GROUND-WATER HYDROLOGY, HISTORICAL WATER USE, AND SIMULATED GROUND-WATER FLOW IN CRETACEOUS-AGE COASTAL PLAIN AQUIFERS NEAR CHARLESTON AND FLORENCE, SOUTH CAROLINA

By Bruce G. Campbell and Marijke van Heeswijk

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CONVERSION FACTORS, VERTICAL DATUM, AND ABBREVIATIONS

Multiply	By	To obtain
cubic foot per day (ft^3/d)	0.02832	cubic meter per day
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
cubic foot per second per mile [(ft^3/s)/mi]	0.01760	cubic meter per second per kilometer
foot (ft)	0.3048	meter
foot per day (ft/d)	0.3048	meter per day
foot per foot (ft/ft)	1	meter per meter
foot per year (ft/yr)	0.3048	meter per year
foot squared per day (ft^2/d)	0.09290	meter squared per day
gallon per minute (gal/min)	0.06309	liter per second
inch per year (in/yr)	2.54	millimeter per year
mile (mi)	1.609	kilometer
million gallons per day (Mgal/d)	0.04381	cubic meter per second
square mile (mi^2)	2.590	square kilometer

Abbreviated water-quality units used in this report:

milligrams per liter = mg/L

Sea Level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929--a geodetic datum derived from general adjustment of the first-order level nets of the United States and Canada, formerly called Sea Level Datum of 1929.

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.

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ABSTRACT

A quasi-three-dimensional, transient, digital, ground-water flow model representing the Coastal Plain aquifers of South Carolina, has been constructed to assist in defining the ground-water-flow system of Cretaceous aquifers near Charleston and Florence, S.C. Both cities are near the centers of large (greater than 150 feet) potentiometric declines in the Middendorf aquifer. In 1989, the diameter of the depressions was approximately 40 miles at Charleston and 15 miles at Florence. The potentiometric decline occurred between predevelopment (1926) and 1982 near Florence, and between predevelopment (1879) and 1989 near Charleston. The city of Charleston does not withdraw water from these aquifers; however, some of the small communities in the area use these aquifers for a potable water supply. The model simulates flow in and between four aquifer systems. The model has a variable-cell-size grid, and spans the Coastal Plain from the Savannah River in the southwest to the Cape Fear Arch in the northeast, and from the Fall Line in the northwest to approximately 30 miles offshore to the southeast. Model-grid cell size is 1 by 1 mile in a 48 by 48 mile area centered in Charleston, and in a 36 by 48 mile area centered in Florence. The model cell size gradually increases to a maximum of 4 by 4 miles outside the two study areas. The entire grid consists of 115 by 127 cells and covers an area of 39,936 square miles.

The model was calibrated to historical water-level data. The calibration relied on three techniques: (1) matching simulated and observed potentiometric map surfaces, (2) statistical comparison of observed and simulated heads, and (3) comparison of observed and simulated well hydrographs. Systematic changes in model parameters showed that simulated heads are most sensitive to changes in aquifer transmissivity.

Eight predictive ground-water-use scenarios were simulated for the Mount Pleasant area, which presently (1993) uses the Middendorf aquifer as a sole-source of potable water. These simulations use various combinations of spatial distribution, and injection of treated wastewater effluent for existing and future Middendorf aquifer wells.

INTRODUCTION

The Coastal Plain aquifer system in South Carolina is an important source of potable water in the state. The aquifer system consists of deltaic and marine sediments that were deposited from Cretaceous through Holocene times. The Coastal Plain sediments cover the southeastern two thirds of the state, and gradually thicken from the Fall Line to the Atlantic shoreline (figs. 1 and 2). The system can be divided into a series of aquifers and confining units, on the basis of the relative permeability of the sediments. One of these aquifers, the Middendorf aquifer, is an important source of potable water for the city of Florence and four towns in the Charleston area (fig. 3). Water levels in the Middendorf aquifer have declined substantially from predevelopment levels in the Charleston and Florence areas due to concentrated withdrawals for potable and industrial water supply. In 1989, water levels in the Middendorf aquifer were -10 ft below sea level (bsl) in the Charleston area and -42 ft bsl in the Florence area (fig. 4). Predevelopment water levels in these areas were 126 ft above sea level (asl) in Charleston and 105 ft asl at Florence (Aucott and Speiran, 1985b). Water-level declines of 136 ft occurred between predevelopment (1879) and 1989 in the Middendorf aquifer near Charleston, and 147 ft between predevelopment (1926) and 1982 near Florence. Ground-water withdrawals are expected to increase in the future as populations grow and development increases. An increased demand on already stressed aquifers could lower water levels further, unless the locations and withdrawal rates of new and existing wells are carefully planned.

To address the concerns of users of Middendorf aquifer water, the U.S. Geological Survey (USGS) in cooperation with S.C. Department of Natural Resources-Water Resources Division (SCDNR-WRD), initiated an investigation to compile existing water-resource information and incorporate the data into a ground-water flow model. Simulations of proposed industrial pumpage were completed by the USGS in cooperation with the Mount Pleasant Waterworks and Sewer Commission. The digital ground-water flow model presented in this report represents the Coastal Plain aquifer system. The model has four layers and a variable-size grid cell. Each model layer is discretized to 1- by 1-mile grid cells centered on the depressions near Charleston and Florence, with the cell size gradually increasing to 4 by 4 mi outside the areas of interest (fig. 5). The finer discretization in these areas allows greater resolution and the simulation of hypothetical withdrawal scenarios. A previous ground-water flow model was constructed for this area of South Carolina by Aucott (1988) as part of the USGS Regional Aquifer System Analysis program.

Purpose and Scope

The purposes of this report are: (1) to describe the hydrogeologic framework of the Cretaceous aquifers underlying the Charleston and Florence, South Carolina areas; (2) develop, calibrate, and apply a quasi-three-dimensional, finite-difference digital model to simulate ground-water flow within the Cretaceous aquifers; and (3) demonstrate model use by evaluating ground-water use scenarios for the Charleston area. Ground-water flow for the period 1879-1989 was simulated in three aquifers -- the Black Creek, the Middendorf, and the Cape Fear. Tertiary and younger aquifers were combined and simulated in a single specified head layer. The model area includes the entire Coastal Plain of South Carolina (fig. 5), but is designed to emphasize simulations in the Charleston and Florence areas.

Existing and new data collected for this study include water levels, water use, hydrologic properties, and well locations. These data are stored in and managed with the U.S. Geological Survey Ground-Water Site Inventory database. The SCDNR-WRD water-use database for 1982-89 was converted to model input for use in the ground-water flow model.

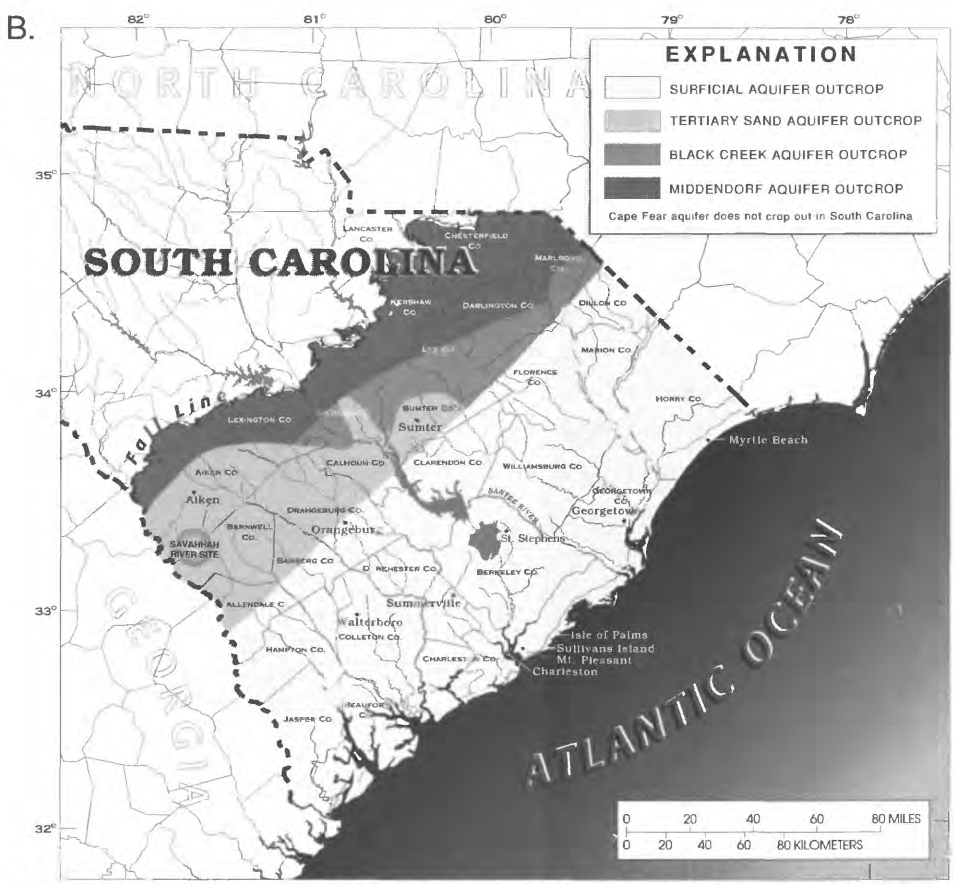


Figure 1. Location of the Pee Dee region of South Carolina, and geohydrologic sections (A), and generalized Coastal Plain aquifer outcrops in South Carolina (B) (Modified from Aucott, 1988).

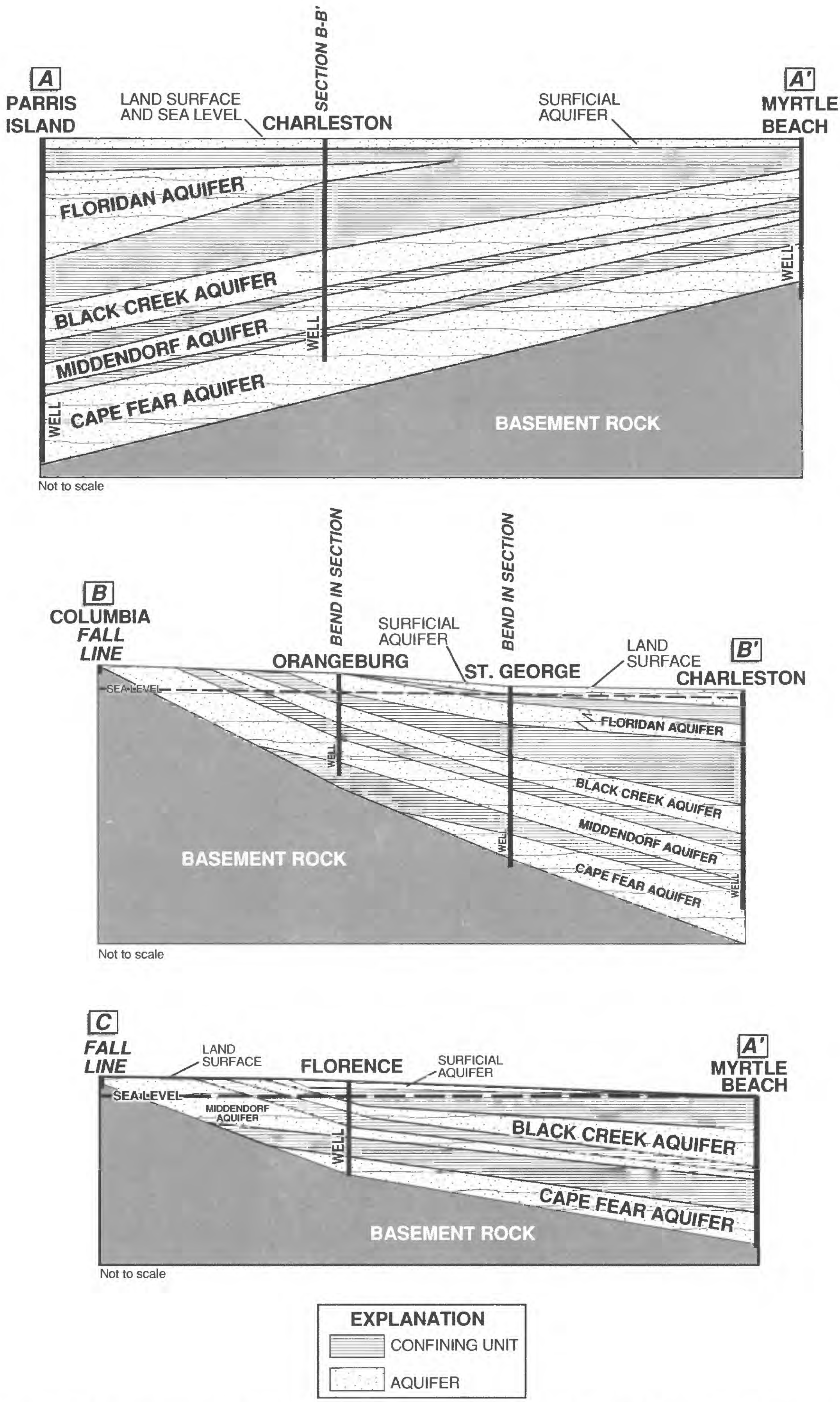


Figure 2. Generalized geohydrologic sections of the South Carolina Coastal Plain. Located in figure 1.

Figure 3. Location of the Florence and Charleston study areas of South Carolina

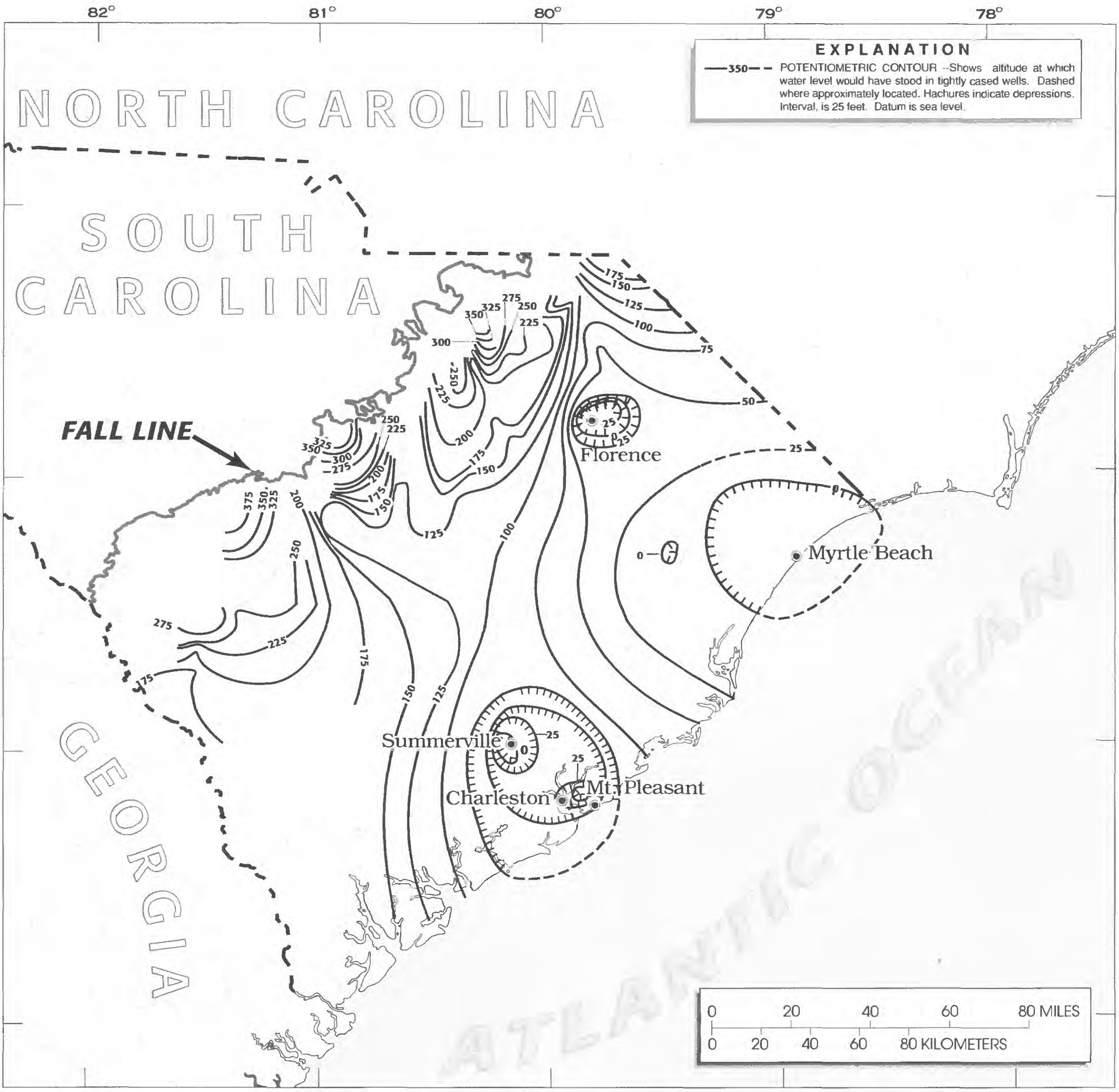


Figure 4. The potentiometric surface of the Middendorf aquifer near Florence and Charleston, S.C., November 1989 (modified from Stringfield and Campbell, 1989).

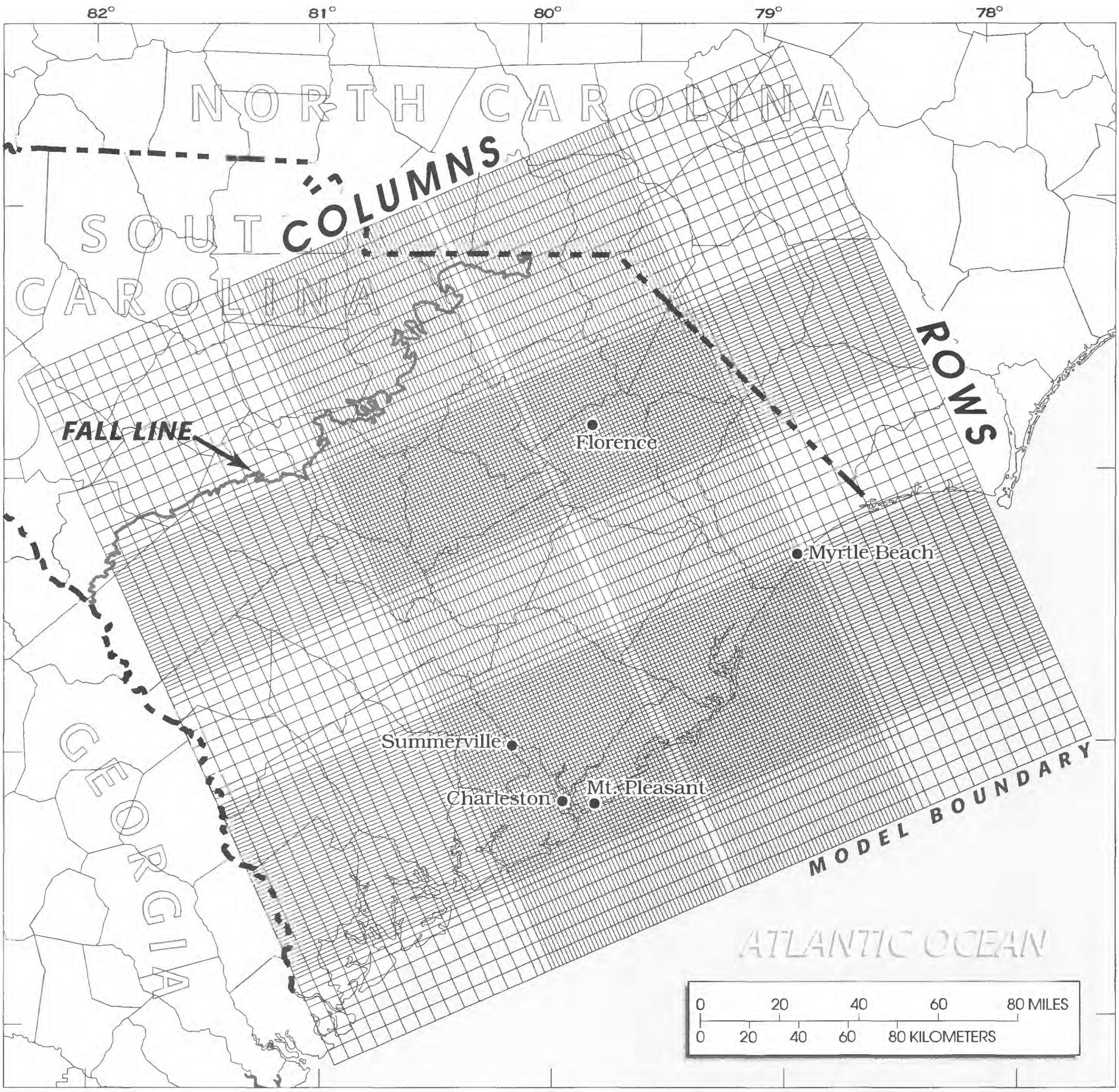


Figure 5. The model grid of the Charleston-Florence ground-water flow model.

Previous Investigations

The South Carolina Coastal Plain aquifer systems have previously been modeled as part of the Regional Aquifer System Analysis (RASA) Program of the U.S. Geological Survey (Sun, 1986). The South Carolina RASA (SCRASA) model simulates steady-state predevelopment and transient potentiometric surfaces for Coastal Plain aquifers (Aucott, in press). The model grid of the present study overlaps most of the SCRASA model with the exception of the southeastern part of Georgia, which is not modeled as part of the present study. The model-grid orientation of the present study coincides with the orientations of the SCRASA model.

Acknowledgments

The authors thank personnel of the Mount Pleasant Waterworks and Sewer Commission, especially Clay Duffie, Lee Bauldin, and Melvin Bennett, for assistance in collection of hydrologic and water-use data in the Mount Pleasant area. We also thank Charles Cuzzel and Joe Yoest, Summerville Commissioners of Public Works, for assistance in the collection of water-levels and water-use data in the Summerville area. We thank Becky Dennis, Kiawah Island Utilities, and Franklin Harrel, Heater Utilities, for assistance in the collection of water levels. Leo Truesdell, Sullivans Island Water and Sewer Department, provided hydrologic data and cuttings from a well in the Cretaceous aquifers. Bill Jenkins, formerly at Wild Dunes Utilities and now Isle of Palms Water and Sewer Commission, assisted in the collection of water levels. Harry Wilson and Pete Coplestone, Charleston Commissioners of Public Works, provided assistance in collecting hydrologic data from the century-old Cretaceous well network in Charleston. Alberto Rodriguez, formerly of the SCDNR-WRD, provided hydrologic data for the Pee Dee region and assistance in conceptualizing the aquifer system there. Drennan Park, SCDNR-WRD, provided hydrologic data for the Cretaceous aquifers in the Charleston area. Mike Mirabella, formerly with the city of Florence, provided water-use data for the city of Florence.

GROUND-WATER HYDROLOGY

The South Carolina Coastal Plain is part of the Southeastern Coastal Plain aquifer system and consists of a wedge-shaped sequence of deltaic and marine deposits that gradually thickens from the Fall Line to the present-day Atlantic coast (Miller, 1990) (fig. 1). The thickness of the sediments range from 1,000 to 4,500 ft northeast to southwest along the coast. These sediments were deposited on crystalline metamorphic rocks, flood basalts, or Triassic sedimentary and igneous rocks. The deltas were deposited during the Late Cretaceous age, as rivers carrying sediments from the Appalachian mountains flowed toward open water. In the southwestern part of South Carolina, Cretaceous sediments are overlain by sands of Tertiary age that grade into carbonate deposits toward the coast. The lower Coastal Plain is overlain by Quaternary and Holocene marine terraces and alluvial deposits.

The Southeastern Coastal Plain aquifer system is adjacent to four other regional aquifer systems: the Northern Atlantic Coastal Plain to the north, the Floridan to the south, the Mississippi Embayment to the southwest, and the Coastal Lowlands to the west (Miller, 1990). These aquifer systems, with the exception of the Floridan, consist primarily of clastic sediments and grade laterally into one another. The Floridan aquifer system is comprised of mostly carbonate sediments of Eocene age.

To distinguish separate aquifers in the Coastal Plain sediments, it is necessary to identify the areal and vertical distribution of multiple cycles of deltaic deposits. Upper delta plain deposits are high in sand content and, when well connected with similar units, can form significant aquifers. Lower delta plain and deep-water deposits primarily consist of clays, generally have low permeabilities, and function as confining beds. The distribution and thickness of these clays determines the extent to which water-bearing units are hydraulically connected. The water-bearing units of the South Carolina Coastal Plain can be divided into six major aquifers (Aucott, 1988). Listed from youngest to oldest, they are the surficial, Floridan, Tertiary Sand, Black Creek, Middendorf, and Cape Fear aquifers (fig. 2). Geohydrologic columns for the Cretaceous sediments underlying the Charleston and Florence areas were developed on the basis of work by Gohn (1992) and Curley (1990) (figs. 6 and 7), respectively. The Florence area stratigraphy was developed by Swift and Heron (1969) with the Black Creek, Middendorf, and part of the Cape Fear Formations corresponding directly to the respective aquifers.

In the Charleston area, Gohn (1992) developed a new stratigraphic column for the upper Cretaceous sediments, which includes a number of new formations (fig. 6). The Black Creek aquifer is composed of fine sands of the Donaho Creek, Bladen, Coachman, and upper part of the Cane Acre Formations. The lower part of the Cane Acre Formation and the Caddin Formation form a confining unit below the Black Creek aquifer. The Middendorf aquifer is composed of sand units within the Shepard Grove, Middendorf, and top of the Cape Fear Formations. A thick, sandy clay sequence in the upper part of the Cape Fear Formation forms a confining unit above the Cape Fear aquifer, which is made of sand units within the lower part of the Cape Fear Formation.

Surficial Aquifer System

The upper and lower Coastal Plain of South Carolina is overlain by sandy marine terrace and alluvial deposits that are approximately 50-ft thick along the Atlantic Coast, and gradually pinch out at the boundary of the upper and lower Coastal Plain (Doering, 1960). Ground water in this unit occurs under unconfined conditions, and the water table is about 10-20 ft below land surface. This aquifer system may be locally truncated by major riverbeds. The aquifer receives recharge from precipitation, which can leak vertically into lower aquifers or move horizontally into the nearest surface-water body. The surficial aquifer also functions as a sink for deeper aquifers in areas with an upward, vertical hydraulic gradient. Few reliable estimates of aquifer properties are available for the surficial aquifer system.

Tertiary Aquifer System

The Tertiary aquifer system is composed of clastic sediments of the Tertiary Sand aquifer and carbonate sediments of the Floridan aquifer. These units grade laterally into one another from northeast to southeast and form the most productive aquifer in the South Carolina Coastal Plain. No distinctive water-level or water-quality differences exist between the two units, so they are combined into one aquifer in the conceptual model (Aucott, 1988).

SYSTEM	SERIES	STAGE	CHN-635 (Figure 11) SULLIVANS ISLAND OBSERVATION WELL (depth in feet below land surface)		AQUIFER OR CONFINING UNIT	CHARACTER OF MATERIAL	THICKNESS (Feet)
Cretaceous	Upper	Maastrichtian	690 Peedee Formation		Black Creek Confining Unit	Silty clay to clayey silt	50
		Maastrichtian	760 Donoho Creek Formation	Black Creek Group	Black Creek Aquifer	Macrofossiliferous clayey, fine to medium sand.	610
		Campanian	910 Bladen Formation	Black Creek Group			
		Campanian	1,120 Coachman Formation	Black Creek Group			
		Campanian	1,260 Cane Acre Formation	Black Creek Group	Middendorf Confining Unit	Gray, calcareous, silty, sandy clay.	300
		Campanian	1,530 Caddin Formation				
		Santonian	1,680 Shepherd Grove Formation		Middendorf Aquifer	Macrofossiliferous medium to course sand; dark, lignitic clay interbeds.	340
		Santonian	1,805 Middendorf Formation				
		Coniacian? Turonian?	2,020 Cape Fear Formation		Cape Fear Confining Unit	Olive to gray silty clay.	180
		Coniacian? Turonian?			Cape Fear Aquifer	Well-sorted silty, fine to medium sand.	200
		Turonian	2,400 Clubhouse Formation		Confining Unit	Gray, calcacareous clay-silts and fine sands	150
		Ceno-maninan					

Not to scale

Figure 6. Hydrostratigraphic column of upper Cretaceous formations in the Charleston and Mount Pleasant areas of South Carolina (modified from Gohn, 1992).

SYSTEM	SERIES	GEOLOGIC UNIT	DESCRIPTION OF SEDIMENTS	AQUIFER
Quaterary	Holocene and Pleistocene	Surficial deposits	Light-colored medium to coarse grained sand, gravel, and lenses of varicolored clay and sandy clay; locally sandy limestone.	
Tertiary	Pliocene	Undif-ferentiated	Light-colored, fine to coarse grained sand, interbedded with dark, sandy calcareous marl; phosphate pebbles locally.	
		Duplin Formation	Light-gray, yellow, brown, and buff, fossilferrous, fine to course-grained sand; green and gray clay, marl and soft fossilferous limestone.	
Cretaceous	Upper Cretaceous	Peedee Formation	Gray, calcareous, fossilferous, clay; gray, glaucontic, calcareous, fine-to medium-grained muddy sand; and coquina.	Confining Unit
		Black Creek Formation	Olive-gray, fine to medium-grained glaucontic, lignitic, phosphatic, and micaceous sand. Dark olive-gray clay with laminae of very fine sand and silt. Occasional beds of sandstone. Traces of pyrite.	Black Creek Aquifer Confining Unit
		Middendorf Formation	Light to dark olive-gray, medium-grained, lignitic and micaceous sand with massive beds of dark yellowish-brown to dark olive-gray, dense, waxy clay. Clay is mottled in places. Traces of feldspar.	Middendorf Aquifer
		Cape Fear Formation	Cycles of light to medium yellowish-brown to greenish gray, medium-grained, feldsparthic sand grading to light yellowish-brown and olive-gray, highly mottled clay. Mottled colors include red, yellow, orange, and purple.	Confining Unit Cape Fear Aquifer
Triassic		Unnamed Triassic Rocks	Red to reddish-brown consolidated claystone, sandstone, shale, and conglomerate; occurs in narrow Triassic basin west southeast of city of Florence.	Confining Unit
Pre-Cretaceous		Unnamed crystalline rocks	Inferred as gneiss, schist, slate, granite, basalt, and diabase.	

Not to scale

Figure 7. Hydrostratigraphic column of the Pee Dee area of South Carolina (modified from Curley, 1990).

Tertiary Sand Aquifer System

The Tertiary Sand aquifer consists of deltaic sands, which were deposited in the southwestern part of the Coastal Plain in South Carolina on top of Cretaceous deposits. The aquifer is unconfined in the upper Coastal Plain and is confined in the lower Coastal Plain. The aquifer gradually merges downdip into its carbonate equivalent in the Floridan aquifer system. Transmissivities in the Tertiary Sand aquifer range from approximately 500 to 2,500 ft^2/d (Aucott and Newcome, 1986).

Floridan Aquifer System and Overlying Confining Unit

The presence of the Floridan aquifer system in South Carolina represents the northernmost extent of limestone deposits that occur from south Florida through Alabama, Georgia, and South Carolina (Miller, 1990). The Floridan aquifer system is one of the most productive aquifers in the United States. Its maximum thickness in South Carolina is approximately 700 ft at the intersection of the Georgia-South Carolina border and the Atlantic coast. Toward the northwest, the Floridan aquifer system gradually grades into the Tertiary Sand aquifer, and toward the northeast it gradually thins and outcrops along the lower Santee River. Transmissivities in the South Carolina part of the Floridan aquifer system range from approximately 750 to 50,000 ft^2/d (Aucott and Newcome, 1986). Transmissivities are greatest in the southeastern part of the state, where aquifer thicknesses are the greatest.

The Floridan aquifer system is confined above by low permeability, phosphatic clayey sand and phosphatic sandy clay of the Miocene Hawthorne Formation. This clay is discontinuous in many areas and allows high leakage rates between the Floridan and surficial aquifer systems (Hayes, 1979).

Cretaceous Aquifer System

The Cretaceous aquifer system is the most extensive and heavily used group of aquifers in the South Carolina Coastal Plain. This aquifer system provides water for a variety of uses across most of the Coastal Plain, including potable supply, industrial, and irrigation. Three separate aquifers (the Black Creek, Middendorf, and Cape Fear) of similar age and lithology combine to form the Cretaceous aquifer system.

The aquifer names are derived from the geologic formations of the same names; however, the aquifer units do not always coincide with formation names. Division by aquifer unit is on the basis of relative permeability. Higher permeability units in the top or bottom of the geologic units may combine to form an aquifer unit that crosses the geologic formation boundaries.

Black Creek Aquifer System and Overlying Confining Unit

The Black Creek aquifer is the uppermost regionally extensive Cretaceous-age aquifer. It is composed of sands of the Black Creek Group (fig. 6) and, locally, sands from the overlying Pee Dee Formation. The Pee Dee Formation, in most areas of its occurrence, functions as a regional confining unit because of its low-permeability, clay-rich sediments. The Black Creek aquifer lies stratigraphically below the surficial, Tertiary Sand, and Floridan aquifer systems and is formed by multiple cycles of superimposed deltaic deposits that consist of well sorted, unconsolidated sands interbedded with organic-rich clays. The Black Creek aquifer is unconfined in the updip area but is confined downdip (fig. 2). The Black Creek aquifer system gradually thickens from a feather-edge at the Fall Line to approximately 900 ft near the coast. This aquifer system is the major source of ground water in the Myrtle Beach, S.C., area.

Transmissivities in the Black Creek aquifer range from approximately 500 to 9,000 ft^2/d (Aucott and Newcome, 1986). The greatest transmissivities are present in the western part of the state, and gradually decrease toward the east and south. The decrease in transmissivity is most rapid toward the south. The decrease in transmissivity is the result of an increased presence of clays that represent lower delta-plain deposits. Few wells are screened in the Black Creek aquifer south of the Santee River in the lower Coastal Plain. Parallel to the Fall Line, along the updip extent of the Black Creek aquifer, transmissivities are lower because sand deposits are thinner than in the downdip area.

Overlying the Black Creek aquifer are low-permeability sediments of the Pee Dee Formation and other clayey Paleocene sediments. This unit separates the Black Creek aquifer system from the Floridan and Tertiary Sand aquifer systems, and is the most effective confining unit in the Coastal Plain. The flow systems and water quality of the Black Creek and Floridan and Tertiary aquifer systems differ to the greatest extent of any of the other adjacent Coastal Plain aquifer systems (Aucott and Sperian, 1985a).

Middendorf Aquifer System and Overlying Confining Unit

The Middendorf aquifer, in the Charleston area, is composed of Late Cretaceous-age sands of the Middendorf Formation and, locally, of sands of the overlying Shepard Grove Formation and the underlying Cape Fear Formation (Gohn, 1992) (fig. 6). In the Florence area, the Middendorf aquifer is composed of the Middendorf Formation only (Curley, 1990) (fig. 7). In outcrop, the Middendorf Formation is an interbedded-clay and white-sand sequence deposited in a delta plain to fluvial environment. In the downdip subsurface, the unit consist of well-sorted, coarse-grained sands, and interbedded, dark, lignitic clays deposited in a variety of marginal-marine environments such as delta plain or estuarine. It is overlain by the Black Creek aquifer, and underlain by the Cape Fear aquifer. The Middendorf aquifer extends from the Fall Line to the coast and is the most extensive aquifer in the South Carolina Coastal Plain. In the upper Coastal Plain, the aquifer is unconfined, but where the Black Creek aquifer is present, the Middendorf aquifer is confined. The maximum thickness of the aquifer is approximately 300 ft near the Atlantic coast. The Middendorf aquifer provides the main supply of ground-water to many upper Coastal Plain communities and to numerous communities in the lower Coastal Plain such as Florence, Sumter, Walterboro, Summerville, Mount Pleasant, and St. Stephens (fig. 3).

Transmissivities for the Middendorf aquifer range from approximately 500 to 14,000 ft^2/d (Aucott and Newcome, 1986). The transmissivity is highest in the western part of the state and gradually decreases toward the east and south. This distribution of transmissivity is probably the result of the depositional sequences of the delta systems. Parallel to the Fall Line, transmissivities are lower, because sand deposits along the updip extent of the Middendorf aquifer are thinner than in the downdip area.

In the Charleston area, the confining unit separating the Black Creek and Middendorf aquifers is formed by low permeability sediments of the lower silt-clay member of the Cane Acre Formation (Gohn, 1992) (fig. 6). The lithology is a medium to light gray, calcareous, silty, and sandy clay. In the Florence area, the confining unit consists of sandy clay in the lower part of the Black Creek Group.

