Prepared in cooperation with the U.S. Nuclear Regulatory Commission

Simulation and Particle-Tracking Analysis of Selected Ground-Water Pumping Scenarios at Vogtle Electric Generation Plant, Burke County, Georgia

Open-File Report 2007-1363

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

Cover photograph: Vogtle Electric Generation Plant cooling towers, Burke County, Georgia
Photograph by Alan M. Cressler, U.S. Geological Survey

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Contents

Figures

Figures—Continued

Tables

Conversion Factors and Datums

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square foot (ft^2)	0.09290	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	3.785	liter (L)
million gallons (Mgal)	3,785	cubic meter (m^3)
	Flow rate	
gallon per minute (gal/min)	0.06309	liter per second (L/s)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)

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

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

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

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

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Abstract

The source of ground water to production wells at Vogtle Electric Generation Plant (VEGP), a nuclear power plant in Burke County, Georgia, was simulated under existing (2002) and potential future pumping conditions using an existing U.S. Geological Survey (USGS) MODFLOW ground-water flow model of a 4,455-square-mile area in the Coastal Plain of Georgia and South Carolina. Simulation results for three steady-state pumping scenarios were compared to each other and to a 2002 Base Case condition. The pumping scenarios focused on pumping increases at VEGP resulting from projected future demands and the addition of two electrical-generating reactor units. Scenarios simulated pumping increases at VEGP ranging from 1.09 to 3.42 million gallons per day (Mgal/d), with one of the scenarios simulating the elimination of 5.3 Mgal/d of pumping at the Savannah River Site (SRS), a U.S. Department of Energy facility located across the Savannah River from VEGP. The largest simulated water-level changes at VEGP were for the scenario whereby pumping at the facility was more than tripled, resulting in drawdown exceeding 4–8 feet (ft) in the aquifers screened in the production wells. For the scenario that eliminated pumping at SRS, water-level rises of as much as 4–8 ft were simulated in the same aquifers at SRS.

Results of MODFLOW simulations were analyzed using the USGS particle-tracking code MODPATH to determine the source of water and associated time of travel to VEGP production wells. For each of the scenarios, most of the recharge to VEGP wells originated in an upland area near the county line between Burke and Jefferson Counties, Georgia, with none of the recharge originating on SRS or elsewhere in South Carolina. An exception occurs for the scenario whereby pumping at VEGP was more than tripled. For this scenario, some of the recharge originates in an upland area in eastern Barnwell County, South Carolina. Simulated mean time of travel from recharge areas to VEGP wells for the Base Case and the three other pumping scenarios was between about 2,700 and 3,800 years, with some variation related to changes in head gradients because of pumping changes.

Introduction

The Vogtle Electric Generation Plant (VEGP), near Waynesboro, Burke County, Georgia, is one of Southern Company's two nuclear-generating facilities in Georgia (fig. 1). On August 15, 2006, Southern Nuclear Company applied to the U.S. Nuclear Regulatory Commission (NRC) for an early site permit (ESP) for an additional two reactors at the site. As part of the ESP permitting process, the NRC is charged with development of an environmental impact statement (EIS) to evaluate the effects of both construction and operation of these new reactors on the site and surrounding area. The EIS must describe the magnitude and nature of expected effects on ground water resulting from present and potential future ground-water withdrawal. The assessment should include the area of VEGP and extend for distances great enough to cover potentially affected aquifers, including those located within the boundary of the U.S. Department of Energy, Savannah River Site (SRS), located in South Carolina across the Savannah River from VEGP (fig. 1A, 1B).

The addition of two new reactors (Units 3 and 4) at VEGP will require an increase in pumping from the lower Dublin and upper and lower Midville aquifers, which currently provide the water needed for reactor Units 1 and 2. NRC would like to evaluate the effects of additional pumpage on ground-water flow in the surrounding area. To help evaluate these effects, and improve understanding of regional ground-water flow in the area, the U.S. Geological Survey (USGS)—in cooperation with NRC—conducted a study using an existing ground-water flow model to simulate the source of ground water to VEGP production wells under current (2002) and potential future pumping conditions.

Purpose and Scope

This report describes the effect of current (2002) and potential future pumping on ground-water levels and flowpaths near VEGP for three pumping scenarios using an existing ground-water flow model (Clarke and West, 1998; Cherry, 2006) of a 4,455-square-mile (mi^2) area near Augusta, Ga. (fig. 1A).

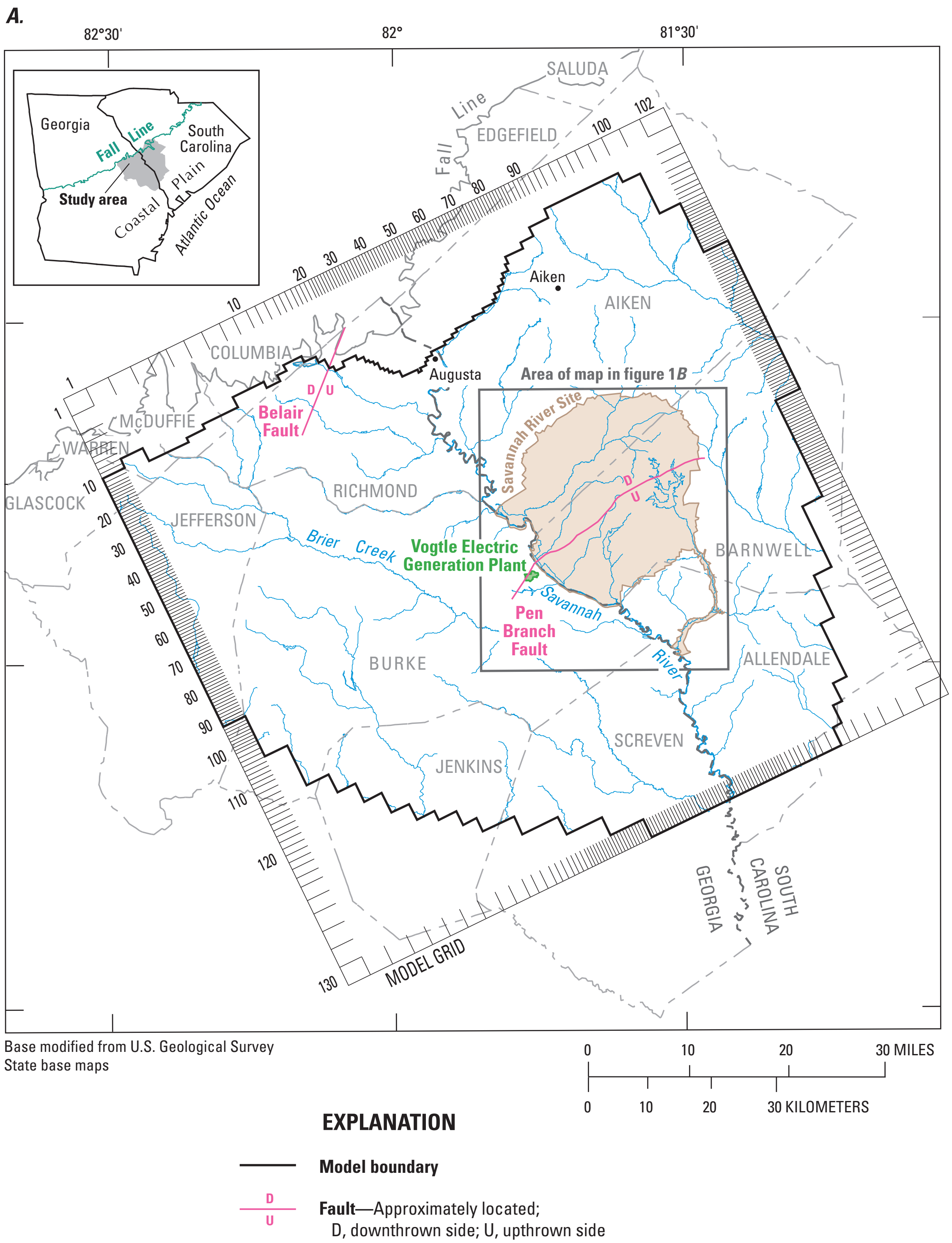


Figure 1. (*A*) Study area, model grid, and model boundary, (*B*) location of Vogtle Electric Generation Plant production wells, Burke County, Georgia, and river and recharge cells in the Gordon aquifer (layer A2) (modified from Clarke and West, 1997) and areal and local ground-water contamination at the Savannah River Site, South Carolina (modified from Arnett and Mamatey, 1996; Cherry, 2006).

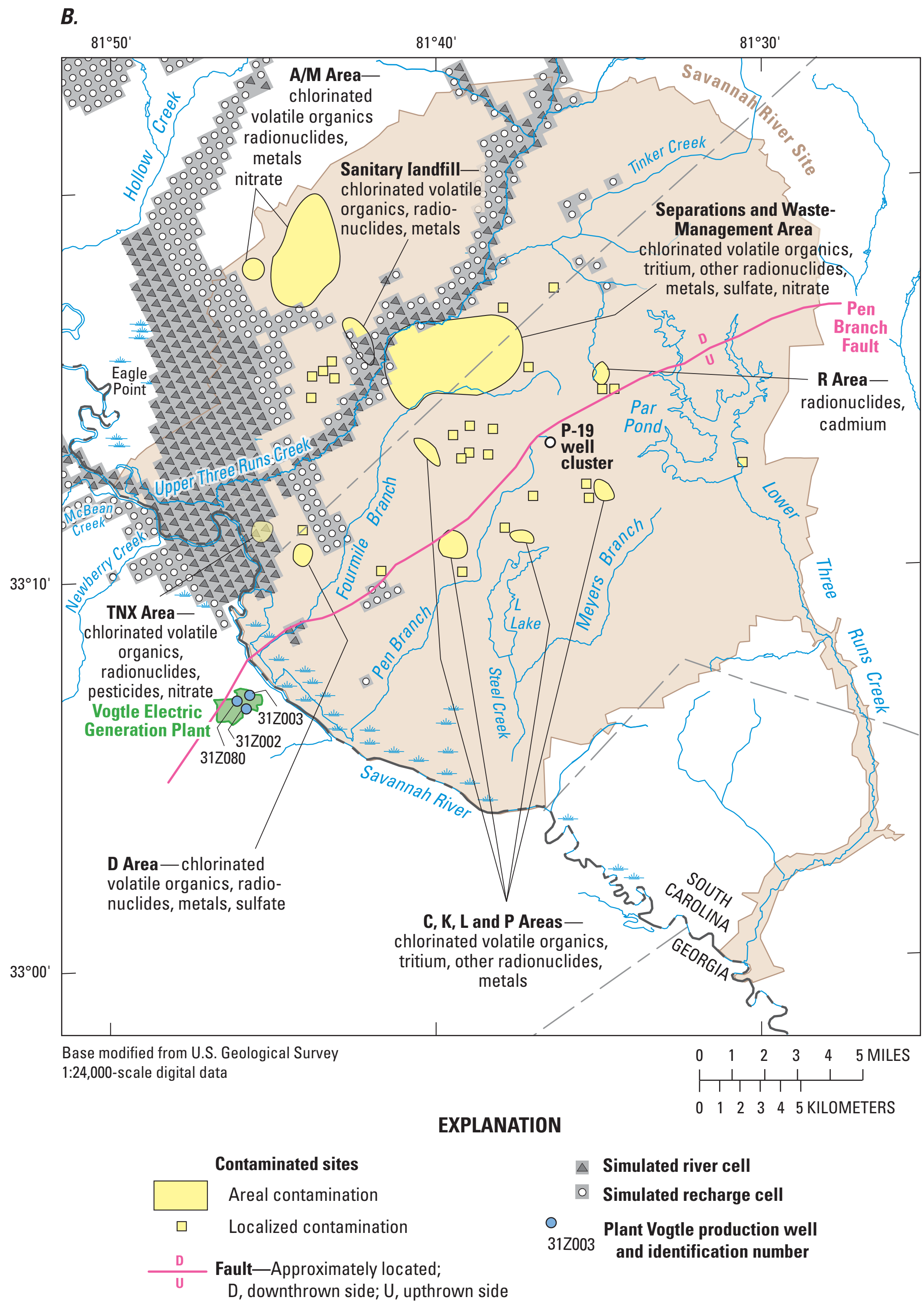


Figure 1. (*A*) Study area, model grid, and model boundary, (*B*) location of Vogtle Electric Generation Plant production wells, Burke County, Georgia, and river and recharge cells in the Gordon aquifer (layer A2) (modified from Clarke and West, 1997) and areal and local groundwater contamination at the Savannah River Site, South Carolina (modified from Arnett and Mamatey, 1996; Cherry, 2006).—Continued

Simulated water levels were compared to a Base Case representing 2002 pumping rates throughout the model area. A particle-tracking analysis was conducted for each scenario to determine the source of water for VEGP production wells. For each scenario, the pumping distribution, simulated water-level changes, and ground-water flowpaths are described relative to the Base Case. Limitations of the model analysis also are provided.

Description of Study Area

The study area is in the northern part of the southeastern Coastal Plain physiographic province (Clark and Zisa, 1976) of Georgia and South Carolina (fig. 1A). The Fall Line marks the boundary between Coastal Plain sediments and crystalline rocks of the Piedmont physiographic province and forms the approximate northern limit of the study area. Topographic relief generally is greatest near the Fall Line, becoming progressively less toward the south and east. Altitudes range from as high as 650 feet (ft) near the Fall Line to less than 100 ft in the southern part of the study area and in the valleys of major streams, such as the Savannah River or Brier Creek. A steep bluff is present along the western bank of the Savannah River in southern Richmond County and most of Burke County, Ga. Relief along the Savannah River bluff is as much as 160 ft from the top of the bluff to the valley floor.

The Coastal Plain province is well to moderately dissected by streams and has a well-developed dendritic drainage pattern. Streams that flow over the relatively soft Coastal Plain sediments develop wider floodplains and greater meander frequency than streams that flow over hard crystalline rocks of the Piedmont (Clark and Zisa, 1976). Most of the floodplain near the principal rivers, such as the Savannah River, has a wide expanse of swamp bordering both sides of the channel.

Forestry and agriculture are the predominant land uses in the study area; major crops are pine timber, cotton, and soybeans. Kaolin is mined in parts of the study area. The largest cities in the study area are Augusta, Ga., with a population of 194,950 during 2000; and Aiken, S.C., with a population of 25,460 during 2000 (U.S. Bureau of the Census, accessed February 3, 2003, at *http://www.census.gov/*).

Savannah River Site and Ground-Water Contamination

The SRS encompasses a 310-mi^2 area across the Savannah River from VEGP in parts of Aiken, Barnwell, and Allendale Counties, S.C. (fig. 1A, 1B). The facility has manufactured nuclear materials for national defense since the early 1950s. A variety of hazardous materials—including radionuclides, volatile organic compounds, and heavy metals—are either disposed of or stored at several locations at SRS. Contamination of ground water has been detected at several locations on the site (fig. 1B) with contamination mostly limited to the Upper Three Runs aquifer. The potential for movement of contaminated water into aquifers beneath the Upper Three Runs aquifer at SRS is dependent on the hydraulic conductivity of intervening confining units and the magnitude of downward hydraulic gradient (see Ground-Water Flow section).

The only documented occurrence of ground-water contaminants into aquifers beneath the Upper Three Runs that the authors are aware of occurred in the vicinity of the A/M Area on SRS (see location, fig. 1B). In this area, Christensen and Gordon (1983) reported volatile organic compounds were detected at depths as great as 480 ft, affecting water-bearing zones in the “Congaree Formation” (Gordon aquifer) and “Tuscaloosa Formation” (lower Dublin aquifer). Contamination in the Congaree Formation was attributed to the discontinuity of the “green clay” that forms the confining unit beneath the Upper Three Runs aquifer. Contamination of the Tuscaloosa Formation was attributed to a poor grout seal in well 53A, which enabled downward migration of contaminated ground water into deeper zones. During the first half of 2007, Washington Savannah River Company (2007) reported concentrations of trichloroethylene in the A/M Area of as high as 18,000 micrograms per liter (μg/L) in the composite “Lost Lake aquifer zone” (Gordon aquifer) and as high as 3,200 μg/L in the “Crouch Branch aquifer” (upper and lower Dublin aquifers). Contaminants in both aquifers occur in southwest-trending plumes with concentrations exceeding 5 μg/L across a distance of nearly 21,000 ft in the Lost Lake aquifer zone, and nearly 15,000 ft in the Crouch Branch aquifer. Contaminants in the source areas are being removed using recovery wells and above-ground air strippers (Washington Savannah River Company, 2007).

Climate and Runoff

A relatively mild climate with warm, humid summers and mild winters characterizes the study area. Precipitation is highest during the winter months when continental storm fronts move through the region and during July and August when afternoon thunderstorms caused by daytime heating are common. Average annual precipitation in the study area for the period 1969–98, ranged from about 46 inches in Burke County, Ga., to greater than 52 inches in central Aiken County, S.C. (Southeast Regional Climate Center, accessed February 11, 2004, at *http://www.dnr.sc.gov/climate/sercc/*).

The Savannah River is the major surface-water feature in the study area and is the boundary between Georgia and South Carolina. The river drains an area of about 10,580 mi^2 (1,140 mi^2 in the study area) and empties into the Atlantic Ocean near Savannah, Ga. During 1941–70, the average annual runoff in Georgia ranged from less than 0.9 cubic feet per second per square mile [$(ft^3/s)/mi^2$] of drainage area in southern Screven, Jenkins, Burke, and Jefferson Counties, and in northern Richmond and Jefferson Counties, to greater than 1.1 $(ft^3/s)/mi^2$ in eastern Richmond and Burke Counties (Faye and Mayer, 1990).

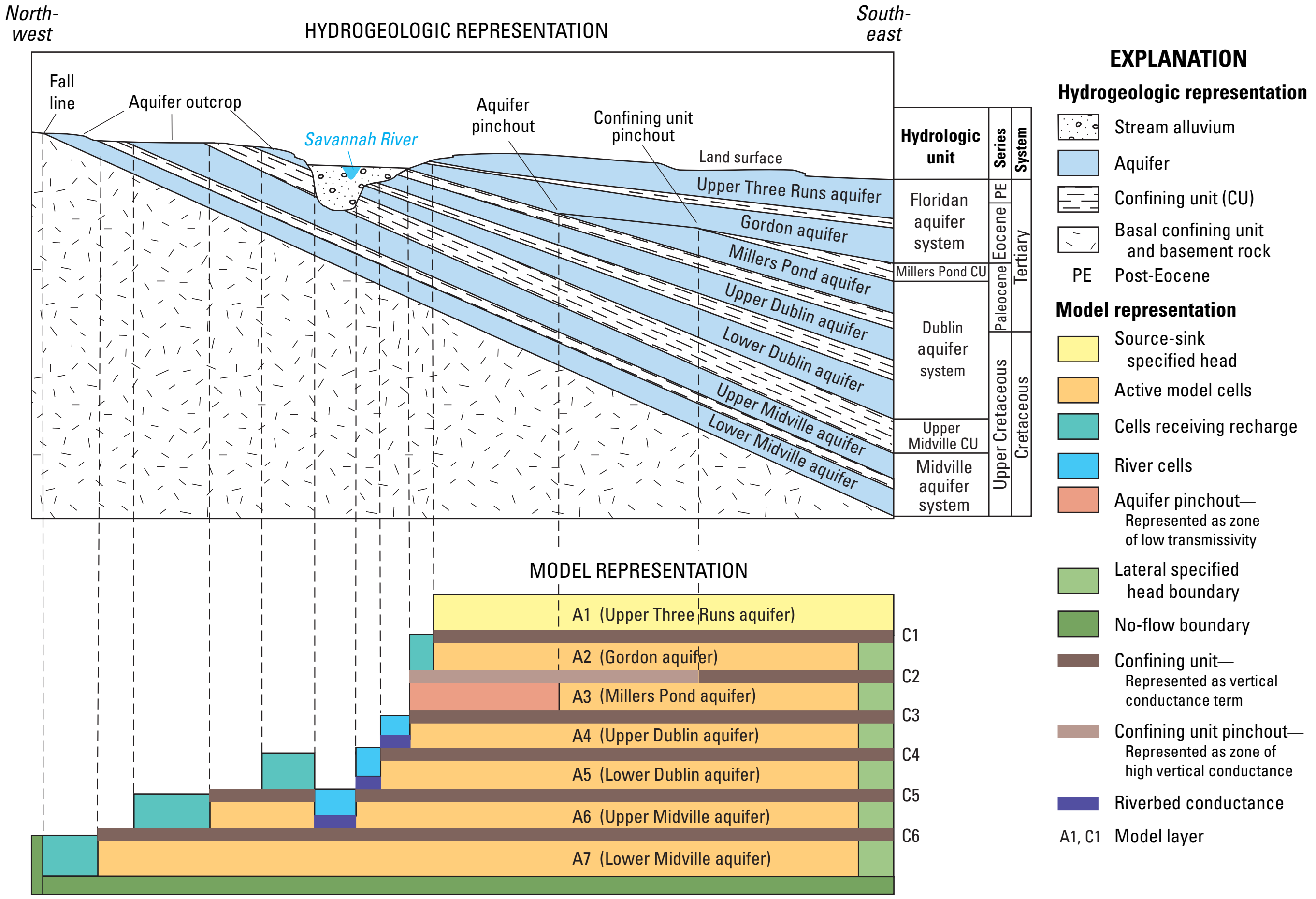


Figure 2. Schematic diagram showing hydrogeologic framework, model layers, and boundary conditions for the Vogtle Electric Generation Plant area, South Carolina (ground-water model modified from Clarke and West, 1998; Cherry, 2006).

Hydrogeologic Setting

Coastal Plain sedimentary strata in the study area consist of layers of sand, clay, and limestone, which range in age from Upper Cretaceous through post-Eocene (fig. 2). The Fall Line (fig. 1A) marks the approximate inner margin of Coastal Plain sediments. The strata dip and progressively thicken from the Fall Line to the southeast, with an estimated thickness of 2,700 ft in the southern part of the study area (Wait and Davis, 1986). The strata crop out in discontinuous belts that generally are parallel to the Fall Line. The sedimentary sequence unconformably overlies Paleozoic igneous and metamorphic rocks, and consolidated Mesozoic red beds (Chowns and Williams, 1983)

Coastal Plain sediments comprise three principal aquifer systems near VEGP. In descending order, these aquifer systems are (1) the Floridan aquifer system, originally defined by Miller (1986) and later redefined by Aadland and others (1995)—comprised largely of Eocene calcareous sand and limestone; (2) the Dublin aquifer system (Clarke and others, 1985)—comprised of Paleocene and Late Cretaceous sand; and (3) the Midville aquifer system (Clarke and others, 1985)—comprised of Late Cretaceous sand. Although this subdivision was suitable for most regional-scale hydrogeologic studies, greater subdivision of units was required to define vertical hydraulic heterogeneity for detailed investigations of ground-water flow near the Savannah River. Accordingly, the three aquifer systems were divided into seven aquifers (fig. 2):

- the Floridan aquifer system was subdivided into the Upper Three Runs aquifer and the Gordon aquifer (Aadland and others, 1995);
- the Dublin aquifer system was subdivided into the Millers Pond aquifer, the upper Dublin aquifer and the lower Dublin aquifer (Falls and others, 1997); and
- the Midville aquifer system was subdivided into the upper Midville aquifer and the lower Midville aquifer (Falls and others, 1997).

