UFA and LFA were not sensitive to changing the MSU K_h (fig. 1–2, table 1–1). Using a fixed K_h of 3 ft/d for the MSU, transmissivity values for the UFA and LFA were 60,288 and 4,595 ft^2/d, respectively (table 1–2).

Aquifer-Test Analysis

A 72-hour aquifer test was completed at the Barbour Pointe test site during November 19–22, 2013, pumping LFA well 36Q398 at a rate of 750 gallons per minute (gal/min). Water levels were monitored in that well and four other wells in the area (see "Aquifer Test" section, fig. 6 for well locations; and "Methods of Investigation" section, table 1). Drawdown response was determined by filtering water-level data from five monitored wells for effects of barometric pressure, earth tide, ocean tide, and pumping using procedures developed by Halford (2006) and Halford and others (2012). Test results were simulated using a two-dimensional, axisymmetric, radial, transient, groundwater-flow model using MODFLOW–2005 (Harbaugh, 2005) to estimate the transmissivity of the UFA and LFA, K_v of the MSU, and storage coefficient of the Floridan aquifer system.

Drawdown Estimation

Values of drawdown were estimated using the Water-Level Modeling utility in SeriesSEE (Halford and others, 2012). The water-level modeling approach assumes that measured water-level fluctuations are the sum of multiple water-level responses to environmental and pumping influences (Halford, 2006; Halford and others, 2012). The Water-Level Modeling utility uses input time series, and one or more pump schedules to synthesize a water-level response to environmental and pumping influences for a target well. Herein, the well that is having its water level modeled is referred to as the "target" well. The synthetic water level is matched to the measured water level. Once the synthetic water level is considered matched, environmental influence is separated from pumping influence, and the water-level change caused by pumping effects is taken as the estimate of drawdown. Input time series for environmental influences include barometric pressure, gravity (a surrogate for earth tide), ocean tidal stage, and water levels from background wells. With respect to the aquifer-test site, background wells are close enough to be affected by the same regional influences as wells affected by the aquifer test, yet far enough to not be affected by aquifer-test pumping. Water levels from background wells include the effects of regional water-level stresses typically not found in other input time series. For pumping influence, input time series is one or more step-wise pump schedules for pumped wells that affect the water levels of the target well.

The synthetic water level is a sum of water-level-model (WLM) components plus an offset (from Halford and others, 2012). Each WLM component is a mathematical transformation of an input time series. Two types of WLM components are used to estimate water-level responses and determine drawdown for the Barbour Pointe aquifer test: (1) moving-average and (2) Theis:

$$S_t = \left[C_0 + m\left(t - t_0\right)\right] + \sum_{i=1}^{n} WLMma_{i,t} + \sum_{j=1}^{p} WLMts_{i,t} \ , \qquad (3)$$

where

S_t is the synthetic water level at time, , in feet above datum;
C_0 is an offset that allows mean values of synthetic water levels to match mean values of measured water levels, in feet;
n is the number of moving-average WLM components;
p is the number of Theis WLM components;
$WLMma_{i,t}$ is the value of the i^{th} moving-average WLM component at t, in feet above datum;
$WLMts_{j,t}$ is the value of the j^{th} Theis WLM component at t, in feet above datum;
m is the slope with respect to time used to improve the fit of synthesized water levels to measured water levels, in feet per day; and
t_0 is an arbitrary base time.

Moving-average WLM components were used to assess water-level changes resulting from environmental influences. The core part of a moving-average WLM component is a central-moving average of an input time series. More than one moving-average WLM component can be derived for a single time series with the number of moving averages and the length of each moving-average specified by the user. As an example, the water levels for background well 36Q008 (see "Methods of Investigation" section, table 1) can be used to make a 2-, 3-, 6-, and 12-hour central moving average. Each of these four central-moving averages can then be the core of a moving-average WLM component derived from background water levels in well 36Q008. Accompanying a central moving average is a multiplier and phase shift to make a moving-average WLM component (Halford and others, 2012):

$$WLMma_{i,t} = a_i V_{i,t+\varphi} \ , \qquad (4)$$

where

$WLMma_{i,t}$ is the i^{th} moving-average WLM component at time, t, in feet above datum;
a_i is the amplitude multiplier of the i^{th} moving-average WLM component, in units of the modeled water level (feet above datum) divided by units of the input time series;

$V_{i,t}$ is the value of the central-moving average of the input time series at t, in units of the input time series;

φ_i is the phase-shift of the i^{th} moving-average WLM component, in days; and

$V_{i,t+\varphi_i}$ is the value of the central moving average of the input time series at time $t+\varphi_i$, in units of the input time series.

Input time-series data for the moving-average WLM components come from a variety of sources (fig. 1–3). Barometric-pressure data were provided by the National Weather Service Station at Savannah International Airport (climatological station 097847, labeled “KSAV” on fig. 1). Ocean-tide data were from U.S. Geological Survey (USGS) streamgage 02198980, Savannah River at Fort Pulaski near Tybee Island, Georgia. SeriesSEE calculates a gravity time series using land-surface altitude, latitude, and longitude at the Barbour Pointe test site. UFA wells 37Q016, 36Q008, and 35P110 were used as indicators of background conditions (see “Introduction” section, fig. 1 for well locations). These background wells were 5–10 miles from the Barbour Pointe test site.

Theis WLM components were used to assess water-level changes resulting from pumping influence. A single Theis WLM component uses multiple Theis solutions (Theis, 1935) that are superimposed in time to simulate water-level response to a pump schedule:

$$WLMts_{j,t} = \pm\sum_{k=1}^{o}\frac{\Delta Q_k}{4\pi T}W\left(u\right) = \pm\sum_{k=1}^{o}\frac{\Delta Q_k}{4\pi T}W\left(\frac{r^2 S}{4T\Delta t}\right), \qquad (5)$$

where

$WLMts_{j,t}$ is the j^{th} Theis WLM component at time, t, in feet;

o is the number of changes in discharge during the pump schedule;

ΔQ_k is the change in flow rate at time, t_k, in cubic feet per day;

T is the transmissivity, in feet squared per day;

r is the radius or lateral distance from pumping, in feet;

$W\left(u\right)$ is the exponential integral solution, dimensionless;

S is the storage coefficient, dimensionless; and

Δt is the elapsed time since the flow rate changed $\left(t-t_k\right)$, in days.

The flow-change times come from the pump schedule. The plus or minus (±) denotes that the sign of the WLM component is set either positive or negative. More than one Theis WLM component typically is used to model water-level response of a single pump schedule of a pumped well. This allows for the synthesized water level to approximate response to non-Theis, complex aquifer conditions such as a recharge boundary, pumping in an aquifer that is different from that of the target well, or a hydraulic barrier. Each Theis WLM component has different values of r or sign. The values of r for different Theis WLM components usually bracket the actual lateral distance of the target well from pumping. Transmissivity and storativity values used to match synthetic water levels to measured water levels usually are not meaningful hydraulic properties to any aquifers because Theis assumptions are violated.

Differences between synthetic and measured water levels are minimized using the parameter estimation program PEST (Doherty, 2010a, and 2010b) by varying the amplitude multiplier and phase shift in the moving-average WLM components, and by varying the transmissivity and storage coefficient in the Theis WLM components. The sum of the squares of the differences between synthetic and measured water levels is used as an objective function for PEST to attain a best fit. The root mean square of the differences is reported because its values can be related to values of drawdown.

SeriesSEE provides time series of synthetic water levels, difference between synthetic and measured water levels (synthetic water-level depth below land surface minus measured water-level depth below land surface), and estimated drawdown for the target well. For this report, the sum of all moving-average WLM components represent environmental influence, and the sum of all Theis WLM components represent pumping influence on water levels of the target well; therefore, equation 3 can be expressed as:

$$S_t = O_t + E_t + P_t, \qquad (6)$$

where

O_t is $\left(C_0 + m\left[t-t_0\right]\right)$ the offset, in feet above datum;

E_t is $\sum_{i=1}^{n} WLMma_{i,t}$ the water-level fluctuation caused by environmental influence at time, t, in feet (represents the sum of all moving-average WLM components);

P_t is $\sum_{j=1}^{p} WLMts_{i,t}$ the water-level change caused by pumping influence at t, in feet (represents the sum of all Theis WLM components).