Cape Fear Aquifer System and Overlying Confining Unit

The Cape Fear aquifer forms the lowermost aquifer for most of the Southeastern Coastal Plain aquifer system (Miller, 1990). The unit is thickest near the coast, and gradually thins and disappears in South Carolina toward the Fall Line. It consists of thick red clays with immature, poorly sorted quartz and feldspar rich sands. Thin bands of more mature, unconsolidated sands are present in the updip part of the aquifer. The sands in the updip part of the aquifer may represent meandering channel deposits. The extent of hydraulic connection between the updip sands and the extent of vertical leakage from the overlying aquifers into the Cape Fear aquifer is not known.

The downdip part of the Cape Fear Formation is described as alternating yellowish-gray, red, and brown non-calcareous clays and tan feldspathic sands (Gohn, 1992). Due to the abundance of low permeability clays, this aquifer is not of regional significance as a source of ground water. As a result, very few aquifer test results are available for the Cape Fear aquifer. Values reported by Aucott and Newcome (1986) suggest that the transmissivities range from 500 to 1,500 ft^2/d. The aquifer typically contains water of marginal drinking-water quality due to high concentrations of total dissolved solids.

The middle to upper part of the Cape Fear Formation, a grayish yellow to dusky yellow, massive, non-calcareous clay, is the confining unit separating the Middendorf and Cape Fear aquifer systems (Gohn, 1992). Large water-level and water-quality differences between the Middendorf and Cape Fear aquifers (Aucott, 1988) indicates that the upper part of the Cape Fear Formation is an effective confining unit between the two aquifers.

Conceptual Model of Regional Ground-Water Flow

Southeastern Coastal Plain aquifers in South Carolina are part of the much more extensive Atlantic Coastal Plain aquifer system. Generally, the regional flow in this system is parallel to the Atlantic coast, from the southwest to the northeast (fig. 8) (Aucott and Speiran, 1985a) except for the Floridan aquifer system, where flow is perpendicular to the coast (fig. 8). In South Carolina, superimposed on the regional flow direction is a component of flow from the updip area that moves downward into the deep-flow system. From the deep-flow system in the downdip area, ground water moves upward by vertical leakage to the shallow aquifers. Therefore, water discharges either to the Atlantic Ocean or the surficial aquifer. Water leaves the surficial aquifer as a result of evapotranspiration or discharge to surface-water bodies. Superimposed upon this natural discharge regime is artificial discharge caused by pumping. Since the early 20th Century, pumping has caused subregional changes in the flow pattern, and has altered the overall regional flowpaths.

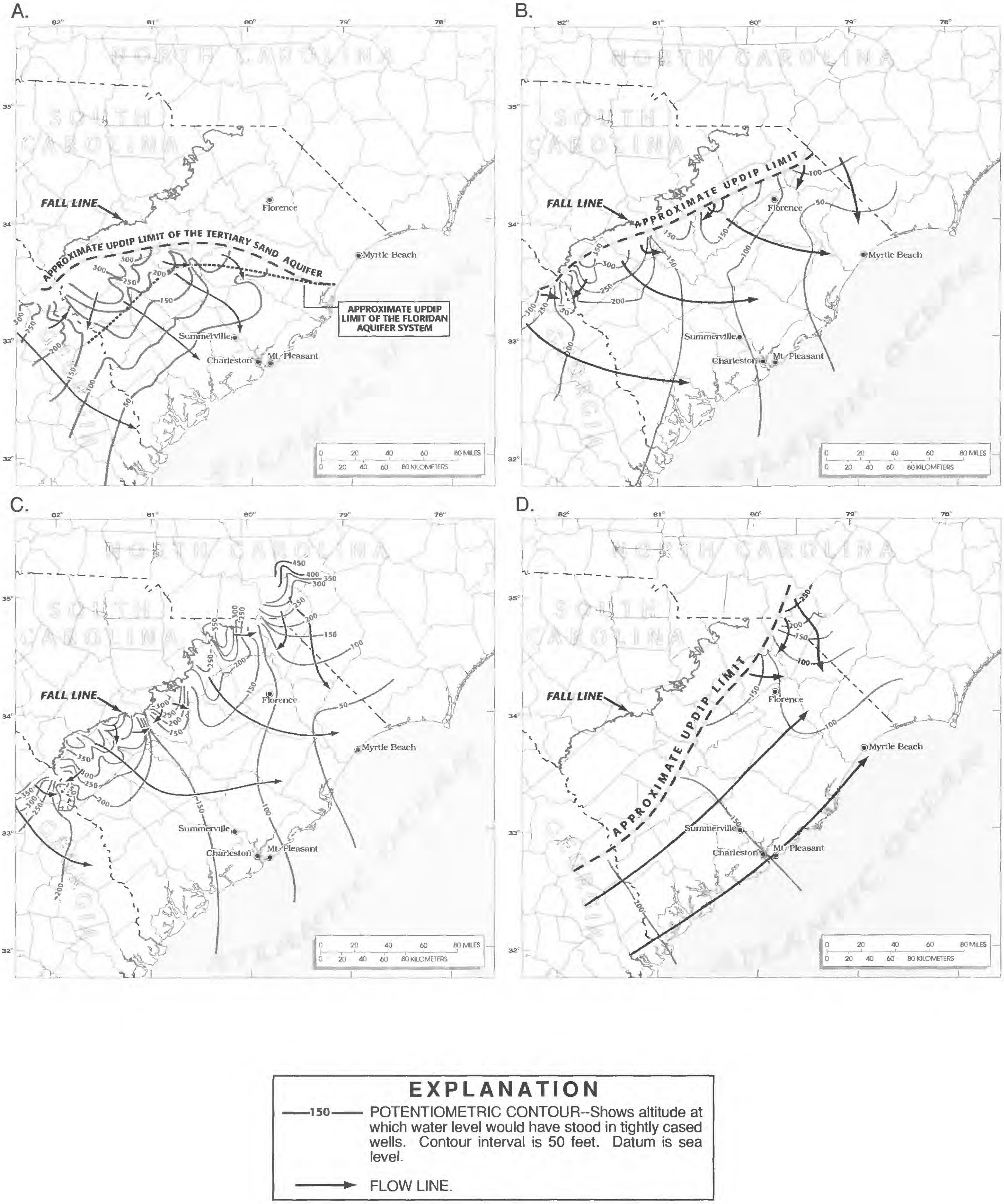


Figure 8. The potentiometric surface of the Floridan and the Tertiary Sand aquifer (A), the Black Creek aquifer (B), the Middendorf aquifer (C), and the Cape Fear aquifer (D) prior to development. (modified from Aucott and Sperian, 1985b).

In the updip part of the South Carolina Coastal Plain, precipitation that does not evaporate or become surface-water runoff recharges exposed aquifers. Aucott (1988) reported that most of this recharge is discharged to major rivers or transpired by vegetation, and that only a small part enters the deep, regional-flow system. Many different ground-water-flow directions are present in the updip area, because the flow direction is locally controlled by recharge, land surface deviation, and river interaction (fig. 8) (Aucott, 1988).

The updip outcrops of the Tertiary Sand, Black Creek, and Middendorf aquifers, and the entire surficial aquifer are unconfined. Downdip, the Tertiary Sand, Black Creek, and Middendorf aquifers are confined. The Floridan and Cape Fear aquifers are confined for their entire extent.

The Cretaceous aquifer system in the South Carolina Coastal Plain contains freshwater (water with less than 1,000 mg/L dissolved solids) to brackish water (water with less than 10,000 mg/L dissolved solids). The concentration of ions that contribute to an increase in dissolved solids along ground-water-flow paths in the downdip direction are a result of abiotic and biotic geochemical processes in the aquifers and adjacent confining units (McMahon and Chapelle, 1991). At some distance seaward from the South Carolina coast, chloride concentrations in the Coastal Plain aquifers reach brackish levels. Data are not available to determine how rapidly salinities increase in water offshore in the Black Creek, Middendorf, and Cape Fear aquifers. It is assumed in this study that chloride concentrations in these aquifers reach 10,000 mg/L approximately 30 mi off the coast (fig. 9). This estimate is based on offshore salinity information from Florida and North Carolina (Lee and others, 1986). According to Smith (1988), salinities in the Upper Floridan aquifer reach concentrations of brackish water close to the South Carolina shoreline near Parris Island.

HISTORICAL WATER USE

Historically, ground water from Coastal Plain aquifers has been an important source of potable water in South Carolina. However, the reconstruction of historical water use is a difficult task, because water-use data were usually not collected in the past. Even today (1996), only significant water users collect this information, and documented water-use data are often incomplete. Water-use data for major withdrawal centers, such as Charleston and Florence, have been collected since the early 1970's and 1980's, respectively.

As part of the SCRASA study, water use for all Coastal Plain aquifers was reconstructed from predevelopment through 1982 (Aucott, in press). This reconstruction relied heavily on water-use estimates based on population statistics and well construction dates. From 1982-89, the SCDNR-WRD water-use database was utilized to construct withdrawal data for the model. All available wells in the Coastal Plain (with the exception of Beaufort, Hampton, and Jasper Counties) were used in the model to distribute pumpage. There are no documented withdrawals from the Cretaceous aquifers in these three counties. The latitude and longitude of each well were used to position the well horizontally on the model grid, and the SCRASA cross sections (Aucott and others, 1987) were used to determine the layer assignments. Entries in this database were verified by field reconnaissance of wells in Florence, Marion, Marlboro, Dillon, and Darlington, and Dorchester, Charleston, and Berkeley counties (fig. 3). The field inventory added many wells to the database resulting in increased withdrawal estimates for the Cretaceous aquifers.

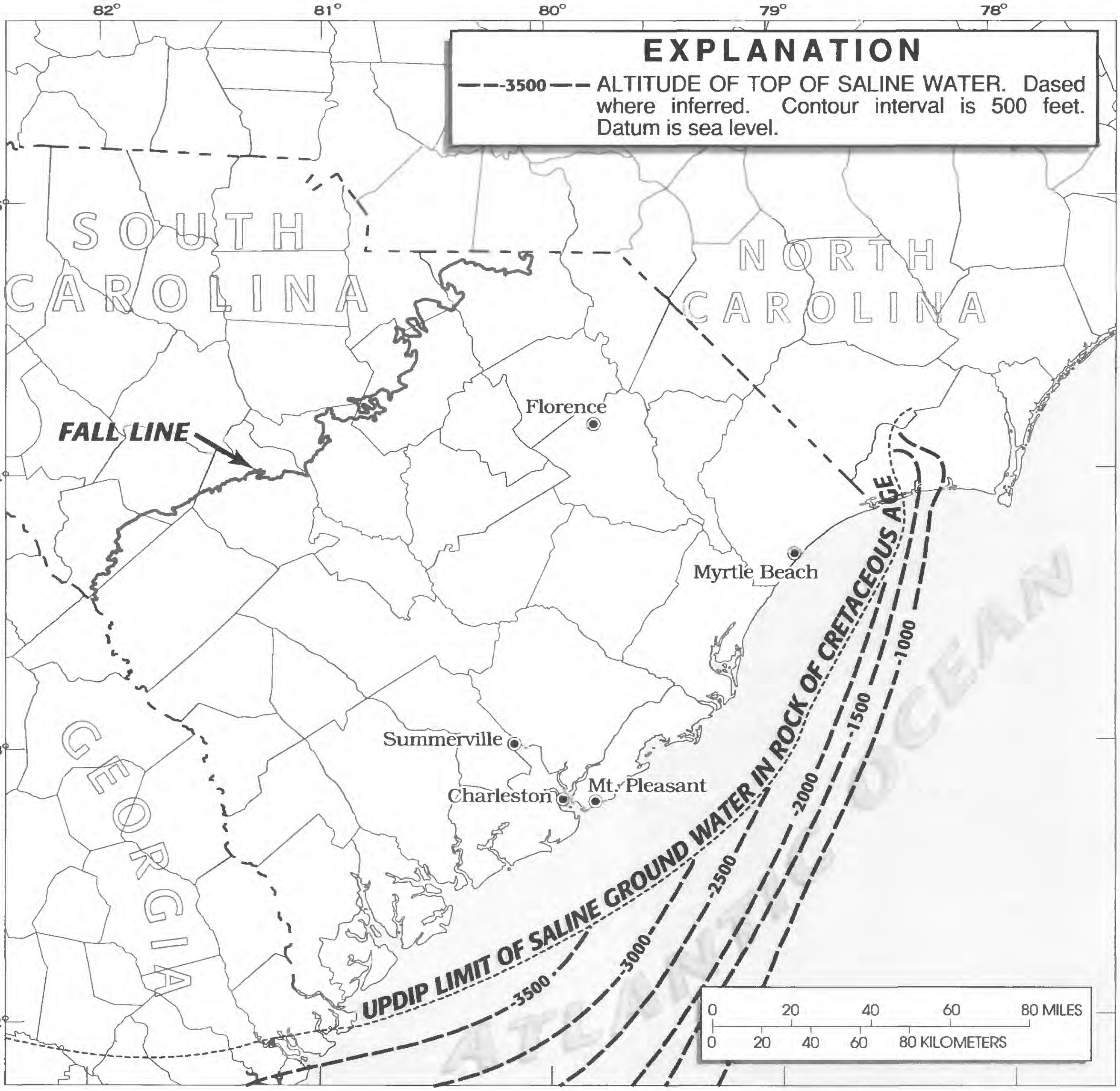


Figure 9. Altitude of the top of the saline ground water in the southeastern Coastal Plain (modified from Lee, 1986).

Ground-water use has increased steadily as industrial development and population have increased (table 1). Ground-water use of the Cretaceous aquifers has increased most near the cities of Charleston and Florence. An exception to this steady increase in ground-water withdrawal occurred from 1934-54 in Charleston County, after the city of Charleston completed a surface-water source in 1930 and ended withdrawals from the Middendorf aquifer.

Withdrawal Distribution

The Middendorf and Black Creek aquifers are the most heavily used aquifers in the South Carolina Coastal Plain. The volume of ground water withdrawn from the Cape Fear aquifer is insignificant compared to the volumes withdrawn from the Black Creek and Middendorf aquifers. Major withdrawal centers for the Black Creek aquifer are the Myrtle Beach area, Georgetown, and small towns in the Pee Dee region. The Middendorf aquifer is utilized at Aiken, the Savannah River Plant, Sumter, Florence, Summerville, Mount Pleasant, Isle of Palms, Sullivans Island, Walterboro, St. Stephens, Orangeburg and numerous other small towns and industrial facilities throughout the Coastal Plain (fig. 1). The total recorded withdrawals of ground water are summarized by county (table 2) for the period 1983-89.

In the Charleston, Berkeley, and Dorchester County (CBD) area, Mount Pleasant and Summerville are the major users of Cretaceous aquifer water. Secondary users include Sullivans Island, Isle of Palms, St. Stephens, and Jamestown. Some water is withdrawn for irrigation by resorts on the Isle of Palms, and Kiawah and Seabrook Islands (fig. 3).

Mount Pleasant has withdrawn water from the Middendorf aquifer since 1968, when the first of six wells was drilled. Daily production averages in 1993 were 5.1 Mgal/d with daily peak demands of 6.0 Mgal/d. Withdrawals have increased from 2.4 Mgal/d in 1984 to 5.1 Mgal/d in 1993 (fig. 10).

The Summerville water supply system consists of five Middendorf aquifer wells. Most of the potable water comes from these wells; however, the town also has the capability to treat surface water from the Edisto and Ashley Rivers. The water use from the Middendorf aquifer at Summerville has increased from 1.85 Mgal/d in 1984 to 3.6 Mgal/d in 1989 (fig. 10). Summerville Commissioners of Public Works ceased withdrawal from the Middendorf aquifer in 1994 and began using a surface-water source.

Withdrawal records for the city of Florence from 1972 to 1989 indicate a steady increase in the volume of water produced from the Middendorf aquifer (fig. 10). The demand for water has increased from 4.5 Mgal/d in 1972 to 9.4 Mgal/d in 1990. The system supplies potable water to about 60,000 people in the city of Florence and the surrounding area of Florence County. There are also several large industrial users of the Middendorf aquifer, including two hospitals and a bottling company. The Florence well field in 1993 consisted of 15 wells screened in the Middendorf aquifer that are distributed throughout the city. The wells have capacities ranging from 400 to 1,000 gal/min. Other large users of the Cretaceous aquifers in the Pee Dee area are Darlington, Hartsville, Bennettsville, Dillon, Marion, Lake City, and Timmonsville (fig. 3).

Table 1. *Ground-water withdrawals from the Cretaceous aquifer system in the Charleston and Florence areas of South Carolina, 1875-1982 (withdrawals in cubic feet per day)*

[--, no data]

County	Stress Period[1]							
	2	3	4	5	6	7	8	9
	1875-1934	1935-44	1945-54	1955-64	1965-69	1970-74	1975-79	1980-82
Darlington	273,366	410,049	716,140	791,539	817,151	861,267	1,152,290	1,005,384
Dillon	--	84,919	258,500	196,628	342,294	258,658	309,673	481,329
Florence	397,303	550,189	1,055,847	1,115,495	1,673,561	1,126,659	1,391,408	1,439,182
Marion	--	105,881	418,762	446,141	533,412	446,424	654,857	768,601
Marlboro	--	--	336,541	621,927	490,803	510,386	659,720	802,463
Charleston	196,000	37,000	49,000	--	234,000	234,000	447,000	410,000
Berkeley	--	--	--	--	--	33,000	41,000	36,000
Dorchester	--	--	--	--	--	--	163,000	337,000

[1]First stress period is steady state with no withdrawals.

Table 2. *Ground-water use data for selected Coastal Plain counties of South Carolina, 1983-89 (withdrawals in million gallons per day)*

[--, no data]

County	1983	1984	1985	1986	1987	1988	1989
Aiken	7.77	15.33	12.16	17.28	17.16	16.51	12.69
Allendale	3.60	10.23	7.30	5.87	12.05	8.91	5.73
Bamberg	1.37	.66	.37	.60	.82	1.52	.38
Barnwell	.73	.81	1.15	3.70	5.10	2.97	2.48
Berkeley	.36	1.16	1.23	8.13	10.20	9.89	9.50
Calhoun	2.02	1.47	.78	2.77	1.77	1.47	.38
Charleston	1.73	2.96	1.18	3.99	3.91	6.03	6.69
Chesterfield	.11	.44	--	.24	.29	.46	.07
Clarendon	.03	.18	.28	.75	1.26	1.10	1.08
Colleton	2.99	3.07	3.28	3.71	3.44	3.35	3.32
Darlington	7.02	4.12	4.57	8.44	7.73	8.33	6.74
Dillon	1.35	2.09	1.26	3.35	3.20	3.35	2.45
Dorchester	2.10	1.95	1.38	.67	4.58	5.11	5.19
Florence	9.76	10.47	5	10.86	11.91	13.45	12.34
Georgetown	3.61	3.64	3.62	3.97	4.26	4.30	4.38
Horry	19.05	13.86	19.64	16.65	18.83	20.82	16.50
Kershaw	3.42	3.21	2.43	4.24	4.34	4.50	4.58
Lancaster	--	--	--	--	--	1.48	--
Lee	1.34	1.73	.51	4.42	2.78	3.67	2.30
Lexington	1.04	10.05	8.31	8.79	3.10	10.41	2.19
Marion	.91	1.34	.99	.44	1.15	1.72	1.27
Marlboro	.63	.39	.31	2.77	1.86	2.18	2.71
Orangeburg	11.76	12.41	11.81	16.85	13.39	13.83	8.63
Richland	.29	.57	.68	.78	.72	.94	.88
Sumter	11.51	9.99	6.14	17.22	9.65	15.24	3.31
Williamsburg	.20	2.31	1.83	3.20	3.46	4.21	4.15
Total	94.7	114.44	96.21	149.69	146.96	165.75	119.94

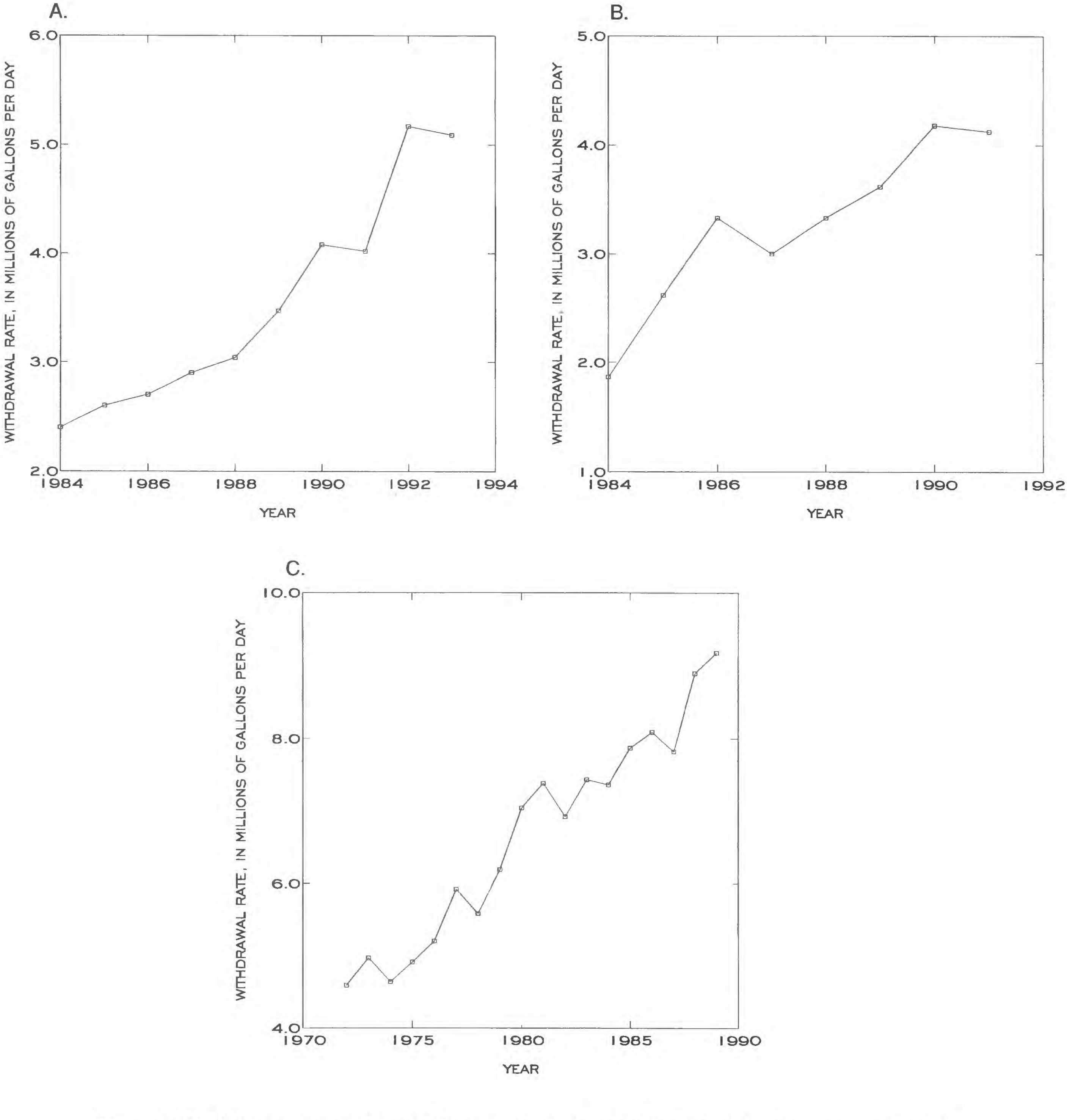


Figure 10. Water use in Mount Pleasant, S.C., 1984-93 (A), in Summerville, S.C., 1984-91 (B), and in the city of Florence, S.C. 1972-89 (C).

Water-Level Changes

Continuous water-level recorders were installed on Middendorf aquifer wells at three locations in the Charleston area. Recording instruments were installed in 1989 near Moncks Corner (well BRK-431), in 1990 near Charleston (well CHN-14) and in 1992 between Charleston and Summerville (well CHN-172) (fig. 11). At CHN-14, Charleston, the water level declined 66 ft between May 1991 and September 1995 in response to aquifer withdrawals at Mount Pleasant (fig. 12). Near Moncks Corner, water levels in BRK-431 declined about 28 ft from September 1989 to November 1994 (fig. 13). No wells in this area withdraw water from the Middendorf aquifer. The steady decline at this location, away from withdrawal centers, indicates that water is being removed from storage in the Middendorf aquifer due to the large withdrawals in the Charleston area. At CHN-172, between Charleston and Summerville, water levels in a Middendorf aquifer declined about 14 ft from January 1992 to August 1993 (fig. 13).

Water-level declines have also been observed in wells that are not continuously monitored (table 3). For example, CHN-173, at Mount Pleasant, has declined a total of about 159 ft from predevelopment to 1992.

SIMULATION OF GROUND-WATER FLOW

The ground-water-flow system in the aquifers of the South Carolina Coastal Plain was simulated using the finite-difference, ground-water flow model developed by McDonald and Harbaugh (1988). The model allows for the two-dimensional simulation of ground-water flow as separate layers. Movement of water in the third dimension was approximated by leakage of water between adjacent model layers. In the Charleston-Florence (CF) model, aquifers were simulated as separate model layers, and the effect of confining units was modeled as ground-water leakage between layers.

The ground-water-flow system of the South Carolina Coastal Plain is conceptualized to consist of four aquifers for the purpose of this study. Layer 1 represents a combination of the surficial, Floridan, and Tertiary Sand aquifers where any of these are immediately above the Black Creek aquifer. Model layer 2 represents the Black Creek aquifer system; layer 3, the Middendorf aquifer system; and layer 4, the Cape Fear aquifer system. Low-permeability pre-Cretaceous-age rocks below the Cretaceous aquifer system are assumed to have no hydraulic connection to the overlying Coastal Plain sediments. Ground-water flow within the pre-Cretaceous is less than flow within the Coastal Plain aquifers (Aucott, 1988). The interface between the Coastal Plain sediments and the pre-Cretaceous rocks is simulated as a no-flow boundary.

Water levels in layer 1 were simulated as constant through time to represent an upper specified-head boundary. Specified-head boundaries may supply or absorb any quantity of water from other model layers, and care was taken to assure that model results indicate that reasonable amounts of water flowed between layer 1 and the deeper model layers. A model layer with this function is referred to as a source-sink layer. The Black Creek, Middendorf, and Cape Fear aquifers are simulated as confined aquifers, but in the updip area where recharge occurs, the Black Creek and Middendorf aquifers are unconfined. Simulating the updip areas of the aquifers as confined is justified, because water-level changes in the unconfined parts of the Black Creek and Middendorf aquifers are small compared to the total saturated thicknesses of the aquifers.

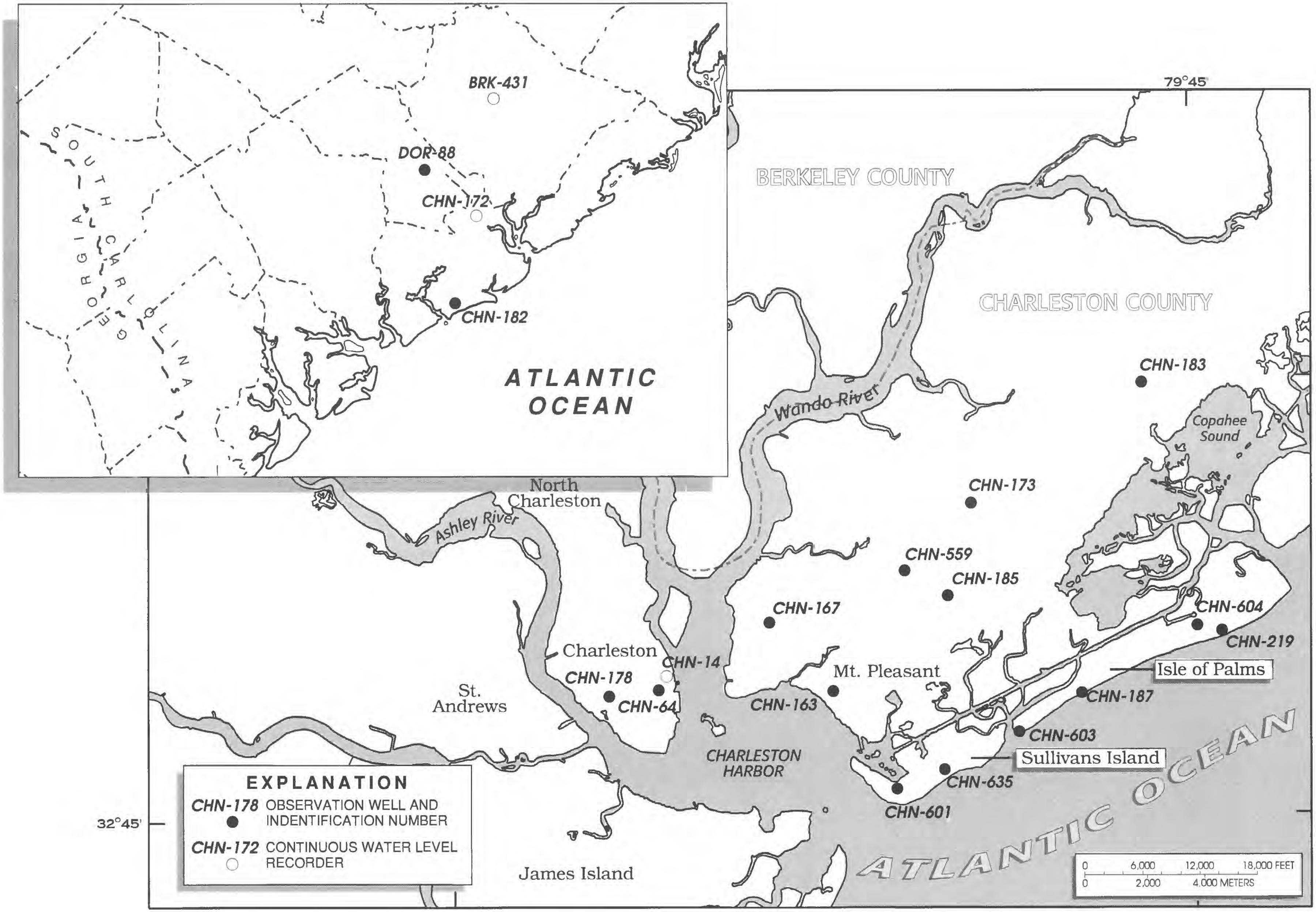


Figure 11. Locations of wells in the Charleston area of South Carolina,1993.

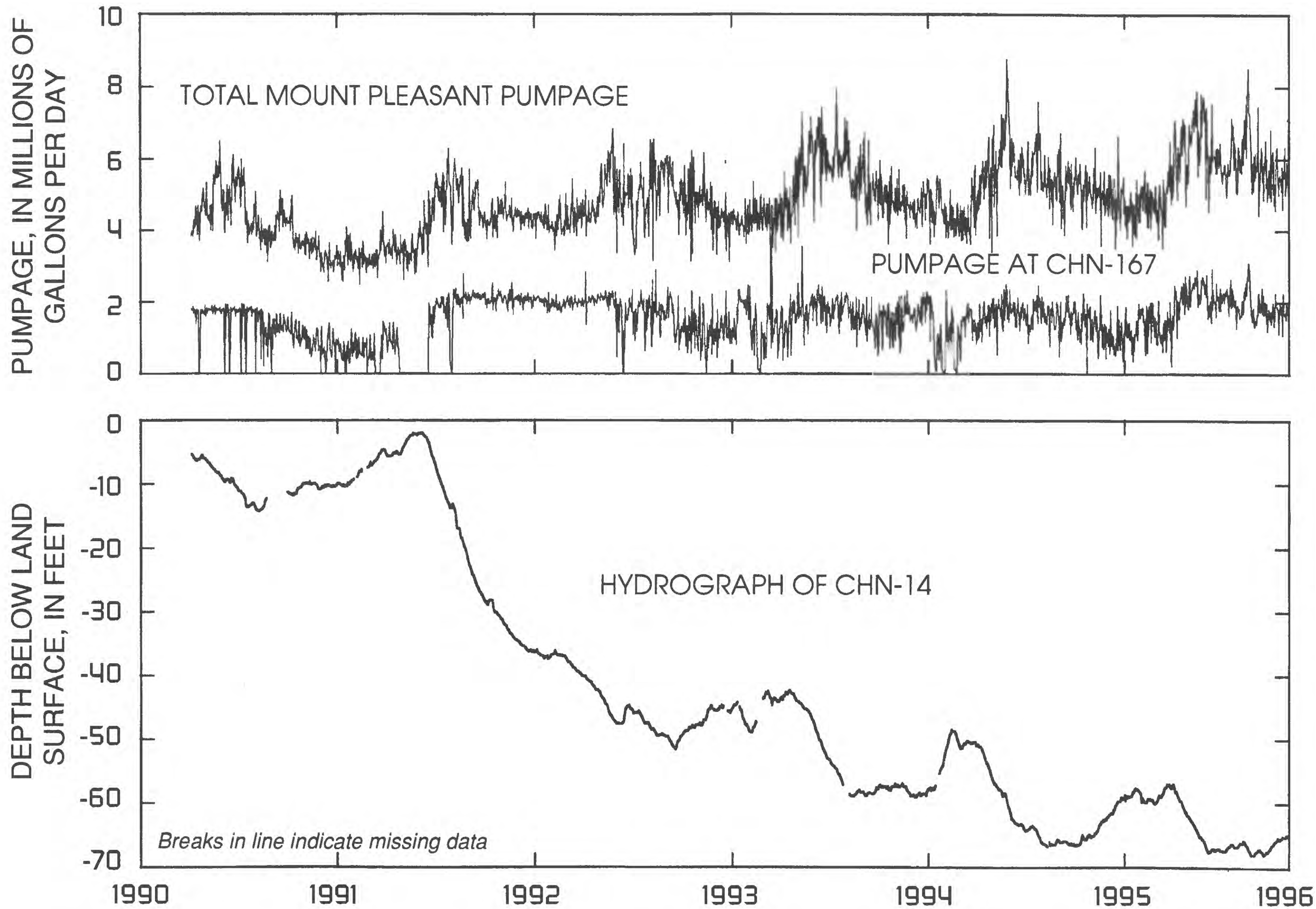
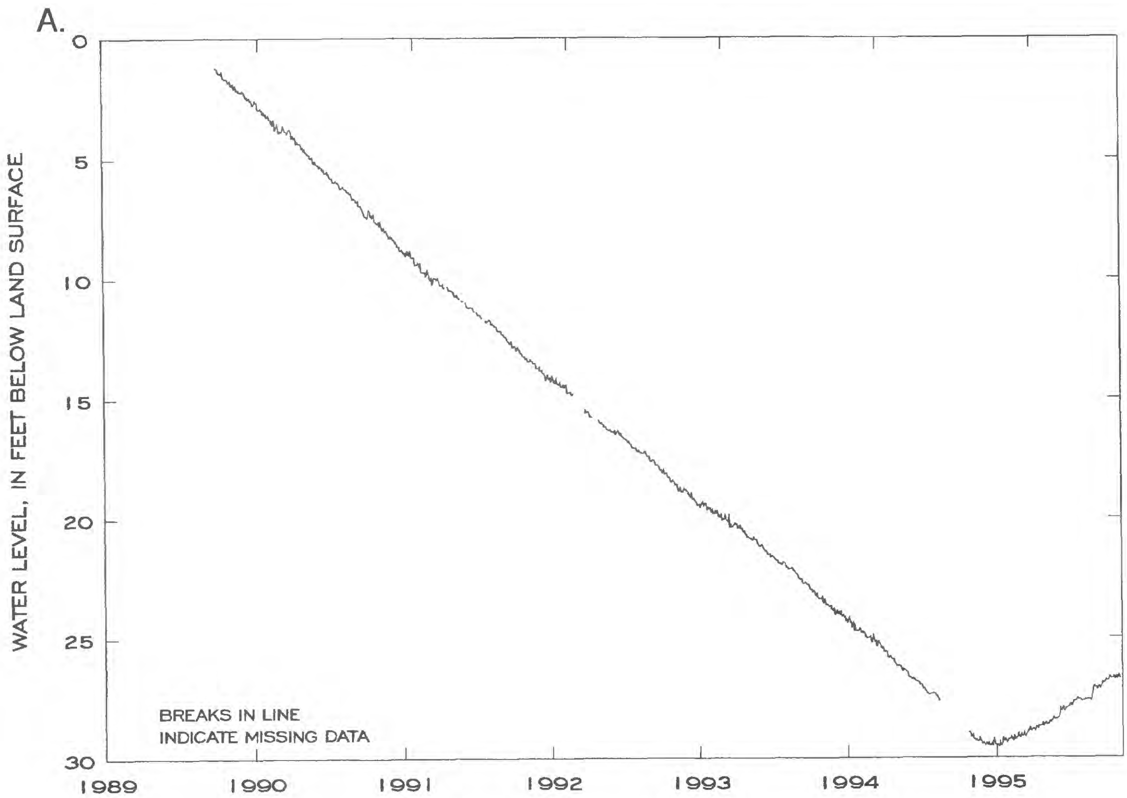


Figure 12. Ground-water pumpage and hydrograph of CHN-14 at Mount Pleasant, S.C., April 1990 to October 1995.



