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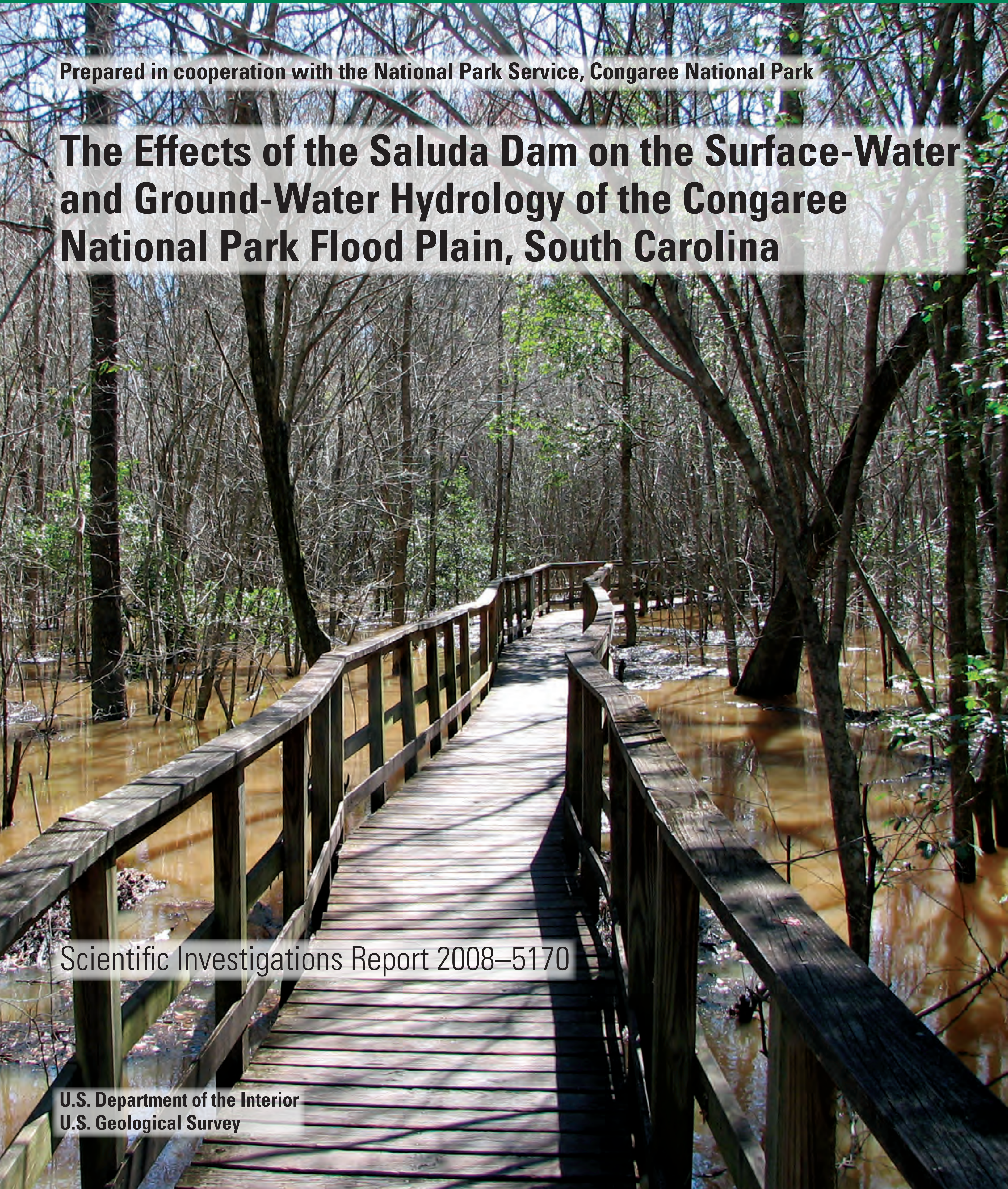
The Effects of the Saluda Dam on the Surface-Water and Ground-Water Hydrology of the Congaree National Park Flood Plain, South Carolina



Scientific Investigations Report 2008–5170

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

Cover. **Front:** Boardwalk in the Congaree National Park. **Back:** Boggy gut in the Congaree National Park *(photographs taken by Theresa Thom, National Park Service)*.

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DIRK KEMPTHORNE, Secretary

U.S. Geological Survey
Mark D. Myers, Director

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Conversion Factors, Definitions, and Acronyms and Abbreviations

Inch/Pound to SI

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	0.004047	square kilometer (km^2)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
cubic foot (ft^3)	0.02832	cubic meter (m^3)
acre-foot (acre-ft)	1,233	cubic meter (m^3)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day (m/d)
	Hydraulic gradient	
foot per mile (ft/mi)	0.1894	meter per kilometer (m/km)

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

$$°C = 0.56 \times (°F - 32)$$

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

Horizontal coordinate information is referenced either to the North American Datum of 1983 (NAD 83) or North American Datum of 1927 (NAD 27).

Unless otherwise stated, elevation, as used in this report, refers to distance above the North American Vertical Datum of 1988 (NAVD 88).

Acronyms and abbreviations used in this report

ANN	artificial neural network
BEP	back error propagation
CNP	Congaree National Park
DCP	data-collection platform
DMSK	Data Miner Software Kit
FEMA	Federal Emergency Management Agency
GA	Georgia
GOES	Geostationary Operational Environmental Satellites
ME	mean error
MLP	multi-layer perceptron
MOVE	Maintenance of Variance Extension
MSE	mean square error
MWA	moving window average
NAVD 88	North American Vertical Datum of 1988
NGVD 29	National Geodetic Vertical Datum of 1929
NPS	National Park Service
NWIS	National Water Information System
OLS	ordinary least squares
PME	percent model error
RMSE	root mean square error
R	Pearson coefficient
R^2	coefficient of determination
SC	South Carolina
SCE&G	South Carolina Electric & Gas
SSE	sum of squared error
USGS	U.S. Geological Survey

The Effects of the Saluda Dam on the Surface-Water and Ground-Water Hydrology of the Congaree National Park Flood Plain, South Carolina

By Paul A. Conrads, Toby D. Feaster, and Larry G. Harrelson

Abstract

The Congaree National Park was established "… to preserve and protect for the education, inspiration, and enjoyment of present and future generations an outstanding example of a near-virgin, southern hardwood forest situated in the Congaree River flood plain in Richland County, South Carolina" (Public Law 94–545). The resource managers at Congaree National Park are concerned about the timing, frequency, magnitude, and duration of flood-plain inundation of the Congaree River. The dynamics of the Congaree River directly affect ground-water levels in the flood plain, and the delivery of sediments and nutrients is constrained by the duration, extent, and frequency of flooding from the Congaree River. The Congaree River is the southern boundary of the Congaree National Park and is formed by the convergence of the Saluda and Broad Rivers 24 river miles upstream from the park. The streamflow of the Saluda River has been regulated since 1929 by the operation of the Saluda Dam at Lake Murray. The U.S. Geological Survey, in cooperation with the National Park Service, Congaree National Park, studied the interaction between surface water in the Congaree River and ground water in the flood plain to determine the effect Saluda Dam operations have on water levels in the Congaree National Park flood plain.

Analysis of peak flows showed the reduction in peak flows after the construction of Lake Murray was more a result of climate variability and the absence of large floods after 1930 than the operation of the Lake Murray dam. Dam operations reduced the recurrence interval of the 2-year to 100-year peak flows by 6.1 to 17.6 percent, respectively. Analysis of the daily gage height of the Congaree River showed that the dam has had the effect of lowering high gage heights (95th percentile) in the first half of the year (December to May) and raising low gage heights (5th percentile) in the second half of the year (June to November). The dam has also had the effect of increasing the 1-, 3-, 7-, 30-, and 90-day minimum gage heights by as much as 23.9 percent and decreasing the 1-, 3-, 7-, 30-, and 90-day maximum gage heights by as much as 7.2 percent. Analysis of the ground-water elevations in the Congaree National Park flood plain shows similar results as the gage-height analysis—the dam has had the effect of lowering high ground-water elevations and increasing low ground-water elevations. Overall, the operation of the dam has had a greater effect on the gage heights within the river banks than gage heights in the flood plain. This result may have a greater effect on the subsurface water levels of the surficial flood-plain aquifer than the frequency and magnitude of inundation of the flood plain.

Introduction

The Congaree National Monument, established in 1976, became South Carolina's first National Park in 2003 (National Park Service, 2006). The Congaree National Park (CNP) is a 22,200-acre palustrine wetland along the northern bank of the Congaree River composed of a forested flood plain made up of virgin bottomland hardwoods (fig. 1). Historically, bottomland hardwood forests existed on forested flood plains throughout the southeastern United States (Patterson and others, 1985). Over time, human activities disturbed many of these bottomland hardwood forests; however, the CNP flood plain remains essentially intact and is one of the last undisturbed stands of bottomland hardwoods remaining in the southeastern United States. The old growth forest preserved at the CNP includes some of the tallest trees and one of the highest forest canopies in the southeastern United States and is recognized as an International Biosphere Reserve, National Natural Landmark, wilderness area, and "globally important bird area" (Patterson and others, 1985).

The Congaree River is formed by the convergence of the Saluda and Broad Rivers at Columbia, South Carolina, approximately 24 river miles upstream from the CNP (fig. 2). The Congaree River defines the southern boundary of the CNP (figs. 1 and 2). As with most river systems, periods of inundation in response to episodic and seasonal surface-water fluctuations affect the flood plain of the Congaree River. The regulation of the Saluda and Broad Rivers pre-dates the establishment of the CNP. As with the majority of large river basins

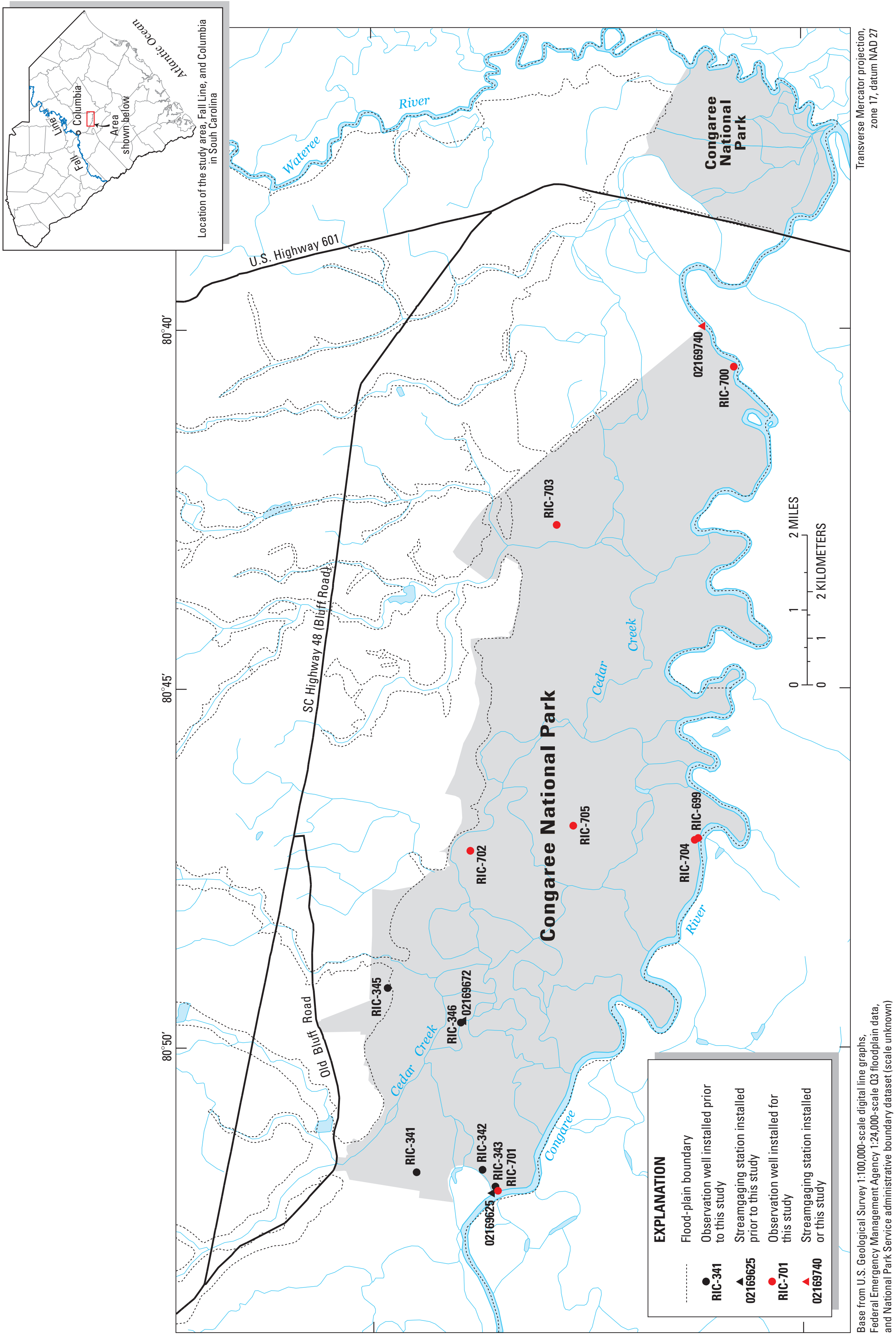

Figure 1. Locations of U.S. Geological Survey observation wells and streamgaging stations in the Congaree National Park, South Carolina.