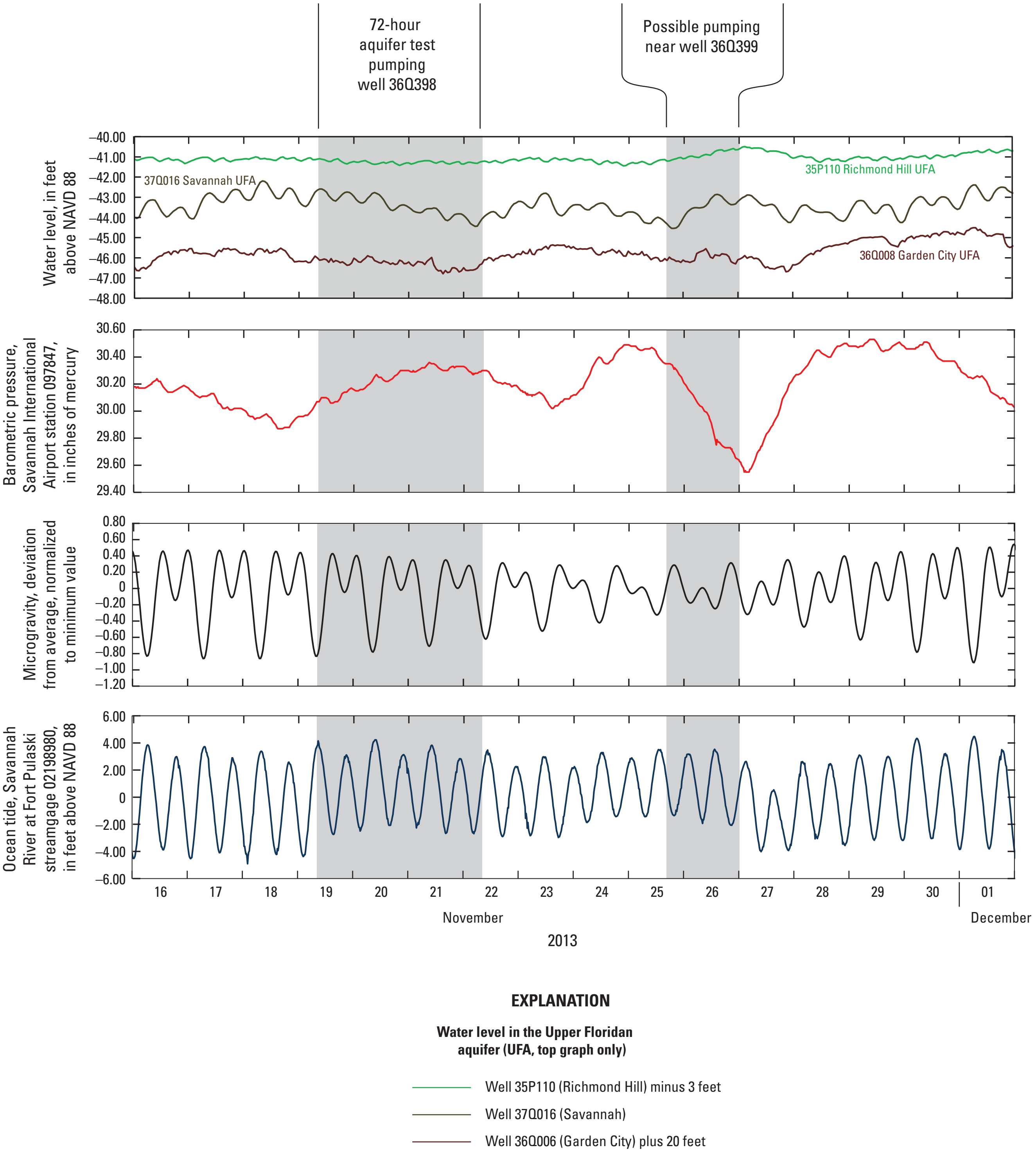

Figure 1–3. Water-level fluctuations in background wells and fluctuations in barometric pressure, microgravity, and ocean tides used in the 72-hour aquifer test at Barbour Pointe test site, near Savannah, Georgia, November 16–December 1, 2013.

The drawdown output by SeriesSEE is the measured water level minus the water-level fluctuation caused by environmental influence:

$$DD_t = M_t - \sum_{i=1}^{n} WLMma_{i,t} = M_t - E_t \ , \qquad (7)$$

where

DD_t is the drawdown at time, t, in feet;
M_t is the measured water-level fluctuation at t, in feet; and
E_t is the water-level fluctuation caused by environmental influence at t, in feet (represents the sum of all moving-average WLM components).

The difference $S_t - M_t$ provides information on the reliability of the estimate of drawdown. The range of values of $S_t - M_t$ should be much smaller than the maximum drawdown as shown by either P_t or DD_t. Values of P_t and DD_t should be similar.

The root mean difference between synthetic and measured water levels from early November 16 to late December 1, 2013, was used as a measure of uncertainty in drawdown estimation listed in table 2 of the “Estimation of Hydraulic Properties and Drawdown Response” section. Graphs of synthetic and measured water levels and estimated drawdown for LFA wells 36Q398 and 36Q330; and UFA wells 36Q399, 36Q331, and 36Q020 are shown in figures 1–4—1–8.

Estimation of drawdown, using DD_t, from SeriesSEE caused negligible modification to the measured water-level decline of well 36Q398 when it was pumped because the magnitude of the drawdown signal (greater than 35 ft) obscured any signals corresponding to nonpumping influences. Water-level fluctuations caused by environmental influences most likely ranged from a few hundredths of a foot to about 0.6 ft. Pretest data indicated a minor (up to 0.2 ft) cyclical diurnal fluctuation in water level, which is characteristic of earth tides, and more substantial (up to 0.6 ft) fluctuations in water levels, which is a characteristic of barometric-pressure fluctuation.

Measured water-level decline (caused by the aquifer test and other influences) at the end of the 72-hour aquifer test in pumped well 36Q398 was 35.5 ft (fig. 1–4). Filtering out environmental influences also indicated an estimated drawdown of 35.5 ft in response to the aquifer test. Drawdown at the pumped well as a function of log (time) was nonlinear as indicated by a continuously decreasing log cycle of drawdown with time (fig. 1–9). The nonlinear nature of drawdown on the semilog plot precluded viable use of an analytical method for estimating the transmissivity of the LFA.

Drawdown estimation for pumped well 36Q398 had the largest amount of uncertainty (±0.18 ft) compared to the other four monitor wells. The large uncertainty was the result of the synthetic water level being unable to change as quickly as the measured water level, which changed more than 25 ft within less than a minute at the beginning and end of the pumping period of the aquifer test. This led to large differences between synthetic and measured water levels, which contributed to uncertainty. Despite uncertainty being the largest of all five monitored wells, the uncertainty was only 0.05 percent of the maximum drawdown, which was the smallest percentage of all five wells.

Measured water-level decline in UFA well 36Q399, located 36 ft to the northeast of the pumped well, was obscured by daily fluctuations and long-term (a month or greater) water-level trends. Water-level decline in well 36Q399 (caused by the aquifer test and other influences) at the end of the 72-hour aquifer test was 0.8 ft (fig. 1–5*A*). Filtering out environmental influences indicates an estimated drawdown of 0.7 ft (fig. 1–5*B*). The uncertainty of ±0.02 ft was slightly less than 3 percent of the maximum drawdown.

Measured water-level decline in LFA well 36Q330, located at Berwick Plantation community 6,017 ft west of the pumped well, was minimally obscured by daily fluctuations or long-term water-level trends. Water-level decline in well 36Q330 (caused by the aquifer test and other influences) at the end of the 72-hour aquifer test was 1.6 ft (fig. 1–6*A*). Filtering out environmental influences also indicated an estimated drawdown of 1.6 ft in response to the aquifer test (fig. 1–6*B*). The uncertainty of ±0.02 ft was slightly more than 1 percent of the maximum drawdown.

Measured water-level decline in UFA well 36Q331, also located at Berwick Plantation community adjacent to well 36Q330, was obscured by daily fluctuations or long-term (a month or greater) water-level trends. Water-level decline in well 36Q331 (caused by the aquifer test and other influences) at the end of the 72-hour aquifer test was 0.3 ft (fig. 1–7*A*). Filtering out environmental influences indicated an estimated drawdown of 0.6 ft in response to the aquifer test (fig. 1–7*B*). The uncertainty of ±0.06 ft for the estimation in drawdown for well 36Q331 was about 10 percent of the maximum drawdown.

Several days after the end of the 72-hour aquifer test, water levels in well 36Q331 declined a second time potentially in response to nearby pumping. This decline can be seen on figure 1–7*A* around November 26, 2013, when water levels in well 36Q331 declined at the same time that water levels in the other four monitored wells started to rise, chiefly, in response to a dip in barometric pressure.

Measured water-level decline in UFA well 36Q020, located 6,863 ft to the south of pumped UFA well 36Q398, was obscured by daily fluctuations or long-term (a month or greater) water-level trends. Water-level decline in UFA well 36Q020 (caused by the aquifer test and other influences) at the end of the 72-hour aquifer test was 1.4 ft (fig. 1–8*A*). Filtering out environmental influences indicated a corrected drawdown of 0.4 ft in response to the aquifer test (fig. 1–8*B*). The uncertainty of ±0.06 ft was more than 15 percent of the maximum drawdown.

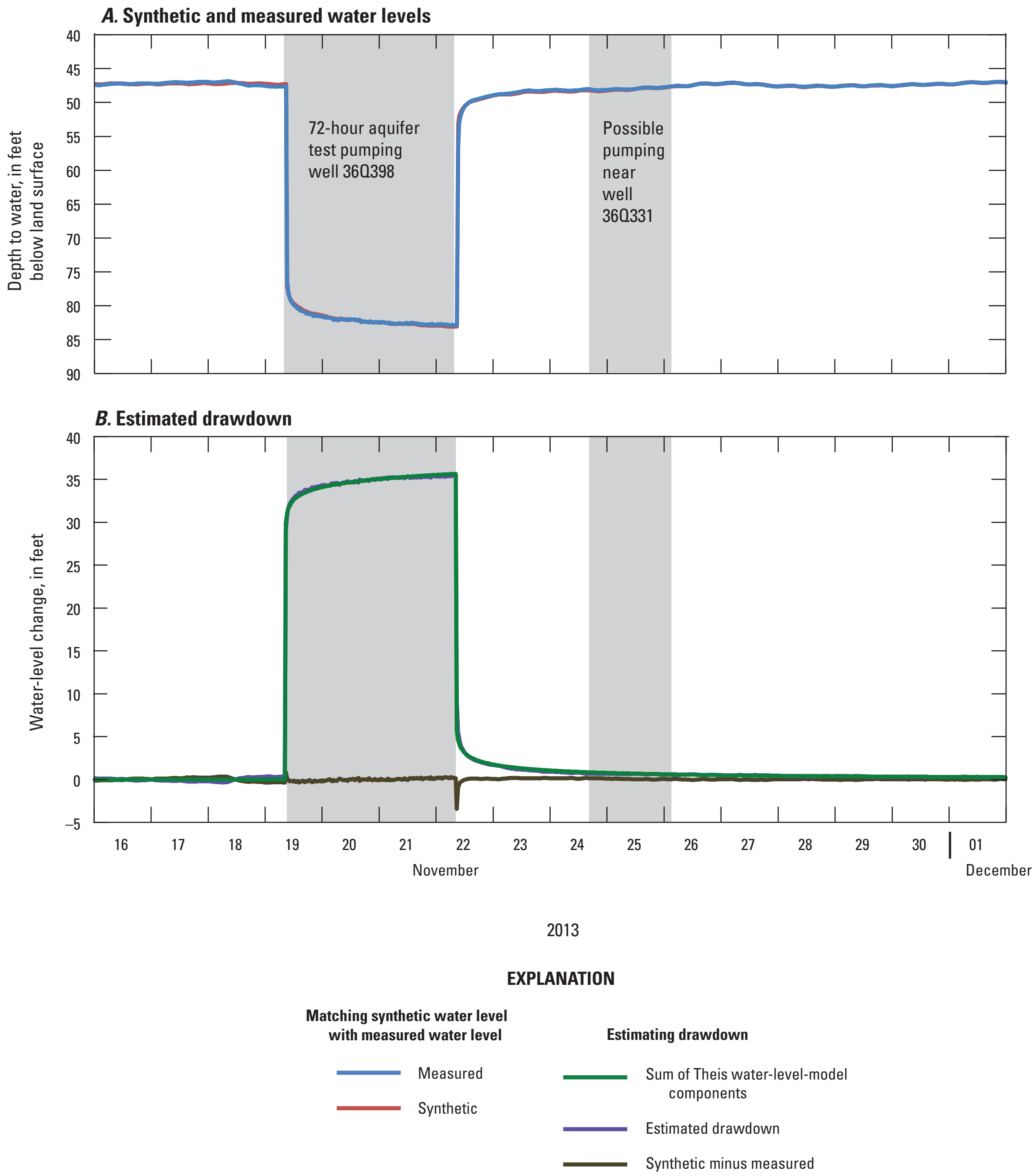

Figure 1–4. Fit of synthetic water levels to measured water levels and estimated drawdown for Lower Floridan aquifer pumped well 36Q398, Barbour Pointe community, near Savannah, Georgia, November 16–December 1, 2013. *A*, synthetic and measured water levels; and, *B*, sum of Theis water-level-model components, estimated drawdown, and synthetic minus measured water level.

