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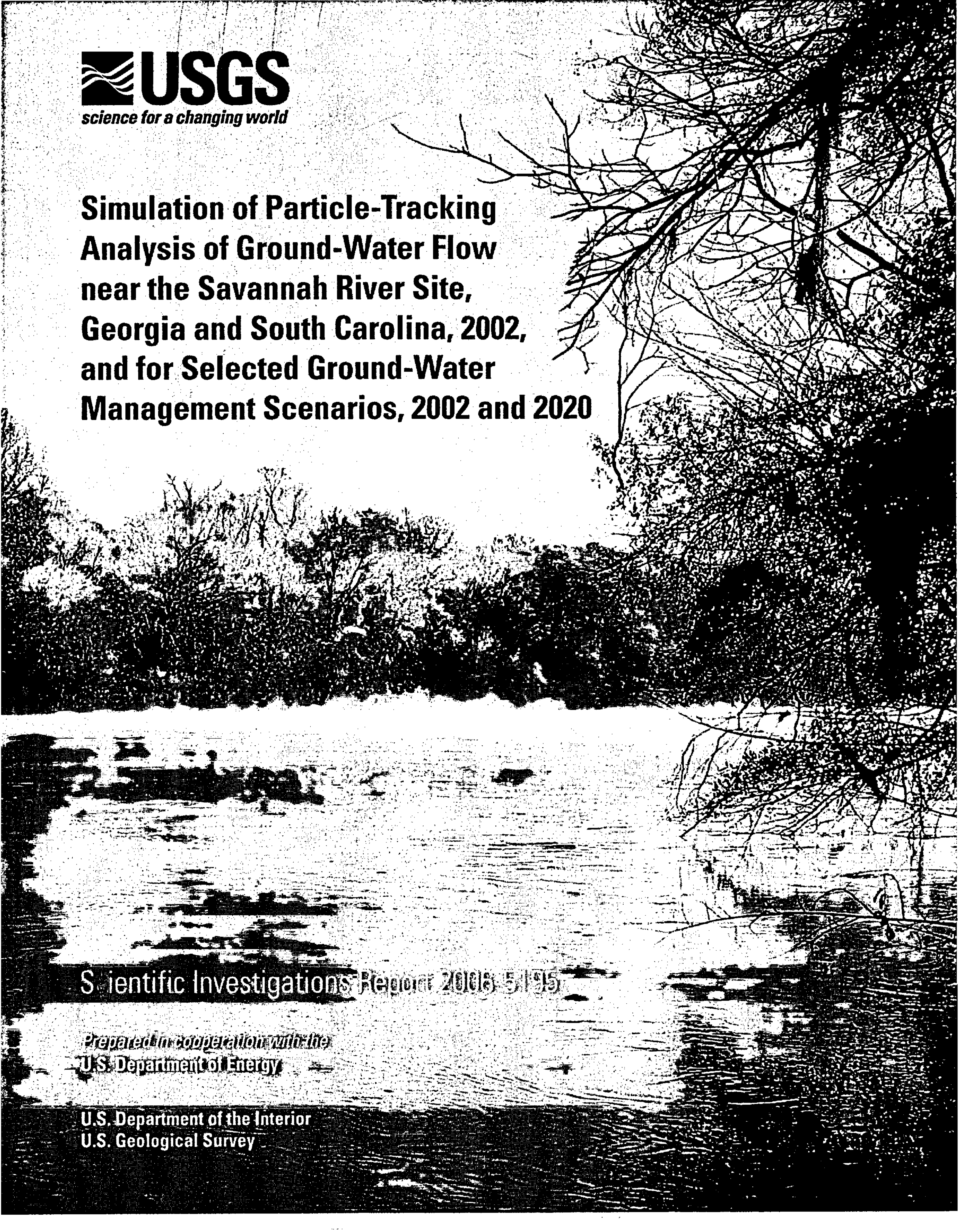

Simulation of Particle-Tracking Analysis of Ground-Water Flow near the Savannah River Site, Georgia and South Carolina, 2002, and for Selected Ground-Water Management Scenarios, 2002 and 2020

Scientific Investigations Report 2006-5195

Prepared in cooperation with the
U.S. Department of Energy

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

Cover photograph: Savannah River at Brighams Landing, Burke County, Georgia

Photograph by Alan M. Cressler, U.S. Geological Survey

Simulation and Particle-Tracking Analysis of Ground-Water Flow near the Savannah River Site, Georgia and South Carolina, 2002, and for Selected Ground-Water Management Scenarios, 2002 and 2020

By Gregory S. Cherry

Prepared in cooperation with the U.S. Department of Energy

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

U.S. Department of the Interior
DIRK KEMPTHORNE, Secretary

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Conversion Factors

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square foot (ft^2)	929.0	square centimeter (cm^2)
square foot (ft^2)	0.09290	square meter (m^2)
square inch (in^2)	6.452	square centimeter (cm^2)
section (640 acres or 1 square mile)	259.0	square hectometer (hm^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)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
cubic foot per second per square mile [(ft^3/s)/mi^2]	0.01093	cubic meter per second per square kilometer [(m^3/s)/km^2]
gallon per minute (gal/min)	0.06309	liter per second (L/s)
gallon per day (gal/d)	0.003785	cubic meter per day (m^3/d)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)
	Radioactivity	
picocurie per liter (pCi/L)	0.037	becquerel per liter (Bq/L)
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day (m/d)
	Transmissivity*	
foot squared per day (ft^2/d)	0.09290	meter squared per day (m^2/d)

*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.

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.

Simulation and Particle-Tracking Analysis of Ground-Water Flow near the Savannah River Site, Georgia and South Carolina, 2002, and for Selected Ground-Water Management Scenarios, 2002 and 2020

By Gregory S. Cherry

Abstract

Ground-water flow under 2002 hydrologic conditions was evaluated in an eight-county area in Georgia and South Carolina near the Savannah River Site (SRS), by updating boundary conditions and pumping rates in an existing U.S. Geological Survey (USGS) ground-water model. The original ground-water model, developed to simulate hydrologic conditions during 1987–92, used the quasi-three-dimensional approach by dividing the Floridan, Dublin, and Midville aquifer systems into seven aquifers. The hydrogeologic system was modeled using six active layers (A2–A7) that were separated by confining units with an overlying source-sink layer to simulate the unconfined Upper Three Runs aquifer (layer A1). Potentiometric-surface maps depicting September 2002 for major aquifers were used to update, evaluate, and modify boundary conditions used by the earlier ground-water flow model.

The model was updated using the USGS finite-difference code MODFLOW–2000 for mean-annual conditions during 1987–92 and 2002. The specified heads in the source-sink layer A1 were lowered to reflect observed water-level declines during the 1998–2002 drought. These declines resulted in a decrease of 12.1 million gallons per day (Mgal/d) in simulated recharge or vertical inflow to the uppermost confined aquifer (Gordon, layer A2). Although ground-water pumpage in the study area has increased by 32 Mgal/d since 1995, most of this increase (17.5 Mgal/d) was from the unconfined Upper Three Runs aquifer (source-sink layer A1) with the remaining 14.5 Mgal/d assigned to the active layers within the model (A2–A7).

The simulated water budget for 2002 shows a decrease from the 1987–92 model from 1,040 Mgal/d to 1,035 Mgal/d. The decreased ground-water inflows and increased ground-water withdrawal rates reduced the simulated ground-water outflow to river cells in the active layers of the model by 43 Mgal/d. The calibration statistics for all layers of the 2002 simulation resulted in a decrease in the root mean square (RMS) of the residuals from 10.6 to 8.0 feet (ft). The residuals indicate 83.3 percent of the values for the 2002 simulation met the calibration error criteria established in the original model, whereas 88.8 percent was within the specified range for the 1987–92 simulation. Simulated ground-water outflow to the Savannah River and its tributaries during water year 2002 was 560 cubic feet per second (ft^3/s), or 86 percent of the observed gain in mean-annual streamflow between streamflow gaging stations at the Millhaven, Ga., and Augusta, Ga. At Upper Three Runs Creek, simulated ground-water discharge during 2002 was 110 ft^3/s, or 83 percent of the observed streamflow at two streamflow gaging stations near the SRS. These results indicate that the constructed model calibrated to 1987–92 conditions and modified for 2002 dry conditions is still representative of the hydrologic system.

The USGS particle-tracking code MODPATH was used to generate advective water-particle pathlines and their associated time-of-travel based on MODFLOW simulations for 1987–92, 2002, and each of four hypothetical ground-water management scenarios. The four hypothetical ground-water management scenarios represent hydrologic conditions for (1) reported pumping for 2002 and boundary conditions for an average year; (2) reported pumping for 2002 with SRS pumping discontinued and boundary conditions for an average year; (3) projected 2020 pumping and boundary conditions for an average year; and (4) projected 2020 pumping and boundary conditions for a dry year. The MODPATH code was used in forward-tracking mode to evaluate flowpaths from areas on the SRS and in backtracking mode to evaluate further areas of previously documented trans-river flow on the Georgia side of the Savannah River. Trans-river flow is a condition in which the local head gradients might allow migration of contaminants from the SRS into the underlying aquifers and beneath the Savannah River into Georgia.

The analysis of ground-water flowpaths using MODPATH was conducted by establishing five zones in which particles were seeded into model cells based on the following criteria: (1) occurrence of recharge from the source-sink layer

A1 (Upper Three Runs aquifer) into layer A2 (Gordon aquifer), (2) downward flow from layer A2 (Gordon aquifer) into layers A3–A5 (Dublin aquifer system), (3) delineated areas of contamination or storage of hazardous materials on the SRS, and (4) defined surface-water drainage divides. Selected areas near streams on the SRS were not considered for the analysis because of localized flow regimes to nearby streams. In the case of trans-river flow areas, particles were placed in cells located on the western side of the Savannah River floodplain near Flowery Gap Landing in Burke County, Ga., and back-tracked to recharge areas on the SRS.

The most influential factors controlling particle movement are vertical and lateral head gradients and pumping distribution within the active layers of the model. MODPATH results indicate that Upper Three Runs Creek and the alluvial valley of the Savannah River are the dominant sinks or areas of ground-water discharge with time-of-travel ranging from 20 to greater than 2,000 years (yr). Simulated ground-water flowpaths for each of the four ground-water management scenarios were generally limited to areas within the SRS boundary because this is the area of concern for contaminant transport.

Five particle seed zones were established in which individual particles were observed from their point of recharge to discharge areas located along local streams within the boundaries of the SRS or the Savannah River. The median time-of-travel listed below for each of the five zones represents a range for the five simulations (2002, Scenarios A, B, C, and D). In general, the elimination of pumping at the SRS (Scenario B) reduces the time-of-travel for particles to reach the discharge areas. In zone 1, median time-of-travel from recharge areas to discharge areas located along Upper Three Runs Creek and west of the SRS boundary ranges from 217 to 264 yr. In zone 2, median time-of-travel from recharge areas to discharge areas located along Upper Three Runs Creek, Pen Branch, Fourmile Branch, and the Savannah River ranges from 524 to 593 yr. In zone 3, median time-of-travel from recharge areas to discharge areas located along Upper Three Runs Creek ranges from 834 to 1,150 yr. In zone 4, median time-of-travel from recharge areas to discharge areas located along the South Carolina side of the Savannah River ranges from 395 to 404 yr. In zone 5, median time-of-travel from recharge areas to discharge areas located along Lower Three Runs Creek and the Savannah River ranges from 1,310 to 1,350 yr. The longer travel times are generally associated with particles that penetrate deeper into the underlying aquifers before moving laterally toward discharge areas.

For the backtracking analysis of particles, three model cells located near Flowery Gap Landing (covering about 1 square mile) on the Georgia side of the Savannah River were chosen based on results from forward-tracking analysis (zone 2), indicating these cells as common discharge areas. Of the 300 particles released in these three cells, as few as 88 particles (29 percent, 2002, Scenario C) to as many as 110 particles (37 percent, Scenario B) backtrack to recharge areas on the SRS (trans-river flow). Of the particles exhibiting trans-river flow, the median time-of-travel along pathlines range from 366 to 507 yr with north of the Pen Branch Fault. Backtrack time-of-travel for the shortest flowpaths ranged from 79 to 82 yr from trans-river flow to interstream areas located north of Fourmile Branch with 10 percent of these particles reaching endpoints at about 100 yr. The results indicate that simulations with active SRS pumping centers (1987–92, 2002, Scenarios A, C, and D) allowed fewer particles to migrate to the Georgia side of the Savannah River. If these SRS production wells are deactivated (Scenario B), the number of particles migrating to trans-river zones increases to 110 and the median time-of-travel decreases to about 370 yr with a shortest time-of-travel period of about 80 yr.

Generally, time-of-travel for particles migrating downward through the Gordon confining unit (C1) and then moving laterally through layer A2 (Gordon aquifer) to discharge areas ranges from 20 to 200 yr. For particles migrating deeper into layers A3 through A5 (Dublin aquifer system), time-of-travel generally ranges from 200 to 1,000 yr. Eliminating pumping on the SRS (Scenario B) reduces the depth of penetration of particles and shortens the pathways to discharge areas with median time-of-travel decreased from 15 to 70 yr in zones 1 and 2. The second most influential factor controlling particle movement is the adjustment of heads in the source-sink layer A1, which affects the amount of recharge entering the system. In areas of trans-river flow, from 29 to 37 percent of the particles placed in three grid cells located near Flowery Gap Landing backtrack to recharge areas on the SRS. For these particles, the shortest travel time from 80 to 415 yr was for particles moving laterally through layer A2 (Gordon aquifer) and upward into the base of the source-sink layer A1 (Upper Three Runs aquifer) in areas south of Fourmile Branch.

Introduction

The U.S. Department of Energy (DOE), Savannah River Site (SRS)—located near Aiken, South Carolina (fig. 1*A*)—has manufactured nuclear materials for national defense purposes since the early 1950s. Hazardous materials—including tritium, other radionuclides, volatile organic compounds, and trace metals—are either disposed of or stored at many locations on the SRS (fig. 1*B*). Tritium, which is a radioactive form of hydrogen with a half-life of 12.33 years (yr), has been manufactured for national defense purposes since the 1950s and must be replenished because of its relatively short half-life. State of Georgia officials have raised concern about the possible migration of tritiated water from the SRS into the underlying aquifers and beneath the Savannah River (trans-river flow) into Georgia. During July 1991, DOE entered into a cooperative agreement with the U.S. Geological Survey (USGS) to investigate the conditions under which trans-river flow might develop. The Georgia Geologic Survey (GGS), a branch of the Georgia Environmental Protection Division (GaEPD), was assigned funding to drill and monitor wells for tritium. As part of a 1991–97 study, the USGS completed a steady-state ground-water flow model simulating predevelopment and 1987–92 flow conditions for the SRS and vicinity (Clarke and West, 1998). The model simulations included particle-tracking analysis of ground-water movement to determine time-of-travel from the present-day Savannah River floodplain to areas of recharge on the SRS.

The USGS, in cooperation with DOE, has been conducting additional work since July 2002 to determine the occurrence of trans-river flow under 2002 and future hydrologic conditions. The major objectives of this study are to (1) update the previously developed ground-water flow model to define and quantify present-day (2002) ground-water flow near SRS, and (2) use the updated model to describe and quantify ground-water flow near SRS under 2002 conditions and for four hypothetical ground-water management scenarios. Modifications to the original ground-water flow model included adjustments to boundary conditions and pumping. Future ground-water use projections to the year 2020 were based on 1980–2000 water use and an estimated increase of 80,000 residents for the eight-county study area. The study included detailed particle-tracking analysis of ground-water flowpaths on SRS for each of the five simulations and assessment of potential tritium migration to the Georgia side of the Savannah River (trans-river flow).

Purpose and Scope

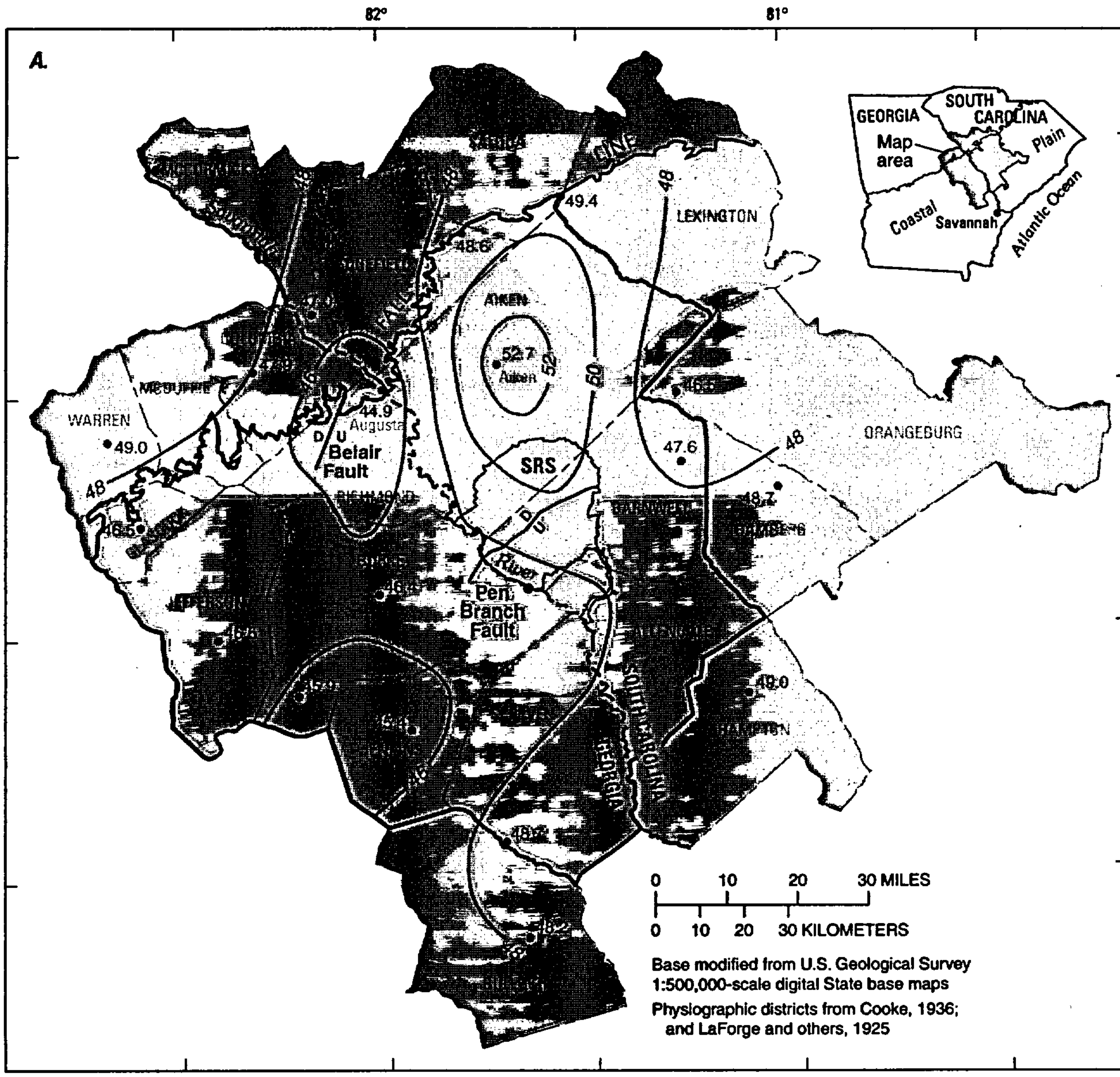
This report describes (1) changes in hydrologic and pumping conditions that have occurred since the calibration of the earlier (1987–92) USGS ground-water model, (2) revisions made to the model on the basis of changing hydrologic conditions, (3) revised calibration statistics for the model for 2002, and (4) results of ground-water flow and particle-tracking analysis for 2002 and for four hypothetical ground-water management scenarios during 2002 and 2020. Synoptic ground-water-level measurements were taken in 189 wells during early September 2002, and potentiometric-surface maps were constructed (Cherry, 2003) for the Upper Three Runs and Gordon aquifers and the Dublin and Midville aquifer systems. The ground-water-level measurements were used as control points to evaluate whether the previously developed model could accurately simulate 2002 hydrologic conditions by limiting changes to boundary and pumping conditions. Potentiometric-surface maps constructed using the September 2002 data served as the basis for adjustments to specified heads for each of the model layers. Continuous and periodic ground-water-level measurements were evaluated to determine trends during 1992–2002. Ground-water use data from 1992 to 2002 were compiled for irrigation, industrial, and public supply categories using published reports and data files for Burke, Jefferson, Jenkins, Richmond, and Screven Counties, Ga., and Aiken, Allendale, and Barnwell Counties, S.C. (fig. 1*A*). During 2000, GGS inventoried irrigation wells within Burke, Jenkins, and Screven Counties and obtained information from individual farmers regarding crop type, irrigated acreage, well depth, and pump capacity. Water-use projections were made for the eight-county study area on the basis of expected population growth and per capita water use during 1980–2000 and ground-water management scenarios were developed for the year 2020 (Scenarios C and D). Additional ground-water management scenarios were developed to evaluate the effects of changing boundary conditions and pumpage on ground-water flowpaths near SRS (Scenarios A and B). Five zones were established for the placement of particles on the SRS based on downward head gradient and the location of contamination or storage of hazardous materials (fig. 1*B*). The particles were analyzed for movement and time-of-travel from recharge areas to potential discharge areas along local streams or the floodplain of the Savannah River. Additional particle analysis was performed in areas of potential trans-river flow, or movement from the SRS toward discharge areas located on the Georgia side of the Savannah River.

Description of Study Area

The 5,147 square mile (mi^2) study area is in the northern part of the southeastern Coastal Plain physiographic province of Georgia and South Carolina (fig. 1*A*). 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. Relief is generally 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 can be 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 stream pattern. Streams that flow over the relatively softer 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). The floodplains near the principal rivers, such as the Savannah River, have a wide expanse of swamp bordering both sides of the channel. The Coastal Plain is subdivided into six topographic districts in the study area: Coastal Terraces, Tifton Upland, Louisville Plateau, Aiken Plateau, Congaree Sand, and Fall Line Hills (Clark and Zisa, 1976). See Clarke and West (1997) for detailed descriptions of each of these features.

Silviculture 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 on February 3, 2003, at *http://www.census.gov/*). The SRS encompasses about 310 mi^2, or 6 percent of the study area, and lies in parts of Aiken, Barnwell, and Allendale Counties, S.C. (fig. 1*A*).



EXPLANATION

- Study area
- Fault—D, downthrown side; U, upthrown side
- — 46 — Line of equal mean-annual rainfall, 1969–98—Interval 2 inches
- •48.2 Precipitation-monitoring site and rainfall amount
- • Brighams Landing well-cluster site

Piedmont Province

Coastal Plain Province

- Fall Line Hills District
- Aiken Plateau District
- Congaree Sand District
- Louisville Plateau District
- Tifton Upland District
- Coastal Terraces District

Figure 1. (*A*) Location of study area, Savannah River Site (SRS), Brighams Landing well-cluster site, precipitation monitoring sites, mean-annual rainfall, 1969–98, and physiographic provinces and districts in Georgia and South Carolina (rainfall data from Southeast Regional Climate Center, accessed February 11, 2004, at *http://www.dnr.sc.gov/climate/sercc/*); and (*B*) areal and local ground-water contamination at the SRS, South Carolina (modified from Arnett and Mamatey, 1996).

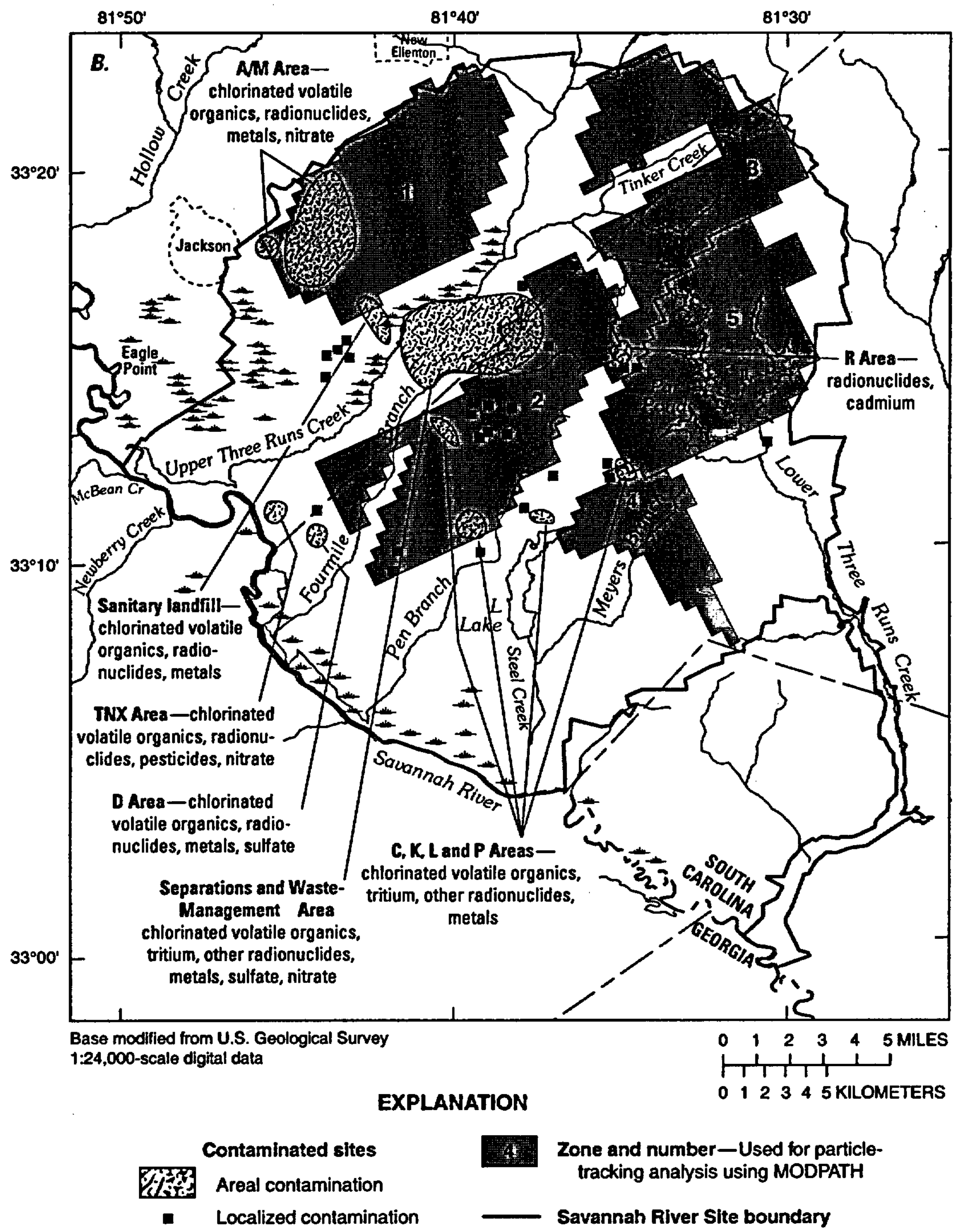


Figure 1. (*A*) Location of study area, Savannah River Site (SRS), Brighams Landing well-cluster site, precipitation monitoring sites, mean-annual rainfall, 1969–98, and physiographic provinces and districts in Georgia and South Carolina (rainfall data from Southeast Regional Climate Center, accessed February 11, 2004, at *http://www.dnr.sc.gov/climate/sercc/*); and (*B*) areal and local ground-water contamination at the Savannah River Site, South Carolina (modified from Arnett and Mamatey, 1996)—continued.

A relatively mild climate with warm, humid summers and mild winters characterize the study area. Wind patterns in the summer are dominated by winds out of the northeast off the Bermuda high-pressure system, and shift to a northwesterly direction during the winter months as fronts move through the area from west to east (Weber, 2003). Precipitation is highest in the winter months when continental storm fronts move through the region 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 50 inches in central Aiken County, S.C. (Cherry, 2003).

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 of which are 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).

Coastal Plain sedimentary strata in the study area consist of layers of sand, clay, and minor limestone that range in age from Late Cretaceous through post-Eocene. The Fall Line (fig. 1*A*) marks the approximate northern limit of the strata and the contact between the Coastal Plain and Piedmont physiographic provinces. 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 are generally parallel to the Fall Line. The sedimentary sequence unconformably overlies igneous and metamorphic rocks of Paleozoic, and consolidated red beds of early Mesozoic (Chowns and Williams, 1983). A generalized correlation of geologic units in the SRS region is shown in figure 2. See Falls and others (1997) for a complete description of geologic units in the study area.

Major structural features in the study area 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 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 normal fault that dips to the southeast and cuts strata of Cretaceous, Paleocene, and Eocene. 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).

Previous Investigations

Previous investigators in Georgia (Miller, 1986; Brooks and others, 1985; Clarke and others, 1985) and South Carolina (Logan and Euler, 1989; Bledsoe and others, 1990; Aadland and others, 1995) defined three principal aquifer systems near the SRS. The aquifer systems are, in descending order: (1) the Floridan aquifer system (Miller, 1986), composed largely of calcareous sand and limestone of Eocene; (2) the Dublin aquifer system (Clarke and others, 1985) composed of sand of Paleocene and Late Cretaceous, and (3) the Midville aquifer system (Clarke and others, 1985) composed of sand of Late Cretaceous. Although this subdivision of geologic strata was suitable for most regional-scale hydrologic studies, greater subdivision of units was required to define vertical hydraulic heterogeneity for detailed investigations of ground-water flow near the Savannah River. Falls and others (1997) divided the three aquifer systems into seven discrete aquifers (fig. 2):

1. The Floridan aquifer system was subdivided into the Upper Three Runs aquifer and the Gordon aquifer.
2. The Dublin aquifer system was subdivided into the Millers Pond aquifer, the upper Dublin aquifer, and the lower Dublin aquifer.
3. The Midville aquifer system was subdivided into the upper Midville aquifer and the lower Midville aquifer.

Layers of clay and silt that become more sandy in updip areas confine the aquifers. Where the confining units are sandy, they do not have lateral continuity and the aquifer systems coalesce. Falls and others (1997) provide a detailed description of the hydrogeologic framework used in the trans-river flow study including areal extent, thickness, and hydraulic properties of hydrogeologic units.

Synoptic ground-water-level measurements were taken in 189 wells during early September 2002, and potentiometric-surface maps were constructed for the Upper Three Runs and Gordon aquifers and the Dublin and Midville aquifer systems as part of initial work for this study (Cherry, 2003). Clarke and West (1998) described development and calibration of the steady-state ground-water model for predevelopment and 1987–92 conditions. Clarke and West (1997) provided the foundation for the earlier ground-water modeling study by reporting ground-water-level fluctuations and trends, water use, precipitation, and estimated ground-water contribution to streamflow. Cherry (2004) updated the model using MODFLOW-2000 and adjusted boundary conditions, pumping rates, and recharge values. Falls and others (1997) defined the hydrogeologic framework for the ground-water model by subdividing the three aquifer systems into seven aquifers and six confining units. Clarke and West (1997) presented a complete overview of previous geologic and hydrogeologic studies in the SRS area.