Figure 2. Locations of the Saluda, Congaree, Savannah, and Broad River basins, and U.S. Geological Survey streamgaging stations (table 1) in Georgia and South Carolina used in the study.

in South Carolina, major reservoirs and low-head dams have altered streamflows in the Saluda and Broad River basins since the late 1800s (South Carolina Water Resources Commission, 1983). On the Saluda River, low-head dams built in conjunction with textile plants were some of the first major structures to alter the natural streamflow under low-flow conditions. The first major regulation affecting high streamflows occurred with the completion of the Saluda Dam forming Lake Murray in 1929, which was built for electric power generation. Low-head dams on the Broad River also have regulated low streamflows since the late 1800s and early 1900s.

The CNP was established "…to preserve and protect for the education, inspiration, and enjoyment of present and future generations an outstanding example of a near-virgin, southern hardwood forest situated in the Congaree River flood plain in Richland County, South Carolina" (Public Law 94–545). The resource managers at CNP are concerned about the timing, frequency, magnitude, and duration of flood-plain inundation of the Congaree River. The dynamics of the Congaree River directly affect the ground water in the flood plain, and the delivery of sediments and nutrients is constrained by the duration, extent, and frequency of flooding from the Congaree River. Flooding in the CNP flood plain replenishes sediment and nutrients, thereby maintaining the viability of the ecosystem. The flora and fauna that inhabit the CNP flood plain are dependent on the amount, type, and distribution of these sediments and nutrients (Patterson and others, 1985).

In 2004, the U.S. Geological Survey (USGS), in cooperation with the National Park Service (NPS), began an investigation to evaluate the effects that regulated streamflow from the Saluda River has on the Congaree River and the ground-water resources of the CNP flood plain. The impetus for this current USGS-NPS investigation was the result of altered streamflow patterns (referred to as "modified run-of-river") from the Saluda Dam Hydroelectric Station due to construction of a back-up dam located downstream from the original dam. Under true run-of-river operations with an unaltered streamflow pattern, the daily mean streamflow in and out of Lake Murray would be equal. Due to constraints of operating a hydroelectric facility, a modified run-of-river operation specified that inflows must be released within a specified time, such as 24 hours.

In the fall of 2002, South Carolina Electric and Gas (SCE&G) began to lower the water level in Lake Murray to 15 feet (ft) below full pool to reduce hydraulic pressure on the dam during the construction of the back-up dam. From December 2002 to June 2004, the Saluda Dam was operated under modified run-of-river conditions to maintain the lower water level in the dam. Figure 3 highlights four streamflow periods on the Saluda River below Lake Murray: (1) before construction of the Saluda Dam, (2) after construction of the Saluda Dam, (3) modified run-of-river, and (4) post run-of-river. From a graphical perspective, the modified run-of-river period does not seem to be drastically different from other historical periods of similar duration. That is, one could take

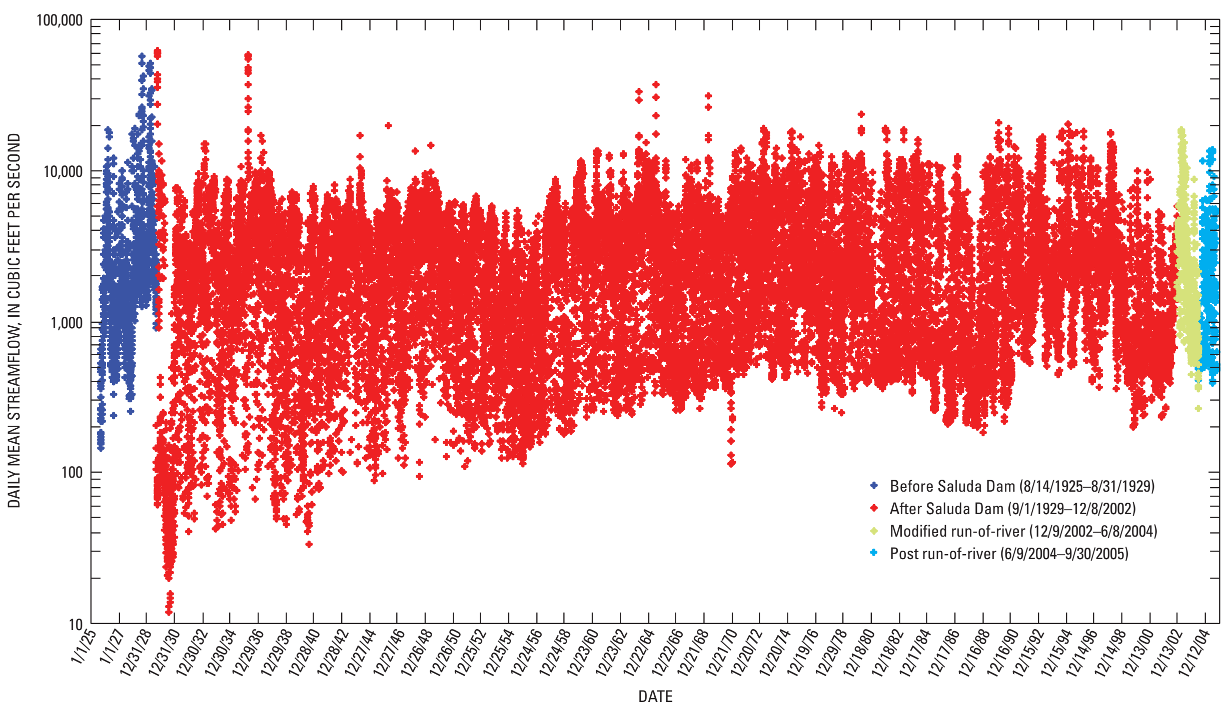

Figure 3. Daily mean streamflow at Saluda River Columbia from August 1925 to September 2005.

the data as a whole from the modified run-of-river period and overlay it on several other historical periods. The 18-month period of modified run-of-river operation only provided a small “snap shot” of unregulated conditions on the Saluda and Congaree Rivers. To further address the issue of the effects of regulation, the USGS compiled and analyzed historic hydrologic data back to the 1800s to evaluate the effect of the altered streamflow patterns on the hydrology of the surface water in the Congaree River and ground water of the CNP flood plain. Water-resource managers can use this information to make informed decisions on the potential effects of future streamflow in the Congaree River.

Purpose and Scope

The purpose of this report is to present the results of the investigation that was conducted to assess the effect that the Saluda Dam has on the annual peak flows and daily gage heights of the Congaree River and ground-water elevations in the flood plain of CNP. The scope of the study area is the Congaree River from the confluence of the Broad and Saluda Rivers to the CNP and the surficial aquifer of the CNP flood plain. The investigation did not include the interactions between surface water and the deeper confined aquifers in the CNP flood plain.

An important part of the USGS mission is to provide scientific information for the effective water-resources management of the Nation. To assess the quantity and quality of the Nation’s surface water, the USGS collects hydrologic and water-quality data from rivers, lakes, and estuaries by using standardized methods, and maintains the data from these stations in a national database. Often this database is underutilized and not well interpreted for addressing contemporary hydrologic issues. The techniques presented in this report demonstrate how to extract valuable information from the USGS database to assist local, State, and Federal agencies to address contemporary water-resource management issues. The statistical analysis of annual peak flows on the Broad, Saluda, and Congaree Rivers and the development of regression models demonstrate how to use historical databases to evaluate the effects of regulation and climate variability on the magnitude of peak flows. The application of data-mining techniques, including Artificial Neural Network (ANN) models, to the Congaree River and ground water in the CNP flood plain demonstrates how to develop empirical models of complex hydrologic systems to integrate disparate databases and how to use the models to address contemporary issues of concern.

Previous Investigations

Whetstone (1982) published a report that presented the peak-flow magnitudes and frequencies of major rivers in South Carolina. The report included a comparison of the magnitude and frequency of peak flows for the Congaree River for the period prior to and after the construction of the Saluda Dam in 1929. Guimaraes and Bohman (1992) and Feaster and Tasker (2002) have subsequently updated the magnitude and frequency of peak flows at South Carolina streamflow stations. Peak flows are defined as the highest instantaneous flow for an independent event at a streamflow gage in a given water year[1].

Patterson and others (1985) published a report specifically describing the hydrology and its effects on distribution of vegetation in the CNP in South Carolina. In a regional hydrogeologic study, Aucott and others (1987) describe the general geohydrologic framework of the Coastal Plain sediments in the CNP area. Aucott (1996) summarizes the hydrology of the southeastern Coastal Plain aquifer system in South Carolina (including the area encompassing the CNP), parts of Georgia, and North Carolina. The report describes the predevelopment and contemporary (as of 1982) ground-water flow systems in addition to the geohydrologic framework, general water-quality characteristics, and the results of ground-water flow simulations.

Koman (2003) investigated the hydrologic effect of dams on the Saluda River. The general objectives of the investigation were to assess if substantial changes in the hydrologic regimes had occurred over time. These changes were assessed primarily on the basis of hydroecological indices from data at numerous USGS streamflow-gaging stations in the Saluda River basin. In addition, an assessment of changes of the Congaree River at Columbia streamflow data was made.

Graf and Stroup (2006) compiled a literature review that summarizes the available technical resources on the physical, chemical, biological, and socioeconomic aspects of the three river basins affecting the CNP. The literature cited includes newspaper articles, reports by State and Federal agencies and universities, books, Internet links, and published papers.

Minchin and Sharitz (2007) analyzed the size distribution of trees in the CNP flood plain and tested for evidence of long-term changes in the forest composition due to changes in the natural hydrology of the flood plain with the operation of the Saluda Dam. Results from the study indicate trends toward less flood-tolerant tree species in the flood plain. They could not, however, definitively attribute the trends as evidence of effects of the operation of the Saluda Dam. They present an alternative hypothesis that long-term climate change, as seen in apparent decreases in annual rainfall, may be driving shifts in the flood-plain forest composition.

Approach

Given the numerous and intrinsic processes that influence regulated streamflow, such as daily, seasonal, interannual rainfall patterns, and power-generation demands, it was concluded that it would be difficult to quantify the effects of the Saluda

[1] Water year in U.S. Geological Survey reports dealing with surface-water supply is the 12-month period, October 1 through September 30. The water year is designated by the calendar year in which the period ends and includes 9 of the 12 months. Thus, the year ending September 30, 1980, is called the “1980 water year.”

Dam on the hydrology of the CNP by using only the 18-month modified run-of-river period during the construction of the back-up dam. Comparing the short periods of streamflows in the Saluda River under modified run-of-river conditions with long-term streamflows under peaking conditions would at best provide a circumstantial depiction of how regulation on the Saluda River may be affecting streamflows in the Congaree River and, subsequently, flooding in the CNP.

The approach of analyzing the 18-month modified-run-of-the-river period was replaced with an analysis of historical streamflow records collected prior to the construction of the Saluda Dam at streamgaging stations on the Congaree, Broad, and Saluda Rivers (fig. 2). Using the historical data dating back to the 1800s, empirical models were developed to generate long-term surface- and ground-water records that represent unregulated conditions on the Saluda and Congaree Rivers. Because the intrinsic nature of the system is captured and accounted for in these historical data, the mathematical relations in the empirical models reflect hydrologic conditions in the Congaree River comparable to those that occurred prior to the construction of the Saluda Dam. Consequently, the simulated long-term records provide a means to assess the effect that regulation on the Saluda River has had on the annual peak flows and daily gage heights in the Congaree River and ground-water elevation in the CNP flood plain since the construction of the Saluda Dam.