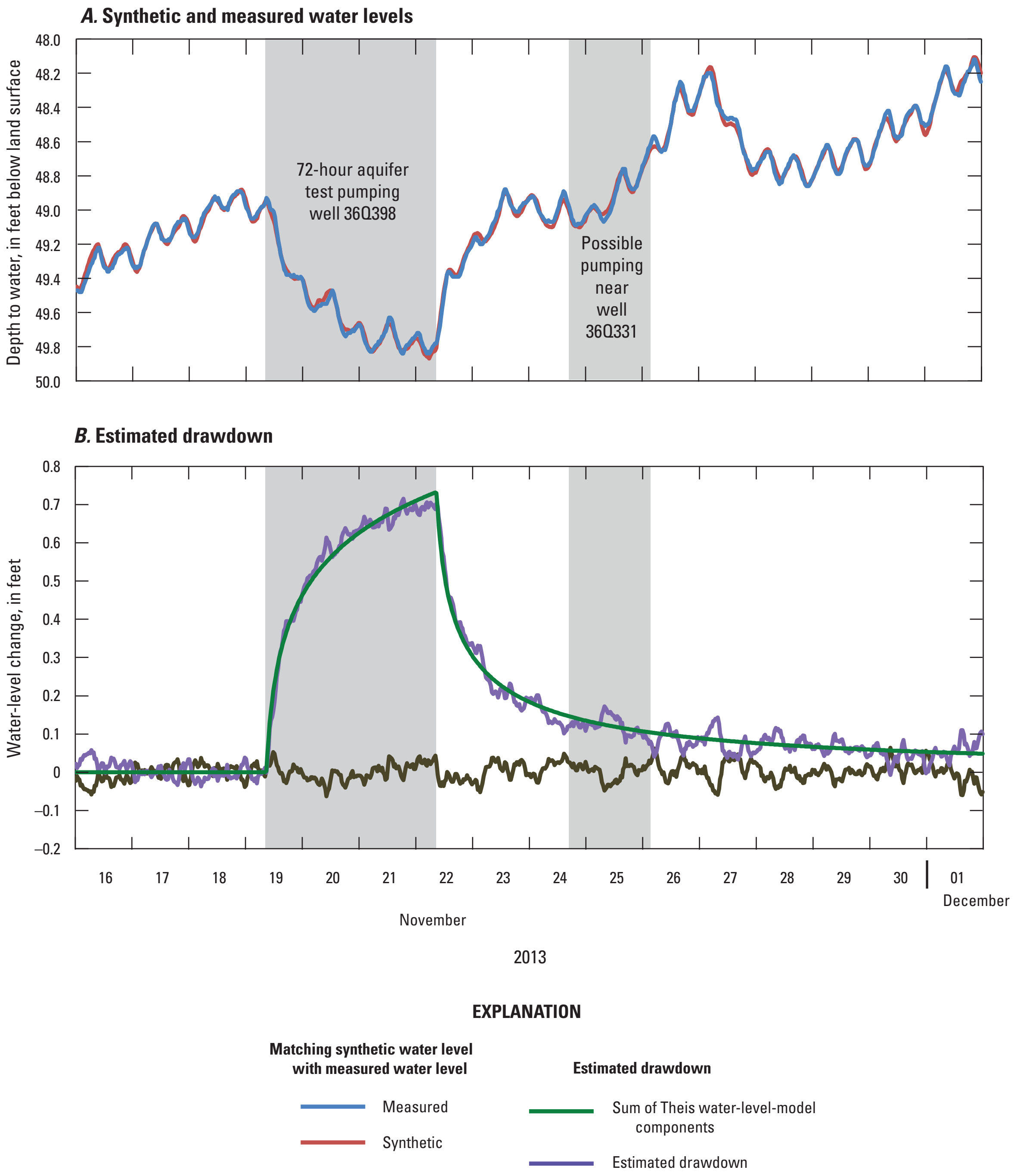

Figure 1–5. Fit of synthetic water levels to measured water levels and estimated drawdown for Upper Floridan aquifer well 36Q399, Barbour Pointe community, near Savannah, Georgia, November 16–December 1, 2013. *A*, synthetic and measured water levels; and, *B*, sum of Theis water-level-model components, estimated drawdown, and synthetic minus measured water level.

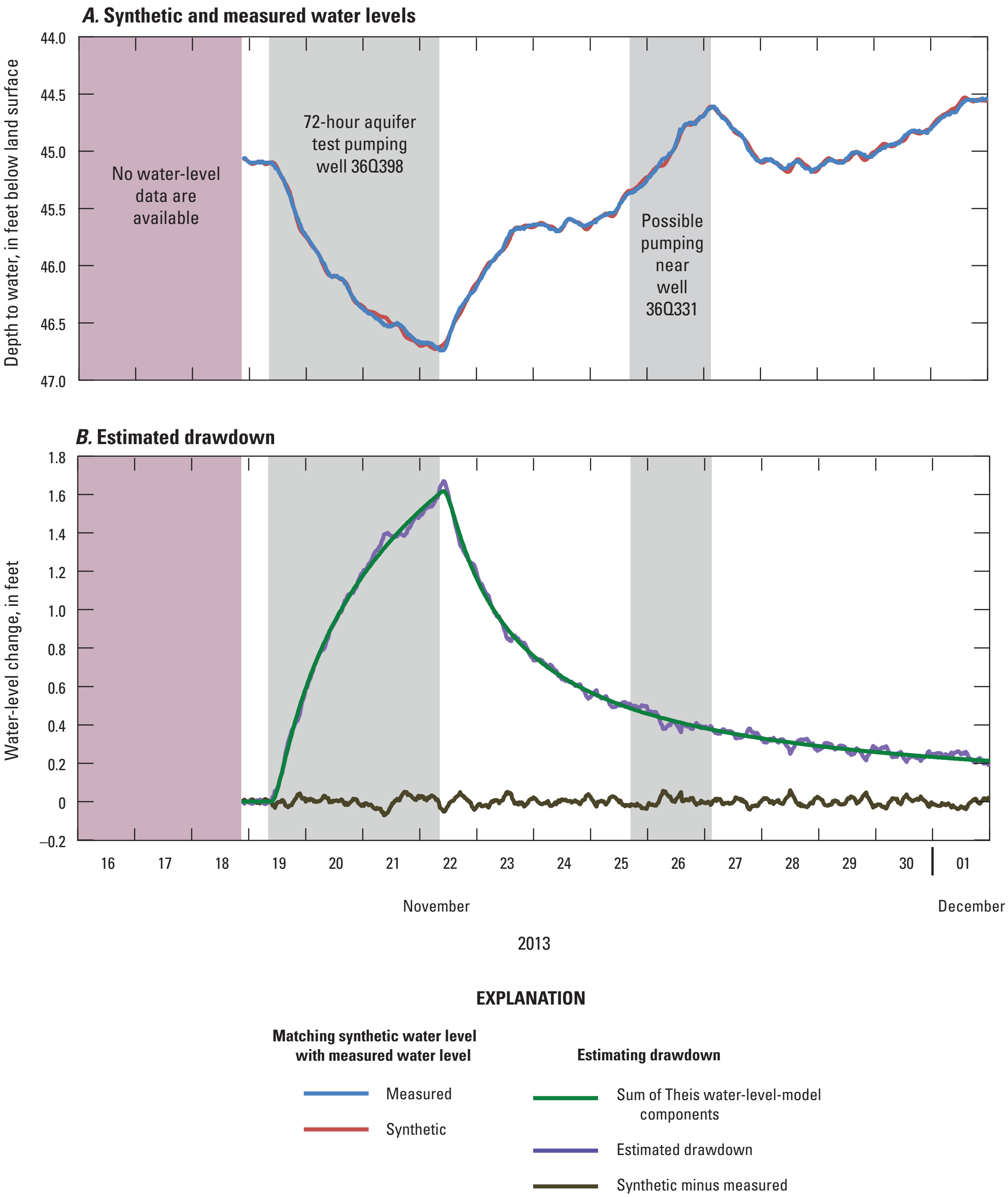

Figure 1–6. Fit of synthetic water levels to measured water levels and estimated drawdown for Lower Floridan aquifer well 36Q330, Berwick Plantation community, near Savannah, Georgia, November 18–December 1, 2013. *A*, synthetic and measured water levels; and, *B*, sum of Theis water-level-model components, estimated drawdown, and synthetic minus measured water level.