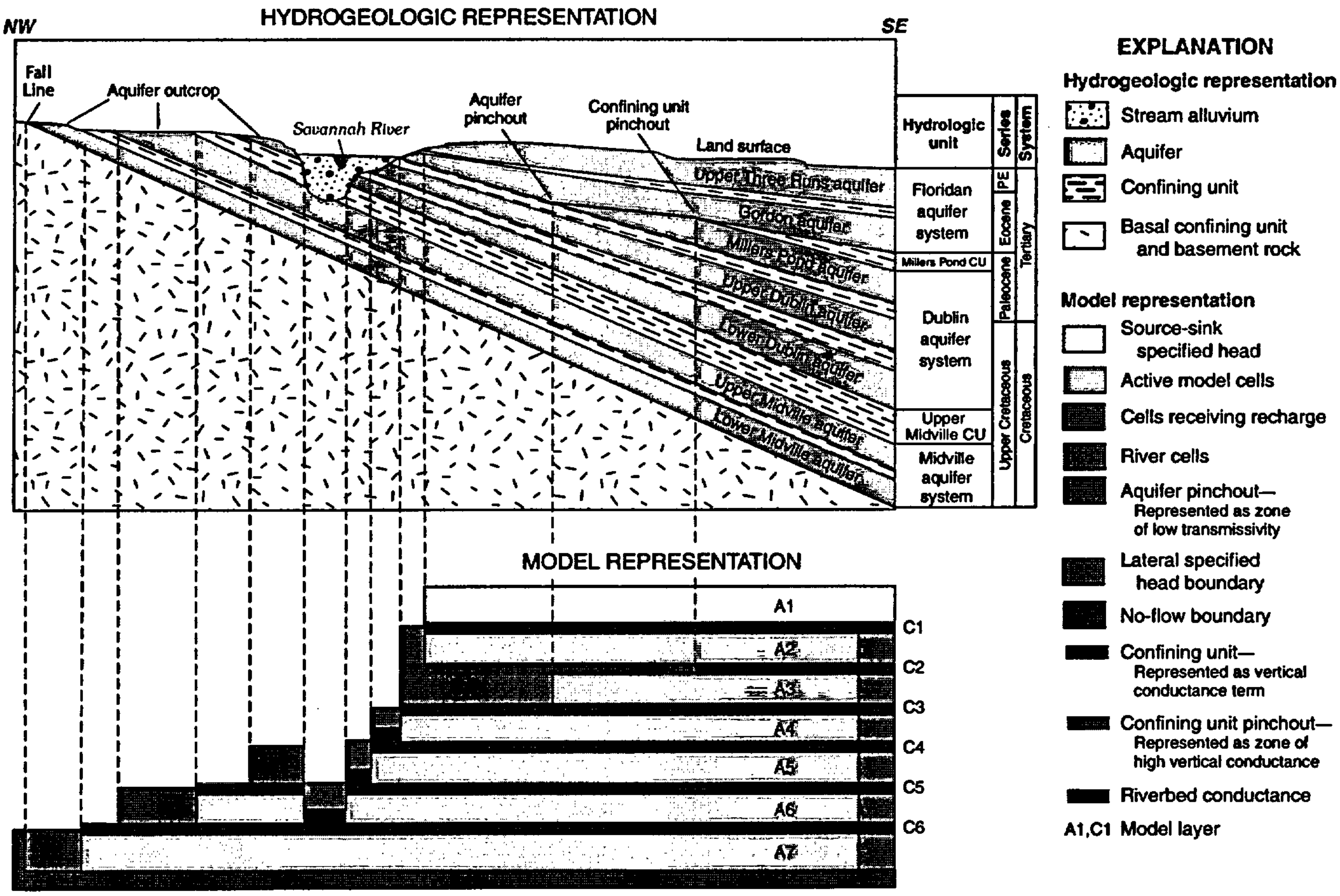


Figure 2. Schematic diagram showing hydrogeologic framework, model layers, and boundary conditions for the Savannah River Site area, South Carolina, ground-water model (modified from Clarke and West, 1998; CU, confining unit; PE, post-Eocene).

Ground-water modeling investigations in the SRS area include Faye and Mayer (1990) and Aucott (1997), who conducted studies as part of the USGS Regional Aquifer-System Analysis Program. Several ground-water flow models were developed as part of hydrogeologic investigations conducted at the SRS. Marine and Root (1975) evaluated flow in the Tuscaloosa aquifer; Parizek and Root (1986) evaluated ground-water velocity at the radioactive waste management facility. Looney and others (1990) evaluated flow at a proposed production reactor site. Camp, Dresser, & McKee, Inc. (1992) evaluated flow at the nuclear weapons complex reconfiguration site. HydroGeoLogic, Inc. (1992) evaluated flow and transport at the TNX Area. Faye and Mayer (1990) and Delaimi (1996) evaluated ground-water flow transverse to the Savannah River using cross-sectional flow models. Flach and others (1996) developed a variably saturated, finite-element ground-water flow model of the SRS Old Burial Ground to predict tritium migration to Fourmile Branch. The Savannah River Technology Center (SRTC) developed the finite-element ground-water modeling code of Flow and Contaminant Transport (FACT) to predict tritium migration on a larger scale (Hamm and others, 1997; Aleman and Hamm, 1999). The FACT code was used to construct ground-water models of varying scale to predict tritium migration to local streams (Flach and others, 1998, 1999a, b, and 2000). The modeling effort focused on transport of tritium within the Upper Three Runs aquifer and the Gordon aquifer was the lowermost unit within the models.

GGS conducted an evaluation of the areal extent and source of tritium detected in domestic wells in Burke County, Ga. Summerour and others (1994) described results of the GGS investigation, including tritium sampling of wells and streams, characterization of the hydrogeologic setting and subsurface geology, ground-water flow directions, and a seismic survey of the Savannah River channel. A follow-up study (Summerour and others, 1998) was conducted to verify the presence of tritium in domestic wells located in Burke County, and concluded that the primary pathway for contamination is through tritiated rainfall entering the Upper Three Runs aquifer as recharge.

Methods of Study

This study updated an existing ground-water flow model of the SRS region (Clarke and West, 1998) in order to describe ground-water flow under 2002 conditions and to evaluate four hypothetical pumping scenarios for the potential to induce trans-river flow. Information on ground-water withdrawal during 1992–2002 on and near the SRS was compiled from the records of DOE; Washington Savannah River Company (WSRC); South Carolina Department of Health and Environmental Control (SCDHEC); Georgia Environmental Protection Division (GaEPD); and USGS. To provide data for model evaluation and possible recalibration and to determine if boundary conditions have changed since 1992, water-level data were collected from 189 wells and potentiometric-surface maps were constructed for each of the major aquifers (Cherry, 2003). These data served as the basis to determine if recalibration of the previous model was necessary. The revised model did not require recalibration because residuals between observed and simulated heads met the same error criteria developed during the earlier study as described in Clarke and West (1998, p. 29–31). After determining recalibration of the model would not be necessary, four ground-water management scenarios were developed to evaluate hypothetical increases in ground-water withdrawal at existing pumping centers and variations to boundary conditions. The USGS particle-tracking code MODPATH (Pollock, 1994) was used to generate advective water-particle pathlines and their associated time-of-travel based on MODFLOW simulations for 2002 and each of four ground-water management scenarios.

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Hydrologic, Climatic, and Ground-Water Use Conditions, 1992–2002

During 1992–2002, the stream-aquifer flow interactions in the study area changed as the result of changes in water use and a prolonged drought during 1998–2002. The following sections describe changes to precipitation, ground-water use, ground-water levels, and streamflow during the 10-year period.

Precipitation

Average annual precipitation for the period 1969–1998 ranged from about 45 inches near Augusta, Ga., to greater than 52 inches near Aiken, S.C. (Cherry, 2003). These values are slightly higher than the rainfall during the previous 30-year period (1941–70) reported in Faye and Mayer (1990).

In this report, normal precipitation is defined as the average monthly rainfall during the 55-year period from 1948–2002; cumulative departure from normal is shown through 2002 for Augusta, Ga., and Aiken, S.C. (fig. 3). During 1992–98, precipitation at Augusta and Aiken mostly was above normal as indicated by the upward slope on the cumulative-departure graph (fig. 3). A prolonged drought during 1998–2002 resulted in below-normal precipitation, as indicated by a steep downward slope on the cumulative-departure graph (fig. 3). The cumulative departure from normal decreased from +42 inches at Aiken and +32 inches at Augusta during mid-1998 to about 0 inches by the end of 2002. The recent drought of 1998–2002 is overshadowed by the severity of the drought in the early to mid-1950s, during which the cumulative departure from normal was –90.1 inches at Aiken and –48.7 inches at Augusta. A study using tree-ring analysis that examined the past 325 years indicates that a drought of 2 or more years on average can be expected in Georgia about once in 25 years (Stooksbury, 2003).

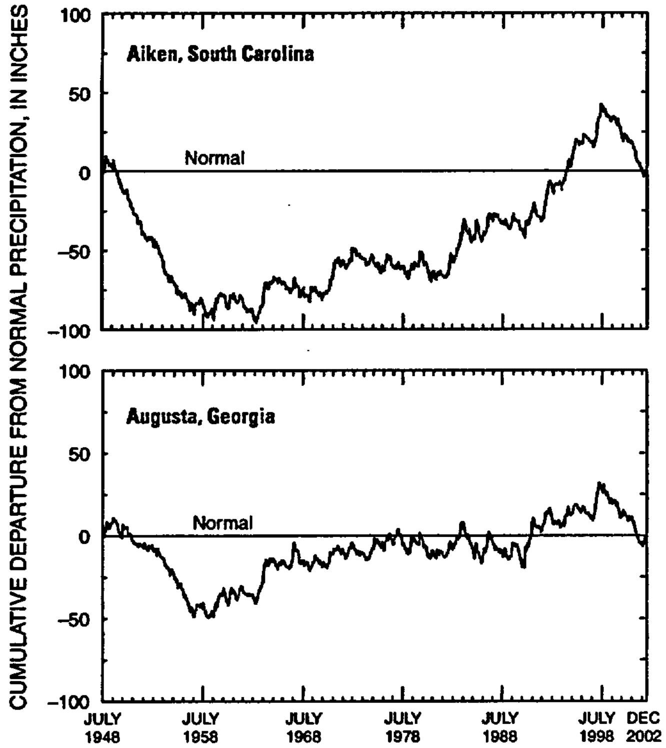


Figure 3. Cumulative departure from normal precipitation for Augusta, Georgia, and Aiken, South Carolina, July 1948 through December 2002 (location of precipitation sites shown in figure 1; data from Southeast Regional Climate Center, accessed February 11, 2004, at *http://www.dnr.sc.gov/climate/sercc/*).

Ground-Water Use

Ground-water use in the eight-county study area showed a substantial increase during the past 10 years (fig. 4). Clarke and West (1997) reported that during 1987–92, total ground-water use was about 80 million gallons per day (Mgal/d). By 1995, the total ground-water use was about 85.4 Mgal/d (Fanning, 1997), and by 2000–2002 (Fanning, 2003; W.J. Stringfield, U.S. Geological Survey, written commun., 2002) total ground-water use had risen to about 117 Mgal/d (table 1).

The largest increase in ground-water use between 1995 and 2000 was in Burke, Jefferson, and Screven Counties, Ga., and Allendale and Barnwell Counties, S.C. (fig. 4, table 1). In these counties, ground-water use for irrigation increased from 16.7 Mgal/d during 1995 to 53.1 Mgal/d during 2000 and irrigated acreage increased from 61,690 acres during 1995 to 97,690 acres during 2000 (Fanning, 2003).

Spatial distribution of irrigation pumping within the hydrogeologic units simulated by the model was based on site-specific data (well depth, open interval, and pump capacity) and interpolating aquifer altitudes at each well location. 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.

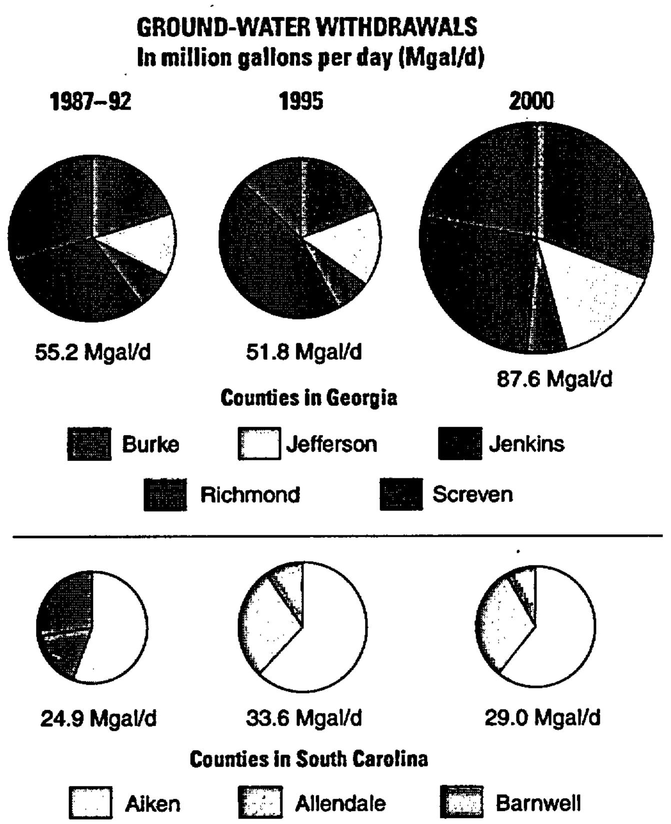


Figure 4. Ground-water use in selected counties in Georgia and South Carolina, 1987–2000 (see table 1 for county totals and data sources).

Table 1. Ground-water use during 1990, 1995, and 2000–2002 near the Savannah River Site, South Carolina.

[Ga., Georgia; S.C., South Carolina; do., ditto]

Year	State	County	Pumpage, in million gallons per day						
			Public supply	Irrigation	Industrial mining	Domestic and commercial	Livestock	Thermo-electric power	Total
1990	Ga.	Burke	1.20	2.57	0.00	0.91	0.04	2.27	6.99
	do.	Jefferson	1.86	2.60	4.78	0.64	0.04	0	9.92
	do.	Jenkins	0.58	1.86	0.11	0.32	0.02	do.	2.89
	do.	Richmond	13.18	0.96	2.55	0.87	0.02	do.	17.58
	do.	Screven	1.07	3.96	2.30	0.74	0.04	do.	8.11
	S.C.	Aiken	3.26	1.44	9.84	2.11	0.35	do.	17.00
	do.	Allendale	0.66	4.78	2.40	0.43	0.04	do.	8.31
	do.	Barnwell	2.54	0.02	0.16	0.52	0.48	do.	3.72
		Total—Ga.	**17.89**	**11.95**	**9.74**	**3.48**	**0.16**	**2.27**	**45.49**
		Total—S.C.	**6.46**	**6.24**	**12.40**	**3.06**	**0.87**	**0**	**29.03**
		Total—eight county	**24.35**	**18.19**	**22.14**	**6.54**	**1.03**	**2.27**	**74.52**
1995	Ga.	Burke	1.17	7.08	0	0.88	0.04	0.78	9.95
	do.	Jefferson	1.89	2.28	3.18	0.70	0.03	0	8.08
	do.	Jenkins	0.52	2.92	0.01	0.35	0.02	do.	3.82
	do.	Richmond	13.87	5.12	3.58	0.79	0.02	do.	23.38
	do.	Screven	0.87	3.24	1.69	0.72	0.04	do.	6.56
	S.C.	Aiken	9.75	0.01	9.40	1.31	0.35	do.	20.82
	do.	Allendale	0.85	4.10	4.03	0.42	0.04	do.	9.44
	do.	Barnwell	2.21	0	0	0.62	0.48	do.	3.31
		Total—Ga.	**18.32**	**20.64**	**8.46**	**3.44**	**0.15**	**0.78**	**51.79**
		Total—S.C.	**12.81**	**4.11**	**13.43**	**2.35**	**0.87**	**0**	**33.57**
		Total—eight county	**31.13**	**24.75**	**21.89**	**5.79**	**1.02**	**0.78**	**85.36**
2000–2002	Ga.	Burke	3.87	21.23	0.15	0.90	0.03	0.78	26.96
	do.	Jefferson	1.84	6.92	3.82	0.64	0.03	0	13.25
	do.	Jenkins	0.54	3.94	0.01	0.33	0.02	do.	4.84
	do.	Richmond	14.88	5.22	2.87	0.22	0.02	do.	23.21
	do.	Screven	1.15	15.62	1.82	0.74	0.03	do.	19.36
	S.C.	Aiken	4.82	0.98	6.06	0.80	0	do.	12.66
	do.	Allendale	1.20	5.62	2.50	0.27	do.	do.	9.59
	do.	Barnwell	2.73	3.73	0.41	0.63	do.	do.	7.50
		Total—Ga.	**22.28**	**52.93**	**8.67**	**2.83**	**0.13**	**0.78**	**87.62**
		Total—S.C.	**8.75**	**10.33**	**8.97**	**1.70**	**0**	**0**	**29.75**
		Total—eight county	**31.03**	**63.26**	**17.64**	**4.53**	**0.13**	**0.78**	**117.37**

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

Ground-water use for public supply increased from 24.4 Mgal/d during 1990 to 31.0 Mgal/d during 2000–2002 (table 1). Burke and Richmond Counties in Georgia and Aiken County in South Carolina accounted for the most of the 6.6 Mgal/d increase during the 10-year period. The Richmond County Water System alone accounted for about 1.4 Mgal/d of the increase; 13.2 Mgal/d was withdrawn during 2000–2002 (Fanning, 2003), primarily from the Midville aquifer system.

Ground-water use for industrial and mining purposes showed a moderate decrease from 22.1 Mgal/d during 1990 to 17.6 Mgal/d during 2002. Most of the decrease can be attributed to reduced withdrawal at the SRS from 9.0 Mgal/d during 1990 to 5.4 Mgal/d during 2002 (R.A. Hiergesell, Westinghouse Savannah River Company, written commun., 2002). The other ground-water use categories of domestic/commercial, livestock, and thermoelectric power remained relatively constant during 1990–2002 (J.L. Fanning, U.S. Geological Survey, written commun., 2002).

Ground-Water Levels

During 1992–2002, water levels in each of the major aquifers generally declined because of below-normal precipitation and increased ground-water use. Declines, based on periodic water-level measurements, in the Upper Three Runs aquifer ranged from 2 to 5 ft in northeastern Burke County and were greater than 20 ft in southern Burke and Screven Counties (Cherry, 2003). Water-level trends in the Gordon aquifer and Dublin and Midville aquifer systems are shown on the hydrographs for wells at Brighams Landing in the Savannah River valley in Burke County (fig. 5). Water-level declines at Brighams Landing were most pronounced in the Gordon aquifer with progressively less declines in the deeper Dublin and Midville aquifer systems, respectively (figs. 1*A*). In well 32Y033, completed in the Gordon aquifer, the water level declined about 16 ft, from a daily mean water-level altitude of 120.4 ft during September 1995 to 104.4 ft during September 2002 (fig. 5). Steep seasonal decline in ground-water levels from 1998 to 2002 coincides with the growing season and heavy ground-water use for irrigation in eastern Burke County and northeastern Screven County during the period of drought. In well 32Y031, completed in the Dublin aquifer system, the water level declined about 7 ft during the same period (fig. 5). The water level in well 32Y030 completed in the Midville aquifer system declined about 5 ft from September 1995 to September 2002 (fig. 5).

The potentiometric-surface map for the Upper Three Runs aquifer was constructed using water-level data from 78 wells (fig. 6*A*). The map reflects the water-level decline that occurred during 1992–2002, especially in topographically higher areas in Burke County, Ga., and Barnwell and Allendale Counties, S.C. Decreased water-level altitudes are illustrated by the northern shift of the 140- and 180-ft contours in Allendale and Barnwell Counties, S.C. Despite these declines, the general contours are similar to the previous map for 1987–92 (Clarke and West, 1997). Because the Upper Three Runs aquifer is the source-sink layer for the ground-water model, it surface during 1992–2002. The areas of greatest water-level decline in the Upper Three Runs aquifer occurred in northern Jenkins and Screven Counties because of increased ground-water pumpage for irrigation. In these counties, the estimated water-level decline ranged from 10 ft to as high as 50 ft. Estimated water use from the Upper Three Runs aquifer increased by about 6 Mgal/d during 1992–2002 in Burke, Jenkins, and Screven Counties, resulting in water-level declines.

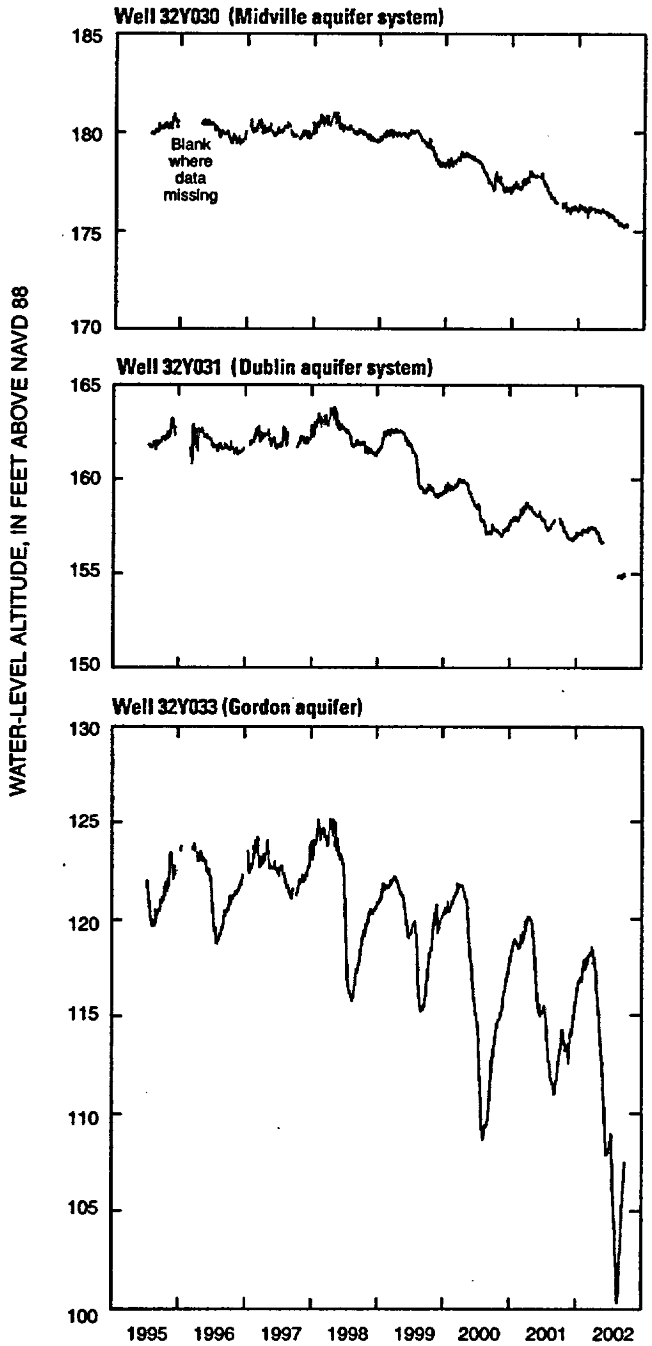


Figure 5. Water-level altitude for wells 32Y030, 32Y031, and 32Y033 at the Brighams Landing well-cluster site, 1995–2002 (see figure 1 for cluster location).

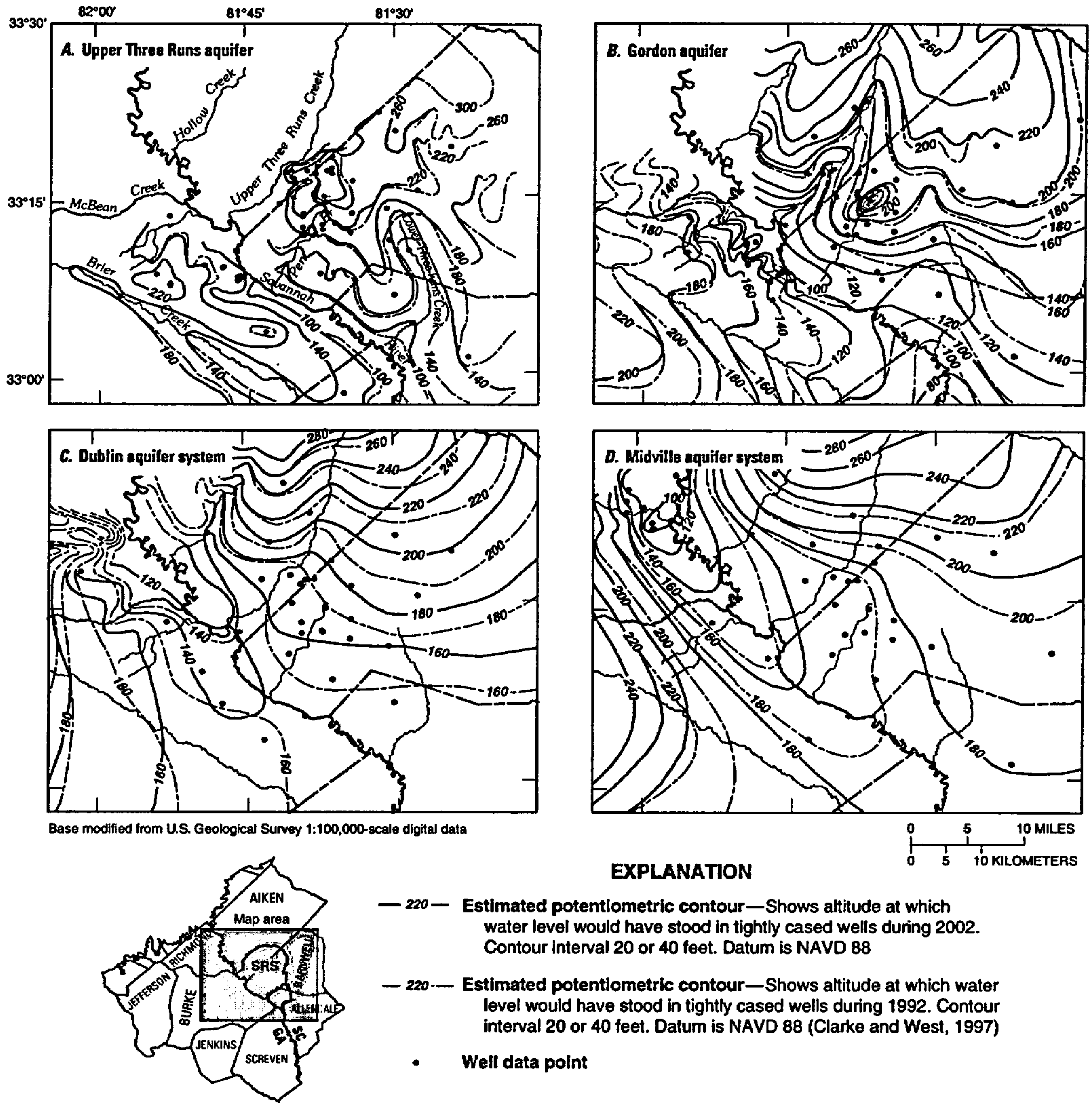


Figure 6. Potentiometric-surface maps for the (*A*) Upper Three Runs aquifer, (*B*) Gordon aquifer, (*C*) Dublin aquifer system, and (*D*) Midville aquifer system during 1992 and 2002, near the Savannah River Site, Georgia and South Carolina (from Cherry, 2003).

The potentiometric-surface map for the Gordon aquifer was constructed using water-level data from 49 wells (fig. 6*B*). The map shows the effect of drought and ground-water withdrawal on the potentiometric surface. Water-level declines are indicated by a northwestern shift of the 120- and 140-ft contours in Georgia, and by a northern shift of the 120-, 140-, 160-, and 180-ft contours in South Carolina. Perhaps the most pronounced effect on the configuration of the potentiometric surface is near a ground-water divide beneath the Savannah River. Here, some ground water flows updip toward the area where the ancient Savannah River breached the confining unit overlying the Gordon aquifer, and another segment flows southward toward the coast. The overall decline in aquifer water-level altitude for the Gordon aquifer is best illustrated by the 120-ft contour that crossed the Savannah River during 1992, but is replaced during 2002 by the 100-ft contour. Thus, the ground-water divide beneath the river has moved northeast since 1992.

The potentiometric-surface map for the Dublin aquifer system was constructed using water-level data from 32 wells (fig. 6*C*). Water-level declines are indicated on the map by the westward shift of the 160-ft contour in Georgia, and by the northern shift of the 160-, 180-, 200-, and 220-ft contours in South Carolina. The southeastern shift of the 140-ft contour beneath the Savannah River reflects water-level decline and shows an apparent movement of the position of the ground-water divide in the southern part of the study area.

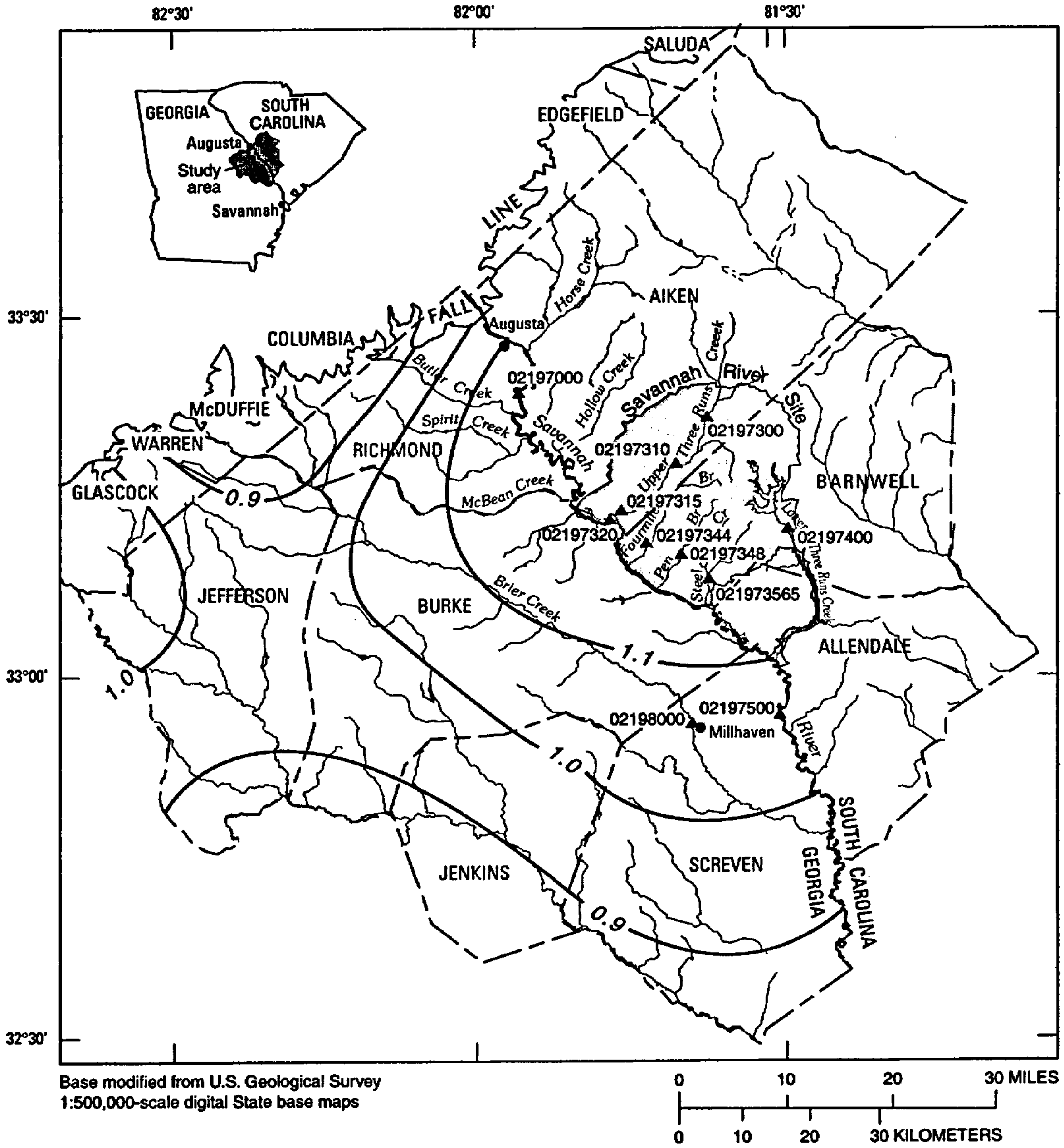
The potentiometric-surface map for the Midville aquifer system was constructed using water-level data from 30 wells (fig. 6*D*). Water-level decline is indicated by the westward shift of the 180-, 200-, and 220-ft contours in Georgia, and by the northern shift of the 180-, 200-, and 220-ft contours in South Carolina. Further evidence of water-level decline is indicated by eastward shift of the 160-ft contour beneath the Savannah River. In addition, it appears that the 180-ft contour, which formerly intersected the river near Brighams Landing, did not intersect the river within the study area during 2002.

Streamflow

The Savannah River is the major surface-water drain in the study area and is the State line between Georgia and South Carolina (fig. 7). The river drains an area of about 10,580 mi^2 (1,140 mi^2 of which are in the study area) and empties into the Atlantic Ocean near Savannah, Ga. Streamflow has been regulated since 1954 with the impoundment of Thurmond Lake storage reservoir located 22 mi upstream from Augusta. Major tributaries of the Savannah River are, in downstream order; Horse Creek, Hollow Creek, Upper Three Runs Creek, Fourmile Branch, Pen Branch, Steel Creek, and Lower Three Runs Creek in South Carolina; and Butler Creek, Spirit Creek, McBean Creek, and Brier Creek in Georgia (fig. 7). Analysis of ground-water discharge to local streams in the study area using many techniques including hydrograph separation concluded that the ground-water contribution to nearby streams during an average period is nearly 60 percent of the total streamflow and 80 percent during dry periods (Priest and Clarke, 2003). During 1941–70, the mean-annual runoff in Georgia (fig. 7) ranged from less than 0.9 (ft^3/s)/mi^2 of drainage area in southern Screven, Jenkins, Burke, and Jefferson Counties, and in northern Richmond and Jefferson Counties to more than 1.1 (ft^3/s)/mi^2 in eastern Richmond and Burke Counties (Faye and Mayer, 1990).

Estimates of mean-annual ground-water discharge in the Savannah River Basin (encompassing about 35 percent of the actively simulated model area) range from 10.8 to 19.8 inches per year (in/yr) with an average of 14.5 in/yr (Clarke and West, 1998). These estimates are based on the gain in ground-water discharge (as streamflow) between the Augusta streamflow gage (02197000), located near the Fall Line, and Millhaven streamflow gage (02197500), located near the southern boundary of the model (fig. 7). Analyses of the streamflow gains since the previous study (see table 2) indicates several water years (WY) (October 1 of previous year through September 30 of designated year) with streamflow gains well above the 14.5 in/yr average reported by Clarke and West (1997). These streamflow gains are a combination of ground-water discharge and a strong overland component of stormwater runoff. The annual net gain in streamflow between the two stations during 1992–2002 ranged from 7.7 to 28.5 in/yr, with an average of 15.9 in/yr. The period of record can be characterized by 4 years of above average streamflow (WY 1993, 1995, 1996, and 1998) and 7 years of below average streamflow (WY 1992, 1994, 1997, and 1999–2002) with a 4-year period of drought from 1999 through 2002.