Three approaches were used to analyze the effect of the Saluda Dam using the historical databases. The first approach analyzed historical annual peak flows for the Broad and Saluda River basins in South Carolina to quantify the effect of the Saluda Dam on reducing peak flows on the Congaree River. For comparison purposes, peak flows from the Broad River in Georgia (fig. 2), which is an unregulated stream with a similar period of record as the Congaree River and Broad River (South Carolina), also were analyzed. Oddly enough, the Georgia station is located on a stream also named the Broad River (Broad River Carlton, table 1) but is not part of the same basin as the Broad River in South Carolina (fig. 2). Using the long-term peak-flow data from the Broad River in Georgia, similar analyses were performed to test the hypothesis that the reduction in peak flows on the Congaree River might not be wholly a result of regulation but could be related to climate variability as a result of fewer large flood events over the last century.

The second approach used streamflow data from the Saluda River prior to the construction of Saluda Dam to develop an empirical model of historical streamflow for the Saluda River as it would have been prior to the impoundment of Lake Murray. The model was used to simulate daily streamflow for the Saluda River for a 75-year period as if the dam were not in place. These simulated data represent unregulated streamflow conditions (without dam). Differences in the simulated unregulated hydrograph and regulated hydrograph (with dam) were compared to quantify differences in the timing, frequency, and magnitude of gage heights at the CNP.

The third approach analyzed the surface-water/ground-water interactions of the CNP flood plain. To evaluate the dynamics of the ground-water system in the CNP, four of the ground-water monitoring wells established by Patterson and others (1985) were reactivated. The ground-water network was expanded by adding seven monitoring wells. Empirical models of ground-water elevations at selected monitoring wells were developed that simulated ground-water elevations as a function of gage heights of the Congaree River. To quantify the effect of the regulation by the Saluda Dam on the ground-water resources of the CNP, the 75-year with-dam and without-dam hydrographs were used as inputs to the ground-water models, and the differences in the ground-water response were determined.

Description of Study Area

The Congaree River begins at the confluence of the Broad and Saluda Rivers at Columbia, SC (fig. 2). The Broad River originates in the mountains of western North Carolina and flows southeast through the foothills of the Blue Ridge Mountains and the Piedmont of South Carolina. The Broad River basin encompasses approximately 5,310 square miles (mi^2) of which 1,510 mi^2 are located in North Carolina and 3,800 mi^2 are in South Carolina (South Carolina Water Resources Commission, 1983; North Carolina Department of Environmental and Natural Resources, 2001). The Saluda River originates in the Blue Ridge Mountains but predominantly drains from the Piedmont of South Carolina and joins the Broad River near the Fall Line to form the Congaree River (fig. 2). The Saluda River basin encompasses approximately 2,500 mi^2.

The first major regulation of the Saluda River occurred with the construction of the Saluda Dam in the 1920s located 10 miles (mi) upstream from the confluence with the Broad River. Logging for the project began in the spring of 1927 and on August 31, 1929, the intake tower gates were closed and the water began to fill Lake Murray (Bayne, 1992). The flood of record on the Saluda River that occurred from September 26 to October 2, 1929, delayed the filling of the reservoir. After this major storm, Lake Murray gradually was filled to a water-surface elevation of 350 ft (National Geodetic Vertical Datum of 1929, NGVD 29) by 1931. Over the next 2 years, the lake water level was raised to 360 ft, which is still considered full pool (South Carolina Electric & Gas, 2008).

In 1958, the McMeekin Station, a coal-fired powerplant, went into operation next to the Saluda Dam Hydroelectric Plant (SCANA, 2006). After the McMeekin Station became operational, the Saluda Hydroelectric Plant transitioned from a base-load powerplant to a peak-load powerplant that generates electricity to quickly meet power demands for short durations of time.

The CNP flood plain is located adjacent to the Congaree River approximately 24 river miles downstream from Columbia near the town of Hopkins in Richland County, SC

Table 1. U.S. Geological Survey surface-water data for streamgaging stations located in South Carolina and Georgia used in the study.

[USGS; U.S. Geological Survey; NAD 83, North American Datum of 1983; SC, South Carolina; RR, railroad; GA, Georgia]

USGS station number and name (fig. 2)	Name used in this report	Latitude (degrees, minutes, seconds, datum NAD 83)	Longitude (degrees, minutes, seconds, datum NAD 83)	Drainage area, in square miles	Period of record
02156500 Broad River near Carlisle, SC	Broad River Carlisle	34° 35' 46"	81° 25' 20"	2,790	October 1938 to current year
02161000 Broad River at Alston, SC	Broad River Alston	34° 14' 35"	81° 19' 11"	4,790	October 1896 to December 1907, October 1980 to current year
02161500 Broad River at Richtex, SC	Broad River Richtex	34° 11' 05"	81° 11' 48"	4,850	October 1926 to July 1928, October 1929 to September 1983
02167000 Saluda River at Chappells, SC	Saluda River Chappells	34° 10' 40"	81° 51' 40"	1,360	October 1926 to current year
02168500 Lake Murray near Columbia, SC	Lake Murray	34° 03' 07"	81° 13' 15"	2,420	August 1929 to current year
02169000 Saluda River near Columbia, SC	Saluda River Columbia	34° 00' 50"	81° 05' 17"	2,520	August 1925 to current year
02169500 Congaree River at Columbia, SC	Congaree River Columbia	33° 59' 35"	81° 03' 00"	7,850	October 1939 to current year
02169625 Congaree River at Congaree National Park near Gadsden, SC	Congaree River CNP	33° 48' 38"	80° 52' 02"	8,290	October 1986 to September 1987, October 1994 to current year
02169672 Cedar Creek at Congaree National Park near Gadsden, SC	Cedar Creek	33° 48' 58"	80° 49' 39"	71	November 1980 to November 1983, June 1985 to September 1986, April 1987 to September 1987, December 1993 to current year
02169740 Congaree River at Southern RR near Fort Motte, SC	Congaree River Fort Motte	33° 46' 12"	80° 39' 58"	Undetermined	December 2003 to September 2005
02191300 Broad River above Carlton, GA	Broad River Carlton	34° 04' 24"	83° 00' 12"	760	July 1897 to current year; only annual peaks between January 1913 and September 1997

(fig. 2). The CNP is approximately 3 mi wide and 12 mi long and encompasses an area of approximately 22,200 acres. The land-surface elevations in the CNP flood plain range from approximately 120 ft above North American Vertical Datum of 1988 (NAVD 88) near the western boundary to approximately 82 ft above NAVD 88 along the eastern boundary, which equates to a southeasterly topographic slope of 3.1 feet per mile (ft/mi). A series of low scarps and terraces located approximately 1,200 ft north of the CNP flood plain is known as the Congaree Sand Hills. The terraces that form the Congaree Sand Hills are known as the Coharie, Hazelhurst, Okefenokee, Sunderland, and Wicomico terraces, and the elevations range from 125 to 270 ft (Colquhoun, 1965; Patterson and others, 1985; not shown in fig. 2).

Underlying the CNP is a complex mix of igneous and metamorphic crystalline basement rocks and unconsolidated sedimentary formations. Overlying the crystalline basement rocks is approximately 500 ft of interbedded sands and clays of late Cretaceous and younger ages (Patterson and others, 1985). The geologic formations presented in this report are discussed beginning with the deepest formation and concluding with the uppermost formation.

The igneous and metamorphic crystalline basement rocks of Paleozoic age beneath the CNP are similar to those found near land surface in the adjacent Piedmont Physiographic Province of South Carolina. Unconsolidated sediments of late Cretaceous to Holocene age cover the older rocks in the eastern parts of South Carolina, and alluvial deposits of Quaternary age typically occupy valleys (Overstreet and Bell, 1965).

In the study area, the Middendorf Formation of late Cretaceous age overlies igneous and metamorphic rocks of the

Paleozoic age. The Middendorf Formation generally consists of fine to coarse-grained sand that is light gray in color. The sediment is micaceous, glauconitic, and may be calcareous in some intervals. The formation also may contain clay that is green, purple, and maroon in color. Greenish-gray micaceous silty sandstone is found in some fraction(s) of the formation (Aucott and others, 1987).

The Black Creek Formation of late Cretaceous age overlies the Middendorf Formation. The Black Creek Formation consists of gray to white, micaceous, phosphatic, quartzose, calcareous, glauconitic sand. Interbedded in the sand are thinly laminated dark gray to black clay layers containing nodules of pyrite and marcasite along with fragments of lignite (Aucott and others, 1987).

The Black Mingo, Congaree, McBean, and Barnwell Formations of Tertiary age overlie the Black Creek Formation. The Black Mingo Formation consists of gray sandy shale, black sandy limestone, and may be carbonaceous and fossiliferous in places. This formation may be present under the CNP flood plain. The Congaree Formation consists of yellowish-brown to green, fine- to coarse-grained sand and sandstone. Also present may be dark green to gray quartzose glauconitic clay. The McBean Formation consists of green to yellow fine-grained glauconitic sand with gray-green glauconitic marl. The Barnwell Formation consists of massive brown to red fine- to coarse-grained sand (Aucott and others, 1987). The Congaree, McBean, and Barnwell Formations pinch out just south of the CNP and are not present in the study area beneath the CNP (Aucott and others, 1987).

Alluvial and terrace deposit(s) of Pleistocene and Holocene age are present in the CNP flood plain. These alluvial deposit(s) overlie the Black Mingo Formation and consist of a fining-upward sequence of gravel, sand, silt, and clay. In the CNP flood plain, the sediment accretes in thin layers during inundation of the flood plain. The amount of sediment accumulation varies within the flood plain; however, sediment accumulation is greatest near the banks of the Congaree River. Sediment deposited near the river is coarser than sediment deposited further inland from the river. Due to the meandering of the Congaree River over geologic time, the lithology in the flood plain varies greatly from place to place over relatively short distances (Patterson and others, 1985; Shelley, 2007a–e). Ground water may be both confined and unconfined in the shallow aquifer beneath the CNP flood plain (Patterson and others, 1985).

Recent information by Shelley (2007a) on the geology, geomorphology, and tectonics of the Congaree River Valley in central South Carolina illustrates the complexity of these individual terraces. Shelley (2007b–f) mapped 14 terraces and collectively named them the Congaree River Valley terrace complex and correlated the new interpretation with the terraces defined in Colquhoun (1965; Shelley, 2007a). A full discussion of the terraces is beyond the scope of this report; however, for more information, the reader is encouraged to review Shelley (2007a) and associated publications (Shelley, 2007b–f).

The hydrogeologic framework of the study area is discussed in descending order in this report and is restricted to the shallow flood plain, Black Creek, and Middendorf aquifers and associated confining units. The shallow flood-plain aquifer includes all sediment from land surface down to the contact between the shallow flood-plain aquifer and the Black Creek confining unit (fig. 4). Within the CNP, sediment that makes up the shallow flood-plain aquifer is the lowermost geologic terrace mapped by Shelley (2007b–f). The shallow flood-plain aquifer is an intricate assortment of intraflood-plain terraces, alluvial fans, rimswamps, dune fields, and meanderbelts of post-late Pleistocene age composed mainly of sand, clay, and peat deposited in the Congaree River flood plain (Shelley, 2007f). These deposits vary in composition, thickness, hydraulic conductivity, and permeability, throughout the CNP. The thickness varies across the CNP flood plain due to differing erosional and depositional patterns beneath and throughout the flood plain. The Floridan-Tertiary sand confining unit, Floridan aquifer system, and Tertiary sand aquifer are absent in the study area. Aucott and others (1987) report the Tertiary sand aquifer pinching out near the lower portion of the CNP flood plain (fig. 4).

The Black Creek aquifer of late Cretaceous age and associated confining unit may underlie the CNP flood plain (fig. 4). The updip limit of the Black Creek aquifer is in the upper Coastal Plain Physiographic Province and generally parallels the Fall Line. The shallow flood-plain aquifer and the Black Creek confining unit may share a common contact (fig. 4); however, the movement of ground water between the two aquifers may be limited due to clay deposits within the shallow flood-plain aquifer and Black Creek confining unit.

The updip limit of the Middendorf aquifer is generally at the Fall Line. The Middendorf aquifer of late Cretaceous age and the associated confining unit underlie the entire Black Creek aquifer and CNP flood plain (fig. 4). In the upper Coastal Plain near the outcrop areas and in the subsurface, the Middendorf aquifer is light gray, white, and buff sand commonly interbedded with lenses of white, pink, or purple clay (Aucott and others, 1987).

Data-Collection Networks

The USGS maintains various streamgaging station networks in the Broad, Saluda, and Congaree River basins and ground-water elevation networks in the CNP. In addition to using the available historical data, four discontinued observation wells were reactivated and seven observation wells and one streamgage were installed for this study.