The aquifers are separated and confined by layers of clay and silt, which become progressively sandy and discontinuous in updip areas. The aquifer systems coalesce where the confining units become sandy. See Falls and others (1997) for a complete description of geologic and hydrogeologic units in the study area.

Structural Features

Major structural features in the study area (fig. 1A) include the Belair Fault (Prowell and O'Connor, 1978) and the Pen Branch Fault (Price and others, 1991). The Belair Fault is a northeast-trending, high-angle reverse fault that dips to the southeast and has a maximum vertical displacement of 100 ft at the base of Coastal Plain strata (Prowell and O'Connor, 1978). The Pen Branch Fault is a northeast-trending, high-angle reverse fault that dips to the southeast. On SRS, the fault consists of a 1.8-mile (mi)-wide zone of subparallel faults and some fault splays (Snipes and others, 1993). The fault is downthrown on the northwestern side, and maximum displacement ranges from 100 ft at the base of Coastal Plain strata to 30 ft at the top of the Eocene Dry Branch Formation (Price and others, 1991).

Seismic data from Burke County, Ga., suggest the Pen Branch Fault zone is about 0.86-mi wide and includes "short fractures" or "stress-release faults" (Summerour and others, 1998). These features appear to cut confining units overlying the Millers Pond aquifer, upper and lower Dublin aquifers, and upper and lower Midville aquifers; however, it is unclear whether they cut into the confining unit overlying the Gordon aquifer (Summerour and others, 1998). The Pen Branch Fault zone includes the area of VEGP (fig. 1A, 1B). The effects of the Pen Branch Fault on sediment deposition and hydraulic properties of hydrogeologic units is unknown; however, there may be some local effects on the hydrologic system (see Effect of Pen Branch Fault section).

Hydrogeologic Characteristics of the Savannah River Alluvial Valley

The hydrogeologic characteristics of the Savannah River alluvial valley (fig. 3) greatly influence the configuration of potentiometric surfaces, ground-water flow directions, and stream-aquifer relations. To determine the effect of paleo-river channel incision on hydrogeologic units, a map was constructed that shows the subsurface extent of hydrogeologic units beneath the mantle of alluvial deposits in the Savannah River floodplain (fig. 3). The map indicates that each of the seven aquifers was incised by the paleo-Savannah River channel and covered with an infill of permeable alluvium, allowing direct hydraulic connection of the aquifers and river along parts of the river's reach. The lateral extent of the paleo-river channel incision corresponds to the width of the Savannah River alluvial valley and includes the modern-day alluvial bottom and terraces as mapped by Prowell (1994). The width of the alluvial valley ranges from a minimum of about 0.5 mi near the Fall Line to about 7 mi near the Richmond–Burke County line.

Summerour and others (1998) reported the possible presence of several "channel features" along a seismic profile collected by Waddell and others (1995) in eastern Burke County, outside of the present Savannah River valley. These features are believed to cover an area about 3,000 ft wide, extending to about 500 ft deep; however, their presence was not confirmed by drilling. Summerour and others (1998) suggested that "the channels, if real, could provide a potential pathway for the movement of groundwater (and pollutants) between aquifers." Because of the uncertainty of these features, they were not included in the ground-water model developed by Clarke and West (1998). If additional data become available to confirm the presence of these features, it may be desirable to incorporate them into future ground-water models of the area.

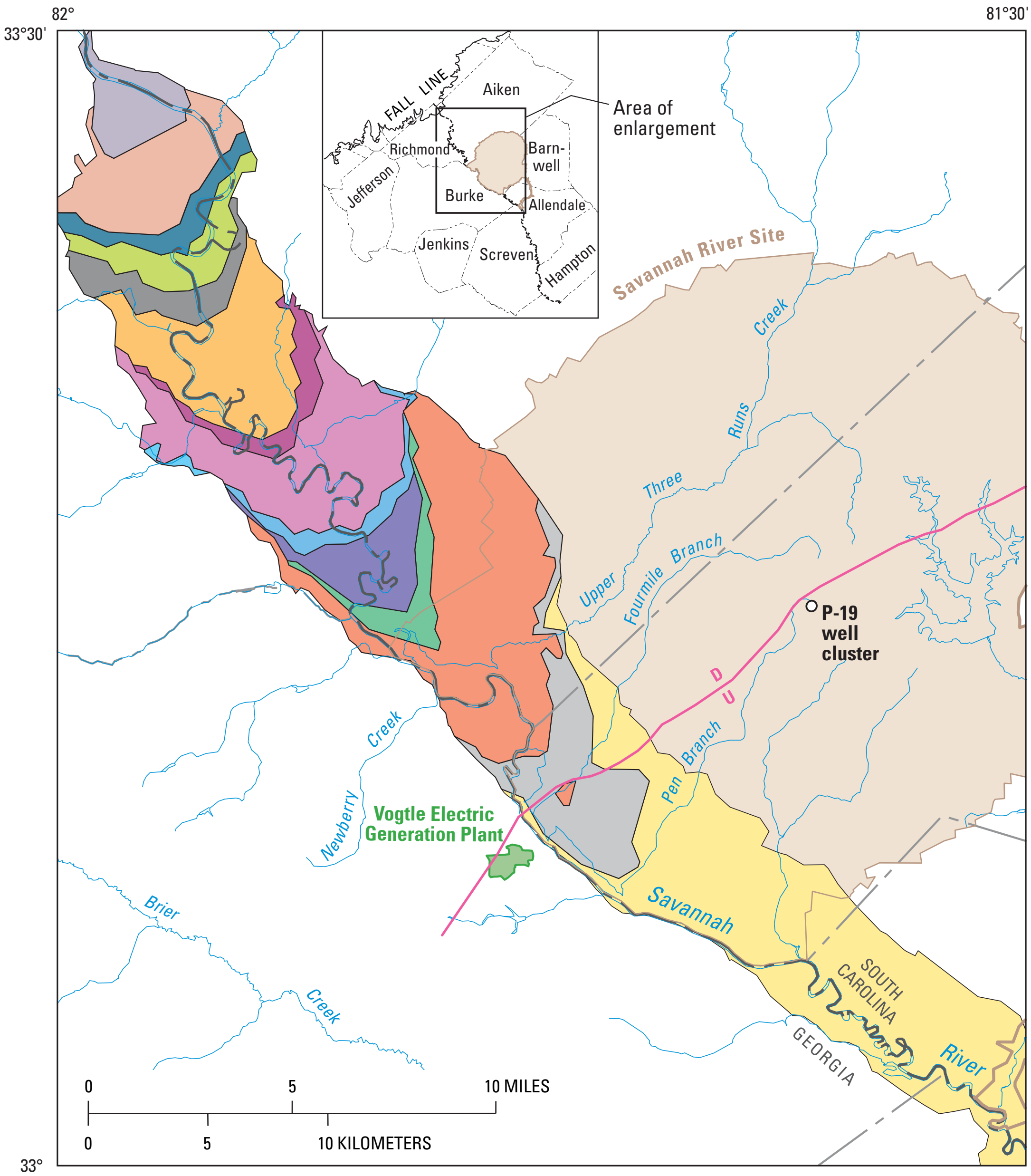
Ground-Water Flow

The ground-water flow system near VEGP is generally considered to be in a state of equilibrium (steady state), whereby rates of aquifer recharge and discharge are about equal, and there is an insignificant loss of water from aquifer storage (Clarke and West, 1998). Recharge enters the ground-water system in upland areas and moves downgradient toward points of discharge (fig. 4). Much of the recharge water is discharged from the shallow flow system into tributaries of the Savannah River. A smaller percentage of recharge infiltrates through clayey confining units and enters the deeper intermediate and regional ground-water flow systems (fig. 4).

Topography plays an important role in defining the position of areas of potential downward and upward flow. Clarke and West (1997) present maps showing head differences and the potential for flow between adjacent units in the study area. In interstream areas throughout most of the study area, the potential for flow between the Gordon aquifer and overlying Upper Three Runs aquifer is downward, indicating possible recharge by ground-water leakage from the Upper Three Runs aquifer to the Gordon aquifer (Clarke and West, 1997). Conversely, in stream valleys and throughout much of the southern part of the study area, the potential for ground-water flow is upward, indicating possible discharge from the Gordon aquifer to the Upper Three Runs aquifer.

The Savannah River serves as the major hydrologic drain in the VEGP area, with its floodplain considered to represent the same or nearly the same hydrologic condition as the river (Clarke and West, 1997). Each of the seven aquifers was incised by the paleo-Savannah River channel and covered with an infill of permeable alluvium (fig. 3), allowing direct hydraulic interconnection between the aquifers and the river (Clarke and West, 1997). This hydraulic connection allows water in confined aquifers to discharge into the river—by way of the alluvium—and may induce ground water to flow updip.

Hydraulic connection between confined aquifers and the Savannah River can be inferred from potentiometric-surface maps (figs. 5–8) that show ground-water discharge areas along the Savannah River valley as lows or depressions in the potentiometric surface (Clarke and West, 1997). Ground water flows toward the depressions from all directions; however, downstream from the depressions, the influence of the river on the aquifers becomes progressively diminished, and ground water resumes the regional gradient toward the southeast. In these downstream areas, a ground-water divide or "saddle" (Siple, 1960, 1967) in the potentiometric surface is perpendicular to the river and separates upstream from downstream ground-water flow.



Base modified from U.S. Geological Survey
State base maps

EXPLANATION

Hydrogeologic units

- Upper Three Runs aquifer
- Gordon confining unit
- Gordon aquifer
- Millers Pond confining unit
- Millers Pond aquifer
- Upper Dublin confining unit
- Upper Dublin aquifer
- Lower Dublin confining unit
- Lower Dublin aquifer
- Upper Midville confining unit
- Upper Midville aquifer
- Lower Midville confining unit
- Lower Midville aquifer
- Pre-Cretaceous basement rock

D/U **Pen Branch Fault**—Approximately located; D, downthrown side; U, upthrown side

Figure 3. Subsurface extent of hydrogeologic units beneath the Savannah River alluvial valley, South Carolina and Georgia (modified from Clarke and West, 1997).

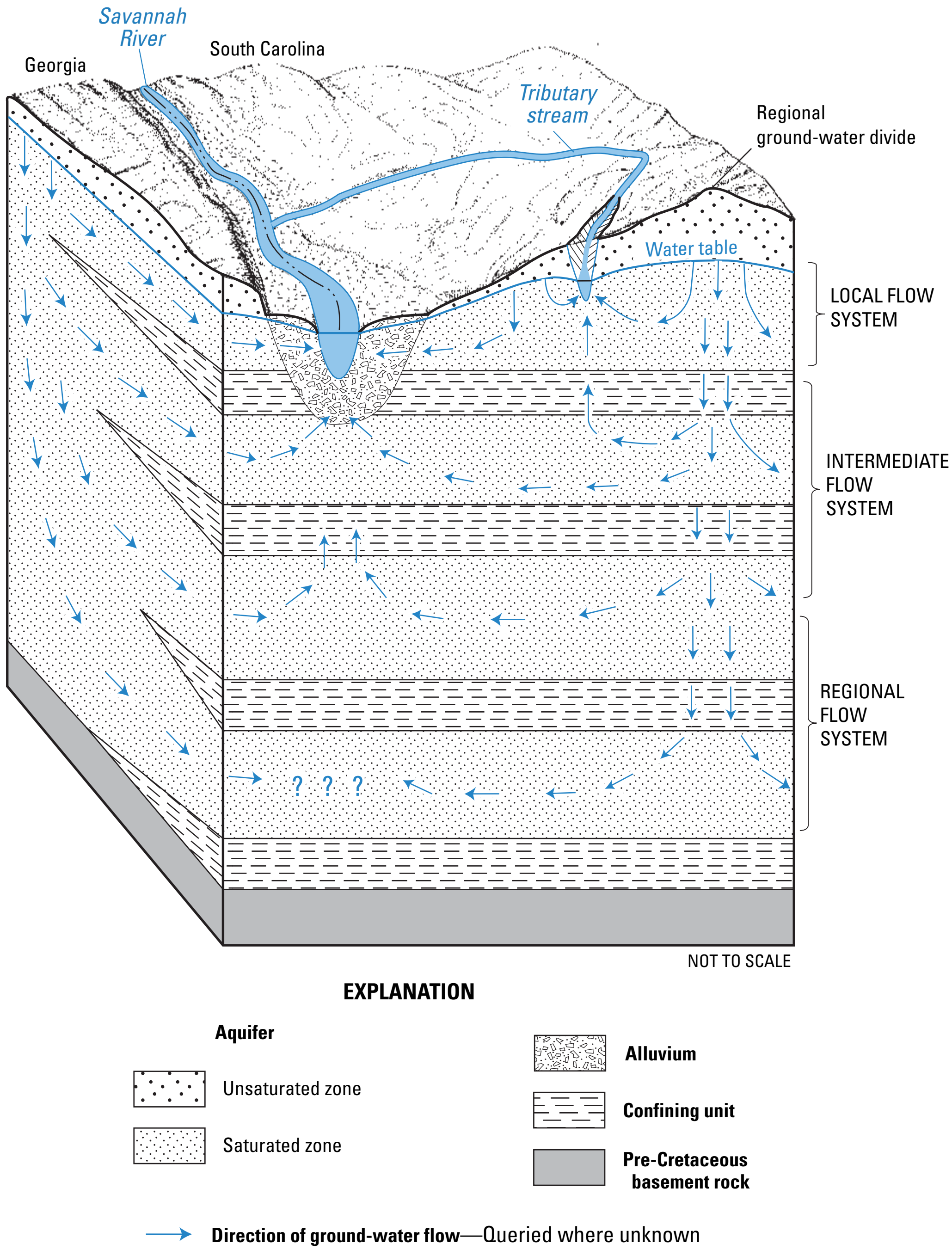


Figure 4. Conceptualized hydrogeologic framework and related ground-water flow near Vogtle Electric Generation Plant, Georgia and South Carolina (modified from Atkins and others, 1996).

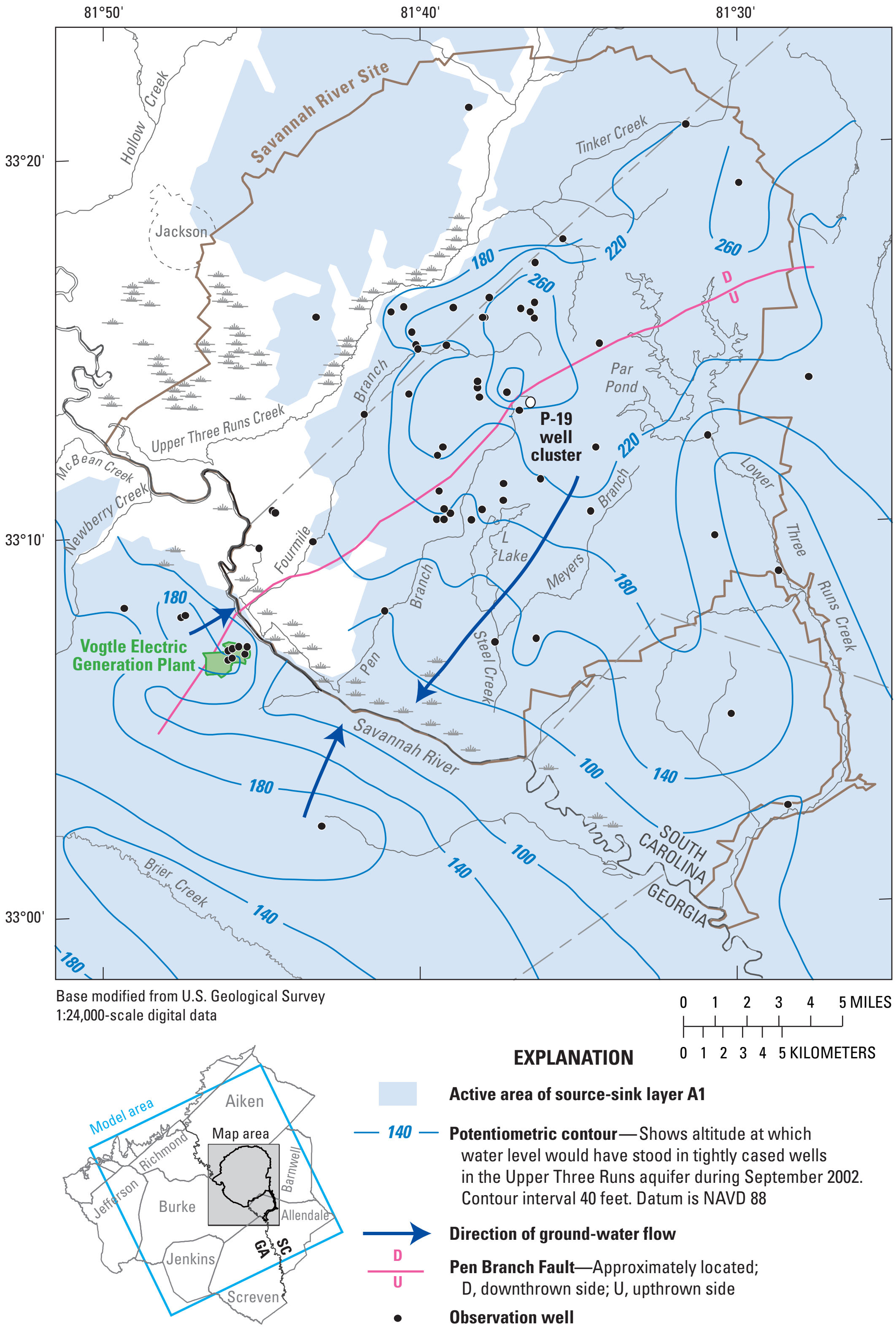


Figure 5. Potentiometric surface for the Upper Three Runs aquifer, near Vogtle Electric Generation Plant, Georgia and South Carolina, September 2002 (modified from Cherry, 2003).

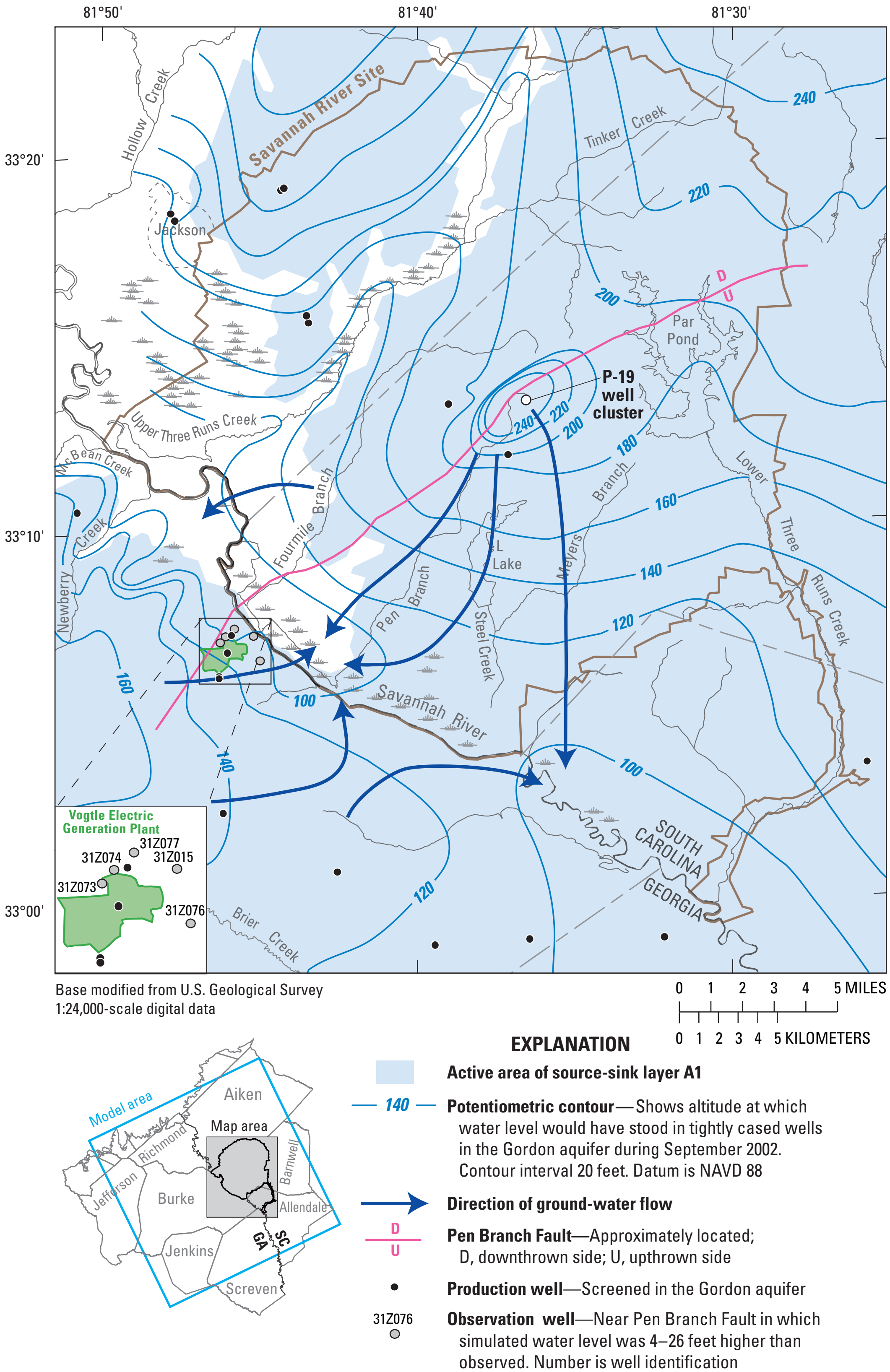


Figure 6. Potentiometric surface for the Gordon aquifer, near Vogtle Electric Generation Plant, Georgia and South Carolina, September 2002 (modified from Cherry, 2003).