In the northern half of the SRS, Upper Three Runs Creek has breached the confining unit of the Gordon aquifer and functions as an important ground-water discharge area for the Gordon aquifer and the Dublin aquifer system, as indicated by the shape of the potentiometric-surface maps for the two aquifers (figs. 6*B*, 6*C*). The net gain in streamflow along Upper Three Runs Creek is evident when comparing the mean-annual streamflow between streamflow gages 02197300 and 02197315, with a contributing drainage area of 116 mi^2 (fig. 7 and table 2). Clarke and West (1997) reported mean-annual ground-water discharge computed using hydrograph separation between the two streamflow gages was 23.5 in/yr during 1987–92. During 1992–2002, mean-annual streamflow gain along this reach ranges from 7.6 in/yr during a dry year (WY 2002) to 23.6 in/yr during a wet year (WY 1993) and averages 15.1 in/yr (table 2).



EXPLANATION

— *1.0* — **Line of equal mean-annual runoff, 1941–70—** Interval 0.1 cubic foot per square mile of drainage area

▲ 02198000 **Streamflow gaging station and identification number—** See table 2

Figure 7. Mean-annual runoff in Georgia part of study area, 1941–70 (modified from Faye and Mayer, 1990); and locations of selected U.S. Geological Survey streamflow gaging stations.

Table 2. Mean-annual discharge to selected streams near the Savannah River Site, Georgia and South Carolina, water years 1992–2002.

[Water year, October 1 of previous year through September 30 of designated year; mi², square miles; ft³/s, cubic feet per second; in/yr, inches per year; NA, not available; SRS, Savannah River Site; S.C., South Carolina; Ga., Georgia]

Station number	Station name	Drainage area (mi²)	Intermediate drainage area (mi²)	Water year — Mean-annual stream discharge (ft³/s) 1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	Average
	Upper Three Runs Creek Basin, S.C.														
2197300	Upper Three Runs Creek near New Ellenton	87	NA	108	118	110	126	117	98	113	100	82	76	68	101
2197310	Upper Three Runs Creek above Road C, SRS	176	89	232	274	235	294	236	206	NA	NA	169	155	119	NA
2197315	Upper Three Runs Creek at Road A, SRS	203	27	256	320	239	284	245	214	301	206	174	167	133	231
	Net gain in stream discharge between stations 2197300 and 2197315	NA	116	148	202	129	158	128	116	188	106	92	91	65	129
	Net gain in stream discharge in in/yr			17.4	23.6	15.1	18.5	15.0	13.6	22.0	12.4	10.8	10.7	7.6	15.1
	Savannah River Basin														
2197000	Savannah River at Augusta, Ga.	7,508	NA	7,660	15,400	8,370	11,110	11,800	9,010	14,150	5,830	4,750	4,770	4,470	8,847
2197320	Savannah River near Jackson, S.C.	8,110	602	8,380	16,680	9,410	12,120	12,991	10,160	15,250	6,960	5,300	5,500	4,860	9,783
2197500	Savannah River at Burtons Ferry near Millhaven, Ga.	8,650	540	8,740	17,800	9,650	12,750	13,440	9,950	16,550	6,710	5,465	5,828	5,120	10,182
	Net gain in stream discharge between stations 2197000 and 2197500	NA	1,142	1,080	2,400	1,280	1,640	1,640	940	2,400	880	715	1,058	650	1,335
	Net gain in stream discharge in in/yr			12.9	28.5	15.2	19.5	19.5	11.2	28.5	10.5	8.5	12.6	7.7	15.9
	Savannah River Site, S.C.														
2197344	Fourmile Branch at Road A12.2	22	NA	40	58	28	37	28	23	45	21	18	14	11	29
2197348	Pen Branch at Road A-13	21	NA	235	48	51	56	45	28	34	15	13	13	8.5	50
21973565	Steel Creek at Road A	NA	NA	117	118	82	86	62	52	53	24	19	26	12	59
2197400	Lower Three Runs Creek near Snelling, S.C.	59	NA	85	102	80	60	60	41	118	49	40	36	32	64
	Brier Creek Basin, Ga.														
2198000	Brier Creek at Millhaven, Ga.	646	NA	596	904	521	821	595	437	1,090	378	297	364	195	563

Simulation of Steady-State Ground-Water Flow, 2002

The USGS conducted a ground-water modeling investigation of ground-water flow and stream-aquifer relations during 1991–97 (Clarke and West, 1998). During that study, the ground-water flow system was simulated with a series of six steady-state pumping periods; 1953–60, 1961–70, 1971–75, 1976–80, 1981–86, and 1987–92. Results were summarized for the predevelopment (pre-1953) and modern-day (1987–92) simulations, with hydrographs of selected wells presented for interim periods. Steady-state ground-water flow was simulated using the USGS three-dimensional finite-difference model, MODFLOW (McDonald and Harbaugh, 1988). 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 was generally in a state of equilibrium and any contributions from aquifer storage were minor. The flow system was modeled using a quasi-three-dimensional approach with seven layers—six active layers and an overlying source-sink layer—that are separated to varying degrees by six confining units (fig. 2). 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. 8). The model grid area encompasses about 4,455 mi², of which about 3,250 mi² is actively simulated.

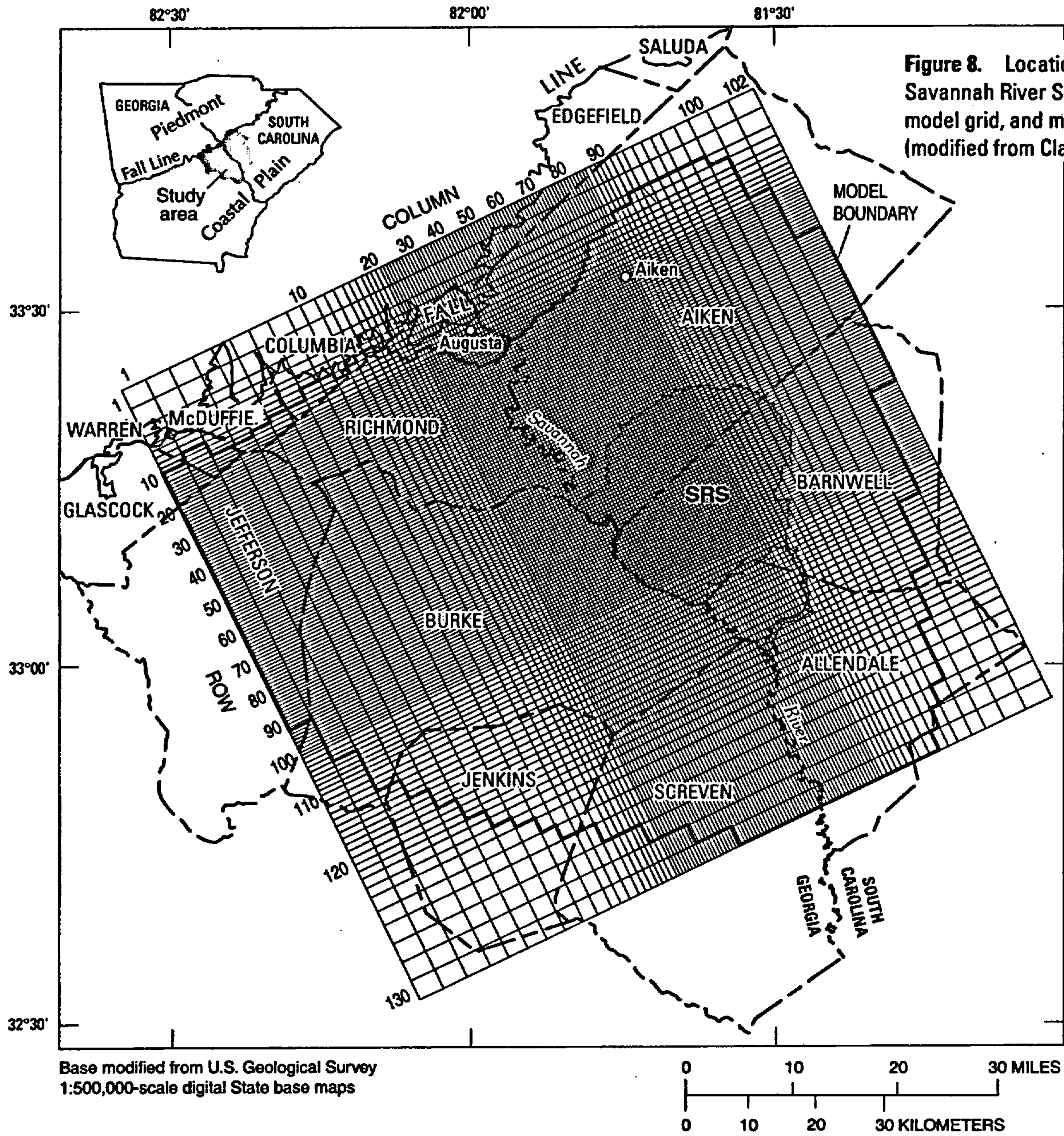


Figure 8. Location of study area, Savannah River Site, South Carolina, model grid, and model boundary (modified from Clarke and West, 1998).

Calibration of the original SRS model (1987–92) was accomplished by adjusting hydrologic properties until a "best fit" was obtained between simulated and observed water levels along with a comparison between simulated ground-water discharge data and measured data obtained from streams and rivers. Model adjustments also were controlled by consideration of "realistic" values for a given hydrologic property based on available field data and accepted limits reported in the literature. Recharge values were assigned to aquifer outcrop areas (layers A2–A7) for individual cells as direct recharge or in cells supplied by inflows from the source-sink layer A1, and were held below the maximum acceptable limit of 20 in/yr (Clarke and West, 1998; fig. 2). The model-calculated downward vertical flux from the source-sink layer A1 represents recharge that has infiltrated downward through the Upper Three Runs aquifer. Hydrologic properties that were adjusted during model calibration were confining unit leakance, streambed conductance, and transmissivity, with most adjustment made to confining unit leakance and streambed conductance (Clarke and West, 1998). These parameters and their corresponding ranges within the study area are summarized in table 3. Boundary conditions adjusted during calibration consisted of head values in the source-sink layer A1; head values along lateral boundaries in deep layers A2 through A7; river stage; and recharge. Simulations using steady-state conditions were deemed suitable because long-term water levels and ground-water discharge from aquifers to rivers and streams showed little change during predevelopment (pre-1953) and modern-day periods (1987–92, Clarke and West, 1998, p. 31). In addition, Clarke and West (1998) conducted a series of transient response tests to determine if the model is sensitive to the effects of storage and the results indicate that contribution from storage to be negligible. Sensitivity analysis of the major input parameters indicate that ground-water levels and the area of trans-river flow mostly were influenced by changes in specified head in the source-sink layer A1, whereas ground-water discharge to streams mostly was influenced by changes in river stage (Clarke and West, 1998).

Updating the Model to 2002 Conditions

The existing regional ground-water model (Clarke and West, 1998) was reformatted to a newer version of MODFLOW (MODFLOW-2000; Harbaugh and others, 2000), which incorporates altitudes of the top and bottom of each hydrogeologic unit. The model was updated to 2002 hydrologic conditions by modifying boundary conditions and pumping stresses on the ground-water system. A steady-state simulation of 2002 hydrologic conditions was deemed appro-

Table 3. Ranges of field observations and estimates for transmissivity, confining unit leakance, and streambed conductance by hydrogeologic unit for ground-water flow model near the Savannah River Site, South Carolina (modified from Clarke and West, 1998).

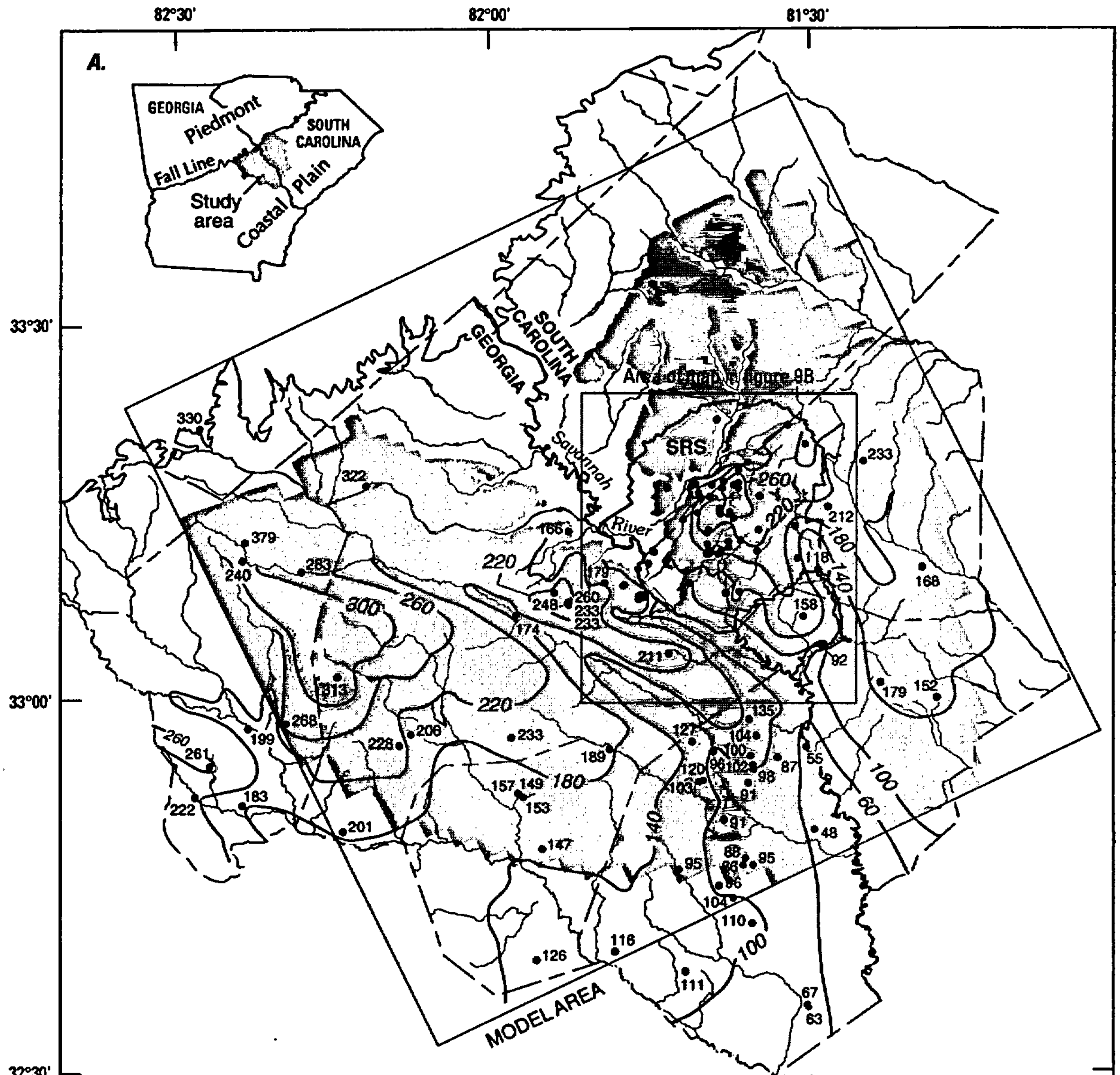
[ft²/d, foot squared per day; min, minimum; max, maximum; ft/d, foot per day; NA, not applicable]

Hydrogeologic unit	Layer number	Number of field observations	Transmissivity (ft²/d)			Reported hydraulic conductivity (ft/d)	Estimated leakance[1]			Number of riverbed conductance values	Streambed conductivity (ft²/d)		
			Min.	Max.	Mean		Min.	Max.	Mean		Min.	Max.	Mean
Upper Three Runs aquifer	A1	8	500	9,500	3,260	8	NA	NA	NA				
Gordon confining unit	C1	6					4.7E-6	1.2E-2	2.1E-3	244	0.1	1,600	140
Gordon aquifer	A2	18	180	12,200	4,460	2–18	NA	NA	NA	443	240	1.6E+6	81,000
Millers Pond confining unit	C2	0					NA	NA	NA	42	1,400	31,000	13,000
Millers Pond aquifer	A3	10	195	2,000	1,020	7	NA	NA	NA	58	28,000	1.6E+6	121,000
Upper Dublin confining unit	C3	9					1.8E-6	1.6E-3	3.6E-4	62	2.3	6,100	1,200
Upper Dublin aquifer	A4	17	555	25,200	5,830	0.7	NA	NA	NA	207	8.6	648,000	44,000
Lower Dublin confining unit	C4	1					2.4E-5	2.4E-5	2.4E-5	113	1.0	6,100	720
Lower Dublin aquifer	A5	21	40	8,900	3,940	0.4–56	NA	NA	NA	176	550	1.6E+6	95,000
Upper Midville confining unit	C5	11					6.7E-7	3.9E-4	7.6E-5	88	140	207,000	25,000
Upper Midville aquifer	A6	15	1,300	5,430	2,760	30	NA	NA	NA	57	1,400	2.5E+6	294,000
Lower Midville confining unit	C6	1					1.0E-5	1.0E-5	1.0E-5	61	0.6	6,100	790
Lower Midville aquifer	A7	37	800	25,500	8,900	65–140	NA	NA	NA	108	95	406,000	85,000

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

priate because of the conclusion from transient response tests conducted for the original model that changes in pumpage are short term and that the model results are insensitive to changes in storage (Clarke and West, 1998). The finite-difference grid and hydraulic properties were not changed for the 2002 simulation.

Boundary conditions for the 2002 simulation were modified based on observed changes in climatic conditions and ground-water levels. Adjustments to heads in the source-sink layer A1 and specified heads along lateral boundaries were made to match closely published potentiometric-surface maps for September 2002 (Cherry, 2003; figs. 6A and 9).



Base modified from U.S. Geological Survey 1:500,000-scale digital State base maps

0 10 20 30 MILES

0 10 20 30 KILOMETERS

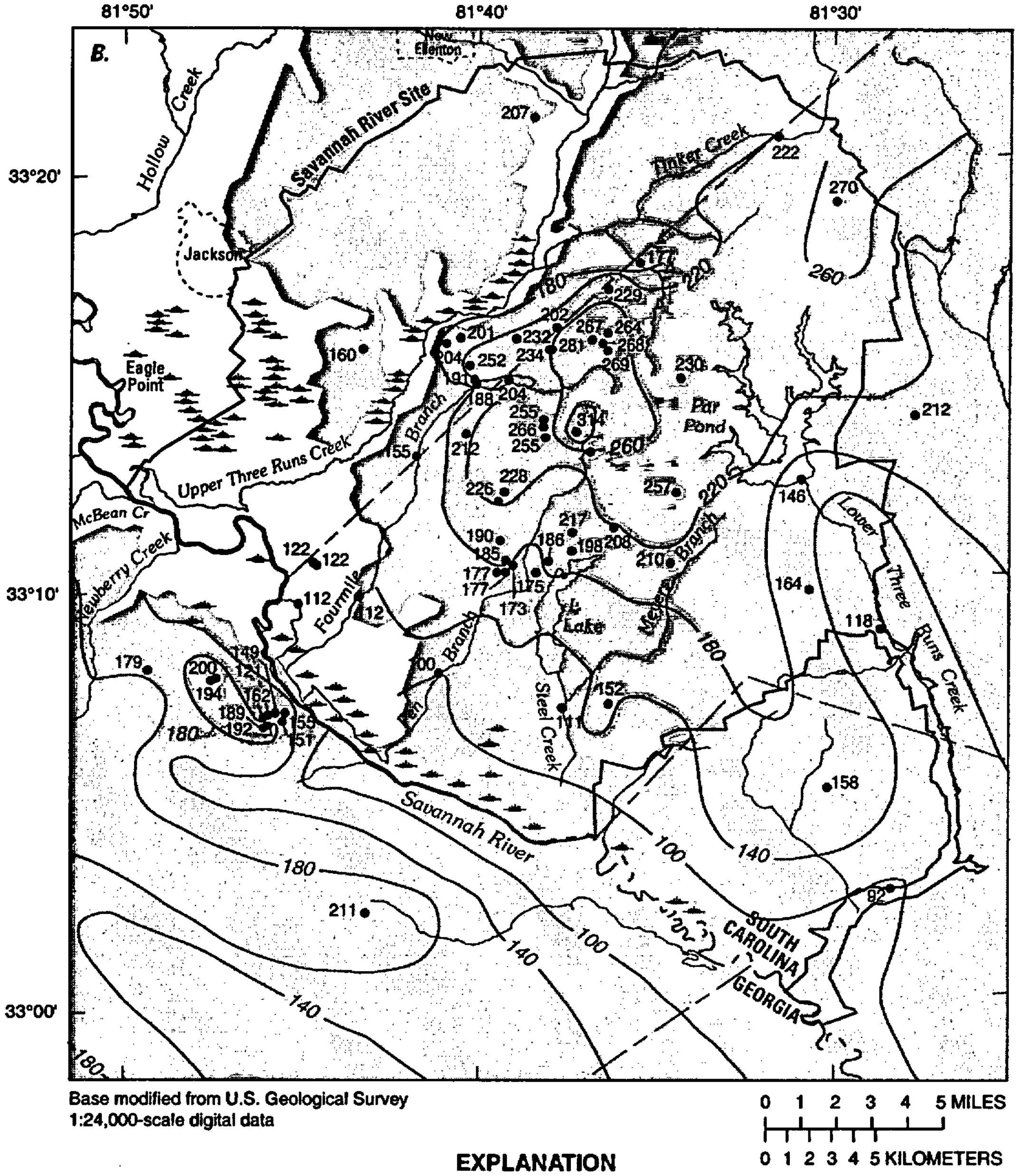
EXPLANATION

Active area of source-sink layer A1

140 — **Potentiometric contour**—Shows altitude at which water level would have stood in tightly cased wells in the Upper Three Runs aquifer during 2002. Contour interval 40 feet. Datum is NAVD 88

•126 **Observation well and water-level elevation**

Figure 9. (*A*) Model area, active area of source-sink layer A1, and potentiometric surface for the Upper Three Runs aquifer during 2002 in the Savannah River Site (SRS) area, South Carolina (Cherry, 2003), and (*B*) enlargement of SRS area.



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

EXPLANATION

Active area of source-sink layer A1

— *140* — **Potentiometric contour**—Shows altitude at which water level would have stood in tightly cased wells in the Upper Three Runs aquifer during 2002. Contour interval 40 feet. Datum is NAVD 88

• 126 **Observation well and water-level elevation**

Figure 9. (*A*) Model area, active area of source-sink layer A1, and potentiometric surface for the Upper Three Runs aquifer during 2002 in the Savannah River Site (SRS) area, South Carolina (Cherry, 2003) and (*B*) enlargement of SRS area—continued.

The observed water levels during 2002 were generally lower because of the prolonged drought; a comparison of water-level measurements is shown in figure 10. In the Upper Three Runs aquifer, 964 water-level measurements were made during 1987–92 compared with 147 made during September of 2002. A direct comparison was made for 82 wells with water-level measurements in both sampling periods (fig. 10). Water-level measurements taken during 1987–92 were compared to the constructed potentiometric surface for 2002 to assign water-level changes in areas lacking sufficient data in 2002. This was done by performing an interpolation using the spline-tension method with grid cell dimensions of 98 ft per side. Thus, sufficient coverage was provided to generate contours of the difference between 1987–92 and 2002 water levels using a combination of measured and interpolated data (fig. 10). The extreme water-level declines ranging from –18.9 to –25.2 in the northern parts of Screven and Jenkins Counties are indicative of the combined effects of drought and ground-water pumpage for irrigation in the Upper Three Runs aquifer. On the SRS, the water-level declines are less and range from –5.8 to –20.0 (fig. 10). The resulting contoured water-level changes indicate areas with water-level declines greater than –40 ft in northern Jenkins County and eastern Jefferson County near the model boundary. The interpolated potentiometric-surface map for the Upper Three Runs aquifer during 2002 was the basis for assigning head values to each of the 13,260 grid centroids in the source-sink layer A1 and comparing the values used for the calibrated 1987–92 steady-state simulation (Clarke and West, 1998).

Specified heads in model layers A2–A7 were lowered to reflect water-level declines attributed to the drought period (figs. 11–16). In the Gordon aquifer (layer A2), the specified heads along the southern boundary of the model were lowered 10 ft and those cells located along the northeastern model boundary were lowered by 5 ft (fig. 11). In the Dublin aquifer system (layers A3–A5), specified heads along the southern boundary of the model were lowered 8 ft and those along the northeastern model boundary were lowered by 5 ft (figs. 12–14). In model layers A3–A5, additional specified-head cells are located along the southeastern model boundary near Barnwell and Allendale Counties. These specified head cells were lowered by 10 ft from the values assigned to the previous model.

In the Midville aquifer system (layers A6–A7), specified-head values along the southern model boundary were lowered 6 ft and along the northeastern model boundary by 5 ft (figs. 15–16). These model layers (layers A6–A7) had additional specified-head cells located along the northern and northwestern model boundaries, which were lowered 6 and 10 ft, respectively.

Ground-water withdrawal rates increased by 42.8 Mgal/d from 1990 to the drought period during 2000–2002 (table 1). A part of this pumpage, however, is assigned to the source-sink layer A1 of the model and is not accounted for in the active layers of the model (layers A2–A7). The large water-level declines in the Upper Three Runs aquifer documented by 2002 water-level measurements indicate some of this decrease is because of increased ground-water use for irrigation. The previously developed model of Clarke and West (1998) assigned 52.7 Mgal/d to active layers of the model (layers A2–A7), which accounts for 22 Mgal/d not actively simulated in the source-sink layer A1. A similar approach was used for 2002 to assign 67.2 Mgal/d to active layers (layers A2–A7) with about 50 Mgal/d of pumping accounted for in the source-sink layer A1 (table 4). The total pumping for a given well was distributed evenly among the aquifers penetrated with a standard open interval of 100 ft if the well depth was known.

The model simulated ground-water discharge to streams from the active layers of the model (layers A2–A7) using river cells that are located in the updip areas of the aquifers along the Savannah River and its major tributaries where the streams have incised into the aquifers and confining units (figs. 11–16). For the purpose of the steady-state simulations, return flow to the source-sink layer A1 is considered as ground-water discharge to streams and occurs along areas such as Brier Creek (table 2 and fig. 6*A*). Assigned river-stage altitudes and hydraulic properties for each river cell remained unchanged from the earlier model for the 2002 steady-state simulation (table 3).

The altitude of stream stage (river cells) for the 1987–92 model was estimated from digitized altitude contours (U.S. Geological Survey, 1989) using GIS, and from limited well data in the Savannah River floodplain. These values are considered an estimation of long-term average stage conditions. The river-stage altitude values assigned in the 1987–92 model also were used in the 2002 simulation. This is considered reasonable for the Savannah River because streamflow is regulated by minimum flow requirements and steady upstream releases for power production at Thurmond Lake north of Augusta, Ga.

Simulated Water Budget

The simulated water budget for 2002 (dry conditions) is 1,035 Mgal/d compared with 1,040 Mgal/d for the 1987–92 simulation (fig. 17). The lowering of the heads in the source-sink layer A1 to match the potentiometric-surface map of the Upper Three Runs aquifer resulted in decreased flow through the stream-aquifer system. Overall, recharge from the source-sink layer A1 was reduced from 789 Mgal/d to 777 Mgal/d, which represents a minor change of only 1.5 percent (fig. 18). The recharge assigned to the outcrop areas of the hydrogeologic units (see fig. 2) remained constant for the 2002 simulation at 153 Mgal/d, which represents 16.5 percent of the total 929.5 Mgal/d simulated recharge to the ground-water system (figs. 17–18).

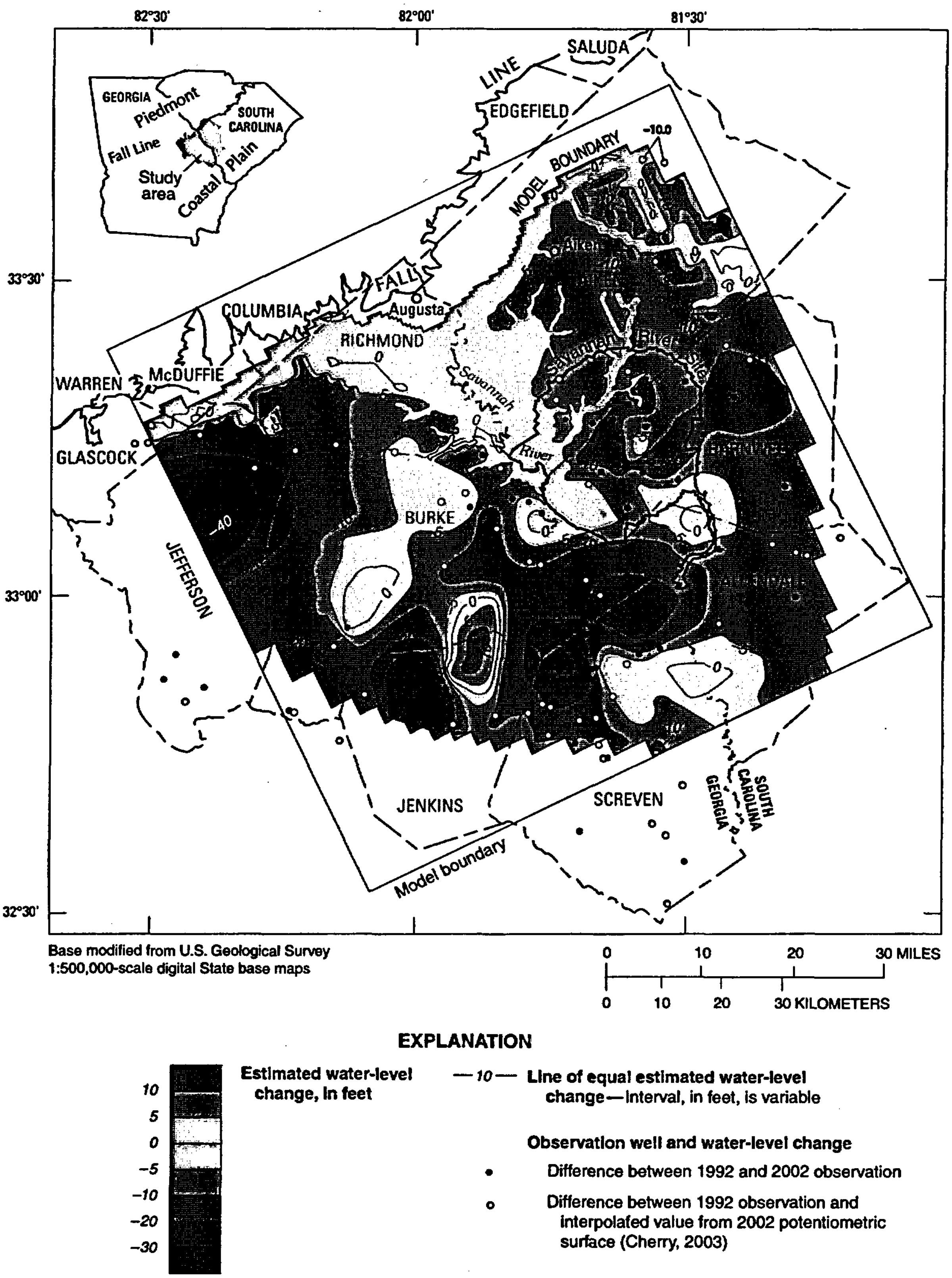


Figure 10. Estimated water-level change between the current (2002) and previously developed (1987–92) models for the Upper Three Runs aquifer (source-sink layer A1) in the Savannah River Site area, South Carolina.