A network of 11 streamgaging stations provided current and historical data and was used for the analysis of streamflow and elevation (table 1; fig. 2). Seven of the gages were located upstream from the CNP flood plain in the Broad and Saluda River basins, and three gages were located in or near the CNP flood plain. One streamgaging station was located in the

Series	South Carolina geologic units	South Carolina aquifers or confining units
Holocene	Alluvium and terrace deposits	Surficial aquifer
Pleistocene		
Miocene	Hawthorn Formation	Floridan-Tertiary sand confining unit
Oligocene (missing)		
Eocene	Santee Limestone	Floridan aquifer system
	Barnwell Formation	Tertiary sand aquifer
	McBean Formation	
	Congaree Formation	
Paleocene	Black Mingo Formation (undifferentiated)	
		Black Creek confining unit
Upper/Late Cretaceous	Black Creek Formation	Black Creek aquifer
		Middendorf confining unit
	Middendorf Formation	Middendorf aquifer
Paleozoic	Crystalline rocks	

Location of hydrogeologic section A to A', Congaree National Park, and the physiographic province line in South Carolina.

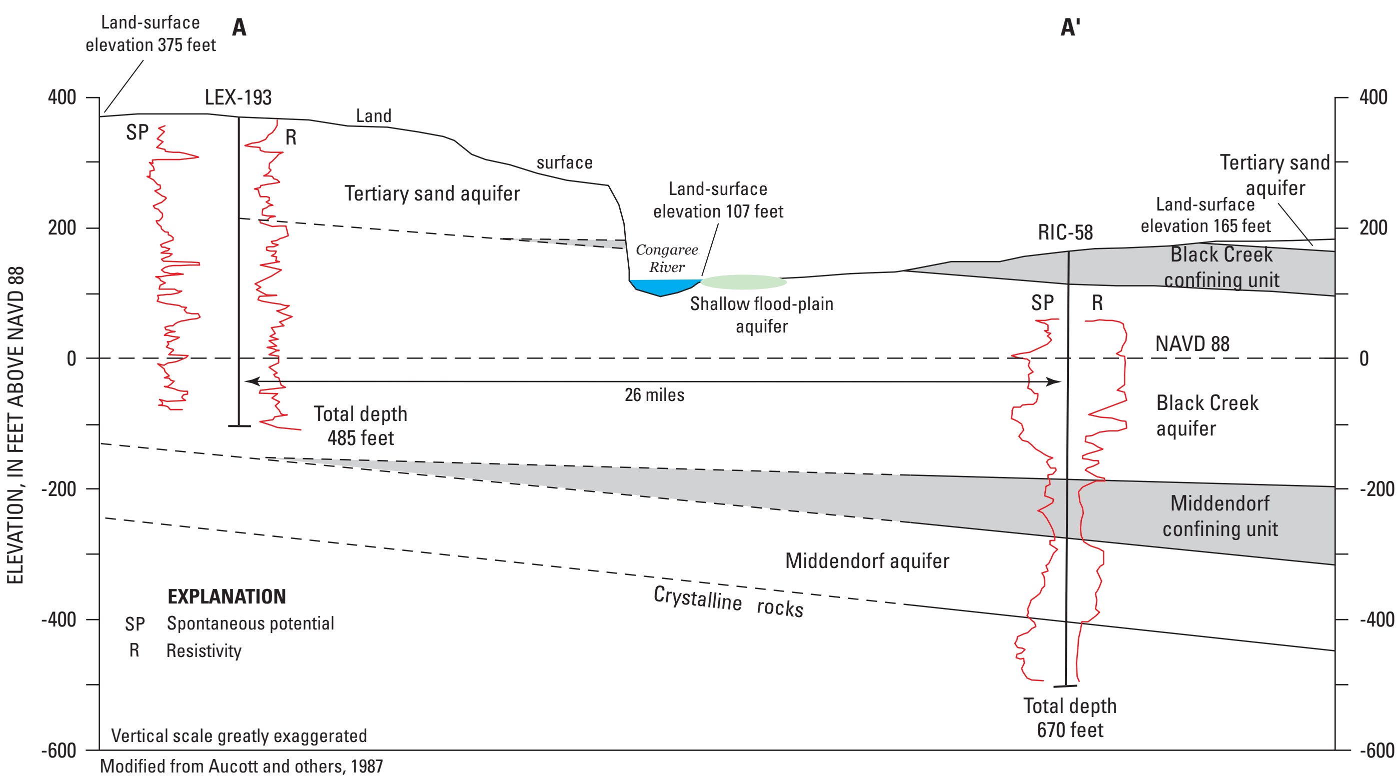

Figure 4. Generalized strike-oriented cross section illustrating the correlation of the hydrogeologic section from well LEX-193 to well RIC-58 through the Congaree National Park, South Carolina.

Broad River basin in Georgia, which is not associated with the Broad River basin in South Carolina. The available data from the streamgaging stations vary from less than 2 years for the newly installed gage at Congaree River Fort Motte to more than 100 years at the Broad River Carlton (table 1). Six of the stations used in the study have greater than 60 years of record. A description of the maintenance of the streamgaging stations, processing the data, determination of streamflow, and archiving the data can be found in Rantz and others (1982) and Cooney (2001). Daily discharge values for the stations are available from the USGS National Water Information System (NWIS) Website (U.S. Geological Survey, 2008).

To create a long-term dataset for the Broad River (SC), the streamflow records for the Broad River Alston and the Broad River Richtex were combined. The drainage area for Broad River Richtex is slightly more than 1 percent larger than the drainage area for Broad River Alston (fig. 2). The two stations have concurrent water-year peaks for 1981–83. The mean percent difference for those peaks is 5.7 percent. Under excellent measuring conditions, which rarely occur in the field, a streamflow measurement is considered to have an uncertainty of approximately 5 percent; therefore, because the mean percent difference between the two stations was within that level of uncertainty, it was concluded that combining the peak flows from the two stations without any adjustment was reasonable. Hereafter, the combined peak-flow records for the Broad River Alston and Broad River Richtex streamgaging stations will be referred to as the peak-flow data for Broad River Richtex. The combined record for the two stations includes water years 1897 to 1907 and 1926 to 2005.

The ground-water network used for the study consisted of 11 observation wells instrumented with continuous (30-minute interval) water-level recorders (table 2; fig. 1). The USGS and the South Carolina Department of Natural Resources share a common well-numbering system, which is used in this report as the USGS identifier. Wells are sequentially numbered in each county using an alphanumeric well designation. The alphabetic prefix refers to the county and the number refers to the chronological order in which the wells were inventoried in that county. For example, the first well inventoried in Richland County, South Carolina, is designated RIC-1.

Four discontinued wells from the 1980s network were reactivated and seven new wells were installed for this study to define ground-water elevation fluctuation throughout the CNP flood plain (table 2; fig. 1). Prior to reactivation, the four discontinued wells (RIC-341, RIC-342, RIC-345, and RIC-346) were inspected and developed with compressed air to remove sediment from the screens and well bore. Other wells from the 1980s network were determined not to be suitable for reactivation. Because the CNP is a designated wilderness area, the new wells were installed close to the existing roads or trails to limit the effect of well construction in the flood plain and to minimize their visibility. Three of these wells were located close to the Congaree River and were accessible by boat.

Table 2. U.S. Geological Survey well data for observation wells located in the Congaree National Park flood plain used in the study.

[USGS; U.S. Geological Survey; NAD 83, North American Datum of 1983; NAVD 88, North American Vertical Datum of 1988]

USGS well identifier (see fig. 1)	USGS station number	Latitude (degrees, minutes, seconds, datum NAD 83)	Longitude (degrees, minutes, seconds, datum NAD 83)	Elevation of land-surface (datum NAVD 88)	Well depth (feet below land surface)	Top of screened zone (feet below land surface)	Bottom of screened zone (feet below land surface)	Period of record used for the study
RIC-341	334930080514400	33° 49' 31"	80° 51' 43"	101.98	18.3	8.0	13.0	11/07/2003–07/28/2005
RIC-342	334844080514200	33° 48' 45"	80° 51' 41"	105.09	28.0	23.0	28.0	11/08/2003–09/28/2005
RIC-345	334950080491000	33° 49' 31"	80° 49' 09"	115.24	22.2	18.0	22.2	11/06/2003–09/02/2006
RIC-346	334859080493900	33° 48' 60"	80° 49' 38"	99.25	23.5	13.5	23.5	10/29/2003–10/04/2006
RIC-699	334613080470400	33° 46' 14"	80° 47' 05"	99.11	14.5	9.5	14.5	11/26/2003–9/30/2005
RIC-700	334548080403100	33° 45' 48"	80° 40' 31"	86.37	13.0	8.0	13.0	11/26/2003–5/30/2005
RIC-701	334833080515800	33° 48' 34"	80° 51' 59"	107.65	14.8	9.8	14.8	10/29/2003–10/15/2006
RIC-702	334852080471400	33° 48' 53"	80° 47' 15"	95.95	13.0	8.0	13.0	10/24/2003–07/20/2005
RIC-703	334751080424200	33° 47' 52"	80° 42' 43"	88.65	12.0	2.0	12.0	12/10/2003–7/25/2005
RIC-704	334616080470600	33° 46' 16"	80° 47' 06"	99.63	14.0	9.0	14.0	11/26/2003–8/25/2005
RIC-705	334741080465400	33° 47' 41”	80° 46' 54"	93.84	14.5	9.5	14.5	7/07/2003–7/02/2007

The new observation wells were installed by hand augering boreholes into the alluvial flood-plain sediment. The borehole refusal depth with a hand auger was approximately 15 ft due to the lithology of the sediments encountered. The typical construction of an observation well is shown in figure 5. The observation wells vary in depth from 12 to 28 ft (table 2). Each well was instrumented with a pressure transducer and data logger. Three of the wells were instrumented with data-collection platforms (DCP) that transmitted water-level data in near real time (4-hour delay) by way of the Geostationary Operational Environmental Satellites (GOES) to a USGS receiving station for display on the NWIS Web page. Well information, including coordinate location, screening intervals, and period of record, are listed in table 2. Lithologic descriptions of fluvial sediment encountered during the installation of the existing and new wells are presented in Appendix 1.

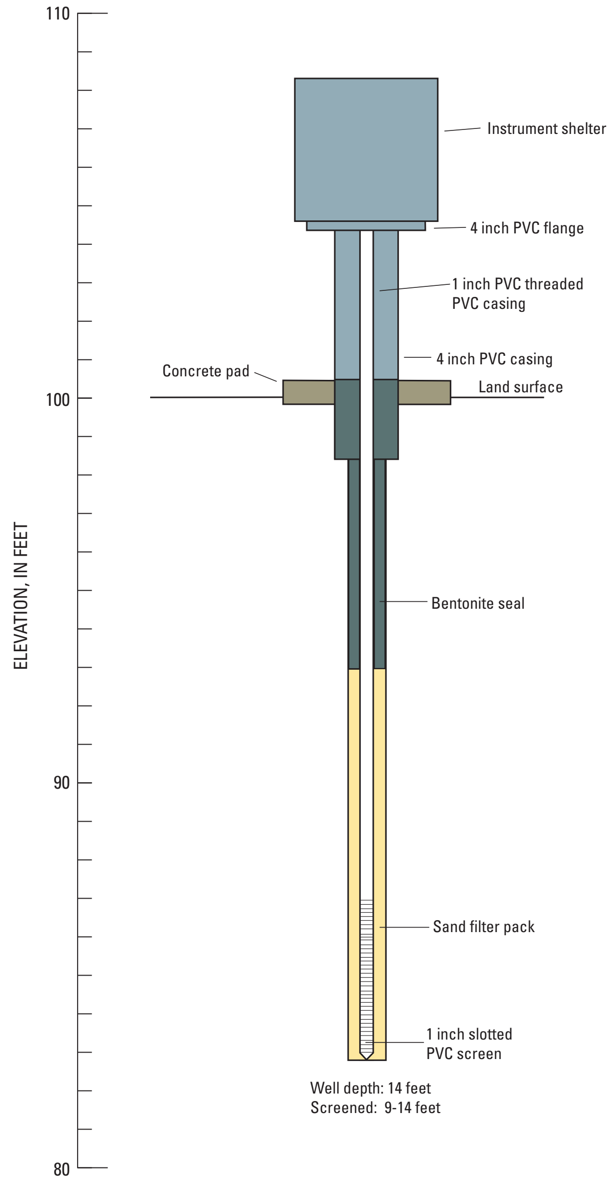

Figure 5. Typical well construction for U.S. Geological Survey observation wells installed in the Congaree National Park, South Carolina.