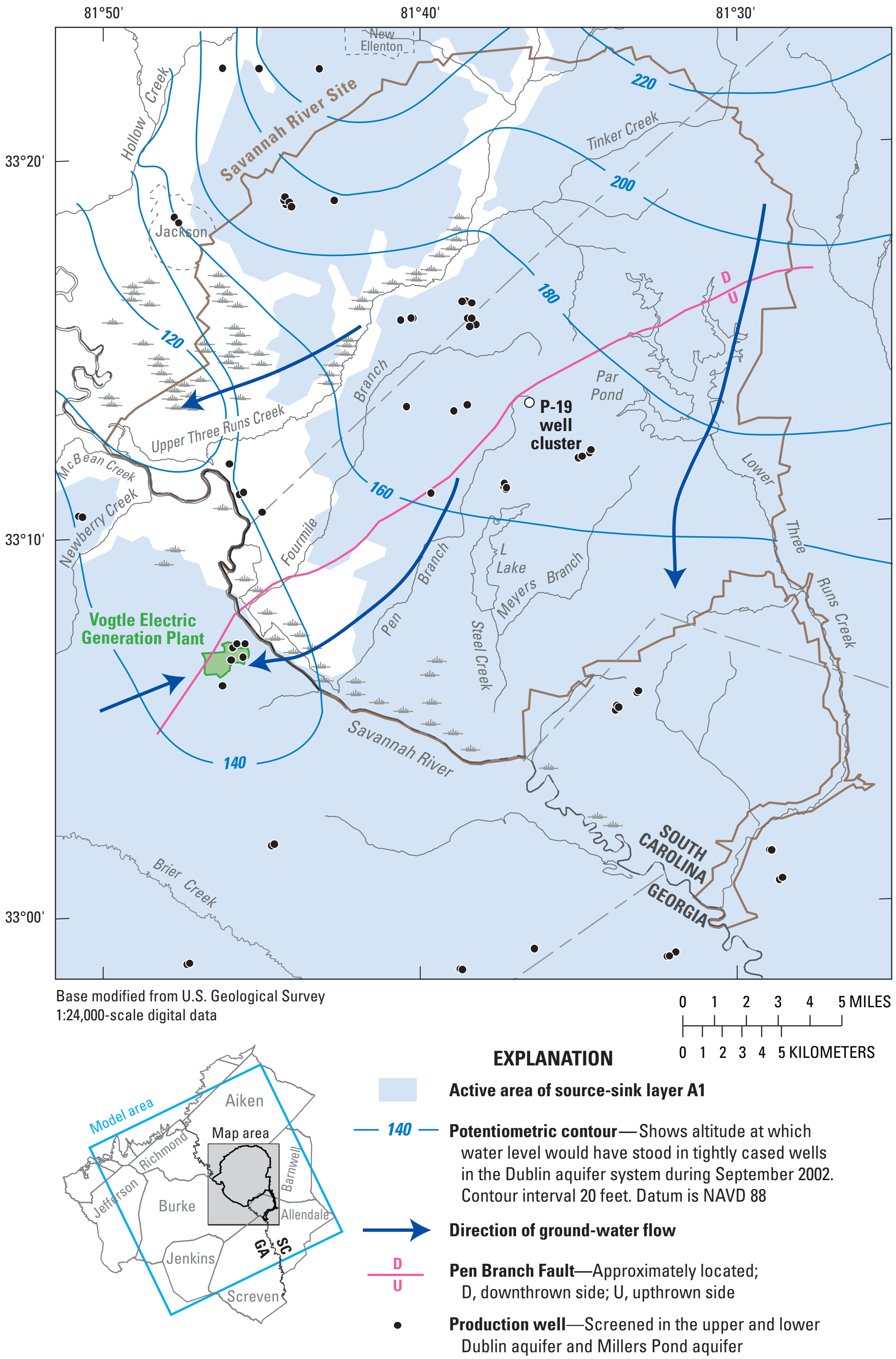


Figure 7. Potentiometric surface for the Dublin aquifer system, near Vogtle Electric Generation Plant, Georgia and South Carolina, September 2002 (modified from Cherry, 2003).

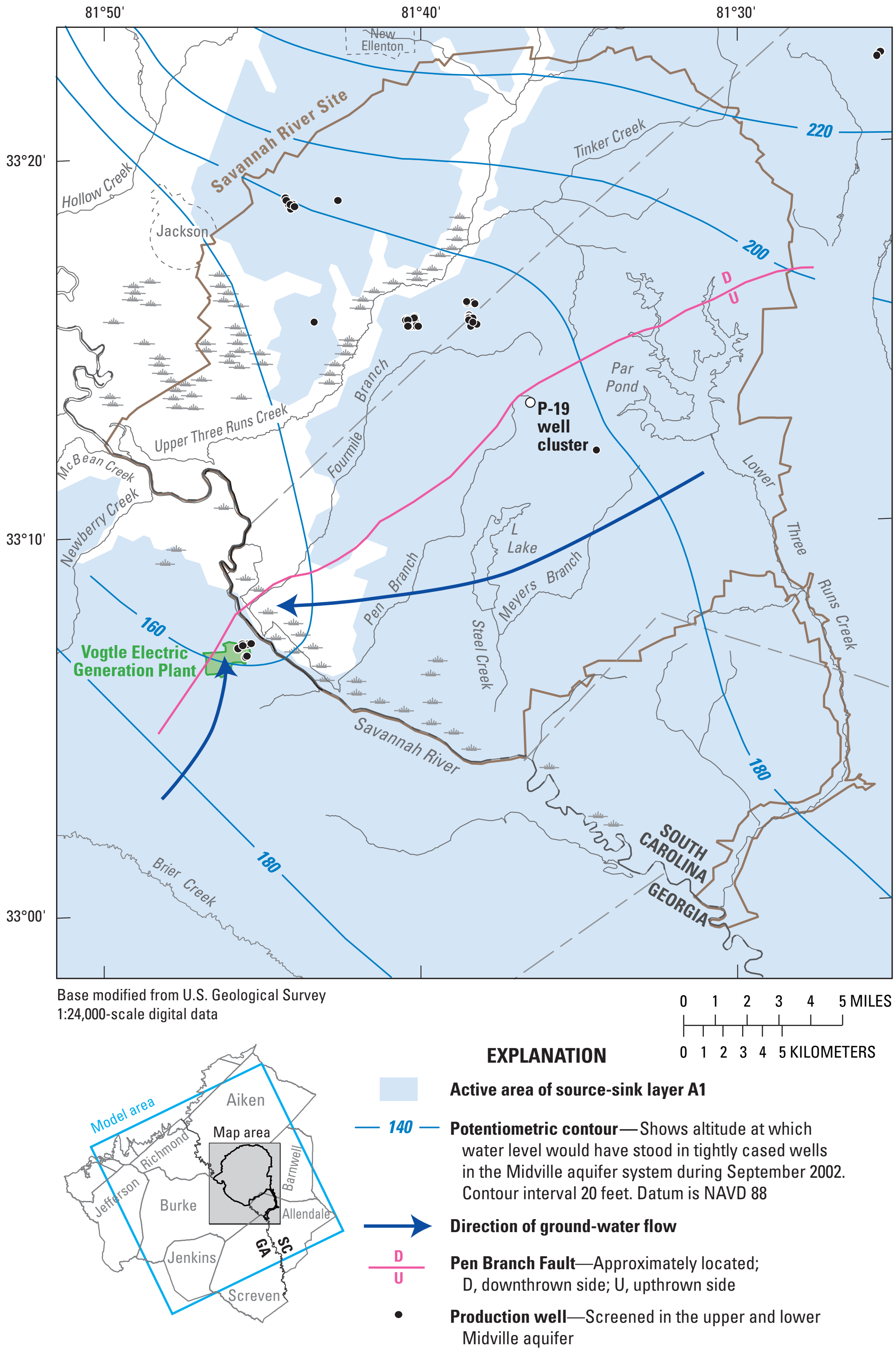


Figure 8. Potentiometric surface for the Midville aquifer system, near Vogtle Electric Generation Plant, Georgia and South Carolina, September 2002 (modified from Cherry, 2003).

Because flow directions derived from potentiometric-surface maps do not account for the vertical component of flow, Clarke and West (1998) applied the USGS particle-tracking code MODPATH (Pollock, 1994) to characterize three-dimensional ground-water flow near the Savannah River. This technique is applied in this report to simulate ground-water flowpaths from the production wells at VEGP to their recharge areas.

Trans-River Flow

Trans-river flow is a term that describes a condition whereby ground water originating on one side of a river migrates to the other side of the river through confined aquifers that underlie the river. Although some ground water could discharge into the river floodplain or alluvium on the opposite side of the river from its point of origin, this flow likely would return to the river. Return flow would occur because a slight hydraulic gradient exists toward the river along the floodplain. Flow lines on potentiometric-surface maps of the confined Gordon aquifer and Dublin and Midville aquifer systems (figs. 6–8) suggest possible occurrences of trans-river flow for a short distance into Georgia prior to discharge into the Savannah River (Clarke and West, 1997). Flow lines on the map for the Upper Three Runs aquifer, however, do not indicate trans-river flow (fig. 5).

Effect of Pen Branch Fault

The Pen Branch Fault may have a local effect on ground-water flow. In the central part of the SRS, water levels in the Gordon aquifer near the P-19 well cluster site are anomalously high, producing a mound in the potentiometric surface (fig. 6). The high water level in this area may be the result of the offset of the Pen Branch Fault, whereby sediments of the Gordon aquifer are juxtaposed against sediments of the Upper Three Runs aquifer (Aadland and others, 1991). Because the units are in hydraulic connection near the fault, water levels and water chemistry of the Gordon aquifer are similar to those of the Upper Three Runs aquifer (Clarke and West, 1997).

Ground-Water Use

Ground-water use in the study area during 2000–2002 (W.J. Stringfield, U.S. Geological Survey, written commun., 2002; Fanning, 2003) was about 117 million gallons per day (Mgal/d) (table 1), most of which was for irrigation (54 percent) and public supply (26 percent). In Georgia, most of the ground water used for irrigation is withdrawn from the Upper Three Runs aquifer in Jenkins County and southern Screven County, and from the Upper Three Runs and Gordon aquifers in Jefferson, Burke, and northern Screven Counties. In South Carolina, most irrigation wells in Barnwell and Allendale Counties pump water from the Upper Three Runs and Gordon aquifers. Ground-water use for public supply and industrial and mining purposes is mainly from the Dublin and Midville aquifer systems in both States.

Table 1. Ground-water use during 2000–2002 near Vogtle Electric Generation Plant, Burke County, Georgia.

[Modified from Cherry, 2006]

State	County[1]	Pumpage, in million gallons per day						
		Public supply	Irrigation	Industrial and mining	Domestic and commercial	Livestock	Thermo-electric	Total
Georgia	Burke	3.87	21.23	0.15	0.90	0.03	0.78	26.96
	Jefferson	1.84	6.92	3.82	0.64	0.03	0.00	13.25
	Jenkins	0.54	3.94	0.01	0.33	0.02	0.00	4.84
	Richmond	14.88	5.22	2.87	0.22	0.02	0.00	23.21
	Screven	1.15	15.62	1.82	0.74	0.03	0.00	19.36
South Carolina	Aiken	4.82	0.98	6.06	0.80	0.00	0.00	12.66
	Allendale	1.20	5.62	2.50	0.27	0.00	0.00	9.59
	Barnwell	2.73	3.73	0.41	0.63	0.00	0.00	7.50
Total—Georgia		**22.28**	**52.93**	**8.67**	**2.83**	**0.13**	**0.78**	**87.62**
Total—South Carolina		**8.75**	**10.33**	**8.97**	**1.70**	**0.00**	**0.00**	**29.75**
Total—eight counties		**31.03**	**63.26**	**17.64**	**4.53**	**0.13**	**0.78**	**117.37**

[1]See figure 1A for location

Data sources: County totals for Georgia are from Fanning (1997, 2003) and Pierce and others (1982); total water-use data for South Carolina from Lonon and others (1983), and W.J. Stringfield (U.S. Geological Survey, written commun., 2002); site-specific data for irrigation wells located in Georgia from J.L. Fanning (U.S. Geological Survey, written commun., 2003) and V. P. Trent (Georgia Geologic Survey, written commun., 2003); and site-specific data for permitted wells located in South Carolina from Paul Bristol and Peter Stone (South Carolina Department of Health and Environmental Control, written commun., 2003).

At VEGP, three wells are each screened in the lower Dublin and upper and lower Midville aquifers, and are used to supply water to operating reactor Units 1 and 2 (wells 31Z002, 31Z003, and 31Z080; fig. 1B; table 2). Screened intervals of wells at VEGP were obtained from drillers records and entered into the USGS National Water Information System (*http://waterdata.usgs.gov/ga/nwis/inventory*). To determine the aquifer supplying water to each screened interval, altitudes of screened intervals were compared to maps showing the altitude of the tops of hydrogeologic units using a Geographic Information System (Harrelson and others, 1997).

During 2002, the wells at VEGP supplied an average 724 gal/min (1.04 Mgal/d). The addition of two additional reactor units is projected to result in an increase in ground-water pumping of 1.09 Mgal/d (Mark Notich, U.S. Nuclear Regulatory Commission, written commun., April 10, 2007). If ground-water pumping during the startup of these reactors is similar to that during the startup of the original two reactors during 1988, then the initial increase in pumping could be as high as 3.42 Mgal/d.

At SRS, estimated pumpage was 5.30 Mgal/d during 2002 (Cherry, 2006). A variety of multiaquifer wells completed in the Gordon aquifer and Dublin and Midville aquifer systems provide water supply at SRS.

Simulation of Ground-Water Flow

The model used in this study is described in detail in Clarke and West (1998) and Cherry (2006); only a brief description is included herein. Clarke and West (1998) simulated predevelopment and 1987–92 conditions using the MODFLOW finite-difference simulator (McDonald and Harbaugh, 1988). Cherry (2006) updated the model to simulate 2002 hydrologic conditions using the MODFLOW-2000 simulator (Harbaugh and others, 2000). Both studies simulated steady-state conditions for each time period. Steady-state simulations were deemed appropriate because of the minimal observed changes in hydraulic head or ground-water discharge to streams from predevelopment (pre-1953) to 1987–92 (Clarke and West, 1997). These minor fluctuations are an indication that the ground-water system generally was in a state of equilibrium and any contributions from aquifer storage were minor. These assumptions are believed to remain valid for the study area for this investigation.

The model encompasses an area of about 4,455 mi^2 (fig. 1) and includes seven aquifers and seven confining units. These units crop out near the Fall Line and generally dip and thicken to the southeast. Aquifer units are, in descending order (fig. 2):

Table 2. Location and construction information for production wells at Vogtle Electric Generation Plant, Burke County, Georgia.

[USGS, U.S. Geological Survey; °, degree; ', minute; ", second; Aquifer: LD, lower Dublin; UM, upper Midville; LM, lower Midville]

USGS well identification[1]	Well number	Latitude	Longitude	Land-surface altitude (feet)	Year constructed	Screened interval (feet below land surface)		Aquifer	Production capacity (gallons per minute)
						Top	Bottom		
31Z002	TW-1	33°08'28"	81°45'42"	219	1972	505	535	LD	1,200
						555	585	LD	
						695	705	UM	
						730	750	UM	
						815	850	LM	
31Z080	MU-2A	33°08'39"	81°46'00"	235	1983	480	510	LD	2,112
						550	570	LD	
						630	650	LD	
						690	790	UM	
31Z003	[2]MU-1	33°08'47"	81°45'37"	197	1977	437	462	LD	3,334
						468	483	LD	
						498	512	LD	
						536	546	LD	
						550	572	LD	
						676	696	UM	
						720	732	LM	
						788	820	LM	

[1]See figure 1B for location

[2]Now called MU-5

- the unconfined Upper Three Runs aquifer modeled as a source-sink layer (specified head layer A1);
- the confined Gordon aquifer (layer A2);
- the Dublin aquifer system consisting of the Millers Pond aquifer (layer A3), upper Dublin aquifer (layer A4), and lower Dublin aquifer (layer A5); and
- the Midville aquifer system consisting of the upper Midville aquifer (layer A6) and lower Midville aquifer (layer A7).

The thickness, extent, and other hydraulic properties of these units, as well as the model development process are described in detail in Clarke and West (1998). A schematic diagram showing model layers and boundary conditions is shown in figure 2. As in the original model of Clarke and West (1998), confining units are not actively simulated, but instead use vertical conductance to simulate leakance between layers. Estimated and calibrated transmissivity values are listed in table 3 and leakance values are listed in table 4 (Clarke and West, 1998). For the MODPATH particle-tracking analysis, a uniform porosity of 30 percent was assigned to aquifer layers and 50 percent was assigned to confining units (Clarke and West, 1998).

The finite-difference grid for the model is aligned nearly parallel to the Savannah River and to the regional dip of the hydrogeologic units, and consists of 130 rows and 102 columns (13,260 grid cells) with a variable grid spacing ranging in size from 0.33 mi by 0.33 mi to 2 mi by 2.5 mi (fig. 1A). The model grid area encompasses about 4,455 mi_2, of which about 3,250 mi is actively simulated. Grid density is higher near the Savannah River (including the Savannah River Site and VEGP) to enable simulation of steeper head gradients (fig. 1A). Each aquifer unit is represented with one layer of grid cells in the vertical dimension.

Table 3. Simulated and estimated values for transmissivity, Vogtle Electric Generation Plant model, Georgia and South Carolina.

[#, number; from Clarke and West (1998)]

Aquifer	Layer number	Transmissivity, in square foot per day						
		Estimated based on field data[1]				Simulated		
		# of values	Minimum	Maximum	Mean	Minimum	Maximum	Mean[2]
Gordon aquifer	A2	18	180	12,200	4,500	100	24,700	10,350
Millers Pond aquifer	A3	10	195	2,000	1,000	10	3,900	1,310
Upper Dublin aquifer	A4	17	555	25,200	5,830	10	20,000	7,220
Lower Dublin aquifer	A5	21	40	8,900	3,940	10	25,500	10,030
Upper Midville aquifer	A6	15	1,300	5,430	2,760	10	12,390	6,270
Lower Midville aquifer	A7	37	800	25,500	8,900	515	34,395	19,020

[1]Determined from aquifer tests and estimated from specific-capacity data and from borehole-resistivity logs.

[2]Mean value weighted according to cell area.

Table 4. Simulated and estimated values for leakance, Vogtle Electric Generation Plant model, Georgia and South Carolina.

[#, number; —, not measured; from Clarke and West (1998)]

Hydrogeologic unit	Layer number	Leakance, in feet per day per foot of confining unit thickness[1]						
		Estimated leakance[2]				Simulated		
		# of values	Minimum	Maximum	Mean	Minimum	Maximum	Mean[3]
Gordon confining unit	C1	6	4.7×10^{-6}	1.2×10^{-2}	2.1×10^{-3}	9.0×10^{-8}	1.3×10^{-3}	1.7×10^{-4}
Millers Pond confining unit	C2	—	—	—	—	3.9×10^{-6}	8.7×10^{-1}	1.9×10^{-2}
Upper Dublin confining unit	C3	9	1.8×10^{-6}	1.6×10^{-3}	3.6×10^{-4}	1.2×10^{-6}	7.3×10^{-3}	1.2×10^{-3}
Lower Dublin confining unit	C4	1	2.4×10^{-5}	2.4×10^{-5}	2.4×10^{-5}	3.0×10^{-7}	6.5×10^{-3}	6.6×10^{-3}
Upper Midville confining unit	C5	11	6.7×10^{-7}	3.4×10^{-4}	7.6×10^{-5}	2.1×10^{-7}	1.0×10^{-1}	9.7×10^{-4}
Lower Midville confining unit	C6	1	1.0×10^{-5}	1.0×10^{-5}	1.0×10^{-5}	7.7×10^{-5}	3.6×10^{-1}	9.0×10^{-3}

[1]Includes low permeability layers within aquifer layers.

[2]Estimated by dividing the vertical hydraulic conductivity unit by the thickness of the confining unit.

[3]Mean value weighted according to cell area.

Lateral model boundaries are a combination of no-flow and specified head for layers A2–A7. For all layers, the southeastern boundary is simulated as a specified-head condition. For layers A2–A3, the southwestern boundary is simulated as no-flow, corresponding to the position of a ground-water divide. Parts of the eastern boundary for layers A2 and A3 are simulated as specified head and no-flow. For layers A4–A7, most of the western boundary is simulated as no-flow, corresponding to the position of a ground-water divide. The eastern boundary for layers A4–A7 is simulated mostly as a specified-head condition. Specified heads for each layer in the model are based on potentiometric surface maps for September 2002 (figs. 5–8) and generally are lower than in the original Clarke and West (1998) model to reflect effects of the 1998–2002 drought (Cherry, 2006).

The bottom boundary of the model is no-flow, whereas the top boundary represented by layer A1 is set as a source-sink specified-head condition with controlling specified heads based on water levels from the 2002 potentiometric-surface map of the Upper Three Runs aquifer (Cherry, 2003). Flow in the deeper active layers (A2–A7) of the model is simulated through a combination of active cells, specified head cells, recharge cells, and river cells.

Most recharge to the simulated ground-water system was provided by leakage from layer A1, with a comparatively smaller amount derived from recharge cells in layers A2–A7. Total simulated recharge is about 930 Mgal/d of which 777 Mgal/d were derived by leakage from layer A1, and 153 Mgal/d were derived from recharge assigned to outcrop areas of hydrogeologic units (Cherry, 2006).

Average annual pumpage for 2002 was assigned to model cells based on site-specific and county-aggregate data (table 1). Site-specific data are available for public supply, thermoelectric, industrial, and mining use and are assigned to known well locations. County aggregate agricultural pumping data were equally divided and assigned to known agricultural well locations Domestic and commercial and livestock use were not simulated by the model because these uses accounted for less than 4 percent of total study area pumpage during 2002 (table 1) with most of the withdrawal derived from shallow wells completed in the Upper Three Runs aquifer.

Where multi-aquifer wells are completed in several aquifer layers (such as at VEGP and SRS), pumpage was evenly proportioned to the various screened intervals in each well. Of the total study area ground-water use during 2000–2002 of 117 Mgal/d, 67.2 Mgal/d were simulated from active layers (table 5) A2 (Gordon aquifer), A3 (Millers Pond aquifer), A4 (upper Dublin aquifer), A5 (lower Dublin aquifer), A6 (upper Midville aquifer), and A7 (lower Midville aquifer). The remaining 49.8 Mgal/d were from the Upper Three Runs aquifer (layer A1), which is not actively simulated. The influence of pumpage from the Upper Three Runs aquifer on the overall flow system during 2002 is simulated by changing the head in that layer based on water-level measurements during September 2002 (fig. 5).

Table 5. Simulated pumpage by model layer for 2002 Base Case, Vogtle Electric Generation Plant model, Georgia and South Carolina.

[Modified from Cherry, 2006]

Aquifer	Model layer	Year 2002 pumpage, in million gallons per day
Gordon	A2	10.7
Millers Pond	A3	7.3
Upper Dublin	A4	5.4
Lower Dublin	A5	14.6
Upper Midville	A6	9.8
Lower Midville	A7	19.4
All layers		**67.2**

The calibrated model used for this study showed a reasonable fit to simulated water levels. Water-level residuals represent the difference between simulated and observed water levels, with positive values indicating that simulated values were greater than observed values. For the 1987–92 simulation, the model was calibrated using the average observed water levels at 313 model cells, with a mean of residuals of 0.8 ft and a root mean square (RMS) of the residuals of 10.6 ft (Clarke and West, 1998). For the 2002 simulation, model calibration was evaluated based on observations at 172 wells during September 2002, with a mean of residuals of 2.8 ft and a RMS of the residuals of 8.0 ft (Cherry, 2006).

Pen Branch Fault

The Pen Branch Fault may locally affect ground-water flow in the study area (see Effect of Pen Branch Fault section). Although hydraulic characteristics of the fault are unknown, the possible effects of the fault are incorporated into the model as follows: (1) by variations in depth, thickness, and hydraulic properties of model layers near the fault; and (2) by incorporation of river cells where incision of the Gordon aquifer (layer A2) is believed to occur along the southern side of the fault in the Savannah River alluvial valley (fig. 1A).

Hydraulic properties of the upper and lower Dublin aquifers (model layers A4 and A5) were adjusted along the southern side of the fault during model calibration (Clarke and West, 1998). A zone of high transmissivity—greater than 15,000 feet squared per day (ft^2/d) and extending as much as 6 mi south of the fault—was required in the two layers to achieve calibration of the model. Although there are no field data to confirm this zone of higher transmissivity, it is possible that such a zone exists based on calibration results. Construction of test wells and aquifer testing in this area would be required to confirm the presence of a high transmissivity zone.