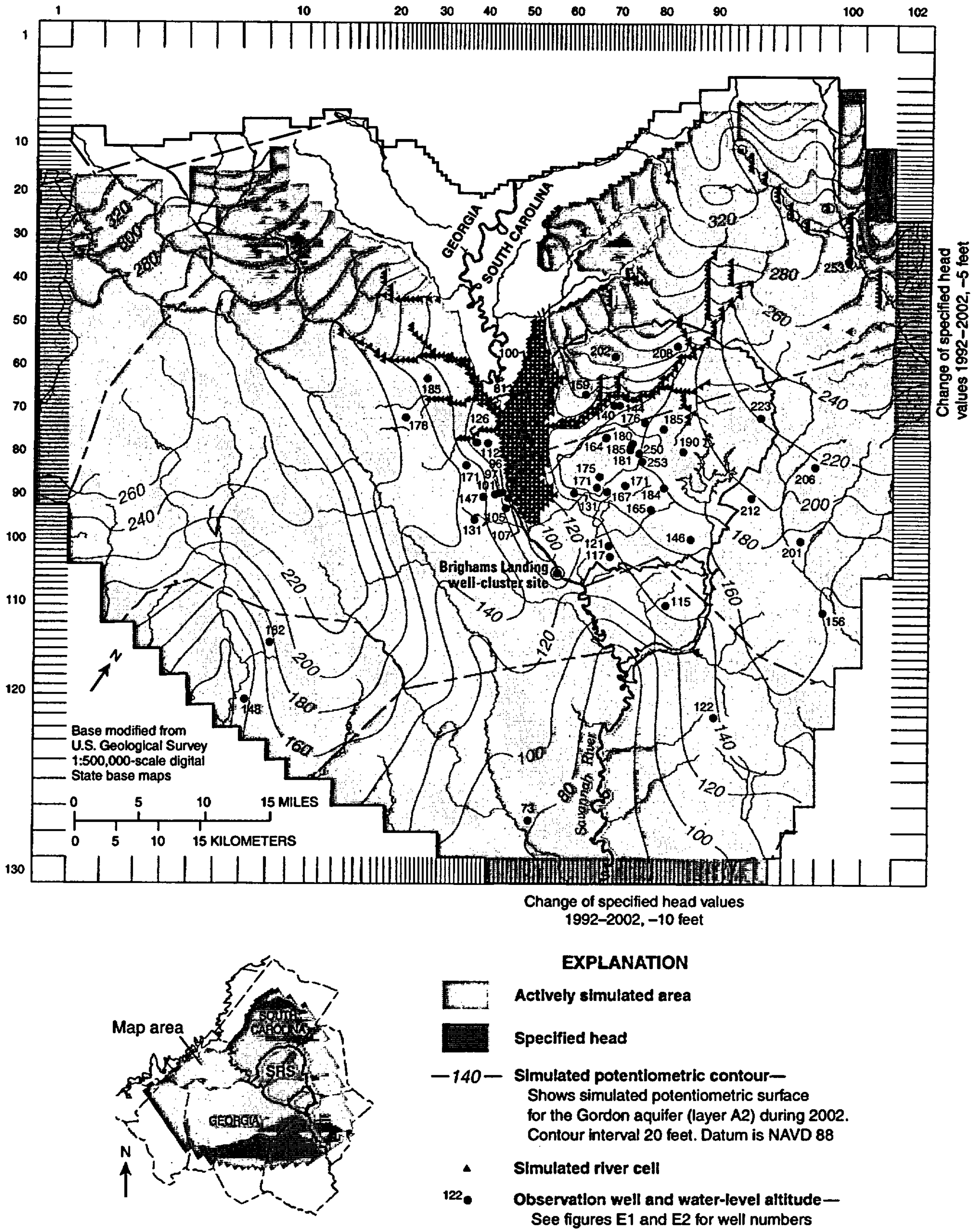
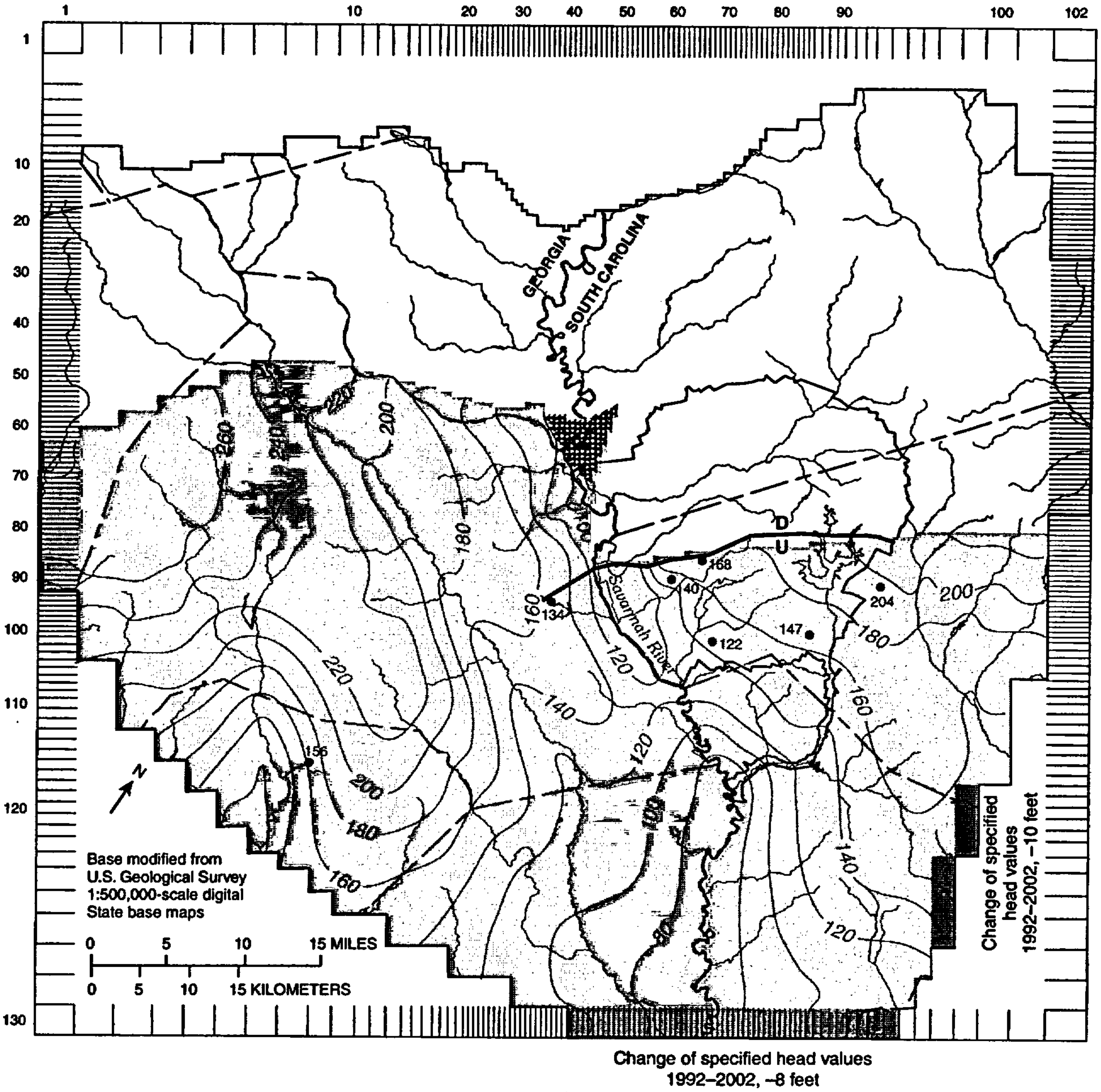
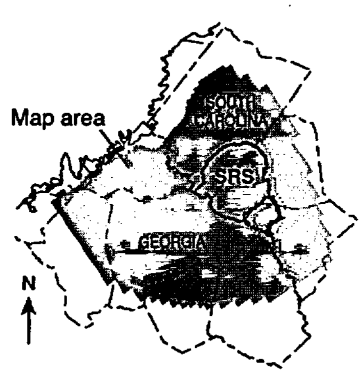


Figure 11. Simulated 2002 potentiometric surface, water-level altitude, and location of simulated river cells for the Gordon aquifer (layer A2) in the Savannah River Site (SRS) area, South Carolina.





EXPLANATION

Actively simulated area

Specified head

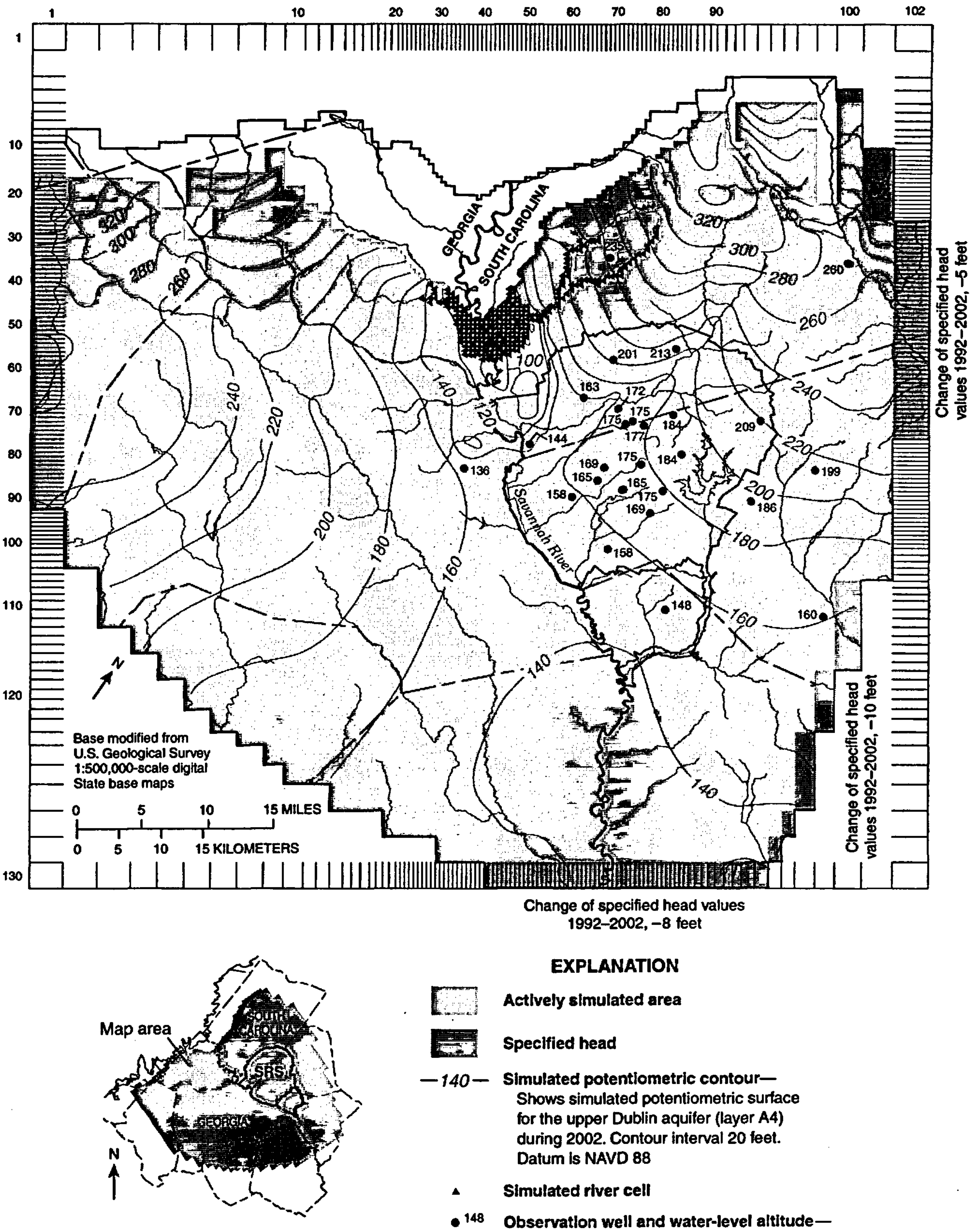
—*140*— **Simulated potentiometric contour**—Shows simulated potentiometric surface for the Millers Pond aquifer (layer A3) during 2002. Contour interval 20 feet. Datum is NAVD 88

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

▲ **Simulated river cell**

•122 **Observation well and water-level altitude**—See figure E3 for well numbers

Figure 12. Simulated 2002 potentiometric surface, water-level altitude, and location of simulated river cells for the Millers Pond aquifer (layer A3) in the Savannah River Site (SRS) area, South Carolina.



EXPLANATION

Actively simulated area

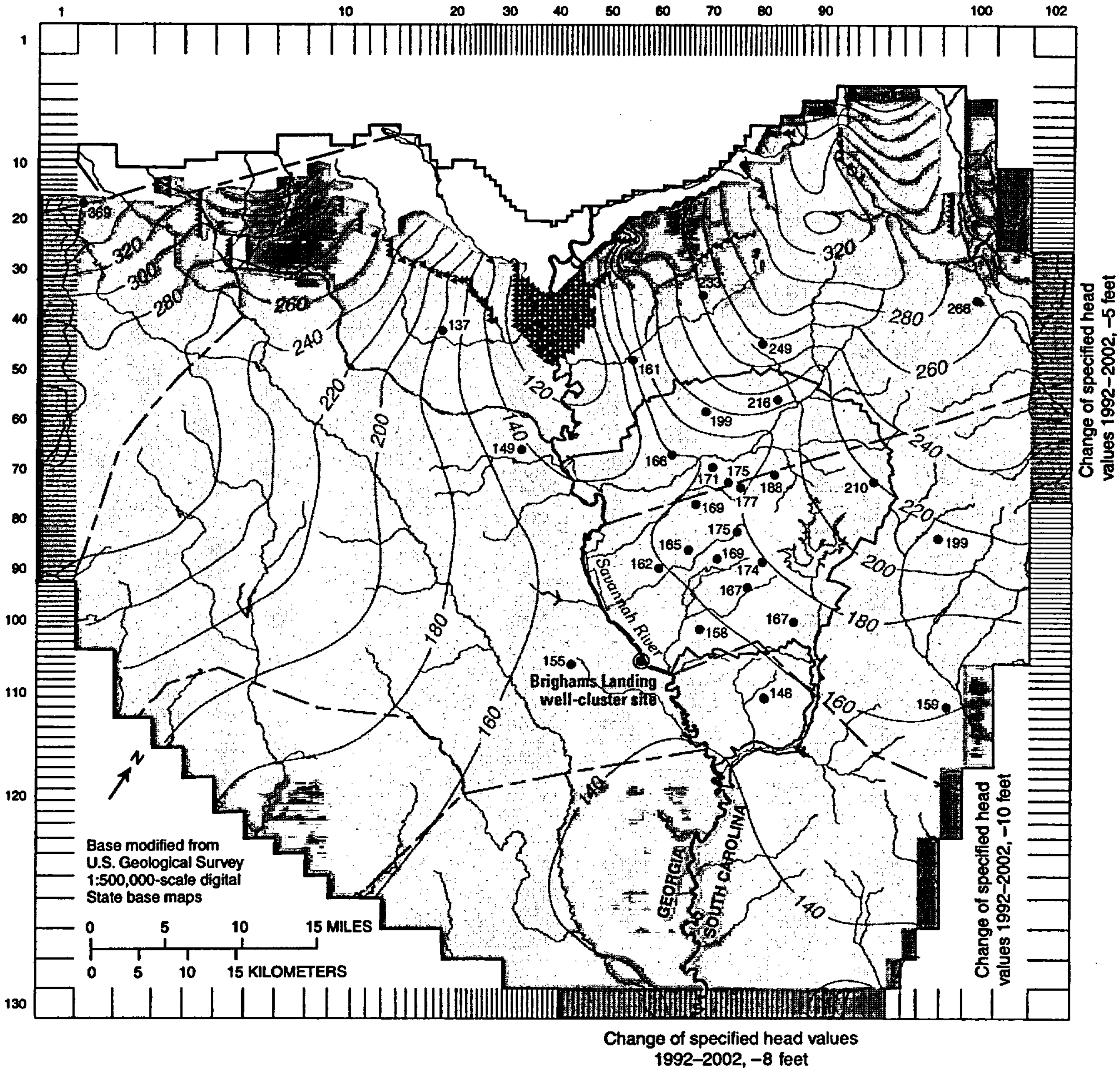
Specified head

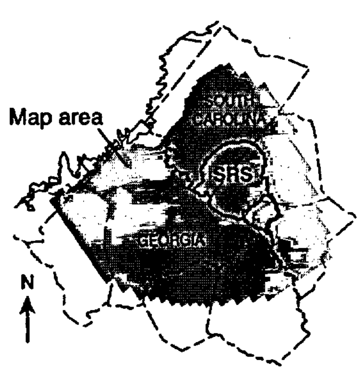
—140— Simulated potentiometric contour—Shows simulated potentiometric surface for the upper Dublin aquifer (layer A4) during 2002. Contour interval 20 feet. Datum is NAVD 88

▲ Simulated river cell

● 148 Observation well and water-level altitude—See figure E4 for well numbers

Figure 13. Simulated 2002 potentiometric surface, water-level altitude, and location of simulated river cells for the upper Dublin aquifer (layer A4) in the Savannah River Site (SRS) area, South Carolina.





EXPLANATION

Actively simulated area

Specified head

—*140*— **Simulated potentiometric contour—** Shows simulated potentiometric surface for the lower Dublin aquifer (A5) during 2002. Contour interval 20 feet. Datum is NAVD 88

▲ **Simulated river cell**

● 148 **Observation well and water-level altitude—** See figure E5 for well numbers

Figure 14. Simulated 2002 potentiometric surface, water-level altitude, and location of simulated river cells for the lower Dublin aquifer (layer A5) in the Savannah River Site (SRS) area, South Carolina.

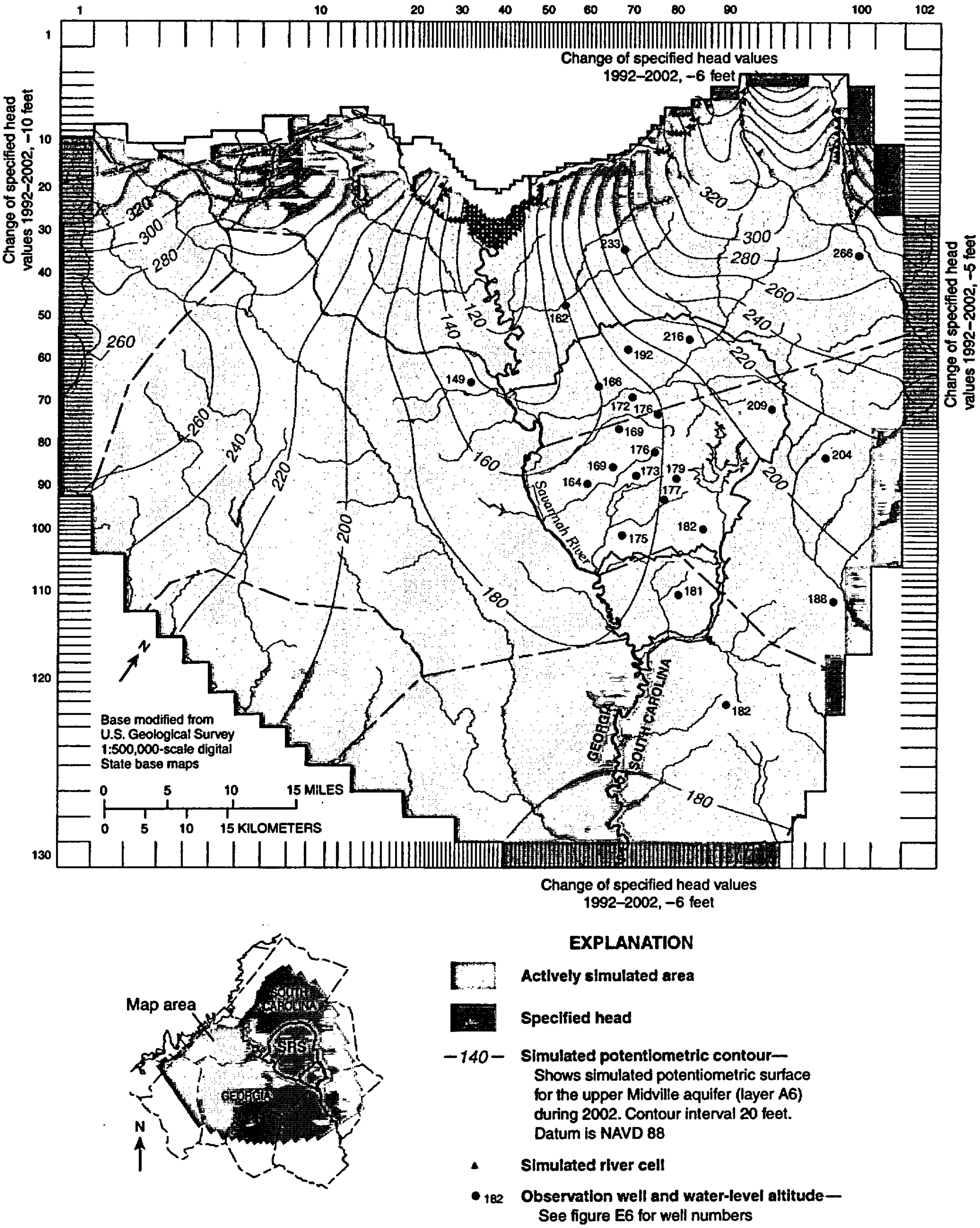


Figure 15. Simulated 2002 potentiometric surface, water-level altitude, and location of simulated river cells for the upper Midville aquifer (layer A6) in the Savannah River Site (SRS) area, South Carolina.

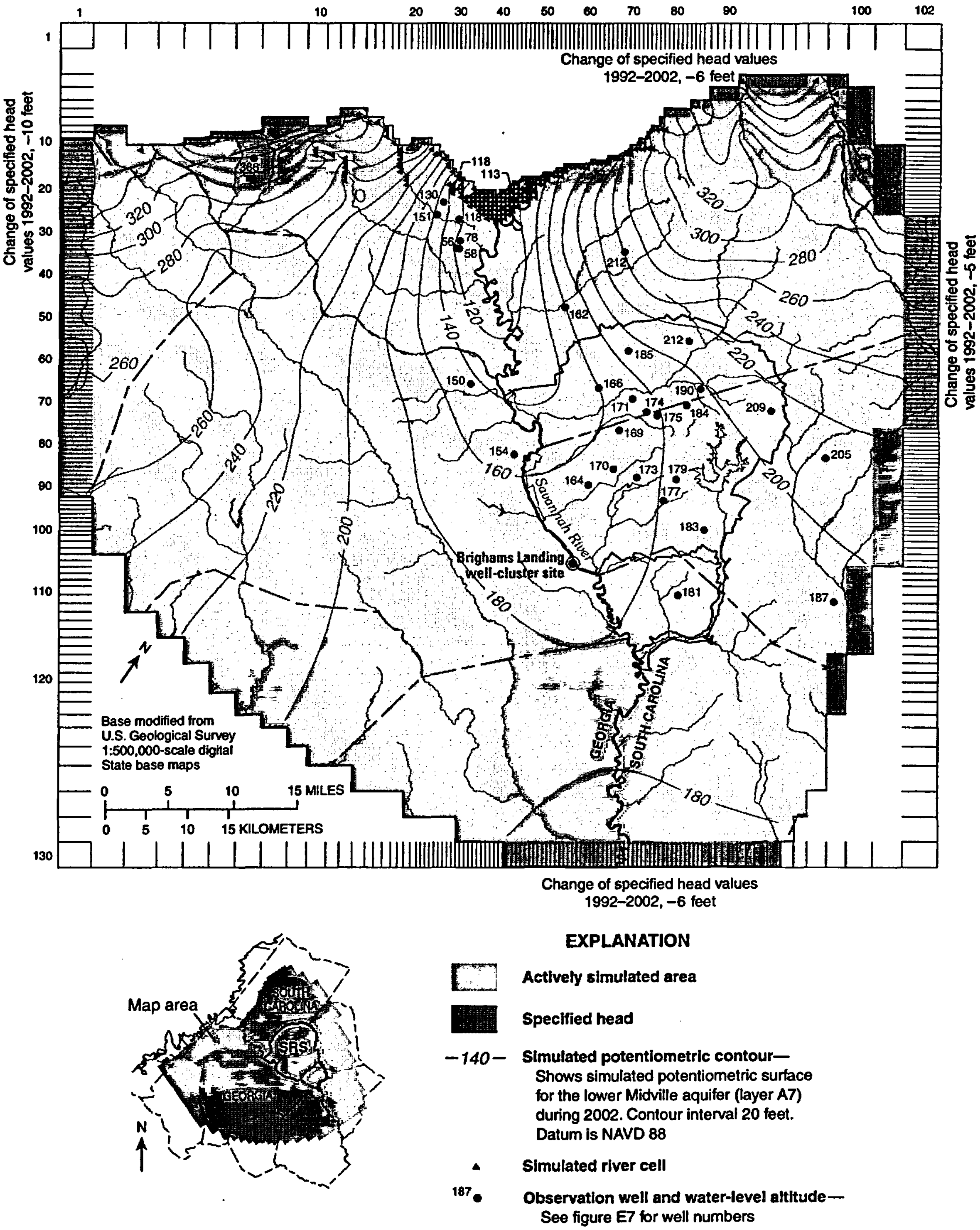


Figure 16. Simulated 2002 potentiometric surface, water-level altitude, and location of simulated river cells for the lower Midville aquifer (layer A7) in the Savannah River Site (SRS) area, South Carolina.

Table 4. Simulated pumpage by model layer 1987–92 and 2002.

Aquifer	Model layer	Pumpage, in million gallons per day	
		1987–92[1]	2002
Gordon	A2	9.9	10.7
Millers Pond	A3	2.1	7.3
Upper Dublin	A4	3.8	5.4
Lower Dublin	A5	9.5	14.6
Upper Midville	A6	6.6	9.8
Lower Midville	A7	20.8	19.4
All layers		52.7	67.2

[1]Clarke and West (1998)

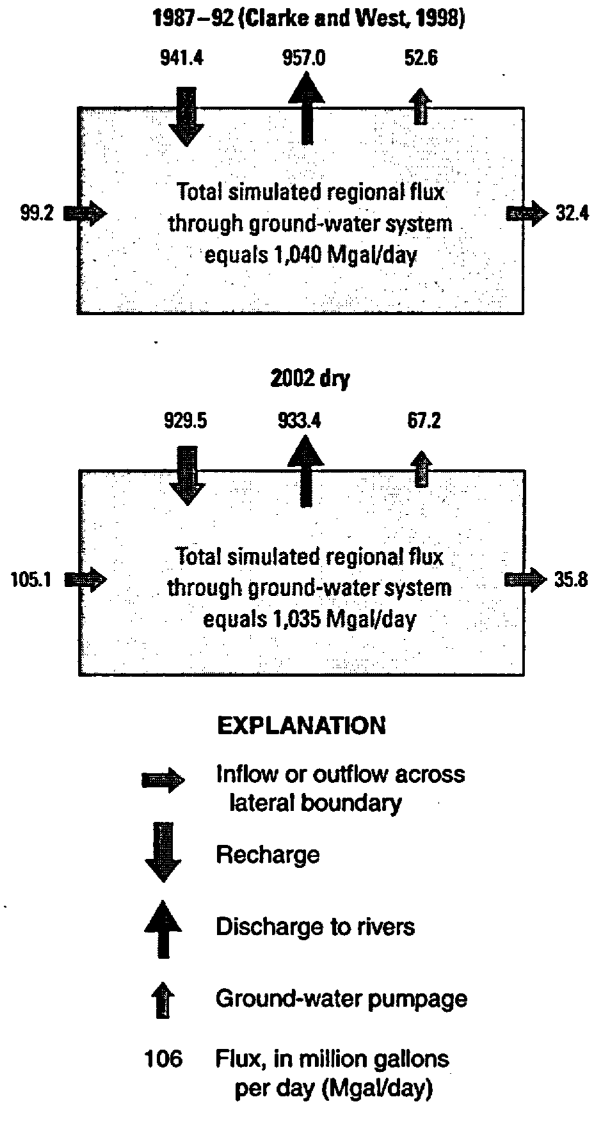


Figure 17. Simulated 1987–92 (Clarke and West, 1998) and 2002 dry water budgets.

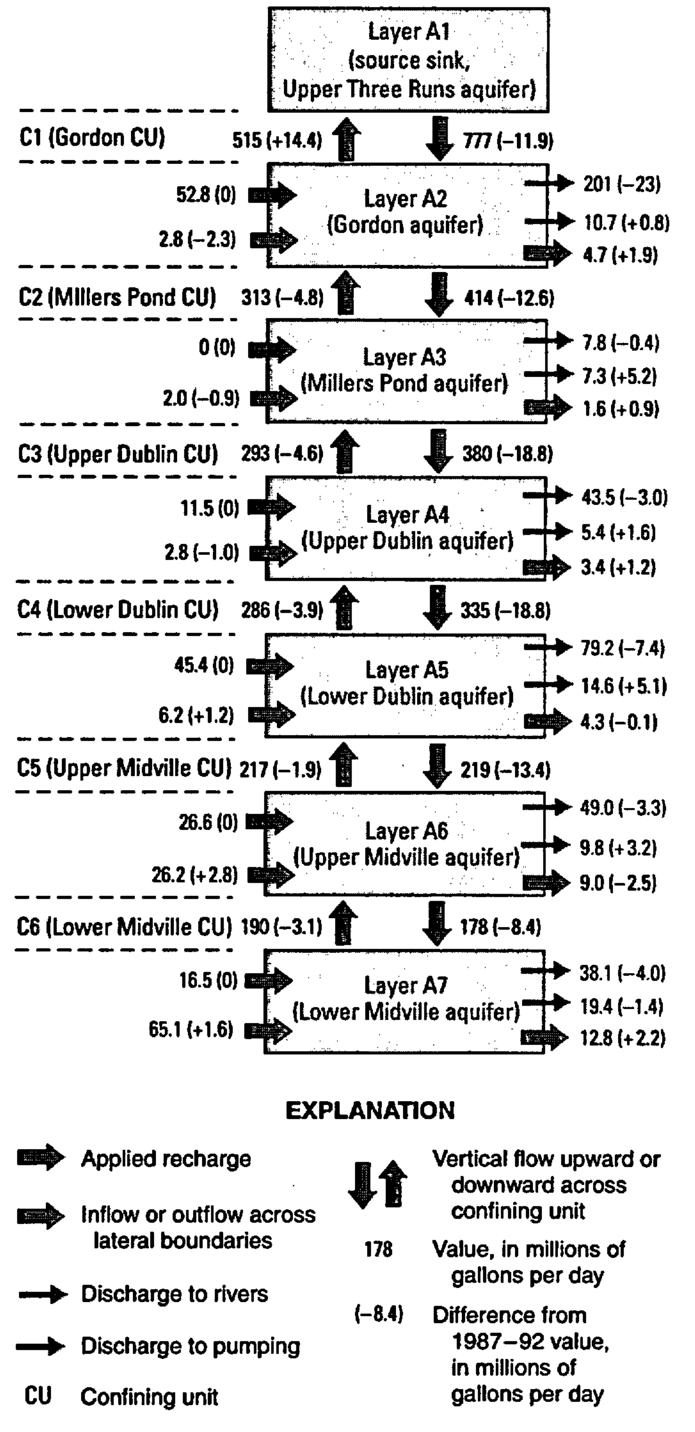


Figure 18. Simulated 2002 dry conditions water budget by layer and comparison of budget terms with 1987–92 long-term average simulation (Clarke and West, 1998).

Simulated ground-water pumpage for 2002 was 14.6 Mgal/d more than that during 1987–92. This represents 40 percent of the 36.5 Mgal/d increase in ground-water pumpage in the study area (fig. 17), with the remaining 21.9 Mgal/d either outside the simulated area or included in the source-sink layer A1, which was not actively simulated by the model (see figs. 2, 4, and 9). The lower simulated recharge from the source-sink layer A1 and increase in ground-water withdrawal reduced the simulated ground-water discharge to streams by 23.6 Mgal/d (fig. 17). Lowering of the specified-head boundaries in the lower layers of the model (A2–A7) induced an additional 6.8 Mgal/d of inflow into the ground-water system, which also increased the outflow along lateral boundaries by 3.4 Mgal/d.

A more detailed analysis of the simulated water budget for 2002 shows the flow through each of the model layers and how each of the flow components changed relative to the 1987–92 simulation (fig. 18). Lowering the heads in the source-sink layer A1 reduced the inflow to layer A2 by 11.9 Mgal/d, but increased the outflow to the source-sink layer A1 by 14.4 Mgal/d, which was considered as discharge to streams for the overall budget. In model layers A2–A5, reduced downward leakage through the confining units and lowering of the specified heads along the lateral boundaries reduced the overall net water into each of these layers by 12.6 to 18.8 Mgal/d. The overall decrease in ground-water inflows to these layers and a 0.8- to 5.2-Mgal/d increase in pumping rates reduced ground-water discharge to river cells by 0.4 to 23 Mgal/d (fig. 18). Vertical leakage through confining unit C5 to the Midville aquifer system (layers A6 and A7) was 13.4 Mgal/d less than for the previous model. This contributed to decreased flow in the Midville aquifer system (layers A6 and A7). In model layer A6, lower specified heads and a 3.2-Mgal/d increase in pumping resulted in increased lateral inflow and decreased lateral out flow, and in decreased discharge to river cells. In layer A7, lateral inflow increased and discharge to rivers decreased, despite a 1.4-Mgal/d decrease in pumpage (fig. 18). These changes are likely the result of lowered head in the source-sink layer A1, which resulted in decreased leakage to the aquifer.