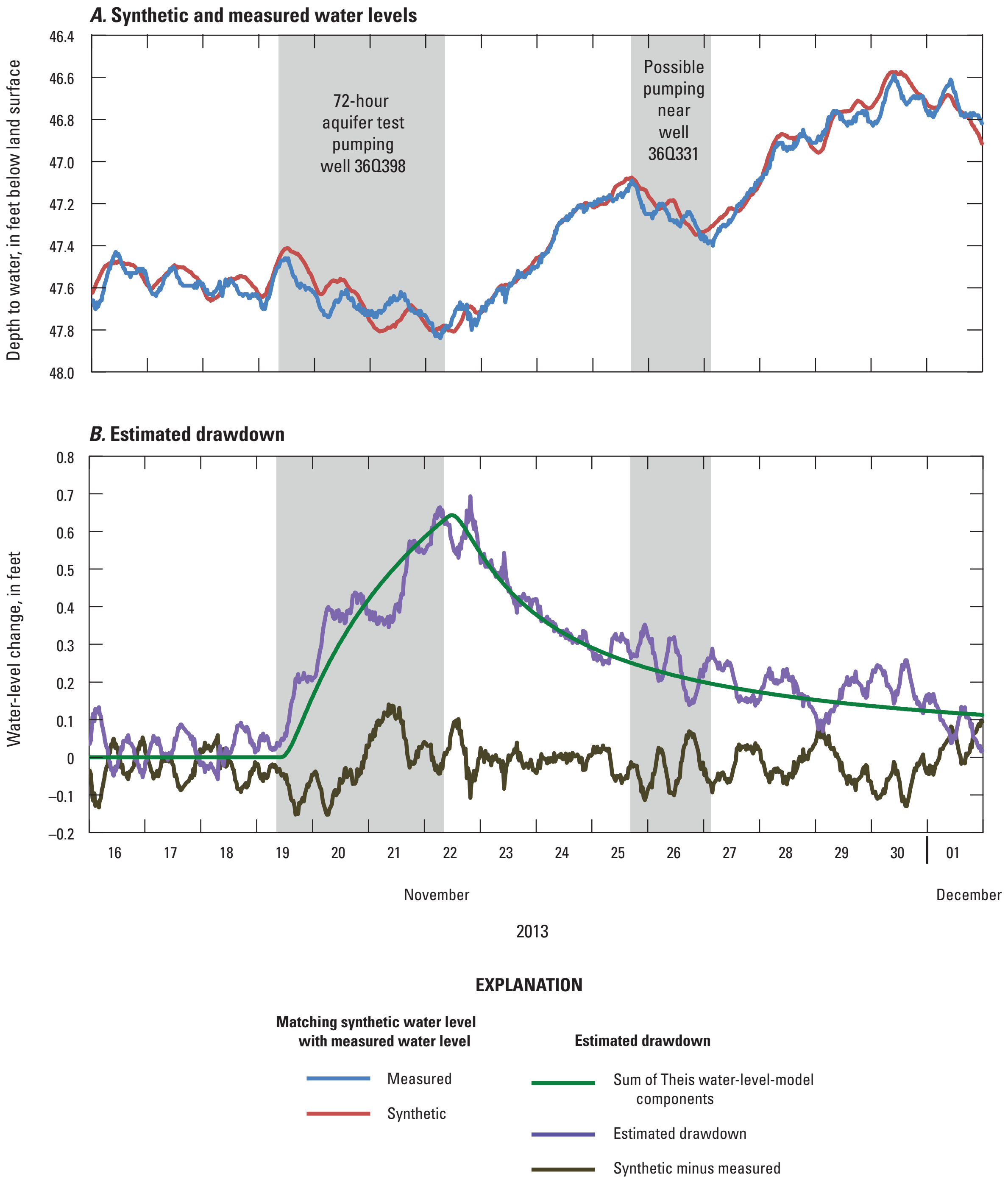

Figure 1–7. Fit of synthetic water levels to measured water levels and estimated drawdown for Upper Floridan aquifer well 36Q331, Berwick Plantation community, near Savannah, Georgia, November 16–December 1, 2013. *A*, synthetic and measured water levels; and, *B*, sum of Theis water-level-model components, estimated drawdown, and synthetic minus measured water level.

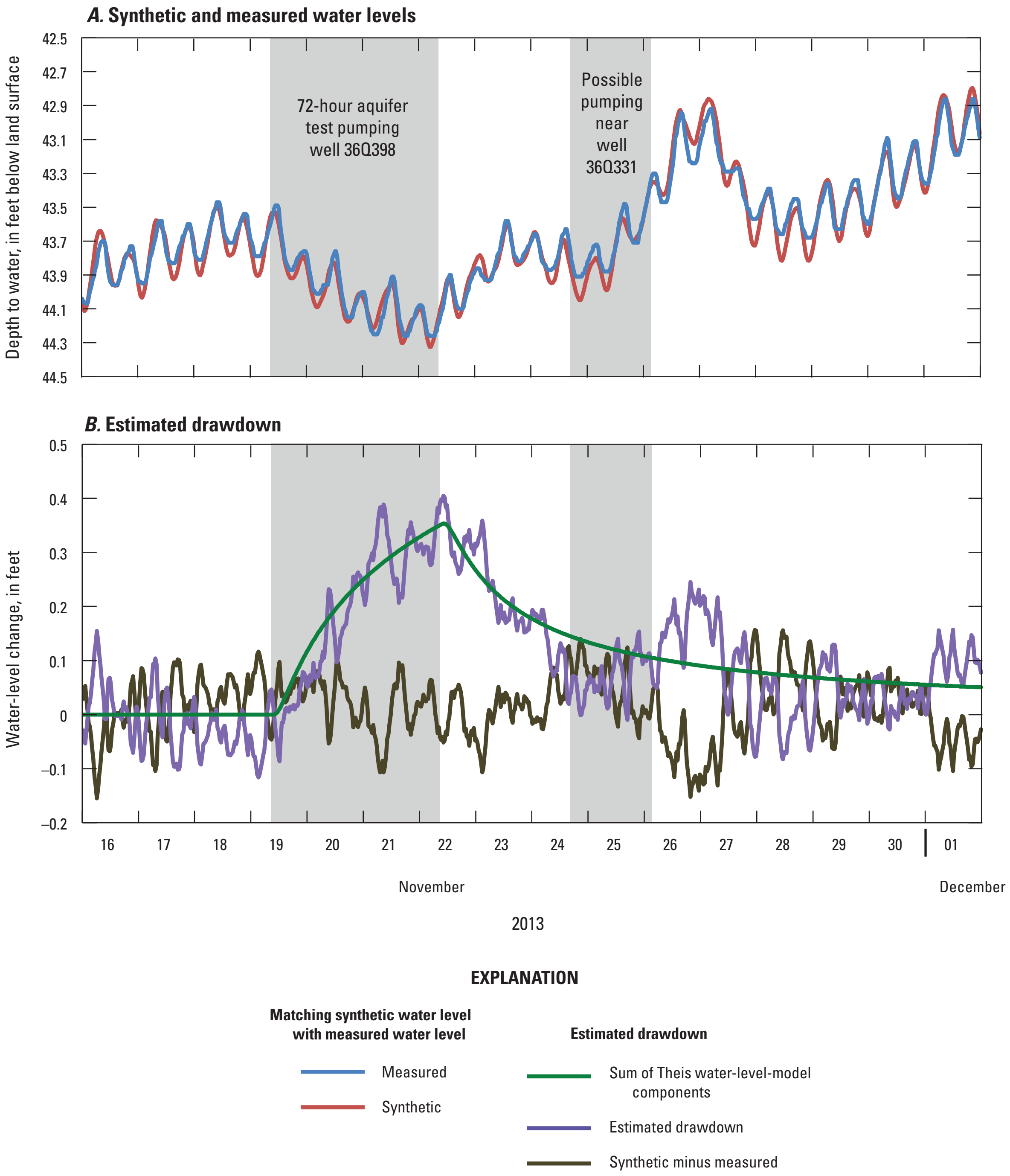

Figure 1–8. Fit of synthetic water levels to measured water levels and estimated drawdown for Upper Floridan aquifer well 36Q020, Morrison Plantation, near Savannah, Georgia, November 16–December 1, 2013. *A*, synthetic and measured water levels; and, *B*, sum of Theis water-level-model components, estimated drawdown, and synthetic minus measured water level.

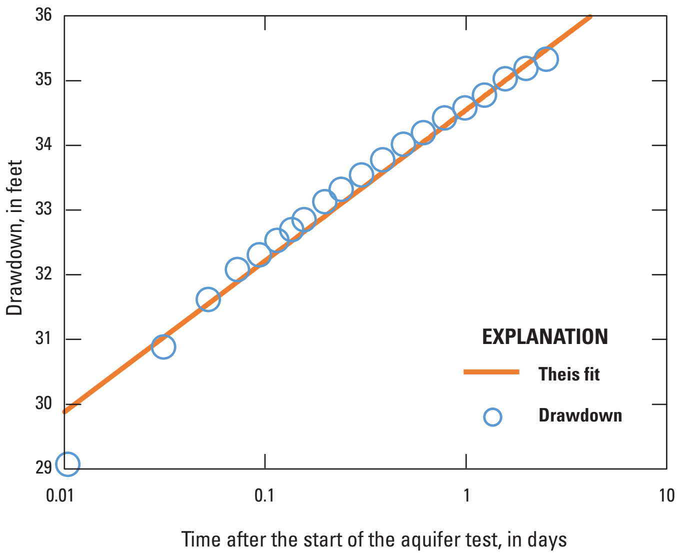

Figure 1–9. Drawdown in pumped Lower Floridan aquifer well 36Q398, as a function of log(time), Barbour Pointe community, near Savannah, Georgia, November 19–29, 2013.

Model Simulation of Aquifer Test

To account for the nonlinear nature of drawdown in pumped LFA well 36Q398 on the semilog plot (fig. 1–9), aquifer-test data were evaluated with a two-dimensional, axisymmetric, radial, transient, groundwater-flow model using MODFLOW-2005 (Harbaugh, 2005). This model was similar to the AnalyzeHOLE model used to simulate the EM flowmeter-survey data. The model incorporated pumping from LFA well 36Q398, and observed drawdown in that well and four observation wells [see “Introduction” section, fig. 1; and “Aquifer Test” section, fig. 6; 36Q399 (UFA), 36Q330 (LFA), 36Q331 (UFA), and 36Q020 (UFA)]. K_h, specific storage, and K_v/K_h were assumed to be homogeneous within subunits of the aquifers and confining unit; herein, these units are referred to as minor hydrogeologic units.

The model of the 72-hour aquifer test is made up of 57 columns, 115 rows, and 1 traditional model layer. The columns represented lateral distance away from the pumped LFA well 36Q398; the rows represented horizontal hydrogeologic units (fig. 1–10). The model radially extends out 200,000 ft from LFA well 36Q398. The left-most column represents the wellbore radius (0.83 ft). Two columns just to the right of the wellbore column represent the well casing (0.05 ft) and annular space (0.2 ft), respectively. The fourth column from the left represents the aquifer adjacent to the annular space and is 0.134 ft wide. Each column to the right increases in width by a factor of 1.27 to a maximum width of 42,520 ft. Each row height ranges from 5 to 50 ft with height increasing with distance from hydrogeologic subunit boundaries. The sides and bottom of the model are no-flow boundaries. The top row of the model is a no-flow boundary representing the water table.