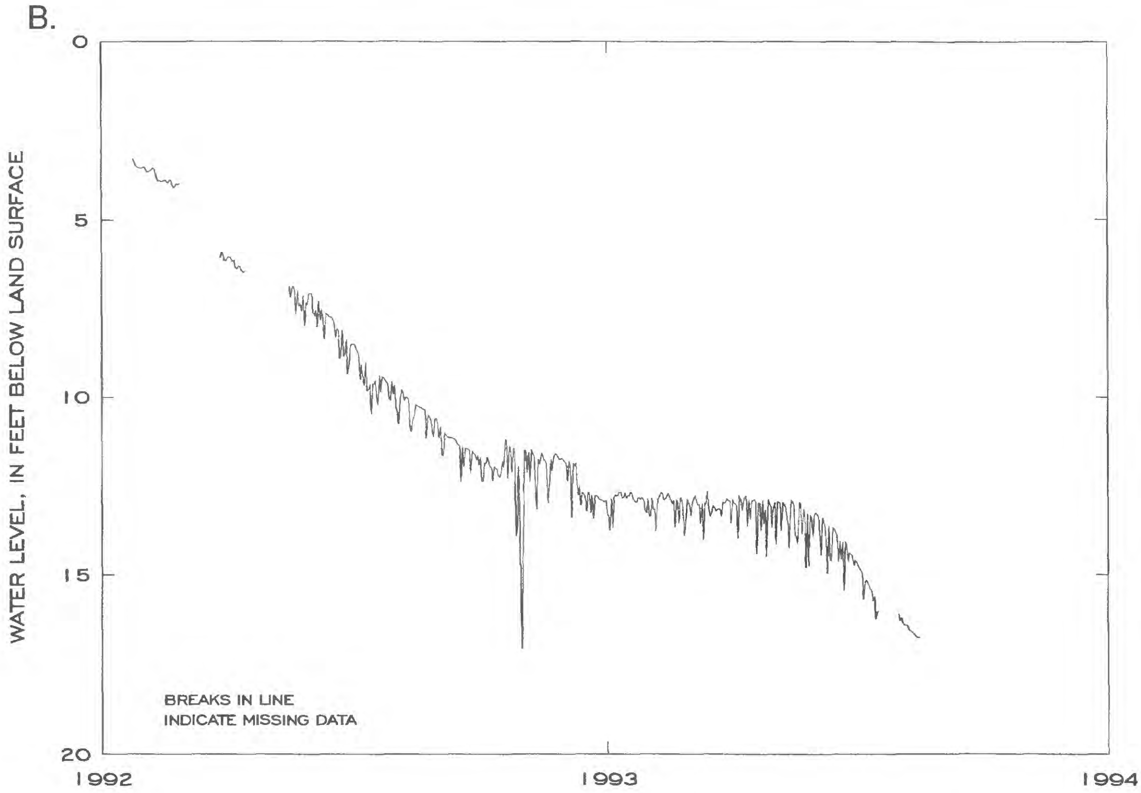


Figure 13. Hydrograph of BRK-431, observation well at Moncks Corner, S.C. (A), and hydrograph of CHN-172, observation well at Charleston, S.C. (B).

Table 3. *Middendorf aquifer water-level measurements in the Charleston, S.C., area, predevelopment to 1992*

[--, no data]

Well number	Local designation	Datum (feet above sea level)	Predevelopment (feet above or below sea level)	1982 (feet above or below sea level)	1989 (feet above or below sea level)	1990 (feet above or below sea level)	1991 (feet above or below sea level)	1992 (feet above or below sea level)	Decline (Predevelopment - 1992)
CHN-163	MP1	25	--	53	--	-42.19	--	--	--
CHN-167	MP2	24	--	--	--	-22.33	--	-70.10	--
CHN-173	MP3	15	126	--	14	-6.20	-13.20	-33.40	-159.40
CHN-559	MP4	20	--	--	--	--	-48	--	--
CHN-185	MP5	18	118	--	55	--	-9.92	--	-127.92
CHN-183	MP6	35	--	92	42.16	33.42	31.70	21.40	--
CHN-187	IOP1	15	--	108	66.74	48.26	38.10	39.71	--
CHN-603	IOP2	8	--	--	42.41	36.64	23.24	12.62	--
CHN-219	WD1	5	107	--	71.06	62.75	53.04	50.38	-56.62
CHN-604	WD2	--	--	--	--	--	--	--	--

Table 3. *Middendorf aquifer water-level measurements in the Charleston, S.C., area, predevelopment to 1992*--Continued

[--, no data]

Well number	Local designation	Datum (feet above sea level)	Predevelopment (feet above or below sea level)	1982 (feet above or below sea level)	1989 (feet above or below sea level)	1990 (feet above or below sea level)	1991 (feet above or below sea level)	1992 (feet above or below sea level)	Decline (Predevelopment - 1992)
CHN-64	George St.	14	87	70	3.19	-0.15	-14.48	--	--
CHN-14	Charlotte St.	9	79	--	2.50	-2.22	-23.52	-38.60	-117.60
CHN-182	Seabrook Island	3	138	--	60.75	27.94	32.10	21.94	-116.06
DOR-88	SCPW1	32	122	--	--	-22.10	-30.66	-30.8	-152.80

The simulation of unconfined aquifers as confined in the updip area means that the model cannot reliably simulate ground-water flow in the updip area near the Fall Line. In the updip area, the shallow ground-water-flow system contains short, shallow-flow paths of local significance. The deep aquifer flow system contains long flowpaths of regional scope. This report presents results of analysis of the deep-flow system. Aucott (1988) provides a detailed discussion of the distinction between the shallow- and deep-flow systems.

The CF model simulates eight rivers in the updip area. These are: the North and South Edisto, Congaree, Wateree, Lynches, Pee Dee, Lumber, and Little Pee Dee Rivers. Base flows of the modeled rivers were calculated by Aucott and others (1987). River stages were obtained from topographic maps. Initial estimates of riverbed conductances for the model were obtained from the calibrated SCRASA model (Aucott, 1988). In model cells where the riverbeds truncate the surficial or deeper aquifers, water levels for the aquifer were set to a constant value equal to the river stage.

No data are available on actual recharge rates of the South Carolina Coastal Plain. Areal recharge in the outcrop areas of the Black Creek and Middendorf aquifers is simulated by using the recharge rates from the calibrated SCRASA model.

Ground-water withdrawal rates were estimated based on historical records, field surveys, aquifer tests, or water-use databases. Special effort was made to get the most reliable withdrawal estimates for the areas surrounding Charleston and Florence. Less detailed estimates for other parts of the South Carolina Coastal Plain should have little influence on Cretaceous aquifer water levels in the Florence and Charleston areas.

Methods

The CF model was used to simulate conditions prior to the initiation of ground-water withdrawals (the late 1800's) and conditions at specific later times. Prior to any ground-water withdrawals, the aquifer system was assumed to be in a state of dynamic equilibrium. These model simulations are referred to as steady-state simulations (natural recharge equals natural discharge). Since the initiation of withdrawals, however, the equilibrium has been disturbed and potentiometric-surface depressions have developed. Simulations with pumpage through time are referred to as transient simulations. The numerical model selected for this application was the modular ground-water flow model by McDonald and Harbaugh (1988).

McDonald and Harbaugh (1988) mathematically described the three-dimensional movement of ground water through porous media using the equation:

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)-W=S_s\frac{\partial h}{\partial t}, \qquad (1)$$

where

K_{xx}, K_{yy}, and K_{zz} are values of hydraulic conductivity along the x, y, and z coordinate axes, which are assumed to be parallel to the major axes of hydraulic conductivity (Lt^{-1});
h is the potentiometric head (L);
W is a volumetric flux per unit volume and represents sources and (or) sinks of water (t^{-1});
S_s is the specific storage of the porous materials (L^{-1});
t is time (t); and
K is hydraulic conductivity (Lt^{-1}).

To simplify equation 1, flow in the third dimension was simulated by leakage of water between adjacent layers. The modified partial-differential equation is solved by the finite-difference method in which a large system of linear equations that are solved simultaneously by an iterative method. The Preconditioned Conjugate Gradient method (Hill, 1990) was used to solve the equations. The solution yields values of the potentiometric head at specific points in space and time.

Transmissivities, vertical hydraulic conductivities, storage coefficients, and starting potentiometric heads are used as model input. Hydraulic parameters are adjusted during model calibration until simulated potentiometric heads reasonably matched observed heads. Final parameter values must be consistent with the hydrogeologic understanding of the aquifer system. The process of model calibration leads to a better understanding of the sensitivity of the flow system to various hydraulic parameters. The calibrated model was used to simulate hypothetical withdrawal scenarios.

Initial estimates of transmissivity, vertical hydraulic conductivity, and starting head data were from the calibrated SCRASA model (Aucott, 1988). In areas where discretization of the model grid of the present study was finer than the SCRASA discretization, transmissivity and vertical hydraulic conductivity values were subdivided, and starting head values were interpolated.

Ground-Water Flow Model Boundaries

Simulation of ground-water flow requires that the aquifer system be enclosed by model boundaries that conceptually represent natural-flow boundaries. The model-flow boundaries can also be located at a distance far enough from the area of interest so that the choice of boundary conditions does not influence the model results pertaining to the area of interest.

The boundaries of the CF model correspond to the ones used in the SCRASA model except for the location of the southwestern boundary, which was moved from approximately 20 mi west of the South Carolina - Georgia border to the border. The SCRASA boundary types and locations are shown in figure 11 of Aucott (1988).

The ground-water flow model extends from the Fall Line southeastward to about 30 mi off the South Carolina coast and from the Savannah River northeastward into North Carolina. All of the aquifers pinch out toward the Fall Line. The updip extent of the aquifers is represented by a no-flow boundary (fig. 14).

No natural hydrologic boundaries are present in a southwesterly direction of the Coastal Plain aquifers at a reasonable distance from Charleston or Florence. The southwestern boundary for all layers in the model is simulated as a specified-head boundary. The location of these boundaries is far enough from the areas of interest so that the effects of these boundaries do not influence model results near Charleston and Florence.

In the northeasterly direction of the model, the Cape Fear Arch forms a natural, no-flow hydrologic boundary for the lower units in the Cape Fear aquifer (Winner and Coble, 1989). The upper Cape Fear units and the Middendorf, Black Creek, and surficial aquifers, however, continue across the Cape Fear arch. Along the updip extent of the Arch, hydrologic divides are present in the upper Black Creek, Middendorf, and Cape Fear aquifers that are approximated by a no-flow boundary for each model layer. Along the downdip extent of the Arch, ground water flows parallel to the Atlantic Coast toward the northeast. The downdip parts of the Black Creek, Middendorf, and Cape Fear aquifers are, therefore, approximated by constant-head boundaries along the Cape Fear Arch.

Figure 14. Model boundary of the surficial, Floridan, and Tertiary Sand aquifers, layer 1 (A), the Black Creek aquifer, layer 2 (B), the Middendorf aquifer, layer 3 (C), and the Cape Fear aquifer, layer 4 (D).

The downdip boundary of the Black Creek, Middendorf, and Cape Fear aquifer systems is a no-flow boundary at the saltwater-freshwater interface. A sharp saltwater-freshwater interface probably does not exist, because aquifer salinities are believed to increase gradually offshore. For the purpose of this study, however, a sharp interface is assumed at the location of the 10,000 mg/L isochlor, about 30 mi offshore (Lee and others, 1986) (fig. 9). The approximation of the saltwater-freshwater interface as a sharp, no-flow boundary is justified, if, on a regional scale, the freshwater and saltwater bodies are in hydrostatic equilibrium. With the information available it is not possible to determine if hydrostatic equilibrium has occurred, but for this study, the assumption is that the 10,000 mg/L isochlor has reached an equilibrium location and remains stationary for the time interval modeled. Also, local withdrawals in the Charleston area would not be significant enough to change the hydrostatic equilibrium at that great a distance. With the freshwater and saltwater bodies in equilibrium, the only exchange of water and solutes is the result of dispersion, which is small compared to the volumes of ground-water moving through the regional flow system.

The source-sink layer (layer 1) also is assumed to extend approximately 30 mi offshore. The chloride concentrations in the upper Floridan aquifer, however, are greater than 10,000 mg/L at this distance (Smith, 1988). This approach was chosen because this layer is not actively simulated, but merely acts as a source-sink to deeper aquifers.

Simulated Stresses on the Aquifer System

Two natural stresses and one man-made stress are applied to the model. The simulated natural stresses are the areally distributed recharge to the outcrop areas of the Black Creek and Middendorf aquifers and the ground-water loss to or gain from eight large rivers that cut through the upper Coastal Plain sediments. The simulated man-made stress is withdrawal of Cretaceous aquifer water by production wells.

Recharge to the Cretaceous aquifer system occurs in the upper Coastal Plain, in the outcrop areas of the Black Creek and Middendorf aquifers (fig. 1). Recharge is not simulated for the surficial-Tertiary aquifer systems because they are modeled as a specified head boundary. Also, no recharge is applied to the Cape Fear aquifer, because it has no outcrop within the modeled area. Recharge is not applied to river nodes within the model.

The average annual precipitation in the upper Coastal Plain is approximately 46 in/yr (Snyder and others, 1983). It is estimated that about 5 percent of the total precipitation actually recharges the deep ground-water-flow system. Most of the precipitation is lost as overland flow and to evapotranspiration. Accurate estimates of the percentage of total precipitation that recharges the flow system are not available. Recharge values were primarily determined during model calibration.

Eight large rivers of the upper Coastal Plain are simulated in the ground-water flow model. Rivers stress the flow system, by draining water from or adding water to the aquifer flow system. In the upper South Carolina Coastal Plain, the simulated rivers act as drains for the aquifers, taking an average of 1.8 [(ft^3/s)/mi] of water out of the aquifer system (Aucott, 1988). This average was determined from base-flow measurements made during extreme low-flow periods.

Ground-water withdrawals from the Cretaceous aquifers began in the Charleston area in 1879, when the city of Charleston completed a 2,000-ft-deep well into the Middendorf aquifer. Many additional wells have been completed in the Middendorf aquifer since then, causing water level declines and changes in the flow directions in the Middendorf aquifer system.

In 1982, water-level measurements were made in wells in all Coastal Plain aquifers (Aucott and Sperian, 1985c). The measurements indicated water-level declines in some areas, but the most pronounced declines were in the Charleston and Florence areas for the Middendorf aquifer, and in the Myrtle Beach and Georgetown areas for the Black Creek aquifer. In November 1989, another set of water level measurements were made in the Black Creek and Middendorf aquifers throughout the South Carolina Coastal Plain (Stringfield and Campbell, 1993). The measurements indicated that water levels continued to decline between the 1982 and 1989 measurements in most areas of heavy use. Declines in the Middendorf aquifer near Charleston were at a rate of approximately 20 ft/yr from 1988 through 1990 (Campbell, 1992).

Simulation of Ground-Water Flow

Initial simulations were made using a steady-state flow model that simulated the predevelopment flow within the Cretaceous aquifers. Steady-state ground-water flow is not time dependent; therefore, transient effects of releasing water from, or taking water into, storage within the Cretaceous aquifers are not simulated. After completion of the predevelopment steady-state model calibration, ground-water withdrawals were simulated with time. The transient simulations show the effects of hundreds of water-supply wells on water levels in the Cretaceous aquifers.

The transient simulations began in 1879, when Cretaceous aquifer wells were initially installed in the Charleston area and end in 1989. The transient simulations were divided into 15 stress periods, during which withdrawal rates are held constant (table 4). Withdrawal rates used in the model differ from the values presented in table 2 due to missing location or screen-interval data. The missing information precluded locating the well in the model.

Ground-Water Flow Model Calibration

Model calibration is a process in which estimated parameters of the aquifer system boundaries and hydraulic properties of the aquifer material are selected to yield the best solution or match of historical data (Konikow and Bredehoeft, 1992). The calibration process was accomplished by comparing water-level measurements from three known potentiometric surfaces to corresponding values calculated by the model. The model input parameters were varied within reasonable ranges until the differences between observed and simulated head values were minimized. The ranges of hydraulic values were based on previous models (Aucott, 1988) and published aquifer test results (Aucott and Newcome, 1986).

Table 4. *Model stress periods and ground-water withdrawal rates*

[ft^3/d, cubic foot per day; Mgal/d, million gallons per day]

Stress period	Years (inclusive)	Ground-water withdrawal rates (ft^3/d)	(Mgal/d)
1	Predevelopment	0	0
2	1879-1934	886,669	6.63
3	1935-44	1,798,000	13.45
4	1945-54	4,270,500	31.94
5	1954-64	7,204,200	53.89
6	1965-69	9,460,900	70.77
7	1970-74	10,794,000	80.74
8	1975-79	13,145,000	98.32
9	1980-82	18,902,000	141.39
10	1983	10,595,000	79.25
11	1984	12,309,000	92.07
12	1985	11,128,000	83.24
13	1986	13,966,000	104.47
14	1987	13,686,000	102.37
15	1988	13,762,000	102.93
16	1989	10,686,000	79.93

The model-calibration process refined the input hydraulic values in the CF model until the model results matched, within specified criteria, the measured and estimated behavior of the physical system. The ability of the model to generate results that match historical data demonstrated that the model can accurately represent the hydrologic system of the South Carolina Coastal Plain. Model calibration was accomplished by the trial-and-error method in which the SCRASA-model input files were used as a starting point. The various input parameters, such as transmissivity or vertical leakage, were varied until a suitable match was found. This process relied on three techniques:

1. A visual comparison of potentiometric surfaces from predevelopment, 1982, and 1989 generated by the model to known potentiometric surfaces of the Black Creek, Middendorf, and Cape Fear aquifers,

2. Statistical comparison of observed and simulated heads from water-level measurements in individual wells, and

3. Comparison of observed and simulated well-water levels with time or hydrographs.

Comparison of Potentiometric Surfaces

Published potentiometric surface maps are available for the South Carolina Coastal Plain for predevelopment (Aucott and Speiran, 1985b), 1982 (Aucott and Speiran, 1985c), and 1989 (Stringfield and Campbell, 1993). However, no potentiometric-surface maps are available for the Cape Fear aquifer for 1982 and 1989. Water levels simulated by the model for predevelopment, 1982, and 1989 were compared to each of the available sets of potentiometric surfaces.

Simulated heads from the predevelopment steady-state calibration have the best fit with the measured heads of the three comparisons (fig. 15). The simulated heads from 1982 transient calibration did not have as close a fit with the measured heads as the predevelopment calibration due to poor-quality withdrawal data prior to 1983.

By 1982, large depressions had developed in the potentiometric surface of the Black Creek aquifer near Myrtle Beach and the Middendorf aquifer near Florence. The depressions significantly altered the rate and direction of ground-water flow (fig. 16). By 1982, withdrawals in Mount Pleasant and Summerville have begun to affect water levels in the Middendorf aquifer.

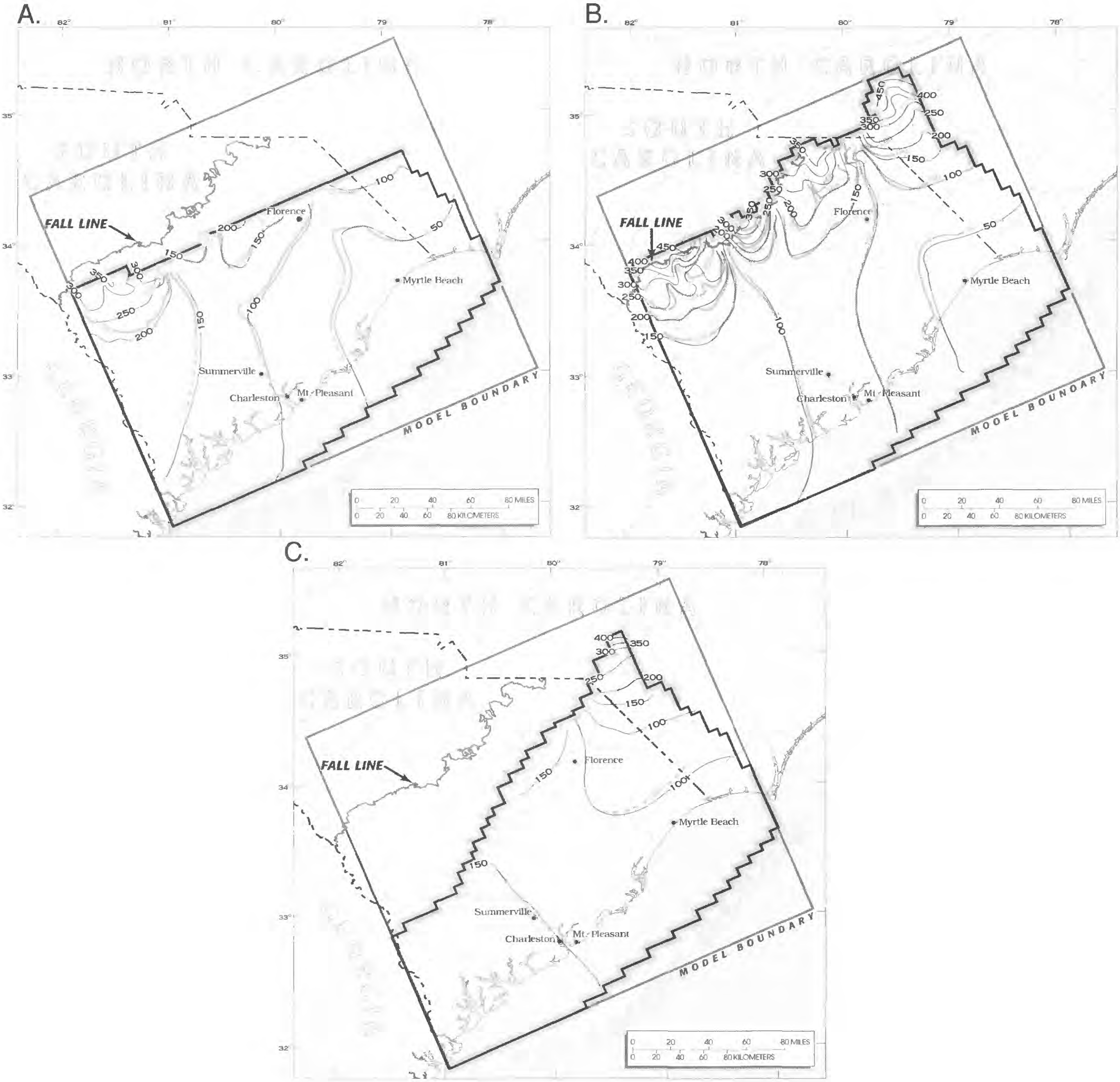
The 1989 transient calibration is generally more accurate than the 1982 calibration, because additional water-use data were available (fig. 17). The Black Creek aquifer heads are not simulated as well as 1982, but the simulated Middendorf aquifer heads are a closer match to the observed heads. No 1989 water-level measurements are available for the Cape Fear aquifer.

By 1989, two large depressions in the potentiometric surface of the Middendorf aquifer began to coalesce into a large regional depression in the Charleston area. Observed lows in the potentiometric surface were -10 ft and -15 ft bsl at Mount Pleasant and Summerville, respectively. This depression was simulated closely by the model (fig. 18). The depression in the Middendorf aquifer near Florence did not change greatly from 1982 to 1989, even though withdrawals increased from about 7 to about 9 Mgal/d. The observed low near Florence in the potentiometric surface was -46 ft in 1982 and -40 ft in 1989 (fig. 19). These values were simulated relatively accurately in the model. A cone of depression shown on figure 19B at Hartsville, S.C., (fig. 3) does not appear on figure 19C. Hartsville converted from a ground-water source to a surface-water source between 1982 and 1989 and ended most withdrawals from the Middendorf aquifer.

Statistical Comparison of Observed and Simulated Water Levels

To quantify the fit of the simulated potentiometric surfaces, water-level residuals were calculated for a subset of observation wells. A residual is defined as the difference between a simulated and observed ground-water level at a point. A small residual value means that the simulated head and observed head is numerically close, whereas a large residual value means that they are not. Generally, small residuals indicate that the model is well calibrated, and that a reasonable combination of aquifer parameters was selected.

Wells were selected for residual calculation on the basis of their location in the model grid and the aquifer in which they were screened. Care was taken to select wells that were located throughout the Coastal Plain, screened in one aquifer, and located in an actively simulated model-grid cell without a specified potentiometric head. Wells screened in multiple aquifers were excluded, because the observed head value is a composite of the potentiometric head of multiple aquifers.



EXPLANATION

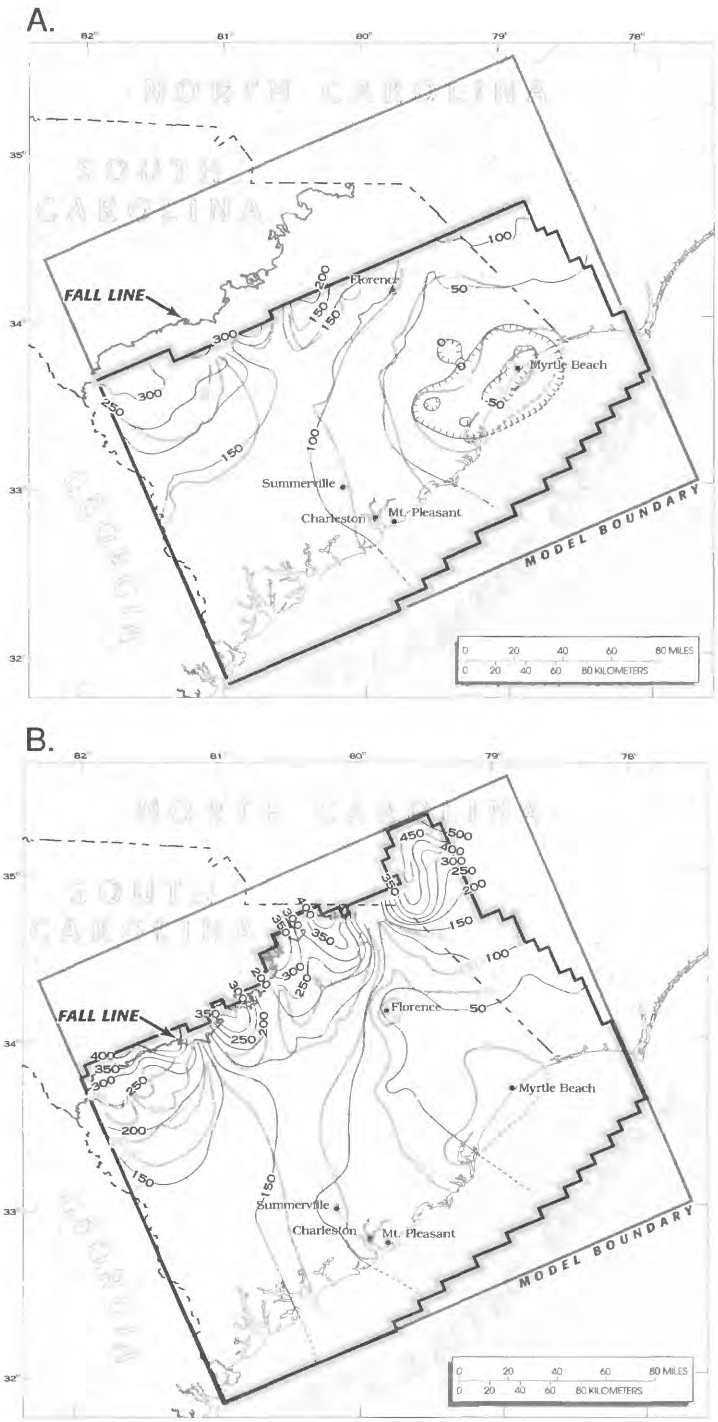
POTENTIOMETRIC CONTOUR DERIVED FROM FIELD MEASUREMENTS--Shows altitude at which water level would have stood prior to development in tightly cased wells. Dashed where approximate. Contour interval 50 feet. Datum is sea level.

50 SIMULATED POTENTIOMETRIC CONTOUR (DERIVED FROM MODEL GENERATED OUTPUT)--Shows altitude at which water level would have stood prior to development in tightly cased wells. Dashed where approximate. Contour interval 50 feet. Datum is sea level.

NO FLOW MODEL BOUNDARY

SPECIFIED HEAD MODEL BOUNDARY

Figure 15. Field and model-derived predevelopment water levels for the Black Creek (A), Middendorf (B), and Cape Fear (C) aquifers.



EXPLANATION

POTENTIOMETRIC CONTOUR DERIVED FROM FIELD MEASUREMENTS--Shows altitude at which water level would have stood prior to development in tightly cased wells. Dashed where approximate. Hachures indicate depressions. Contour interval 50 feet. Datum is sea level.

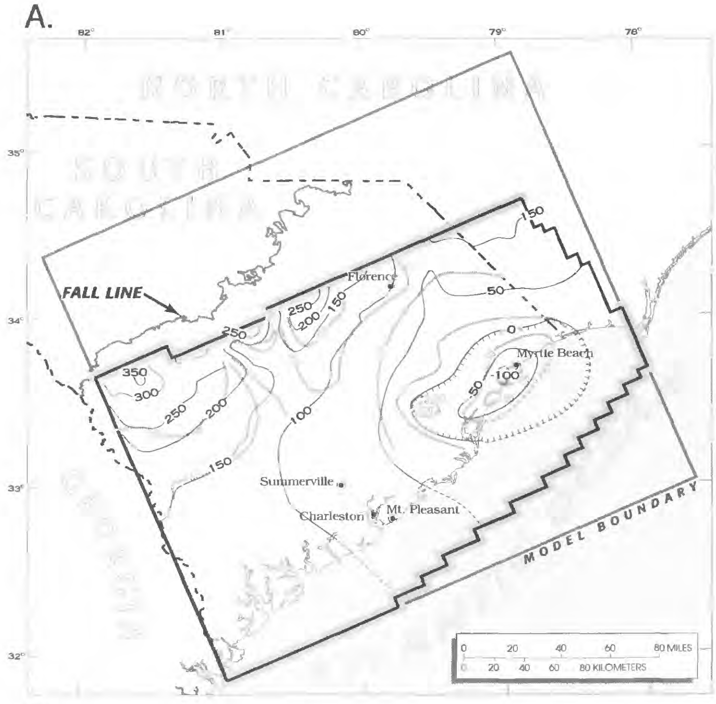
50 — SIMULATED POTENTIOMETRIC CONTOUR (DERIVED FROM MODEL GENERATED OUTPUT)--Shows altitude at which water level would have stood prior to development in tightly cased wells. Dashed where approximate. Hachures indicate depressions. Contour interval 50 feet. Datum is sea level.

NO FLO W MODEL BOUNDARY

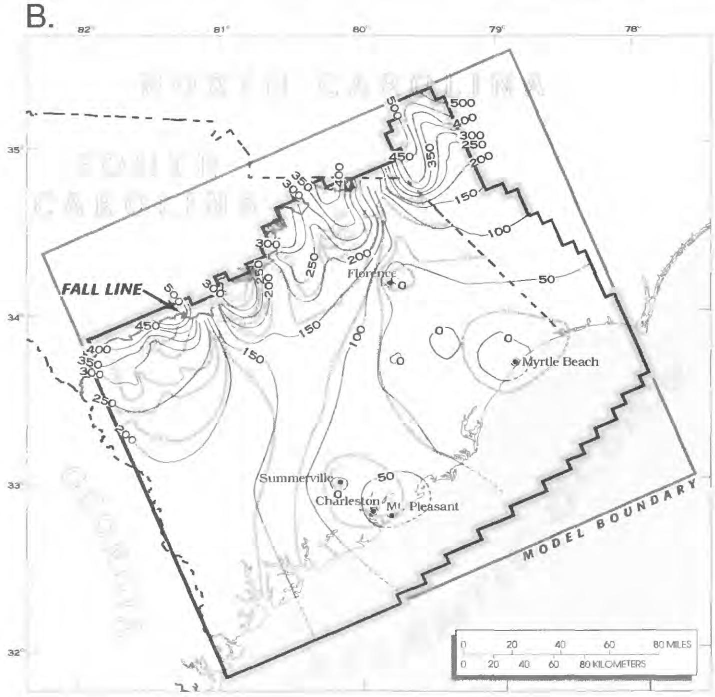
SPECIFIED HEAD MODEL BOUNDARY

Figure 16. Field and model-derived 1982 water levels for the Black Creek (A) and Middendorf (B) aquifers.

A.



B.



EXPLANATION

100	POTENTIOMETRIC CONTOUR DERIVED FROM FIELD MEASUREMENTS--Shows altitude at which water level would have stood prior to development in tightly cased wells. Dashed where approximate. Hachures indicate depressions. Contour interval 50 feet. Datum is sea level.
50	SIMULATED POTENTIOMETRIC CONTOUR (DERIVED FROM MODEL GENERATED OUTPUT)--Shows altitude at which water level would have stood prior to development in tightly cased wells. Dashed where approximate. Hachures indicate depressions. Contour interval 50 feet. Datum is sea level.
	NO FLO W MODEL BOUNDARY
	SPECIFIED HEAD MODEL BOUNDARY

Figure 17. Field and model-derived 1989 water levels for the Black Creek (A) and Middendorf (B) aquifers.