During 2002, simulated ground-water discharge to the Savannah River and its tributary streams was 60 cubic feet per second (ft^3/s) (38.8 Mgal/d) lower than that simulated for 1987–92 (fig. 19). Similarly, simulated ground-water discharge to Upper Three Runs Creek was 12 ft^3/s (7.8 Mgal/d) lower than simulated for 1987–92. These decreases reflect the severity of the 1998–2002 drought, as was simulated by lowering specified-head cells in the model. Simulated ground-water outflows to the Savannah River and its tributaries during 2002 was 560 ft^3/s, or 86 percent of the observed gain in mean-annual streamflow between the Millhaven and Augusta streamflow gaging stations for WY 2002 (October 1, 2001, through September 30, 2002, table 2, fig. 19). The observed gain between these two streamflow gaging stations is considered a good indicator of ground-water contributions within the Savannah River Basin (Clarke and West, 1997, p. 93).

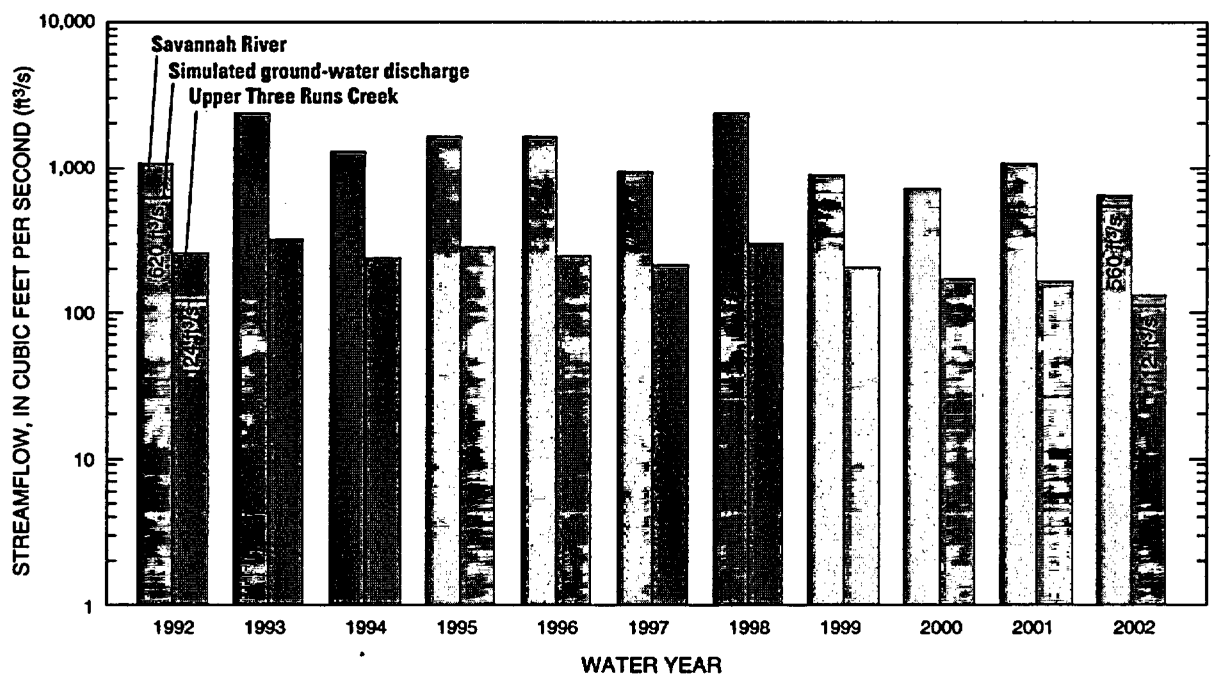


Figure 19. Mean-annual net gain in streamflow for the Savannah River (Augusta [02197000] to Millhaven [02197500], Georgia) and mean-annual streamflow for Upper Three Runs Creek (02197315) for water years 1992–2002, and simulated ground-water discharge for 1992 and 2002. See figure 7 for locations.

At Upper Three Runs Creek, simulated ground-water discharge during 2002 was 110 ft^3/s, or 83 percent of the observed streamflow at gaging station 02197315 during WY 2002 (table 2, fig. 19). The simulated ground-water discharge approximates findings from a recent study, which concluded that ground-water contribution to nearby streams during a dry period is nearly 80 percent of the total streamflow in upland coastal areas (Priest and Clarke, 2003).

Simulated Water-Level Changes

Model results indicate that the previously calibrated model (Clarke and West, 1998) is still representative of the hydrologic system. The earlier model was calibrated to 1987–92 conditions using the average observed water levels at 313 model cells, whereas the current model evaluation used observed water levels during September of 2002 at 172 well locations (table 5, Appendix E). The residuals represent the difference between simulated and observed water levels, with positive values indicating that simulated values were greater than observed values. The error criteria is determined by evaluating uncertainties associated with each observed measurement such as land-surface altitude, water-level measurement, seasonal water-level fluctuations, and difference in hydraulic head across a given grid cell (Clarke and West, 1998, p. 31; Appendix E). The mean of residuals for all layers was 0.8 ft during 1987–92 compared with 2.8 ft during 2002 (table 5 and fig. 20). The root mean square (RSM) of the residuals for all layers decreased from 10.6 ft during 1987–92 to 8.0 ft during 2002. The RSM of the residuals showed an improvement from the 1987–92 model in layers A4 (from 7.4 to 4.5 ft), A5 (from 9.5 to 5.5 ft), A6 (from 8.5 to 3.1 ft), and A7 (from 13.2 to 8.9 ft). The RSM increased in layers A2 (from 11.5 to 12.1 ft) and A3 (from 9 to 12 ft). Overall, the percentage of residuals within the established error criteria was 83.3 percent for the 2002 simulation and 88.2 percent for the 1987–92 simulation.

Simulated water levels were compared for the steady-state simulations 1987–92 and 2002 after designating simulated water levels for the 1987–92 model as initial heads for the 2002 simulation. The computed water-level changes are shown for each active layer of the model (figs. 21–26). Most of the simulated water-level change is attributed to the lowering of specified heads in the source-sink layer and along lateral boundaries of the model. The simulated water-level changes were generally largest near southern Burke County and northern Jenkins and Screven Counties because of observed water-level declines in the Upper Three Runs aquifer.

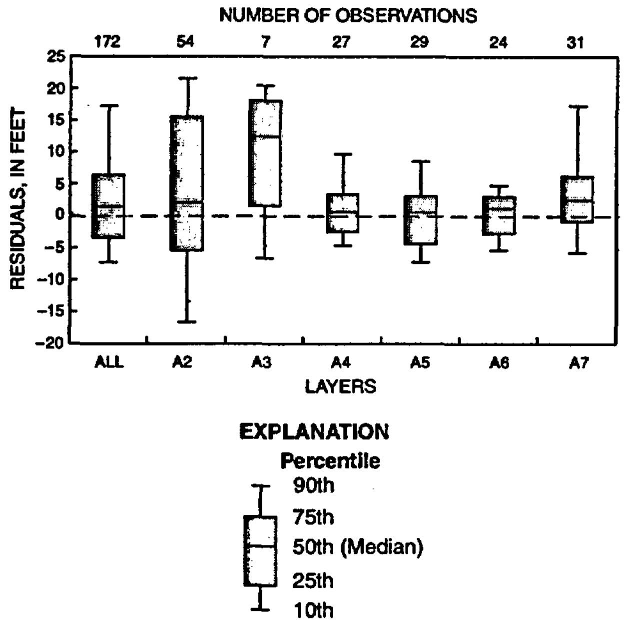


Figure 20. Difference (residuals) between observed and simulated heads for the 2002 simulation.

Table 5. Comparison of calibration statistics between the 1987–92 and 2002, dry steady-state model simulations.

Aquifer (model layer)	Number of observations		Mean of residuals (foot)		Root mean square of residuals (foot)	
	[1]1987–92	2002	[1]1987–92	2002	[1]1987–92	2002
Gordon (A2)	136	54	–0.1	2.5	11.5	12.1
Millers Pond (A3)	10	7	5.4	9.6	9.0	12.0
Upper Dublin (A4)	54	27	1.2	1.5	7.4	4.5
Lower Dublin (A5)	40	29	1.0	0.9	9.5	5.5
Upper Midville (A6)	28	24	–2.8	0.6	8.5	3.1
Lower Midville (A7)	45	31	4.1	6.5	13.2	8.9
All layers (A2–A7)	313	172	0.8	2.8	10.6	8.0

[1]Clarke and West (1998)

In layer A2, the largest simulated water-level declines from 35 ft to more than 40 ft occur near lateral no-flow boundaries of the model in northern Jenkins County and central Jefferson County (fig. 21). In simulated water levels in southern Burke County and northern Screven County, water-level declines ranging from 20 to 30 ft as a result of decreased heads in the source-sink layer A1 and pumping from 12 nearby irrigation wells that withdrew a combined 1.1 Mgal/d from layer A2. On the SRS, Upper Three Runs Creek is simulated using river cells in layer A2, which remain constant and would represent areas of no head change. From areas near Upper Three Runs Creek, simulated water-level declines increase to the south in Barnwell County and are generally greater than –5 ft throughout the southern half of the SRS.

In layer A3, the largest simulated water-level changes occur near model boundaries in central Jefferson County (–20 ft) and northern Jenkins County (–40 ft). The large decreases in simulated water levels in these areas are the result of reduced inflows from the source-sink layer A1 into the underlying layers (figs. 18 and 22). In addition to changes in the source-sink layer A1, specified heads in layer A3 located along the southern and eastern model boundaries were lowered 8–10 ft (fig. 12). In central Burke County, 14 production wells used for irrigation withdrew a combined 2.6 Mgal/d from layer A3, and simulated water-level changes range between –15 and –25 ft. In northern Screven County, 13 production wells used for irrigation withdrew a combined 2.1 Mgal/d, and simulated water levels for 2002 declined by more than 20 ft. On the SRS, simulated water-level decline of greater than 5 ft was similar to those in overlying layer A2 (figs. 21–22).

In layers A4 and A5, only slight changes in water levels were simulated across most of the model area because of relatively minor increases in pumpage from the previous model of 1.2 Mgal/d (layer A4) and 0.9 Mgal/d (layer A5), respectively (figs. 23–24). The largest declines of 30 ft occurred along the northwestern model boundary as a result of nearby pumping, decreased head in the overlying source-sink layer A1, and effects of the no-flow boundary conditions applied in that area. On the SRS and surrounding areas, the simulated water-level change was generally between –5 and –10 ft. In southern Burke and northern Screven Counties, the simulated water-level decline was between 10 and 15 ft.

In layers A6 and A7, the simulated water-level decline was less than 10 ft across most of the model area (figs. 25–26). The largest declines of greater than 30 ft occurred along the northwestern model boundary, and are likely the result of a combination of reduced head in the source-sink layer A1, upward interaquifer leakage in response to pumping in overlying layers, and effects of the no-flow boundary condition, which limited the amount of water available to flow laterally into the aquifer. On the SRS, the simulated water-level changes generally range between –2.5 and –5 ft.

Particle-Tracking and Time-of-Travel Analysis

The USGS particle-tracking code MODPATH (Pollock, 1994) was used to generate advective water-particle pathlines and their associated time of travel based on MODFLOW simulations for 1987–92, 2002, and each of four ground-water management scenarios. MODPATH computes three-dimensional flow directions and time-of-travel using imaginary particles in either a forward-tracking mode that follows direction of ground-water flow toward ground-water discharge areas or a backtracking mode from discharge areas toward recharge areas. For the current study, MODPATH was used to assess ground-water flow in both a forward- and backtracking mode. This section describes results of forward tracking; the section "Trans-River Flow" describes results of backtracking. For all simulations, the active model layers (layers A2–A7) were assigned a uniform effective porosity of 30 percent and the confining units (layers C1 through C6) assigned a value of 50 percent to match values from the previous model (Clarke and West, 1998, p. 86).

The MODPATH code was used in forward-tracking mode to evaluate flowpaths from areas on the SRS. The analysis was conducted by establishing zones in which particles were seeded into model cells based on the following criteria: (1) occurrence of recharge from the source-sink layer A1 (Upper Three Runs aquifer) into layer A2 (Gordon aquifer), (2) downward flow from layer A2 (Gordon aquifer) into layers A3 through A5 (Dublin aquifer system), (3) delineated areas of contamination or storage of hazardous materials on the SRS, and (4) defined surface-water drainage divides. Selected areas near streams on the SRS were not considered for the analysis because of localized flow regimes characterized by short time-of-travel and discharge to either Upper Three Runs Creek or other streams on the SRS.

Five particle seed zones were established where individual particles were observed from their point of recharge to discharge areas located near local streams or along the floodplain of the Savannah River (fig. 1*B*). Within each zone, four particles were placed in each model cell at the base of the source-sink layer A1 (Upper Three Runs aquifer) or top of the Gordon confining unit (C1). Downward movement of particles within the source-sink layer A1 (Upper Three Runs aquifer) cannot be calculated by MODPATH. According to modeling results presented by Flach and others (2000), however, downward travel times within the Upper Three Runs aquifer can be expected to be several decades near C Area. Also, the Gordon confining unit (C1) is generally from 20 to 30 ft thick between D Area and K Area and time-of-travel from the base of the Upper Three Runs aquifer (source-sink layer A1) into the Gordon aquifer (layer A2) is about 10 yr. For each simulation, movement of particles at selected time intervals are shown using only one particle per cell to avoid clutter and to enable distinguishing individual pathlines.

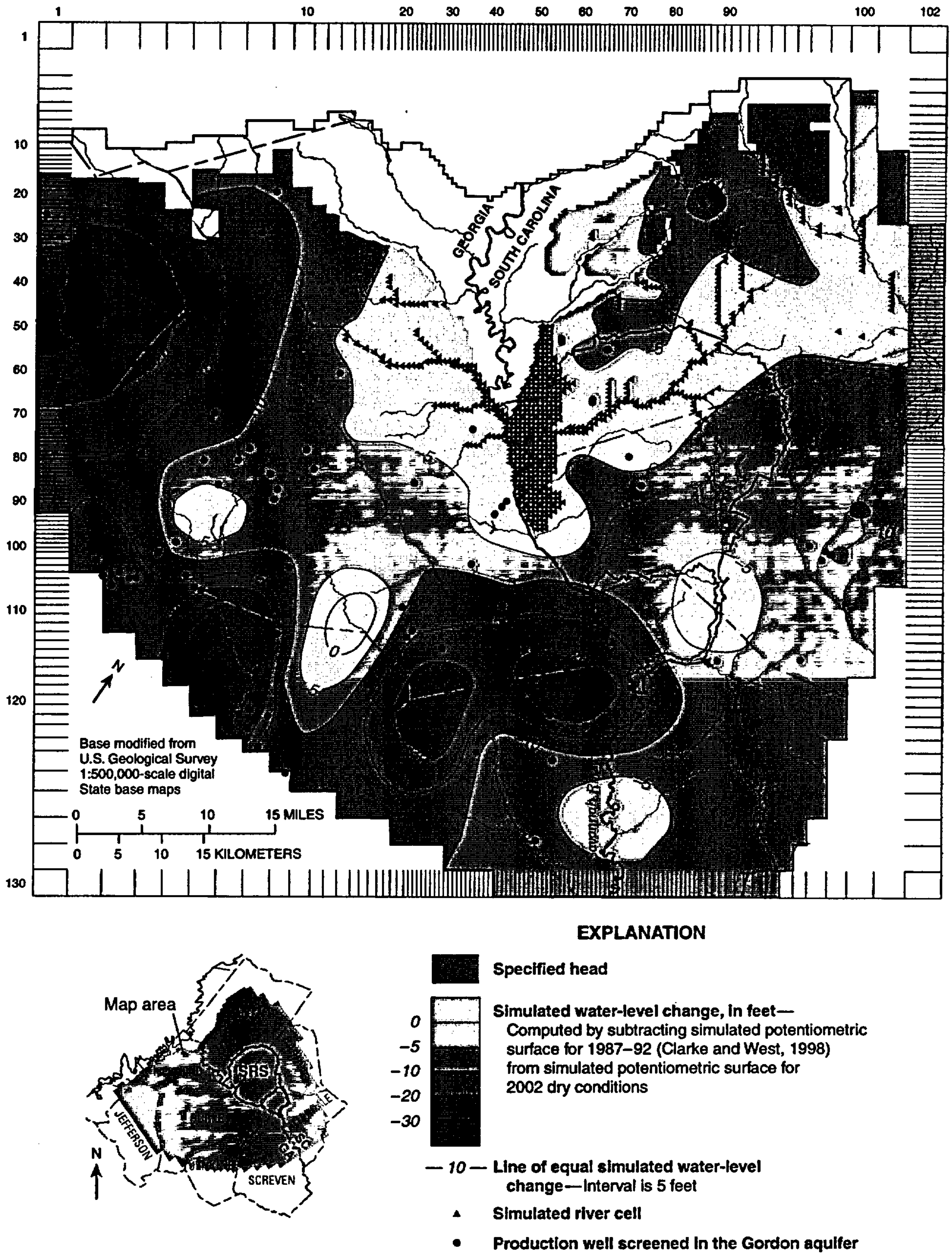
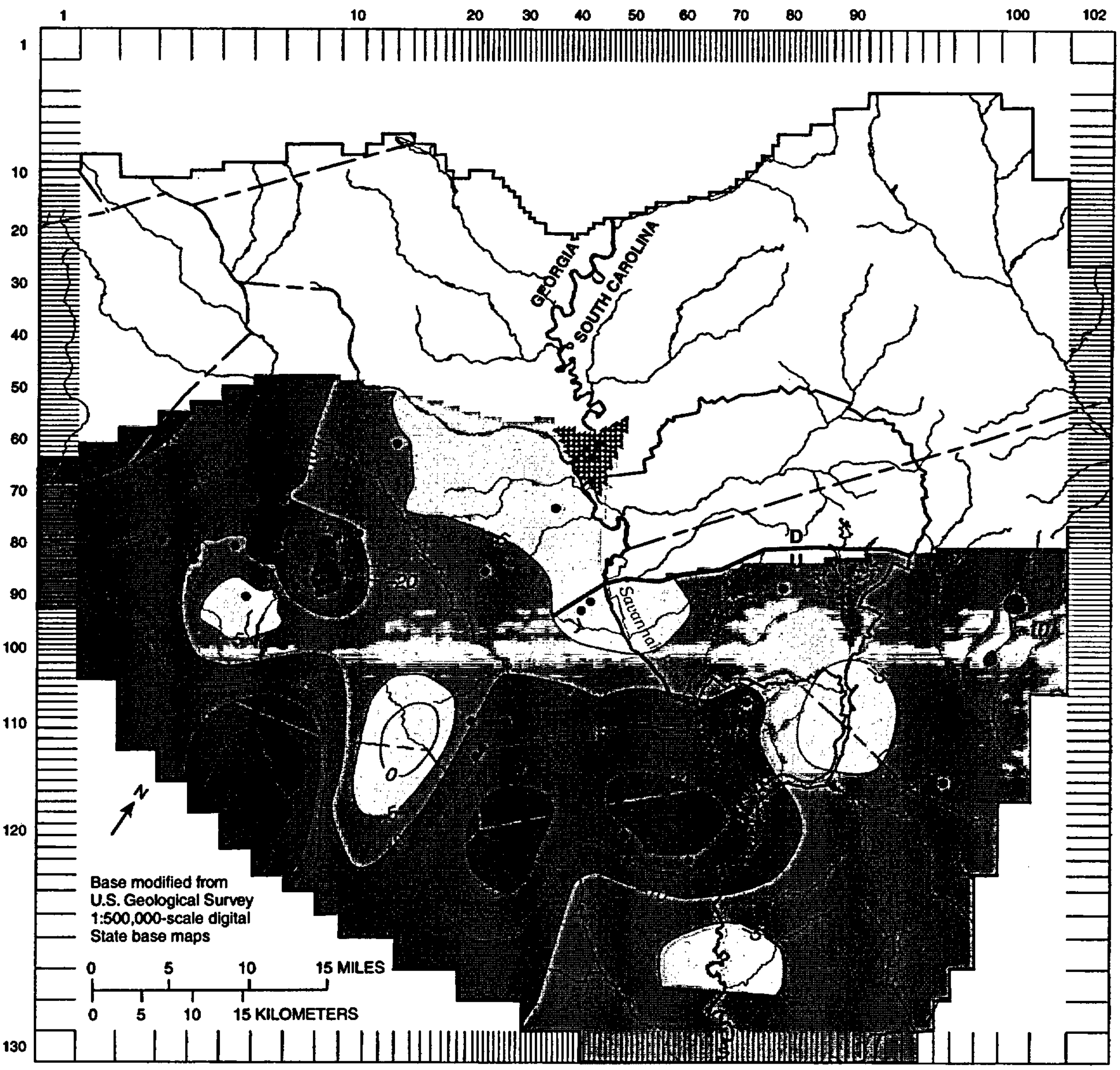
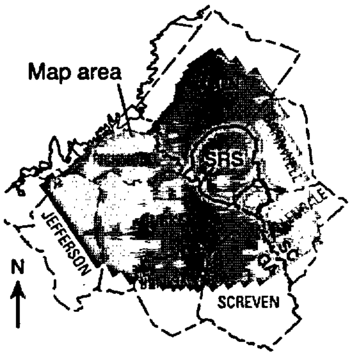


Figure 21. Simulated water-level change between 1987–92 long-term average and 2002 dry conditions and locations of simulated pumpage in the Gordon aquifer (layer A2) in the Savannah River Site (SRS) area, South Carolina.





EXPLANATION

Specified head

Simulated water-level change, in feet—
Computed by subtracting simulated potentiometric surface for 1987–92 (Clarke and West, 1998) from simulated potentiometric surface for 2002 dry conditions

0
−5
−10
−20
−30

— 10 — Line of equal simulated water-level change—Interval, in feet, is variable

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

▲ Simulated river cell

● Production well screened in the Millers Pond aquifer

Figure 22. Simulated water-level change between 1987–92 long-term average and 2002 dry conditions and locations of simulated pumpage in the Millers Pond aquifer (layer A3) in the Savannah River Site (SRS) area, South Carolina.

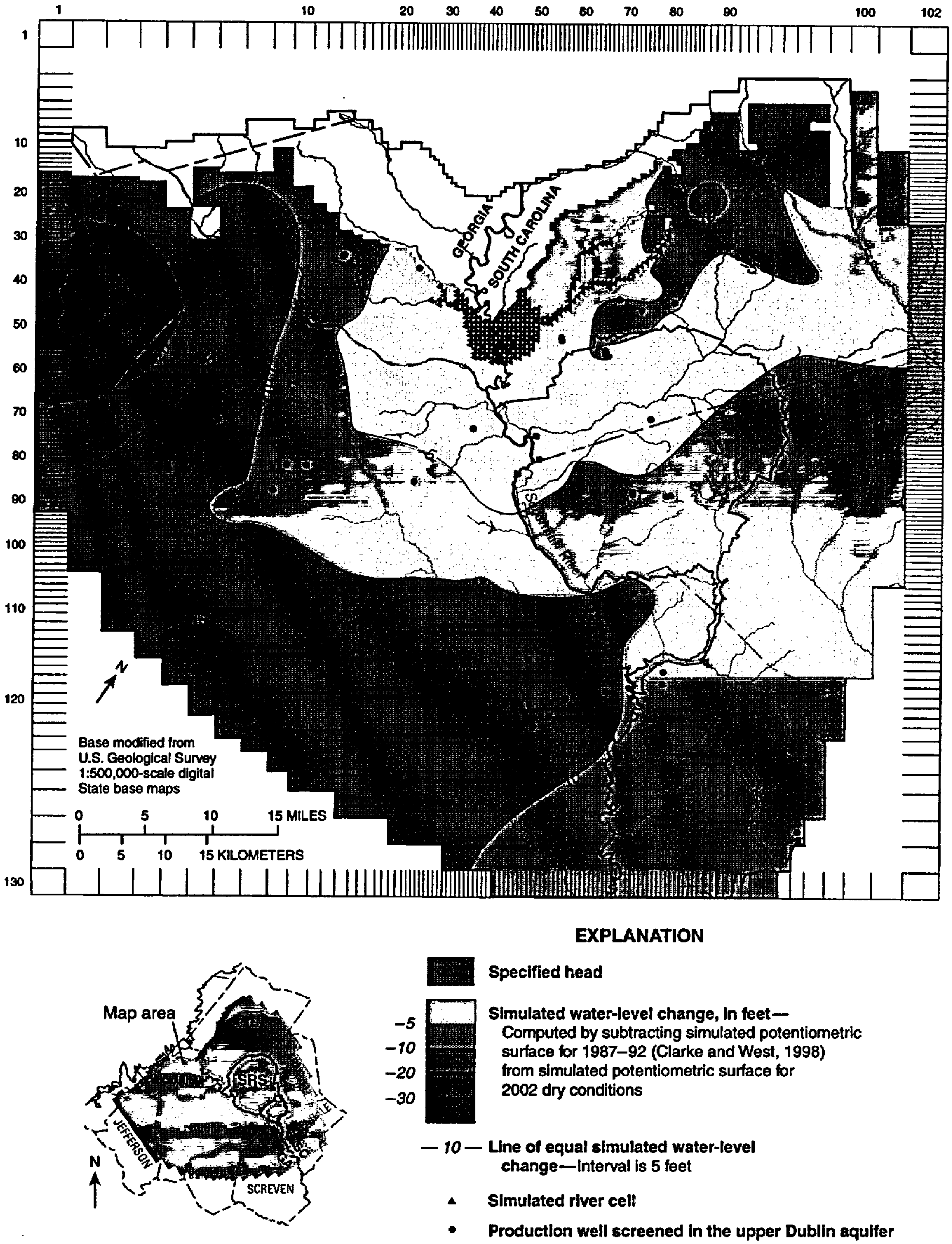


Figure 23. Simulated water-level change between 1987–92 long-term average and 2002 dry conditions and locations of simulated pumpage in the upper Dublin aquifer (layer A4) in the Savannah River Site (SRS) area, South Carolina.

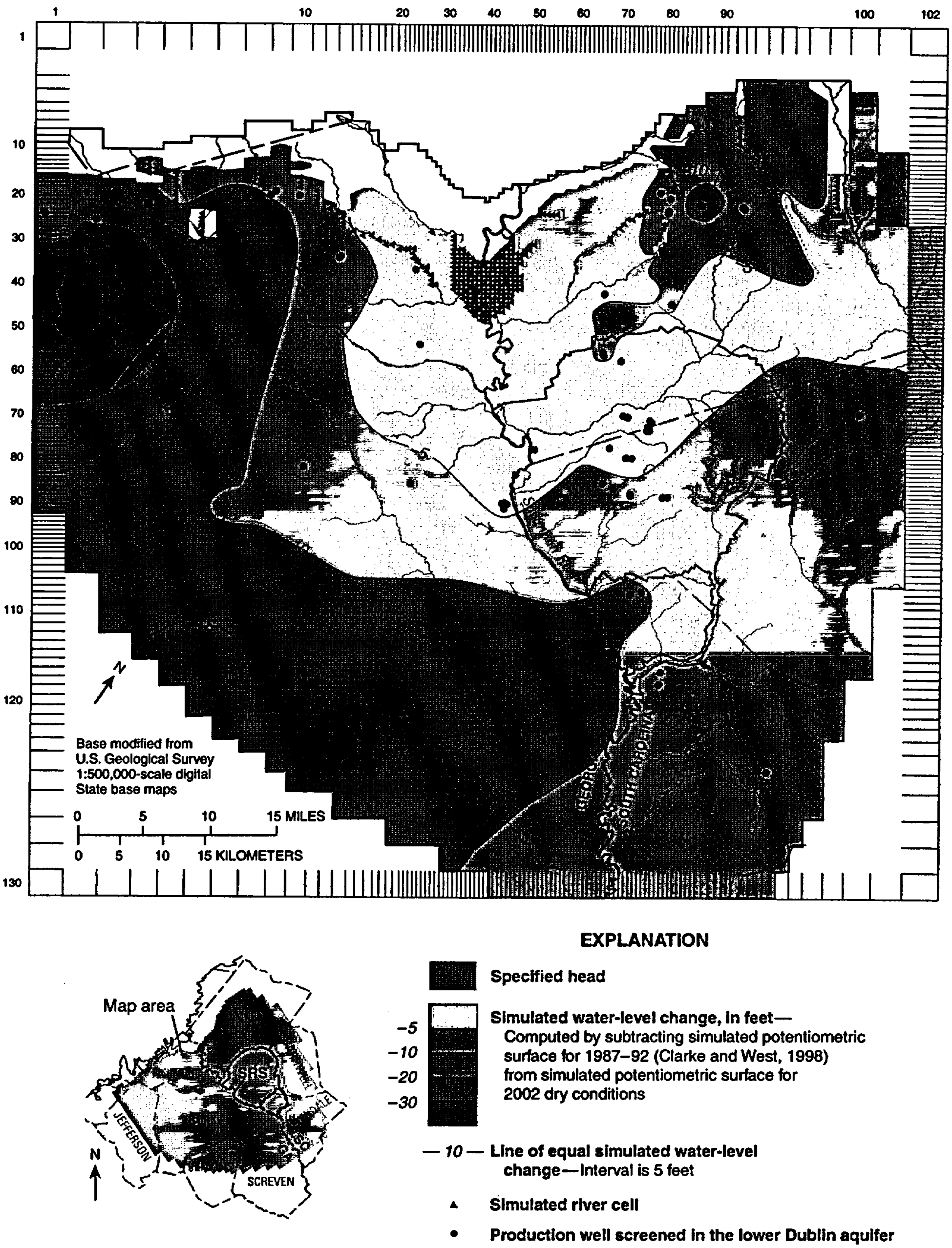
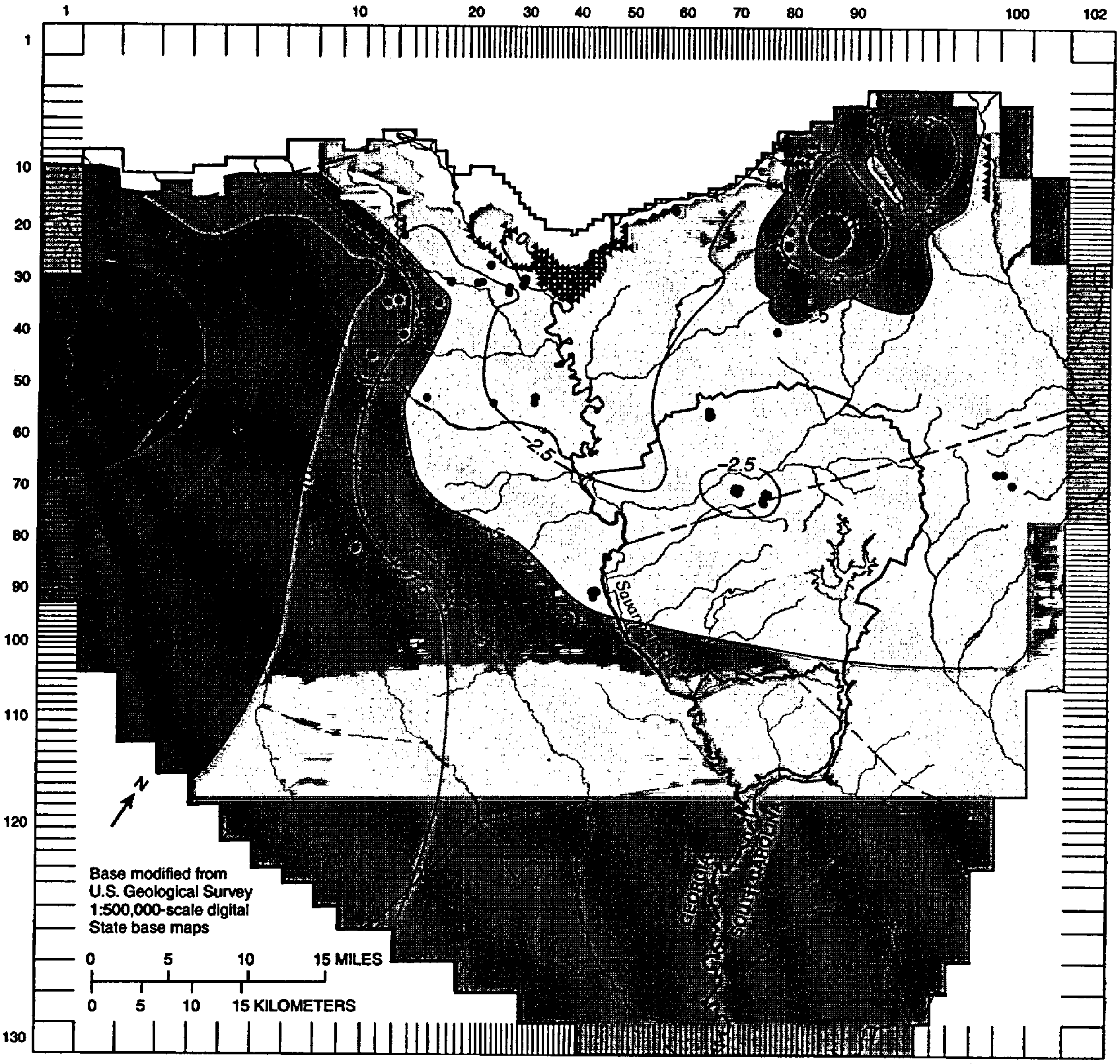
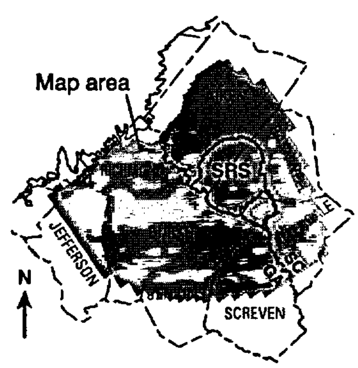


Figure 24. Simulated water-level change between 1987–92 long-term average and 2002 dry conditions and locations of simulated pumpage in the lower Dublin aquifer (layer A5) in the Savannah River Site (SRS) area, South Carolina.