The model was subdivided by row to characterize 5 major hydrogeologic units that are subdivided into 21 hydrogeologic subunits on the basis of lithology (sand and clay) and differences in productivity of limestone units based on results of the EM flowmeter survey (nonwater-bearing limestone and water-bearing limestone). Major hydrogeologic units are (fig. 1–10):

- unit 1, represents the surficial aquifer system, Brunswick aquifer system, and the nonwater-bearing limestone (NWBL) above the UFA;
- unit 2, represents the UFA;
- unit 3, represents the MSU;
- unit 4, represents the LFA; and
- unit 5, represents the lower confining unit underlying the Floridan aquifer system.

The distal edge of the model was considered beyond the radius of influence. Maximum drawdown at the distal edge of the model was less than 0.00001 ft. Drawdown at the base and top of the model near the pumped well was about 0.05 and 0.06 ft, respectively.

The model was run with two stress periods that represent (1) drawdown response during the aquifer test and (2) recovery of groundwater levels after the aquifer test concluded. The aquifer-test stress period was represented by 54 time steps totaling 3 days. Time steps ranged from 2.7 seconds to 12 hours and 2 seconds, and each succeeding time step increased from the previous time step by a multiplier of 1.2. The recovery stress period is represented by 61 time steps totaling 10 days. Time steps ranged from 2.6 seconds to 40 hours and 2 seconds, and each succeeding time step increased from the previous time step by a multiplier of 1.2.

The model simulated the drawdown in response to the 72-hour aquifer test. No other influences were simulated so that initial heads and flow within the model were zero. Rather than pumping from the model, water was injected at the same rate that water was withdrawn at the pumped well (750 gal/min); therefore, simulated increase in water level may be interpreted inversely as drawdown in the pumped well. The water was injected into a cell that represents a part of the wellbore (column 1, row 13) using the MODFLOW WEL package (Harbaugh, 2005). High values for hydraulic conductivity (1,260,000,000 ft/d) and specific storage (0.0002 ft^{-1}) are assigned to the cells representing the wellbore.

Drawdown observations for monitored wells were culled so that only about 46 data points (20 observations during the aquifer test; 26 observations during recovery; tables 1–3—1–7) per well were used to calibrate the model, and these observation times are spaced fairly evenly on a semilog plot. Time between each succeeding interval between drawdown observations increased from the previous interval by a factor of roughly 1.26.

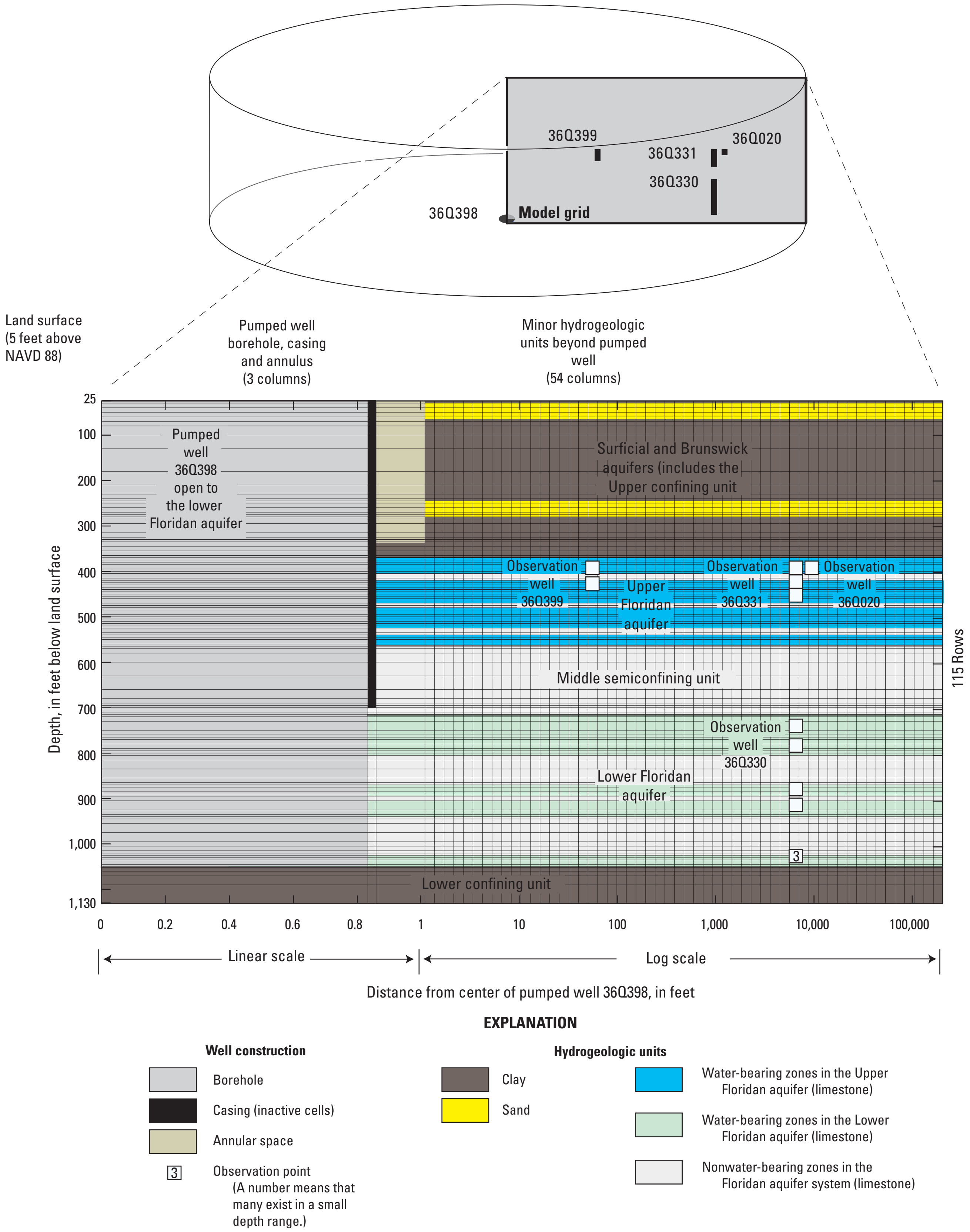

Figure 1–10. Axisymmetric model for 72-hour aquifer test at Lower Floridan aquifer well 36Q398, Barbour Pointe community, near Savannah, Georgia, November 19–22, 2013.

Table 1-3. Estimated drawdown at select times for Lower Floridan pumped well 36Q398, Barbour Point community, near Savannah, Georgia, November 19–December 2, 2013. Drawdown values were used to calibrate axisymmetric model.

[Time, time after the start of aquifer test pumping, November 19, 2013 at 8:30 AM; Time', time after the end of aquifer-test pumping, November 22, 2013 at 8:30 AM; –, no data]

Time (days)	Time′ (days)	Drawdown (feet)
0.010417	–	29.92
0.031250	–	31.03
0.052083	–	31.55
0.072917	–	31.89
0.093750	–	32.15
0.114583	–	32.35
0.135417	–	32.52
0.156250	–	32.66
0.197917	–	32.90
0.239583	–	33.10
0.302083	–	33.33
0.385417	–	33.58
0.489583	–	33.82
0.614583	–	34.05
0.781250	–	34.29
0.989583	–	34.53
1.239583	–	34.76
1.572917	–	35.00
1.989583	–	35.24
2.510417	–	35.48
3.010417	0.010417	5.74
3.031250	0.031250	4.63
3.052083	0.052083	4.12
3.072917	0.072917	3.79
3.093750	0.093750	3.54
3.114583	0.114583	3.34
3.135417	0.135417	3.18
3.156250	0.156250	3.04
3.197917	0.197917	2.82
3.239583	0.239583	2.64
3.302083	0.302083	2.42
3.385417	0.385417	2.20
3.489583	0.489583	1.99
3.614583	0.614583	1.79

Table 1-3. Estimated drawdown at select times for Lower Floridan pumped well 36Q398, Barbour Point community, near Savannah, Georgia, November 19–December 2, 2013. Drawdown values were used to calibrate axisymmetric model.—Continued

[Time, time after the start of aquifer test pumping, November 19, 2013 at 8:30 AM; Time’, time after the end of aquifer-test pumping, November 22, 2013 at 8:30 AM; –, no data]

Time (days)	Time′ (days)	Drawdown (feet)
3.781250	0.781250	1.60
3.989583	0.989583	1.41
4.239583	1.239583	1.25
4.572917	1.572917	1.08
4.989583	1.989583	0.93
5.510417	2.510417	0.80
6.156250	3.156250	0.68
6.968750	3.968750	0.57
8.010417	5.010417	0.48
9.302083	6.302083	0.39
10.927083	7.927083	0.33
12.989583	9.989583	0.27

Table 1-4. Estimated drawdown at select times for Upper Floridan well 36Q399, Barbour Point community, near Savannah, Georgia, November 19–December 2, 2013. Drawdown values were used to calibrate axisymmetric model.

[Time, time after the start of aquifer test pumping, November 19, 2013 at 8:30 AM; Time’, time after the end of aquifer-test pumping, November 22, 2013 at 8:30 AM; –, no data]

Time (days)	Time′ (days)	Drawdown (feet)
0.010417	–	0.00
0.031250	–	0.05
0.052083	–	0.09
0.072917	–	0.13
0.093750	–	0.16
0.114583	–	0.19
0.135417	–	0.21
0.156250	–	0.23
0.197917	–	0.27
0.239583	–	0.30
0.302083	–	0.34
0.385417	–	0.38
0.489583	–	0.42
0.614583	–	0.45
0.781250	–	0.50
0.989583	–	0.54
1.239583	–	0.58

Table 1-4. Estimated drawdown at select times for Upper Floridan well 36Q399, Barbour Point community, near Savannah, Georgia, November 19–December 2, 2013. Drawdown values were used to calibrate axisymmetric model.—Continued

[Time, time after the start of aquifer test pumping, November 19, 2013 at 8:30 AM; Time’, time after the end of aquifer-test pumping, November 22, 2013 at 8:30 AM; –, no data]

Time (days)	Time′ (days)	Drawdown (feet)
1.572917	–	0.62
1.989583	–	0.66
2.510417	–	0.70
3.010417	0.010417	0.73
3.031250	0.031250	0.69
3.052083	0.052083	0.64
3.072917	0.072917	0.61
3.093750	0.093750	0.58
3.114583	0.114583	0.55
3.135417	0.135417	0.53
3.156250	0.156250	0.51
3.197917	0.197917	0.48
3.239583	0.239583	0.45
3.302083	0.302083	0.41
3.385417	0.385417	0.38
3.489583	0.489583	0.34
3.614583	0.614583	0.31
3.781250	0.781250	0.28
3.989583	0.989583	0.25
4.239583	1.239583	0.22
4.572917	1.572917	0.19
4.989583	1.989583	0.16
5.510417	2.510417	0.14
6.156250	3.156250	0.12
6.968750	3.968750	0.10
8.010417	5.010417	0.08
9.302083	6.302083	0.07
10.927083	7.927083	0.06
12.968750	9.968750	0.05

Table 1-5. Estimated drawdown at select times for Lower Floridan well 36Q330, Berwick Plantation community, near Savannah, Georgia, November 19–December 4, 2013. Drawdown values were used to calibrate axisymmetric model.