Maps showing the altitude of the top of hydrogeologic units (Falls and others, 1997) indicate that uplift along the southern side of the Pen Branch Fault resulted in shallower depths of units compared to equivalent units north of the fault. Near the Pen Branch Fault and the P-19 well cluster site on SRS, simulated head values for the Gordon aquifer (layer A2) during 1987–92 are considerably lower than observed values, with a residual of –81.1 ft (Clarke and West, 1998). Clarke and West (1997) reported that the anomalously high observed head in the Gordon aquifer in this area may be the result of (1) a high degree of aquifer interconnection between the Upper Three Runs and Gordon aquifers due to the Pen Branch Fault (Aadland and others, 1991), or (2) the possibility that the water-level measurement in the Gordon aquifer at the P-19 well cluster site may not be representative of the head in layer A2 because of problems with well construction or measurement error. Because the reason for the high water level in the Gordon aquifer was not definitively established, the earlier study (Clarke and West, 1998) did not adjust model parameters to attempt to match water levels in the Gordon aquifer at the P-19 well cluster. Simulation of higher head in the Gordon aquifer in this area would require increasing the leakance of the Gordon confining unit (layer C1) to enable greater connection between the Upper Three Runs and Gordon aquifers.

In the Savannah River valley, uplift along the southern side of the Pen Branch Fault and erosion by the paleo-Savannah River appears to have resulted in exposure of the Gordon aquifer (layer A2) in a local area (fig. 3). This local exposure is simulated in the model as river cells in the Gordon aquifer that enables a higher degree of connection between the Gordon aquifer and the Savannah River (fig. 1B). Despite this adjustment, simulated water levels in the Gordon aquifer (layer A2) near this feature during 2002 generally are high in the model, ranging from 4 to 26 ft higher than observed levels (wells 31Z015, 31Z073, 31Z074, 31Z076, and 31Z077; fig. 6).

Another area where uplift on the southern side of the fault is represented by the model occurs between Pen Branch and Four Mile Branch on SRS (fig. 1B). In this upland area adjacent to the Savannah River Valley, units overlying the Gordon aquifer appear to have been eroded away and the aquifer is near land surface. Here, the Gordon aquifer is simulated using recharge cells, which enable direct infiltration of precipitation into the aquifer.

Several hypothesized channel features (Summerour and others, 1998) along a seismic profile near the Pen Branch Fault in eastern Burke County, Ga., were not incorporated into the ground-water model because their existence was not confirmed by test drilling. According to Summerour and others (1998), these features potentially could affect a zone 3,000 ft wide and 500 ft deep, and provide a potential pathway for movement of ground water between aquifers. If such a feature were simulated, high vertical hydraulic conductivity would be assigned to confining units overlying layers A2–A7, and would facilitate movement of water between the zones. This modification could result in reducing the simulated head in the Gordon aquifer by allowing water to discharge from the unit and would reduce the aforementioned difference between observed and simulated head. Because the presence, depth, and areal extent of these features, are unknown, they were not simulated by the current model.

Ground-Water Pumping Scenarios

The updated and calibrated model (Cherry, 2006) was used to simulate the effect of current and potential future pumping on ground-water levels and flowpaths near VEGP for a Base Case and three pumping scenarios (table 6). The Base Case represents 2002 pumping rates throughout the model area (Cherry, 2006). The three scenarios were designed to simulate steady-state water levels resulting from (1) pumping increases at VEGP with pumping elsewhere in the study area held at 2002 rates (Scenarios A and C), and (2) the effects of increased pumping at VEGP combined with a shutdown of pumping at the SRS (Scenario B).

Steady-state conditions in response to pumping changes are believed to be reached rapidly in the study area. Clarke and West (1998) indicated that for each of six stress periods during 1953–92, "heads showed an almost instantaneous stabilization, suggesting that the prevalence of steady-state conditions were achieved immediately following a change in pumpage." For each scenario, the pumping distribution, simulated water-level changes, and ground-water flowpaths are described relative to the year 2002 Base Case.

A particle-tracking analysis was conducted for the Base Case and for each scenario to determine the source of water withdrawn from the VEGP production wells. The USGS particle-tracking code MODPATH (Pollock, 1994) was used to generate advective water-particle pathlines and their associated time of travel based on the MODFLOW simulations. MODPATH was used to compute three-dimensional flow directions and time of travel using imaginary particles in a backtracking mode from the production wells at VEGP toward recharge areas in a map perspective. Generally, the greater the number of particles applied vertically and horizontally in a model cell, the more accurate the definition of flowpaths for a given model layer. For this study, particles were placed at the center of each of the three grid cells containing a VEGP production well at increments representing 10 percent of the aquifer thickness (10 total particles per aquifer layer in each of the three grid cells). Particles were placed in the lower Dublin (layer A5), and upper (layer A6) and lower Midville (layer A7) aquifers, which provide water to the VEGP production wells. To avoid clutter and simplify display of particle flowpaths on maps, the number of particles displayed on the figure was reduced from 10 to 5. Simulated time of travel for all particles (10 per model cell) is summarized for the Base Case and for Scenarios A–C in table 7.

Table 6. Simulated pumpage at Vogtle Electric Generation Plant, Burke County, Georgia, for 2002 Base Case and pumping Scenarios A, B, and C.

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

Scenario	Pumping rate		Remarks
	gal/min	Mgal/d	
Base Case 2002	724	1.04	Current conditions for existing reactor units
A	1,482	2.13	Additional pumping capacity of new reactor units at average projected withdrawal rates
B	1,482	2.13	Additional pumping capacity of new reactor units at average projected withdrawal rates and elimination of 5.3 Mgal/d pumpage at Savannah River Site
C	3,099	4.46	Scenario represents a higher rate of withdrawal for the proposed new reactor units during their startup period (3.42 Mgal/d), and continuation of year 2002 pumping rates (1.04 Mgal/d) in the existing reactor units. The higher withdrawal in the new reactors is similar to that reported during 1988 for the startup of the existing reactors. Southern Nuclear Company has noted that the high pumping rates during startup of Units 1 and 2 were related to achieving water-quality criteria and not to ground-water demand by the facilities. Water treatment methods are now used to achieve the water-quality criteria and have greatly reduced ground-water pumping rates (Mark Nodich, U.S. Nuclear Regulatory Commission, written commun., September 10, 2007).

Table 7. Summary of simulated time of travel for 2002 Base Case and for Scenarios A, B, and C, Vogtle Electric Generation Plant model, Georgia and South Carolina.

[Ten particles were assigned to each aquifer layer in 3 model cells for a total of 30 particles per layer]

Aquifer (model layer)	Statistic	Simulated time of travel in years			
		Base Case	Scenario		
		2002	A	B	C
Lower Dublin (A5)	Mean	2,700	2,700	2,700	3,800
	Median	2,700	2,600	2,700	3,000
	Maximum	3,600	3,700	3,900	12,600
	Minimum	2,100	2,100	2,100	1,800
Upper Midville (A6)	Mean	3,100	3,100	3,300	2,800
	Median	2,800	2,700	2,700	2,500
	Maximum	3,700	4,700	5,200	4,000
	Minimum	2,700	2,300	2,300	1,800
Lower Midville (A7)	Mean	3,100	3,100	3,200	2,800
	Median	2,900	2,800	2,800	2,500
	Maximum	3,800	4,200	4,600	4,000
	Minimum	2,700	2,400	2,400	2,400

2002 Base Case Condition

The year 2002 simulation represents the Base Case for comparison to each of the pumping scenarios. The simulated hydrologic condition during 2002 represents effects of the 1998–2002 drought in which irrigation pumpage was above average and recharge and boundary-condition head were low due to decreased precipitation. Results of model simulations for 2002 are presented in Cherry (2006); results of particle-tracking analyses at VEGP are presented herein.

The simulated 2002 potentiometric-surface maps for the Dublin and Midville aquifer systems (figs. 7 and 8, respectively) indicate VEGP is within the Savannah River regional ground-water discharge zone in which the principal direction of ground-water flow is toward the Savannah River. None of the various scenarios resulted in large changes in the configuration of the simulated potentiometric surface and related ground-water flow directions.

The source of water to the VEGP production wells, as indicated by MODPATH analysis for year 2002, is recharge occurring in an upland area near the county line between Burke and Jefferson Counties, Ga. (fig. 9), with none of the water originating on SRS or elsewhere in South Carolina. Simulated mean time of travel from recharge areas to the VEGP production wells are about 2,700 years (yr) in the lower Dublin aquifer and about 3,100 yr in the upper and lower Midville aquifers (table 7). The fastest simulated time of travel, about 2,100 yr, was for a particle in the lower Dublin aquifer, and the longest was about 3,800 yr for a particle in the lower Midville aquifer.

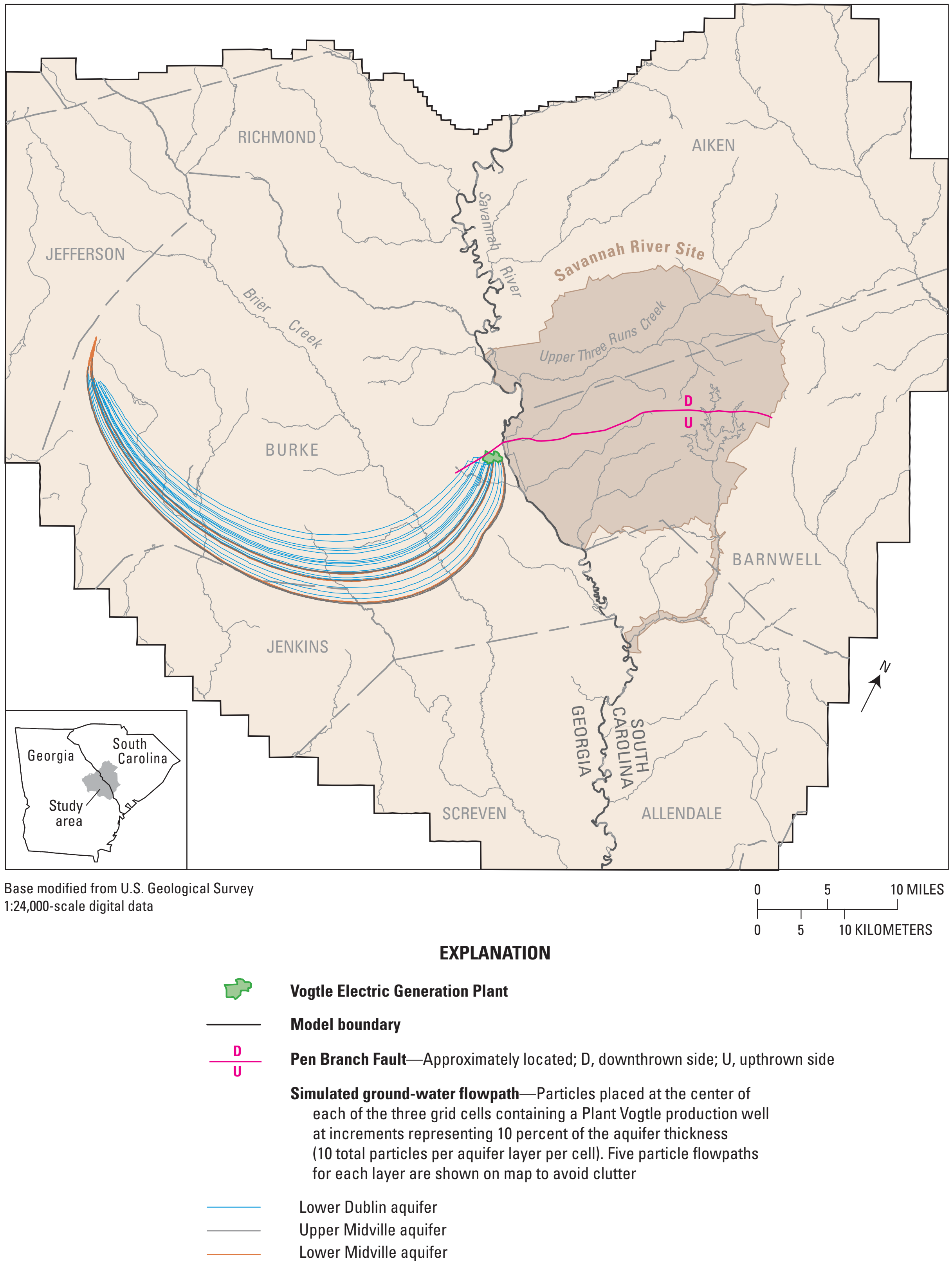


Figure 9. Particle-tracking results for the year 2002, Base Case, near Vogtle Electric Generation Plant, Georgia and South Carolina.

Scenario A

Scenario A simulates a 1.09-Mgal/d increase in average pumping rates at VEGP for the operation of existing reactors (Units 1 and 2) and an increase for the proposed new reactors (Units 3 and 4). The pumping increase was distributed evenly among the three production wells at VEGP. Simulated water-level changes are shown in figures 10–15; particle-tracking results are shown in figure 16 and listed in table 7.

For Scenario A, water-level changes were minimal, with maximum declines of greater than 0.25 ft in the Gordon aquifer (fig. 10), greater than 0.5 ft in the Millers Pond aquifer (fig. 11), greater than 1 ft in the upper and lower Dublin aquifers (figs. 12 and 13, respectively), and greater than 2 ft in the upper and lower Midville aquifers (figs. 14 and 15, respectively). Drawdown response in the shallow aquifers (Gordon, Millers Pond, and upper Dublin) is due to leakage through confining units in response to decreased head in the pumped zones (lower Dublin and upper and lower Midville aquifers). In the upper and lower Dublin and upper and lower Midville aquifers, the zone of pumping influence (defined as greater than 0.5 ft of change) extends from about 3 to 4.5 mi onto SRS in South Carolina (figs. 12–15).

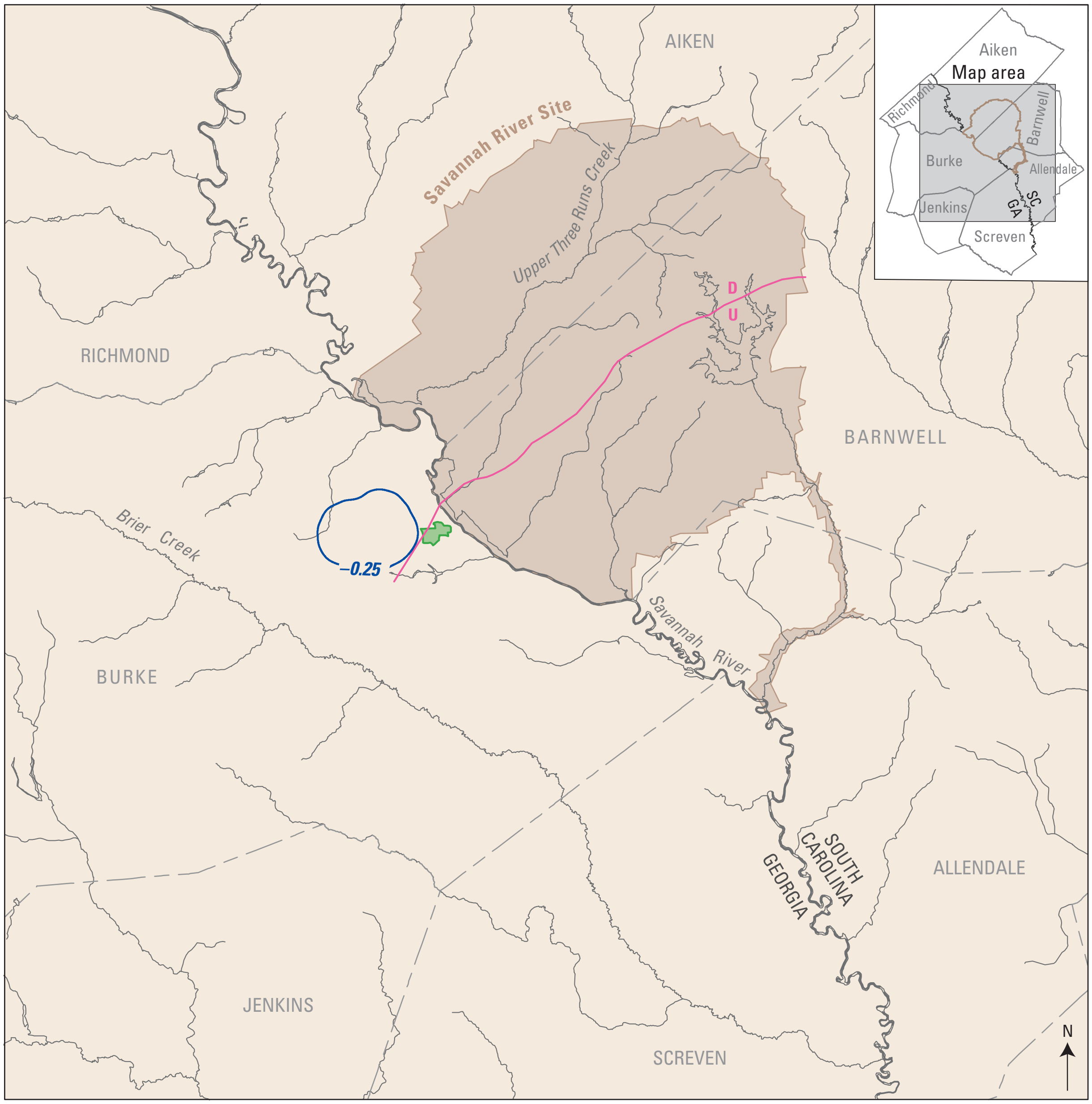
For Scenario A, the source of water to VEGP production wells, as indicated by MODPATH analysis, is recharge in an upland area near the county line between Burke and Jefferson Counties, Ga. (fig. 16). Simulation results indicate that none of the recharge originated on SRS or elsewhere in South Carolina, despite the small amount of drawdown extending into that area in the lower and upper Dublin and lower and upper Midville aquifers (figs. 12–15). Because vertical-head gradients are steep beneath the Savannah River alluvial valley, large changes in head are required to induce flow from the other side of the river. Mean simulated time of travel from recharge areas to the VEGP wells for Scenario A are about 2,700 yr in the lower Dublin aquifer and about 3,100 yr in the upper and lower Midville aquifers (table 7). The fastest simulated time of travel, about 2,100 yr, was for a particle in the lower Dublin aquifer and the slowest was about 4,700 yr for a particle in the upper Midville aquifer.

Scenario B

Scenario B simulates a 1.09-Mgal/d increase in pumping at VEGP, as was simulated in Scenario A, and total elimination of 5.3 Mgal/d pumping at the SRS facility (table 6). For this scenario, the 1.09 Mgal/d increase was distributed evenly among three production wells at VEGP completed in the lower Dublin and upper and lower Midville aquifers, and the 5.3 Mgal/d decrease was subtracted evenly among 12 production wells at the SRS completed in one or more of the following aquifers: Gordon, Millers Pond, upper and lower Dublin, and upper and lower Midville. Simulated water-level changes are shown in figures 17– 22; particle-tracking results are shown in figure 23 and listed in table 7.

For Scenario B, the largest water-level changes were on SRS, with maximum increases of greater than 4 ft in the Gordon aquifer, greater than 1 ft in the Millers Pond aquifer, greater than 4 ft in the upper Dublin aquifer (fig. 19), greater than 8 ft in the lower Dublin aquifer (fig. 20), and greater than 4 ft in the upper and lower Midville aquifers (figs. 21 and 22, respectively). At VEGP, the magnitude and extent of water-level decline resulting from increased pumping was less pronounced than that observed in Scenario A for an equivalent increase in pumping. The water-level rise resulting from elimination of SRS pumping reduced the effect of pumping at VEGP on ground-water levels. Maximum declines near VEGP were greater than 2 ft in the upper and lower Midville aquifers (figs. 21 and 22, respectively), greater than 1 ft in the lower Dublin aquifer (fig. 20), and greater than 0.5 ft in the upper Dublin aquifer (fig. 19). There was no observed change at VEGP in the overlying Gordon and Millers Pond aquifers (figs. 17 and 18, respectively).

Despite the large water-level rise at SRS, the source of water to VEGP production wells, as indicated by MODPATH analysis (fig. 23), remained nearly identical to Scenario A (fig. 16). Simulation results indicate that ground-water recharge is provided in an upland area near the county line between Burke and Jefferson Counties, Ga. (fig. 23), with a mean simulated time of travel of about 2,700 yr in the lower Dublin aquifer; about 3,300 yr in the upper Midville aquifer; and about 3,200 yr in the lower Midville aquifer (table 7). The fastest simulated time of travel was for a particle in the lower Dublin aquifer (about 2,100 yr), and slowest was for a particle in the upper Midville aquifer (about 5,200 yr). As was the case for Scenario A, none of the recharge originated on SRS or elsewhere in South Carolina.



Base modified from U.S. Geological Survey
1:24,000-scale digital data

0 5 10 MILES
0 5 10 KILOMETERS

EXPLANATION

Vogtle Electric Generation Plant

D / U **Fault**—Approximately located; D, downthrown side; U, upthrown side

−0.25 **Line of equal simulated water-level change**—Computed by subtracting the simulated potentiometric surface for 2002 Base Case from the simulated potentiometric surface for Scenario A (see table 6 for description of scenario)

Figure 10. Simulated water-level change for Scenario A in the Gordon aquifer, near Vogtle Electric Generation Plant, Georgia and South Carolina.