Characterization of Surface Water and Ground Water

Large river basins, like the Congaree River basin, are complex systems where surface-water and ground-water resources are constantly responding to changing hydrologic, meteorologic, and anthropogenic conditions from small to large subwatersheds within the basin. The headwaters of the 8,290-mi^2-basin of the Congaree River CNP begin in the Saluda and Broad River basins in the Blue Ridge Mountains of western North Carolina. The Saluda River flows through the Piedmont Province, including the I–85 corridor and the metropolitan areas of Greenville and Spartanburg, SC. The Broad River also flows through the Piedmont Province and joins the Saluda River at Columbia, SC, just before flowing into the Coastal Plain near the CNP. The following sections characterize the streamflow of the lower Saluda and lower Broad Rivers and the Congaree River, the gage heights of the Congaree River, and ground-water elevations in the Congaree River flood plain at the CNP.

Surface Water

As mentioned previously, the Congaree River is formed by the confluence of the Saluda and Broad Rivers near the Fall Line at Columbia, SC (fig. 2). The Broad River basin comprises about two-thirds of the drainage area of the Congaree River. At high streamflows, the Broad River essentially is unregulated because of the limited storage capacity of the various dams throughout the basin. On the other hand, the Saluda Dam significantly regulates downstream streamflow in the Saluda River. The Lake Greenwood Dam upstream from Lake Murray (fig. 2) also regulates streamflow in the Saluda River but to a lesser degree than the Saluda Dam.

Although surface-water regulation in the Broad River basin has been extensive, most of the regulation has been for the production of hydroelectric power rather than flood control and, therefore, generally has little effect on streamflow except during low- to medium-flow conditions. The storage capacity for most of the reservoirs on the Broad River, when compared to highest daily mean streamflow, is such that large floods are not significantly altered. A quick assessment of this assumption can be made from the storage capacity of the Parr Shoals Reservoir (fig. 2), which is the largest reservoir on the Broad River in South Carolina. For example, the difference between the normal storage and maximum storage in Parr Shoals Reservoir (fig. 2) is 12,000 acre-feet, (5.23 x 10^8 cubic feet (ft^3); U.S. Army Corps of Engineers, 2006). At the Broad River Carlisle gage, which is located upstream from Parr Shoals Reservoir, the highest daily mean streamflow for water year 2005 was 31,200 cubic feet per second (ft^3/s) (Cooney and others, 2005). Thus, assuming that streamflow rate and no outflow (for simplicity and ease of comparison with the storage capacity of other reservoirs), the reservoir would rise from normal storage to maximum storage in slightly less than 5 hours. Once the reservoir reaches maximum storage, the streamflow would be the same as if there were no reservoir. The highest daily mean peak flow for Broad River Carlisle from 1939 to 2005 is 114,000 ft^3/s. At that streamflow rate and assuming no outflow, the Parr Shoals Reservoir would rise from normal storage to maximum storage in just over an hour and a half.

In the upper part of the Saluda River basin above Lake Greenwood, several small water-supply reservoirs affect streamflow. Controlled releases from Lake Murray and Lake Greenwood have altered natural streamflow patterns of the lower part of the Saluda River since 1930 and 1940, respectively (South Carolina Water Resources Commission, 1983). The storage capacity for Lake Murray and Lake Greenwood is 2,114,000 and 270,000 acre-feet, respectively. The difference between the normal storage and the maximum storage for Lake Murray is 100,000 acre-feet (4.3 x 10^9 ft^3; U.S. Army Corps of Engineers, 2006). The highest daily mean streamflow measured at Saluda River Chappells for water year 2005 was 8,520 ft^3/s. Thus, assuming that streamflow rate and no outflow, it would take 142 hours (5.9 days) for Lake Murray to rise from normal to maximum storage. Using the highest daily mean streamflow for 1941–2005 (14,800 ft^3/s), it would take 82 hours (3.4 days) to rise from normal to maximum storage.

The USGS has monitored streamflow on the Saluda River near Columbia at a site located 8.8 mi downstream from the Saluda Dam since August 1925 (fig. 3; table 1). Figure 3 shows four streamflow periods on the Saluda River: (1) before the construction of Saluda Dam, (2) after construction of the Saluda Dam, (3) modified run-of-river, and (4) post modified run-of-river. The lower and upper daily mean streamflows for the period prior to the construction of the Saluda Dam appear to be higher than streamflows for the period after the completion of the Saluda Dam. In addition, the minimum daily mean streamflows tended to increase until some time in the mid to late 1960s when streamflow began to reach a more stable pattern of variation. As previously mentioned, this is probably associated with the McMeekin Station coming online in 1958.

Duration hydrographs for Congaree River Columbia based on 67 years of data are shown in figure 6. Daily duration graphs characterize the state of streamflow with respect to time. The plotted percentiles are best explained by an example.

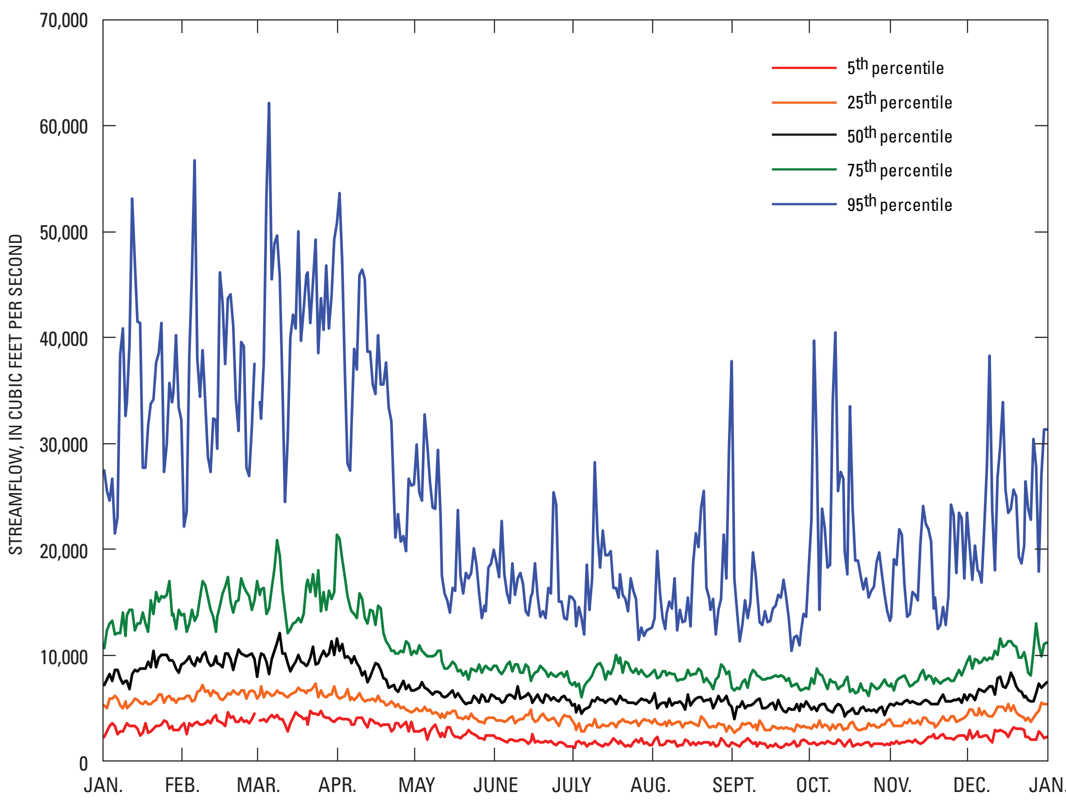

Figure 6. Duration hydrographs for Congaree River Columbia. Percentiles are based on streamflow data for 1940 to 2006.

Based on 67 years of daily mean streamflow data at Congaree River Columbia, the 75th-percentile daily mean streamflow for March 8 is 21,000 ft^3/s. This means that 75 percent of all daily mean streamflows that occurred on March 8 of each of the 67 years of data were equal to or less than 21,000 ft^3/s. Streamflows between the 0 and 10th percentiles occur during very dry hydrologic conditions, and streamflows between the 90th and 100th percentiles occur during very wet hydrologic conditions. Streamflows between the 25th and 75th percentiles occur during normal hydrologic conditions. Daily mean streamflow at Congaree River Columbia ranges from a minimum of less than 1,500 ft^3/s during periods of low streamflow to greater than 60,000 ft^3/s or more during periods of high streamflows (fig. 6). Seasonally, the highest streamflows typically occur in late winter and early spring (January through April), and the lowest streamflows occur in late summer and early fall (July through November).

The Congaree River flows 24 river miles from the Congaree River Columbia streamgage to the Congaree River CNP streamgage. Through this reach, the river transitions from the high gradient streams of the Saluda and Broad Rivers in the Piedmont to a low gradient river of the Coastal Plain Physiographic Province. With the decrease in gradient, there is a decrease in stream velocity that results in deposition of sands, silts, and clays, especially during floods when the sediment load is large (Patterson and others, 1985). At the CNP, the flood plain of the Congaree River is wide and portions of the bank are incised with many guts and sloughs hydraulically connecting the flood plain and river through a large range of river elevations.

The surface-water elevations for three stations in or near the CNP flood plain—Congaree River CNP, Cedar Creek, and Congaree River Fort Motte—are shown in figure 7 along with Congaree River Columbia. The hydrograph for Congaree River CNP generally shows broadened and attenuated pulses compared to the Congaree River Columbia hydrograph. Surface-water elevations at Congaree CNP change sharply and rapidly compared to those measured at the Congaree River Fort Motte gage. The sharp response may be due to the elevation of the riverbank at this location. Water begins to enter the creeks of the flood plain at an elevation of approximately 102 ft. The well-defined banks at the Congaree River CNP

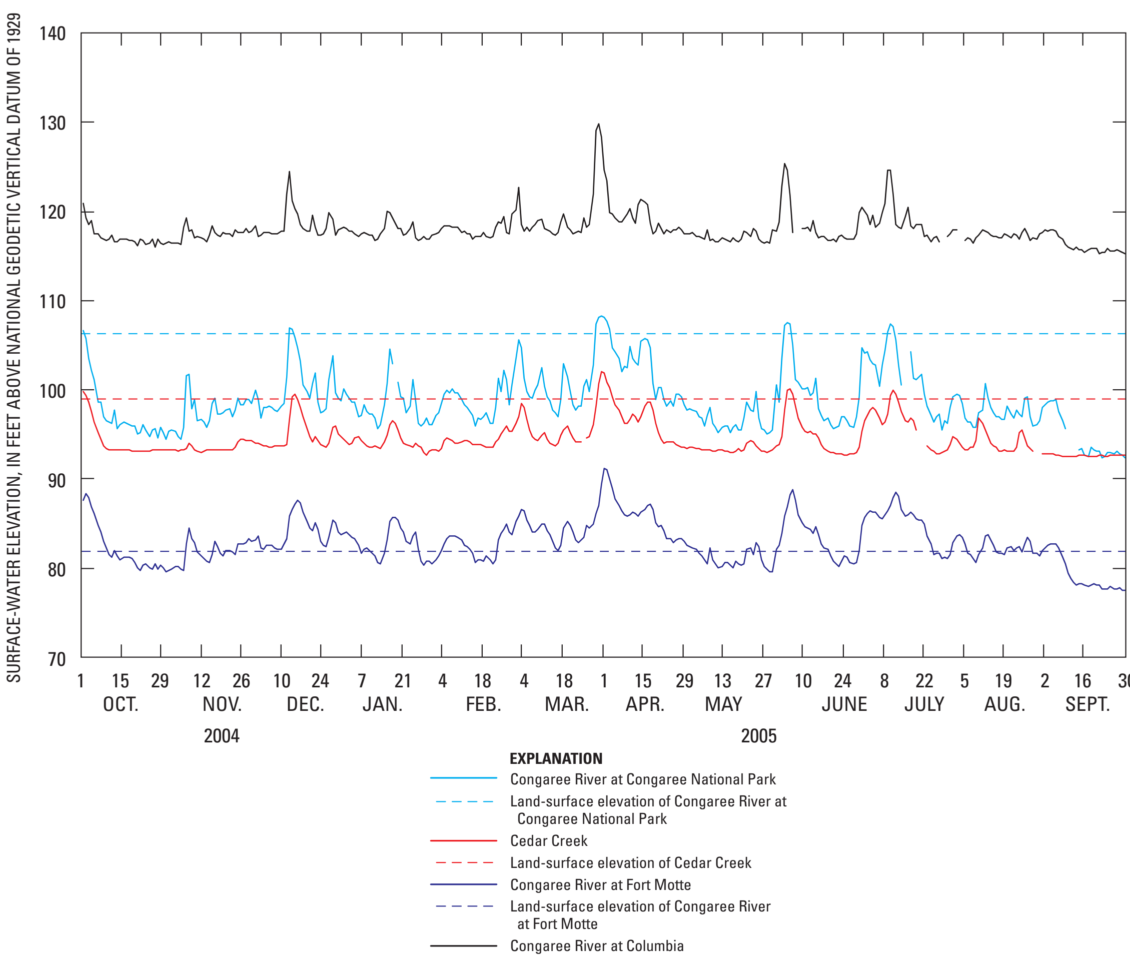

Figure 7. Surface-water and land-surface elevations at Congaree River Columbia, Congaree River Congaree National Park, Cedar Creek, and Congaree River Fort Motte for the 2005 water year.

gage may limit the dispersion of streamflow into the flood plain, producing the highly variable hydrograph. Flooding at Congaree River CNP begins with bankfull conditions when the surface water reaches an elevation of approximately 106.4 ft (NGVD 29; Patterson and others, 1985).