EXPLANATION

Specified head

Simulated water-level change, in feet—
Computed by subtracting simulated potentiometric surface for 1987–92 (Clarke and West, 1998) from simulated potentiometric surface for 2002 dry conditions

-5
-10
-20
-30

— *10* — Line of equal simulated water-level change—Interval, in feet, is variable

▲ Simulated river cell

● Production well screened in the upper Midville aquifer

Figure 25. Simulated water-level change between 1987–92 long-term average and 2002 dry conditions and locations of simulated pumpage in the upper Midville aquifer (layer A6) in the Savannah River Site (SRS) area, South Carolina.

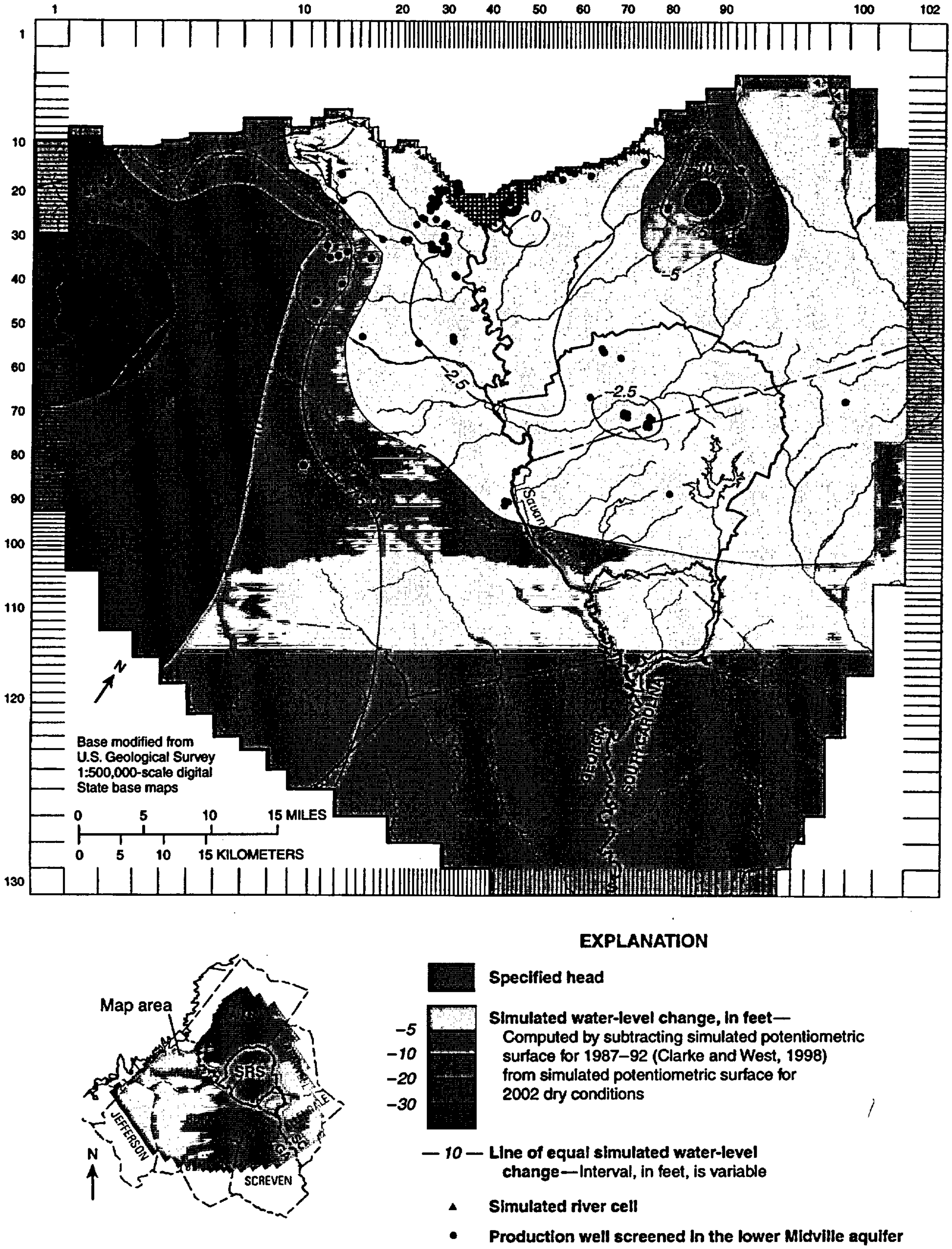


Figure 26. Simulated water-level change between 1987–92 long-term average and 2002 dry conditions and locations of simulated pumpage in the lower Midville aquifer (layer A7) in the Savannah River Site (SRS) area, South Carolina.

In zones 1 and 2, time intervals of 100 and 200 years (yr) were selected for display purposes because of the shorter time-of-travel. In zones 3 through 5, time intervals of 200 and 500 yr were used based on longer time-of-travel. For all five zones, flowpaths are presented for the entire time-of-travel to the final discharge location. The discharge areas on the SRS are represented in the model as: (1) river cells in layer A2 (Gordon aquifer) along Upper Three Runs Creek and the Savannah River, (2) return flow to the source-sink layer A1 simulating local streamflow, and (3) zones of well production in the Dublin and Midville aquifer systems. It should be noted that the Savannah River and its alluvial valley encompass a large area that is nearly 7 mi wide near Hollow Creek and about 4 mi wide farther south near the mouth of Upper Three Runs Creek (fig. 1*B*). The alluvial deposits are generally from 30 to 50 ft thick, and thin to the southeast along the course of the river (Leeth and Nagle, 1996).

MODPATH results indicate that for the 2002 simulation, Upper Three Runs Creek and the alluvial valley of the Savannah River are the dominant sinks or areas of ground-water discharge with time-of-travel ranging from 20 yr to greater than 2,000 yr (figs. 27–31). Generally, time-of-travel for particles that migrate downward through the Gordon confining unit (C1) and then move laterally through layer A2 (Gordon aquifer) to discharge areas ranges from 20 to 200 yr. For particles migrating deeper into layers A3 through A5 (Dublin aquifer system), time-of-travel generally ranges from 200 to 1,000 yr. Although pathlines are substantially longer and time-of-travel is slowed by additional confining units (C2–C4), eventual particle movement is laterally toward ground-water discharge areas where particles can migrate upward. Ground-water movement and discharge outside the SRS boundary is limited to recharge areas from: (1) zone 1 moving toward Eagle Point at greater than 100-yr time-of-travel (fig. 27), (2) zone 2 moving near trans-river flow areas at greater than 200-yr time-of-travel (fig. 28), (3) zone 3 moving toward an area north of Flowery Gap Landing at greater than 1,000-yr time-of-travel (fig. 29), (4) zone 4 moving toward irrigation wells located in Allendale County at greater than 200-yr time-of-travel (fig 30); and (5) zone 5 moving toward Lower Three Runs Creek and the Savannah River at greater than 200-yr time-of-travel (fig. 31).

Zone 1

In zone 1, located in the northwestern part of the SRS, the mean time-of-travel for particles to reach discharge areas using the model depicting 2002 conditions was 294 yr (fig. 27; table 6). The primary discharge areas for zone 1 occur along the middle sections of Upper Three Runs Creek to the south and the alluvial valley of the Savannah River to the southwest (fig. 27). The A/M Area of the SRS occupies the western part of zone 1 and has production wells screened in the Dublin and Midville aquifer systems. The A/M Area is the site of a large chlorinated solvent plume and concern has been raised about possible contamination migrating toward public-supply wells in the town of Jackson, S.C., located west of the SRS boundary (Westinghouse Savannah River Company, 2004). Ground-water models constructed to evaluate plume migration have focused on the interaction of the Upper Three Runs (subdivided into three units) and Gordon aquifers (Hiergesell and others, 1994). The ground-water models indicate that eventual discharge areas from the primary plume would occur along Upper Three Runs Creek and Eagle Point (Westinghouse Savannah River Company, 2004). For this study, particle-tracking analysis indicates downward movement in the upper half of zone 1 into the Dublin aquifer system, with some migration as deep as the upper Midville aquifer before moving laterally toward Upper Three Runs Creek. In zone 1, layer A3 (Millers Pond aquifer) is either thin or absent, so downward movement from the Gordon aquifer (layer A2) is through the confining units overlying layers A4–A6 (Dublin and Midville aquifer systems).

Once the particles enter the deeper aquifers, lateral movement is initiated toward the south prior to upward migration toward discharge areas within layer A2 (Gordon aquifer). The shortest time-of-travel from zone 1 ranges from 22 to 94 yr (table 6) and occurs when particles do not penetrate beneath layer A2 and move laterally for short distances in layer A2 before discharging to areas along Upper Three Runs Creek.

General ground-water flow directions are either south toward Upper Three Runs Creek or southwest from the A/M Area toward the SRS boundary (fig. 27). At the 100-yr time-of-travel interval, some particles have migrated laterally for distances ranging from 1 to 3 mi, with downward movement as deep as layer A5 (lower Dublin aquifer). At 200 years, several particles are captured in A/M Area production wells screened in the lower Dublin and upper Midville aquifers (layers A5 and A6). These wells intercept ground water that has been recharged outside the areas of contamination to the northeast and is moving laterally to the southwest with downward movement into the lower layers. The 200-yr time interval approximates the median time-of-travel of 231 yr (table 6) and particle endpoints delineate the ground-water discharge zones in the alluvial valley of the Savannah River and along sections of Upper Three Runs Creek (fig. 27). Particles not intercepted by the A/M Area production wells continue movement toward the southwest and migrate downward into layer A7 (lower Midville aquifer). At the SRS boundary, vertical movement is initiated upward through layers A6 (upper Midville aquifer) into layer A2 (Gordon aquifer) and particles are discharged along the alluvial valley east of Eagle Point (fig. 27). Several particles have travel times exceeding 1,000 yr as a result of low head gradients in the Gordon aquifer (layer A2) along the alluvial valley of the Savannah River. These stagnation areas result in slow movement in the area at times ranging from 600 to 700 yr.

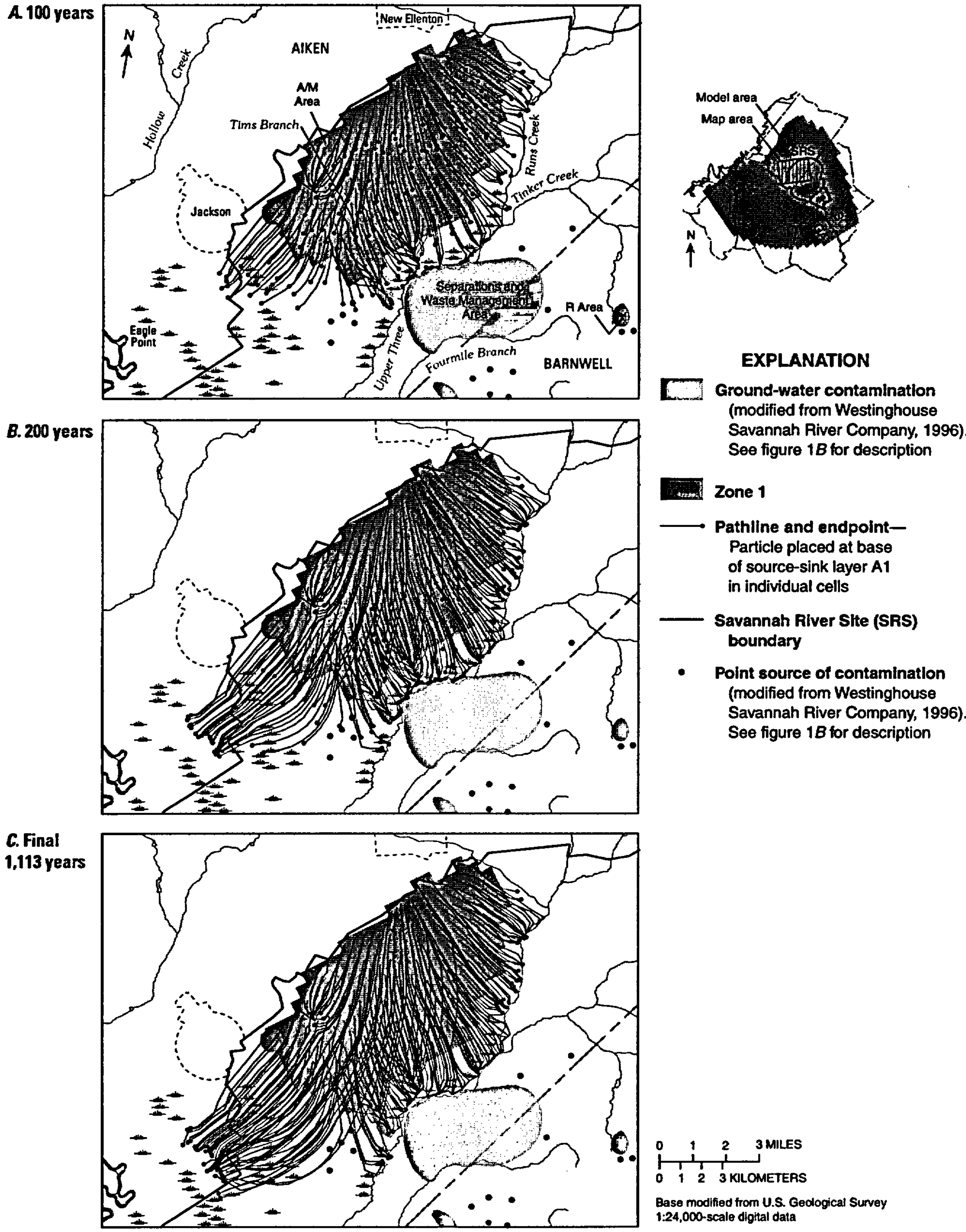


Figure 27. Particle-tracking results from the simulation of 2002 dry conditions at selected time intervals in zone 1 located in the northwestern part of the Savannah River Site, South Carolina.

Zone 2

In zone 2, located between the Separations and Waste Management Area and K Area, primary discharge areas for the 2002 simulation occur to the west along Upper Three Runs Creek or to the south along Pen Branch (fig. 28). Zone 2 includes three areas where ground-water contamination has been documented: (1) Separations and Waste Management Area, (2) K Area, and (3) C Area (fig. 28). The primary concern in these areas is that tritiated water from earlier operations, formerly stored in seepage basins between 1959 and 1970, could enter into the ground-water system and migrate to discharge areas (Flach and others, 2000). A tritium release of about 1,600 curies occurred during 1977 near the K Area (Flach and others, 1999a). The model developed by Flach and others (1999a) to predict solute transport determined that tritium concentrations greater than the Federal drinking water standard of 20,000 picocuries per liter (pCi/L) would begin to appear north of Pen Branch during 1998 and would peak during 2020 at values near 240,000 pCi/L. Zone 2 was delineated based on the downward gradient from layer A2 (Gordon aquifer) into layers A3–A5 (Dublin aquifer system). Surrounding areas near zone 2, upward gradients are common from layer A2 (Gordon aquifer) into the source-sink layer A1 (Upper Three Runs aquifer), and flow is toward the stream reaches of Fourmile Branch and Pen Branch. Baseflow studies conducted along these stream segments from 1997 to 1998 indicate gaining streams as a result of ground-water discharge from the Upper Three Runs aquifer (Flach and others, 1999b).

Particle-tracking results for the 2002 simulation in zone 2 indicate that ground-water discharge occurs along Upper Three Runs Creek, Fourmile Branch, and Pen Branch with a mean time-of-travel of 917 yr (table 6). The mean time-of-travel represents movement from the base of the source-sink layer A1 through layer A2 (Gordon aquifer) into layers A3–A5 (Dublin aquifer system) before moving laterally toward discharge areas located along Upper Three Runs Creek and the Savannah River (fig. 28 and table 6).

In the northern part of zone 2, east of the Separations and Waste Management Area, pathlines generally are toward Upper Three Runs Creek and particles penetrate into layer A4 (upper Dublin aquifer). At 100 years, the shortest particle flowpaths migrate downward through the Gordon confining unit and move laterally through layer A2 (Gordon aquifer) to discharge areas near the Separations and Waste Management Area along Upper Three Runs Creek (fig. 28). At 200 years, some particles that are influenced by a strong downward gradient penetrate as deep as layer A5 (lower Dublin aquifer) while particles moving laterally through layer A2 (Gordon aquifer) have moved across the Separations and Waste Management Area toward Upper Three Runs Creek. Ground-water flowpaths are dominated by pathlines toward Upper Three Runs Creek with some particles moving directly underneath the creek for great distances before discharge to river cells (fig. 28).

In C Area, ground-water flowpaths move westward through layer A2 (Gordon aquifer) and pass beneath Fourmile Branch to discharge areas along Upper Three Runs Creek. The mean time-of-travel for these particles is 365 yr, with values ranging between 290 and 470 yr. In the areas located between C Area and R Area, depth of penetration is into layers A4–A5 (upper and lower Dublin aquifers) with travel times for downward migration ranging from 100 to 300 yr prior to moving laterally to discharge areas along Upper Three Runs Creek. South of C Area, pathlines diverge along the general ground-water divide between Upper Three Runs Creek and Pen Branch. Here flowpaths are northward toward Upper Three Runs Creek, southward toward Pen Branch, or westward toward trans-river zones along the Georgia side of the Savannah River (fig. 28).

Particles terminating on the Georgia side of the Savannah River (trans-river flow) originate in the area between D Area and K Area in the southern part of zone 2. Trans-river particles moving toward the Savannah River either take a direct westerly flowpath south of D Area or move northwestward toward Upper Three Runs Creek before redirecting toward the south (fig. 28). The shortest time-of-travel to trans-river zones is about 200 yr through layer A2 (Gordon aquifer) from recharge areas, about 2 mi west of K Area (fig. 28). Time-of-travel to trans-river zones varies depending on the discharge cell, and ranges from 400 to 2,000 yr for the southernmost cell and from 1,000 to 7,300 yr for the adjacent cell. The longer travel times generally involve flowpaths that have greater depth of penetration into the Dublin aquifer system before moving laterally toward the Savannah River. In addition, the stagnation of flow near the Savannah River is because of low head gradients in layer A2 (Gordon aquifer), which results in longer travel times.

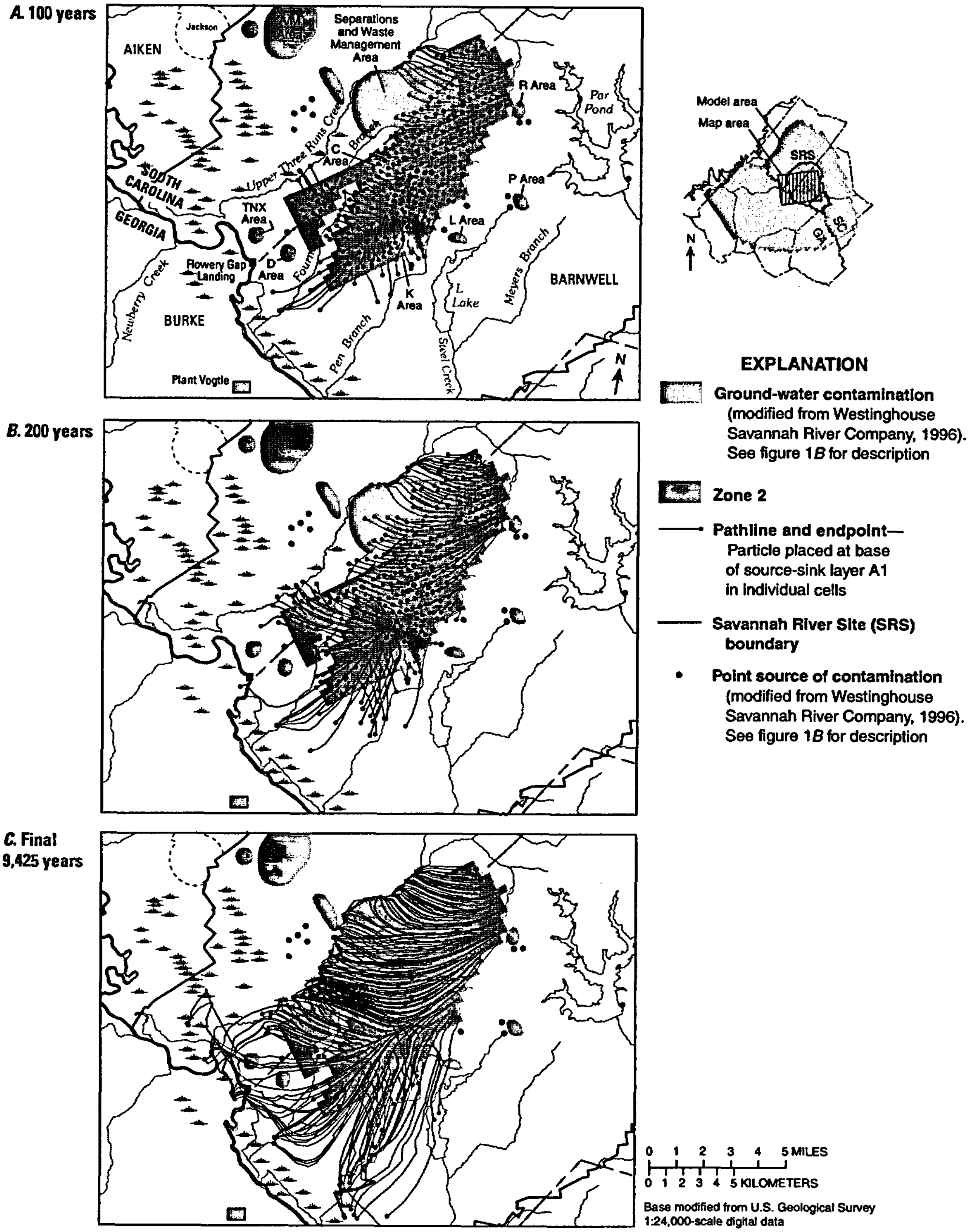


Figure 28. Particle-tracking results from the simulation of 2002 dry conditions at selected time intervals in zone 2 located in the central part of the Savannah River Site, South Carolina.

Zone 3

In zone 3, located within the Tinker Creek drainage basin, ground-water flowpaths in the 2002 simulation are dominated by large vertical head gradients and westward flow toward discharge areas along Upper Three Runs Creek (figs. *1B* and 29). Zone 3 is located to the northeast away from any contamination sources, but the criteria for downward ground-water flow from layer A2 (Gordon aquifer) to the lower layers (A3 through A5, Dublin aquifer system) was met, so further analysis was performed. The mean time-of-travel in zone 3 is 1,100 yr with a maximum value of 9,724 yr (table 6). Particle positions and pathlines at the 500-yr time-of-travel interval indicate nearly 25 percent of the particles have discharged along Upper Three Runs Creek while several have moved south toward K Area (fig. 29). Generally, the shorter flowpaths involve lateral migration in layers A2 and A4 (Gordon and upper Dublin aquifers) followed by vertical movement toward Upper Three Runs Creek. In zone 3, layer A3 (Millers Pond aquifer) is either thin or absent and increases in thickness south of the Pen Branch Fault. The longer flowpaths (beyond K, P, and L Areas) penetrate as deep as layer A5 (lower Dublin aquifer) before initiating lateral movement. By 1,000 years, some particles have migrated farther west along Upper Three Runs Creek and south through layer A5 (lower Dublin aquifer) to areas near Pen Branch (fig. 29). Time-of-travel for upward migration from layer A5 (lower Dublin aquifer) to discharge points within the source-sink layer A1 east of the Savannah River ranges from 300 to 600 yr.

Zone 4

In zone 4, located south of P Area, simulated flowpaths are generally south toward discharge areas on the eastern side of the Savannah River (fig. 30). Simulated time-of-travel in zone 4 is slowed by movement through the Gordon confining unit (C1), which has a thickness of about 25 ft in zone 4. Travel times through this unit range from 100 to 500 yr. Maximum depth of penetration is downward into layer A3 (Millers Pond aquifer) with most particles moving laterally through layer A2 (Gordon aquifer). The primary ground-water discharge areas for zone 4 are located in the Savannah River valley between Pen Branch and Steel Creek, and between Steel Creek and Furse Mill Creek. In these areas, movement is upward from layer A2 (Gordon aquifer) into the source-sink layer A1 (Upper Three Runs aquifer). Mean time-of-travel for the 2002 simulation in zone 4 was 505 yr and ranges from a minimum of 125 yr to a maximum of 1,589 yr (table 6). By 200 years (fig. 30), several particles have moved beyond the SRS boundary into Allendale County, S.C., while particles originating in the southern part of the zone remain in the Gordon confining unit (C1). By 500 years, most particles have migrated to areas near the two discharge zones with some particles showing minimal lateral or downward movement. These particles eventually move toward discharge areas located west of Steel Creek, while some migrate farther south toward Allendale County (fig. 30).

Zone 5

In zone 5, located in areas adjacent to Par Pond, simulated ground-water flowpaths are similar to those of zone 4 with southward movement and downward penetration into layers A3 through A5 (Dublin aquifer system, fig. 31). The primary ground-water discharge areas for zone 5 are in the Savannah River valley between Pen Branch and Steel Creek, and between Steel Creek and Furse Mill Creek. Here, particle movement is upward from layer A2 (Gordon aquifer) into the source-sink layer A1 (Upper Three Runs aquifer). Mean time-of-travel for the 2002 simulation in zone 5 was 1,553 yr and ranged from a minimum of 34 yr to a maximum of 16,045 yr (table 6). By 200 years, about 2 percent of the particles have discharged into the source-sink layer A1 along Lower Three Runs Creek with the remaining active particles moving near P Area or in proximity to the southern SRS boundary (fig. 31). Maximum depth of particle penetration within the initial 200 yr interval is near the bottom of layer A2 (Gordon aquifer). By 500 yr, lateral movement of particles continues in a southwesterly direction with several particles reaching the two principle discharge areas. A third area of simulated discharge occurs within an active production well withdrawing water from layers A3 and A5 (Millers Pond and lower Dublin aquifers). The irrigation well, located in Allendale County, S.C., intercepts particles moving southward with travel times ranging from 660 to 14,800 yr.

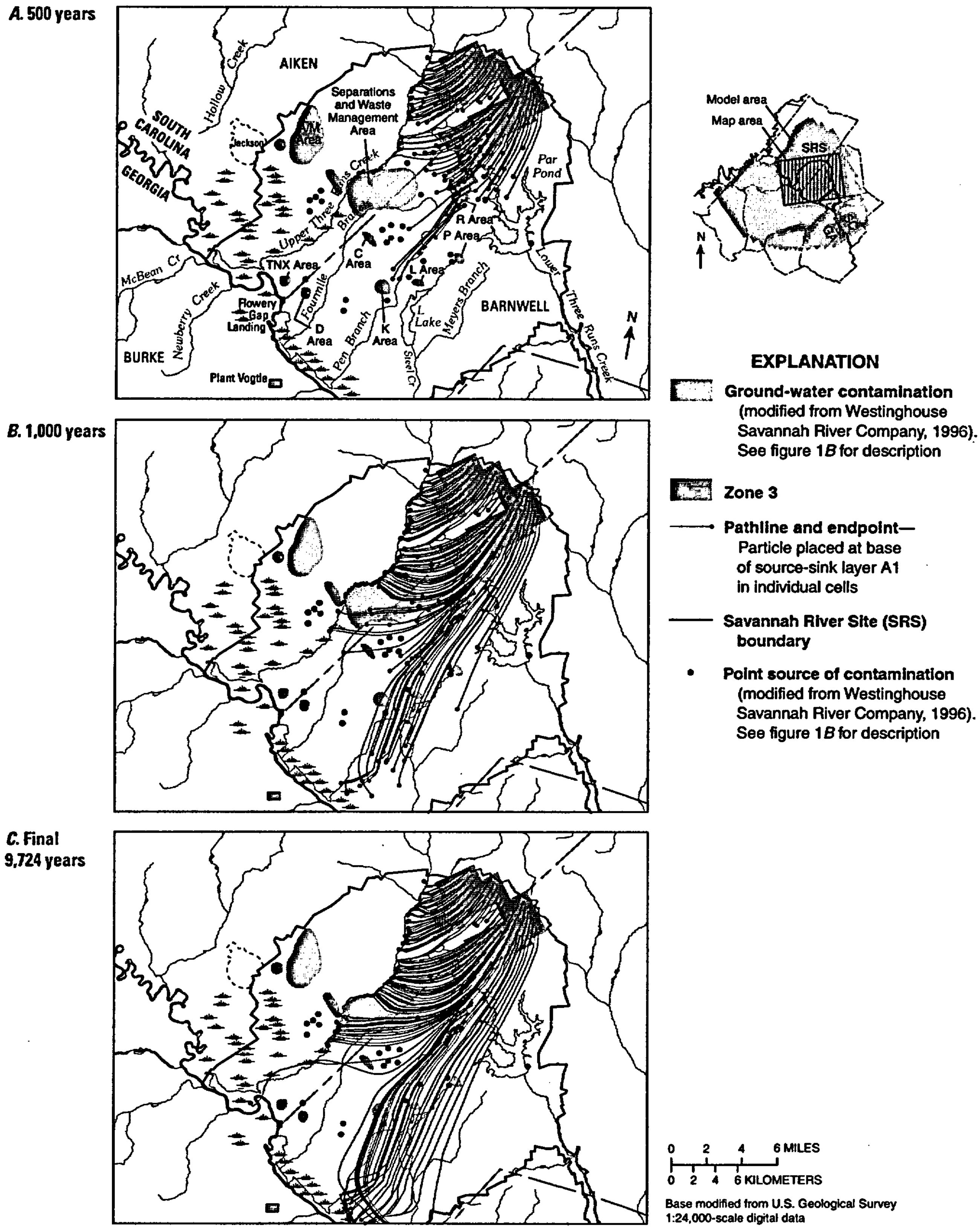


Figure 29. Particle-tracking results from the simulation of 2002 dry conditions at selected time intervals in zone 3 located in the north-eastern part of the Savannah River Site, South Carolina.

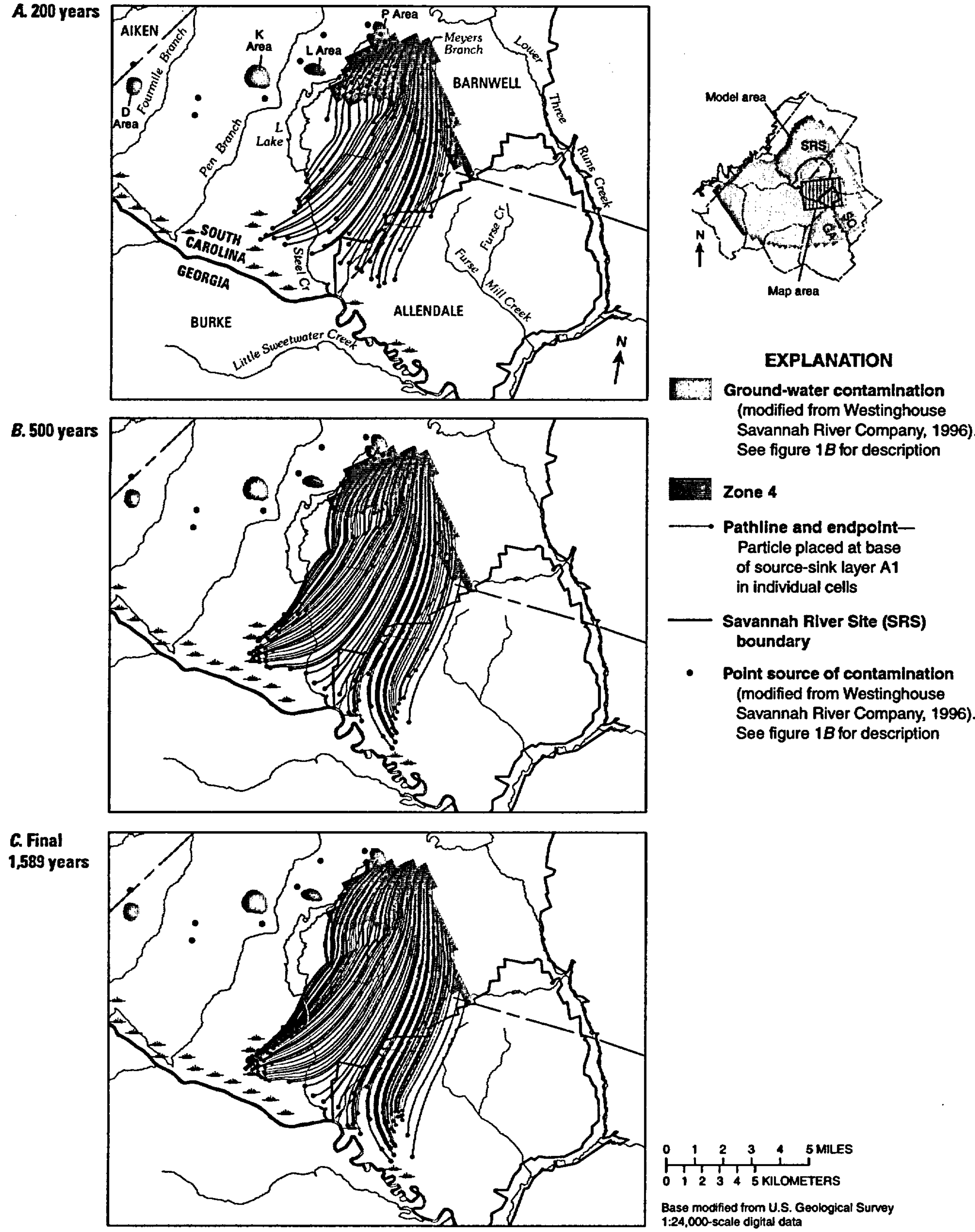


Figure 30. Particle-tracking results from the simulation of 2002 dry conditions at selected time intervals in zone 4 located in the south-central part of the Savannah River Site, South Carolina.