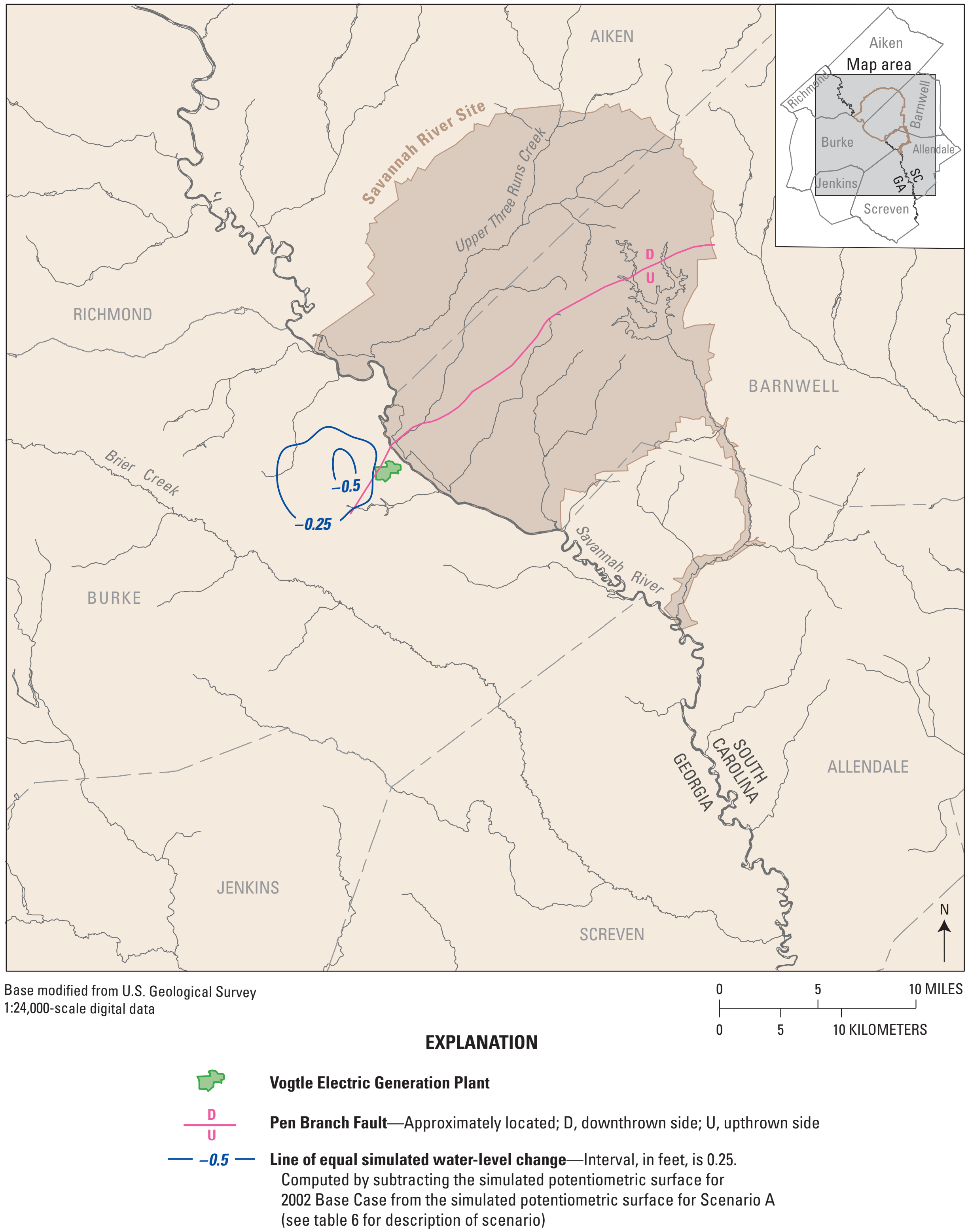


Figure 11. Simulated water-level change for Scenario A in the Millers Pond aquifer, near Vogtle Electric Generation Plant, Georgia and South Carolina.

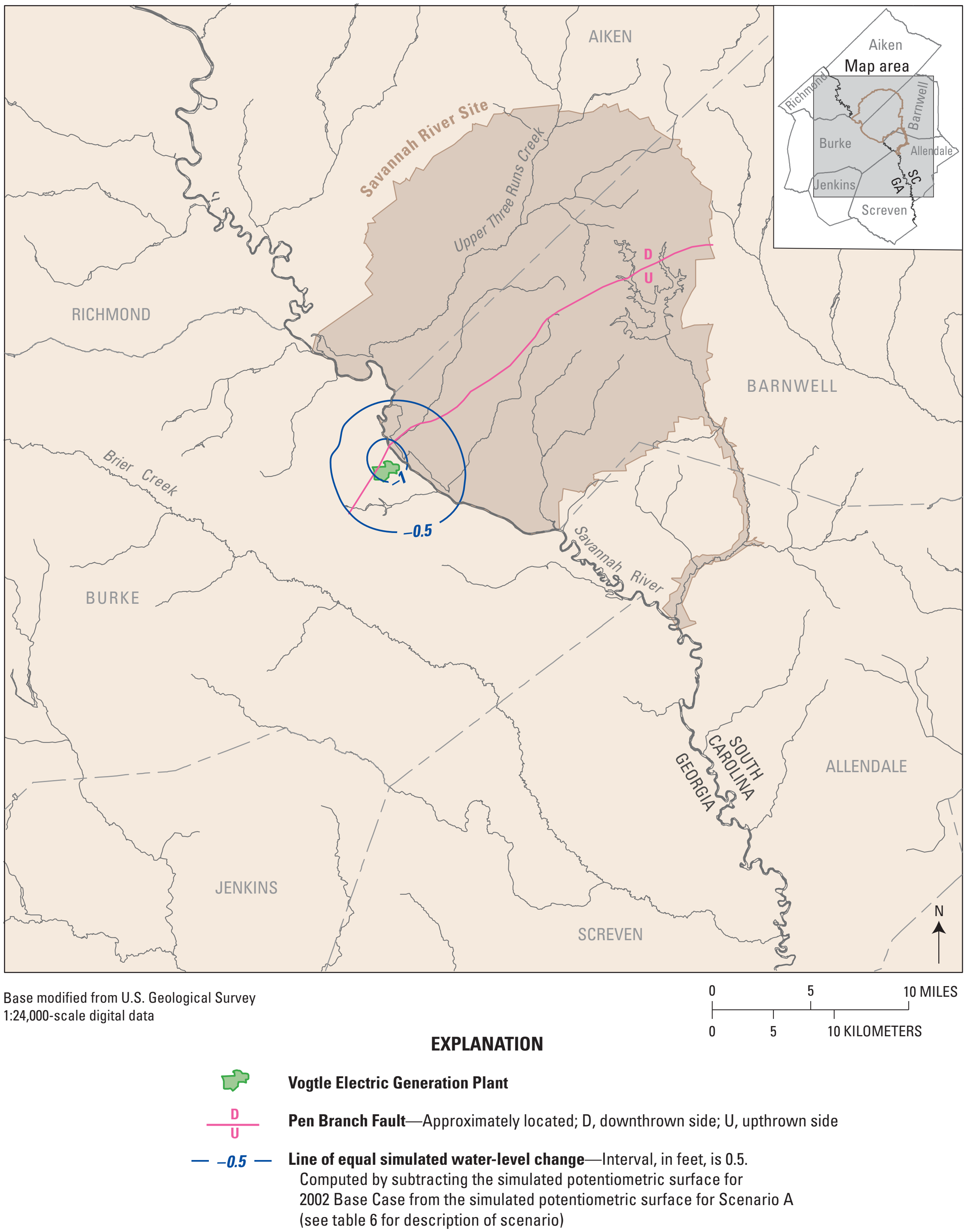
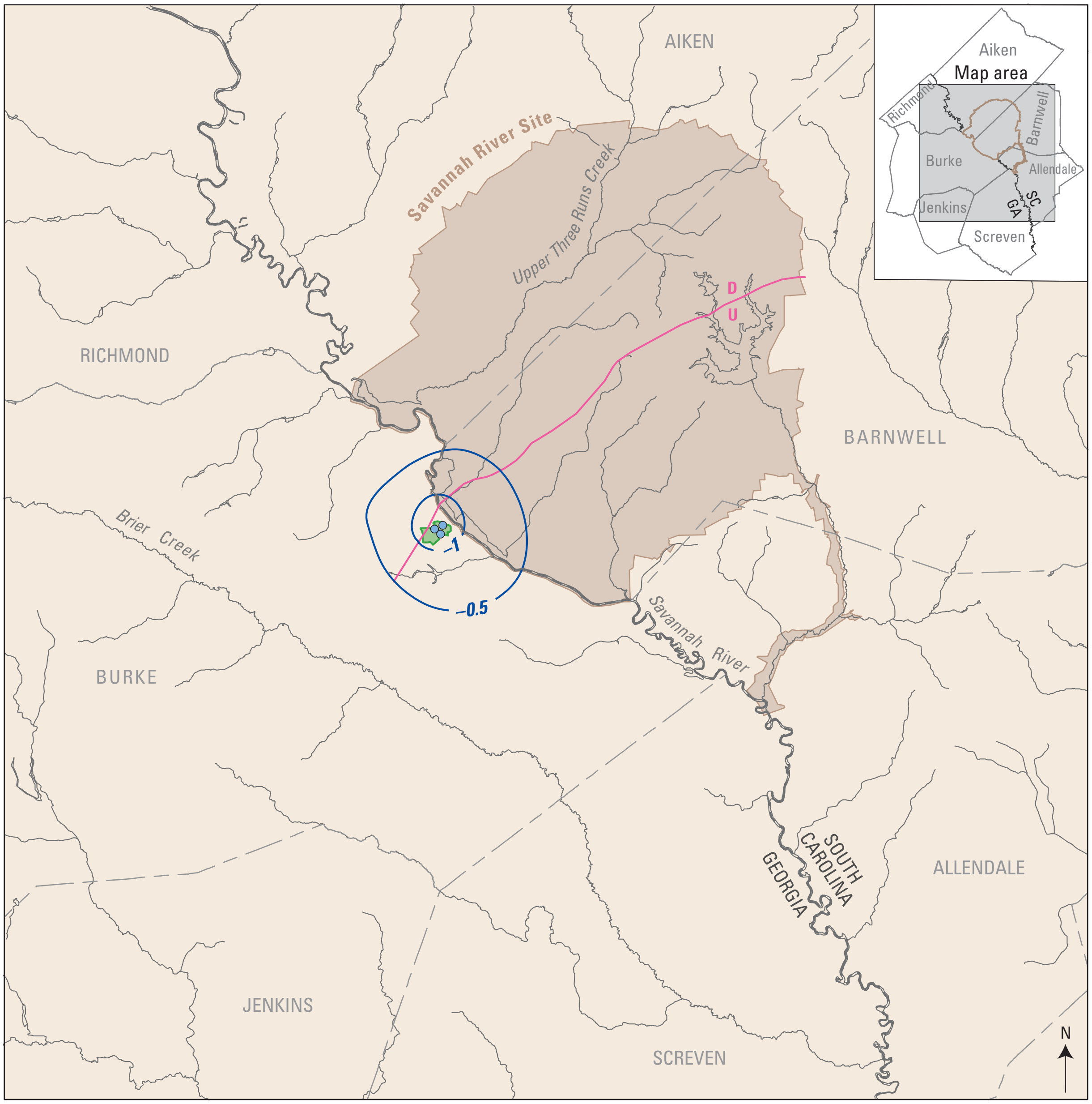


Figure 12. Simulated water-level change for Scenario A in the upper Dublin aquifer, near Vogtle Electric Generation Plant, Georgia and South Carolina.



Base modified from U.S. Geological Survey
1:24,000-scale digital data

0 5 10 MILES
0 5 10 KILOMETERS

EXPLANATION

Vogtle Electric Generation Plant

Pen Branch Fault—Approximately located; D, downthrown side; U, upthrown side

Line of equal simulated water-level change—Interval, in feet, is 0.5. Computed by subtracting the simulated potentiometric surface for 2002 Base Case from the simulated potentiometric surface for Scenario A (see table 6 for description of scenario)

Production well—Completed in the lower Dublin aquifer in which pumping was adjusted for scenario

Figure 13. Simulated water-level change for Scenario A in the lower Dublin aquifer, near Vogtle Electric Generation Plant, Georgia and South Carolina.

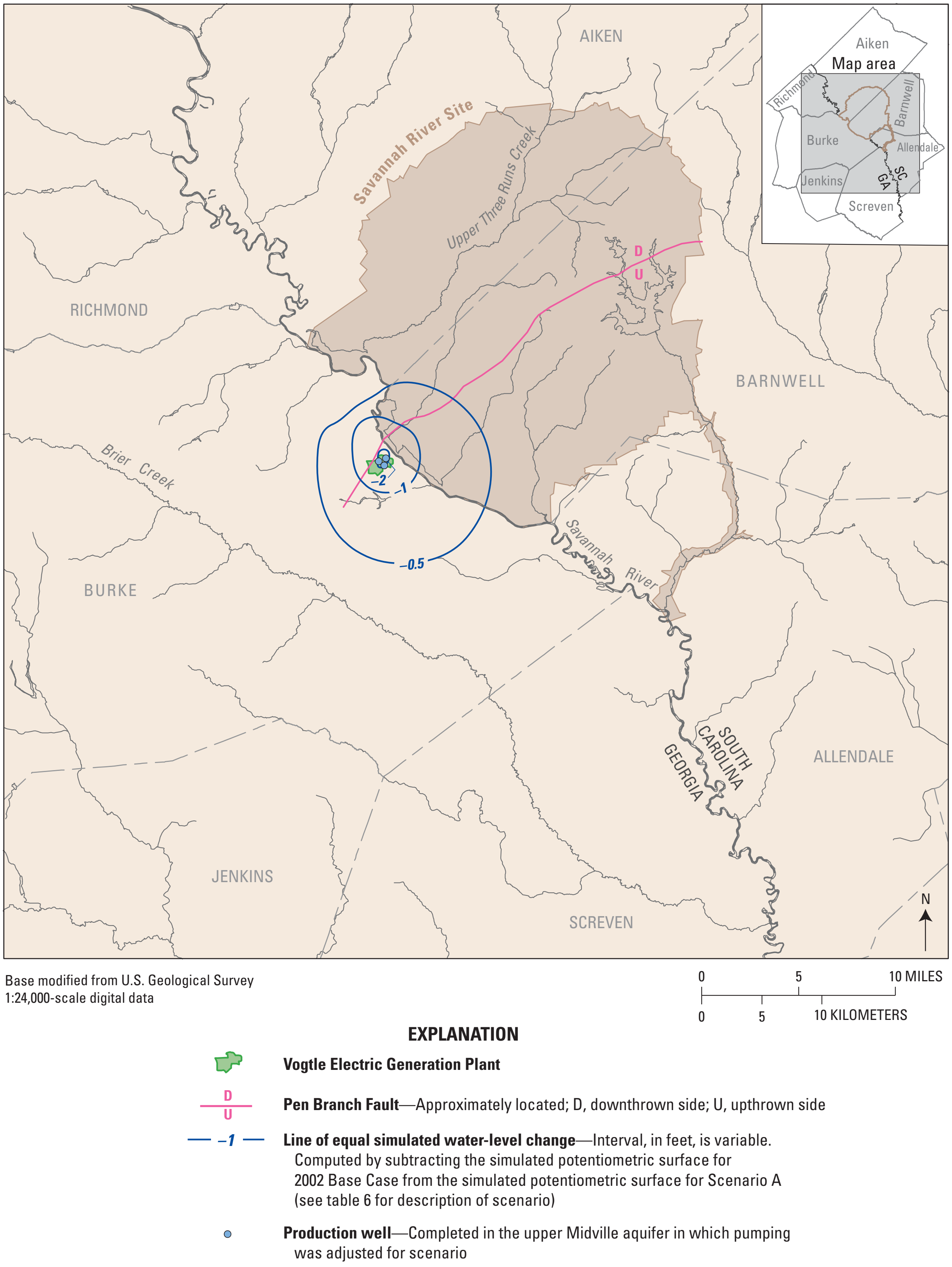
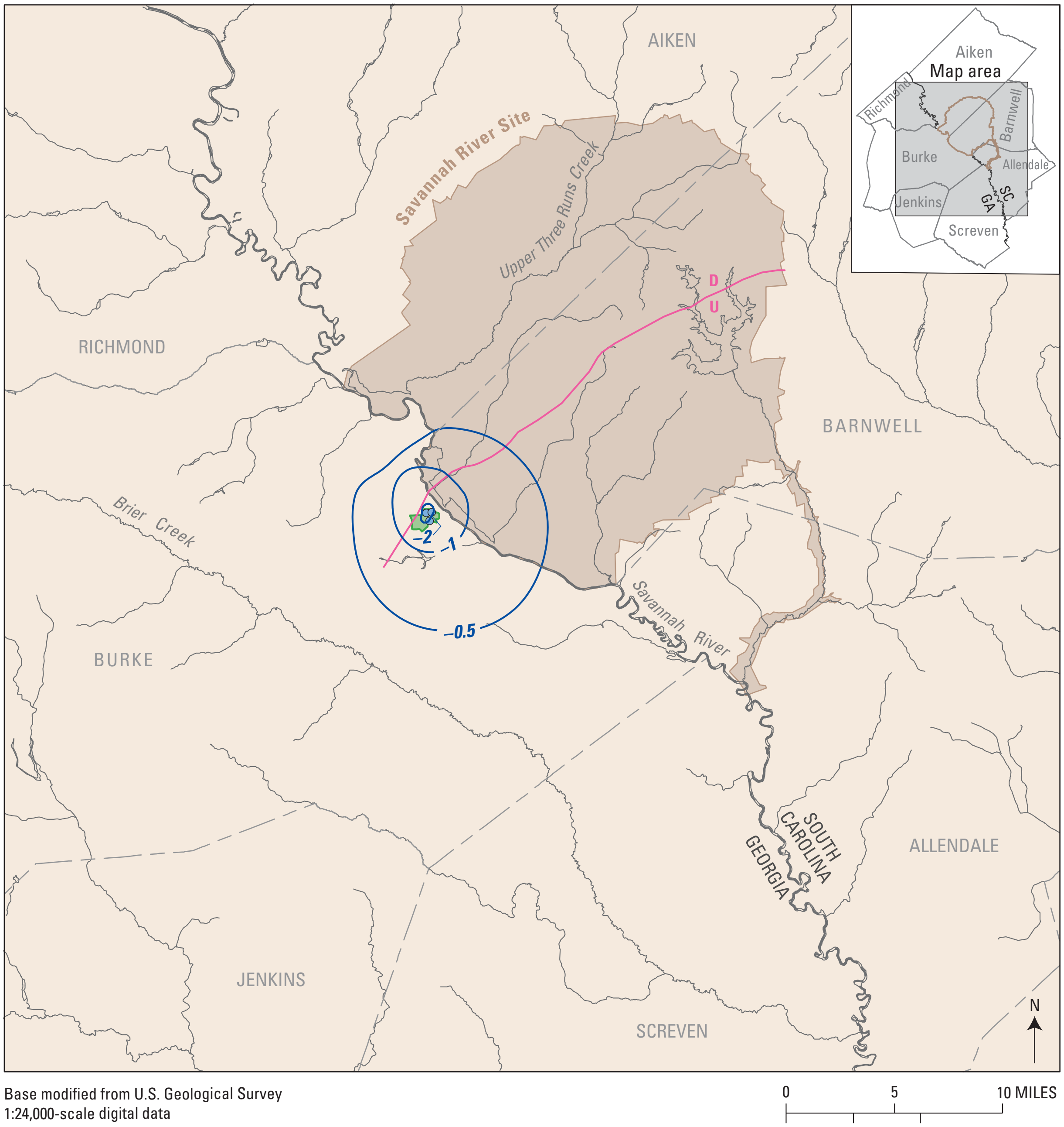


Figure 14. Simulated water-level change for Scenario A in the upper Midville aquifer, near Vogtle Electric Generation Plant, Georgia and South Carolina.



EXPLANATION

Vogtle Electric Generation Plant

D / U **Pen Branch Fault**—Approximately located; D, downthrown side; U, upthrown side

−1 **Line of equal simulated water-level change**—Interval, in feet, is variable. Computed by subtracting the simulated potentiometric surface for 2002 Base Case from the simulated potentiometric surface for Scenario A (see table 6 for description of scenario)

Production well—Completed in the lower Midville aquifer in which pumping was adjusted for scenario

Figure 15. Simulated water-level change for Scenario A in the lower Midville aquifer, near Vogtle Electric Generation Plant, Georgia and South Carolina.

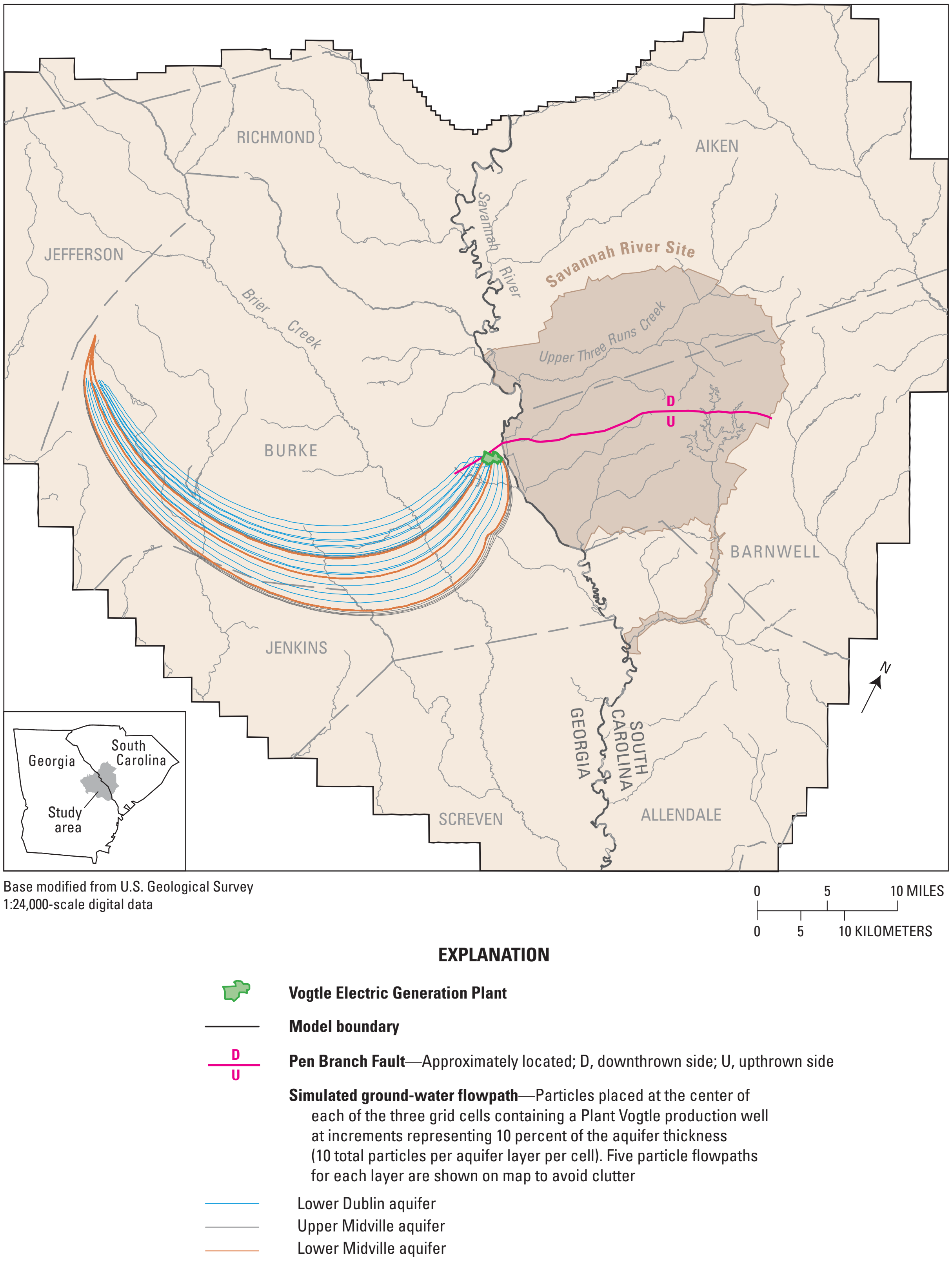
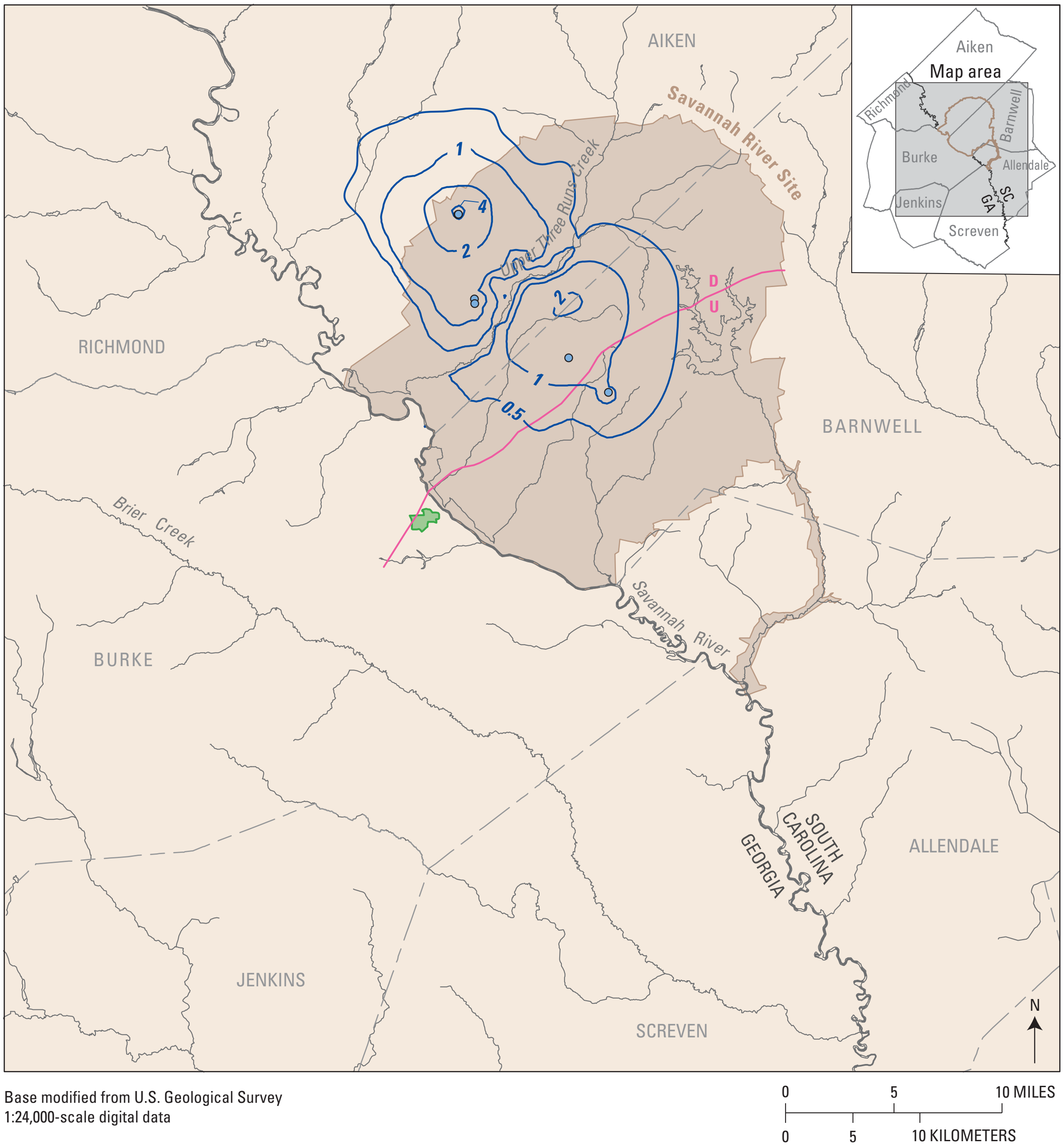


Figure 16. Particle-tracking results for the year 2002, Scenario A, near Vogtle Electric Generation Plant, Georgia and South Carolina.