[Time, time after the start of aquifer test pumping, November 19, 2013 at 8:30 AM; Time’, time after the end of aquifer-test pumping, November 22, 2013 at 8:30 AM; –, no data]

Time (days)	Time′ (days)	Drawdown (feet)
0.020833	–	0.00
0.041667	–	0.00
0.062500	–	0.00
0.083333	–	0.01
0.104167	–	0.02
0.125000	–	0.04
0.145833	–	0.06
0.166667	–	0.08
0.187500	–	0.11
0.208333	–	0.13
0.229167	–	0.16
0.250000	–	0.18
0.312500	–	0.25
0.395833	–	0.35
0.500000	–	0.46
0.625000	–	0.57
0.791667	–	0.71
0.979167	–	0.83
1.250000	–	0.99
1.583333	–	1.15
1.979167	–	1.31
2.500000	–	1.47
3.020833	0.020833	1.61
3.041667	0.041667	1.62
3.062500	0.062500	1.62
3.083333	0.083333	1.62
3.104167	0.104167	1.61
3.125000	0.125000	1.60
3.145833	0.145833	1.58
3.166667	0.166667	1.56
3.187500	0.187500	1.54
3.208333	0.208333	1.53
3.229167	0.229167	1.51
3.250000	0.250000	1.48
3.312500	0.312500	1.42
3.395833	0.395833	1.35

Table 1-5. Estimated drawdown at select times for Lower Floridan well 36Q330, Berwick Plantation community, near Savannah, Georgia, November 19–December 4, 2013. Drawdown values were used to calibrate axisymmetric model.—Continued

[Time, time after the start of aquifer test pumping, November 19, 2013 at 8:30 AM; Time’, time after the end of aquifer-test pumping, November 22, 2013 at 8:30 AM; –, no data]

Time (days)	Time′ (days)	Drawdown (feet)
3.500000	0.500000	1.26
3.625000	0.625000	1.18
3.791667	0.791667	1.08
3.979167	0.979167	0.98
4.250000	1.250000	0.88
4.583333	1.583333	0.77
4.979167	1.979167	0.68
5.500000	2.500000	0.59
6.145833	3.145833	0.51
6.979167	3.979167	0.43
8.000000	5.000000	0.36
9.291667	6.291667	0.30
10.937500	7.937500	0.25
12.979167	9.979167	0.21

Table 1-6. Estimated drawdown at select times for Upper Floridan well 36Q331, Berwick Plantation community, near Savannah, Georgia, November 19–December 4, 2013. Drawdown values were used to calibrate axisymmetric model.

[Time, time after the start of aquifer test pumping, November 19, 2013 at 8:30 AM; Time’, time after the end of aquifer-test pumping, November 22, 2013 at 8:30 AM; –, no data]

Time (days)	Time′ (days)	Drawdown (feet)
0.030359	–	0.00
0.051192	–	0.00
0.072025	–	0.00
0.092859	–	0.00
0.113692	–	0.00
0.134525	–	0.00
0.155359	–	0.01
0.197025	–	0.01
0.238692	–	0.02
0.301192	–	0.04
0.384525	–	0.07
0.488692	–	0.11
0.613692	–	0.15
0.780359	–	0.20
0.988692	–	0.26

Table 1-6. Estimated drawdown at select times for Upper Floridan well 36Q331, Berwick Plantation community, near Savannah, Georgia, November 19–December 4, 2013. Drawdown values were used to calibrate axisymmetric model.—Continued

[Time, time after the start of aquifer test pumping, November 19, 2013 at 8:30 AM; Time’, time after the end of aquifer-test pumping, November 22, 2013 at 8:30 AM; –, no data]

Time (days)	Time’ (days)	Drawdown (feet)
1.238692	–	0.33
1.572025	–	0.40
1.988692	–	0.48
2.509525	–	0.57
3.009525	0.009525	0.63
3.030359	0.030359	0.63
3.051192	0.051192	0.64
3.072025	0.072025	0.64
3.092859	0.092859	0.64
3.113692	0.113692	0.64
3.134525	0.134525	0.64
3.155359	0.155359	0.64
3.197025	0.197025	0.64
3.238692	0.238692	0.64
3.301192	0.301192	0.62
3.384525	0.384525	0.61
3.488692	0.488692	0.58
3.613692	0.613692	0.55
3.780359	0.780359	0.51
3.988692	0.988692	0.47
4.238692	1.238692	0.43
4.572025	1.572025	0.39
4.988692	1.988692	0.34
5.509525	2.509525	0.30
6.155359	3.155359	0.26
6.967859	3.967859	0.22
8.009525	5.009525	0.19
9.301192	6.301192	0.16
10.926192	7.926192	0.13
12.988692	9.988692	0.11

Table 1-7. Estimated drawdown at select times for Upper Floridan well 36Q020, Morrison Plantation, near Savannah, Georgia, November 19–December 4, 2013. Drawdown values were used to calibrate axisymmetric model.

[Time, time after the start of aquifer test pumping, November 19, 2013 at 8:30 AM; Time’, time after the end of aquifer-test pumping, November 22, 2013 at 8:30 AM]

Time (days)	Time’ (days)	Drawdown (feet)
0.010417	–	0.00
0.031250	–	0.00
0.052083	–	0.00
0.072917	–	0.00
0.093750	–	0.00
0.114583	–	0.00
0.135417	–	0.01
0.156250	–	0.01
0.197917	–	0.02
0.239583	–	0.03
0.302083	–	0.04
0.385417	–	0.06
0.489583	–	0.09
0.614583	–	0.11
0.781250	–	0.14
0.989583	–	0.17
1.239583	–	0.21
1.572917	–	0.24
1.989583	–	0.28
2.510417	–	0.32
3.010417	0.010417	0.35
3.031250	0.031250	0.35
3.052083	0.052083	0.35
3.072917	0.072917	0.35
3.093750	0.093750	0.35
3.114583	0.114583	0.35
3.135417	0.135417	0.35
3.156250	0.156250	0.35
3.197917	0.197917	0.34
3.239583	0.239583	0.33
3.302083	0.302083	0.32
3.385417	0.385417	0.31
3.489583	0.489583	0.29
3.614583	0.614583	0.27
3.781250	0.781250	0.25
3.989583	0.989583	0.23

Table 1-7. Estimated drawdown at select times for Upper Floridan well 36Q020, Morrison Plantation, near Savannah, Georgia, November 19–December 4, 2013. Drawdown values were used to calibrate axisymmetric model.—Continued

[Time, time after the start of aquifer test pumping, November 19, 2013 at 8:30 AM; Time’, time after the end of aquifer-test pumping, November 22, 2013 at 8:30 AM]

Time (days)	Time′ (days)	Drawdown (feet)
4.239583	1.239583	0.20
4.572917	1.572917	0.18
4.989583	1.989583	0.16
5.510417	2.510417	0.14
6.156250	3.156250	0.12
6.968750	3.968750	0.10
8.010417	5.010417	0.09
9.302083	6.302083	0.07
10.927083	7.927083	0.06
12.968750	9.989583	0.05

The model was calibrated by comparing simulated and observed drawdown on semilog plots, and by minimizing the root mean square of the differences (RMS) between simulated and observed drawdown values. Values of RMS for the wells were normalized by dividing the RMS value by the maximum drawdown value for each well (as listed in table 2). The lower is the value of RMS/maximum drawdown (Max*DD*), the better is the fit between simulated and observed drawdown through both the aquifer-test pumping and recovery periods. Unlike the EM flowmeter-survey model (AnalyzeHOLE), specific storage and K_v/K_h were modified to match the simulated drawdown to observed drawdown. Also unlike the AnalyzeHOLE model, the aquifer-test model was manually calibrated.

Drawdown used for model calibration in the observation wells (figs. 1–5–1–8) was based on the sums of the Theis WLM components as described above (P_t ; Halford and others, 2012). Values of DD_t in the UFA wells 36Q399, 36Q331, and 36Q020 (figs. 1–5, 1–7, and 1–8) were erratic enough to make it difficult to objectively select representative points that could be used for model calibration. Therefore P_t values were used as a smoother alternative to DD_t values especially for the UFA wells in calculating RMS values.

The limestone of the Floridan aquifer system is classified as either nonwater-bearing or water-bearing based on the EM flowmeter survey from the Barbour Pointe test site. Nonwater-bearing zones are defined as zones that do not have a detectable change in flow with depth using this specific borehole geophysical tool. It is conceptualized that nonwater-bearing zones do yield a small amount of water and also have K_h values greater than 0.

The model represents the boundaries between two zone types by moving each boundary from the EM flowmeter survey to the nearest row boundary. An example is the top of the uppermost water-bearing zone in the UFA, which is 369 ft below land surface. The top of this zone is set to the nearest row boundary, which is at 370 ft below land surface in the model. The K_h of rows that represent the MSU and other nonwater-bearing zones within the UFA and the LFA were set at a fixed value of 3 ft/d based on slug-test results of the MSU at Pooler, Ga. (Gonthier, 2012). Above the Floridan aquifer system, K_h of clay layers was set at 0.2 ft/d. Sand layers in the surficial and Brunswick aquifers were assigned a K_h of 10 ft/d.

For different model simulations, transmissivity of the UFA and LFA is changed by changing the K_h of rows that represent water-bearing zones while keeping the K_h of the nonwater-bearing zones fixed at 3 ft/d:

$$T_{aq} = K_{n0} \sum_{i=1} b_{ni} + m \sum_{i=1} Y_{wi} b_{wi} \ , \qquad (8)$$

where

T_{aq} is the target transmissivity of the aquifer (UFA or LFA), in feet squared per day (ft^2/d);

K_{n0} is the fixed horizontal hydraulic conductivity (K_h of 3 ft/d) for the rows that represent the nonwater-bearing zones, in feet per day (ft/d);

b_{ni} is the thickness of i^{th} row that represents part or all of a nonwater-bearing zone within the aquifer (UFA or LFA), in feet (ft);

m is a multiplier used to achieve the target transmissivity of the aquifer (UFA or LFA), in feet squared per day divided by gallons per minute;

Y_{wi} is the yield of the i^{th} row that represents part or all of a water-bearing zone within the aquifer, in gallons per minute per foot; and

b_{wi} is the thickness of the i^{th} row that represents part or all of a water-bearing zone within the aquifer, in feet.