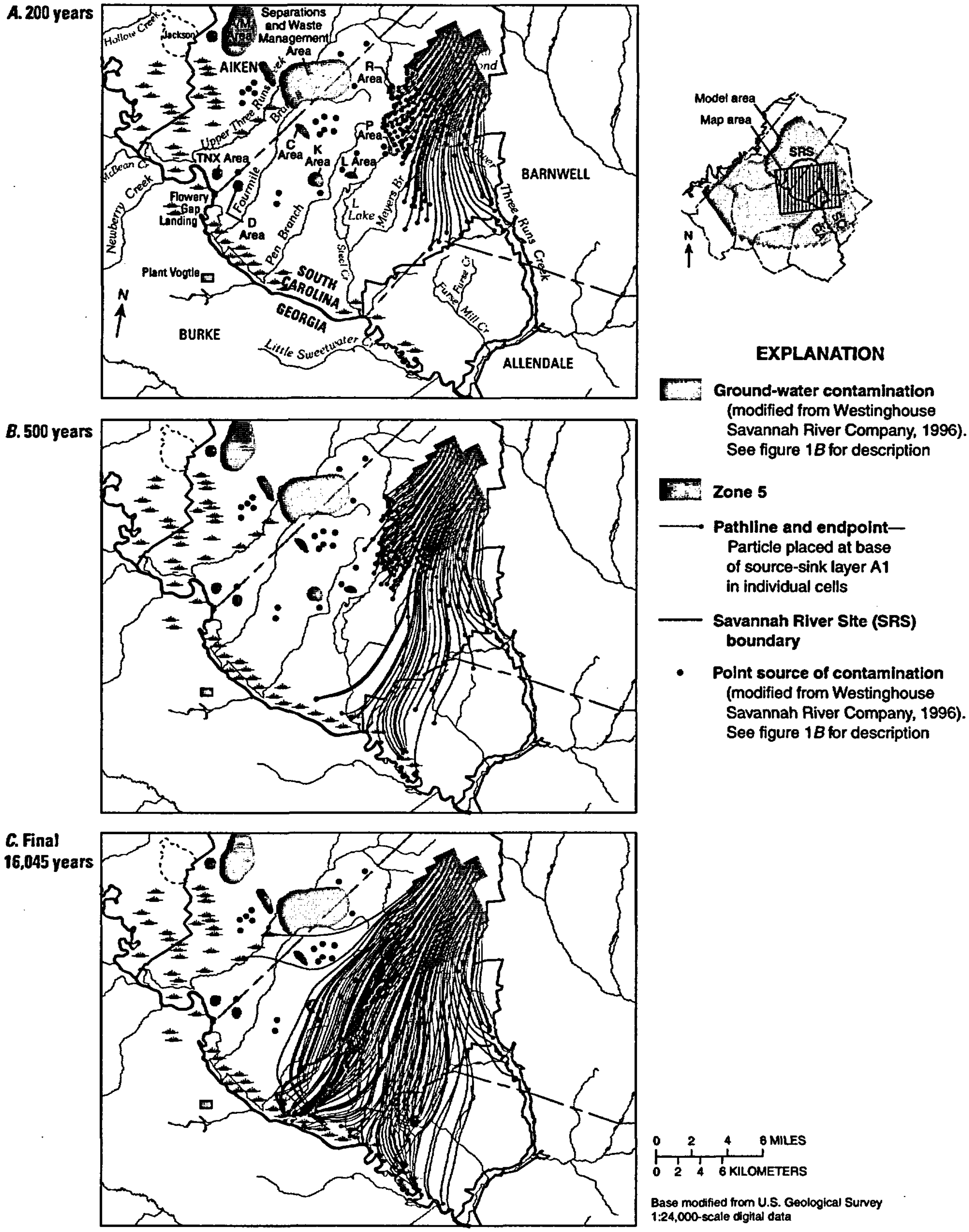


Figure 31. Particle-tracking results from the simulation of 2002 dry conditions at selected time intervals in zone 5 located in the eastern part of the Savannah River Site, South Carolina.

Table 6. Time-of-travel for particles seeded in recharge areas (five zones) on Savannah River Site, South Carolina, and forward tracked through time to discharge areas.

[All time-of-travel values shown are in years]

Zone number	Number of particles applied	Statistic	[1]1987–92	2002	Scenario A	Scenario B	Scenario C	Scenario D
			Boundary conditions					
			Wet	Dry	Average	Average	Average	Dry
			Time-of-time, in years					
Zone 1	984	Mean	301	294	294	249	293	293
		90th percentile	545	561	552	440	550	560
		75th percentile	404	412	407	335	408	417
		Median	264	231	228	217	228	234
		25th percentile	166	164	163	150	163	149
		10th percentile	92	94	91	64	91	94
		Maximum	2,121	1,113	2,481	1,294	1,393	1,284
		Minimum	19	22	21	20	21	22
Zone 2	1,148	Mean	823	917	848	866	861	928
		90th percentile	1,289	1,554	1,364	1,524	1,384	1,587
		75th percentile	828	874	813	819	827	875
		Median	543	591	561	524	564	593
		25th percentile	367	408	388	323	388	407
		10th percentile	212	218	222	144	220	213
		Maximum	6,715	9,425	6,703	27,276	6,699	11,426
		Minimum	28	30	29	29	29	30
Zone 3	1,161	Mean	1,051	1,100	1,095	947	1,085	1,120
		90th percentile	1,553	1,740	1,804	1,764	1,773	1,856
		75th percentile	1,275	1,419	1,375	1,339	1,373	1,429
		Median	1,020	1,146	1,105	834	1,084	1,142
		25th percentile	442	523	470	411	469	518
		10th percentile	178	207	183	181	183	207
		Maximum	58,102	9,724	11,778	5,916	14,658	9,916
		Minimum	61	80	63	63	63	79
Zone 4	882	Mean	522	505	508	494	495	502
		90th percentile	961	969	949	926	940	967
		75th percentile	624	595	600	592	595	594
		Median	402	404	398	395	397	402
		25th percentile	324	335	329	327	327	335
		10th percentile	225	238	233	232	229	236
		Maximum	2,870	1,589	5,741	3,015	1,560	1,647
		Minimum	123	125	124	143	122	123
Zone 5	668	Mean	1,570	1,553	1,532	1,491	1,532	1,552
		90th percentile	2,296	2,218	2,391	2,303	2,453	2,207
		75th percentile	1,575	1,609	1,628	1,596	1,612	1,626
		Median	1,340	1,337	1,349	1,307	1,348	1,354
		25th percentile	1,132	966	1,052	998	1,138	1,108
		10th percentile	672	444	510	460	463	434
		Maximum	13,217	16,045	12,874	11,443	12,071	19,304
		Minimum	38	34	36	36	36	34

[1]Clarke and West (1998)

Trans-River Flow

The USGS particle-tracking code MODPATH (version 3; Pollock, 1994) also was used in backtracking mode by calculating particle movement from documented areas of trans-river flow (Clarke and West, 1998, p. 89). Particles were placed in trans-river flow areas, located on the western side of the Savannah River floodplain in Burke County, Ga., and backtracked to recharge areas on the SRS. The original particle-tracking analysis for 1987–92 (Clarke and West, 1998) applied five particles to each model cell, centrally positioning each particle from bottom to top at 25-percent increments of aquifer thickness. To improve definition of flowpaths and corresponding recharge areas for the 2002 model, a greater number of particles were applied to each model cell, at 10-percent thickness increments for particles closest to the cell walls, and at 20-percent thickness increments for particles located in the cell interior for a total of 100 particles per cell (fig. 32).

The most recent release of MODPATH (version 3) includes MODPATH-PLOT, which allows particle-tracking profiles to be viewed along a designated row or column of the model. The MODPATH program uses output from each steady-state simulation (1987–92, 2002, and Scenarios A–D; Appendixes A–D) to calculate particle positions and time-of-travel along horizontal cell faces and at the top and bottom of each hydrogeologic unit. The results are presented for a profile along row 82 of the model (fig. 8), which includes documented areas of trans-river flow on the Georgia side of the Savannah River and recharge areas on the SRS located between D Area and K Area (fig. 33). Figure 33 shows flowpaths in map view and along the profile with 100-yr increments of time shown as dots on the flowlines.

For the backtracking of particles, three model cells located near Flowery Gap Landing (covering about 1 mi²) on the Georgia side of the Savannah River were chosen based on results from the 1987–92 simulation (Clarke and West, 1998, p. 89) and on results from zone 2 (forward-tracking mode) that indicate that the area west of the Savannah River is a common point of ground-water discharge. Of the 300 particles applied in the three cells for the 2002 dry simulation, 88 particles (29 percent) backtrack to recharge areas on the SRS compared with 93 particles (31 percent) for the 1987–92 simulation (table 7). The remaining particles backtracked to recharge areas on the Georgia side of the Savannah River.

Simulated flowpaths for 2002 indicate that time-of-travel from trans-river areas in Georgia to recharge areas near central SRS (D Area and K Area) range from about 82 to 1,519 yr (table 7, fig. 33). Mean time-of-travel for trans-river particles for 2002 is 518 yr compared with 534 yr for the 1987–92 simulation (table 7). The shortest travel time (from 82 to 415 yr) was for particles moving laterally through layer A2 (Gordon aquifer) and upward into the base of the source-sink layer A1 (Upper Three Runs aquifer) near D Area and K Area (fig. 33). The point of recharge for these particles is the same interstream area south of Fourmile Branch, documented in Clarke and West (1998). Based on time-of-travel for the 2002 simulation, particles with greater depth of penetration into layers A3 through A5 (Dublin aquifer system) had longer flowpaths and travel times ranging from 340 to 1,519 yr. These particles move downward from trans-river flow areas into the lower layers A3 though A5 (Dublin aquifer system) before migrating laterally toward D Area and K Area where the final movement is upward toward recharge areas at the base of the source-sink layer A1 (Upper Three Runs aquifer). In the 1987–92 simulation, several particles move laterally through the Dublin aquifer system to recharge areas north of Pen Branch. The time-of-travel for these particles ranges from about 1,600 to 2,356 yr.

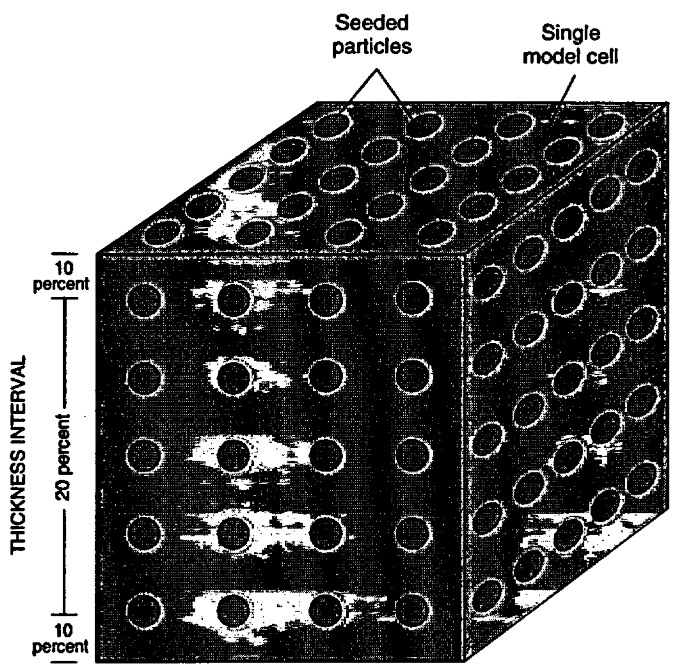
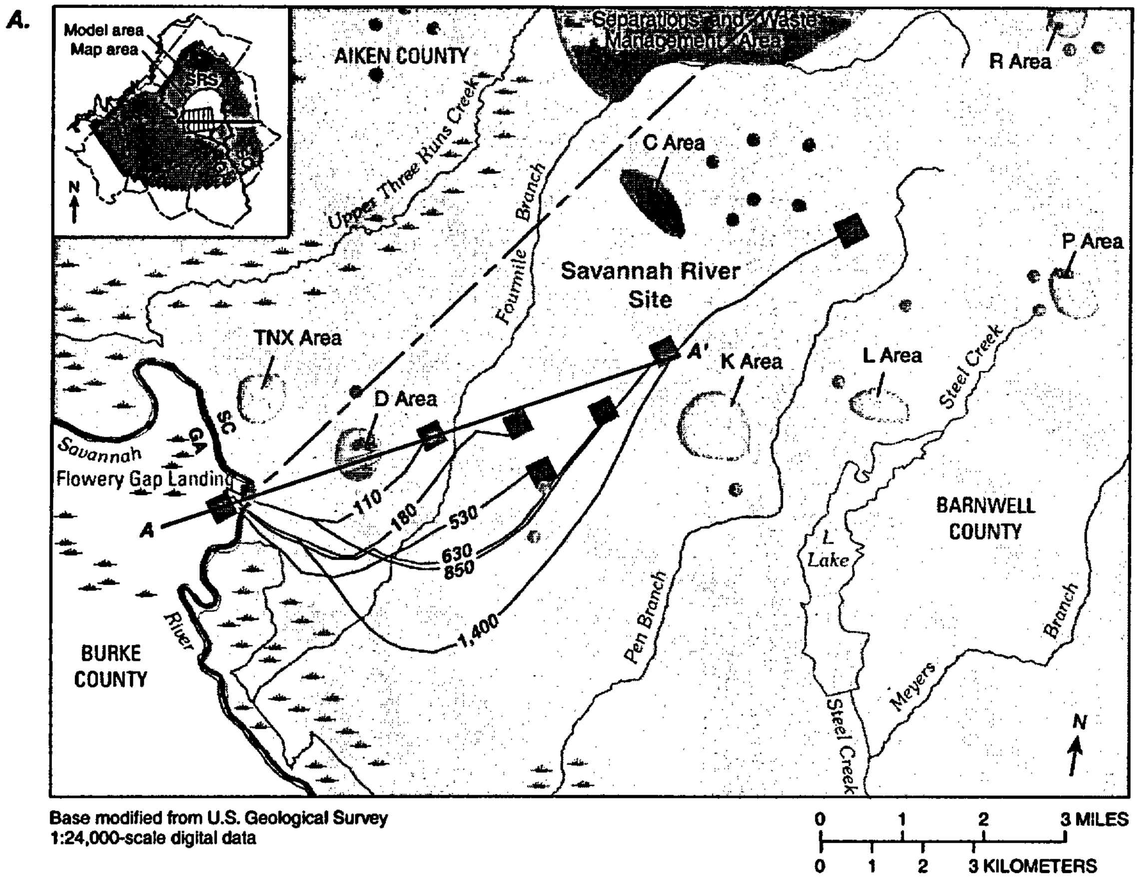
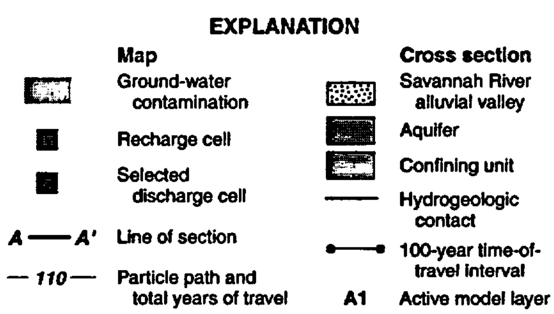


Figure 32. Schematic diagram showing particle-seeding distribution for cells located in trans-river zones.

A.





	Simulation	
	[1]1987–92	2002
Boundary conditions	Long-term average	Dry
Particles released	300	300
Recharge on SRS	93	88
Time-of-travel, in years		
Mean	534	518
90th percentile	978	985
75th percentile	753	785
Median	486	481
25th percentile	140	147
10th percentile	102	104
Maximum	2,356	1,519
Minimum	80	82

[1]Clarke and West, 1998

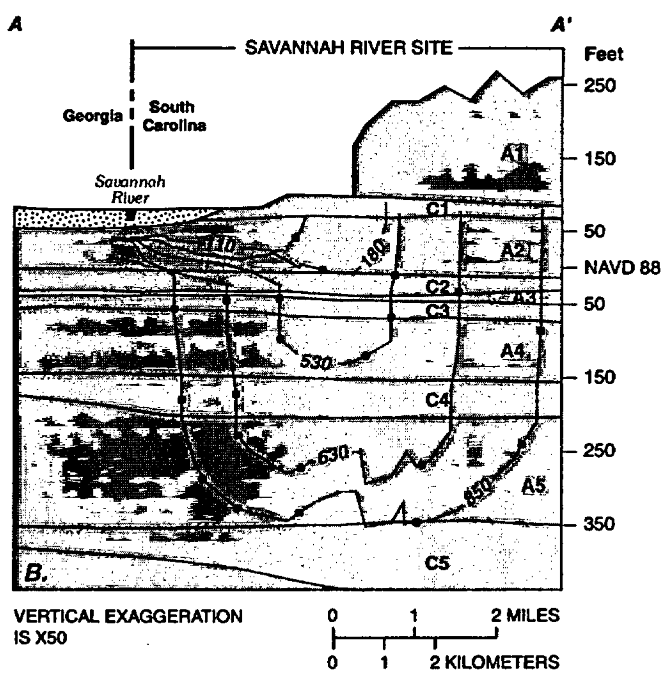


Figure 33. (*A*) Simulated trans-river flow for 2002 dry conditions and selected ground-water pathlines in map view, and (*B*) selected ground-water pathlines in cross-sectional view along row 82 (see figure 8) at the Savannah River Site (SRS), South Carolina.

Table 7. Results of particle backtracking from trans-river areas in Georgia to recharge cells located in the Savannah River Site, South Carolina.

	[1]1987–92	2002	Scenario A	Scenario B	Scenario C	Scenario D
	Boundary conditions					
	Wet	Dry	Average	Average	Average	Dry
Particles released	300	300	300	300	300	300
Trans-river particles	93	88	89	110	88	92
	Time-of-travel, in years					
Mean	534	518	516	460	541	535
90th percentile	978	985	934	904	940	1,011
75th percentile	753	785	736	722	757	757
Median	486	481	462	366	454	507
25th percentile	140	147	145	120	148	151
10th percentile	102	104	103	110	103	103
Maximum	2,356	1,519	2,299	2,572	2,305	1,845
Minimum	80	82	81	79	81	79

[1]Clarke and West (1998)

Simulation of Ground-Water Management Scenarios, 2002 and 2020

Four hypothetical ground-water management scenarios were developed to assess the effect of changing pumping and boundary conditions on ground-water flow and the potential migration of contaminants from the SRS. The four scenarios represent hydrologic conditions for (A) reported pumping for 2002 and boundary conditions for an average year, (B) reported pumping for 2002 with SRS pumping discontinued and boundary conditions for an average year, (C) projected 2020 pumping and boundary conditions for an average year, and (D) projected 2020 pumping and boundary conditions for a dry year (table 8). Results of the four scenarios are summarized briefly below, but are described in detail including maps, tables, and schematic diagrams in Appendixes A–D. Projected 2020 pumping assumes average hydrologic condition; this is less than 2002 pumping, which was during an extreme drought.

Adjustments to Boundary Conditions

The previous model simulation (1987–92) represents hydrologic conditions during a relatively average period, whereas the current model (2002) simulates extreme drought conditions (table 8). In both simulations, the heads assigned in the source-sink layer A1 and along lateral boundaries were based on potentiometric-surface maps (Clarke and West, 1997; Cherry, 2003) for their respective time periods. In three of four ground-water management scenarios (Scenarios A, B, and C), the specified heads in the source-sink layer A1 and along lateral boundaries (layers A2–A7) of the model were averaged between long-term average (1987–92) and extremely dry (2002) hydrologic conditions. In the remaining pumping scenario (Scenario D), specified heads in the source-sink layer A1 and along lateral boundaries (layers A2–A7) of the model were adjusted to represent dry hydrologic conditions similar to the 2002 simulation. The focus of the discussion is on the forward tracking of particles from zones 1 and 2, and backtracking of particles from the trans-river area on the Georgia side of the Savannah River as a result of potential migration of tritiated water from the SRS. Zones 3–5 represent areas of minimal contamination and the median time-of-travel ranges from 395 to 1,354 yr (table 6).

Table 8. Ground-water management scenarios developed for the Savannah River Site region and relative changes to specified heads in the source-sink layer A1, specified heads located along lateral boundaries in the active model layers (A2–A7), and simulated pumping.

[Mgal/d, million gallons per day]

Simulated condition	[1]1987–92	2002	Scenario 2002 A	Scenario 2002 B	Scenario 2020 C	Scenario 2020 D
Source-sink layer A1, specified heads	Long-term average	Dry	Average	Average	Average	Dry
Lateral specified head boundaries, layers A2–A7	Long-term average	Dry	Average	Average	Average	Dry
Pumpage (active layers A2–A7), in mgal/d	52.7	67.2	67.2	61.9	55.3	56.9

[1]Clarke and West (1998)

Projected Pumping

Pumping projections in the SRS region through 2020 (Scenarios C and D) were developed (1) for public supply and industry based on water-management plans and population-growth projections, and (2) for irrigation based on an "average" quantity of water applied (gallons per acre per day, gal/acre/day) to the total irrigated acreage of 106,000 (93 percent of 2000 estimate).

Population in the eight-county study area is expected to increase by 80,000 residents by the year 2020 (table 9) with most of the growth centered around the Augusta, Ga., and North Augusta, S.C., areas and the counties of Richmond, Ga., and Aiken, S.C. (Rutherford & Associates, 2000a, b, and c; U.S. Census Bureau, accessed February 3, 2003, at *http://www.census.gov/*; J.M. Dole, Lower Savannah Council of Governments, written commun., 2003). Most rural communities have experienced an overall decline in population during the past 70 years, which has stabilized during the past 20 years, and modest increases are predicted by the year 2020. The analysis of water-use trends and population growth during 1980–2000 is available from many sources (Fanning, 1997, 2003; Fanning and others, 1992; Harrelson and others, 2002; Lonon and others, 1983; Newcome, 1995, 2000; Pierce and Barber, 1982; Pierce and others, 1982, 1984; Rutherford & Associates, 2000a, b, and c; Stringfield, 1989; Trent and others, 1990; Turlington and others, 1987; U.S. Census Bureau, accessed February 3, 2003, at *http://www.census.gov/*; U.S. Geological Survey, accessed February 11, 2003, at *http://water.usgs.gov/watuse/*), which were used to estimate a ground-water use of 102 Mgal/d in the year 2020 (table 9).

Table 9. Ground-water use during 2002 and projected pumpage for 2020 average hydrologic conditions near the Savannah River Site, South Carolina and Georgia.

[Ga., Georgia; S.C., South Carolina; do., ditto]

Year	State	County	Population[1]	Pumpage, in million gallons per day							
				Public supply[2]	Irrigation[3]	Industrial mining	Domestic and commercial	Livestock	Thermoelectric power	Total
2002	Ga.	Burke	22,794	1.42	21.23	0.09	0.90	0.03	1.17	24.84
	do.	Jefferson	17,138	1.76	6.92	4.01	0.64	0.03	0	13.36
	do.	Jenkins	8,647	0.54	3.94	0.01	0.33	0.02	do.	4.84
	do.	Richmond	197,842	12.59	2.63	2.47	0.02	0.02	do.	17.74
	do.	Screven	15,201	1.06	15.62	1.82	0.79	0.03	do.	19.32
	S.C.	Aiken	145,276	13.54	1.19	4.50	0	0	do.	19.23
	do.	Allendale	10,949	0.84	10.16	1.97	do.	do.	do.	12.97
	do.	Barnwell	23,407	2.32	0.32	0	do.	do.	do.	2.64
		Total—Ga.	**261,622**	**17.37**	**50.34**	**8.40**	**2.68**	**0.13**	**1.17**	**80.10**
		Total—S.C.	**179,632**	**16.70**	**11.67**	**6.47**	**0**	**0**	**0**	**34.84**
		Total—eight county	**441,254**	**34.07**	**62.01**	**14.87**	**2.68**	**0.13**	**1.17**	**114.94**
2020	Ga.	Burke	[4]30,647	1.47	11.46	0.00	0.90	0.03	1.17	15.03
	do.	Jefferson	[5]17,190	1.87	5.38	3.59	0.64	0.03	0	11.51
	do.	Jenkins	[4]10,388	0.67	4.62	0.01	0.33	0.02	do.	5.65
	do.	Richmond	[6]216,400	15.32	0.63	2.87	0.22	0.02	do.	19.06
	do.	Screven	[4]21,916	1.39	9.94	2.00	0.79	0.03	do.	14.16
	S.C.	Aiken	[7]188,525	14.42	0.39	5.08	0.80	0.18	do.	20.87
	do.	Allendale	[7]11,090	1.02	3.07	4.67	0.36	0.04	do.	9.16
	do.	Barnwell	[7]27,230	2.90	2.32	0.72	0.73	0	do.	6.67
		Total—Ga.	**296,541**	**20.73**	**32.03**	**8.47**	**2.88**	**0.13**	**1.17**	**65.41**
		Total—S.C.	**226,845**	**18.34**	**5.78**	**10.47**	**1.89**	**0.22**	**0**	**36.70**
		Total—eight county	**523,386**	**39.07**	**37.81**	**18.94**	**4.77**	**0.35**	**1.17**	**102.11**

[1]U.S. Census Bureau, accessed February 3, 2003, at *http:www.census.gov/*

[2]J.L. Fanning, U.S. Geological Survey, written commun., 2003.

[3]Kerry Harrison, University of Georgia, Cooperative Extension Service, written commun., 2003.

[4]Rutherford & Associates, 2000a, b, c.

[5]Central Savannah River Area Regional Development Center, 2003.

[6]Mike Little & Associates, 1996.

[7]J.M. Dole, Lower Savannah Council of Government, written commun., 2003.

The total projected increase in water demand for public supply (12 Mgal/d from 2002 to 2020) will perhaps be met by additional surface-water withdrawals from the Savannah River and increased ground-water withdrawals of 5 Mgal/d. These projections are based on the per capita water use of 150 gallons per day applied to the entire eight-county study area. In general, population centers located in the northern part of the study area such as Augusta, Ga., and North Augusta, S.C., rely on surface-water filtration plants along the Savannah River near the Fall Line. Farther south in Richmond County, Ga., and Aiken County, S.C., downdip sediments thicken and well yields provide sufficient amounts of ground water for public supply. Future pumping estimates represent a shift in the distribution of pumpage from irrigation wells in rural areas to public-supply wells in areas of projected population growth. In these areas, projected increases for public-supply wells range from 5 to 25 percent from current rates (Fanning, 2003; Mike Little & Associates, 1996; Rutherford & Associates, 2000a, b, and c; J.M. Dole, Lower Savannah Council of Governments, written commun., 2003; P.A. Stone, South Carolina Department of Health and Environmental Control, written commun., 2003; table 9). One area of anticipated growth is near Augusta, Ga., particularly in the southern part of Richmond County, Ga., where ground-water withdrawals from the Midville aquifer system are expected to increase by 2.7 Mgal/d. Low to moderate growth rates can be expected in Burke, Jenkins, and Screven Counties, Ga., as a result of highway expansion on the Savannah River Parkway between Augusta and Savannah (Rutherford & Associates, 2000a, b, and c; G.M. Brewer, Georgia Department of Transportation, written commun., 2003; table 9). According to population growth estimates for South Carolina (J.M. Dole, Lower Savannah Council of Governments, written commun., 2003), the area of the highest anticipated growth rate is Aiken County. Additional water demands in this area will be met through a combination of increased surface-water withdrawals from the Savannah River and well production near the City of Aiken (P.A. Stone, South Carolina Department of Health and Environmental Control, written commun., 2003).

Because irrigation withdrawal can be substantially higher during periods of drought, two projections were completed to the year 2020—one for average climatic conditions (Scenario C) and one for average dry climatic conditions (Scenario D). Estimated values for 2020 were derived by multiplying projected acres of irrigated land in each county by an average application rate derived during the period 1980–2002 (table 10).

Table 10. Total water use for irrigation, irrigated acreage, and ground-water withdrawals for irrigation during 2000–2002, mean application rate during 1980–2002, and projected water-use for irrigation in the year 2020 for the Savannah River Site region, South Carolina and Georgia.

[Mgal/d, million gallons per day; gal/acre/day, gallons per acre per day; Ga., Georgia; S.C., South Carolina]

County/state	2000–2002				1980–2002	2020—Projected		
	Total water use for irrigation (Mgal/d)	Irrigated acreage	Ground-water withdrawals for irrigation		Mean application rate (gal/acre/day)	Total water use for irrigation (Mgal/d)	Ground-water withdrawals for irrigation (Mgal/d)	Irrigated acreage
			Mgal/d	(Percent)				
Burke, Ga.	28.36	27,530	21.23	74.9	526	15.30	11.46	25,713
Jefferson, Ga.	17.29	24,190	6.92	40	477	13.44	5.38	22,593
Jenkins, Ga.	5.78	12,200	3.94	68.2	443	6.78	4.62	11,395
Richmond, Ga.	6.63	1,450	5.22	78.7	1,265	0.81	0.63	1,354
Screven, Ga.	21.53	24,660	15.62	72.5	534	13.70	9.94	23,032
Aiken, S.C.	3.94	2,150	0.98	24.9	868	1.56	0.39	2,008
Allendale, S.C.	14.06	10,620	5.62	40	1,090	7.69	3.07	9,919
Barnwell, S.C.	12.45	10,690	3.73	30	615	7.74	2.32	9,984
Total—Ga.	**79.59**	**90,030**	**52.93**	**66.5**	**560**	**50.03**	**32.03**	**84,088**
Total—S.C.	**30.45**	**23,460**	**10.33**	**33.9**	**900**	**16.99**	**5.78**	**21,912**
Total—eight county	**110.04**	**113,490**	**63.26**	**57.5**	**617**	**67.02**	**37.81**	**106,000**

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

The mean application rate used for counties in Georgia was 560 gal/acre/day (7.5 in/yr) and was considerably lower than the rate of 900 gal/acre/day (12.1 in/yr) for counties in South Carolina. These values were adjusted prior to multiplying by the estimated irrigated acreage to obtain the total water use for irrigation in 2020. The two adjusted application rates were 595 gal/acre/day (8.0 in/yr) for counties in Georgia and 775 gal/acre/day (10.4 in/yr) for counties in South Carolina. The estimates for total water use for irrigation for each county were adjusted using existing ratios of surface to ground-water irrigation pumpage during 2000–2002 to determine the pumping rate for 2020 (table 10). Projected annual ground-water use for irrigation for average conditions (Scenario C) during 2020 is 38 Mgal/d and for typical dry conditions (Scenario D) is 43 Mgal/d (fig. 34). Both of these values represent a decrease from the estimated irrigation use of 63 Mgal/d during the drought of 2002. As Stooksbury (2003) noted, the severity of the 2002 drought was considered extreme, so an "average" application rate for dry conditions was considered to represent a 60:40 mix of normal and dry conditions. According to this formula, the application rate for a wet year (436 gal/acre/day—1995) was multiplied by 0.6 and then added to the resulting multiplication of the application for a dry year (960 gal/acre/day—2000) by 0.4. Thus, the resulting application rate used for typical dry conditions (Scenario D) was 662 gal/acre/day. The projected ground-water use for 2020 in the water-use categories of commercial, industrial, and thermoelectric power was held at either the 2000 or 2002 ground-water withdrawal rates.