Although the drainage area at the Cedar Creek gage is small compared to Congaree River CNP (71.0 and 8,290 mi^2, respectively), the hydrographs show similar responses due to hydrologic connections in the flood plain. The Cedar Creek gage is located approximately 2.3 mi northeast from the Congaree River CNP gage. A distinct attenuation in the surface-water hydrograph is evident and likely is due to the smaller drainage area, limited runoff from the watershed, local precipitation, and flood-plain characteristics. Most of the Cedar Creek basin is under direct influence of the surface-water elevations in the Congaree River as a result of surface-water and ground-water interactions between the Congaree River and the CNP flood plain.

The shape of the hydrograph for Congaree River Fort Motte also is attenuated when compared to the hydrographs for Congaree River CNP and Congaree River Columbia due to the storage capacity of the flood plain and to the configuration of the riverbank at this location. In this area, the riverbanks of the Congaree River are lower in elevation relative to the river than the riverbanks near Congaree River CNP. This lower elevation allows main-channel streamflows to move into the flood plain and disperse, thereby attenuating the shape of the hydrograph at the downstream gage.

Ground Water

Ground-water and surface-water systems are more closely interrelated in swamps, such as the CNP, than in most other environments. In a flood-plain aquifer that is hydraulically connected to an adjacent river, the elevation of the surface water in the river tends to dominate the lateral and vertical movement of the adjacent ground-water system. Downward infiltration from precipitation tends to have less of an effect on the water level in flood-plain aquifers compared to adjacent river stages (Munster and others, 1996). The flow system in the CNP flood plain can be classified as a local flow system that is characterized by shallow and short flow paths (from recharge to discharge areas) and interaction with local rivers or surface-water bodies (Winter and others, 1998).

The depth of the ground water in the CNP flood plain is shallow and may be confined or unconfined depending on the underlying type(s) of sediment (Patterson and others, 1985). The permeability, hydraulic conductivity, hydraulic head, and saturated thickness of the heterogeneous sediments vary across the flood plain. Ground water flows from the higher elevations outside the flood plain toward streams and creeks that flow to the flood plain. Ground-water discharge from the flood plain is to the Congaree River, to evapotranspiration, and to the tributaries where the low-permeability surface sediments are breached (Patterson and others, 1985).

The ground- and surface-water interactions between the flood-plain aquifer and adjacent river are classified in terms of a losing river, gaining river, or both gaining in some reaches and losing in other reaches (Winter and others, 1998). A losing river reach exists where the surface water in a river seeps into the adjacent ground-water system through the riverbed or temporary bank storage as the elevation of the ground water becomes lower than the surface-water elevation in the adjacent river (fig. 8*A*). A gaining river reach occurs when ground water seeps into an adjacent river through the riverbed or bank as the elevation of the ground water adjacent to the river becomes greater than the surface-water elevation in the river (fig. 8*B*). Depending on the frequency, magnitude, and duration of the fluctuating surface-water elevations in the Congaree River, the surface-water and adjacent ground-water systems are continuously in a dynamic state of adjustment between bank storage and overbank flooding (fig. 9). Precipitation, evaporation, and evapotranspiration affect the ground-water levels to some degree in the CNP flood plain, but these fluxes are unknown and are not as influential as changes in the surface-water elevations in the Congaree River.

To gain a better understanding of the surface- and ground-water dynamics and spatial variability, a time-series clustering algorithm was applied to the time series of surface- and ground-water elevations to subdivide the data into groups of gages having similar behaviors (Risley and others, 2003;

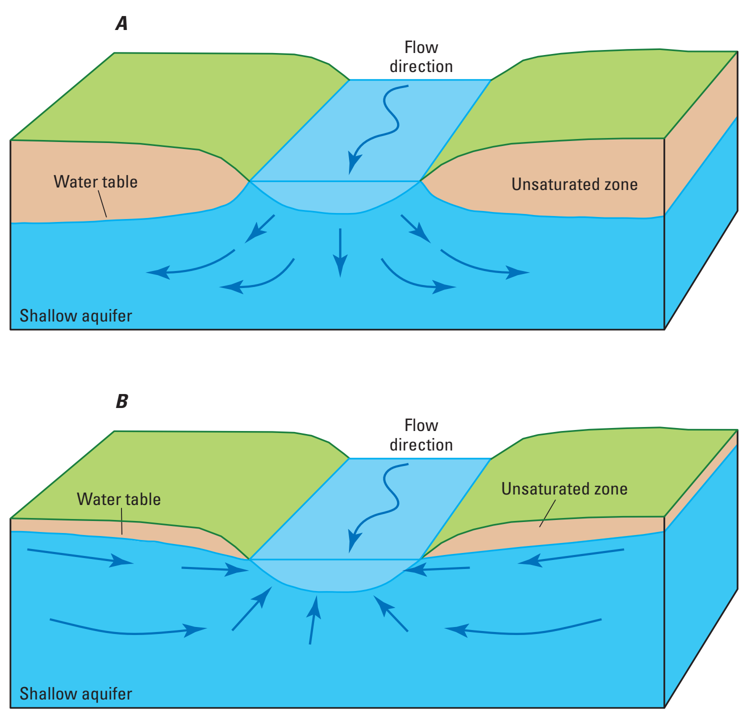

Figure 8. *A,* Losing stream, water level in stream higher than water level in adjacent aquifer; *B,* Gaining stream, water level in aquifer higher than water level in adjacent stream (modified from Winter and others, 1998).

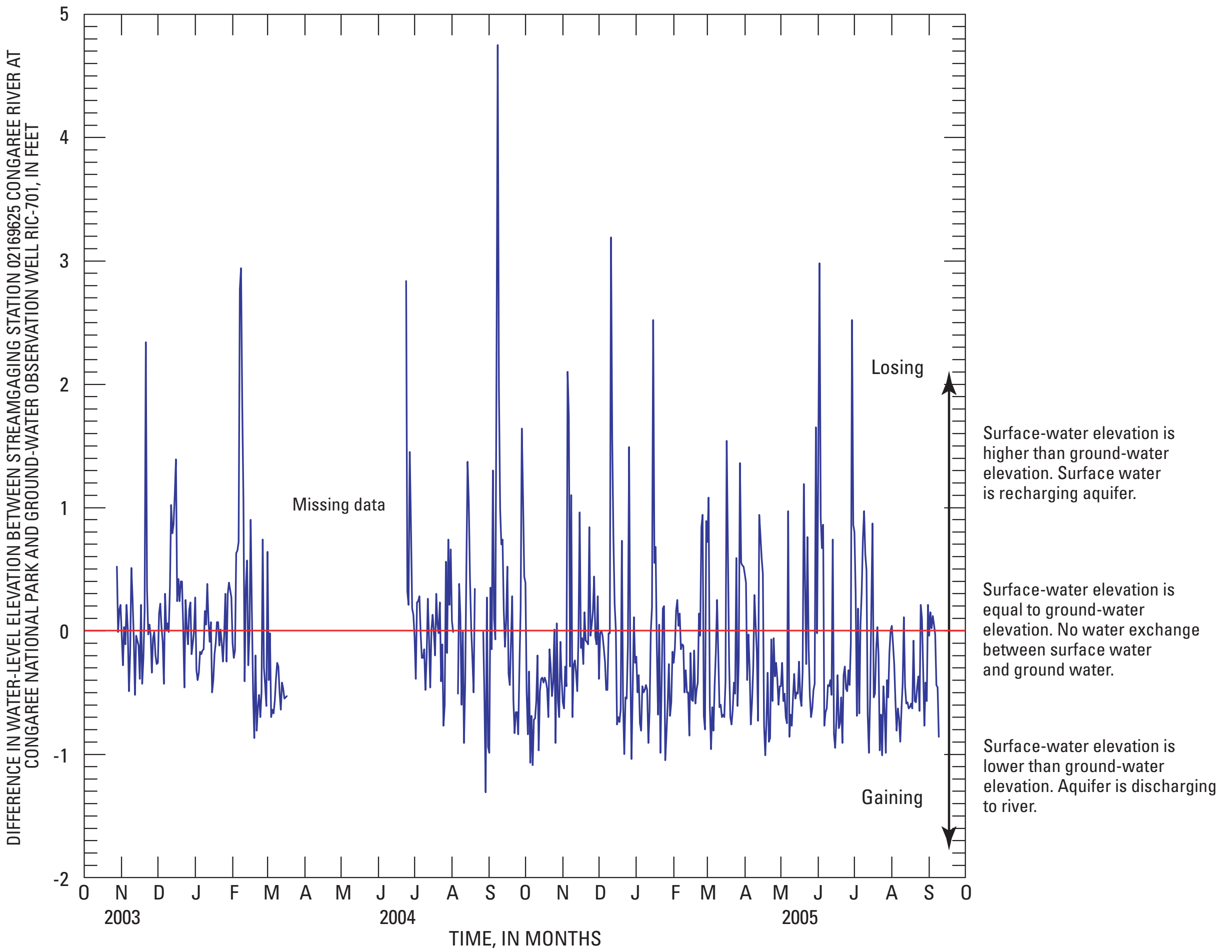

Figure 9. Hydraulic interaction between flood-plain ground water and surface water in the Congaree River for the period October 28, 2003, to September 10, 2005, in the Congaree National Park, South Caroina. Positive differences indicate period when the river water is either stored in the river bank or is recharging the aquifer system, and negative differences indicate periods when the aquifer is discharging to the river.

Roehl and others, 2006; Stewart and others, 2006). By using a statistical technique, such a time-series clustering, sites of similar behavior can be objectively grouped together rather than subjectively grouping the sites with a preconceived conceptual model of the system.

The ground-water hydrographs were cross-correlated to produce matrices of Pearson coefficients (table 3) and coefficients of determination (R^2). The Pearson coefficient (R) is a measure of the correlation between two variables, and the R^2 is a measure of the proportion of the variation between two variables. Each row and column of the correlation matrix in table 3 represents a different gaging station and its behavioral similarity to each of the other gaging stations. The k-means clustering analysis, using the Data Miner Software Kit (DMSK) package, (Weiss and Indurkhya, 1998) was used to optimize the stations that should be in a group based on the cumulative distances between each vector (the R^2 between two stations) and the mean of that vector's group. Two stations can have a high correlation and be assigned to different groups on the basis of the mean of the group to which they are assigned. The number of groups (k) was determined by the sensitivity of the root mean square error to k.

Cluster analysis of the dynamic variability of the daily time series indicated three groups of wells with similar dynamic behavior (fig. 10). Compared to Congaree River CNP, the hydrographs of the Group 1 wells (RIC-346, RIC-699, RIC-700, and RIC-701) are the most similar to the streamgage hydrographs. The correlations for the Group 1 wells with the streamgages range from 0.81 to 0.99. For this report, Pearson coefficients from 0.0 to 0.3 are considered weak, from 0.3 to 0.7 are considered moderate, and from 0.7 to 1.0 are considered strong. The Group 2 wells are RIC-342, RIC-703, and RIC-705, and their correlation to the streamgages range from 0.82 to 0.91. The Group 3 wells include RIC-341, RIC-702, and RIC-704, and correlations are the least similar to the streamgages. The correlation coefficients for the Group 3 wells with streamgages range from 0.66 to 0.82 (table 3).

Table 3. Pearson correlation coefficient matrix of surface- and ground-water elevations for selected U.S. Geological Survey data-collection sites at the Congaree National Park, South Carolina.