As mentioned above, K_{n0} in this model is 3 ft/d. The yield of a row is the difference in the upward flow between the row bottom and row top divided by the row thickness. The K_h of each row within the target aquifer is then proportional to its yield by the multiplier, m. Equation 8 is arranged, below, to show what multiplier to use to obtain the target transmissivity for the aquifer (T_{aq}):

$$m = \frac{T_{aq} - K_{n0} \sum_{i=1} b_{ni}}{\sum_{i=1} Y_{wi} b_{wi}} \ , \qquad (9)$$

This approach of assigning K_h to water-bearing rows is valid for the range of transmissivities that were considered reasonable and used in sensitivity analysis for the UFA and LFA.

Values of UFA transmissivity, LFA transmissivity, specific storage, and K_v/K_h ratio were adjusted within the model until simulated drawdown was best fit to observed drawdown. Wells with simulated drawdowns that were most sensitive to changes in a parameter tended to have the most influence on determining the calibration value of that parameter. Priority was given to matching drawdown in Barbour Pointe wells 36Q398 (LFA) and 36Q399 (UFA) since these are the two principal (local) wells being used to assess the effect of LFA withdrawals on water levels in the UFA following GaEPD protocol (Nolton Johnston, Georgia Environmental Protection Division, written commun., January 28, 2003). Matching drawdown at local wells 36Q398 and 36Q399 was most important, and lower priority was given to wells located at farther distances from pumped LFA well 36Q398.

The model was calibrated using a UFA transmissivity of 59,875 ft^2/d; LFA transmissivity of 5,150 ft^2/d; specific storage of 1.16×10^{-6} ft^{-1}; and K_v/K_h ratio of 0.14 (fig. 1–11). For these parameter values, there was a good match for the Barbour Pointe wells (36Q398, LFA; and 36Q399, UFA) and the Morrison Plantation well (36Q020, UFA), and a poor match for the wells at Berwick Plantation community (36Q330, LFA; and 36Q331, UFA).

Simulated drawdown for the two Berwick wells (LFA 36Q330 and UFA 36Q331) was consistently much less than observed drawdown (fig. 1–11; simulated drawdown was 75 and 42 percent less than observed drawdown, respectively). The underestimation in simulated drawdown in the Berwick wells is probably due to heterogeneity of hydrogeologic units, which the axisymmetric model does not adequately represent.

The calibrated transmissivity value of the UFA from the model of the aquifer-test data is consistent with the value from the AnalyzeHOLE simulation of the August 2013 EM flowmeter survey (60,288 ft^2/d; see “Estimation of Hydraulic Properties and Drawdown Response” section, tables 2 and 1–2) and greater than what was reported by Faye and Gill (2005) at nearby Berwick Plantation community (46,000 ft^2/d). The calibrated transmissivity value of the LFA from the model of the aquifer-test data was similar to the value from the AnalyzeHOLE simulation of the August 2013 EM flowmeter survey (4,595 ft^2/d; tables 2 and 1–2) and less than what was reported by Faye and Gill (2005) at Berwick Plantation community (8,200 ft^2/d).

To assess the viability of model results, a sensitivity analysis of water-level responses (drawdown) to changes in transmissivity of the UFA and LFA, specific storage, and K_v/K_h ratio was completed (figs. 1–12, and 1–13). The sensitivity analysis consisted of 21 model runs whereby the tested parameter was adjusted while all other calibrated model parameter values were held constant. A lower RMS/Max*DD* value corresponds to a better fit between simulated and observed drawdown.

Simulated drawdown is sensitive to changes in UFA transmissivity in two UFA wells: Barbour Pointe well 36Q399 and Morrison Plantation well 36Q020 (fig. 1–12*A*). Simulated drawdown best fits observed drawdown of well 36Q399 and 36Q020 (have the lowest value of RMS/Max*DD*) with a UFA transmissivity of about 60,000 ft^2/d (actual input value was 59,875 ft^2/d). Both the UFA and LFA wells at Berwick Plantation community (36Q331 and 36Q330) had decreasing RMS/Max*DD* values with decreasing UFA transmissivity assigned to the model (fig. 1–12*A* and 1–12*B*). The best fits for the Berwick Plantation community wells were with lowest run value of UFA transmissivity (about 26,000 ft^2/d, actual input value was 25,886 ft^2/d).

Simulated drawdown is sensitive to changes in LFA transmissivity in Barbour Pointe LFA well 36Q398 (fig. 1–12*C* and 1–12*D*). Simulated drawdown best fits observed drawdown of well 36Q398 with a LFA transmissivity of 5,150 ft^2/d.

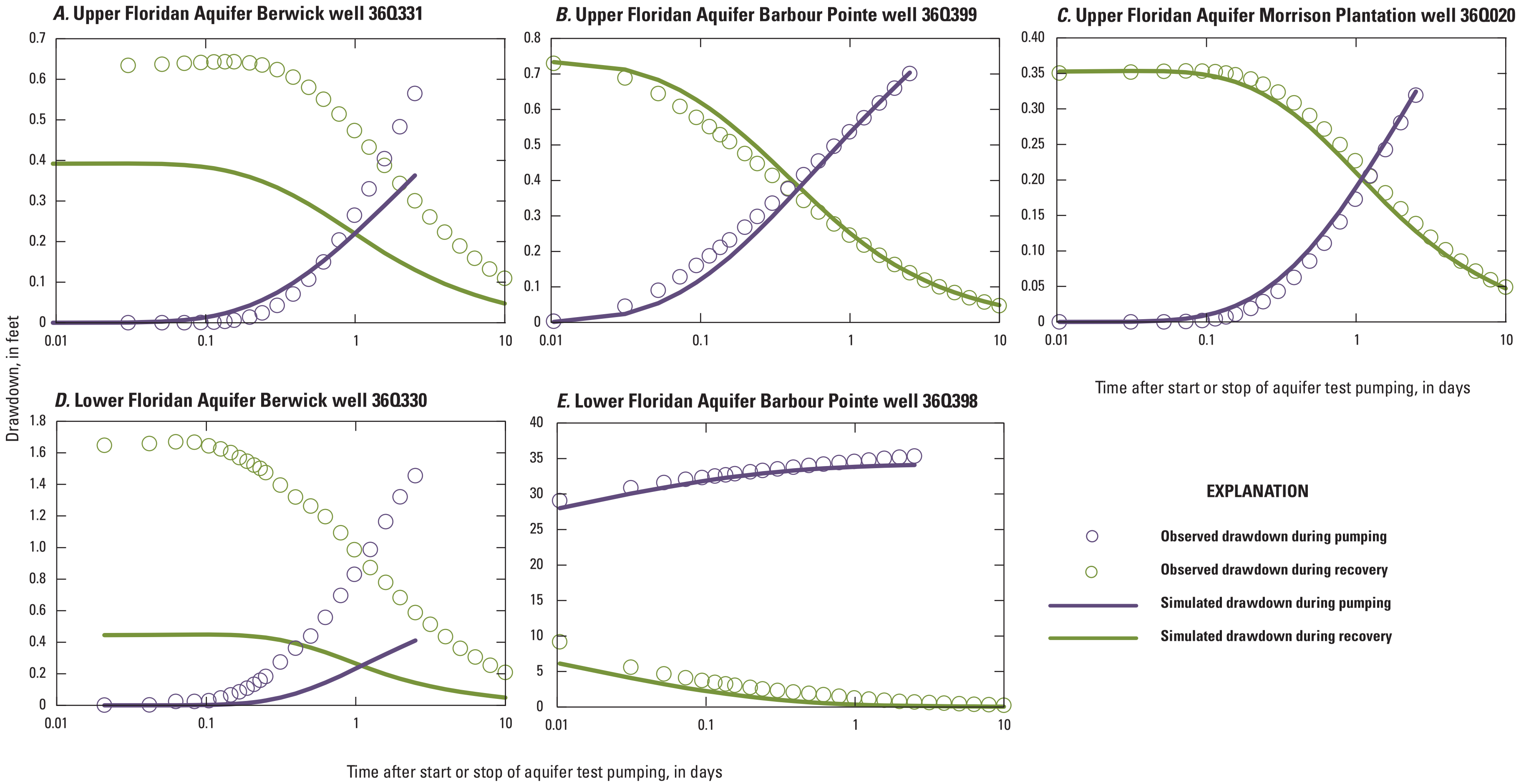

Figure 1–11. Comparison of simulated and observed drawdown for calibrated two-dimensional, axisymmetric, radial, transient, groundwater-flow model of 72-hour aquifer test at Lower Floridan aquifer (LFA) well 36Q398, Barbour Pointe community, near Savannah, Georgia, November 19–29, 2013. *A*, Upper Floridan aquifer (UFA) Berwick well 36Q331; *B*, UFA Barbour Pointe well 36Q399; *C*, UFA Morrison Plantation well 36Q020; *D*, LFA Berwick well 36Q330; and, *E*, LFA Barbour Pointe well 36Q398.