Base modified from U.S. Geological Survey
1:24,000-scale digital data

EXPLANATION

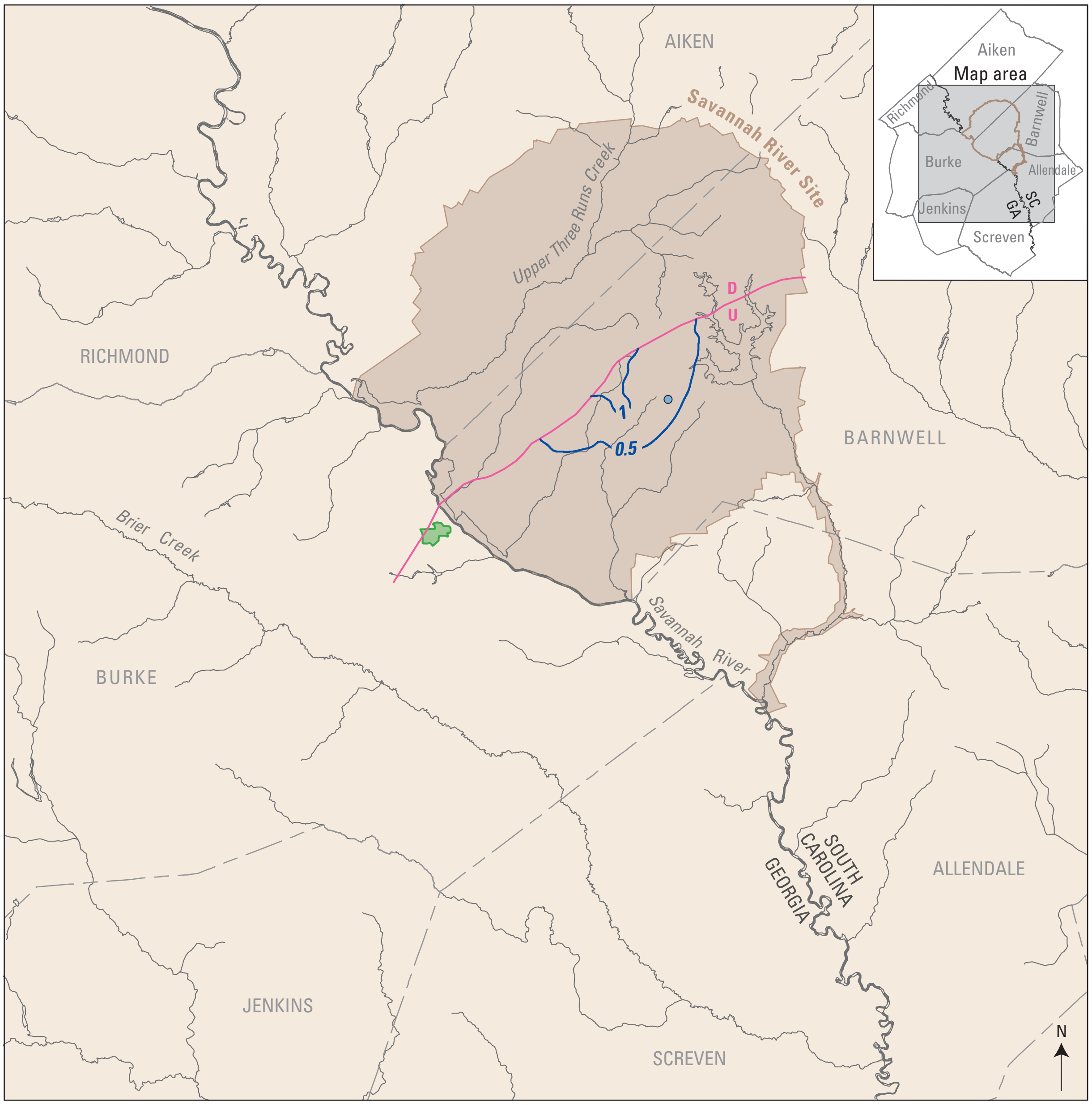
Vogtle Electric Generation Plant

Pen Branch Fault—Approximately located; D, downthrown side; U, upthrown side

Line of equal simulated water-level change—Interval, in feet, is variable. Computed by subtracting the simulated potentiometric surface for 2002 Base Case from the simulated potentiometric surface for Scenario B (see table 6 for description of scenario)

Production well—Completed in the Gordon aquifer in which pumping was adjusted for scenario

Figure 17. Simulated water-level change for Scenario B in the Gordon aquifer, near Vogtle Electric Generation Plant, Georgia and South Carolina.



EXPLANATION

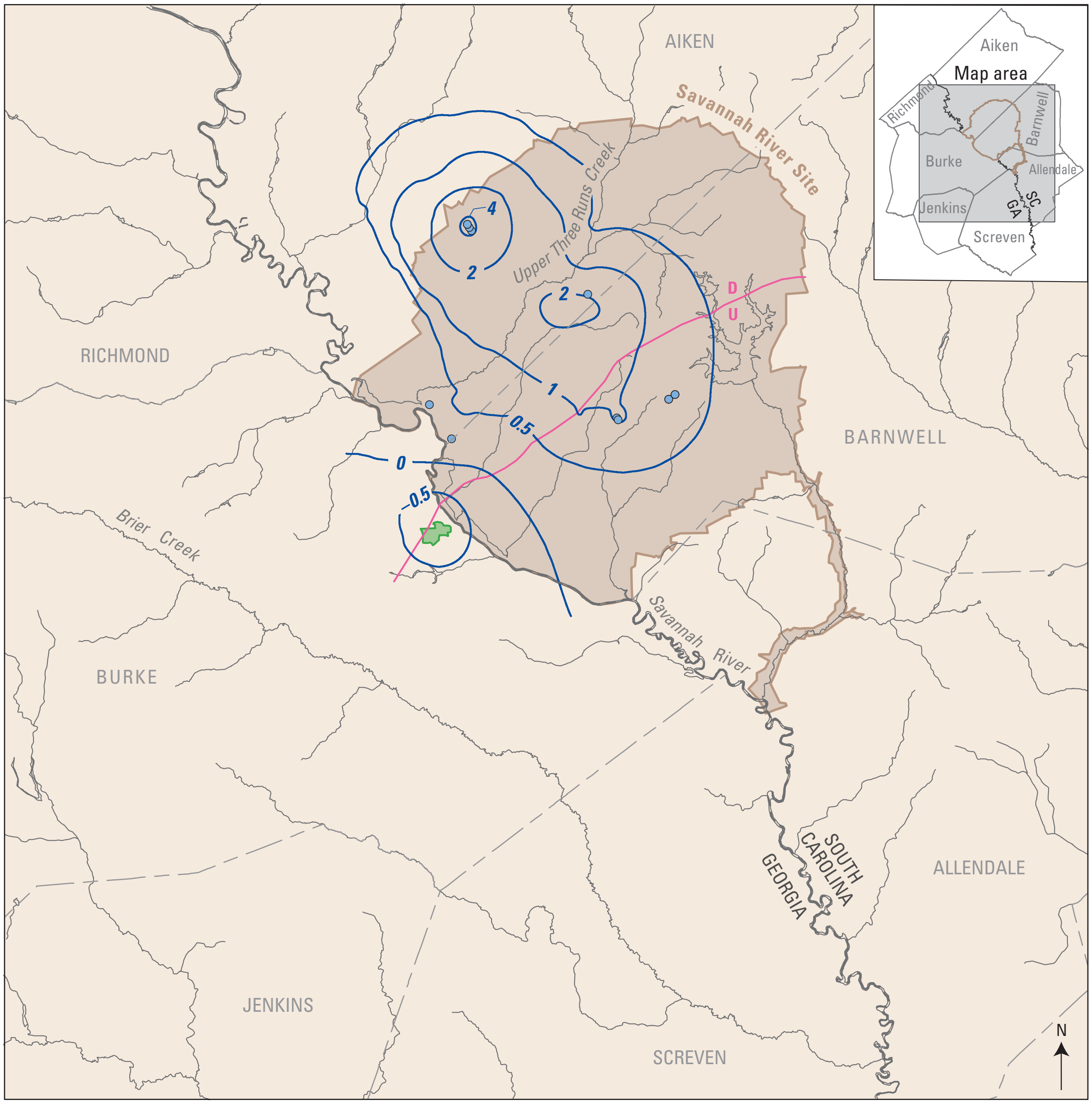
Vogtle Electric Generation Plant

D / U **Pen Branch Fault**—Approximately located; D, downthrown side; U, upthrown side

0.5 **Line of equal simulated water-level change**—Interval, in feet, is 0.5. Computed by subtracting the simulated potentiometric surface for 2002 Base Case from the simulated potentiometric surface for Scenario B (see table 6 for description of scenario)

Production well—Completed in the Millers Pond aquifer in which pumping was adjusted for scenario

Figure 18. Simulated water-level change for Scenario B in the Millers Pond aquifer, near Vogtle Electric Generation Plant, Georgia and South Carolina.



Base modified from U.S. Geological Survey
1:24,000-scale digital data

0 5 10 MILES

0 5 10 KILOMETERS

EXPLANATION

Vogtle Electric Generation Plant

D / U **Pen Branch Fault**—Approximately located; D, downthrown side; U, upthrown side

0.5 **Line of equal simulated water-level change**—Interval, in feet, is variable. Computed by subtracting the simulated potentiometric surface for 2002 Base Case from the simulated potentiometric surface for Scenario B (see table 6 for description of scenario)

Production well—Completed in the upper Dublin aquifer in which pumping was adjusted for scenario

Figure 19. Simulated water-level change for Scenario B in the upper Dublin aquifer, near Vogtle Electric Generation Plant, Georgia and South Carolina.

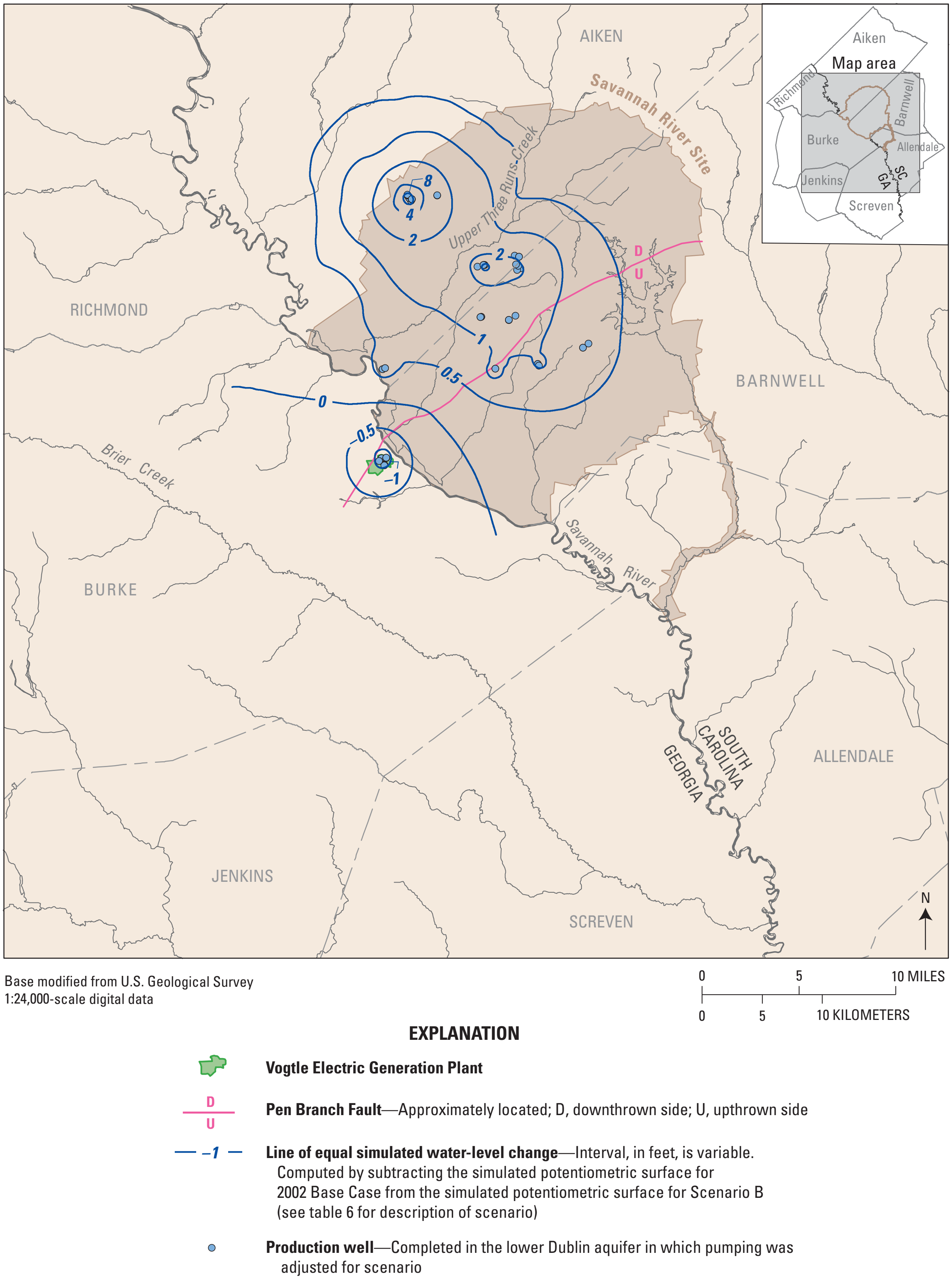


Figure 20. Simulated water-level change for Scenario B in the lower Dublin aquifer, near Vogtle Electric Generation Plant, Georgia and South Carolina.

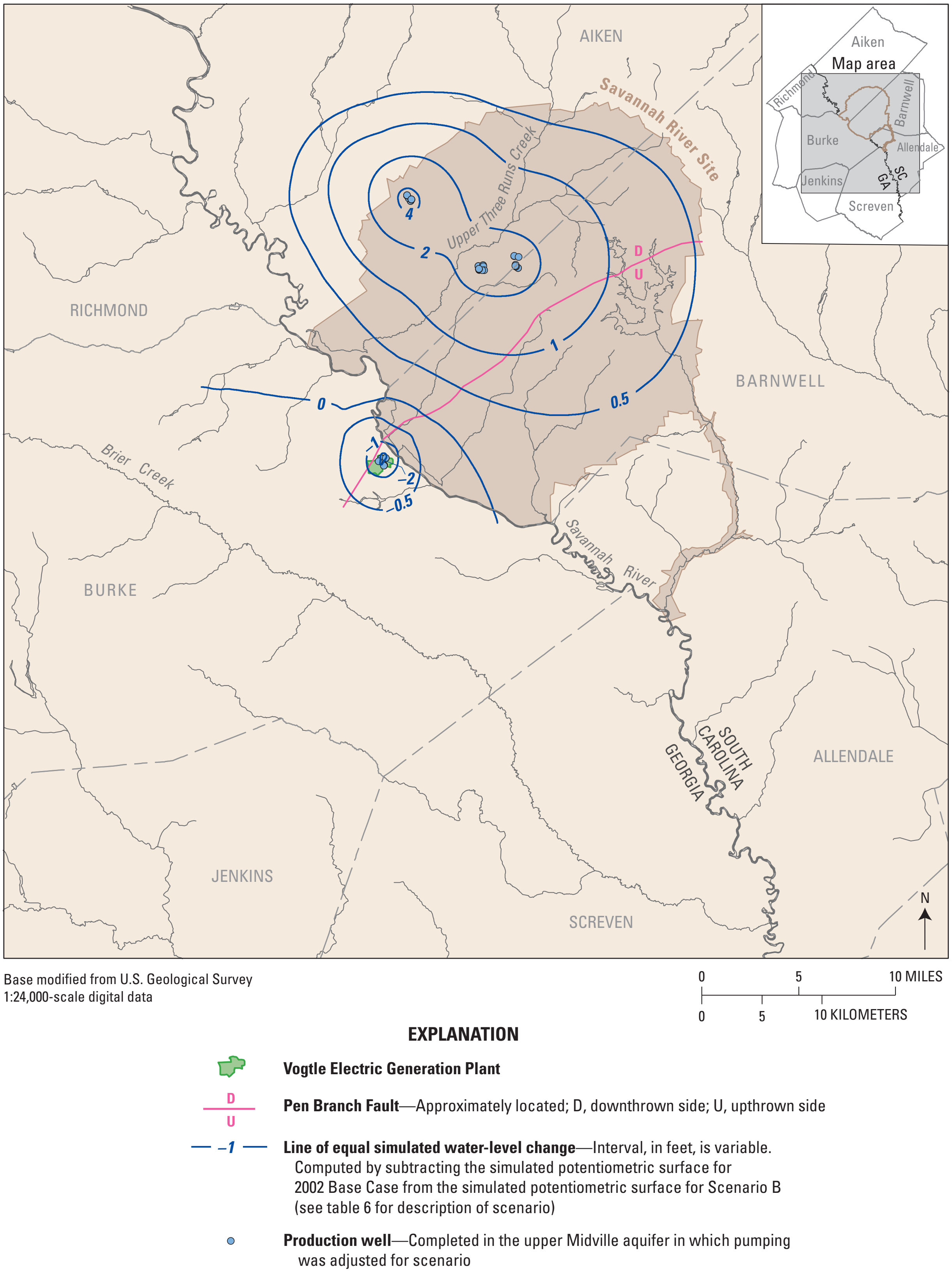
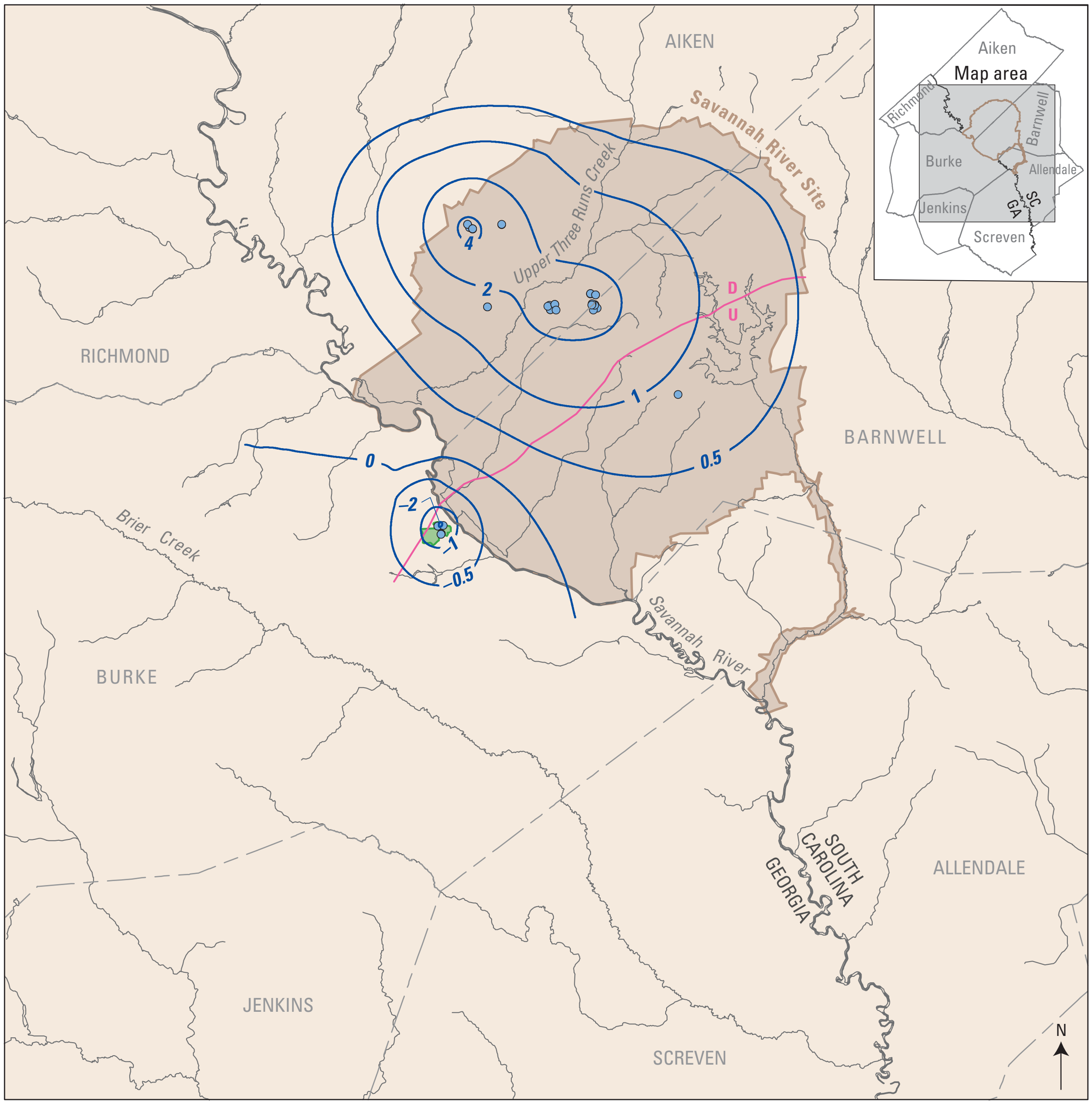


Figure 21. Simulated water-level change for Scenario B in the upper Midville aquifer, near Vogtle Electric Generation Plant, Georgia and South Carolina.