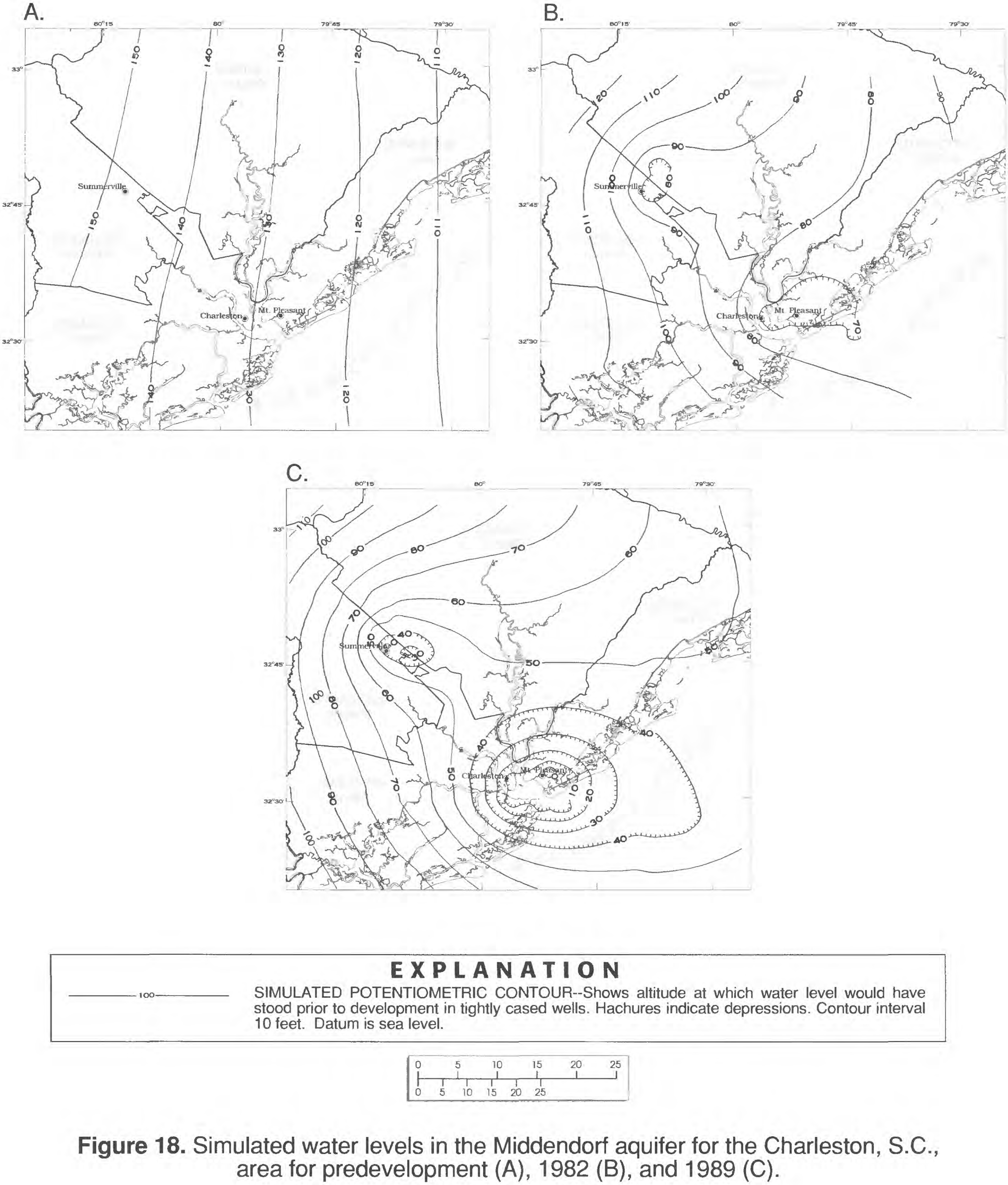
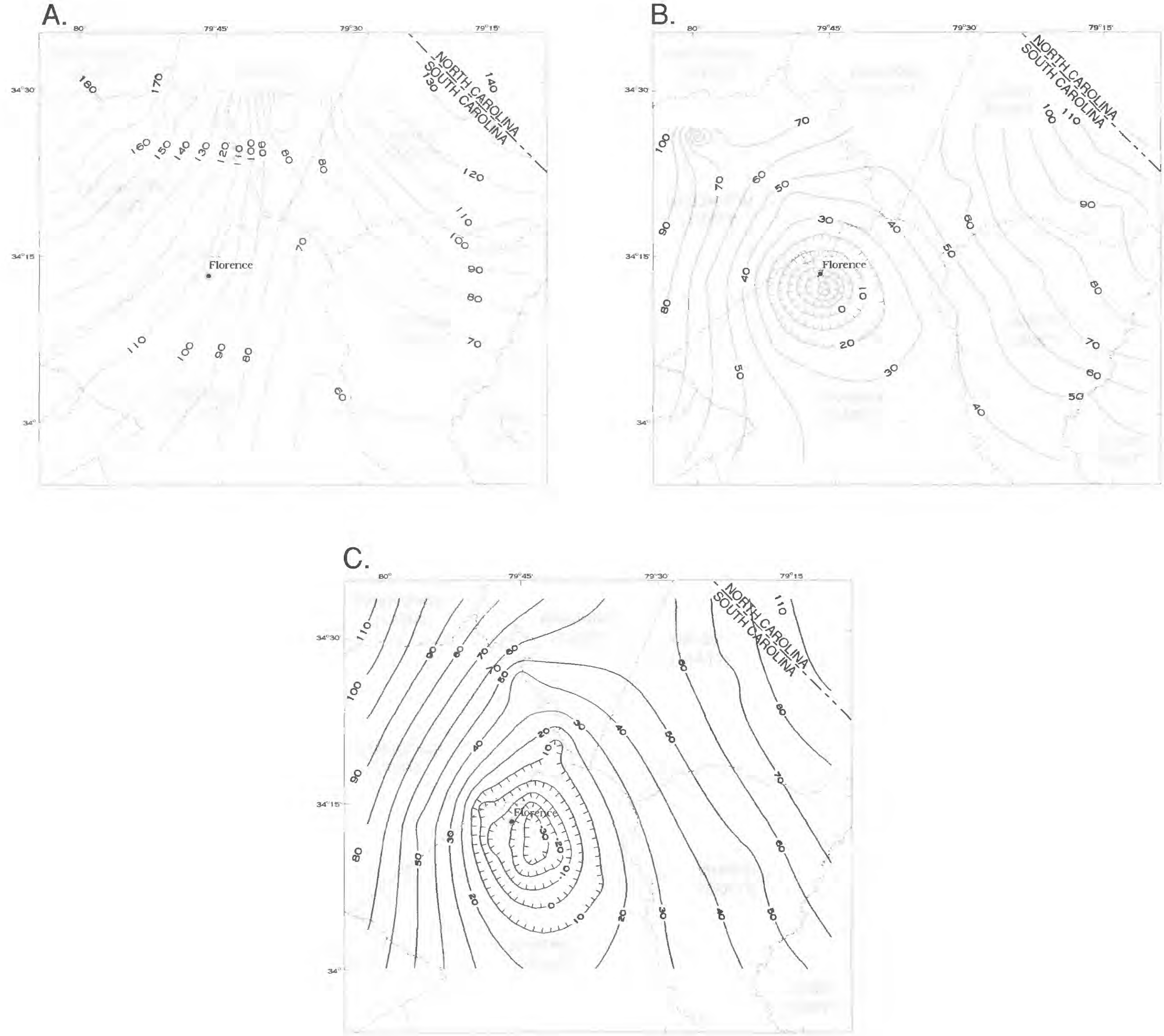


Figure 18. Simulated water levels in the Middendorf aquifer for the Charleston, S.C., area for predevelopment (A), 1982 (B), and 1989 (C).



EXPLANATION

——100—— SIMULATED POTENTIOMETRIC CONTOUR--Shows altitude at which water level would have stood prior to development in tightly cased wells. Hachures indicate depressions. Contour interval 10 feet. Datum is sea level.

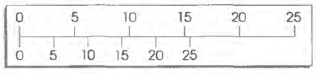


Figure 19--Simulated water levels in the Pee Dee area of South Carolina in the Middendorf aquifer for predevelopment (A), 1982 (B), and 1989 (C).

Descriptive statistics of root-mean-square-error (RMSE), variance (VAR), and standard deviation (SD) were computed for the predevelopment, 1982, and 1989 calibrations to quantify the fit of the calibrated model (table 5). The RMSE is defined as the square root of the mean of squared residuals. The VAR is the average of the squared deviations of all possible observations from the population mean, and the SD is the positive square root of the variance and is a measure of dispersion of residuals about the mean.

The statistics of the water-level residuals show that the predevelopment calibration is the best fit of the three calibration intervals (fig. 20). The 1982 and 1989 statistics are approximately the same with a slightly poorer fit of the point data to the potentiometric surfaces. Cross plots of observed and simulated water levels illustrate the degree of model calibration.

With increased development of the aquifers, water levels and flow directions change, and the calibration process becomes more difficult. This is reflected in the higher RMSE values for the 1982 (fig. 21) and 1989 calibrations (fig. 22).

The largest source of error for a comparison of observed and simulated water levels is the lack of accurate land-surface altitudes at observation wells. Most of the land-surface altitudes are estimated using topographic maps and, therefore, may be in error of as much as 10 ft. Another limitation is the lack of spatial distribution control. The location of the wells tends to be clustered in certain areas of the Coastal Plain in the various aquifers. The set of predevelopment water-level measurements was the largest and most extensive (fig. 23). In 1982, measurements were made for the Black Creek and Middendorf aquifers, but few measurements were made for the Cape Fear aquifer (fig. 24). Water-level measurements were made only in Black Creek and Middendorf aquifer wells in 1989 (fig. 25).

A simulated water level represents the potentiometric head value in the center of the model cell and the observed water level represents the head at the location of the well, which may be anywhere within the cell. As a result, the comparison between simulated and observed heads is better in small model cells than in large cells. In the water-level residual analysis, residuals were computed in large and small cells. This technique, combined with potentiometric surface and hydrograph comparisons, provides a reasonable evaluation of the overall calibration effort.

Comparison of Observed and Simulated Well Hydrographs

Twelve Black Creek and Middendorf aquifer wells in the South Carolina Coastal Plain were selected to compare observed and simulated well hydrographs. These wells were selected, because they have relatively long-term, continuous, water-level data (table 6; fig. 26). Most of the water-level records begin in the 1970's or early 1980's; one well, SU-9, in Sumter, has a period of record that extends from 1943 through 1989. For comparison, wells were selected on the basis of presence in the actively modeled area, knowledge of well-construction data, and length of record. No surficial, Tertiary Sand, or Floridian aquifer hydrographs were included, because water levels in these aquifers are modeled as constant through time. No hydrographs are available for Cape Fear aquifer wells.

Mean yearly water levels observed in the selected wells were compared with simulated water levels at the same locations. Because water levels vary seasonally, the closeness of the match between the simulated and the observed head is less important than the similarities between observed and simulated trends in potentiometric heads.

Table 5. *Descriptive model calibration statistics relating observed and simulated water levels (in feet)*

[NA, not available; SD, standard deviation; VAR, variance; RMSE, root-mean-square-error]

Predevelopment Calibration - Stress period 1			
	Aquifer system (number of wells)		
Statistic	Black Creek (84)	Middendorf (94)	Cape Fear (15)
SD	7	19	8
VAR	49	365	66
RMSE	7	19	10

1982 Calibration - Stress period 9			
Statistic	Black Creek (106)	Middendorf (119)	Cape Fear (2)
SD	22	32	12
VAR	514	1,122	155
RMSE	22	32	12

1989 Calibration - Stress period 16 (No observed Cape Fear aquifer water levels available)			
Statistic	Black Creek (86)	Middendorf (106)	Cape Fear (0)
SD	23	33	NA
VAR	516	1,092	NA
RMSE	26	33	NA

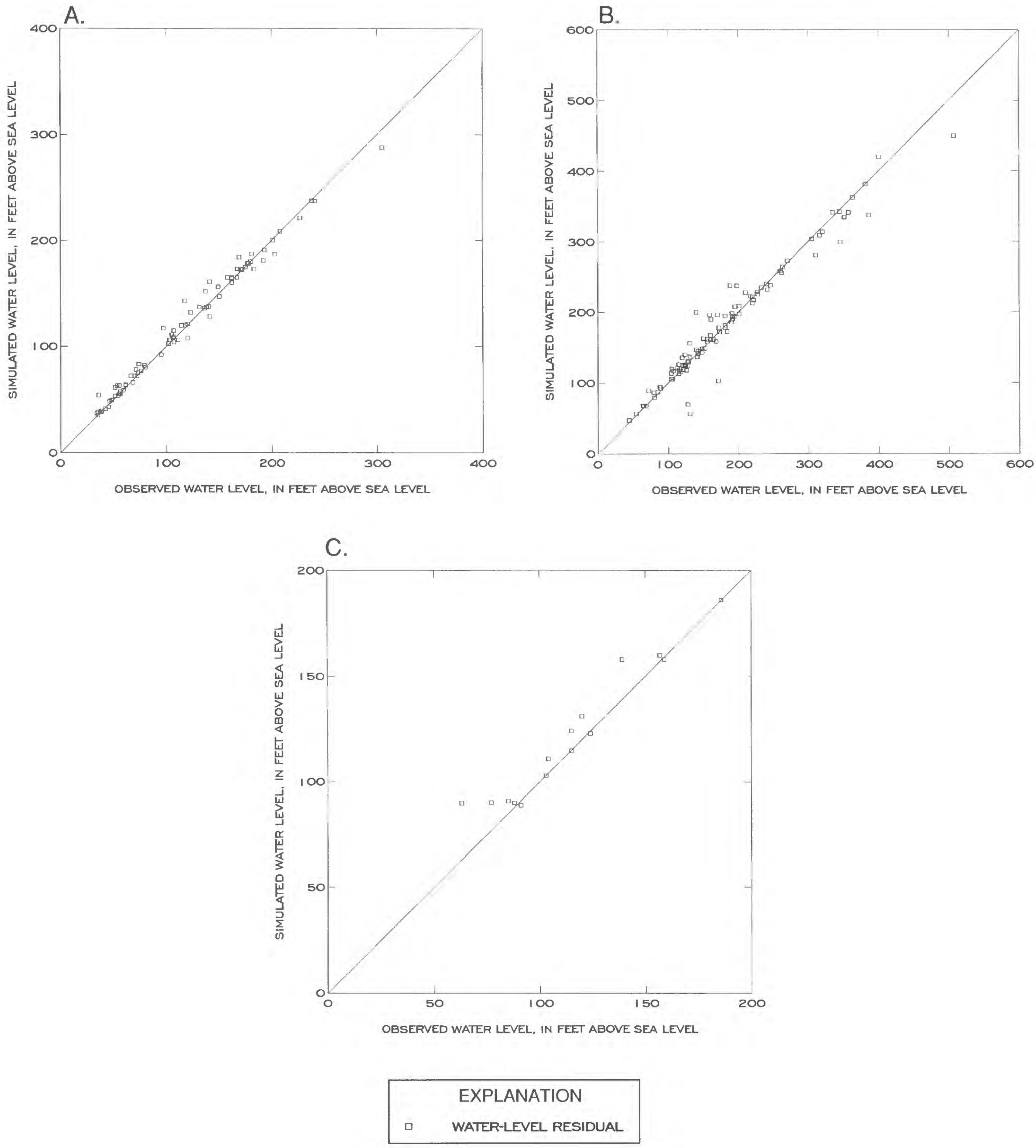


Figure 20. Relation of simulated and observed predevelopment water-levels for the Black Creek (A), Middendorf (B), and Cape Fear aquifers (C).

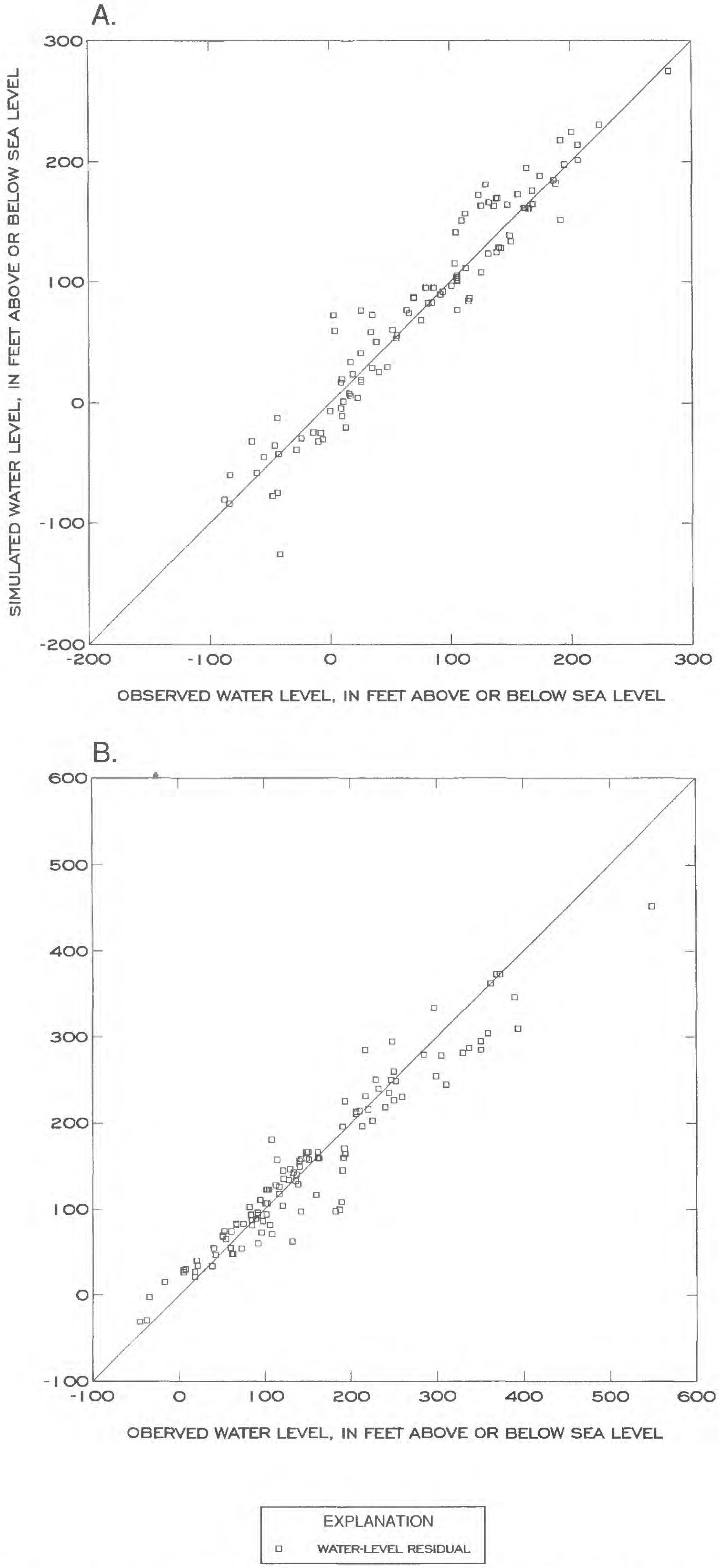


Figure 21. Relation of simulated and observed 1982 water-levels for the Black Creek (A) and Middendorf (B) aquifers.

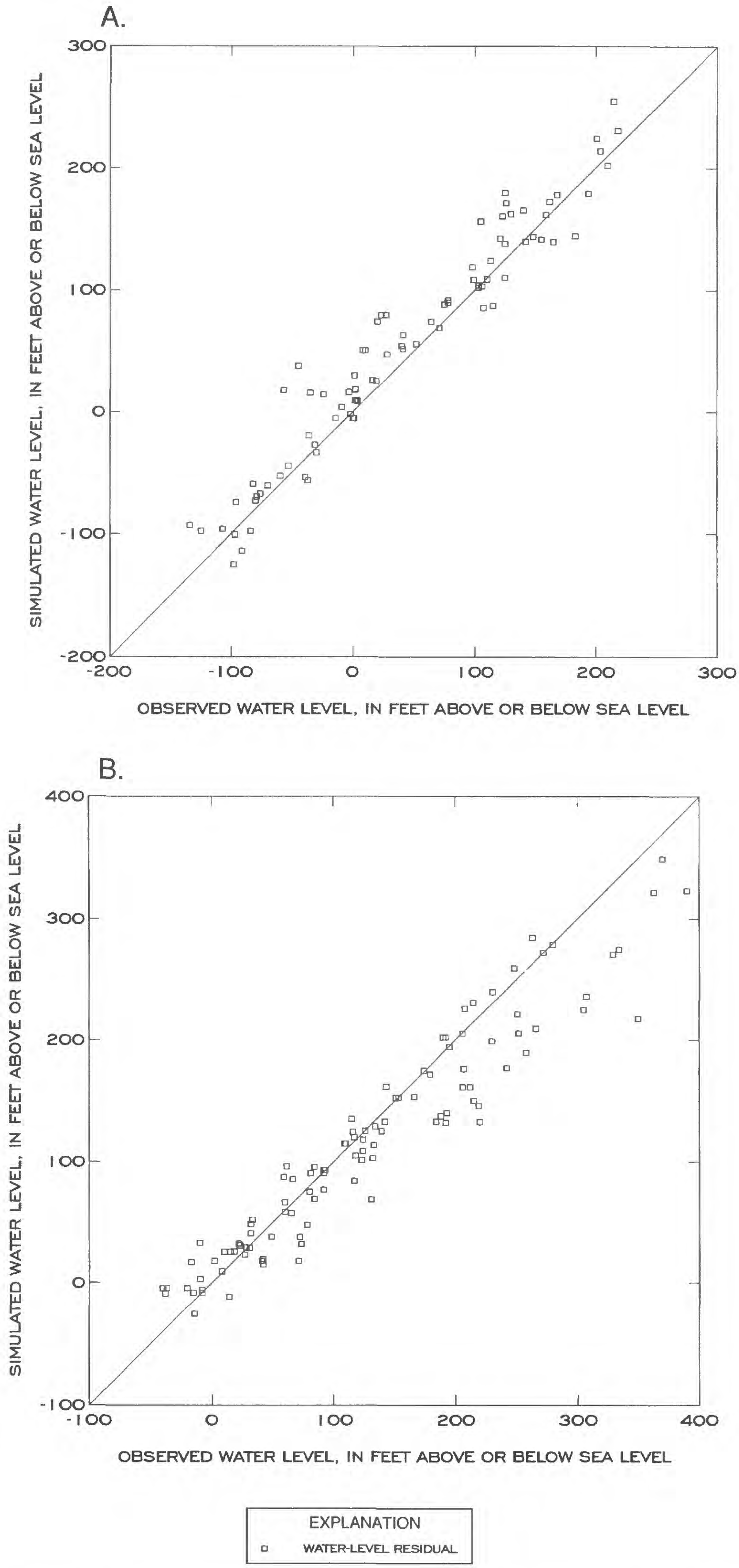


Figure 22. Relation of simulated and observed 1989 water-levels for the Black Creek (A) and Middendorf (B) aquifers.

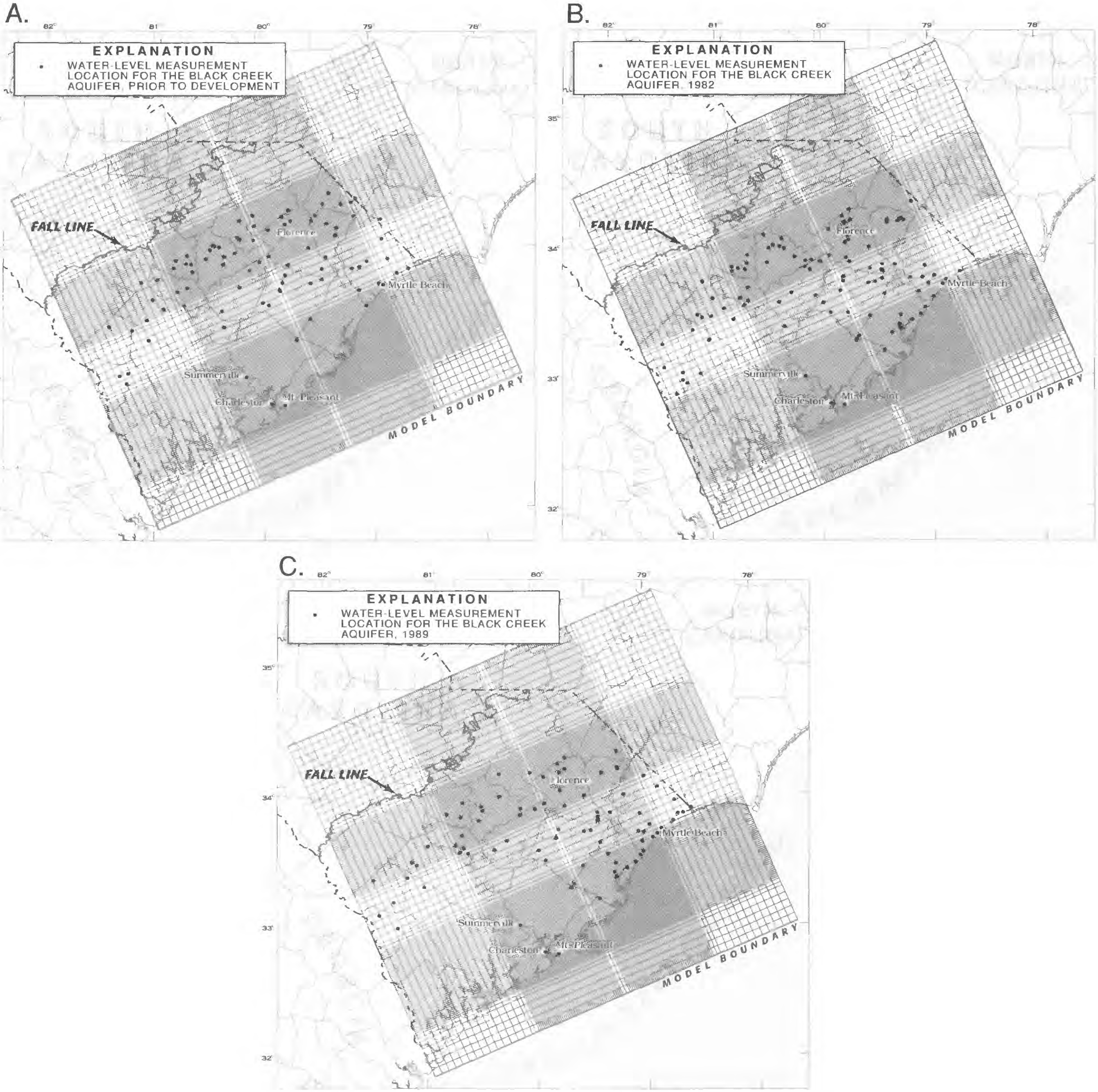


Figure 23. Location of water-level measurements, for the Black Creek aquifer for predevelopment (A), 1982 (B) and 1989 (C).

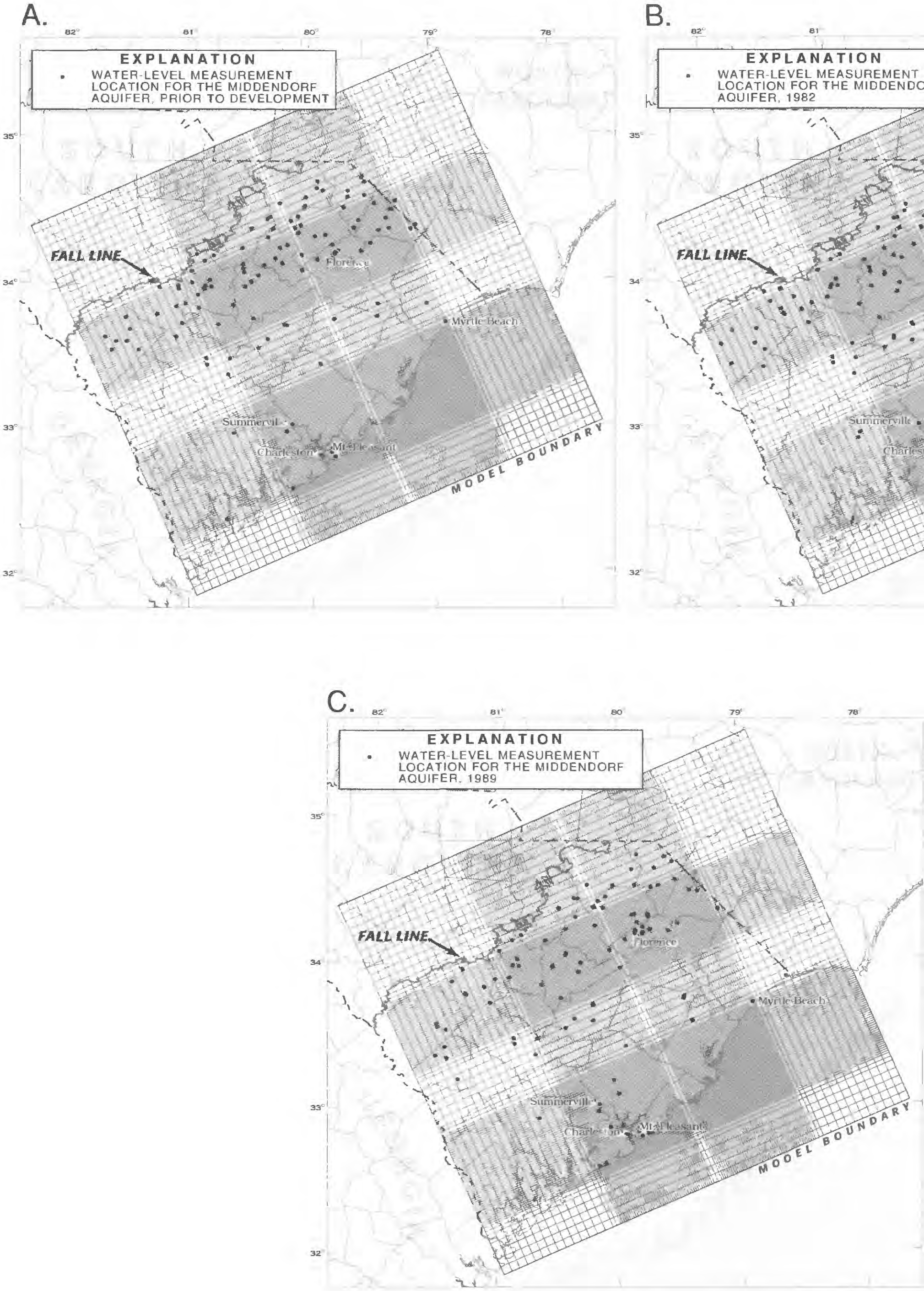


Figure 24. Location of water-level measurements, for the Middendorf aquifer for predevelopment (A), 1982 (B) and 1989 (C).

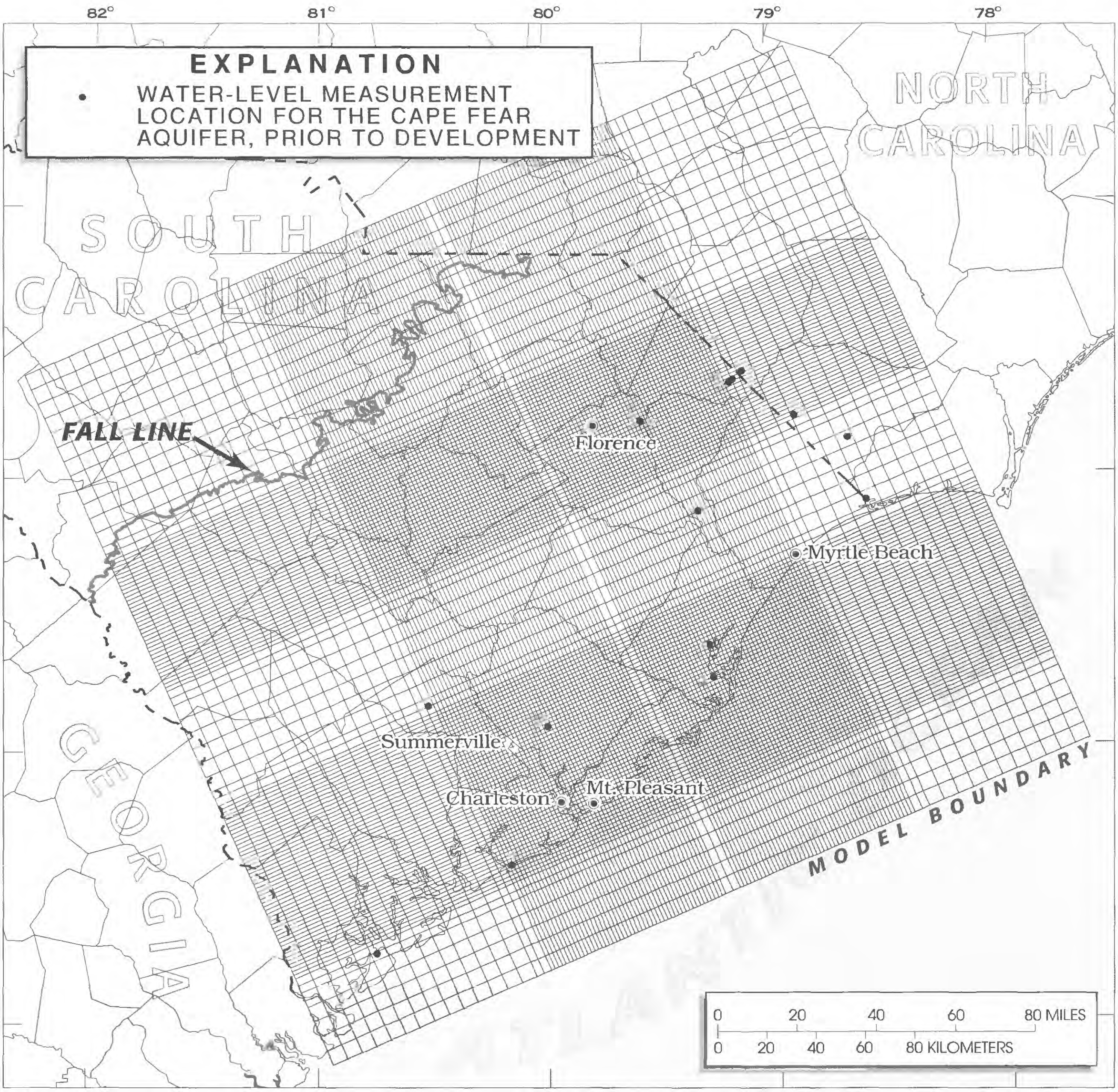


Figure 25. Locations of water-level measurements for the Cape Fear aquifer for predevelopment.

Figure 26. Location of observation wells used for hydrograph comparison of observed and simulated water levels.

Table 6. *Black Creek and Middendorf aquifer wells in South Carolina selected for observed and simulated hydrograph comparison*

County	Well number	Aquifer	Period of record
Florence	FLO-128	Middendorf	1982-1989
Marlboro	MLB-110	Middendorf'	1981-1989
Florence	FLO-85	Black Creek	1981-1989
Florence	FLO-99	Black Creek	1981-1989
Marion	MN-77	Black Creek	1982-1989
Georgetown	GEO-77	Black Creek	1970-1989
Georgetown	GEO-84	Black Creek	1977-1989
Horry	HO-269	Black Creek	1977-1989
Horry	HO-307	Black Creek	1974-1989
Sumter	SU-9	Middendorf	1943-1989
Richland	RIC-63	Middendorf	1981-1989
Williamsburg	WL-76	Black Creek	1981-1989

Five locations in the Florence area were chosen for hydrograph comparison; two represent Middendorf aquifer water levels near the Pee Dee River in Florence County (FLO-128) and near Bennettsville in Marlboro County (MLB-110, fig. 27), and three represent Black Creek aquifer water levels near Timmonsville (FLO-85), Florence (FLO-99) (both in Florence County), and Brittons Neck (MN-77) (Marion County) (fig. 28). The Middendorf aquifer hydrographs have a reasonable agreement with the simulated values, except for the early values in 1982. The Black Creek aquifer hydrographs for Florence and Timmonsville compare favorably in overall trend, but the simulated water levels are about 20 ft less than the observed. The Brittons Neck's hydrograph compares poorly with the simulated hydrograph in the early part of the record (1982-84), but it compares well from 1985-89.

Four locations in the Myrtle Beach area were chosen for hydrograph comparison (fig. 29). All (Georgetown County wells GEO-77 and GEO-84, and Horry County wells HO-269 and HO-307) are close in trend and absolute water-level elevation to simulated hydrographs.

Simulated and observed hydrographs for one Middendorf aquifer well in Sumter County were compared (fig. 30). SU-9, a well located in the city of Sumter, has a long and continuous record that extends from 1943 through 1989. The simulated hydrograph during this time period matches the observed hydrograph closely. In fact, the observed and simulated hydrograph match for SU-9 is the best of any of the 12 hydrographs considered in this calibration. The water level in this observation well is heavily influenced by local withdrawal, as the hydrograph demonstrates.

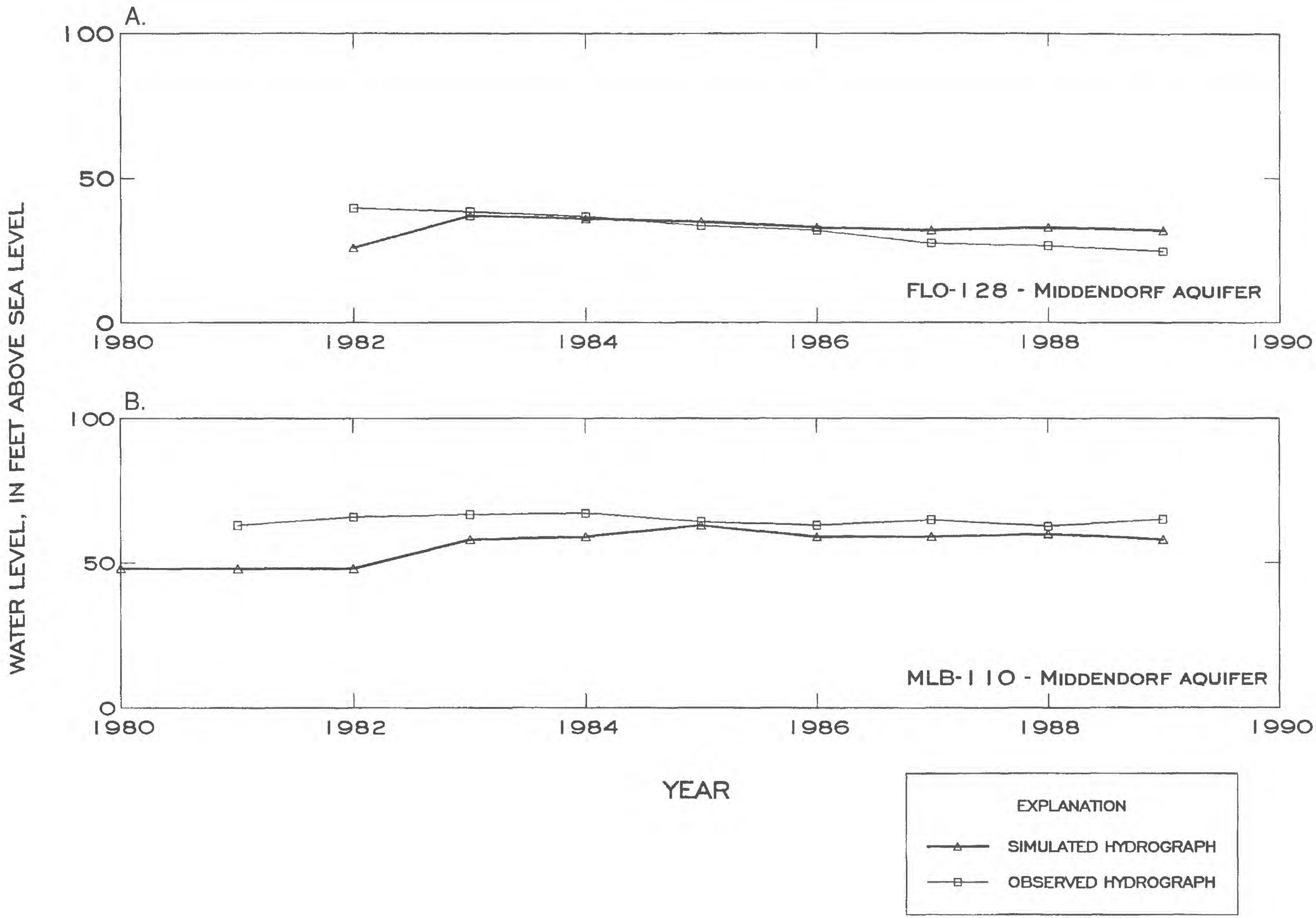


Figure 27. Observed and simulated hydrographs for FLO-128 near Mars Bluff, S.C. (A) and MLB-110 at Bennettsville, S.C. (B), for layer 3.