	Congaree River CNP (Station 02169625)	Cedar Creek (Station 02169672)	Congaree River Fort Motte (Station 02169740)	RIC-341	RIC-342	RIC-345	RIC-346	RIC-699	RIC-700	RIC-701	RIC-702	RIC-703	RIC-704	RIC-705
02169625	1.00													
02169672	0.91	1.00												
02169740	0.93	0.91	1.00											
RIC-341[c]	0.69	0.72	0.74	1.00										
RIC-342[b]	0.82	0.84	0.88	0.92	1.00									
RIC-345	0.15	0.24	0.18	0.19	0.28	1.00								
RIC-346[a]	0.81	0.92	0.86	0.80	0.86	0.41	1.00							
RIC-699[a]	0.97	0.91	0.98	0.75	0.89	0.17	0.83	1.00						
RIC-700[a]	0.92	0.91	0.99	0.79	0.92	0.16	0.86	0.97	1.00					
RIC-701[a]	0.88	0.80	0.89	0.70	0.82	0.06	0.75	0.91	0.88	1.00				
RIC-702[c]	0.66	0.68	0.72	0.97	0.91	0.17	0.75	0.73	0.77	0.62	1.00			
RIC-703[b]	0.83	0.90	0.91	0.88	0.93	0.15	0.91	0.88	0.93	0.81	0.87	1.00		
RIC-704[c]	0.75	0.76	0.82	0.93	0.98	0.24	0.79	0.84	0.87	0.77	0.93	0.90	1.00	
RIC-705[b]	0.83	0.88	0.89	0.91	0.95	0.15	0.89	0.88	0.91	0.82	0.90	0.97	0.92	1.00

[a] Group 1 observation wells. [b] Group 2 observation wells. [c] Group 3 observation wells.

One well was not included in the group assignments from the time-series cluster analysis. Observation well RIC-345 is located on a bluff just north of the flood plain and outside of the CNP flood plain. Though ground-water elevations for this well are influenced somewhat by the change in surface-water elevation in the Congaree River, the predominant influence on ground-water elevations may have more to do with local precipitation and evapotranspiration. Well RIC-345 has a much weaker correlation with the Congaree River gages (0.15 and 0.18) and the Cedar Creek gage (0.24) than the other wells (table 3).

A representative ground-water hydrograph for one well from each group of wells (RIC-699, RIC-703, RIC-341, respectively) is shown in figure 11*A* along with the hydrograph for Congaree River CNP. The Group 1 well (RIC-699) response is highly similar to the riverine response. The change in the surface-water elevation is reflected at RIC-699 nearly instantaneously and illustrates the dynamic relation that exists between surface water in the Congaree River and ground water along the interface connecting the two water bodies. The Pearson coefficient (R) between the Group 1 well (RIC-699) and Congaree River CNP is 0.97. The response of the Group 2 well (RIC-703) is attenuated as compared to the Group 1 well but shows a similar overall response. The R between RIC-703 and Congaree River CNP is 0.83. The Group 3 well (RIC-341) shows very little similarity to the daily variability of the river but does show general similarity in seasonal responses. The R between RIC-341 and Congaree River CNP is 0.69.

It is interesting to note the seemingly anomalous group assignments, such as the Group 3 gage, RIC-704, that is proximal to the Group 1 gage, RIC-699, near the Congaree River (fig. 10). The ground-water elevations at RIC-704, either due to the flood-plain aquifer characteristics, proximity to the surface-water features, screen depth and length, or some other hydrogeologic factor, are similar to the ground-water elevations of the Group 3 gages, which are much farther from the river. The ground-water elevations for these gages and the Group 3 well RIC-702 are shown in figure 11*B*, and it is apparent that the Group 3 ground-water elevations are more similar to each other than to the Group 1 well levels. The dissimilarities between RIC-699 and RIC-704 and the similarities between RIC-704 and RIC-702 illustrate the complexities of the flood-plain aquifer hydrogeologic properties.

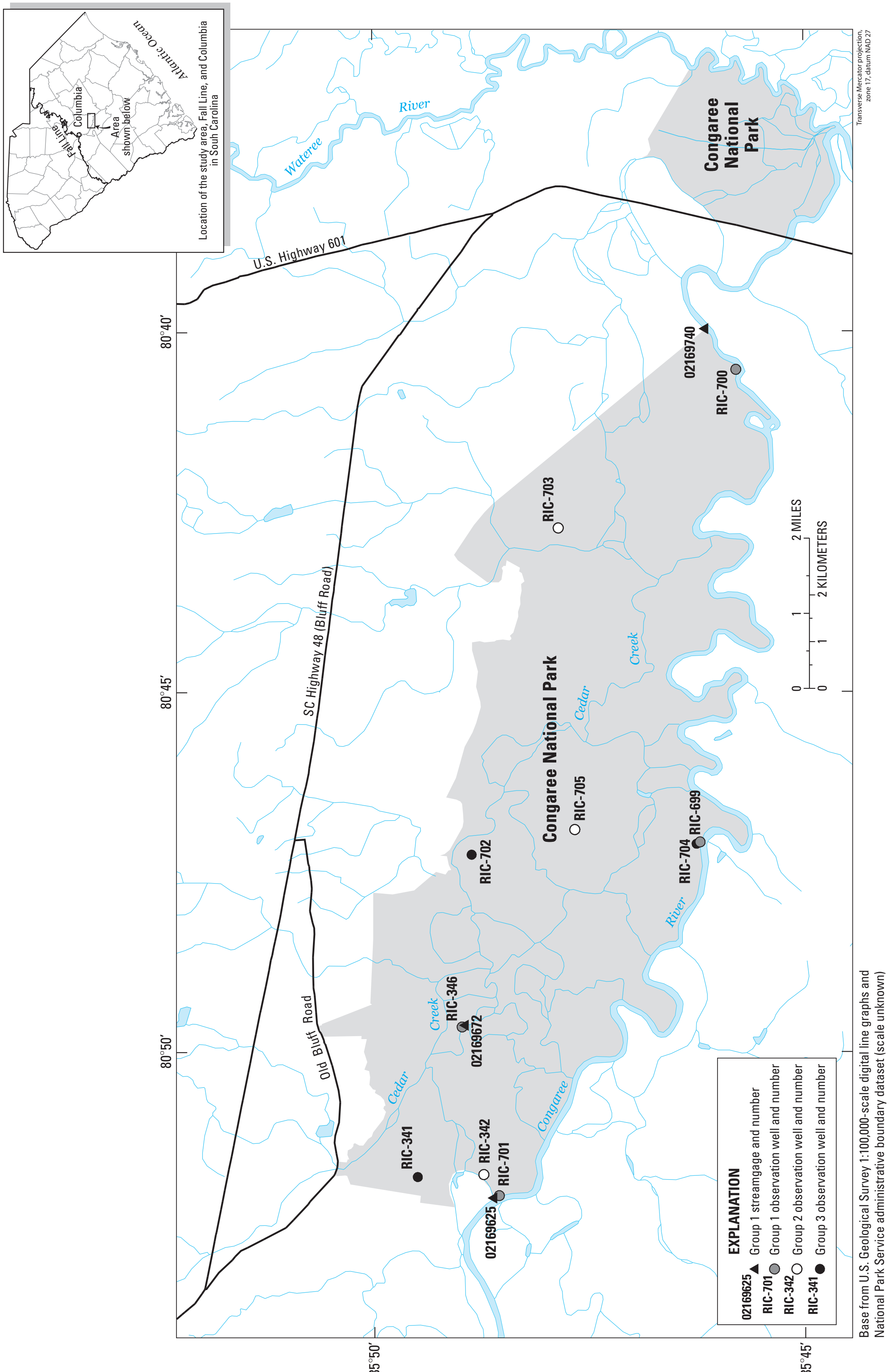

Figure 10. Spatial distribution of Group 1, Group 2, and Group 3 streamgages and observation wells.

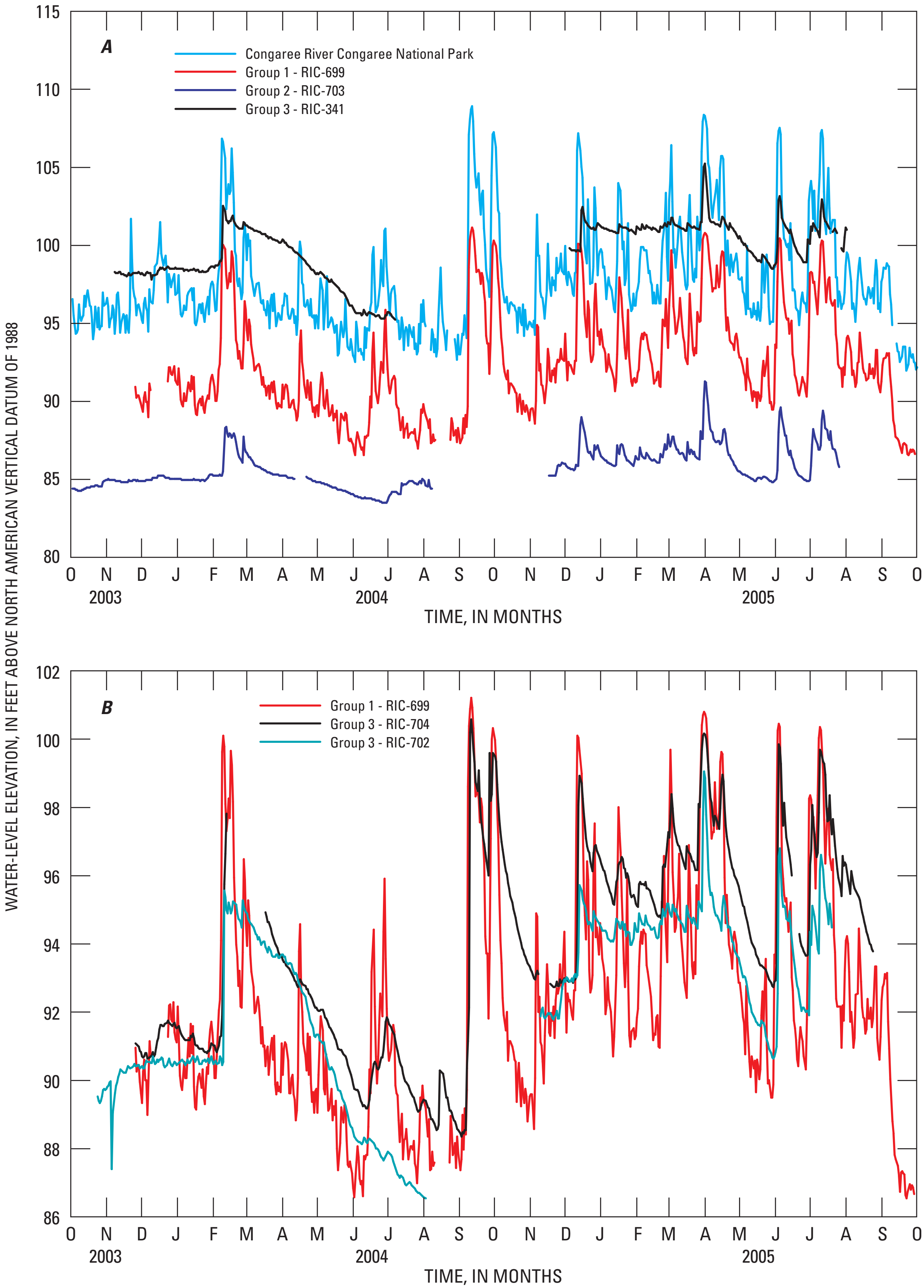

Figure 11. *A,* Surface- and ground-water elevations at Congaree River Congaree National Park, RIC-699 (Group 1 well), RIC-703 (Group 2 well), and RIC-341 (Group 3 well); *B,* Ground-water elevations at RIC-699 (Group 1 well), and RIC-702 and RIC-704 (Group 3 wells).

Water-Table Elevation Distribution

Surface- and ground-water elevations in and near the CNP flood plain varied throughout the data-collection period. Synoptic surface- and ground-water elevations for selected data-collection locations are shown in figure 12 for two dates when the lowest (September 10, 2005) and the highest (September 11, 2004) surface-water elevations were recorded at the Congaree River CNP gage during the study. Due to the limited number of data points in the CNP flood plain (10 sites in 22,200 acres) and the complexities of the ground-water flow paths through the CNP, ground-water contour maps were not generated for high- and low-water conditions. The missing data noted in figure 12 represent periods when data collection was interrupted because of equipment failure. Observation well RIC-345 is outside of the flood plain, and the ground-water elevations presented on the map correspond to the dates of the lowest and highest water levels of the Congaree River and not for the period of record of this particular observation well.