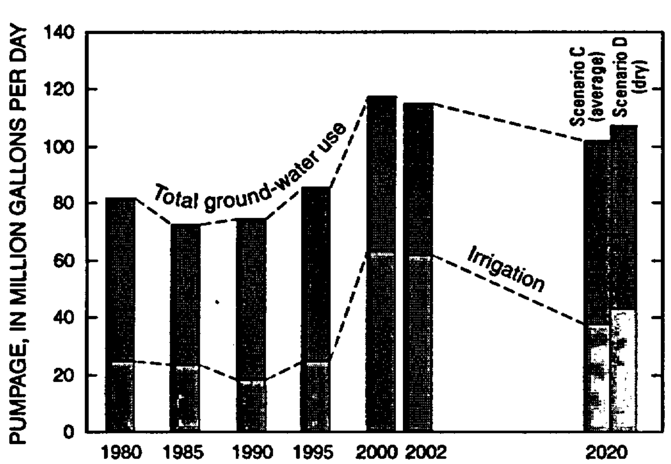


Figure 34. Total ground-water withdrawals including irrigation (1980–2002), and projected pumpage including irrigation (Scenarios C and D) during 2020 for the eight-county study area (see table 1 for county totals from 1990 to 2000 and data sources; table 10 for county totals from 2002 and projections to 2020).

Comparison of Scenarios

The most influential factors controlling particle movement are vertical and lateral head gradients and pumping distribution within the active layers of the model. The specified heads in the source-sink layer A1 control the vertical movement of water entering the ground-water system as recharge and influence the lateral head gradient from contaminant source areas to discharge areas along creeks and rivers. In three of four ground-water management scenarios (Scenarios A, B, and C), the specified heads in the source-sink layer A1 and along lateral boundaries (layers A2–A7) of the model were averaged between long-term average (1987–92) and dry (2002) hydrologic conditions. In the remaining pumping scenario (Scenario D), specified heads in the source-sink layer A1 and along lateral boundaries (layers A2–A7) of the model were adjusted to represent dry hydrologic conditions similar to 2002. Results and discussion of each of the scenarios is presented in Appendixes A–D. A comparison of budget terms of the steady-state simulations for each model layers is included in table 11.

In zone 1, median time-of-travel from recharge areas to discharge areas along Upper Three Runs Creek and west of the SRS boundary ranges from 217 to 264 yr for all simulations (table 6). Pumpage in the A/M Area of SRS has the most influence on particle movement and depth of penetration for this area of the model. Ground-water withdrawals from this area were 3.3 Mgal/d during 2002 (R.A. Hiergesell, Westinghouse Savannah River Company, written commun., 2002). This pumping rate was used for Scenarios A, C, and D. For the period from 1987 to 1992, the pumping rate was slightly less at 2.6 Mgal/d (Clarke and West, 1998). Most of this production is from the Dublin and Midville aquifer systems (model layers A4–A7). Scenario B was developed for measuring the effects of pumping in the event of the closure of the SRS and pumping rates declining to zero. In general, eliminating pumping in the A/M Area reduces the depth of penetration of particles and shortens the pathways to discharge areas. The median time-of-travel for Scenario B in zone 1 is 217 yr compared with 228 yr for Scenario A (table 6). The second most influential factor controlling particle movement is the adjustment of heads in the source-sink layer A1, which affects the amount of recharge entering the system and flow though each of the confining units. In the SRS, the variability in recharge entering the ground-water system through the source-sink layer A1 is 1.4 Mgal/d between wet (1987–92) and dry (2002 and Scenario D) hydrologic conditions. The reduction in flow through each of the confining units lowers the simulated heads in each of the active layers of the model (layers A2–A7), which reduces the horizontal gradient toward discharge areas.

In general, median time-of-travel for both simulations of dry conditions (2002 and Scenario D) were longer at 231 and 234 yr, respectively. Overall, the mean time-of-travel is similar for simulations with active SRS pumping (2002, Scenarios A, C, and D; table 6) with a reduction of about 50 yr when pumping is eliminated (Scenario B). All particles originating in zone 1 eventually migrate to discharge areas along the floodplain of the Savannah River west of the SRS boundary or to the south along Upper Three Runs Creek. Although downward movement of particles generally extends into the Dublin and Midville aquifer systems, migration is upward to discharge areas in the Gordon aquifer (layer A2).

In zone 2, median time-of-travel from recharge areas to discharge areas along Upper Three Runs Creek, Pen Branch, Fourmile Branch, and the Savannah River ranges from 524 to 593 yr (table 6). In general, particles migrate downward with depth of penetration into the Dublin aquifer system before migrating laterally toward discharge areas. General particle movement is initially lateral for short distances, and then movement is upward toward discharge areas within the Gordon aquifer (layer A2), or as return flow to the source-sink layer A1. The model is most sensitive to pumpage with 1.3 Mgal/d withdrawn during 2002 (R.A. Hiergesell, Westinghouse Savannah River Company, written commun., 2002) where the pumping rate was held constant for Scenarios A, C, and D with most of the production from the Midville aquifer system (layers A6–A7). Scenario B was developed to simulate the effects of pumping in the event of the SRS closure with pumping eliminated. For the period from 1987 to 1992, the pumping rate was 3.7 Mgal/d higher in zone 2 than during 2002 (Clarke and West, 1998). The median time-of-travel for Scenario B (SRS shutdown) of 524 yr is less than the value for Scenario A (561 yr), which indicates the depth of penetration for particles is reduced and lateral movement toward discharge areas is predominant. The variability in recharge entering the ground-water system though the source-sink layer A1 in zone 2 is about 1.0 Mgal/d between long-term average (1987–92) and dry (2002 and Scenario D) hydrologic conditions. The reduction in flow though each of the confining units lowers the simulated heads in each of the active layers of the model (layers A2–A7), which reduces the horizontal gradient toward discharge areas. An example of this is the median time-of-travel of 543 yr for the 1987–92 simulation, which is less than each of the median values for the other simulations (2002, Scenarios A, C, and D; table 6) owing steeper lateral head gradients in the active layers of the model. The earliest arrival times to trans-river areas located on the Georgia side of the Savannah River is 120 yr for particles originating in recharge areas located about 1 mi southeast of D Area. Particle movement is dominated by lateral migration through the Gordon aquifer (layer A2) toward the Savannah River. From the State line, these particles migrate farther to the west and eventually discharge to the adjacent cell (row 81, column 47; fig. 33) located near Flowery Gap Landing, which is a river cell simulating the contact between the Gordon aquifer (layer A2) and the alluvial floodplain of the Savannah River. The time-of-travel for this short distance ranges from 240 to 260 yr, which gives an indication of the relatively flat head gradients near the discharge area. In extreme cases, the time-of-travel in this same zone can range from 2,000 to 3,000 yr. This cell (row 81, column 47; fig. 33) represents the farthest westward potential movement of particles and is not influenced by any local pumping. The closest pumping center on the Georgia side of the Savannah River is located 3 mi south at the Vogtle Electric Generating Plant in Burke County. Of the 1,148 particles released in zone 2 (table 6) using the forward-tracking mode, 6 percent (69 particles) migrate toward trans-river zones located on the Georgia side of the Savannah River.

Areas of trans-river flow were evaluated further using MODPATH in backtracking mode as a comparison to forward-tracking mode from zone 2 in the SRS. Although other areas of trans-river flow exist according to model simulations (Clarke and West, 1998), the focus of this evaluation is on potential migration of contaminants from the SRS to the Georgia side of the Savannah River.

For the backtracking of particles, three model cells located near Flowery Gap Landing (covering about 1 mi^2) on the Georgia side of the Savannah River were chosen based on results from the previous model (Clarke and West, 1998, p. 89). Also, particle tracking results from zone 2 (forward-tracking mode) indicate that the area west of the Savannah River on the Georgia side (trans-river zone) is a common point of ground-water discharge. The results indicate that simulations with active SRS pumping centers (1987–92, 2002, Scenarios A, C, and D) moved fewer particles to the Georgia side of the Savannah River and ranged from 88 to 93 particles (table 7). If these SRS production wells are deactivated (Scenario B), the number of particles migrating to trans-river zones increases to 110 and the median time-of-travel decreases to about 370 yr (table 7).

Table 11. Water budgets for 1987–92, 2002, and Scenarios A–D, Savannah River Site, South Carolina.

[A with number, aquifer; C with number, confining unit]

Aquifer	Model layer	Simulated flows inflow or outflow	[1]1987–92	2002	Scenario A	Scenario B	Scenario C	Scenario D
			Wet	Dry	Average	Average	Average	Dry
			Million gallons per day					
Upper Three Runs	[2]A1	Inflows:						
		Across source-sink layer[3]	788.6	776.7	783.1	781.0	778.9	773.2
		Layer A2 to A1 through C1	500.8	515.2	502.8	503.2	506.4	518.3
		Total—Layer A1 inflows	**1,289.5**	**1,291.8**	**1,285.9**	**1,284.2**	**1,285.3**	**1,291.5**
	[2]A1	Outflows:						
		Across source-sink layer[4]	500.8	515.2	502.8	503.2	506.4	518.3
		Layer A1 to A2 through C1	788.6	776.7	783.1	781.0	778.9	773.2
		Total—Layer A1 outflows	**1,289.5**	**1,291.8**	**1,285.9**	**1,284.2**	**1,285.3**	**1,291.5**
Gordon	A2	Inflows:						
		Across lateral boundaries	5.1	2.8	3.6	3.6	3.6	2.8
		Recharge (aquifer outcrop areas)	52.8	52.8	52.8	52.8	52.8	52.8
		Layer A1 to A2 through C1	788.6	776.7	783.1	781.0	778.9	773.2
		Layer A3 to A2 through C2	317.4	312.6	312.9	315.1	315.5	314.8
		Total—Layer A2 inflows	**1,164.0**	**1,144.9**	**1,152.5**	**1,152.5**	**1,150.8**	**1,143.8**
	A2	Outflows:						
		Across lateral boundaries	2.8	4.7	3.4	3.4	3.4	4.7
		Active wells	9.9	10.7	10.7	10.7	8.0	8.8
		Streams (ground-water discharge)	224.0	200.6	212.0	213.9	212.9	201.3
		Layer A2 to A1 through C1	500.8	515.2	502.8	503.2	506.4	518.3
		Layer A2 to A3 through C2	426.4	413.8	423.6	421.5	420.2	410.8
		Total—Layer A2 outflows	**1,164.0**	**1,144.9**	**1,152.5**	**1,152.6**	**1,150.8**	**1,143.8**
Millers Pond	A3	Inflows:						
		Across lateral boundaries	2.9	2.0	2.5	2.5	2.5	2.0
		Layer A2 to A3 through C2	426.4	413.8	423.6	421.5	420.2	410.8
		Layer A4 to A3 through C3	297.8	293.2	293.8	296.1	296.2	295.4
		Total—Layer A3 inflows	**727.0**	**709.1**	**720.0**	**720.0**	**718.8**	**708.3**
	A3	Outflows:						
		Across lateral boundaries	0.7	1.6	1.1	1.1	1.1	1.6
		Active wells	2.1	7.3	7.3	7.3	4.4	5.0
		Streams (ground-water discharge)	8.2	7.8	8.0	8.1	8.1	7.9
		Layer A3 to A2 through C2	317.4	312.6	312.9	315.1	315.5	314.8
		Layer A3 to A4 through C3	398.6	379.8	390.6	388.4	389.7	379.0
		Total—Layer A3 outflows	**727.1**	**709.1**	**720.0**	**720.0**	**718.8**	**708.3**
Upper Dublin	A4	Inflows:						
		Across lateral boundaries	3.8	2.8	3.5	3.5	2.8	2.2
		Recharge (aquifer outcrop areas)	11.5	11.5	11.5	11.5	11.5	11.5
		Layer A3 to A4 through C3	398.6	379.8	390.6	388.4	389.7	379.0
		Layer A5 to A4 through C4	290.2	286.3	287.1	289.5	288.6	287.7
		Total—Layer A4 inflows	**704.1**	**680.5**	**692.7**	**693.0**	**692.6**	**680.4**
	A4	Outflows:						
		Across lateral boundaries	2.2	3.4	2.6	2.6	2.8	3.7
		Active wells	3.8	5.4	5.4	5.2	3.9	4.1
		Streams (ground-water discharge)	46.5	43.5	44.7	45.0	45.0	43.8
		Layer A4 to A3 through C3	297.8	293.2	293.8	296.1	296.2	295.4
		Layer A4 to A5 through C4	353.8	335.0	346.3	344.1	344.8	333.4
		Total—Layer A4 outflows	**704.1**	**680.5**	**692.8**	**693.0**	**692.7**	**680.4**

Table 11. Water budgets for 1987–92, 2002, and Scenarios A–D, Savannah River Site, South Carolina.—Continued

[A with number, aquifer; C with number, confining unit]

Aquifer	Model layer	Simulated flows inflow or outflow	[1]1987–92	2002	Scenario A	Scenario B	Scenario C	Scenario D
			Boundary condition					
			Wet	Dry	Average	Average	Average	Dry
			Million gallons per day					
Lower Dublin	A5	Inflows:						
		Across lateral boundaries	5.0	6.2	6.2	6.1	4.9	4.9
		Recharge (aquifer outcrop areas)	45.4	45.4	45.4	45.4	45.4	45.4
		Layer A4 to A5 through C4	353.8	335	346.3	344.1	344.8	333.4
		Layer A6 to A5 through C5	219.1	217.2	217.5	219.4	218.4	217.9
		Total—Layer A5 inflows	**623.4**	**603.8**	**615.3**	**615.1**	**613.5**	**601.6**
	A5	Outflows:						
		Across lateral boundaries	4.4	4.3	4.2	4.3	4.5	4.7
		Active wells	9.5	14.6	14.6	12.6	12.3	11.7
		Streams (ground-water discharge)	86.6	79.2	82.5	82.6	82.6	79.2
		Layer A5 to A4 through C4	290.2	286.3	287.1	289.5	288.6	287.7
		Layer A5 to A6 through C5	232.8	219.4	226.9	226.1	225.7	218.4
		Total—Layer A5 outflows	**623.5**	**603.9**	**615.4**	**615.2**	**613.6**	**601.7**
Upper Midville	A6	Inflows:						
		Across lateral boundaries	23.4	26.2	24.4	24.4	24.4	26.2
		Streams (ground-water recharge)	0.3	0.3	0.2	0.2	0.2	0.3
		Recharge (aquifer outcrop areas)	26.6	26.6	26.6	26.6	26.6	26.6
		Layer A5 to A6 through C5	232.8	219.4	226.9	226.1	225.7	218.4
		Layer A7 to A6 through C6	193.4	190.3	191.6	192.4	192	190.7
		Total—Layer A6 inflows	476.6	462.8	469.8	469.8	468.9	462.2
	A6	Outflows:						
		Across lateral boundaries	11.5	9.0	9.8	9.9	9.8	9.1
		Active wells	6.6	9.8	9.8	8.2	7.6	8.1
		Streams (ground-water discharge)	53.3	49.0	51.4	51.4	51.5	49.2
		Layer A6 to A5 through C5	219.1	217.2	217.5	219.4	218.4	217.9
		Layer A6 to A7 through C6	186.3	177.9	181.6	181.2	181.8	178.3
		Total—Layer A6 outflows	**476.8**	**463**	**470.1**	**470.1**	**469.2**	**462.4**
Lower Midville	A7	Inflows:						
		Across lateral boundaries	63.5	65.1	63.6	63.5	63.6	65.1
		Streams (gound-water recharge)	0.2	0.7	0.2	0.2	0.3	0.8
		Recharge (aquifer outcrop areas)	16.5	16.5	16.5	16.5	16.5	16.5
		Layer A6 to A7 through C6	186.3	177.9	181.6	181.2	181.8	178.3
		Total—Layer A7 inflows	**266.4**	**260.1**	**261.9**	**261.3**	**262.2**	**260.7**
	A7	Outflows:						
		Across lateral boundaries	10.6	12.8	11.4	11.5	11.4	12.9
		Active wells	20.8	19.4	19.4	17.9	19.2	19.3
		Streams (ground-water discharge)	42.1	38.1	39.9	39.9	40.1	38.3
		Layer A7 to A6 through C6	193.4	190.3	191.6	192.4	192	190.7
		Total—Layer A7 outflows	**266.8**	**260.5**	**262.3**	**261.7**	**262.6**	**261.1**

[1]Clarke and West (1998).

[2]Inactive, source-sink layer.

[3]Simulated recharge derived from vertical leakage from specified head cells in source/sink layer into underlying units.

[4]Simulated discharge derived from vertical leakage from underlying units into specified head cells in source/sink layer.

Limitations of Digital Simulation and Particle Tracking

The digital ground-water flow model developed for the study area is subject to uncertainties inherent in ground-water models, such as small number of control sites for hydraulic properties and placement of vertical and lateral boundaries. The objective was to develop a model that can respond to applied hydrologic changes and simulate movement of ground water through a seven-layer aquifer system near the Savannah River Site on a regional scale. The model achieves the original objectives, but is limited by simplification of the hydrogeologic framework, and obtaining sufficient measurements to define properly a complex system can be difficult. Some of the model boundaries are not coincident with natural boundaries and are placed at sufficient distance to limit their effect on the area of interest. Also, distribution of the pumpage for each active production well was based on well depth, and divided equally between the aquifers penetrated. Analysis of individual wells using a flowmeter generally indicates that most of the production is from discrete zones. The relative importance of hydraulic properties and boundary conditions on the calibrated model results are presented in the section "Sensitivity Analysis" (Clarke and West, 1998). Steady-state simulations were deemed satisfactory because of minor observed seasonal fluctuations in each of the aquifers, which are generally less than 4 ft (Clarke and West, 1997).

The model was designed with a finer grid resolution near the SRS to allow a more accurate representation of localized ground-water flowpaths and to simulate steep aquifer gradients near outcrop areas. Lateral discretization of the model into a variably spaced grid required an averaging of hydraulic properties such as specified heads in the source-sink layer A1 for each model cell and along lateral boundaries in the active layers of the model (layers A2–A7). In outlying areas near the model boundaries, increased cell dimensions forced greater generalization of field conditions.

Representation of flow in the uppermost layer A1, the Upper Three Runs aquifer, was simulated as a source-sink inactive layer. Assigned heads in this layer were often averaged between long-term average (1987–92) and dry conditions (2002), and, in certain cases, the model could not simulate the lateral observed variation despite grid refinement. In addition, the Upper Three Runs aquifer may consist of at least two aquifers (Flach and others, 1998, 1999a, b, and c), which would require discretization into several active model layers. The focus of this study, however, was on a regional scale and ground-water flow within the confined aquifers, which are the active layers of the model (layers A2–A7). The Upper Three Runs aquifer (layer A1) was simulated using specified heads to allow water to enter the ground-water system as recharge or exit as localized flow to streams.

The three-dimensional distribution of head is, in turn, a major control on the configuration of flowpaths in the ground-water system (Franke and others, 1998). The lateral and vertical head gradients, along with the hydraulic properties of the aquifers and confining units, influence the direction and flow rate through a ground-water system. Additional controls affecting the movement of ground water are pumping centers and assigned effective porosity in the aquifers and confining units. In the SRS area, data on the vertical hydraulic conductivity of aquifers, streambeds, and confining units are sparse.

An additional limitation of particle tracking using MODPATH is its inability to determine whether a particle of water exits the system in a 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. Further grid refinement near selected wells is one possible solution, but is considered impractical given the number of production wells in the study area.

MODPATH results presented herein do not allow for weak sinks, and, thus, are indicative of the worst-case scenario for trans-river flow—that which allows water to travel from one side of the river to another without being intercepted by wells that are weak sinks. Also, MODPATH simulates advective transport and does not account for any adsorption or diffusion in the ground-water flowpaths, which also provides a worst-case scenario.

Summary and Conclusions

This report documents the use of an existing U.S. Geological Survey (USGS) digital ground-water flow model to evaluate potential flowpaths from the Savannah River Site (SRS). The U.S. Department of Energy (DOE), SRS facility has manufactured nuclear materials for national defense purposes since the early 1950s. A variety of hazardous materials including tritium, other radionuclides, volatile organic compounds, and trace metals are either disposed of or stored at many locations on the SRS. State of Georgia officials have raised concern about the possible migration of tritiated water from the SRS into the underlying aquifers and beneath the Savannah River (trans-river flow) into Georgia. The model was used to document (1) changes in hydrologic and pumping conditions that have occurred since the calibration of the earlier (1987–92) USGS ground-water model, (2) ground-water flowpaths and particle tracking during previous (1987–92) and 2002 hydrologic conditions, and (3) comparison of results from previous simulations (1987–92, 2002) and from four hypothetical pumping scenarios during 2002 and 2020.

In the earlier 1987–92 simulation, total ground-water use was about 80 million gallons per day (Mgal/d) in the eight-county area. By 1995, the total ground-water use was about 85.4 Mgal/d and increased to 117 Mgal/d by 2000. The major increase in documented ground-water use between 1995 and 2000 is for Burke, Jefferson, and Screven Counties, Ga.; and Allendale and Barnwell Counties, S.C. In these counties, ground-water use for irrigation increased from 16.7 Mgal/d during 1995 to 53.1 Mgal/d during 2000, and irrigated acreage increased by 36,000 acres during the same period. Ground-water use for public supply increased from 24.4 Mgal/d during 1990 to 31.0 Mgal/d during 2000, with Burke and Richmond Counties, Ga., and Aiken County, S.C., accounting for most of the increase during the 10-year period. Ground-water use for industrial and mining purposes decreased from 22.1 Mgal/d during 1990 to 17.6 Mgal/d during 2000, primarily because of the decrease in ground-water use at the SRS from 9.0 Mgal/d during 1990 to 5.3 Mgal/d during 2002.

During 1992–2002, water levels in each of the major aquifers generally declined because of below-normal precipitation and increased ground-water use. Declines, based on periodic water-level measurements, in the Upper Three Runs aquifer ranged from 2 to 5 feet (ft) in northeastern Burke County, Ga., and were greater than 20 ft in southern Burke and Screven Counties, Ga. Water-level declines at Brighams Landing, Ga., were most pronounced in the Gordon aquifer (16 ft) as a result of ground-water use for irrigation with smaller declines in the deeper Dublin and Midville aquifer systems (7 and 5 ft, respectively).

During the previous study, the flow system was modeled using a quasi-three-dimensional approach with seven layers—six active layers and an overlying source-sink layer—that are separated to varying degrees by six confining units. The model grid area encompasses about 4,455 square miles (mi^2), of which about 3,250 mi^2 is actively simulated. Boundary conditions adjusted during the 1987–92 calibration process consisted of specified-head values in the source-sink layer A1 and specified-head values along lateral boundaries in active layers A2–A7.

To provide data for model calibration and to determine if boundary conditions have changed since 1992, water-level data were collected from 189 wells and potentiometric-surface maps were constructed for each of the major aquifers. The potentiometric-surface maps served as the basis for adjustments to boundary conditions and were used to determine that recalibration of the previous model was unnecessary; however, the previous model was updated to a newer version of the USGS finite-difference code (MODFLOW–2000). Adjustments to heads in the source-sink layer (layer A1, Upper Three Runs aquifer) of the model and specified heads along lateral boundaries in the active layers A2–A7 were made to match closely the constructed potentiometric-surface maps. The root mean square (RSM) of the residuals for all layers decreased from 10.6 ft during 1987–92 to 8.0 ft during 2002, which is an indication that the model is representative of 2002 dry conditions. Simulated ground-water outflows to the Savannah River and its tributaries during 2002 was 560 cubic feet per second, or 87 percent of the observed gain in mean-annual streamflow between the Millhaven and Augusta streamflow gaging stations for water year 2002.

The simulated water budget for 2002 conditions was 1,035 Mgal/d compared with 1,040 Mgal/d during the 1987–92 simulation. Lowering the heads in the source-sink layer A1 to match the potentiometric-surface map of the Upper Three Runs aquifer for 2002 reduced the simulated recharge to the Gordon aquifer (A2) from 789 Mgal/d (1987–92) to 777 Mgal/d (2002). Recharge applied to the outcrop areas of the hydrogeologic units remained constant for the 2002 simulation at 153 Mgal/d, which represents 16.4 percent of the total 930-Mgal/d simulated recharge to the ground-water system. Simulated ground-water withdrawal for 2002 increased by 14.5 Mgal/d from the 1987–92 model. The remaining 22-Mgal/d increase in ground-water use either was outside the simulated area (Screven and Jefferson Counties, Ga.) or was included in the source-sink layer A1, which was not actively simulated for the Upper Three Runs aquifer. The combination of reduced inflow to the source-sink layer A1 and simulated increase in pumpage reduced the simulated ground-water discharge to streams by about 24 Mgal/d.

The USGS particle-tracking code MODPATH was used in backtracking mode to seed areas of document trans-river flow, near Flowery Gap Landing along the Savannah River, in a 1-mi^2 marshy area located in Burke County, Ga. To improve definition of flowpaths and corresponding recharge areas for each simulation, a greater number of particles were applied to each model cell for the updated model compared to the 1987–92 model. Also, the MODPATH code was used in forward-tracking mode to evaluate flowpaths from areas of contamination on the SRS. Five particle seed zones were established in which individual particles were observed from their point of recharge to discharge areas located along stream segments. For each zone, four particles were placed in individual cells at the base of the source-sink layer A1 (Upper Three Runs aquifer)/top of the Gordon confining unit (C1) before initiating forward movement. The model is not capable of calculating vertical travel times through the source-sink layer A1 (Upper Three Runs aquifer); however, modeling results using a finite-element code encompassing C Area and K Area on the SRS indicate travel times downward within the Upper Three Runs aquifer of several decades. In backtracking mode, travel times are computed to the base of the source-sink layer A1 (Upper Three Runs aquifer), which does not include travel times within the uppermost aquifer. The Gordon confining unit (C1) is generally from 20 to 30 ft thick between D Area and K Area and time-of-travel from the base of the Upper Three Runs aquifer (source-sink layer A1) into the Gordon aquifer (layer A2) is about 10 years (yr).

The results from the MODPATH forward-tracking analysis indicate that Upper Three Runs Creek and the alluvial valley of the Savannah River are the dominant sinks or areas of ground-water discharge with time-of-travel ranging from 20 yr to greater than 2,000 yr. Generally, time-of-travel for particles migrating downward through the Gordon confining unit (C1) and then moving laterally through layer A2 (Gordon aquifer) to discharge areas ranges from 20 to 200 yr. For particles migrating deeper into layers A3 through A5 (Dublin aquifer system), time-of-travel generally ranges from 200 to 1,000 yr.

Four hypothetical ground-water management scenarios were developed to assess the effect of changing pumping and boundary conditions on ground-water flow and the potential migration of tritiated water from the SRS. These scenarios represent hydrologic conditions for: (A) 2002 observed pumping and boundary conditions for an average year; (B) 2002 observed pumping and boundary conditions for an average year with SRS pumping discontinued; (C) projected 2020 pumping and boundary conditions for an average year; and (D) projected 2020 pumping and boundary conditions for a dry year. In the 1987–92 and 2002 simulations, the assigned heads in the source-sink layer A1 were based on the constructed potentiometric-surface maps of the Upper Three Runs aquifer. In three of the four ground-water management scenarios (Scenarios A, B, and C), the specified heads in the source-sink layer A1 and along lateral boundaries (layers A2–A7) of the model were averaged between long-term average (1987–92) and dry (2002) hydrologic conditions. In the remaining ground-water management scenario (Scenario D), specified heads in the source-sink layer A1 and along lateral boundaries (A2 through A7) of the model were adjusted to represent dry hydrologic conditions similar to 2002.

Pumping projections in the SRS vicinity through 2020 (Scenarios C and D) were developed (1) for public supply and industry, based on water-management plans and population-growth projections; and (2) for irrigation based on an "average" quantity of water applied (gallons per acre per day) to the total irrigated acreage of 106,000. Population in the eight-county study area is expected to increase by 80,000 residents by the year 2020 with most of the growth centered around the Augusta, Ga., North Augusta, S.C., areas and the counties of Richmond, Ga., and Aiken, S.C. The analysis of water-use trends and population growth during the period of 1980–2000 were used to estimate ground-water use in the year 2020. The total projected increase in water demand for public supply (12 Mgal/d from 2002 to 2020) may be met through a combination of additional surface-water withdrawals from the Savannah River and increased ground-water withdrawals of 5 Mgal/d from the major aquifers. Pumping projections represent a redistribution of pumpage from irrigation wells in rural areas to production wells for public supply in areas of anticipated population growth.

The overall demand for ground water is projected to decrease from 115 Mgal/d during 2002 to 102 Mgal/d during 2020 given the severity of the drought during 2002 and reduced water requirements for irrigation during "average" hydrologic conditions. Because withdrawal rates for irrigation can be substantially higher during periods of drought, two projections were completed to the year 2020—one for average climatic conditions (Scenario C) and one for dry climatic conditions (Scenario D). Estimated values for 2020 were derived by multiplying the projected 106,000 acres of irrigated land by county application rates for average (1980–2000) and typical dry conditions. These estimates were adjusted using existing ratios of surface water (39 percent) to ground water (61 percent) irrigation pumpage to determine the percentage of irrigation usage from ground-water sources. Projected annual ground-water use for irrigation for average conditions during 2020 is 38 Mgal/d and for dry conditions is 43 Mgal/d. Both of these values represent a decrease from the estimated irrigation use of 63 Mgal/d during the drought of 2002. The severity of the 2002 drought was considered extreme, so the application rate for dry conditions was adjusted to represent a 60:40 ratio of average and dry conditions. This resulted in a lower calculated application rate of 662 gal/acre/day (Scenario D) compared with that of 960 gal/acre/day estimated during the drought year of 2000 and used in the 2002 simulation.

Simulated ground-water flowpaths for each of the four ground-water management scenarios were generally limited to areas within the SRS boundary because this is the area of concern for transport of tritium. Water that originated at the base of the Upper Three Runs aquifer (source-sink layer A1) generally discharged into the Gordon aquifer (layer A2) within the SRS boundaries. Common ground-water discharge areas include Upper Three Runs Creek (layer A2) and the alluvial valley of the Savannah River (source-sink layer A1 and layer A2). All calculated time-of-travel for particles does not include downward movement within the source-sink layer A1 (Upper Three Runs aquifer), which according to model simulations conducted by the SRS could take several decades. Five particle seed zones were established where individual particles were observed from their point of recharge to discharge areas located along local streams within the boundaries of the SRS or the Savannah River.

Appropriate ranges for median time-of-travel of particles from each of five zones are represented for all simulations, including 1987–92, 2002, and the four ground-water management scenarios (Scenarios A–D). In zone 1, median time-of-travel from recharge areas to discharge areas located along Upper Three Runs Creek and west of the SRS boundary ranges from 217 to 264 yr. In zone 2, median time-of-travel from recharge areas to discharge areas located along Upper Three Runs Creek, Pen Branch, Fourmile Branch, and the Savannah River ranges from 524 to 593 yr. In zone 3, median time-of-travel from recharge areas to discharge areas located along Upper Three Runs Creek ranges from 834 to 1,150 yr. In zone 4, median time-of-travel from recharge areas to discharge areas located along the South Carolina side of the Savannah River ranges from 395 to 404 yr. In zone 5, median time-of-travel from recharge areas to discharge areas located along Lower Three Runs Creek and the Savannah River ranges from 1,310 to 1,350 yr.

Ground-water movement and discharge for each of the four ground-water management scenarios outside the SRS boundary is limited to recharge areas from: (1) zone 1 moving toward Eagle Point located in Aiken County, S.C., at greater than 100-yr time-of-travel; (2) zone 2 moving near trans-river flow areas located in Georgia at greater than 200-yr time-of-travel; (3) zone 4 moving toward irrigation wells located in Allendale County, S.C., at greater than 200-yr time-of-travel; and (4) zone 5 moving toward Lower Three Runs Creek and the Savannah River located in Allendale County, S.C., at greater than 200-yr time-of-travel. Time-of-travel for each of the scenarios varies only slightly with the exception of Scenario B, which allows particles placed near deactivated wells on the SRS to migrate laterally to discharge areas with shorter travel times. When active, the SRS production wells screened in the Dublin and Midville aquifer systems (layers A3–A7) create a steep vertical gradient that permits particles to penetrate deeper into the lower layers of the model, thereby increasing the overall time-of-travel.

For the backtracking analysis of particles, three model cells located near Flowery Gap Landing (covering about 1 mi^2) on the Georgia side of the Savannah River were chosen based on results from forward-tracking analysis (zone 2), indicating these cells as common discharge areas. Of the 300 particles released in these three cells, as few as 88 particles (29 percent, 2002, Scenario C) to as many as 110 particles (37 percent, Scenario B) backtracked to recharge areas on the SRS (trans-river flow). Of the particles exhibiting trans-river flow, the median time-of-travel along pathlines ranged from 366 to 507 yr with primary recharge areas located between D Area and K Area. Backtrack time-of-travel for the shortest flow-paths ranged from 79 to 82 yr from trans-river flow to inter-stream areas located between D Area and K Area with 10 percent of these particles reaching endpoints at about 100 yr. The results indicate that simulations with active SRS pumping centers (1987–92, 2002, Scenarios A, C, and D) allowed fewer particles to migrate to the Georgia side of the Savannah River. If these SRS production wells are deactivated (Scenario B), the number of particles migrating to trans-river zones increases to 110 and the median time-of-travel decreases to about 370 yr with a shortest time-of-travel period of about 80 yr.

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