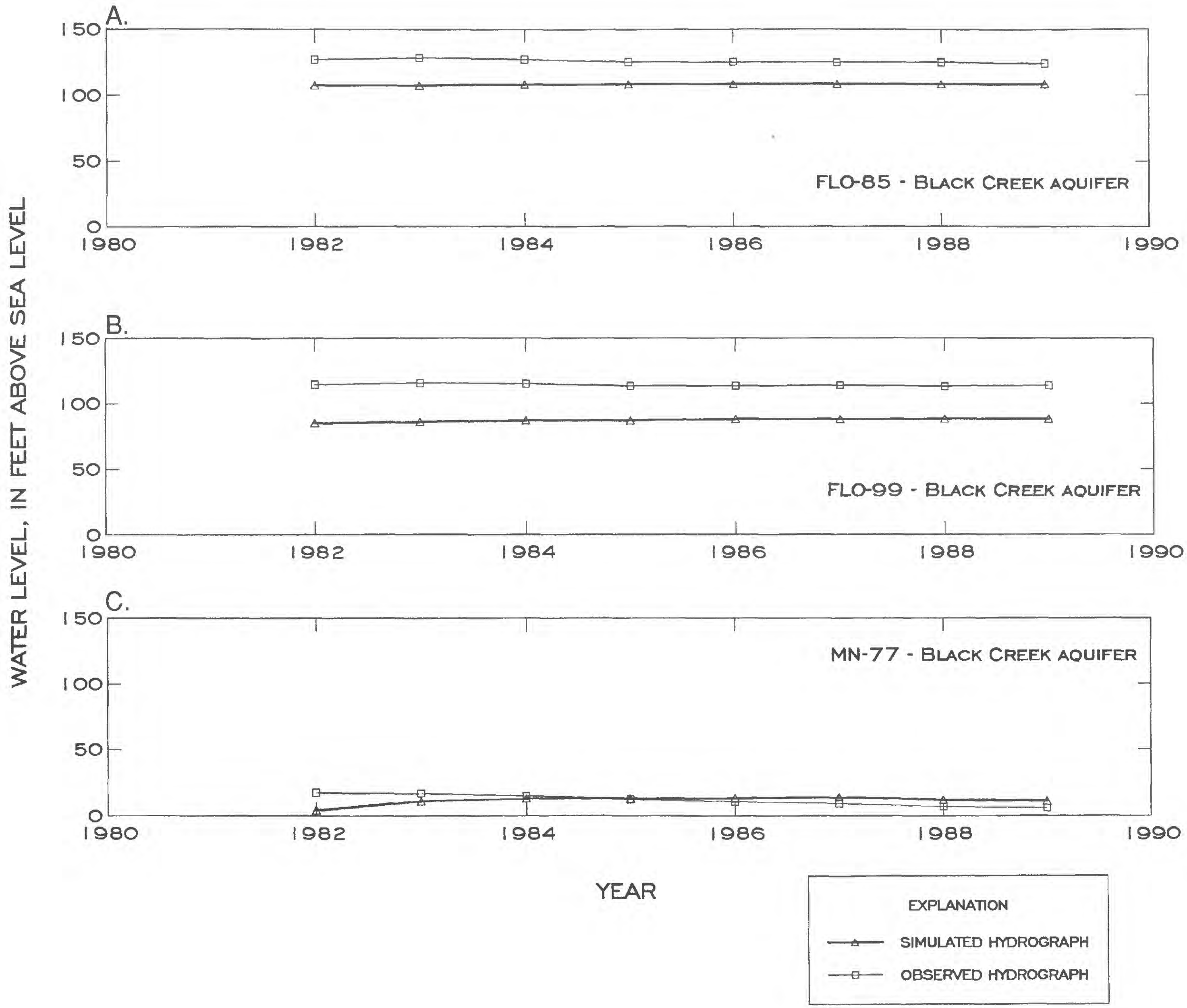


Figure 28. Observed and simulated hydrographs for FLO-85 in Timmonsville S.C. (A), FLO-99 in Florence, S.C. (B), and MN-77 at Brittons Neck, S.C. (C), for layer 2.

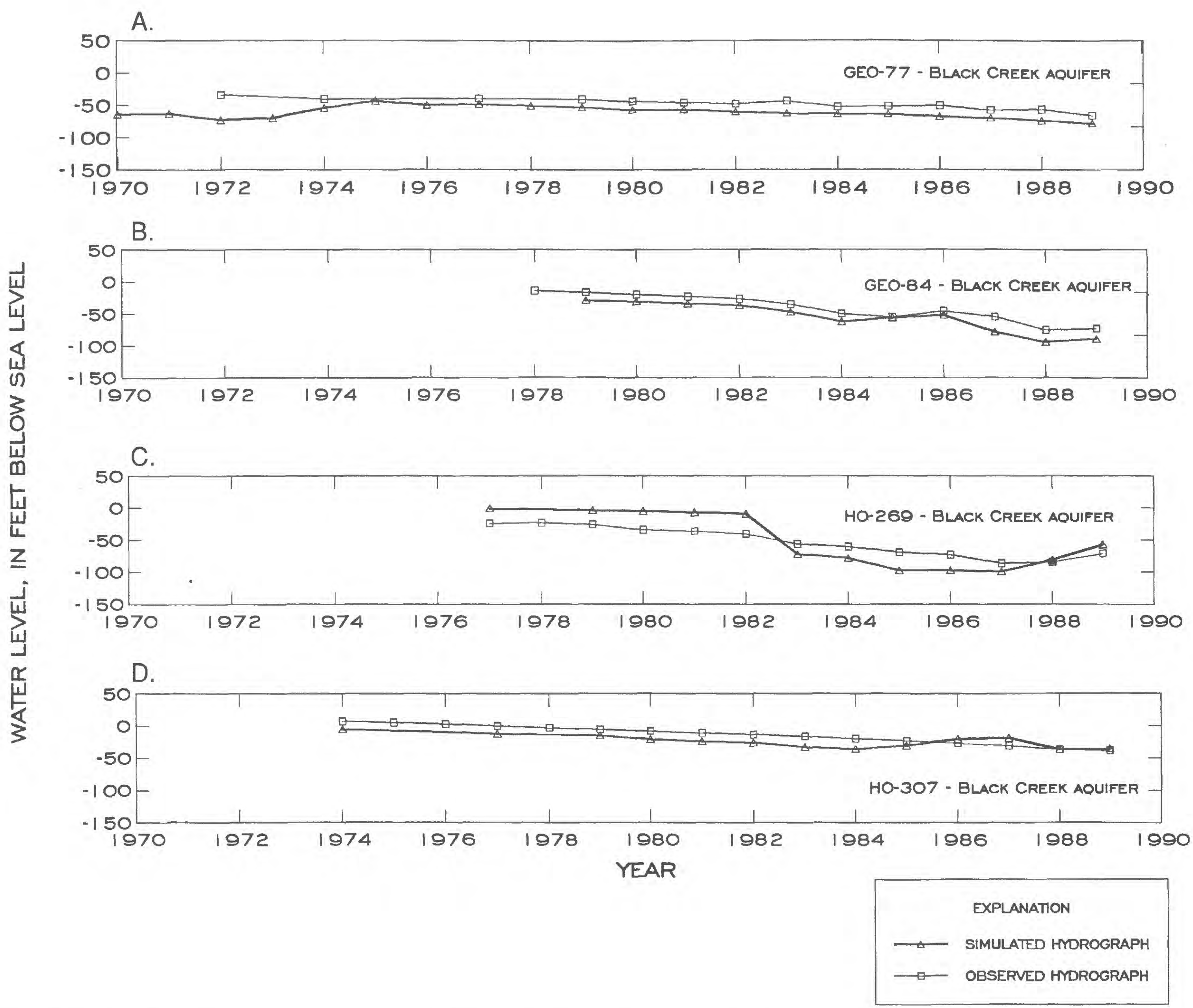


Figure 29. Observed and simulated hydrographs for GEO-77 at Georgetown, S.C. (A), GEO-84 near Pawleys Island, S.C., (B) HO-269 at Conway, S.C. (C), and HO-307 at North Myrtle Beach. S.C. (D), for layer 2.

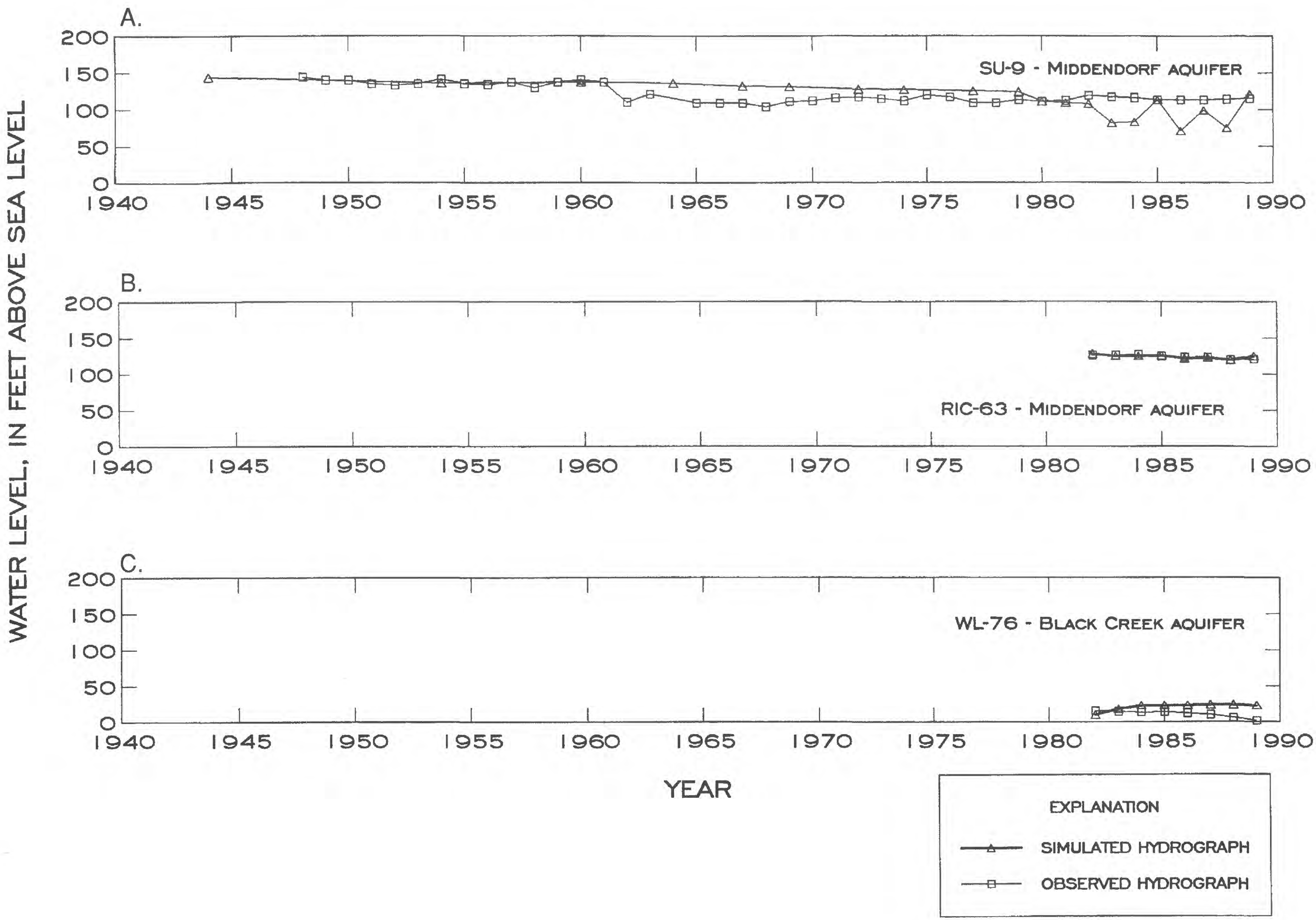


Figure 30. Observed and simulated hydrographs for SU-9 at Sumter, S.C. (A), and RIC-63 near Wateree, S.C. (B), and WL-76 at Stucky, S.C. (C), for layer 2.

Observed hydrographs for two other wells were compared with simulated hydrographs. One well is located in southern Richland County and is screened in the Middendorf aquifer; the other one is in Williamsburg County in the Black Creek aquifer (fig. 30). The simulated hydrograph of the Richland County well (RIC-63, fig. 30) matches the observed hydrograph closely; however, the simulated hydrograph of the Williamsburg County well (WL-76, fig. 30) matches the absolute water level of the observed hydrograph closely, but the trend fit is poor. The Williamsburg County area is heavily influenced by withdrawals from the Black Creek aquifer at Andrews and the Myrtle Beach area (fig. 3).

In areas with accurate ground-water withdrawal data, such as Myrtle Beach or Sumter, the simulated hydrographs closely approximated the observed values. Areas with sparse withdrawal data, such as Lee and Williamsburg Counties, had a poor fit between the observed and simulated hydrographs.

Simulated Hydrologic Characteristics

During model calibration, input parameters were changed from initial estimates obtained from the SCRASA model to values that achieved the best match of potentiometric surfaces and water levels in individual wells. Transmissivity and vertical leakage were the parameters that varied most often. Values for recharge, riverbed conductance, and storage coefficients were changed the least. The following discussion is a description of the calibrated values for transmissivity, vertical conductance, storage, recharge, and riverbed conductance.

Transmissivity

Transmissivity can be expressed as the measure of the volume of water that can pass horizontally through the fully saturated thickness of the aquifer under a hydraulic gradient of 1 ft/ft (Lohman, 1972). The units of transmissivity are cubic feet per day per square foot of aquifer material ([$(ft^3/d)/ft^2$], simplified to ft^2/d). Aquifer transmissivities have areal variability in the South Carolina Coastal Plain due to variations in the type and composition of aquifer material that result from depositional and post-depositional processes such as solution or precipitation of minerals.

Simulated transmissivities for the combined surficial and Floridan-Tertiary Sand aquifer range from 1,300 to 39,900 ft^2/d, with the highest values in the Beaufort and Jasper County area in the Floridan aquifer system. The lowest values are in the surficial-Floridan-Tertiary Sand aquifer in the eastern section of the Coastal Plain. Because this layer is simulated with specified heads in the model, the values are not presented graphically.

Simulated transmissivities for the Black Creek aquifer (layer 2) range from a low of 650 ft^2/d in the Charleston area to 7,000 ft^2/d in the northwestern and western parts. In the Florence area, the values range from 3,000 to 7,000 ft^2/d (fig. 31). In the Charleston area, there are few wells open to the Black Creek aquifer and, therefore, very little aquifer-test data is available for use as model input. The values, for the most part, are derived from the model-calibration process and range from 650 to 1,300 ft^2/d.

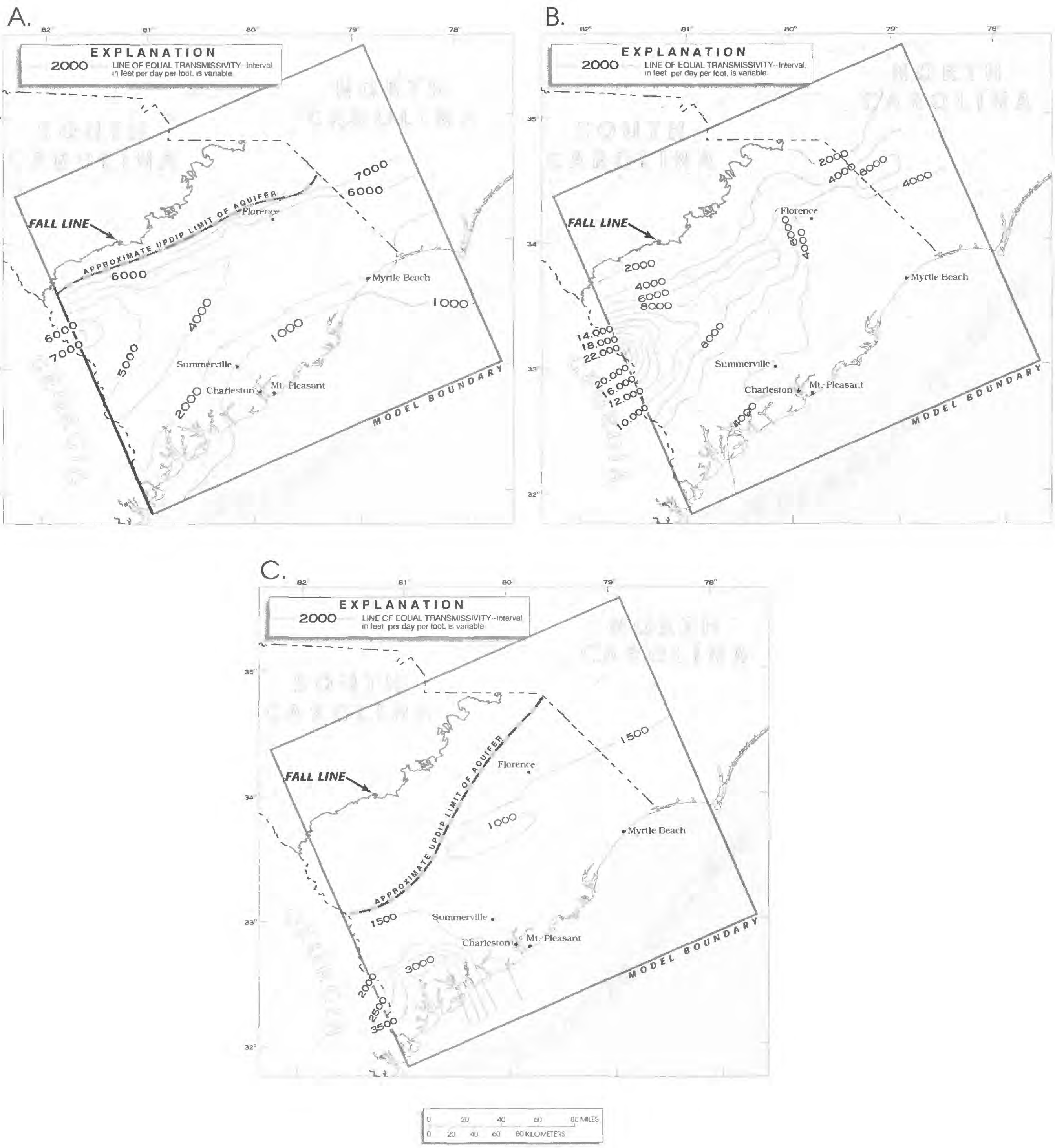


Figure 31. Simulated transmissivity of the Black Creek (A), Middendorf (B), and Cape Fear (C) aquifers.

Simulated transmissivities in the Middendorf aquifer (layer 3) range from 2,000 ft^2/d in the Fall Line area to 22,000 ft^2/d in the Aiken County area (fig. 31). The higher values reflect a large sand thickness and high hydraulic conductivities found in Aiken and Barnwell Counties (Aucott, 1988). The low values result from a higher percentage of clay in the Middendorf Formation toward the coast. The Charleston and Florence areas have experienced large (>150 ft) water-level declines during the 1970's and 1980's, which were difficult to accurately simulate with a homogeneous transmissivity value. Aucott (in press) attributes difficulties in accurately simulating the water-level declines with reasonable hydraulic parameters in the Florence area due to the highly stratified nature of the Middendorf Formation sediments. The alternating clay and sand beds of the formation inhibit the vertical flow of water when water levels are declining. This results in simulated transmissivity values that are lower than values obtained from aquifer tests in the area.

In the Charleston area, the Middendorf aquifer consists of three separate sand layers divided by two black, lignitic clay layers. The lower two sand layers are typically a fining-upward, well-sorted channel or estuarine sand. The upper sand is a macrofossilferous, fine to medium sand with a relatively constant thickness (Gohn and Campbell, 1992; Campbell and Gohn, 1994). Transmissivities in the Charleston area range from 2,200 to 4,000 ft^2/d, with the highest being in the northern Dorchester County and the lowest in Charleston County.

Simulated transmissivities for the Cape Fear aquifer (layer 4) range from 1,000 to 3,500 ft^2/d (fig. 31). These low values illustrate that movement of water through the aquifer is comparatively sluggish, and that the Cape Fear aquifer is likely to be a poor source for water-supply use (Aucott, 1988).

Vertical Leakance

Resistance to vertical flow is controlled by vertical leakance, which is the ratio of the vertical hydraulic conductivity to the thickness of sediments through which vertical flow must occur, and whose units are in per day (d^{-1}). When a confining unit is simulated between two aquifers, the effective leakance is equal to the harmonic mean (because flow must occur in series) of the leakances of the lower half of the upper aquifer and the upper half of the lower aquifer and the leakance of the confining unit (Williamson and others, 1990). This term allows for leakage of water between the various layers according to head relations. Little data are available on vertical hydraulic conductivity in the South Carolina Coastal Plain. Confining unit thicknesses were derived from interpretations of geophysical logs. Model calibration adjustments were made to obtain subjective results of leakage volumes. In this model, three layers simulate the vertical leakance between the four aquifer layers. Vertical leakance from layer 1 to the Black Creek aquifer is lowest in the coastal area of Beaufort, Jasper, Colleton, and southern Charleston counties ($1.0x10^{-9}$ d^{-1}) and highest (>$1.0x10^{-5}$ d^{-1}) in the updip parts of the Coastal Plain (fig. 32).

Leakage from and to the constant-head cells in layer 1 is controlled by a vertical leakance term and the head difference between layer 1 and the underlying layer. In the Florence area, layer 1 vertical leakance controls the amount of water that enters the Middendorf aquifer. A high leakance value between layer 1 and 2 at Florence would increase simulated vertical leakage to the Middendorf aquifer and reduce drawdown of Middendorf aquifer water levels.

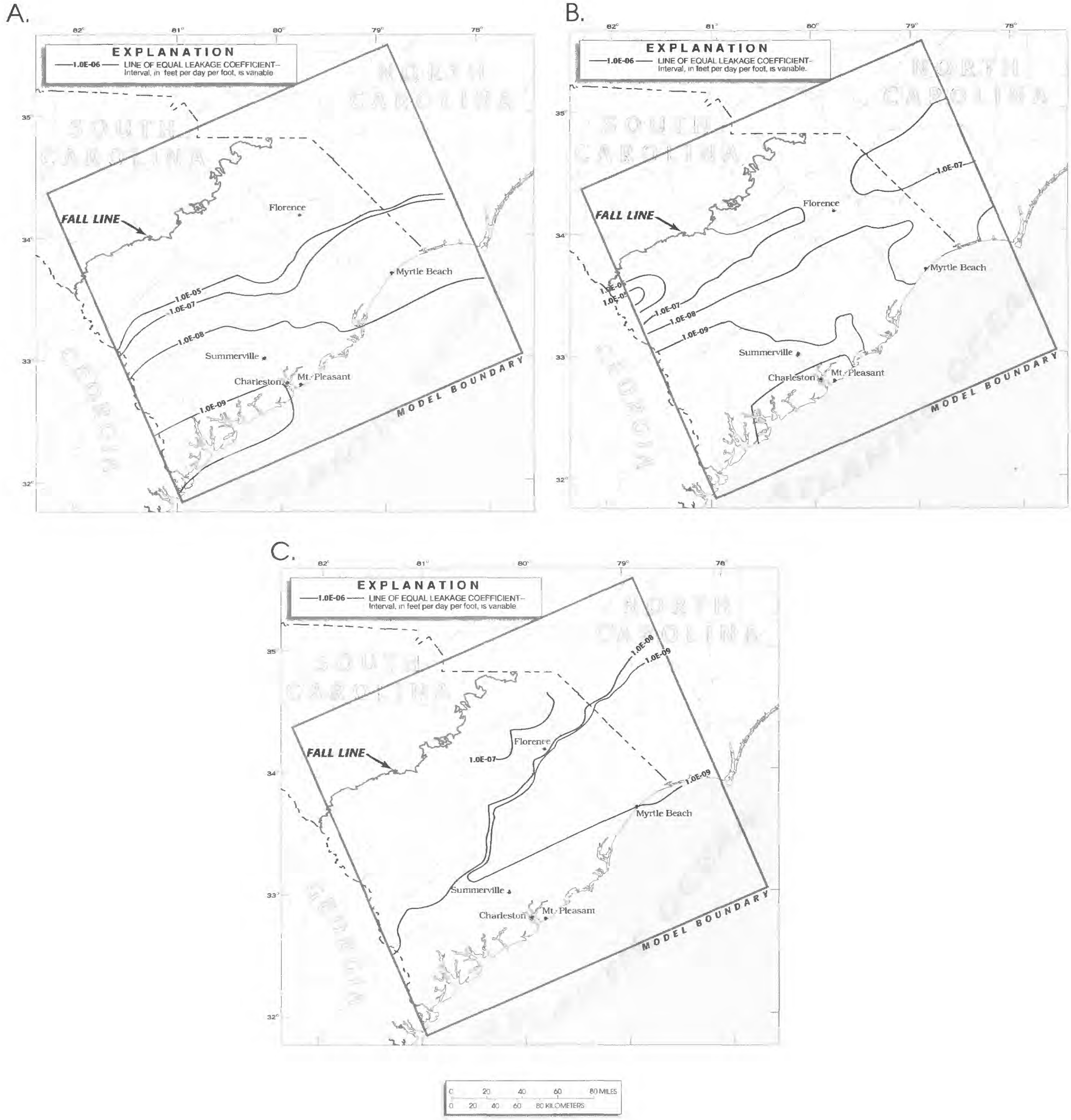


Figure 32. Simulated leakage coefficients for the surficial, Floridan, and Tertiary Sand aquifers to the Black Creek aquifer (A), Black Creek aquifer to the Middendorf aquifer (B), and Middendorf and Cape Fear aquifer (C).

Vertical leakance between the Black Creek and Middendorf aquifers is important to the overall model. Areas of large water-level declines in the Middendorf aquifer have induced vertical leakage from adjacent aquifers. Calibrated values of vertical leakance range from 1.0×10^{-9} d^{-1} in the southern part of the Coastal Plain and near Charleston to 1.0×10^{-5} d^{-1} in Aiken and Barnwell Counties. Near Florence, the calibrated value is between 1.0×10^{-8} and 1.0×10^{-7} d^{-1} (fig. 32).

The vertical leakance between the Middendorf and Cape Fear aquifers is relatively low and homogeneous throughout the modeled area. There is little exchange of water between these two aquifers. The vertical leakance values are highest in the northern Pee Dee region, lowest in the southern part of the state, and range from 1.0×10^{-9} to 1.0×10^{-7} d^{-1} (fig. 32).

Storage Coefficient

An aquifer storage coefficient is defined as the volume of water that an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head. Storage coefficient is a dimensionless parameter that is used only for transient simulations (Lohman, 1972). Layer 1 is not actively simulated, so a graphical presentation of the storage coefficient is not included. In the transient simulations for the Black Creek and Middendorf aquifers, their outcrop areas are simulated with a storage coefficient of 0.2, which is within the range usually associated with unconfined aquifers (Lohman, 1972). In the confined part of the aquifers, the simulated storage coefficient is 0.0003 (fig. 33). The Cape Fear aquifer is simulated as confined over the entire model area and a storage coefficient of 0.0003 is used.

Recharge

The South Carolina Coastal Plain receives about 46 in/yr of precipitation (Snyder and others, 1983). Overland flow to surface-water bodies, evapotranspiration, and recharge to the shallow ground-water system account for most of this water. Most of the surficial aquifer system recharge is discharged into nearby surface-water bodies and, therefore, not simulated. A small part of the precipitation, however, recharges the Cretaceous aquifer system in its outcrop area (Aucott, 1988). The amount of recharge to the Cretaceous aquifer system is not known. Recharge rates cannot be measured directly in the field; therefore, rates are determined by model calibration.

The model is designed to simulate areally distributed recharge to the ground-water system as a result of precipitation that percolates into the ground (McDonald and Harbaugh, 1988). In the CF model, recharge is applied at a constant rate throughout the stress periods to the outcrop areas of the Black Creek and Middendorf aquifers.

The simulated rate of recharge is expressed in feet per day of water and ranges from 9.9×10^{-5} to 7.99×10^{-4} ft/d (0.43 to 3.5 in/yr) (fig. 34). The highest recharge rates occur near the Congaree River and the lowest in the northern Pee Dee region.

To accurately simulate recharge to the southern part of the Black Creek aquifer in the Pee Dee region is not possible. During model calibration, applying recharge to the Pee Dee area produced inaccurate water-level declines resulting from withdrawals in the Middendorf aquifer. Because recharge occurs in this area, the assumption is that the local surface-water system removes the water and very little flows vertically from the Black Creek aquifer into the Middendorf aquifer. The CF model is regional, so local surface-water bodies are not simulated.

A.

B.

Figure 33. Simulated storage coefficients for the Black Creek (A) and Middendorf aquifers (B).

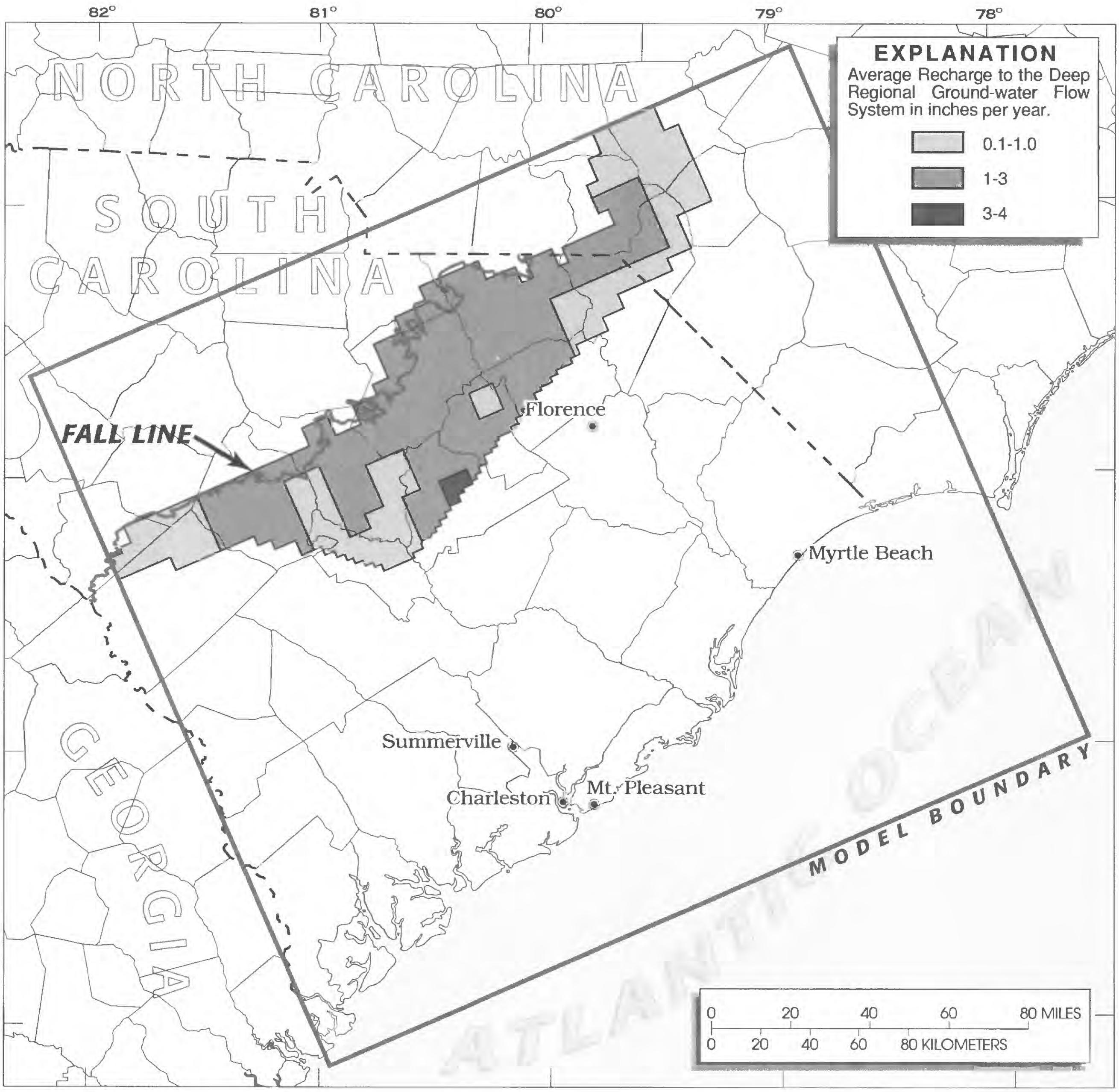


Figure 34. Recharge rate for the Charleston-Florence, S.C. model.

Rivers

Rivers and streams may add or remove water from the ground-water-flow system. The direction of the hydraulic gradient between the river and the surrounding aquifer determines if water is added to or drained from the ground-water system. The amount of water that is lost or gained is a function of the head difference between the river and the aquifer, and the riverbed conductance.

Aucott and others (1987) determined base flow of eight large rivers in the upper Coastal Plain region of the model (table 7). All of these rivers are simulated in the model, where they serve primarily as drains for the Black Creek and Middendorf aquifers (fig. 35). Riverbed conductances were estimated from model calibrations by matching observed and simulated baseflow (table 7).

Few of the aquifer-to-river discharges are accurately simulated by either the SCRASA or CF model. The Lumber River and the South Fork Edisto River are closely matched by the SCRASA model, whereas only the Lumber River is matched fairly well by the CF model (table 7). The lack of fit by the CF model compared to the SCRASA model is attributable to the finer discretization of the model grid. The SCRASA model used a 4 by 4 mi regularly spaced grid and the CF model used a variably spaced grid that generally has smaller grid cells ranging from 1 by 1 mi to 1 by 4 mi. This gives a smaller cross-sectional area to simulate riverbed leakance; as a result, smaller simulated volumes of water drained from the aquifers. Increasing the riverbed conductance did not produce a closer fit of the potentiometric surface data, nor did increasing the recharge rates.

Table 7. *Simulated and observed baseflow for selected rivers in the upper Coastal Plain of South Carolina (All values are in cubic feet of water per second)*

River	Observed[1]	South Carolina Regional Aquifer System Analysis model[2]	This report
South Fork Edisto	45	42	17
North Fork Edisto	100	79	22
Lynches	110	41	32
Pee Dee	101	70	42
Lumber	29	28	17

[1]From Aucott and others, 1986.
[2]From Aucott, 1988.

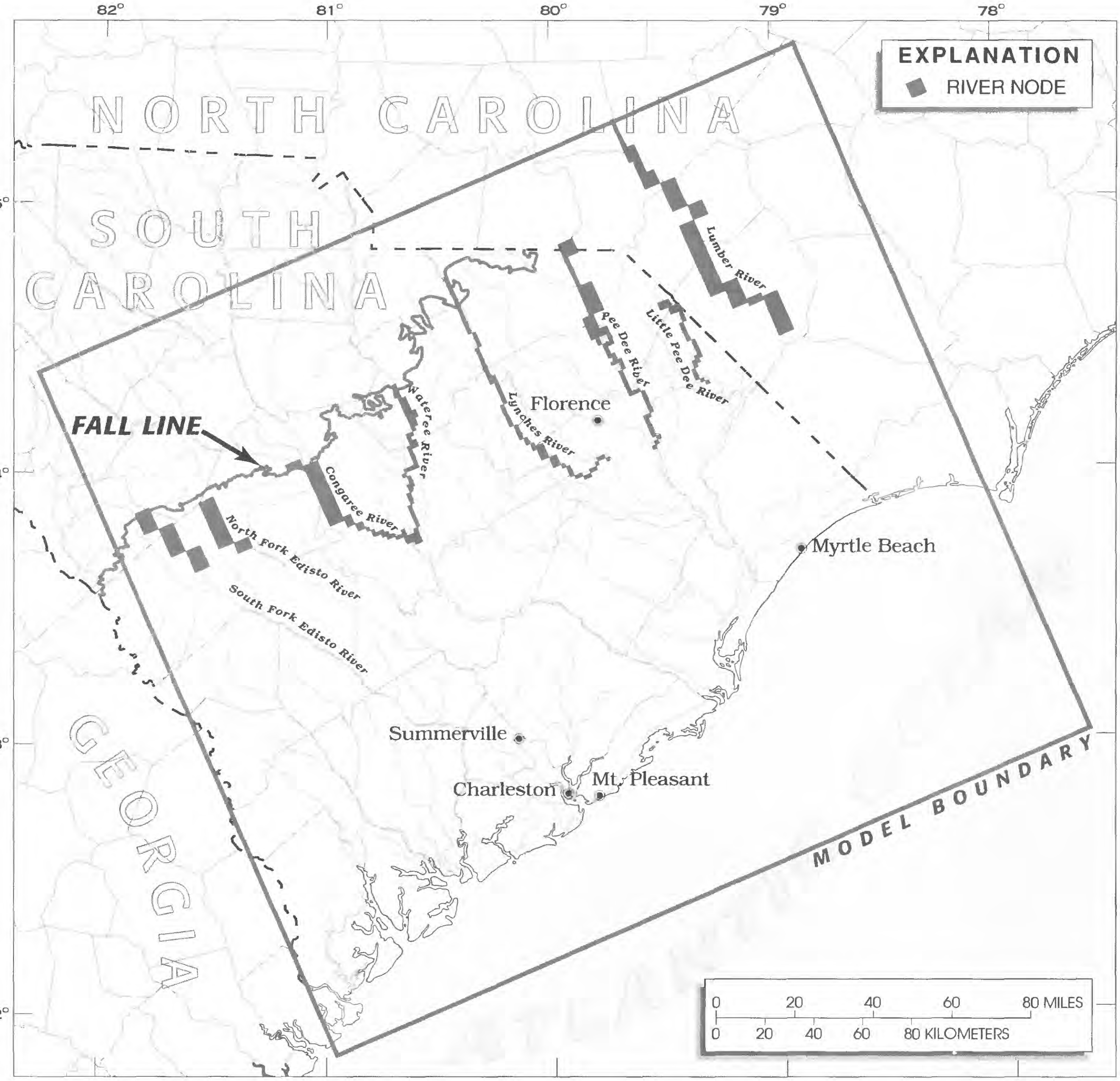


Figure 35. Locations of river nodes on the Charleston-Florence model grid.