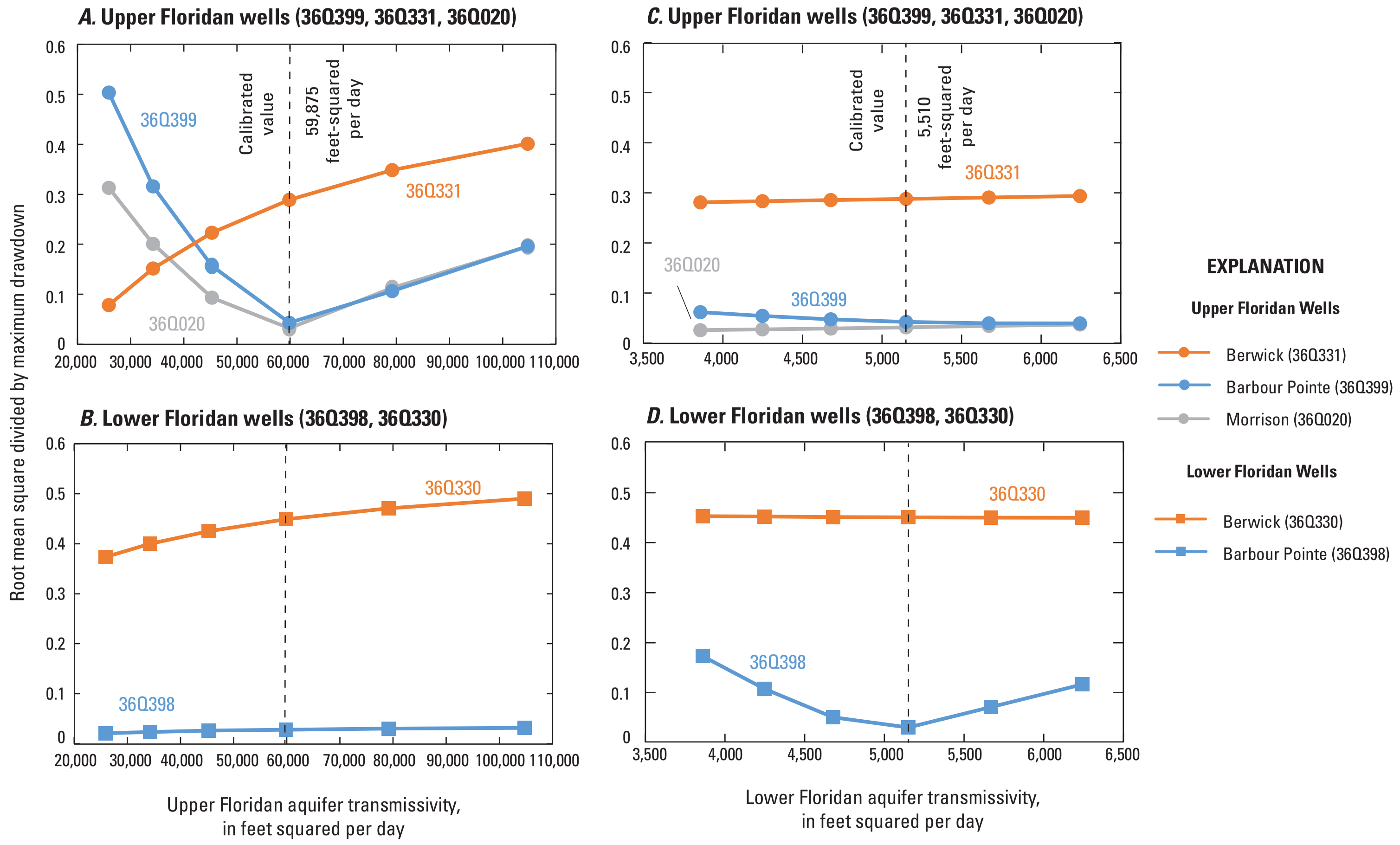

Figure 1–12. Sensitivity of simulated drawdown in the Upper and Lower Floridan aquifer (UFA and LFA) wells to changes in UFA and LFA transmissivity, two-dimensional, axisymmetric, radial, transient, groundwater-flow model of the 72-hour aquifer test in LFA well 36Q398, Barbour Pointe community, near Savannah, Georgia, November 19–22, 2013. *A*, UFA wells, UFA transmissivity; *B*, LFA wells, UFA transmissivity; *C*, UFA wells, LFA transmissivity; and, *D*, LFA wells, LFA transmissivity.

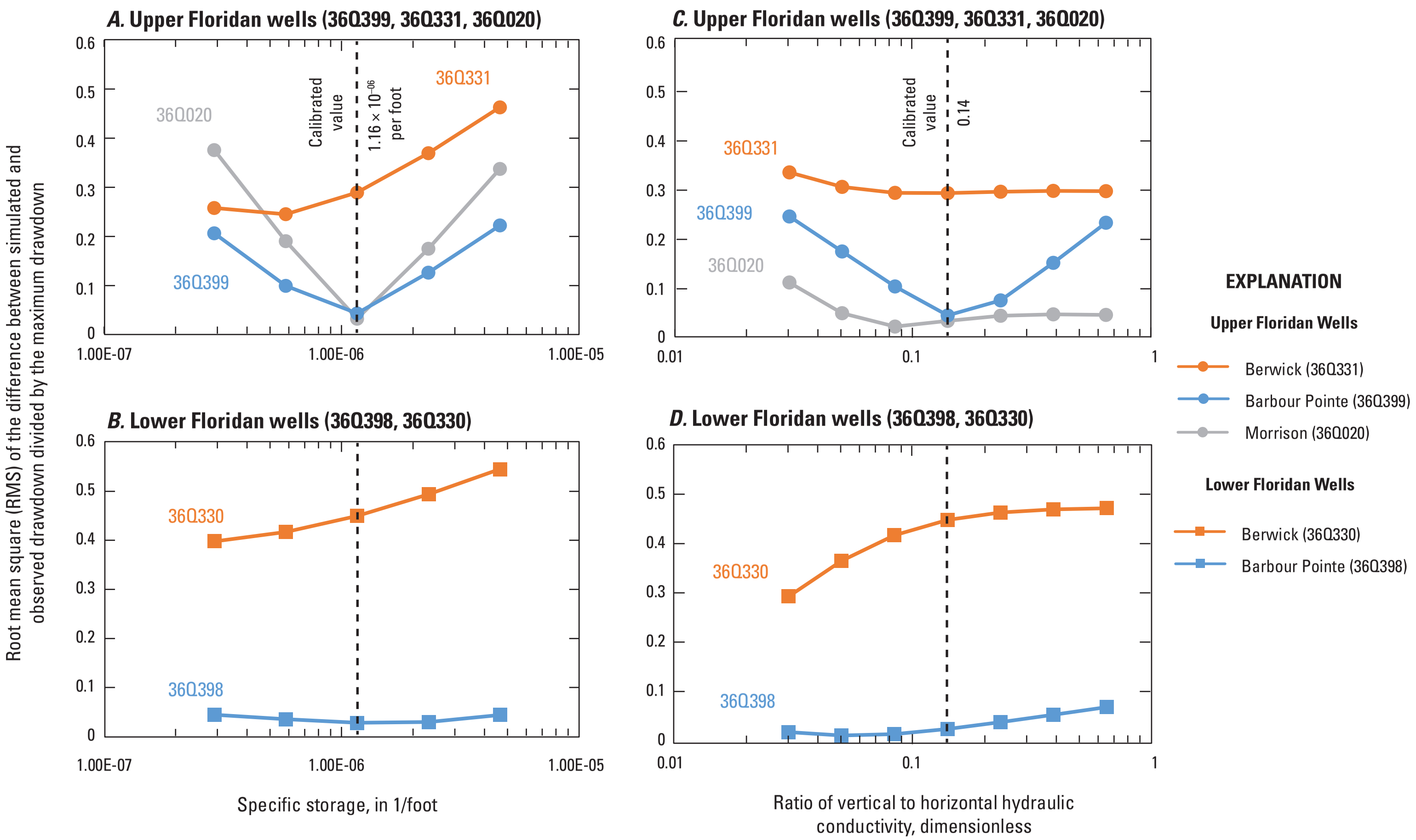

Figure 1–13. Sensitivity of simulated drawdown in the Upper and Lower Floridan aquifer (UFA and LFA) wells to changes in specific storage and ratio of vertical to horizontal hydraulic conductivity (K_v/K_h) in the Floridan aquifer system, two-dimensional, axisymmetric, radial, transient, groundwater-flow model of the 72-hour aquifer test in LFA well 36Q398, Barbour Pointe community, near Savannah, Georgia, November 19–22, 2013. *A*, UFA wells, specific storage; *B*, LFA wells, specific storage; *C*, UFA wells, K_v/K_h; and, *D*, LFA wells, K_v/K_h.

Simulated drawdown is sensitive to changes in specific storage in two UFA wells: Barbour Pointe well 36Q399 and Morrison Plantation well 36Q020 (fig. 1–13*A*); drawdown from the distant Morrison Plantation well is the most sensitive. Simulated drawdown best fits observed drawdown of well 36Q399 and 36Q020 with a value of specific storage of 1.16×10^{-6} ft^{-1}. Both the UFA and LFA wells at Berwick Plantation community (36Q331 and 36Q330) were also sensitive to changes in specific storage, and had better fits between simulated and observed drawdown with values of specific storage of less than 1.16×10^{-6} ft^{-1}(fig. 1–13*A* and 1–13*B*). Berwick Plantation community UFA well had the best fit with a specific storage value of 5.80×10^{-7} ft^{-1}.

Simulated drawdown is most sensitive to changes in K_v/K_h in Barbour Pointe UFA well 36Q399 (fig. 1–13*C*). Simulated drawdown best fits observed drawdown of well 36Q399 with a K_v/K_h of 0.14. Simulated drawdown of the other four wells is also sensitive to changes in K_v/K_h though to a lesser degree than well 36Q399. Different values of K_v/K_h allow for a best fit between simulated and observed drawdown of each well (fig. 1–13*C* and 1–13*D*). Simulated drawdown best fits observed drawdown for Berwick Plantation community UFA well 36Q331 with a K_v/K_h value of 0.14, Morrison Plantation UFA well 36Q020 with a K_v/K_h value of 0.084, Barbour Pointe LFA well 36Q398 with a K_v/K_h value of 0.0504, and Berwick Plantation community LFA well 36Q330 with minimum tested K_v/K_h value of 0.03024. A value of K_v/K_h of 0.14 and a fixed K_h for the LFCU (3 ft/d) equates to a K_v value for the LFCU of 0.42 ft/d, which is close to the median value of 0.46 for core analyses from Pooler, Ga. (Gonthier, 2012), and HAAF (Clarke and others, 2010).

The first-order line that is fit to the drawdown data for the pumped well 36Q398 in figure 1–9 yields an estimated transmissivity of 11,000 ft^2/d for the LFA based on the Cooper-Jacob method (Cooper and Jacob, 1946). This estimate is more than twice the value determined from the two-dimensional, axisymmetric, radial, transient, groundwater-flow model. Though the drawdown curve is slightly nonlinear, the influence of the UFA on the LFA during pumping likely decreased the drawdown and caused the magnitude of drawdown in late time on the semilog plot to be lower than if the LFA were completely hydraulically separated from the UFA. To avoid overestimation of transmissivity, care must be taken not to try to use Theis-based methods when there is any indication of aquifer leakage.

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