EXPLANATION

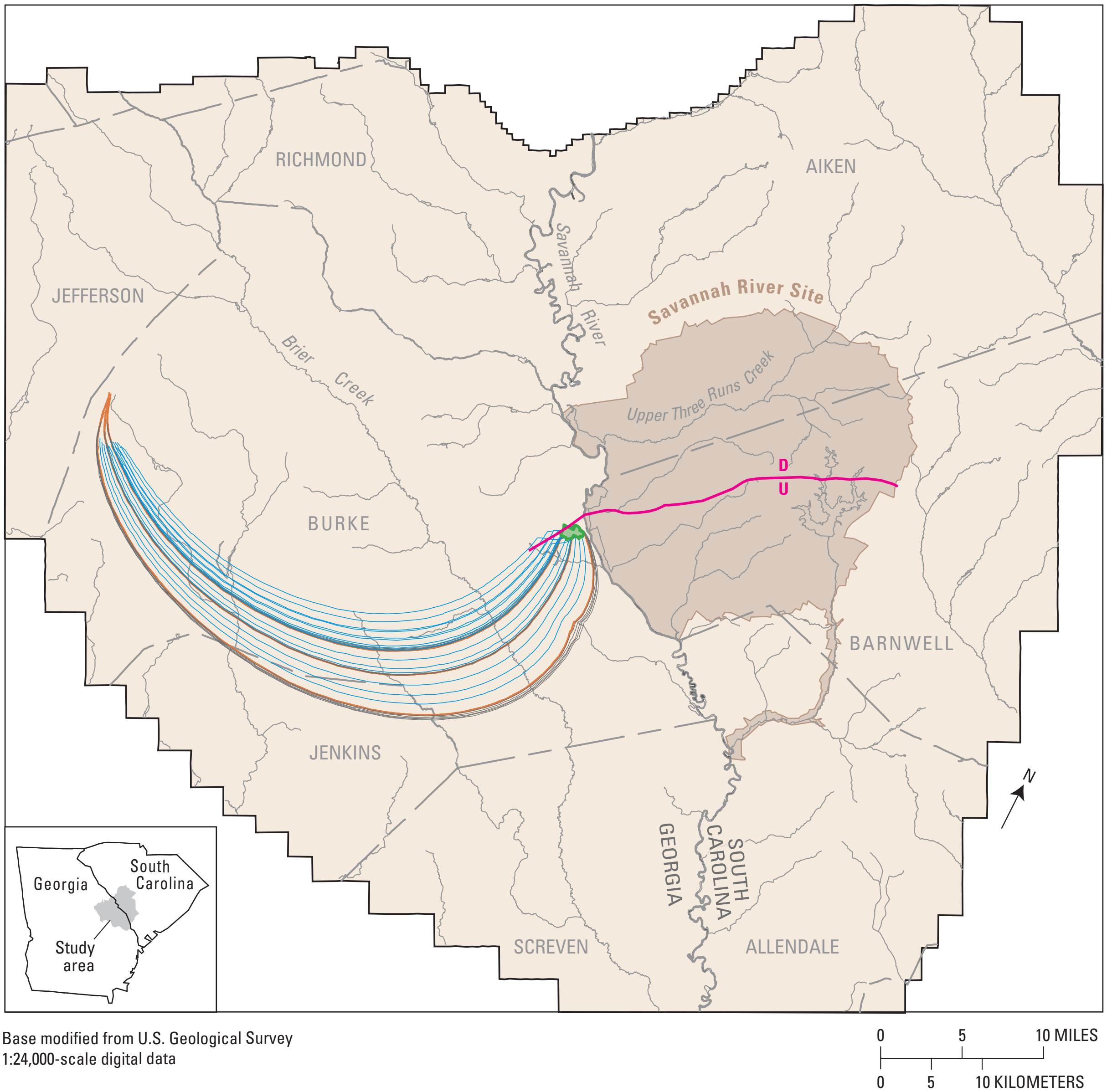
Vogtle Electric Generation Plant

Pen Branch Fault—Approximately located; D, downthrown side; U, upthrown side

0.5 **Line of equal simulated water-level change**—Interval, in feet, is variable. Computed by subtracting the simulated potentiometric surface for 2002 Base Case from the simulated potentiometric surface for Scenario B (see table 6 for description of scenario)

Production well—Completed in the lower Midville aquifer in which pumping was adjusted for scenario

Figure 22. Simulated water-level change for Scenario B in the lower Midville aquifer, near Vogtle Electric Generation Plant, Georgia and South Carolina.



EXPLANATION

Vogtle Electric Generation Plant

Model boundary

D / U **Pen Branch Fault**—Approximately located; D, downthrown side; U, upthrown side

Simulated ground-water flowpath—Particles placed at the center of each of the three grid cells containing a Plant Vogtle production well at increments representing 10 percent of the aquifer thickness (10 total particles per aquifer layer per cell). Five particle flowpaths for each layer are shown on map to avoid clutter

Lower Dublin aquifer

Upper Midville aquifer

Lower Midville aquifer

Figure 23. Particle-tracking results for the year 2002, Scenario B, study area, near Vogtle Electric Generation Plant, Georgia and South Carolina.

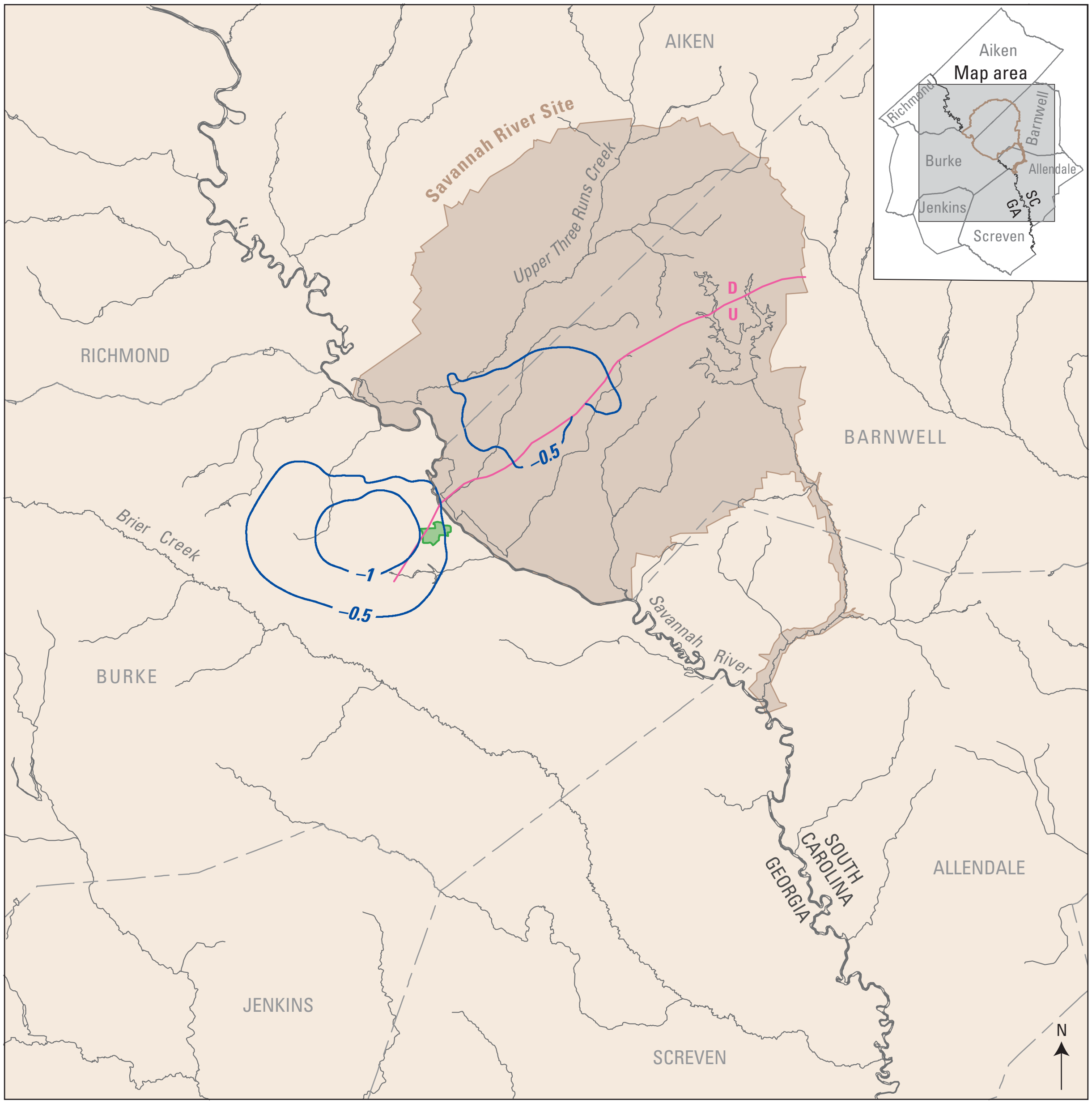
Scenario C

Scenario C simulates a 3.42-Mgal/d increase in pumping at VEGP that represents a 2.33-Mgal/d higher rate of withdrawal than was simulated for Scenario A for the proposed new reactor units (table 6). The higher withdrawal for wells providing water to the new reactors is similar to that reported for the startup of the two existing reactors (Units 1 and 2) during 1988 (Mark Notich, U.S. Nuclear Regulatory Commission, written commun., April 10, 2007). Southern Nuclear Company has noted that the high pumping rates during startup of Units 1 and 2 were related to achieving water-quality criteria and not to ground-water demand by the facilities. Water treatment methods are now used to achieve the water-quality criteria and have greatly reduced ground-water pumping rates (Mark Nodich, U.S. Nuclear Regulatory Commission, written commun., September 10, 2007).

Although pumping rates simulated by Scenario C are viewed as implausible for long-term operation of proposed Units 3 and 4, and the pumping rates are not proposed by Southern Nuclear Company, the scenario is designed to simulate pumping rates necessary to draw ground water from South Carolina to the VEGP production wells. The 3.42-Mgal/d increase was distributed evenly among three production wells at VEGP. Simulated water-level changes are shown in figures 24–29; particle-tracking results are shown on figure 30 and listed in table 7.

The maximum simulated drawdown for Scenario C was greater than 1 ft in the Gordon aquifer (fig. 24), greater than 2 ft in the Millers Pond aquifer (fig. 25), greater than 4 ft in the upper Dublin aquifer (fig. 26), greater than 4 ft in the lower Dublin aquifer (fig. 27), and greater than 8 ft in the upper and lower Midville aquifers (figs. 28 and 29, respectively). The extent of drawdown is largest for Scenario C when compared to Scenarios A and B, with the 0.5-ft drawdown contour in the upper and lower Midville aquifers extending about 29 mi to the southwestern model boundary in Jenkins and Screven Counties, Ga., and about 14 mi eastward into SRS (figs. 28 and 29, respectively). In the overlying Gordon, Millers Pond, and upper Dublin aquifers (figs. 24–26, respectively), drawdown response is due to leakage through confining units in response to decreased head in the production zones (lower Dublin and upper and lower Midville aquifers, figs. 27–29, respectively).

For Scenario C, the source of water to VEGP production wells, as indicated by MODPATH analysis (fig. 30), is recharge at a somewhat different location than that simulated for Scenario A (fig. 16). As was the case for Scenario A, simulation results indicate that much of the ground-water recharge for Scenario C occurs in an upland area near the county line between Burke and Jefferson Counties, Ga.; however, there is an additional source of water in an upland area in eastern Barnwell County, S.C. As was the case for Scenarios A and B, none of the recharge originated on SRS. When compared to Scenarios A and B, simulated mean time of travel for Scenario C (table 7) was slower in the lower Dublin aquifer (about 3,800 yr), and faster in the upper and lower Midville aquifers (about 2,800 yr). For Scenario C, the fastest simulated time of travel of about 1,800 yr was for particles in the lower Dublin and upper Midville aquifers and slowest (about 12,600 yr) was for a particle in the lower Dublin aquifer. The slower time of travel in the lower Dublin aquifer may be the result of the greater length and extent of flowlines shown on figure 30.



Base modified from U.S. Geological Survey
1:24,000-scale digital data

0 5 10 MILES
0 5 10 KILOMETERS

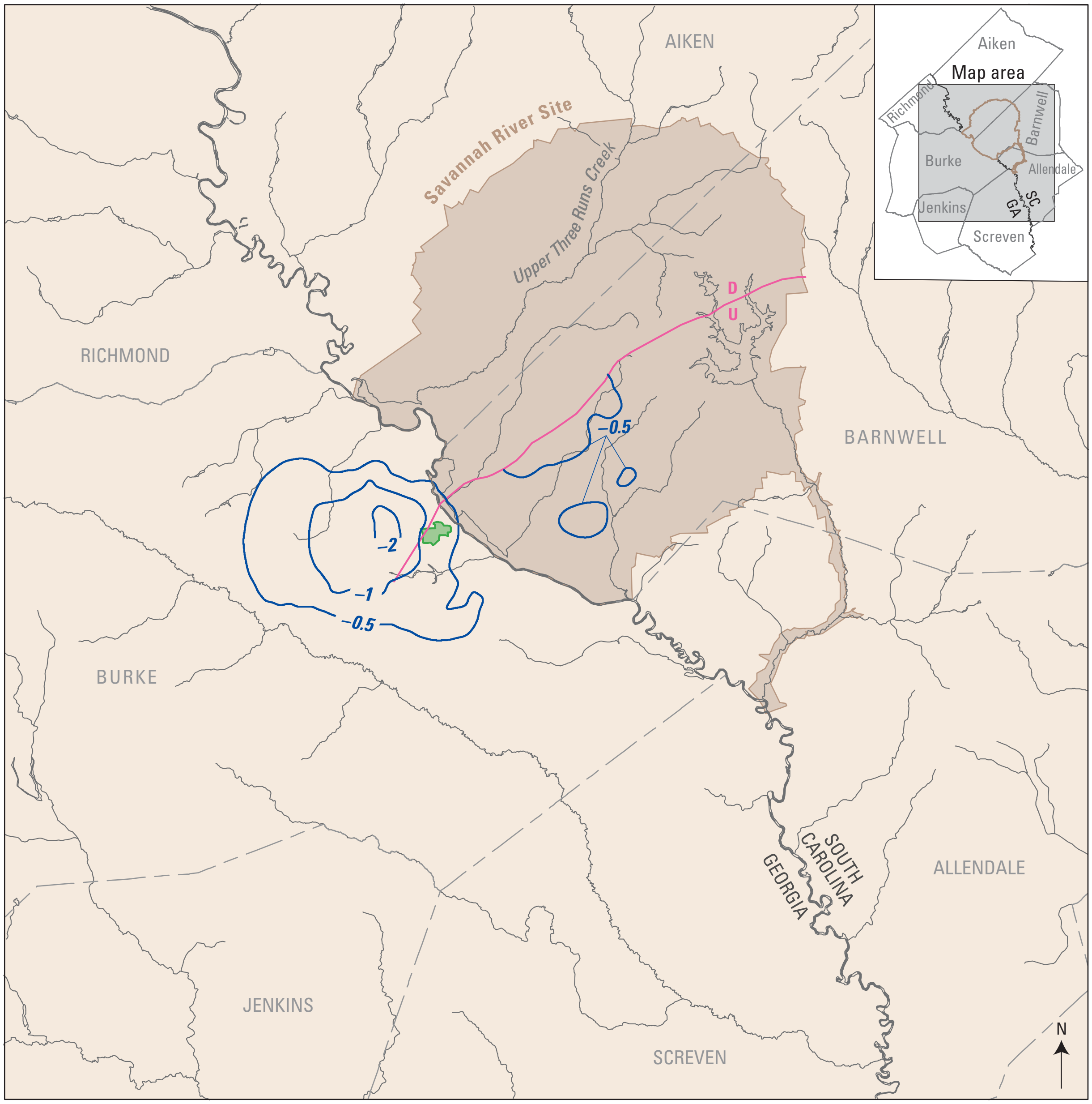
EXPLANATION

Vogtle Electric Generation Plant

D / U **Pen Branch Fault**—Approximately located; D, downthrown side; U, upthrown side

–0.5 **Line of equal simulated water-level change**—Interval, in feet, is 0.5. Computed by subtracting the simulated potentiometric surface for 2002 Base Case from the simulated potentiometric surface for Scenario C (see table 6 for description of scenario)

Figure 24. Simulated water-level change for Scenario C in the Gordon aquifer, near Vogtle Electric Generation Plant, Georgia and South Carolina.



Base modified from U.S. Geological Survey
1:24,000-scale digital data

0 5 10 MILES
0 5 10 KILOMETERS

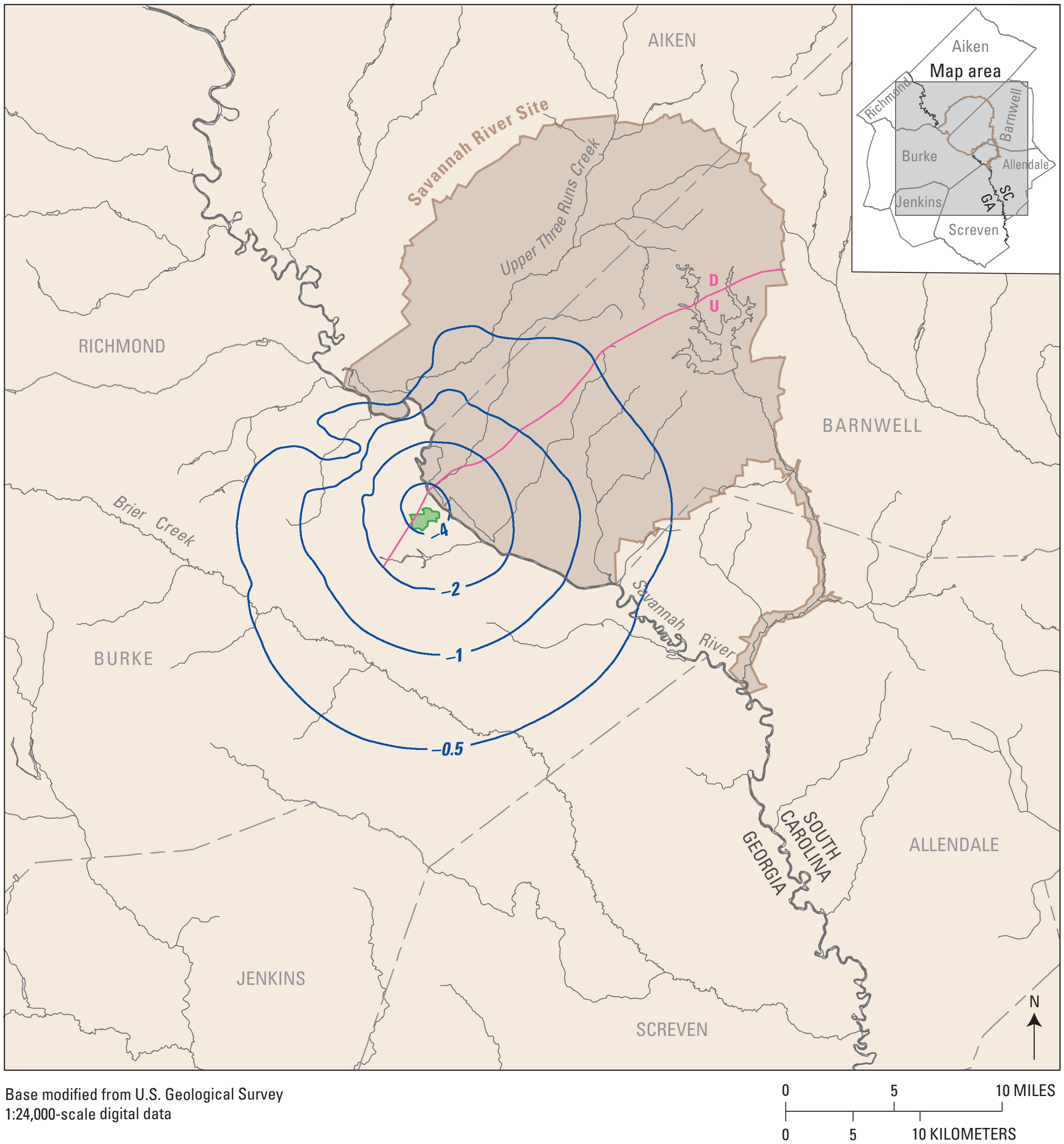
EXPLANATION

Vogtle Electric Generation Plant

D / U **Pen Branch Fault**—Approximately located; D, downthrown side; U, upthrown side

—1— **Line of equal simulated water-level change**—Interval, in feet, is variable. Computed by subtracting the simulated potentiometric surface for 2002 Base Case from the simulated potentiometric surface for Scenario C (see table 6 for description of scenario)

Figure 25. Simulated water-level change for Scenario C in the Millers Pond aquifer, near Vogtle Electric Generation Plant, Georgia and South Carolina.



EXPLANATION

Vogtle Electric Generation Plant

Pen Branch Fault—Approximately located; D, downthrown side; U, upthrown side

Line of equal simulated water-level change—Interval, in feet, is variable. Computed by subtracting the simulated potentiometric surface for 2002 Base Case from the simulated potentiometric surface for Scenario C (see table 6 for description of scenario)

Figure 26. Simulated water-level change for Scenario C in the upper Dublin aquifer, near Vogtle Electric Generation Plant, Georgia and South Carolina.