Sensitivity Analysis

The effects of independently changing hydraulic parameters on simulated ground-water levels were determined in a sensitivity analysis of the calibrated model. The objective of this analysis was to determine which model parameter, when changed in a systematic manner from the values used in the calibrated model, produced the greatest or least changes in water levels in the Black Creek and Middendorf aquifers. The response of the model to changes in these properties indicates the degree of accuracy necessary in simulating these parameters in the model.

For the CF model, a sensitivity analysis was made by adjusting vertical hydraulic conductances, recharge, storage coefficients, transmissivities, and withdrawal rates (fig. 36). Systematic changes were made to a particular parameter, while holding the remaining input parameters constant. The values of the RMSE of simulated and observed water levels of the Black Creek and Middendorf aquifers for the 1989 set of water-level measurements were used for statistical comparison of the sensitivity model runs (figs. 23 and 24) (table 8).

The calibrated model is most sensitive to decreases in transmissivity and least sensitive to decreases in recharge. Increases of a factor of 1.1 and 1.2 of the withdrawal rate produces a lower RMSE than in the calibrated model, indicating that the available water-use data for the Coastal Plain underestimates the true water use. RMSE's for the Middendorf aquifer increase if withdrawal rates, transmissivity, storage coefficient, and vertical leakance are decreased. Increases in the parameters give larger RMSE's for transmissivity, storage coefficient, recharge, and vertical leakance. The model is relatively insensitive to decreases in recharge, increases in withdrawal rates, and decreases in vertical leakance for the Middendorf aquifer.

Table 8. *Results of sensitivity analyses for 1989 conditions (in feet)*

VERTICAL CONDUCTANCE

Root-mean-square-errors

Aquifer	Multiplier				
	0.01	0.1	1	10	100
Black Creek	85	61	27	45	52
Middendorf	29	27	28	34	40

RECHARGE

Root-mean-square-errors

Aquifer	Multiplier				
	0.01	0.1	1	10	100
Black Creek	26	26	27	110	1,082
Middendorf	37	34	28	392	4,170

Table 8. *Results of sensitivity analyses for 1989 conditions (in feet)*--Continued

STORAGE

Root-mean-square-errors

Aquifer	Multiplier				
	0.01	0.1	1	10	100
Black Creek	30	29	27	32	52
Middendorf	39	36	28	40	50

TRANSMISSIVITY

Root-mean-square-errors

Aquifer	Multiplier						
	0.1	0.25	0.50	1	1.25	1.50	2
Black Creek	217	165	134	27	103	98	92
Middendorf	2,263	1,048	621	28	343	309	263

WITHDRAWALS

Root-mean-square-errors

Aquifer	Multiplier						
	0.8	0.9	0.95	1	1.05	1.10	1.20
Black Creek	32	29	28	27	27	27	27
Middendorf	35	31	29	28	27	26	25

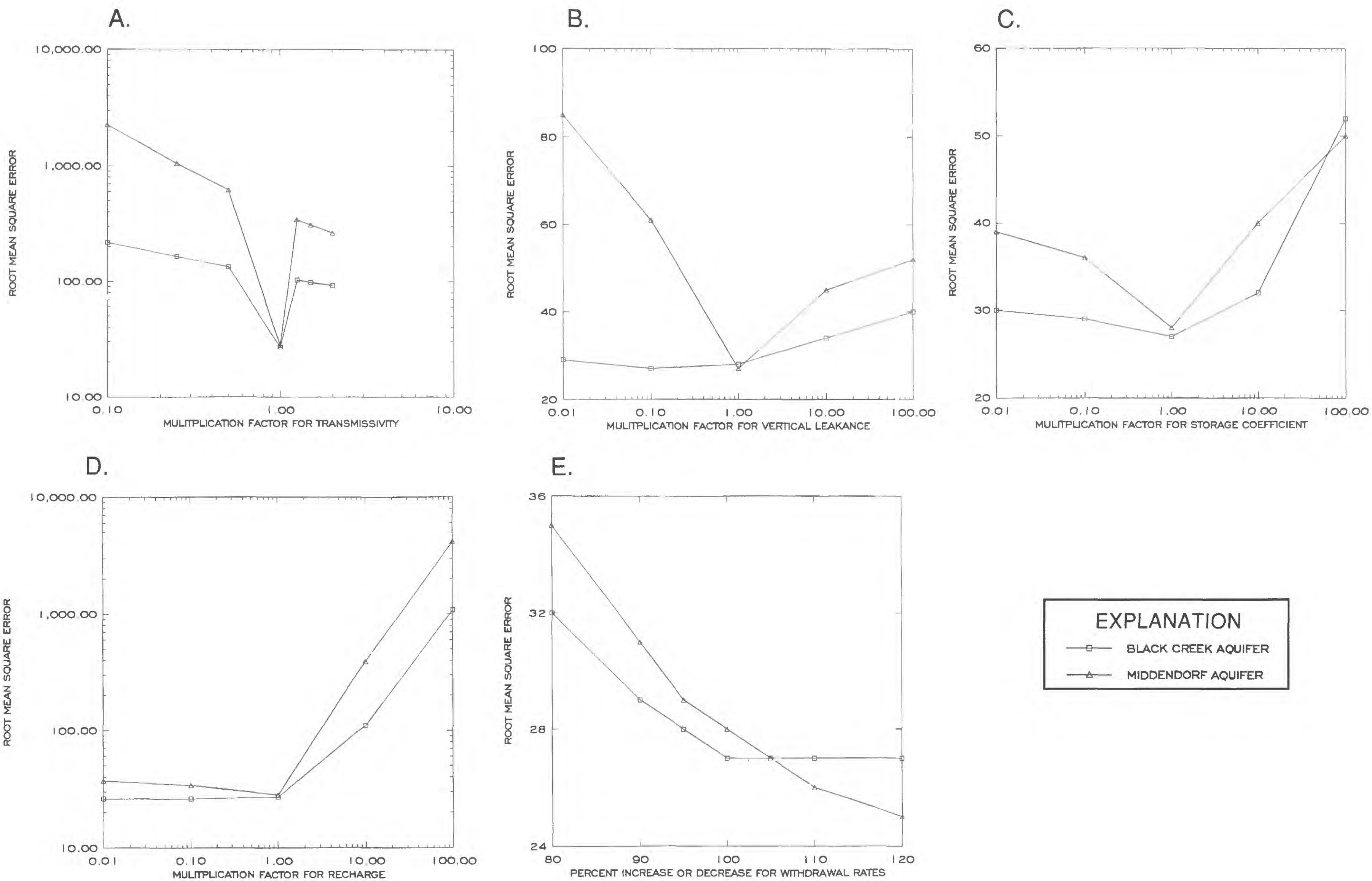


Figure 36. Sensitivity analyses of root-mean-square-error of the Black Creek and Middendorf aquifer water-level residuals, 1989, for transmissivity (A), vertical leakanc e (B), storage coefficient (C), recharge (D), and withdrawal rates (E).

Decreases in the transmissivity produces a significant effect on water levels, which is reflected in the extreme RMSE. Increases also have a large effect, but there is little difference between the 1.25 and 2 factors. This indicates the model is sensitive only to a point to increases in transmissivity, and then water levels remain constant (fig. 36). Decreases in transmissivity appear to produce increasingly larger RMSE's indicating extreme sensitivity of the model to transmissivity. For vertical leakance, increases in this parameter in both aquifers or decreases in the Black Creek aquifer produce changes in RMSE values, which indicates the model is moderately sensitive to this parameter (fig. 36). Vertical leakance and transmissivity were the parameters varied the most during the calibration procedure. Decreases in the storage coefficient produce small increases in RMSE's in both aquifers, whereas increases in the coefficient produce increased RMSE's both aquifers (fig. 36). This is probably due to the smaller outcrop area of the Black Creek aquifer and, therefore, the larger percentage of unconfined aquifer storage coefficient for the Middendorf aquifer used in the model. Increases in recharge have a large effect on the simulated water levels because the model heads increase drastically due to the extra water (fig. 36). Decreasing the recharge rate reduces the amount of water available to the system, but has little effect on the RMSE's.

The model was also tested for sensitivity to changes in the withdrawal rates for the total modeled time (1875 through 1989). The withdrawal rates were increased and decreased by factors of 5, 10, and 20, percent and the results compared the RMSE's of the 1989 water-level measurements. Increasing the withdrawal rate by 5, 10, and 20 percent produced a lower RMSE for the Middendorf aquifer. Decreasing the withdrawal rates produced large RMSE's for both aquifers (fig. 36). The lower RMSE, with increases in withdrawal rate, is attributed to missing water-use data. Many wells are entered into the database without withdrawal rates, locations, or screened intervals, and therefore, cannot be accurately utilized in the model.

Simulated Water Budgets

Predevelopment, 1982, and 1989 water budgets are presented for the entire modeled area of the South Carolina Coastal Plain, the city of Florence, and the town of Mount Pleasant near Charleston (fig. 37). These budgets account for inflow and outflow of water to and from the ground-water-flow system by hydrologic component and model layer. Water budget components of the entire model are volumes of recharge, inflow to or outflow from rivers, inflow to or outflow from specified-head boundaries, net changes in storage, withdrawal by wells, and flow between model layers. The Florence and Mount Pleasant area water budgets incorporate net changes in storage, withdrawal by wells, and volume of flow across the vertical boundaries of these two areas and flow between the model layers.

The water budget for the entire model shows that the major changes from predevelopment to 1982 and from predevelopment to 1989 are the changes in flows between model layers and the net storage changes (fig. 38). Flow between the model layers increased from a net flux of 8,611,000 ft^3/d for predevelopment to a net flux of 18,560,000 ft^3/d for 1989. Most of this change was a result of withdrawals in the Charleston, Florence, and Myrtle Beach areas. Concentrated withdrawals at these pumping centers withdraws water from storage, which results in the lowering of water levels. This, in turn, leads to an increase in inter-aquifer flow, which is induced by the greater vertical hydraulic gradients.

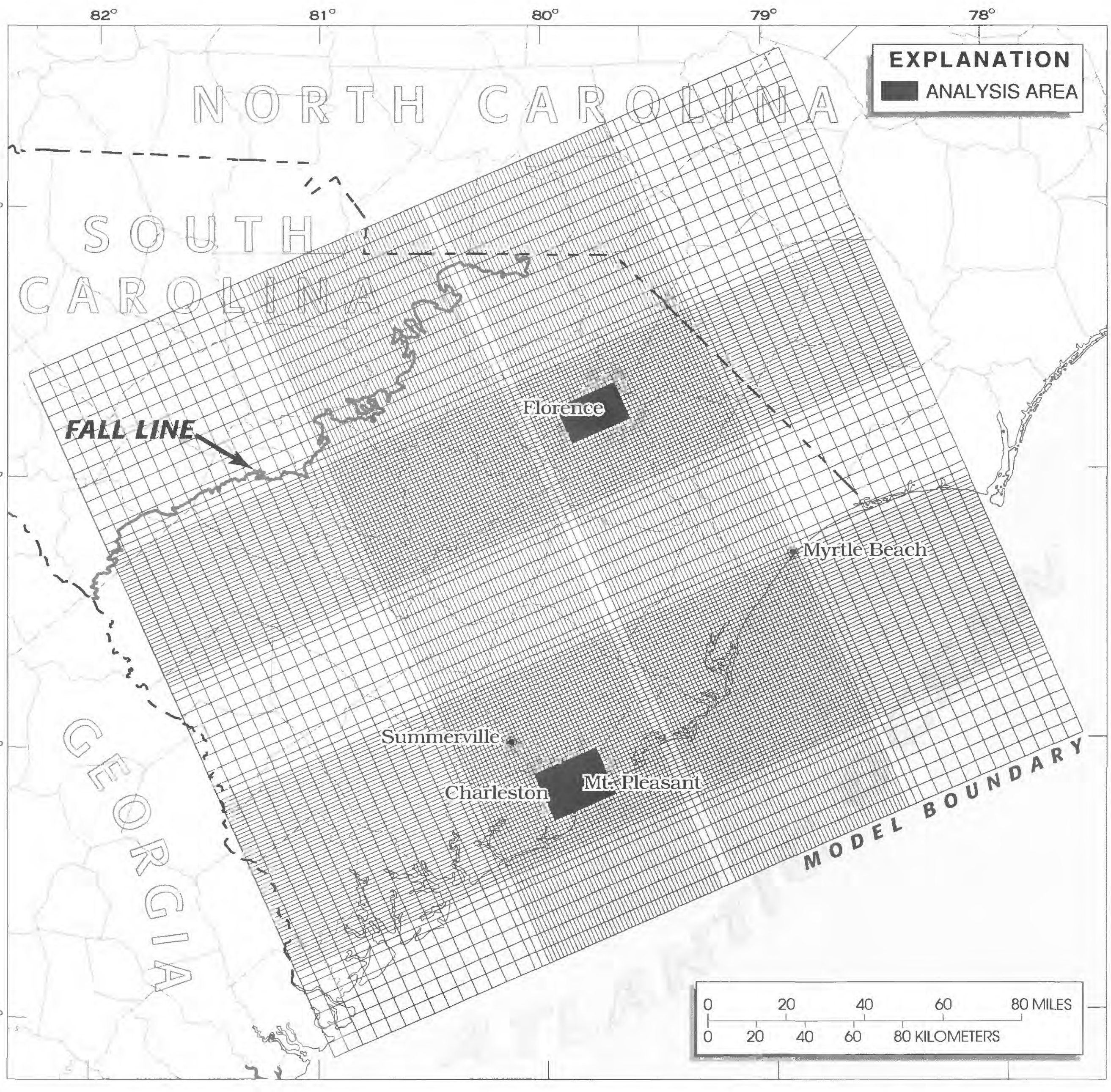


Figure 37. Map showing areas of water-budget analysis for the Florence and Mount Pleasant areas of South Carolina.

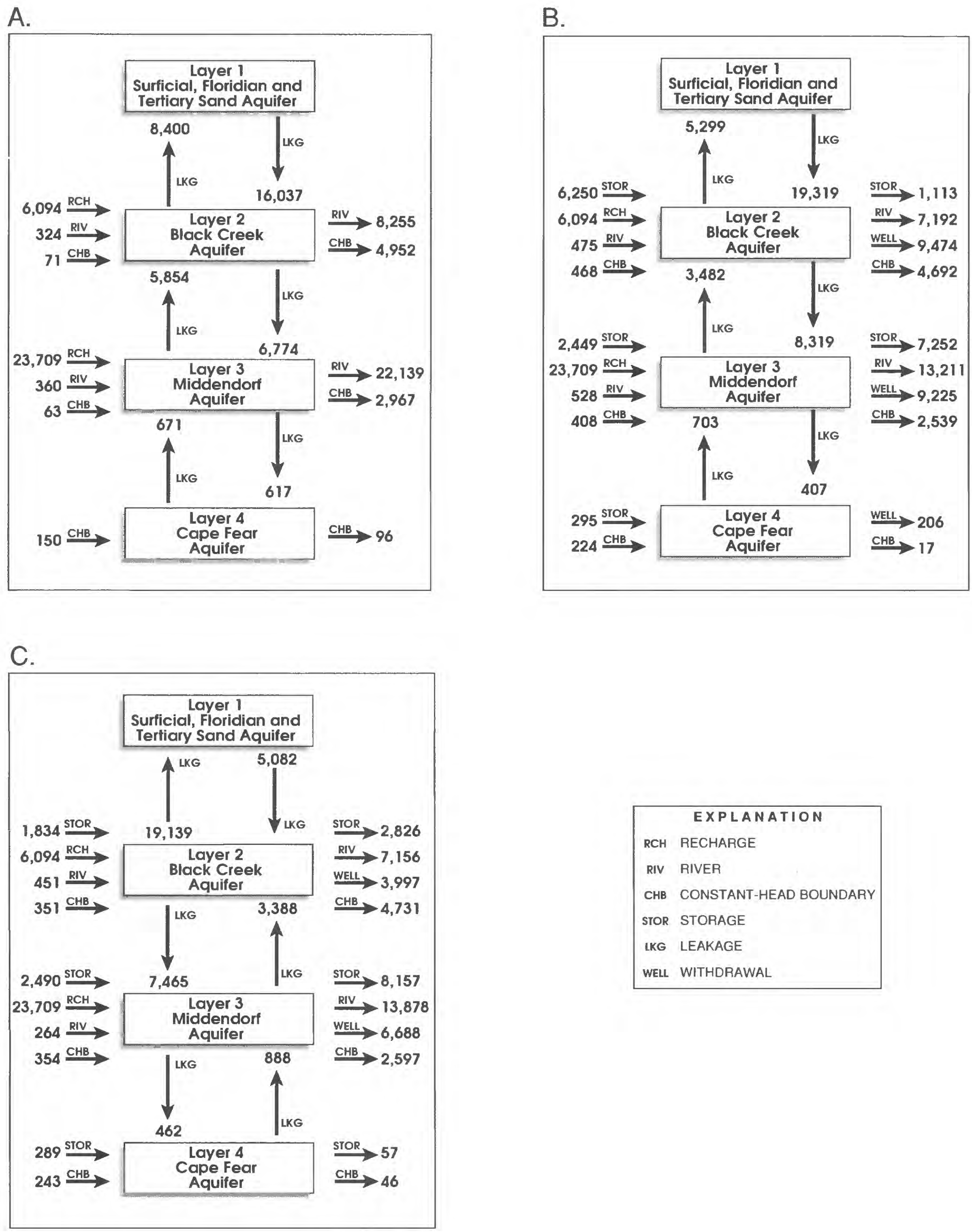


Figure 38. Water budget for the total model area for predevelopment (A), 1982 (B), and 1989 (C) (units are 1,000 cubic feet per day).

The Florence area water budget is presented to understand the source of water produced from the Middendorf aquifer wells (fig. 39). Predevelopment fluxes through the aquifer were rather small: 220,000 ft^3/d in the Black Creek aquifer; 197,000 ft^3/d in the Middendorf aquifer; and 28,000 ft^3/d in the Cape Fear aquifer (fig. 39). There was also a contribution of 101,000 ft^3/d to the Black Creek aquifer from the surficial aquifer. In 1982, these fluxes had increased due to the volume of water being withdrawn from the Black Creek and Middendorf aquifers. The 1982 fluxes were 154,000 ft^3/d from the surficial aquifer, 373,000 ft^3/d in the Black Creek aquifer, 871,000 ft^3/d in the Middendorf aquifer, and 78,000 ft^3/d in the Cape Fear aquifer (fig. 39). In the 1982 budget, pumping from the Middendorf aquifer in the Florence area captured most of the outflow of the area for which a budget was computed. In addition, pumping from the Middendorf aquifer reversed the vertical hydraulic gradient between this aquifer and the Black Creek aquifer, and induced greater vertical leakage from the Cape Fear aquifer. Predevelopment leakage from the Middendorf aquifer to the Black Creek aquifer was 42,000 ft^3/d. In 1982, this flow direction had reversed and 63,000 ft^3/d of water moved downward from the Black Creek aquifer to the Middendorf aquifer.

By 1982, there is little net-storage change due to the stabilization of water levels. Large storage changes occurred prior to 1982 from the time withdrawals began in the Florence area in 1926. By 1982, a large depression had been created in the Middendorf potentiometric surface that was inducing flow into the Florence area from all horizontal directions and vertically from the Black Creek and Cape Fear aquifers. In 1982, large net storage changes in the Black Creek aquifer indicated that the water level in this aquifer was declining due to withdrawals in the Middendorf aquifer. Conditions in 1989 were similar to 1982 (fig. 39).

In the Mount Pleasant budget area (fig. 40), predevelopment fluxes were low in the Cretaceous aquifers. Flow rates were 30,000 ft^3/d for the Black Creek aquifer, 45,000 ft^3/d for the Middendorf aquifer, and 16,000 ft^3/d for the Cape Fear aquifer (fig. 40).

Predevelopment vertical flow in the Cretaceous aquifers was upward with 5,000 ft^3/d flowing from the Cape Fear aquifer to the Middendorf aquifer and 23,000 ft^2/d flowing from Middendorf aquifer to the Black Creek aquifer. Flow from the Black Creek aquifer to the constant-head boundary of layer 1 was 6,000 ft^3/d.

In 1982, a situation similar to the Florence area had developed in the Mount Pleasant area. Water levels were declining in the Middendorf aquifer due to increasing rates of ground-water withdrawal. This was beginning to produce a moderately sized depression in the potentiometric surface that affected water levels in the Charleston, Berkeley, and Dorchester County area. Withdrawals at Summerville also contributed to the declines. Fluxes were 26,000 ft^3/d in the Black Creek aquifer, 252,000 ft^3/d in the Middendorf aquifer, and 29,000 ft^3/d in the Cape Fear aquifer (fig. 40).

By 1989, a regional depression had developed in the potentiometric surface of the Middendorf aquifer near Mt. Pleasant. In addition to declining water levels, net storage in the Middendorf aquifer near Mount Pleasant decreased by 53,000 ft^3/d. Fluxes in the Black Creek aquifer were 52,000 ft^3/d with a negative net-storage change of 18,000 ft^3/d. Fluxes in the Middendorf aquifer were 658,000 ft^3/d and 40,000 ft^3/d in the Cape Fear aquifer (fig. 40). Water withdrawn from wells open to the Middendorf aquifer captured all of the horizontal ground-water flow in the aquifer and induced vertical flux from the Black Creek (47,000 ft^3/d) and Cape Fear (30,000 ft^3/d) aquifers.

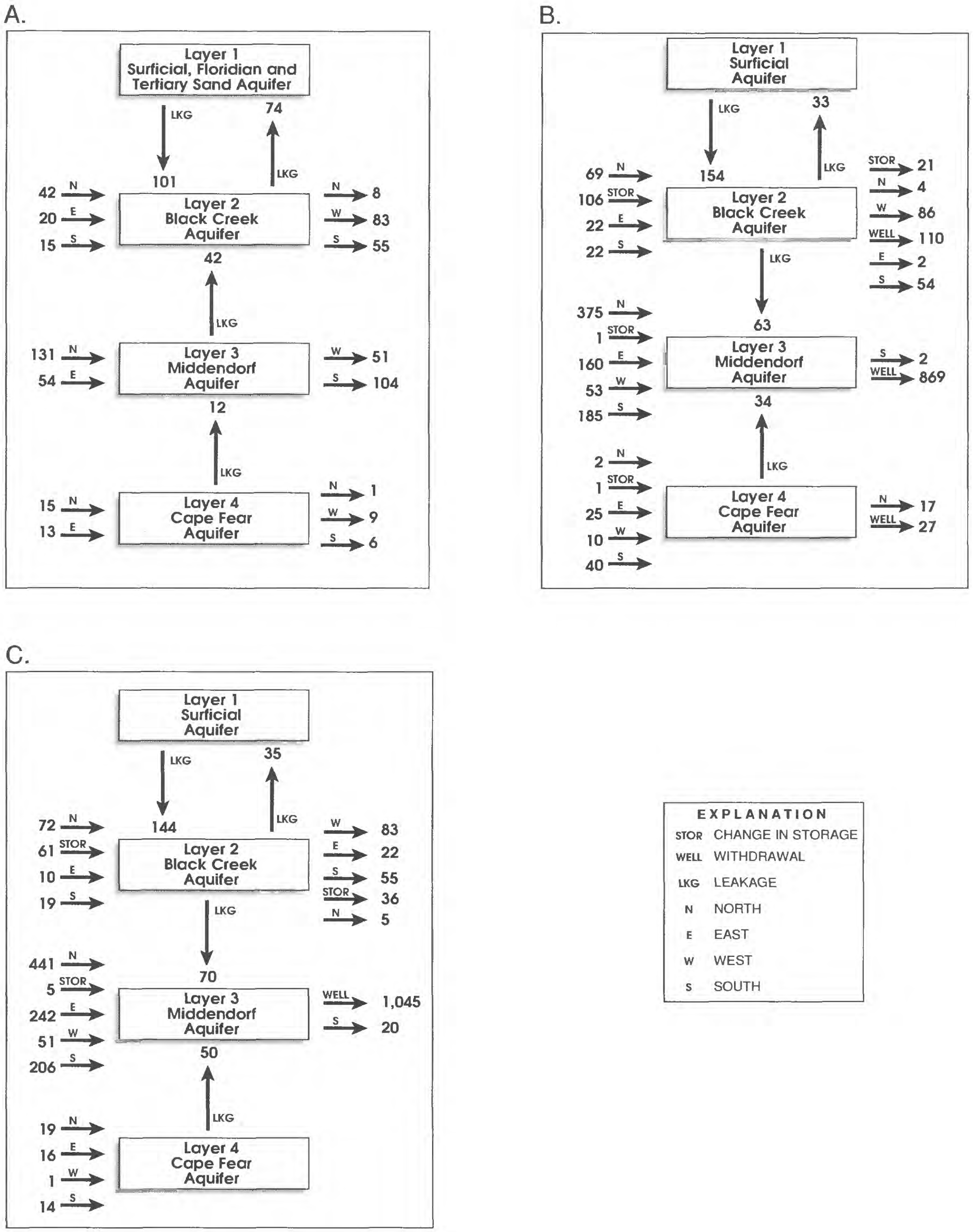


Figure 39. Water budget for the Florence, S.C., area for predevelopment (A), 1982 (B), and 1989 (C) units are 1,000 cubic feet per day.

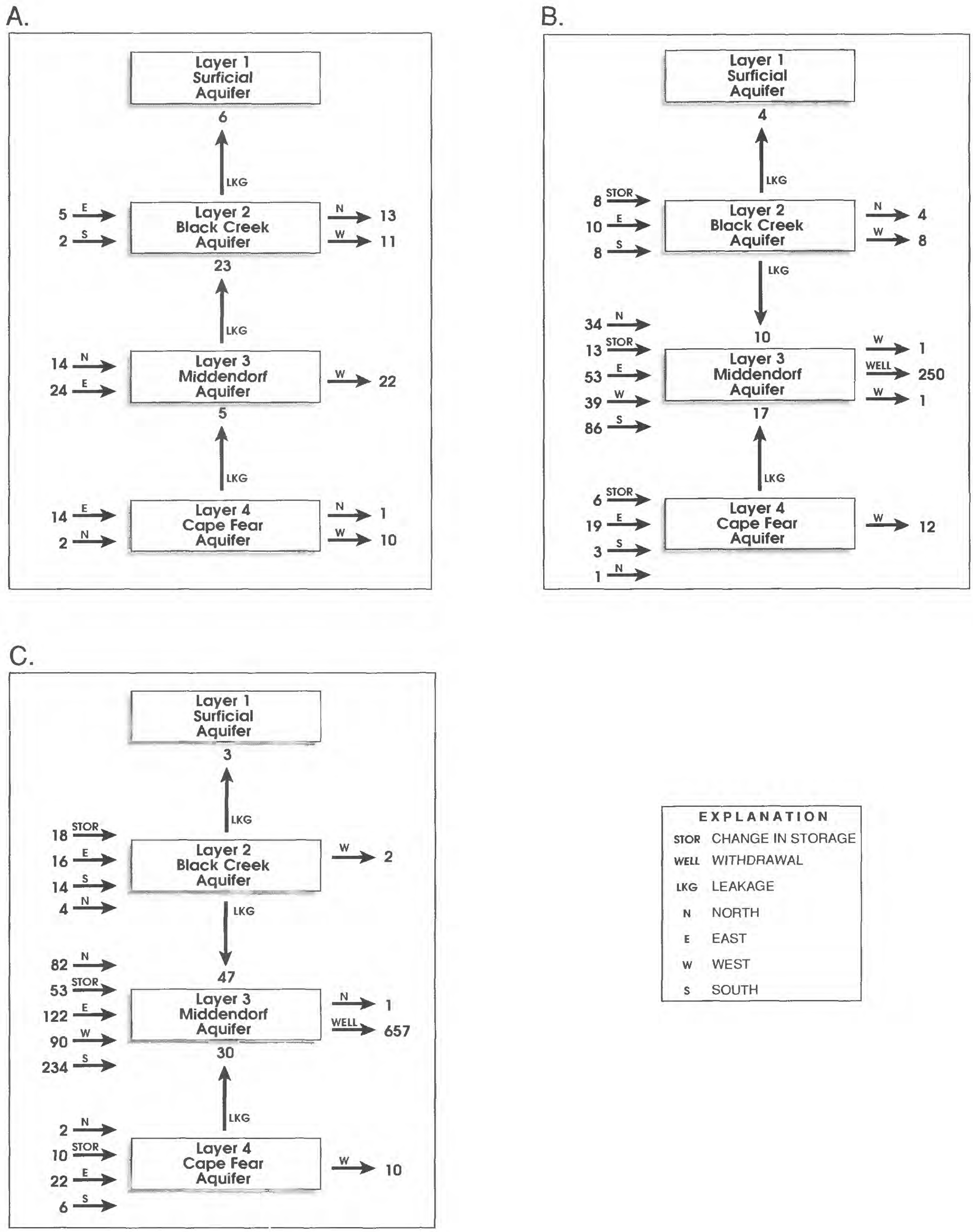


Figure 40. Water budget for the Mount Pleasant, S.C., area for predevelopment (A), 1982 (B), and 1989 (C) units are 1,000 cubic feet per day.

Ground-Water Flow Model Reliability and Limitations

Several factors can affect the reliability of the results from the CF model simulation. The major factor is the validity of the calibrated hydraulic characteristics of the Cretaceous aquifer system. Only some of the calibrated hydraulic values can be compared with observed values. Field verification is difficult because the observations have a limited spatial distribution (such as, transmissivities from aquifer tests) or because the parameters have not been measured (such as, recharge). Because the simulated aquifers are in the deep subsurface in most of the Coastal Plain, only point data from wells are available to verify aquifer thicknesses and potentiometric heads. Another factor that affects model reliability is how well the model design represents the physical aquifer system. Choice and location of boundaries has the greatest influence in this case.

When analyzing model results, factors of scale must be considered. Attempts to use the model to quantify problems in localized areas or for individual wells may not be an appropriate use of the model, because the model lacks resolution for such applications. Large-scale changes, such as gradually increasing withdrawal rates at any given location in the two study areas, could be addressed, but using the model to determine the level of drawdown in an individual well would not give reliable results. Site specific analysis would require a more detailed model and more hydrologic information. The estimation of aquifer properties, the choice of the type and location of model boundaries, and the potentiometric surfaces used for calibration rely on indeterminate hydrogeologic data. Also, because of the large number of variables used as input to the model, the solution for head values is not unique. There are a number of different combinations of transmissivity, vertical conductance, and storage coefficient that could be combined to yield the same head value at any given point in the model. The model input and output should be evaluated using any future hydrogeologic data collected in the study areas.

Care should be taken in interpreting model results from outside the two study areas. Water-use data from outside the study areas tends to be incomplete due to several factors, including lack of screen zone data, missing location data, and unknown withdrawal rate. Poor-quality water-use data could provide erroneous model results.

The CF model did not simulate base flow in the modeled rivers very accurately due to the variable-spaced model grid. Model results from the up-dip part of the model should be used with care due to this limitation.

Simulated Withdrawal Scenarios

The utility of the CF model is demonstrated by eight ground-water withdrawal scenarios simulated for the Mount Pleasant area. Mount Pleasant presently (1993) uses the Middendorf aquifer as a sole source of potable water. These simulations use various combinations of existing and future Middendorf aquifer wells, their spatial distribution, and injection of treated wastewater effluent (fig. 41). Withdrawal and injection rates were varied in time and space in the various scenarios. The following are the scenarios that were simulated from 1990 to 2015:

1A. Maximize use of existing wells--Withdrawals from existing wells to be at the present design capacity, and new wells are to be pumped only at a rate required to meet anticipated average annual demands (table 9).

1B. Distributing demands--Same as 1A, but distributes the withdrawal evenly from all wells (table 10).

2A. Reduced demand from the Middendorf aquifer by developing other water sources (table 11).

2B. Same as 2A, but reclaimed water is to be available for irrigation use for half of the service area (table 12).

2C. Same as 2A, but reclaimed water is to be available for irrigation use for the entire service area (table 13).

3. Inject highly treated, reclaimed water into the Middendorf aquifer (table 14).

4. End all withdrawal from the Middendorf aquifer in 1994.

5. Summerville withdrawals at a rate of 7 percent annual increase to 2015.

Table 9. *Withdrawal rates for scenario 1A*

[Mgal/d, million gallons per day]

	Withdrawal (Mgal/d)						
Well	1990	1993	1995	2000	2005	2010	2015
1	1.40	1.40	1.40	1.40	1.40	1.40	1.40
2	2.10	2.10	2.10	2.10	2.10	2.10	2.10
3	0	.50	.50	.64	.73	.79	.96
4	.40	.50	.50	.64	.73	.79	.96
5	.40	.50	.50	.64	.73	.79	.96
6	0	0	.50	.64	.73	.79	.96
7	0	0	0	.64	.73	.79	.96
8	0	0	0	0	.73	.79	.96
9	0	0	0	0	0	.79	.96
Total	4.3	5	5.5	6.7	7.9	9	10.2

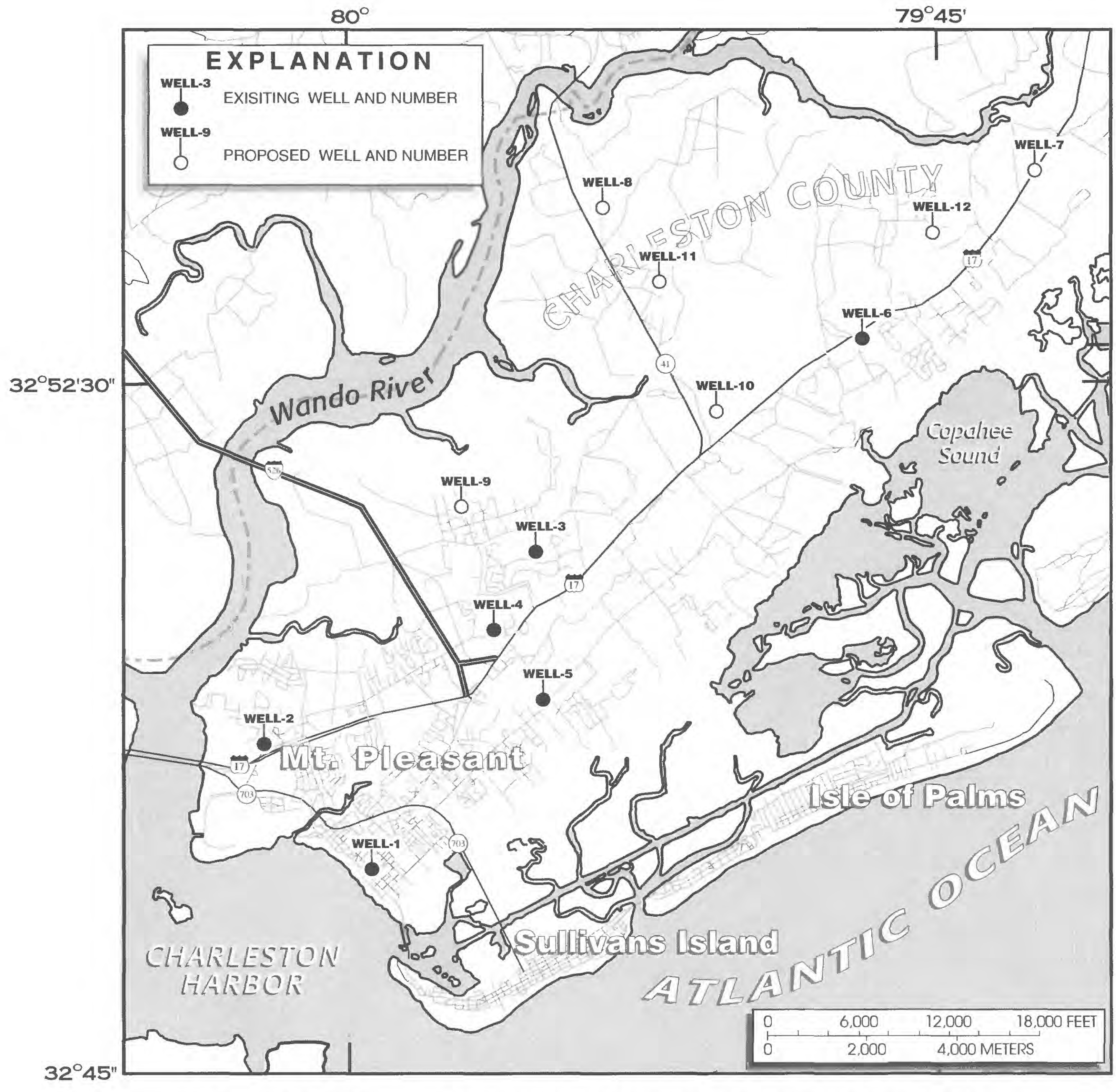


Figure 41. Existing and proposed Middendorf aquifer wells in the Mount Pleasant, S.C., area.