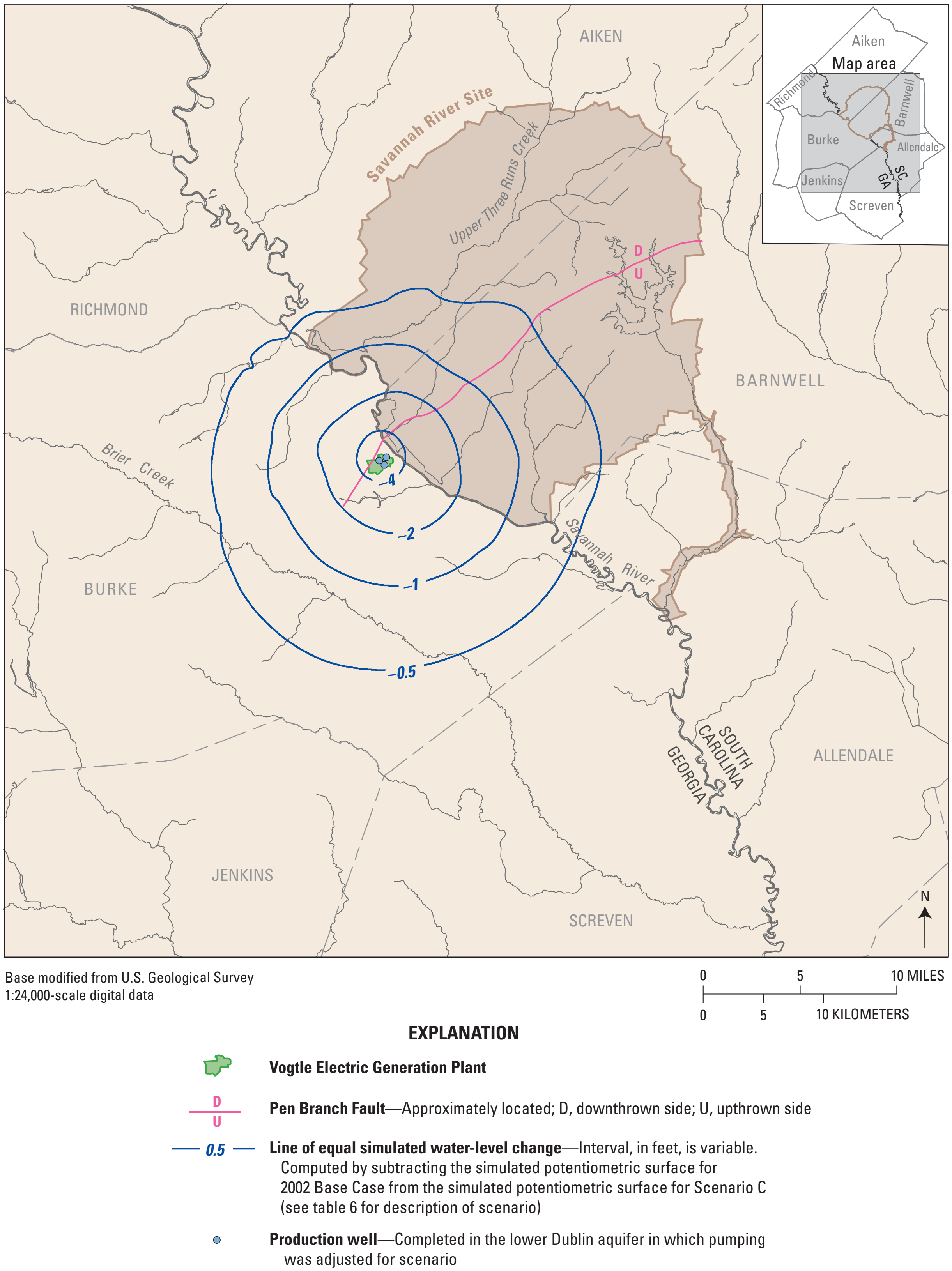
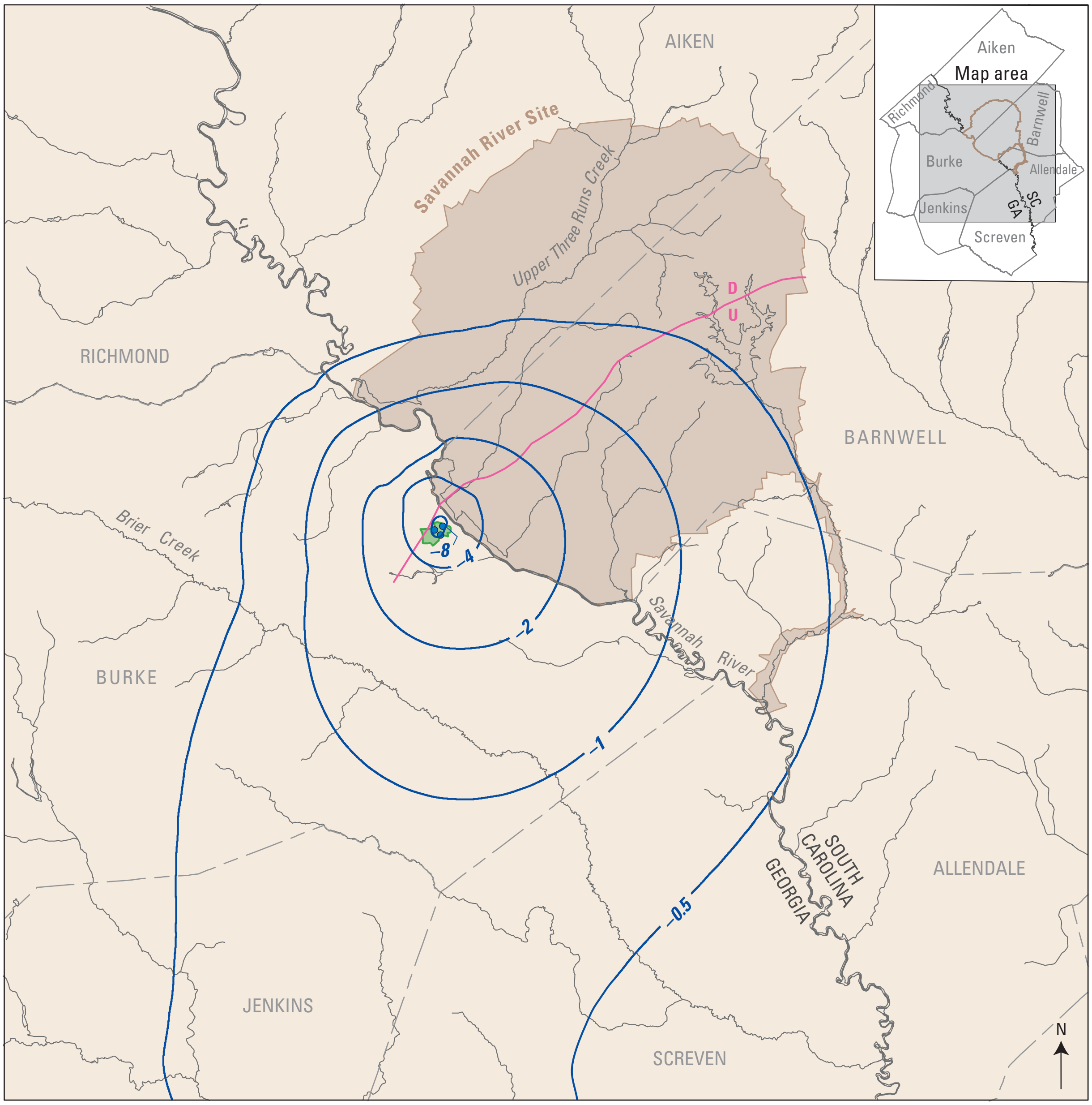


Figure 27. Simulated water-level change for Scenario C in the lower Dublin aquifer, near Vogtle Electric Generation Plant, Georgia and South Carolina.



Base modified from U.S. Geological Survey
1:24,000-scale digital data

EXPLANATION

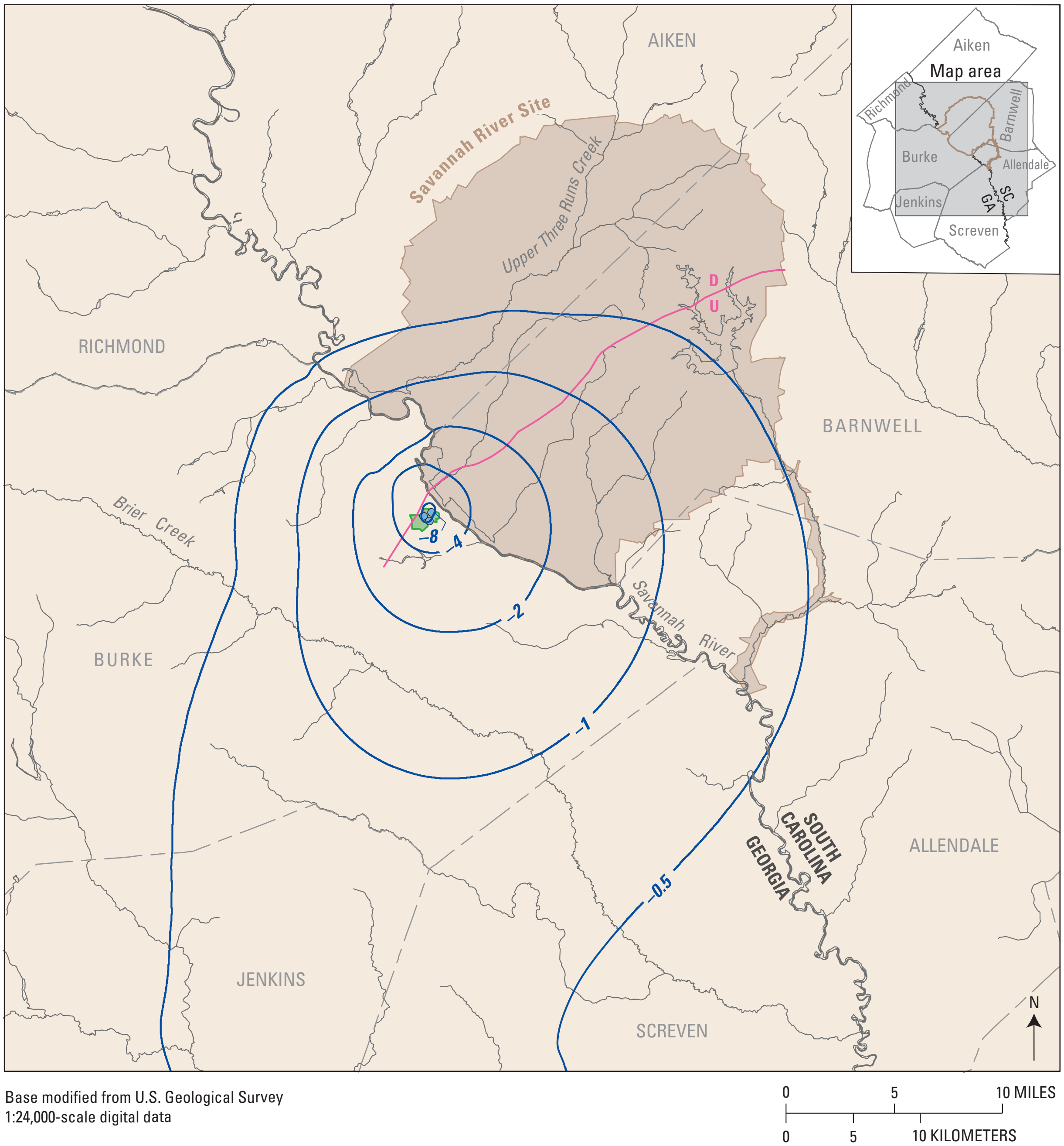
Vogtle Electric Generation Plant

Pen Branch Fault—Approximately located; D, downthrown side; U, upthrown side

0.5 **Line of equal simulated water-level change**—Interval, in feet, is variable. Computed by subtracting the simulated potentiometric surface for 2002 Base Case from the simulated potentiometric surface for Scenario C (see table 6 for description of scenario)

Production well—Completed in the upper Midville aquifer in which pumping was adjusted for scenario

Figure 28. Simulated water-level change for Scenario C in the upper Midville aquifer, near Vogtle Electric Generation Plant, Georgia and South Carolina.



EXPLANATION

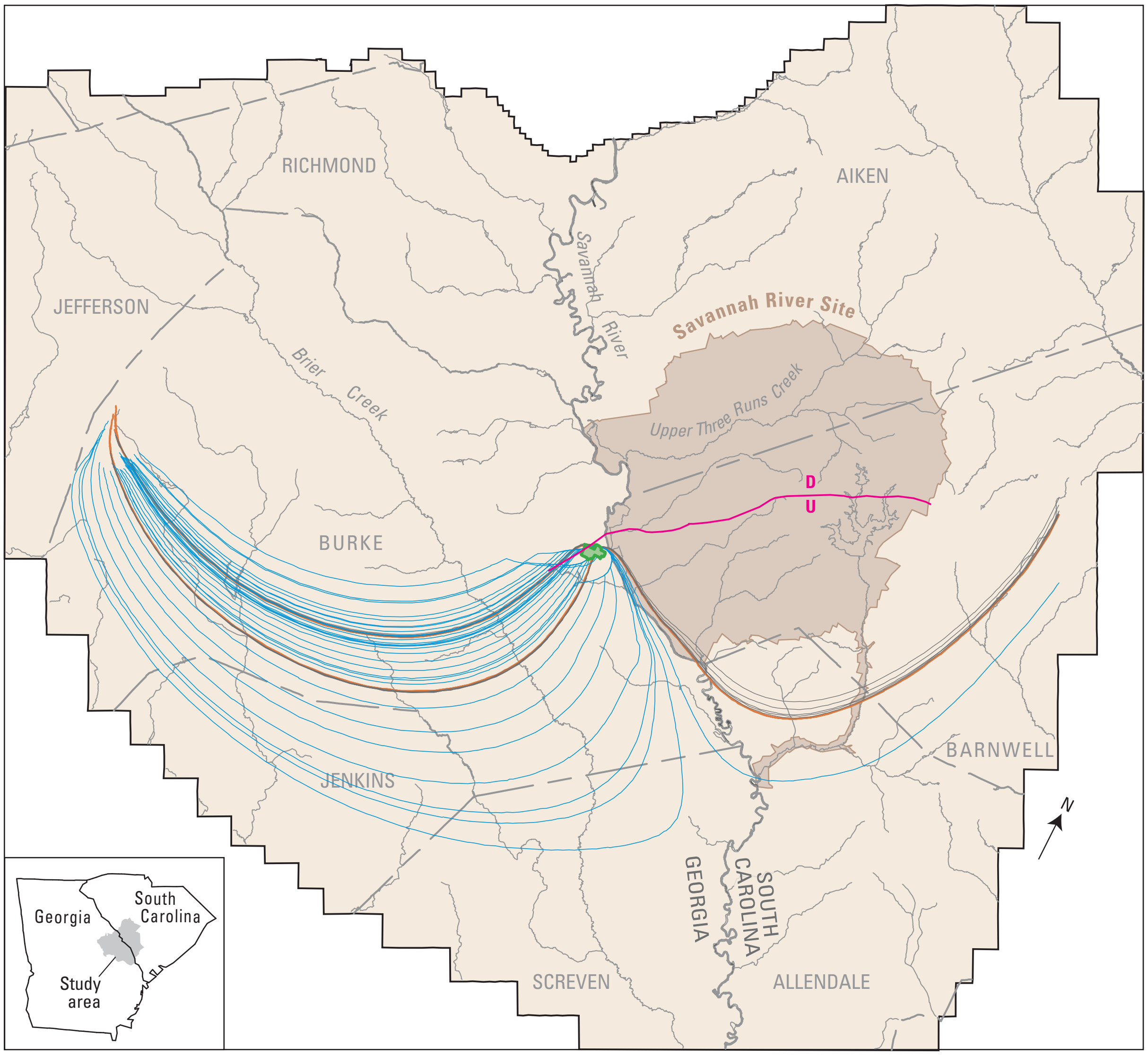
Vogtle Electric Generation Plant

D / U — **Pen Branch Fault**—Approximately located; D, downthrown side; U, upthrown side

–1 — **Line of equal simulated water-level change**—Interval, in feet, is variable. Computed by subtracting the simulated potentiometric surface for 2002 Base Case from the simulated potentiometric surface for Scenario C (see table 6 for description of scenario)

Production well—Completed in the lower Midville aquifer in which pumping was adjusted for scenario

Figure 29. Simulated water-level change for Scenario C in the lower Midville aquifer, near Vogtle Electric Generation Plant, Georgia and South Carolina.



Base modified from U.S. Geological Survey
1:24,000-scale digital data

0 5 10 MILES
0 5 10 KILOMETERS

EXPLANATION

Vogtle Electric Generation Plant

Model boundary

D / U **Pen Branch Fault**—Approximately located; D, downthrown side; U, upthrown side

Simulated ground-water flowpath—Particles placed at the center of each of the three grid cells containing a Plant Vogtle production well at increments representing 10 percent of the aquifer thickness (10 total particles per aquifer layer per cell). Five particle flowpaths for each layer are shown on map to avoid clutter

Lower Dublin aquifer

Upper Midville aquifer

Lower Midville aquifer

Figure 30. Particle-tracking results for the year 2002, Scenario C, near Vogtle Electric Generation Plant, Georgia and South Carolina.

Model Limitations

The steady-state simulations presented herein are believed to depict reasonably changes in ground-water levels that resulted from pumping increases of 1.09 to 3.42 Mgal/d at VEGP and from a pumping decrease of 5.3 Mgal/d at SRS, which together represent less than 1 percent of the total simulated ground-water flow of 1,035 Mgal/d for 2002 (Cherry, 2006). Because these pumping changes are of low magnitude and occur near the center of the simulated area, lateral boundaries generally have little influence on simulation results. An exception occurs for Scenario C in which drawdown in the upper and lower Midville aquifers extends to the model's southwestern "no-flow" boundary. Simulated drawdown that reaches a no-flow boundary results in higher values than would occur if the boundary was not intercepted. Steady-state simulations are believed to be representative of local hydrologic conditions because response to changes in pumpage is short term and previous testing indicates the model is insensitive to changes in storage (Clarke and West, 1998).

The revised ground-water flow model (Cherry, 2006) used for this investigation is based on a drought period (2002) in which boundary head was lowered to reflect decreased recharge to the ground-water system. It is likely that boundary conditions reflecting average or wet periods would result in somewhat different patterns of water-level change than were simulated for this study. Despite these possible variations, it is likely that ground-water flowpaths and recharge areas would be largely the same.

The ground-water flow model used in this study is subject to the limitations described in Cherry (2006). These limitations include error and uncertainty in field measurements of water level and in estimates of pumping, limitations of the conceptual models, approximations made in representing the physical properties of the flow system and errors inherent in estimating the spatial distribution of these properties, approximations made in the formulation and application of model boundary and initial conditions, errors associated with numerical approximation and solution of the mathematical model of the flow system, and assumptions made in using the models to predict the future behavior of the flow system.

In some local areas near the Pen Branch Fault, simulated water levels poorly matched observed water levels in the Gordon aquifer (layer A2). Near the P-19 well cluster site on SRS, and in the Savannah River alluvial valley near VEGP, simulated head was consistently lower than the observed head. The reasons for this mismatch are unknown; however, a localized hydraulic connection between layers A1 (Upper Three Runs) and A2 (Gordon) near the Pen Branch Fault on SRS has been suggested by previous investigators (Aadland and others, 1991). Because the reason for the high water level in the Gordon aquifer was not substantiated by field investigations, it was decided by previous investigators (Clarke and West, 1998) not to account for this effect in the calibration of the ground-water flow model.

Particle tracking using MODPATH is controlled largely by lateral and vertical head gradients, along with the hydraulic properties of the aquifers and confining units. In the VEGP area, data on the vertical hydraulic conductivity of aquifers, streambeds, and confining units are sparse. An additional limitation of particle tracking using MODPATH is the inability to determine whether a particle of water exits the flow system in a model cell containing a weak sink. A weak sink can be described as a discharge well that does not remove all the water entering a cell, so that some water continues to move through the system. Finally, the no-flow boundary condition along the southwestern boundary of the model limits the available area for a simulated flowpath. This limitation may have resulted in faster simulated time of travel in the lower Dublin aquifer for Scenario C than might have occurred if the no-flow boundary was located farther away from the pumping at VEGP.

Summary and Conclusions

An updated and calibrated MODFLOW ground-water flow model (Cherry, 2006) was used to simulate the effect of current and potential future pumping on ground-water levels and flowpaths near Vogtle Electric Generation Plant (VEGP), Ga., for a Base Case representing year 2002 conditions and three pumping scenarios:

Scenario A simulates a 1.09-million gallons per day (Mgal/d) increase in pumping at VEGP assuming average withdrawal rates with the operation of existing reactors (Units 1 and 2) and the proposed new reactors (Units 3 and 4).

Scenario B simulates a 1.09-Mgal/d increase in pumping at VEGP, as was simulated in Scenario A, combined with a shutdown of the SRS facility (reduction of 5.3 Mgal/d).

Scenario C simulates a 3.42-Mgal/d increase in pumping at VEGP that represents a higher rate of withdrawal for the proposed new reactor units during their startup period (3.42 Mgal/d), and continuation of year 2002 pumping rates (1.04 Mgal/d) in the existing reactor units.

Maximum water-level change resulting from increased pumping at VEGP (without changes at Savannah River Site (SRS) or elsewhere in the study area) were simulated in the pumped layers at VEGP—the lower Dublin and upper and lower Midville aquifers. Simulated maximum declines in these units were from 1 to greater than 2 feet (ft) for Scenario A and from 4 to greater than 8 ft for Scenario C. Although none of the VEGP wells are completed in the upper Dublin aquifer, simulated water-level changes were similar to those observed in the pumped lower Dublin aquifer, suggesting a large degree of interconnection between the two aquifers. A muted water-level decline from 0.25 to greater than 2 ft was simulated in the shallow Gordon and Millers Pond aquifers for Scenarios A and C as the result of leakage through confining units in response to decreased head in the production zones (lower Dublin and upper and lower Midville aquifers).

The largest simulated water-level changes at VEGP were for Scenario C, which represents a tripling of current pumpage at the facility. Although such pumping rates are viewed as implausible for long-term operation of proposed Units 3 and 4, and are not proposed by Southern Nuclear Company, the scenario is designed to simulate pumping rates necessary to draw ground water from South Carolina to the VEGP production wells. For this scenario, drawdown was greater than 8 ft in the upper and lower Midville aquifers, and greater than 4 ft in the upper and lower Dublin aquifers. Drawdown exceeding 0.5 ft in these aquifers extended about 29 miles (mi) to the southwestern model boundary in Jenkins and Screven Counties, Ga., and about 14 mi eastward onto SRS in South Carolina.

For Scenario B, elimination of pumping at SRS resulted in large water-level changes near SRS, with rises of greater than 8 ft in the lower Dublin aquifer and greater than 4 ft in the upper Dublin and upper and lower Midville aquifers. At VEGP, the magnitude and extent of water-level decline resulting from increased pumping was less than in Scenario A with maximum declines of greater than 2 ft in the upper and lower Midville aquifers, greater than 1 ft in the lower Dublin aquifer, and greater than 0.5 ft in the upper Dublin aquifer. The water-level rise resulting from elimination of SRS pumping reduced the effect of pumping at VEGP on ground-water levels.

Results of MODFLOW simulations were analyzed using the USGS particle-tracking code MODPATH (Pollock, 1994) to determine the source of water and associated time of travel to VEGP production wells. For each of the scenarios, most of the recharge to VEGP wells originated in an upland area near the county line between Burke and Jefferson Counties, Ga., with none of the recharge originating on SRS or elsewhere in South Carolina. An exception occurs for Scenario C, in which some of the recharge originates in an upland area in eastern Barnwell County, S.C. Simulated mean time of travel from recharge areas to the VEGP wells for the Base Case and the three scenarios was between about 2,700 and 3,800 years, with some variation related to changes in head gradients due to pumping changes.

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