Table 10. *Withdrawal rates for scenario 1B*

[Mgal/d, million gallons per day]

	Withdrawal (Mgal/d)						
Well	1990	1993	1995	2000	2005	2010	2015
1	1.08	1	0.92	0.96	0.99	1	1.13
2	1.08	1	.92	.96	.99	1	1.13
3	0	1	.92	.96	.99	1	1.13
4	1.08	1	.92	.96	.99	1	1.13
5	1.08	1	.92	.96	.99	1	1.13
6	0	0	.92	.96	.99	1	1.13
7	0	0	0	.96	.99	1	1.13
8	0	0	0	0	.99	1	1.13
9	0	0	0	0	0	1	1.13
Total	4.3	5	5.5	6.7	7.9	9	10.2

Table 11. *Withdrawal rates for scenario 2A*

[Mgal/d, million gallons per day]

	Withdrawal (Mgal/d)						
Well	1990	1993	1995	2000	2005	2010	2015
1	1.4	1.4	1.4	1.4	1.4	1.4	1.4
2	2.1	2.1	2.1	2.1	2.1	2.1	2.1
3	0	.5	.5	.5	.5	.5	.5
4	.4	.5	.5	.5	.5	.5	.5
5	.4	.5	.5	.5	.5	.5	.5
6	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0
Total	4.3	5	5	5	5	5	5

Table 12. *Withdrawal rates for scenario 2B*

[Mgal/d, million gallons per day]

	Withdrawal (Mgal/d)						
Well	1990	1993	1995	2000	2005	2010	2015
1	1.4	1	0.9	0.9	0.9	0.9	1
2	2.1	1	.9	.9	.9	.9	1
3	0	1	.9	.9	.9	.9	1
4	.4	1	.9	.9	.9	.9	1
5	.4	1	.9	.9	.9	.9	1
6	0	0	.9	.9	.9	.9	1
7	0	0	0	.9	.9	.9	1
8	0	0	0	0	.9	.9	1
9	0	0	0	0	0	.9	1
Total	4.3	5	5.4	6.3	7.2	8.1	9

Table 13. *Withdrawal rates for scenario 2C*

[Mgal/d, million gallons per day]

	Withdrawal (Mgal/d)						
Well	1990	1993	1995	2000	2005	2010	2015
1	1.4	1	0.9	0.9	1.1	1.2	1.4
2	2.1	1	.9	.9	1.1	1.2	1.4
3	0	1	.9	.9	1.1	1.2	1.4
4	.4	1	.9	.9	1.1	1.2	1.4
5	.4	1	.9	.9	1.1	1.2	1.4
6	0	0	.9	.9	1.1	1.2	1.4
7	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0
Total	4.3	5	5.4	5.4	6.6	7.2	8.4

Table 14. *Withdrawal and injection rates for scenario 3*

[Mgal/d, million gallons per day; -, minus]

	Withdrawal/injection (Mgal/d)						
Well	1990	1993	1995	2000	2005	2010	2015
1	1.40	1.40	1.40	1.40	1.40	1.40	1.40
2	2.10	2.10	2.10	2.10	2.10	2.10	2.10
3	0	.50	-1.00	-1.00	-1.05	-1.30	-1.24
4	.40	.50	-1.00	-1.00	-1.05	-1.30	-1.24
5	.40	.50	1.00	1.07	1.10	1.10	1.34
6	0	0	1.00	1.07	1.10	1.10	1.34
7	0	0	0	0	0	1.10	1.34
8	0	0	0	1.07	1.10	1.10	1.34
9	0	0	0	0	1.10	1.10	1.34
10	0	0	0	-1.00	-1.05	-1.30	-1.24
11	0	0	0	0	-1.05	-1.30	-1.24
12	0	0	0	0	0	0	-1.24
Withdrawal total	4.3	5	5.5	6.7	7.9	9	10.2
Injection total	0	0	-2	-3	-4.2	-5.2	-6.2

These scenarios were simulated using the calibrated transient model. Two methods were used to analyze the results; potentiometric surface maps and hydrographs of two observation wells open to the Middendorf aquifer. Scenarios 1A, 1B, 2B, and 2C produced low water levels of about -150 ft (table 15; figs. 42 and 43), and scenario 5 produced the lowest water level of -186 ft. Scenarios 2A and 3 (figs. 43 and 44), which reduce the demand on the Middendorf aquifer and inject reclaimed water back into it, produced the highest water levels of -76 ft and -52 ft, respectively. Ending all withdrawal at Mount Pleasant in 1994 (scenario 4) produced a gradual recovery and a low water level of 16 ft in 2015 (fig. 44). Leaving the withdrawal at Summerville in the model with a 7 percent annual increase (scenario 5) resulted in a low water level of -186 ft at Mount Pleasant, indicating that withdrawal at Summerville has little affect on the water levels at Mount Pleasant (fig. 44). Two hydrographs of existing Middendorf aquifer wells also were simulated. The wells (CHN-14 and BRK-431) are located in downtown Charleston and Moncks Corner, respectively (figs. 45, 46, and 47). The hydrographs give Middendorf aquifer water levels at these two points from 1969 through 2015. Historic water-level data are available for these two wells (figs. 12 and 13) to compare with the ending potentiometric surfaces.

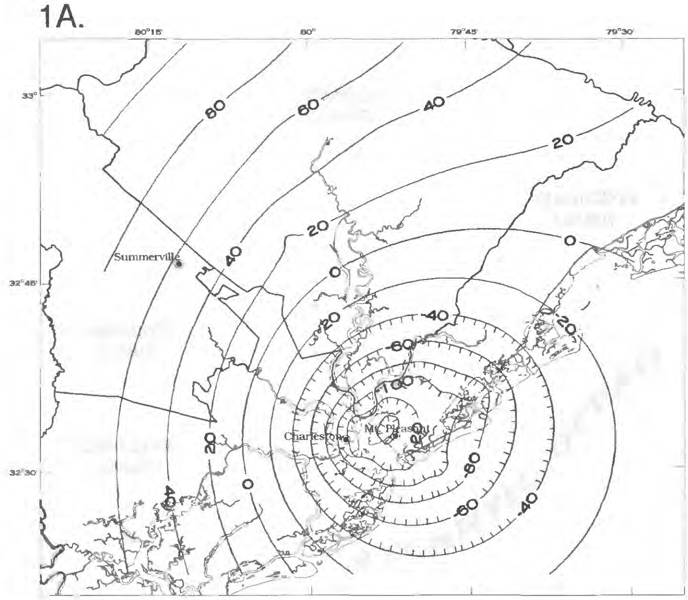
Further simulations were performed to test the models response to additional pumpage at a proposed industrial site 11 mi north of Mount Pleasant. The results of these simulations are presented in the appendix.

Table 15. *Minimum simulated water levels for year 2015 and total drawdown from predevelopment to year 2015 in the Middendorf aquifer for the Mount Pleasant, S.C., area*

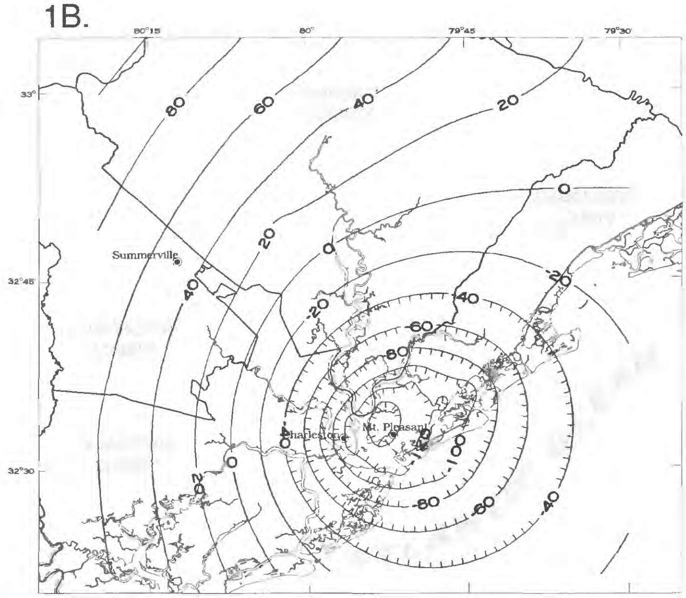
[ft bsl, feet above or below (-) sea level; ft, feet]

Scenario	Minimum water level (ft bsl)	Total drawdown from predevelopment (ft)
1A	-150	276
1B	-155	281
2A	-76	304
2B	-142	268
2C	-150	276
3	-52	178
4	16	142
5	-186	312

1A.



1B.



EXPLANATION

——60—— SIMULATED POTENTIOMETRIC CONTOUR--Shows altitude at which water level would have stood prior to development in tightly cased wells. Hachures indicate depressions. Contour interval 20 feet. Datum is sea level.

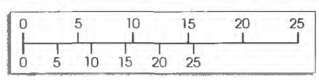
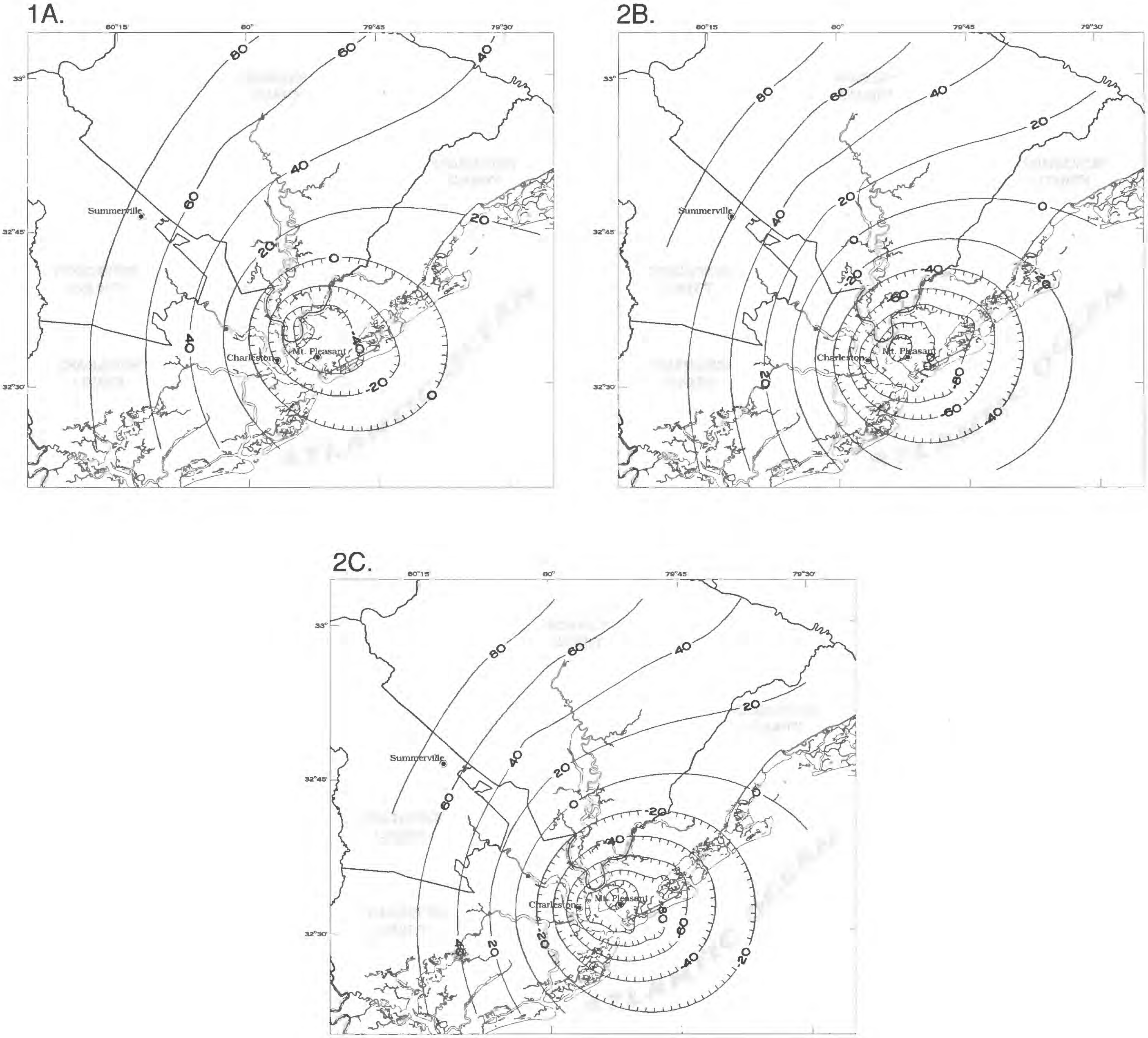


Figure 42. Simulated potentiometric surface of the Middendorf aquifer in the year 2015 using Scenarios 1A and 1B.



———60———	**EXPLANATION** SIMULATED POTENTIOMETRIC CONTOUR--Shows altitude at which water level would have stood prior to development in tightly cased wells. Hachures indicate depressions. Contour interval 20 feet. Datum is sea level.

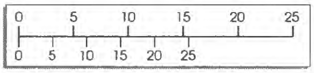
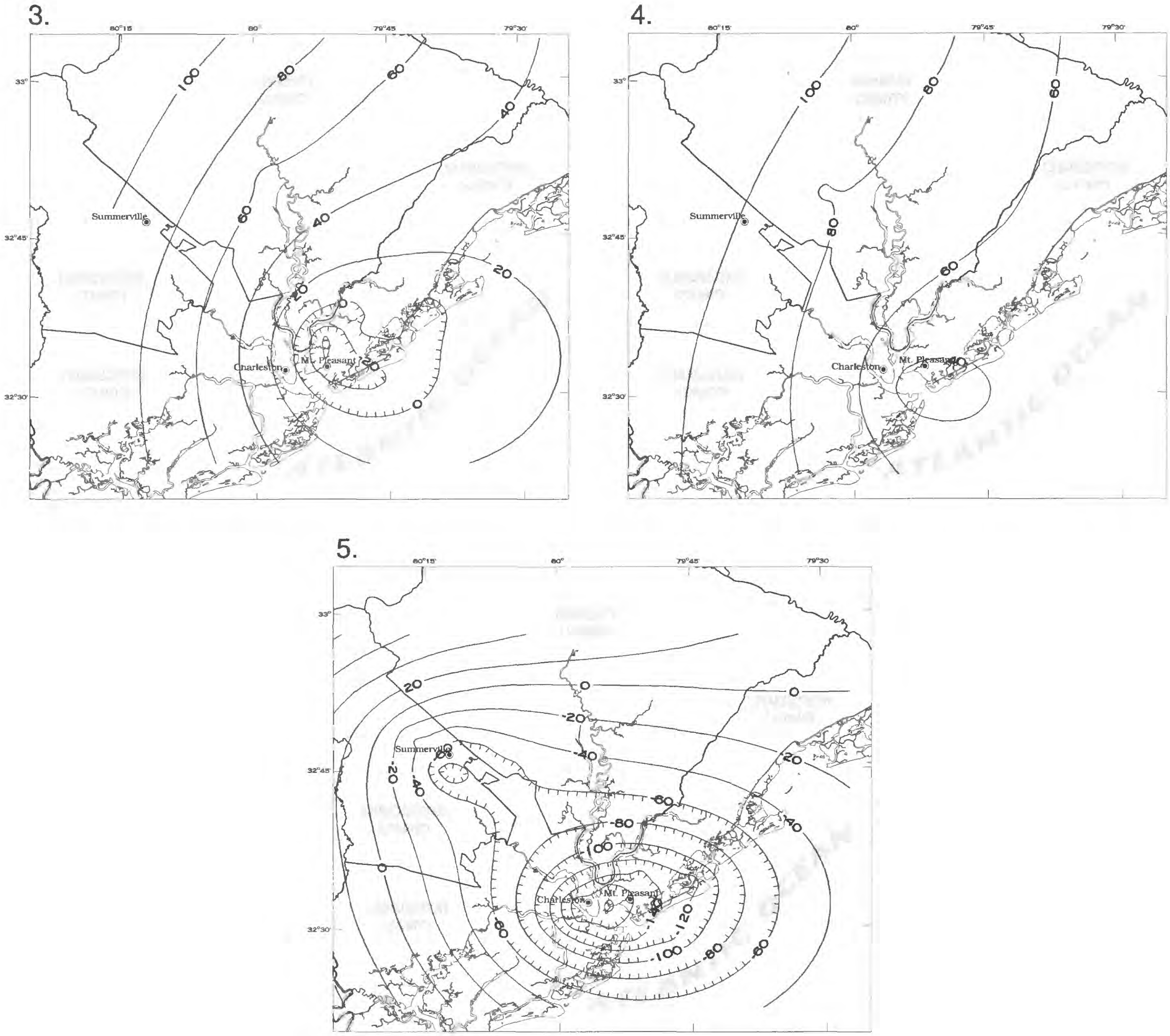


Figure 43. Simulated potentiometric surface of the Middendorf aquifer in the year 2015 using Scenarios 2A, 2B, and 2C.



EXPLANATION

——— 100 ——— SIMULATED POTENTIOMETRIC CONTOUR--Shows altitude at which water level would have stood prior to development in tightly cased wells. Hachures indicate depressions. Contour interval 20 feet. Datum is sea level.

0 5 10 15 20 25

0 5 10 15 20 25

Figure 44. Simulated potentiometric surface of the Middendorf aquifer in the year 2015 using Scenarios 3, 4, and 5.

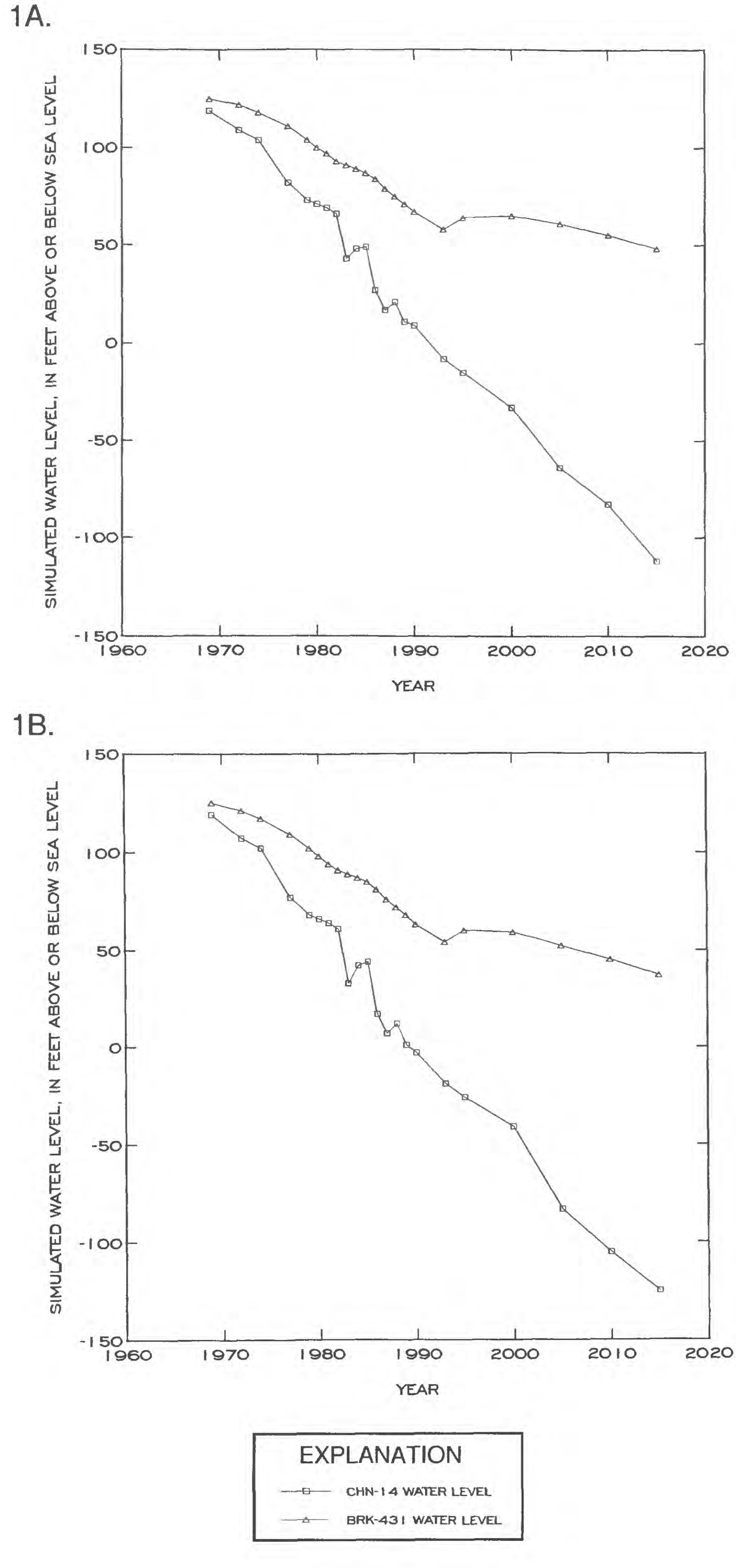


Figure 45. Simulated hydrographs of CHN-14 and BRK-431 using scenarios 1A, 1B for 1969-2015.

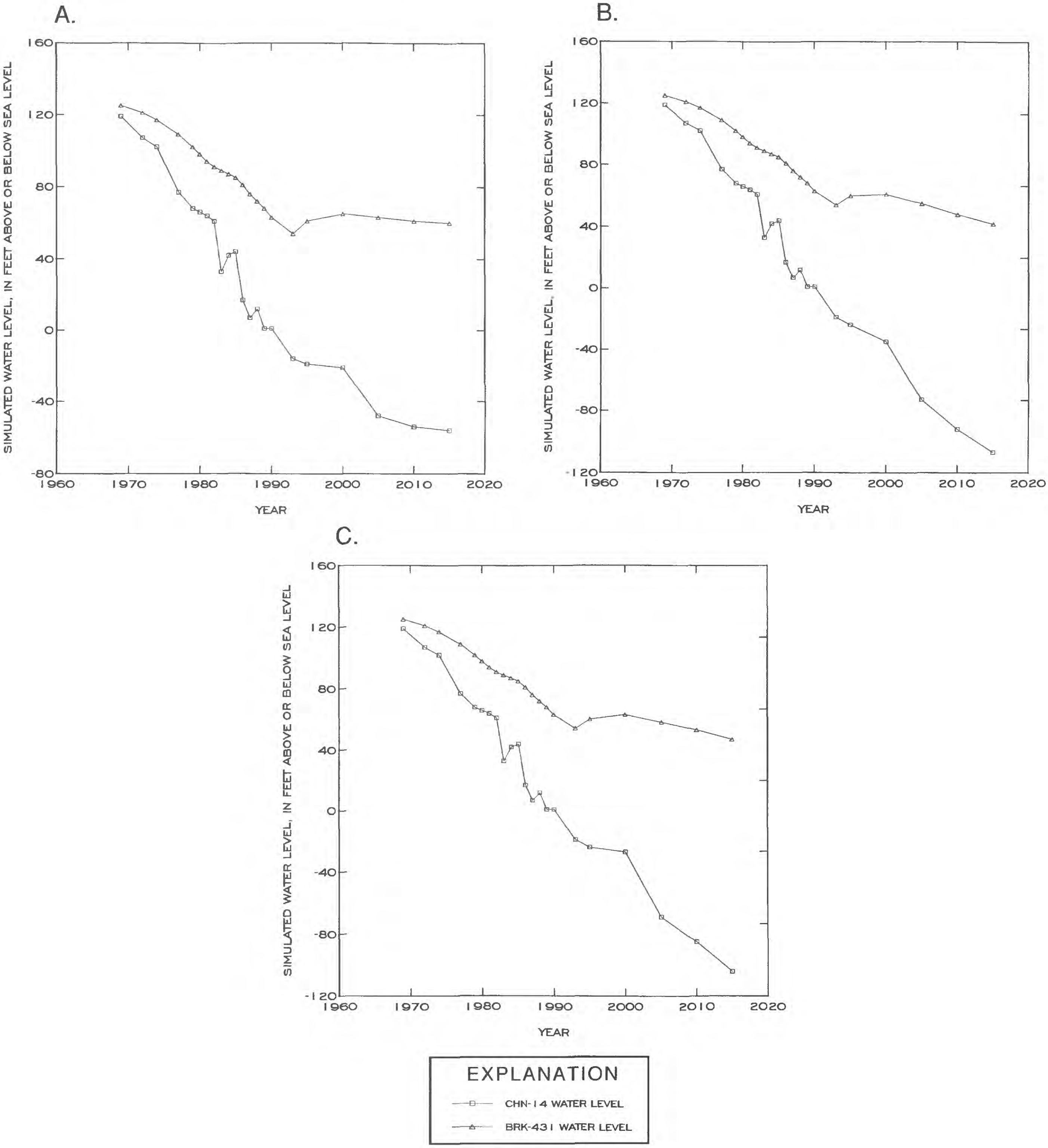


Figure 46. Simulated hydrographs of CHN-14 and BRK-431 using scenarios 2A, 2B, and 2C for 1969-2015.

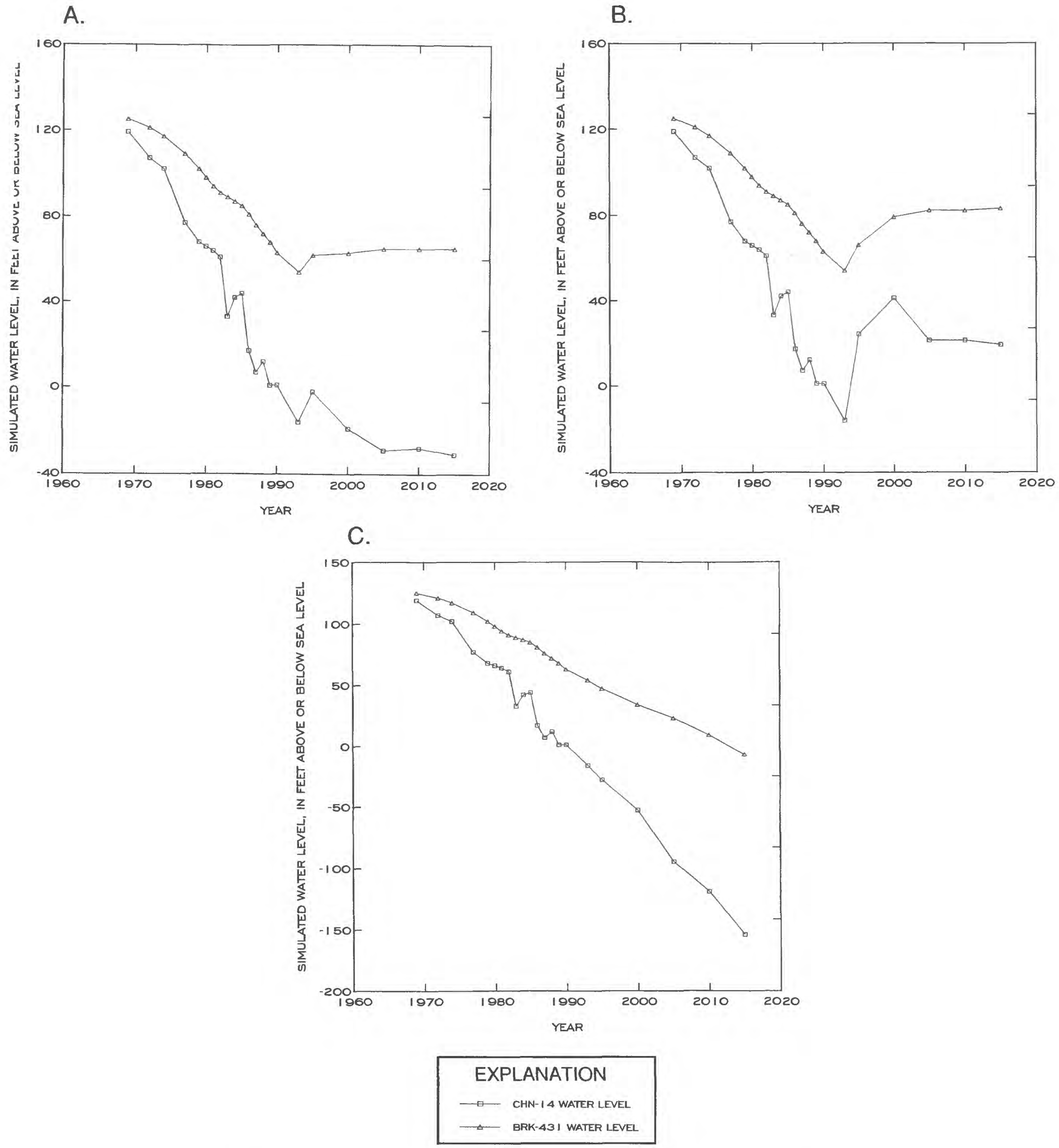


Figure 47. Simulated hydrographs of CHN-14 and BRK-431 using scenarios 3, 4, and 5 for 1969-2015.

SUMMARY

Ground-water withdrawals from the Middendorf aquifer near Charleston and Florence, S.C., have caused the development of large, regional depressions in the potentiometric surface that cover hundreds of square miles. The depth, size, and shape of the depressions depend on the withdrawal volumes and the hydraulic characteristics of the aquifers and confining units. Leakage through adjacent confining units, water removed from storage, and horizontal flow are the major sources of water for these ground-water withdrawals. Simulations indicate that large volumes of water are supplied to the aquifer systems from recharge in the outcrop areas. A total of 29,803,000 ft^3/d of water is simulated as recharge to the outcrop areas of the Black Creek and Middendorf aquifers. Under predevelopment conditions, 30,394,000 ft^3/d of water discharged to large rivers where they are incised into the upper Coastal Plain.

Ground-water flow in the Cretaceous aquifers in the Charleston and Florence areas is simulated using a finite-difference model of four aquifers (of which three are actively simulated) and three intervening confining beds. The model grid has 115 rows and 127 columns, and has a variable grid size that ranges from 1 by 1 mile to 4 by 4 mile cells. The simulated area was bounded on the northwest by a no-flow boundary, on the northeast by a no-flow or specified-head boundary, on the southeast by a no-flow boundary, and on the southwest by a specified-head boundary. The bottom of the model is simulated as a no-flow boundary on the basis of the assumption of low hydraulic conductivity in the pre-Cretaceous rock units. The top layer of the model is a simulated source-sink, specified-head layer representing a combination of three aquifer systems: the surficial, Tertiary Sand, and Floridan. An estimated stationary saltwater and freshwater interface at the 10,000 mg/L chloride concentration corresponds to the southeast boundary of the model.

Transmissivities in layer 1, which combines the Floridan-Tertiary Sand aquifer with the surficial aquifer, range from 1,300 to 39,900 ft^2/d, with highest values being in the Beaufort and Jasper County area in the Floridan aquifer system. Simulated transmissivities for the Black Creek aquifer (layer 2) range from a low of 650 ft^2/d in the Charleston area in the northeastern part of the South Carolina Coastal Plain to 7,000 ft^2/d in the northwestern and western part. In the Middendorf aquifer (layer 3), transmissivities range from 2,000 ft^2/d in the Fall Line area to 22,000 ft^2/d in the Aiken County area. Transmissivities are generally low in the Cape Fear aquifer (layer 4), ranging from 1,000 to 3,500 ft^2/d.

Vertical leakage from layer 1 to the Black Creek aquifer is lowest in the coastal area of Beaufort, Jasper, Colleton, and southern Charleston Counties ($1.0x10^{-9}$ d^{-1}) and highest ($>1.0x10^{-5}$ d^{-1}) in the updip parts of the Coastal Plain. Vertical leakance between layer 2 and layer 3 (Black Creek to Middendorf aquifers) ranges from $1.0x10^{-9}$ d^{-1} in the southern part of the Coastal Plain and the Charleston area to $1.0x10^{-5}$ d^{-1} in Aiken and Barnwell Counties. The vertical leakance between layer 3 and layer 4 (Middendorf to Cape Fear aquifer) is highest in the northern Pee Dee region and lowest in the southern part of the state ranging from $1.0x10^{-9}$ to $1.0x10^{-7}$ d^{-1}.

The storage coefficient for the outcrop areas of the Black Creek and Middendorf aquifers are simulated as 0.2. In the confined part of the aquifers, the simulated storage coefficient is 0.0003. The rate of recharge varies from $9.9x10^{-5}$ (0.43 in/yr) to $7.99x10^{-4}$ ft/d (3.5 in/yr). The highest recharge rates are near the Congaree River and the lowest in the northern Pee Dee region. Eight large rivers are simulated in the upper Coastal Plain. The rivers act as drains that remove large quantities of recharge from the aquifers.

The predevelopment-flow system was simulated using a steady-state modeling approach. Using the predevelopment results as initial conditions, a transient modeling approach was used to simulate the flow system in 16 stress periods during each of which withdrawal rates were held constant. The model was calibrated to three potentiometric surfaces (predevelopment (prior to 1875), 1982, and 1989), using the trial and error approach. Aquifer transmissivity, vertical leakance, recharge rates, and riverbed conductance were adjusted until steady-state and transient-model heads closely matched observed heads. Potentiometric surfaces, individual water-level measurements, and well hydrographs were used to compare the simulated and observed heads.

Root-mean-square-errors were computed for the Black Creek, Middendorf, and Cape Fear aquifers for water-level residuals at selected locations for the predevelopment, 1982, and 1989 simulations. RMSE's were the smallest for the predevelopment simulation, and the largest for the 1989 simulation. The larger RMSE's in the transient model was caused by increasingly widespread usage of the aquifers.

Simulated hydrographs for Black Creek aquifer wells in the Myrtle Beach area compare well with observed hydrographs. Simulated hydrographs for Middendorf aquifer wells in the Florence area correspond fairly closely to observed hydrographs, but simulated and observed Black Creek aquifer hydrographs from this area do not match well. No hydrographs are available from the Charleston area for this simulated time period.

A sensitivity analysis of the ground-water flow model was made by adjusting transmissivity, vertical leakance, storage coefficient, and recharge to evaluate the reliability of model calibration. As part of the sensitivity analysis, the parameters were increased and decreased by various factors. The effect of the parameter changes was assessed by computing RMSE's of water-level residuals for observed and newly simulated water levels for the Black Creek and Middendorf aquifers. The model is most sensitive to changes in transmissivity and least sensitive to decreases in recharge.

Eight ground-water withdrawal scenarios were simulated for the Mount Pleasant area. These scenarios involve various combinations of using existing and future Middendorf aquifer wells, their spatial distribution, and injection of treated waste water. The first scenario (1A) maximized use of existing wells by pumping then at present capacity and having new wells pumped at required rate to meet anticipated demand. In the second scenario (1B) demand would be distributed to all wells evenly. Third, fourth, and fifth scenarios (2A, 2B, and 2C) reduced demand from the Middendorf aquifer by developing other water sources three different ways. A sixth scenario injected reclaimed water into the Middendorf aquifer. A seventh scenario ended all withdrawals from the Middendorf aquifer in 1994. An eighth scenario continued Summerville Commissioners of Public Works withdrawals to year 2015. Four of the scenarios produce a similar low water level in the Middendorf aquifer of about -150 ft, while two produce the highest water level of -76 ft and -52 ft. Two hydrographs of existing Middendorf aquifer wells were also simulated and used to compare the results of the scenarios.

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APPENDIX

Simulation of proposed industrial pumpage

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APPENDIX

SIMULATION OF PROPOSED INDUSTRIAL PUMPAGE

Four simulations were made to estimate the effects of proposed industrial pumpage from the Middendorf aquifer on a well field in Mount Pleasant, S.C. The proposed industrial pumpage is located approximately 11 mi north of Mount Pleasant. These projections simulate pumpage from one well, in a 1-mi^2 model cell at two rates of withdrawal: 6,000 gal/min and 3,000 gal/min. The results of these simulations were compared to the original scenario 1B and a revised scenario 1B. The revised scenario 1B simulated the effect of the communities of Sullivans Island and Isle of Palms stopping all withdrawals from the Middendorf aquifer in 1996. The original scenario 1B resulted in a Middendorf aquifer potentiometric surface low of -155 ft below sea level (bsl) by 2015 (table 15). The revised scenario 1B gave a low of -118 ft bsl at that time.

The CF model was configured with two the versions of scenario 1B to simulate the potentiometric surface in the Middendorf aquifer in the Mount Pleasant area in 2015. The ground-water flow model produces water levels in the 1-mi^2 model cells in the Mount Pleasant area. These simulated water levels do not represent pumping levels in an individual well, but do represent the average water level for the entire cell. Water levels in individual pumped wells would be lower than the average level for the entire cell.

Projected withdrawals (scenario 1B, with Sullivans Island and Isle of Palms still pumping through 2015) with an additional 6,000 gal/min at the proposed industrial site could result in an 84-ft lower Middendorf aquifer potentiometric surface in the Mount Pleasant area in 2015 (table 15; table A1; fig. A1). A withdrawal rate of 3,000 gal/min at the proposed industrial site could result in a 44-ft lower Middendorf aquifer potentiometric surface (table 15; table A1; fig. A2).

The 6,000 gal/min pumping rate could result in an average water level of -340 ft bsl in the model cell at the industrial site; the potentiometric low in the Mount Pleasant area could be -239 ft bsl. Pumpage at a rate of 3,000 gal/min resulted in a water level of -185 ft bsl in the model cell and a water level of -199 ft bsl in the Mount Pleasant area (table A1).

Using the revised scenario 1B, with Sullivans Island and Isle of Palms withdrawals ending in 1996, slightly higher water levels are simulated than using the original scenario 1B. With the industrial pumpage at 6,000 gal/min, the simulated potentiometric low in Mount Pleasant was -205 ft bsl and the lowest water level in the industrial-well model cell was -320 ft bsl (fig. A3). At 3,000 gal/min, the Mount Pleasant low was -158 ft bsl and the industrial-well model cell low was -165 ft bsl (table A1; fig. A4).

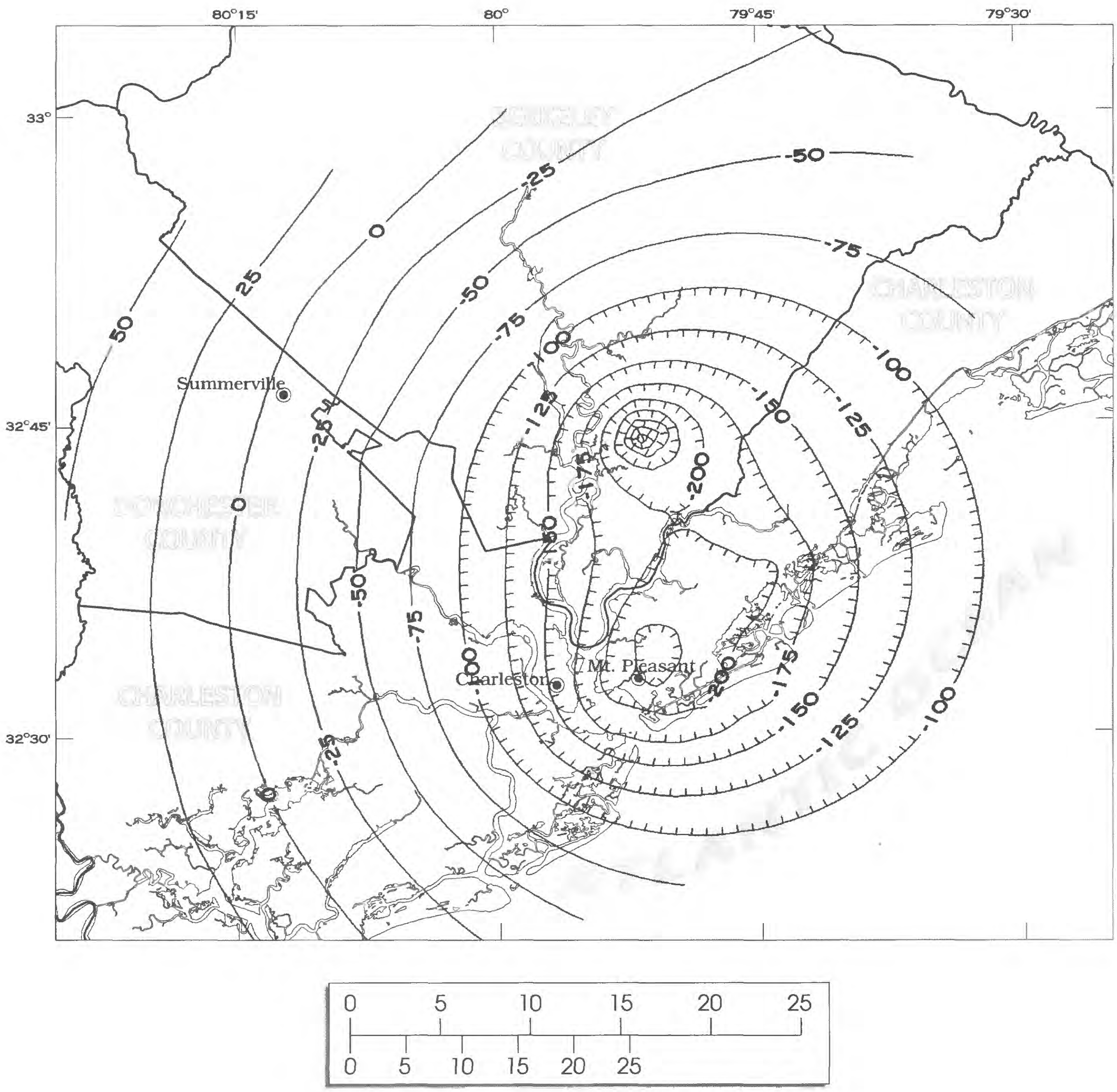
Table A1.--*Minimum water levels of the Middendorf aquifer in the year 2015 predicted by the Charleston-Florence model at Mount Pleasant, S.C., and an industrial site 11 miles north of Mount Pleasant, S.C. (in feet below sea level)*

[gal/min, gallons per minute]

Scenario	Minimum water level	
	Mount Pleasant	Industrial site
Original 1B		
6,000 gal/min	-239	-340
3,000 gal/min	-199	-185
Revised 1B		
6,000 gal/min	-205	-320
3,000 gal/min	-158	-165

Two Middendorf aquifer wells in the Charleston area (CHN-14 and BRK-431) are equipped with continuous water-level recorders (fig. 11). Water levels at these wells were estimated by the model for the original scenario 1B and the revised scenario 1B. Using the original scenario 1B, an industrial withdrawal rate of 6,000 gal/min could produce a water level of -200 ft bsl in CHN-14 and -42 ft bsl in BRK-431 in the year 2015 (fig. A5). A withdrawal rate of 3,000 gal/min could result in a water level of -164 ft bsl in CHN-14 and -6 ft bsl in BRK-431 in the year 2015 (fig. A6).

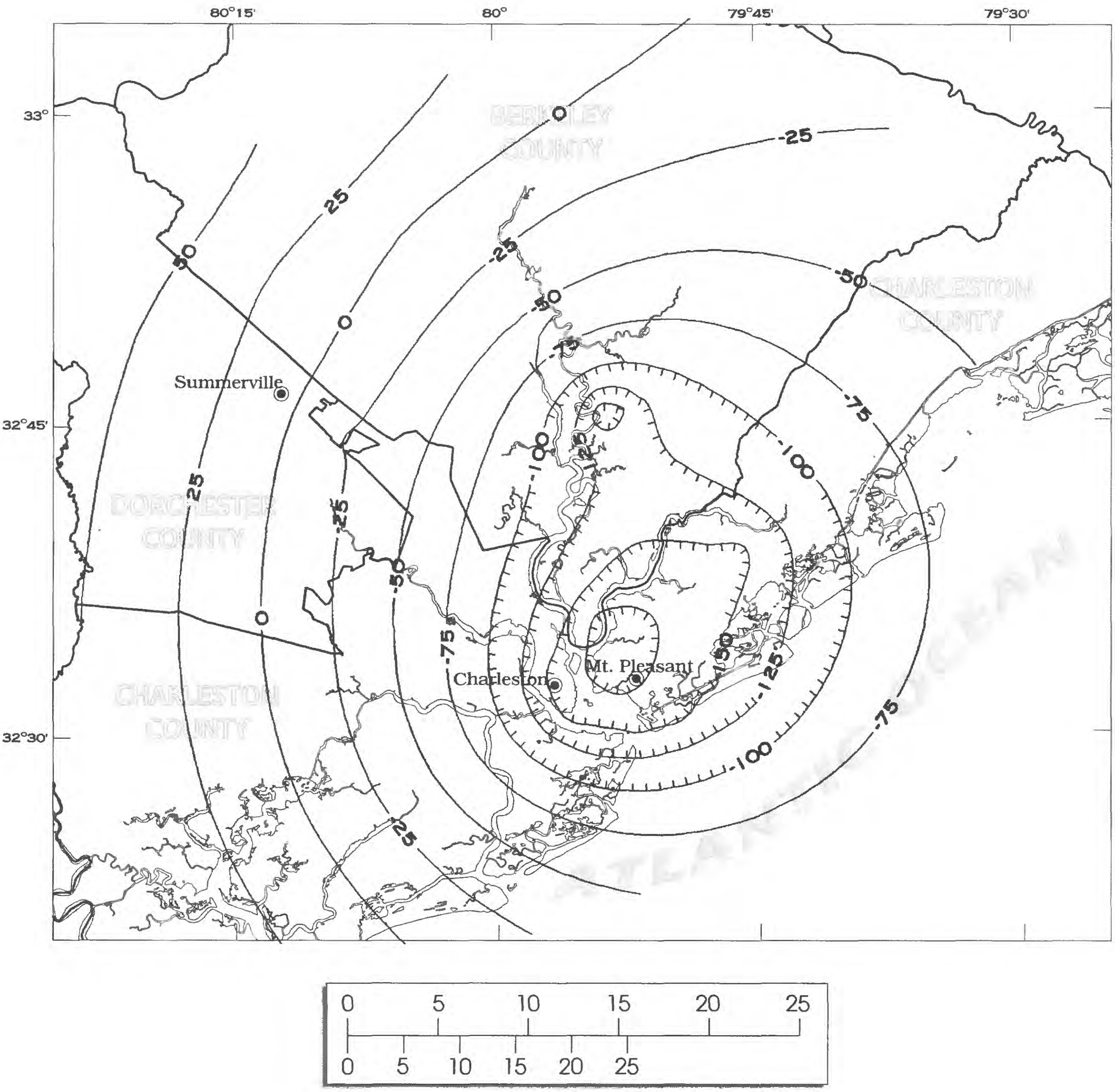
Using the revised scenario 1B, with an industrial withdrawal rate of 6,000 gal/min could produce a water level of -133 ft bsl in CHN-14 and -31 ft bsl in BRK-431 in the year 2015 (fig. A7). A withdrawal rate of 3,000 gal/min resulted in a water level of -98 ft bsl in CHN-14 and 5 ft above sea level in BRK-431 in the year 2015 (fig. A8).



EXPLANATION

——— 25 ——— SIMULATED POTENTIOMETRIC CONTOUR--Shows altitude at which water level would have stood in tightly cased wells. Hachures indicate depressions. Interval is 25 feet. Datum is sea level.

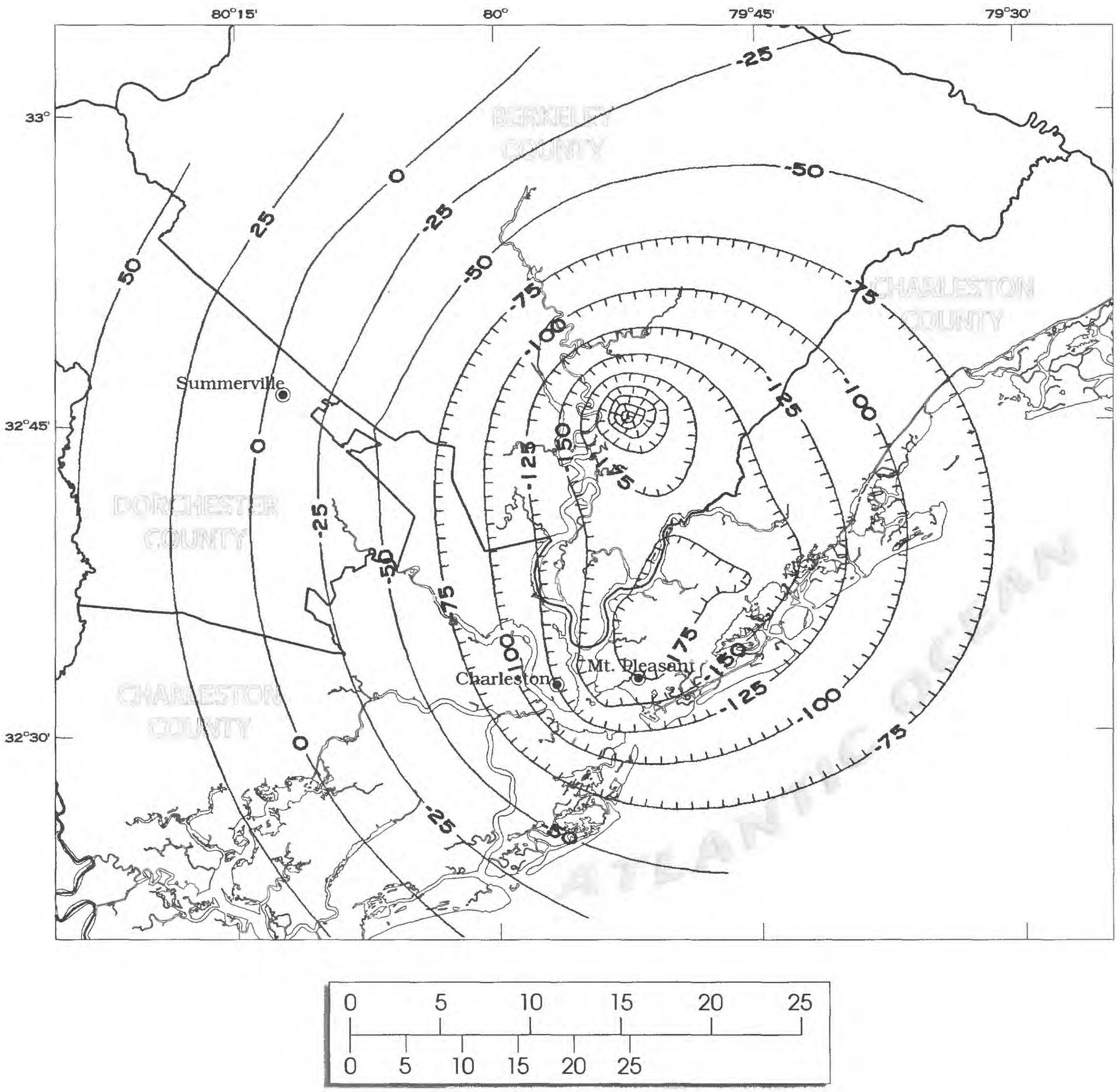
Figure A1. Simulated potentiometric surface of the Middendorf aquifer in 2015 in the Charleston, S.C., area, using Scenario 1B with industrial pumpage at 6,000 gallons per minute from one well 11 miles north of Mount Pleasant, S.C.



EXPLANATION

——— 25 ——— SIMULATED POTENTIOMETRIC CONTOUR--Shows altitude at which water level would have stood in tightly cased wells. Hachures indicate depressions. Interval is 25 feet. Datum is sea level.

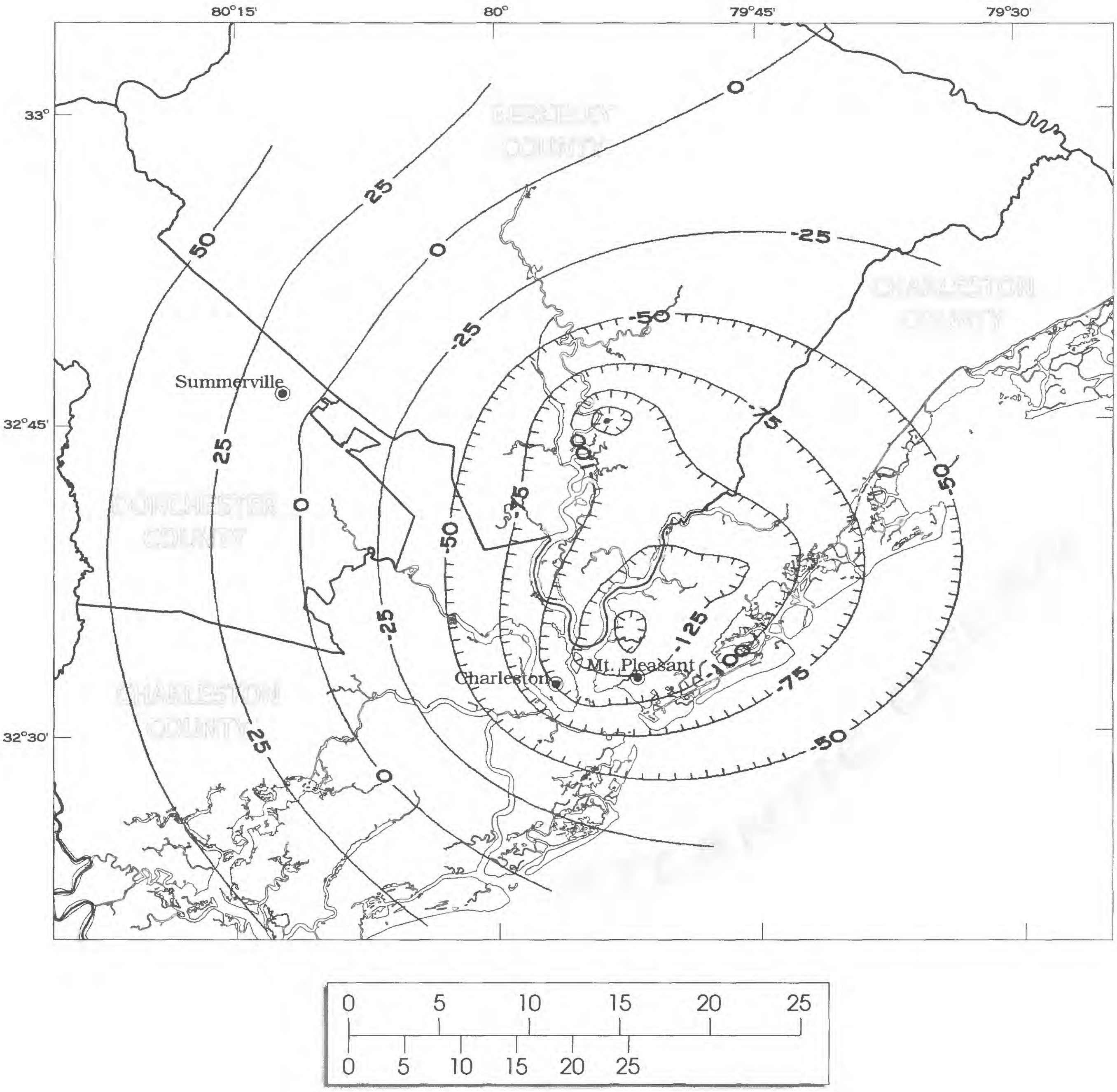
Figure A2. Simulated potentiometric surface of the Middendorf aquifer in 2015 in the Charleston, S.C., area, using Scenario 1B with industrial pumpage at 3,000 gallons per minute from one well 11 miles north of Mount Pleasant, S.C.



EXPLANATION

—— 50 —— SIMULATED POTENTIOMETRIC CONTOUR--Shows altitude at which water level would have stood in tightly cased wells. Hachures indicate depressions. Interval is 5 feet. Datum is sea level.

Figure A3. Simulated potentiometric surface of the Middendorf aquifer in 2015 in the Charleston, S.C., area, using revised Scenario 1B with industrial pumpage at 6,000 gallons per minute from one well 11 miles north of Mount Pleasant, S.C.



EXPLANATION

——— 25 ——— SIMULATED POTENTIOMETRIC CONTOUR--Shows altitude at which water level would have stood in tightly cased wells. Hachures indicate depressions. Interval is 25 feet. Datum is sea level.

Figure A4. Simulated potentiometric surface of the Middendorf aquifer in 2015 in the Charleston, S.C., area, using revised Scenario 1B with industrial pumpage at 3,000 gallons per minute from one well 11 miles north of Mount Pleasant, S.C.

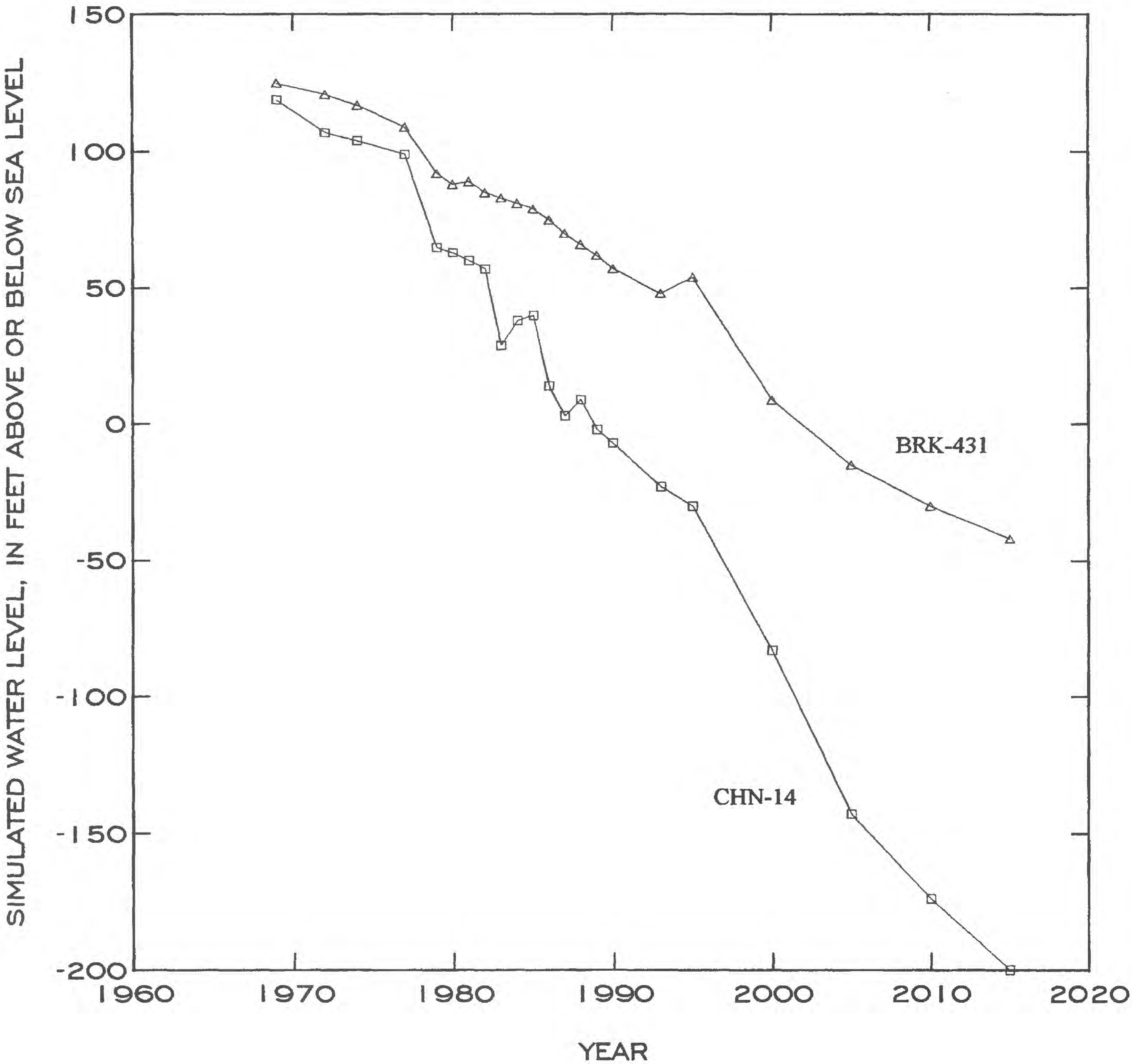


Figure A5. Simulated hydrographs of CHN-14 and BRK-431, 1969-2015, with original Scenario 1B with industrial pumpage of 6,000 gallons per minute.

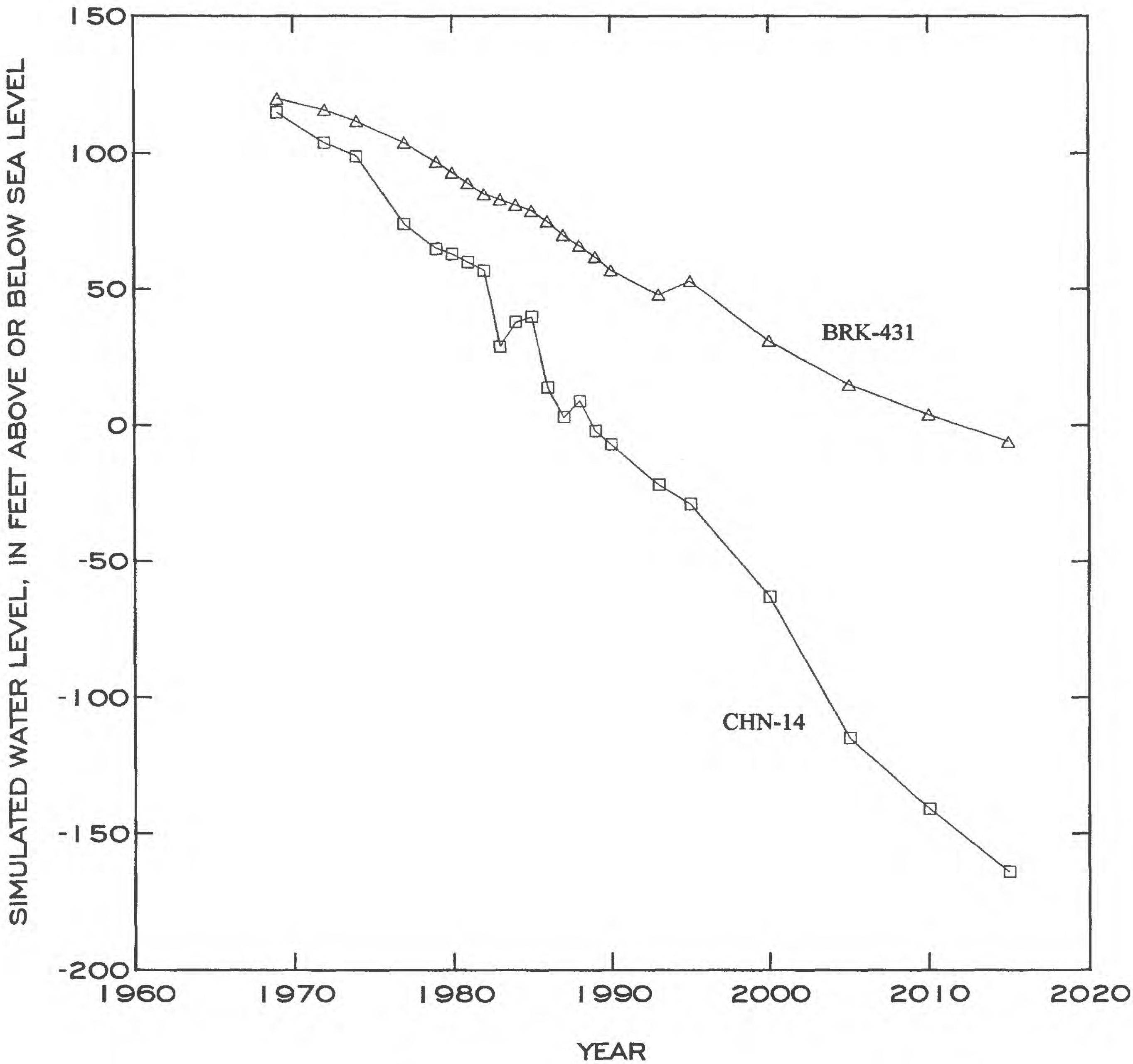


Figure A6. Simulated hydrographs of CHN-14 and BRK-431, 1969-2015, with original Scenario 1B with industrial pumpage of 3,000 gallons per minute.

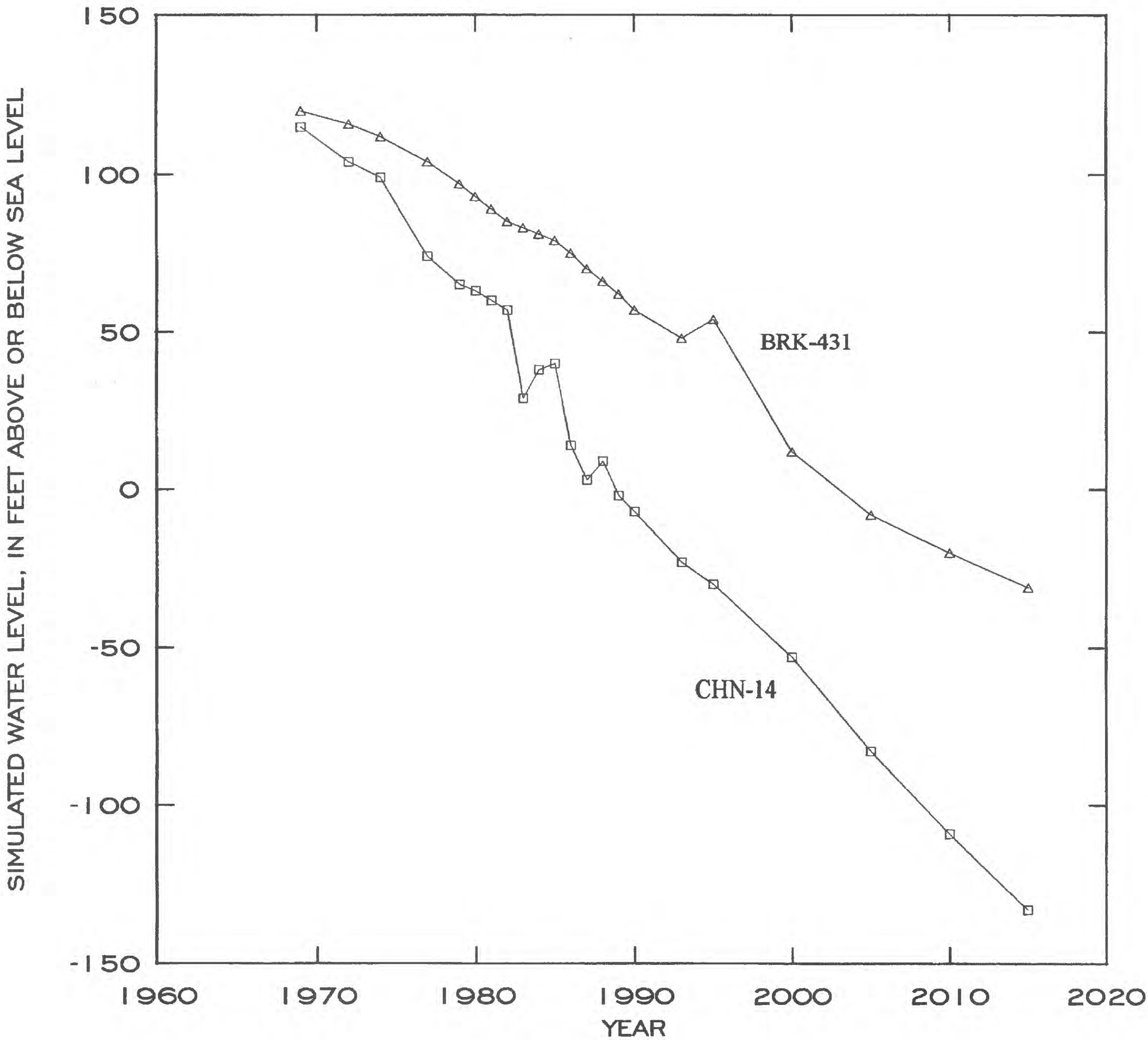


Figure A7. Simulated hydrographs of CHN-14 and BRK-431, 1969-2015, with revised Scenario 1B with industrial pumpage of 6,000 gallons per minute.

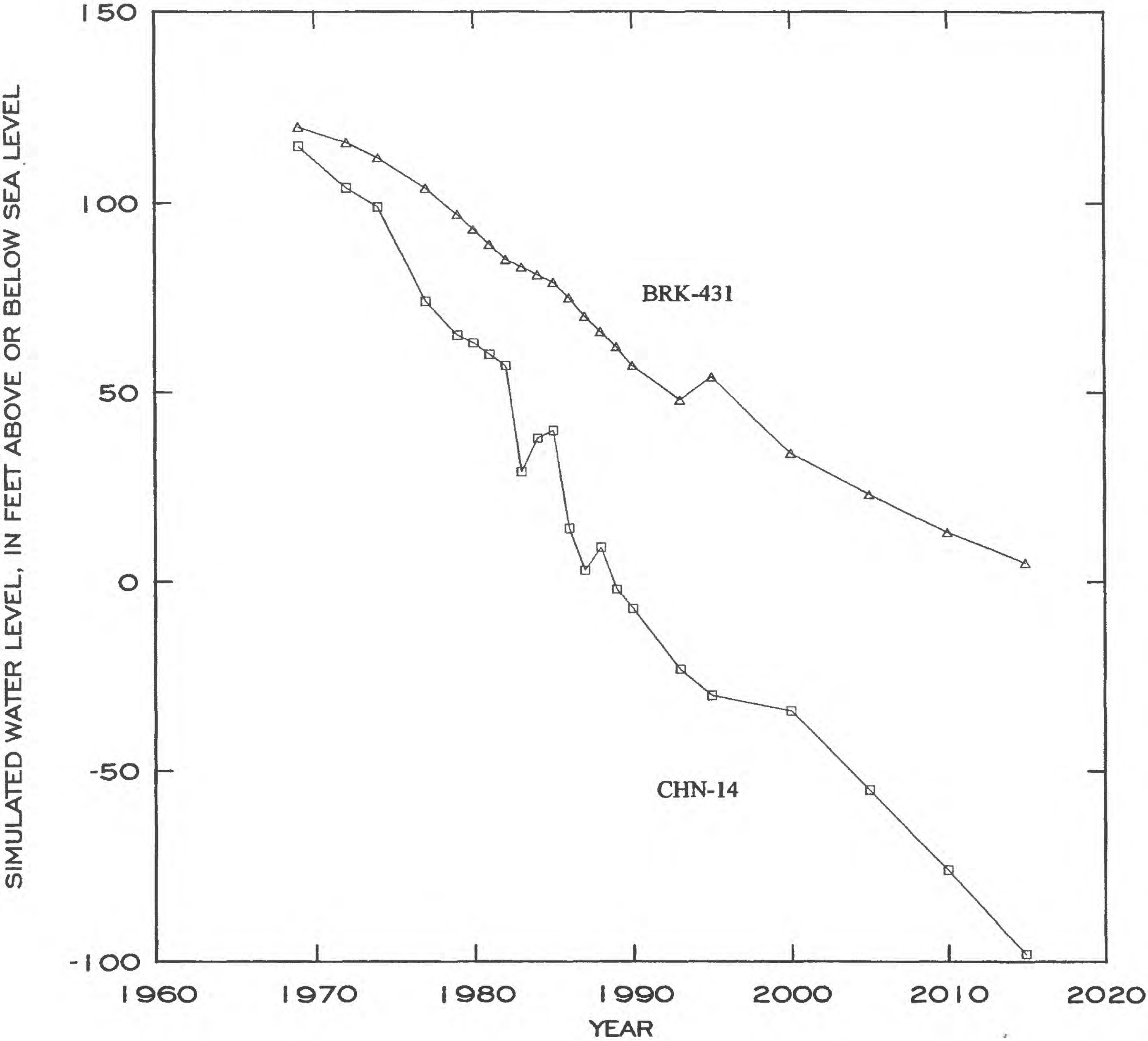


Figure A8. Simulated hydrographs of CHN-14 and BRK-431, 1969-2015, with revised Scenario 1B with industrial pumpage of 3,000 gallons per minute.

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