The lowest surface-water elevation of 89.98 ft was recorded at Congaree River CNP on September 10, 2005, at 4:30 p.m. when the Congaree River and the CNP flood plain were experiencing a relatively dry period. During this period of low surface-water elevation, the thickness of the unsaturated zone beneath the CNP flood plain was the greatest observed during the study. The thickness of the unsaturated zone beneath an observation well is determined by subtracting the measured ground-water elevation from the land-surface elevation. Of the three wells recording water levels in the flood plain during this period, the thickness of the unsaturated zone was 7.61 ft, 6.23 ft, and 10.14 ft at observation wells RIC-342, RIC-346, and RIC-699, respectively. North of the flood plain, at observation well RIC-345, the thickness of the unsaturated zone was 13.16 ft.

The highest surface-water elevation of 108.15 ft was recorded at Congaree River CNP on September 11, 2004, at 8:30 p.m. when the Congaree River and the CNP flood plain were experiencing a relatively wet period. During this period of high surface-water elevations, the unsaturated zone beneath the CNP flood plain was at its thinnest or absent, and the water elevations at some sites were above land surface, indicating flooding in the CNP. Of the five observation wells recording during this period, floodwater depths of 0.92 ft, 1.40 ft, 5.54 ft, and 2.06 ft were recorded at RIC-704, RIC- 342, RIC-700, and RIC-699, respectively. The unsaturated zone at RIC-345, outside of the flood plain, was 13.16 ft, illustrating that no flooding was occurring at this site during this time.

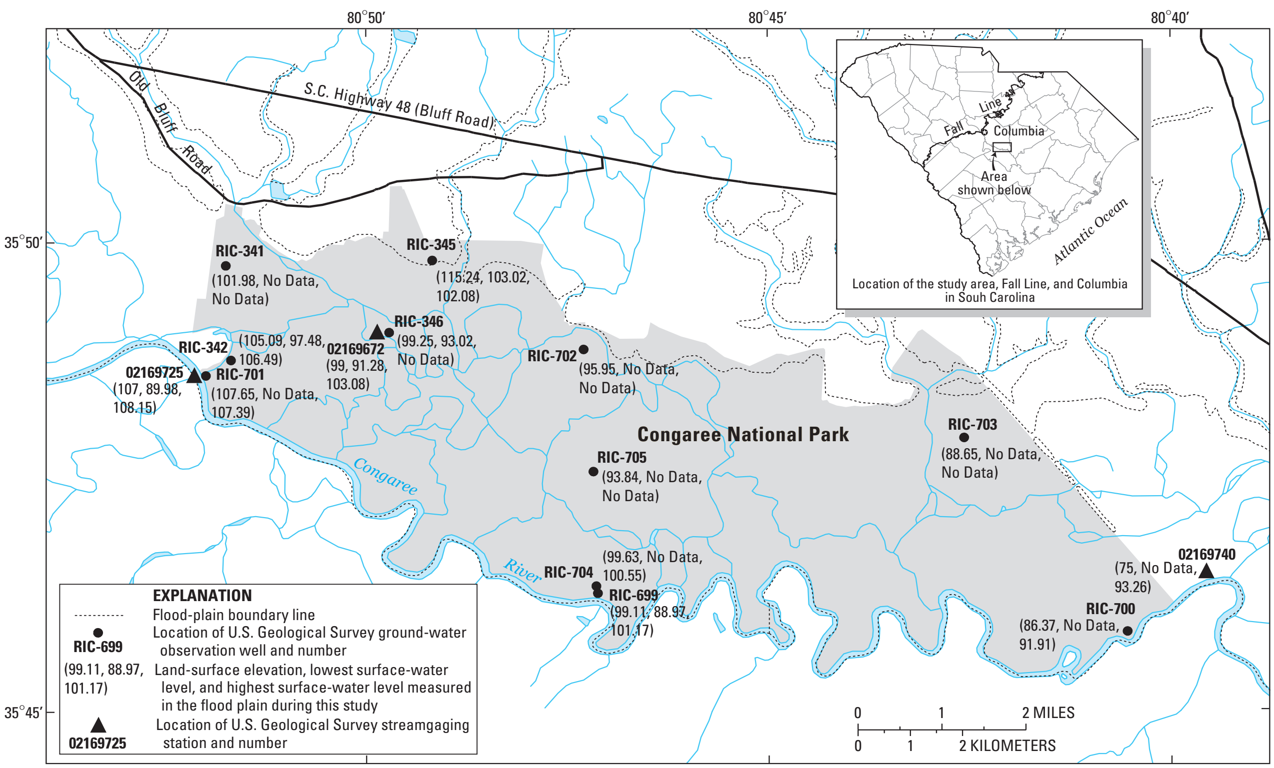

Figure 12. Location, land-surface, and surface- and ground-water elevations for U.S. Geological Survey streamgages and observation wells in the Congaree National Park flood plain near Hopkins, South Carolina. Water levels represent the lowest (September 10, 2005) and the highest (September 11, 2004) surface-water elevations recorded at streamgage 02169625 in the Congaree River during this study. Note that observation well RIC-345 is outside of the flood plain, and the ground-water elevations presented on the map correspond to the dates of the lowest and highest water levels of the Congaree River and not for the period of record of the well.

Analysis of Surface-Water and Ground-Water Dynamics

The analysis of surface- and ground-water dynamics was quantified to describe the interaction between surface water in the Congaree River and ground water in the CNP flood plain. Historical peak-flow data were evaluated using linear regression to quantify how regulation of the Saluda Dam has affected peak flows on the Congaree River. The effects of the Saluda Dam on the daily water level of the Congaree River and CNP flood-plain aquifer were evaluated using long-term synthetic surface- and ground-water datasets simulated using artificial neural network (ANN) models.

Analysis of Surface-Water Peak Flows and Potential Effect of Climatic Variability

A previous investigation compared the magnitude and frequency of floods at the Congaree River Columbia for two different periods (Whetstone, 1982): (1) 1892–1929, representing the period before the construction of Lake Murray (pre-regulation), and (2) 1930–1978, representing the period after construction of Lake Murray (post-regulation) (fig. 13). Patterson and others (1985) presented information (fig. 13) implying that the operation of the Saluda Dam had significantly affected the magnitude and frequency of floods at Congaree River Columbia. As an example, the report stated that the 2-year recurrence-interval flow for the pre-regulation period was equivalent to a 4.5-year recurrence-interval flow for the post-regulation period. The report also stated that a 5-year recurrence-interval flow for the pre-regulation period equated to a 25-year recurrence-interval flow for the post-regulation period. Following that same line of reasoning and examining figure 13, it would appear that the 10-year recurrence-interval flow for the pre-regulation period would equate to something beyond the 100-year recurrence-interval flow for the post-regulation period. Although not explicitly stated by Patterson and others (1985), the implication was that construction of the Saluda Dam had significantly altered flooding in the Congaree River and subsequently in the CNP. However, current statistical analysis of the available data along with comparisons of other long-term USGS streamgaging stations indicate otherwise.

The USGS has collected streamflow data in the conterminous United States since the late 1800s. In South Carolina, Congaree River Columbia, has one of the longest records of water-year maximum peak flows in the State. The USGS has collected streamflow data at the current site since 1939. The National Weather Service collected daily streamflow data at the current site and at a site 1,000 ft upstream from Congaree River Columbia from 1891 to 1939 (Cooney and others, 2005). From the perspective of climatic variability, 114 years of record may provide only a narrow view of the long-term behavior of such systems.

Climatic variability can be assessed from lake and ocean sediments, mass balance of glaciers, and from paleohydrologic data (Jarrett, 1991). Such research has shown that in the past 10,000 years, there have been numerous periods where the climate has varied from present conditions with annual mean temperatures varying by about plus or minus 4 degrees Fahrenheit (°F) and annual mean precipitation varying by as much as plus or minus 20 percent from modern values. An investigation on the Colorado River (Jarrett, 1991) included paleohydrologic techniques using standardized tree-ring chronologies to reconstruct annual average streamflows for a 450-year period before 1960. The data showed that a 35-year period (8 percent of the total record) from 1896 to 1930 contained the longest series of high-flow years during the

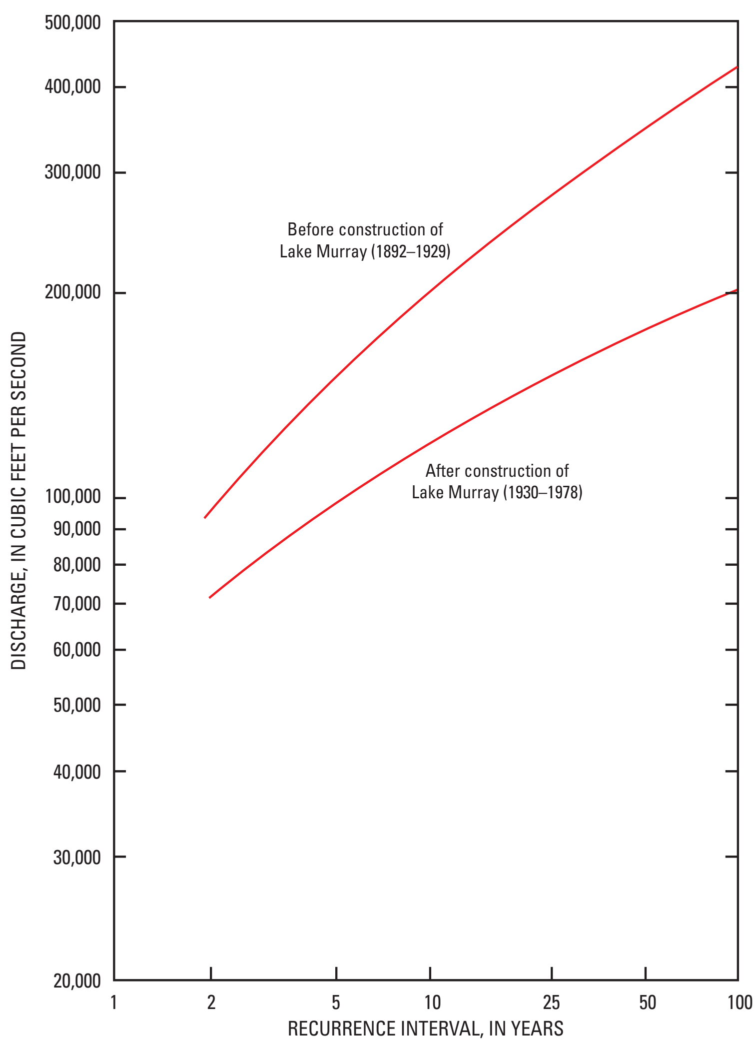

Figure 13. Flood frequency for the Congaree River Columbia streamgaging station (station 02169500; from Patterson and others, 1985).

entire 450-year period. This example highlights how a water-resources assessment made from a relatively short period of record that is, by chance, collected during an unusually wet or dry period could significantly skew the more long-term reality of what might be expected to occur.

From long-term streamgaging information and historical documents, the latter part of the 1800s and early part of the 1900s was a period in which many significant floods occurred in and around South Carolina. The peak-flow record at Congaree River Columbia shows that the five largest floods (in order of decreasing magnitude) occurred in 1908, 1928, 1929, 1916, and 1912 (fig. 14). The peak-flow record from historical documents also includes the gage height for a major flood in 1852. The 1908 flood has been noted as being the most extensive flood in South Carolina with all major rivers in the State rising from 9 to 22 ft above flood stage (Paulson and others, 1991). The peak-flow record at the Savannah River at Augusta, GA, streamgaging station includes continuous peak-flow data since 1876. Prior to that, local residents marked the crest of large floods, which local newspapers also reported (Hess and Stamey, 1993). The USGS peak-flow record for Savannah River at Augusta further validates this was a particularly wet period in the late 1800s and early 1900s with the largest four floods occurring in October 1929, September 1929, 1908, and 1888. The October 1929 flood is the largest recorded since 1796.

Most long-term streamgages in and around South Carolina are located on streams that are now regulated. This is the case with both the Congaree River and Savannah River gages mentioned in the previous paragraph. For comparison purposes, the USGS streamflow database was reviewed to find unregulated streamflow gages in and around South Carolina that also had long-term records similar to that at Congaree River Columbia. Such records would help determine how the wet period of the late 1800s and early 1900s relates to the subsequent record at a long-term, unregulated site. Along with the stations in the lower part of the Broad River in South Carolina, an unregulated gage with long-term record in the

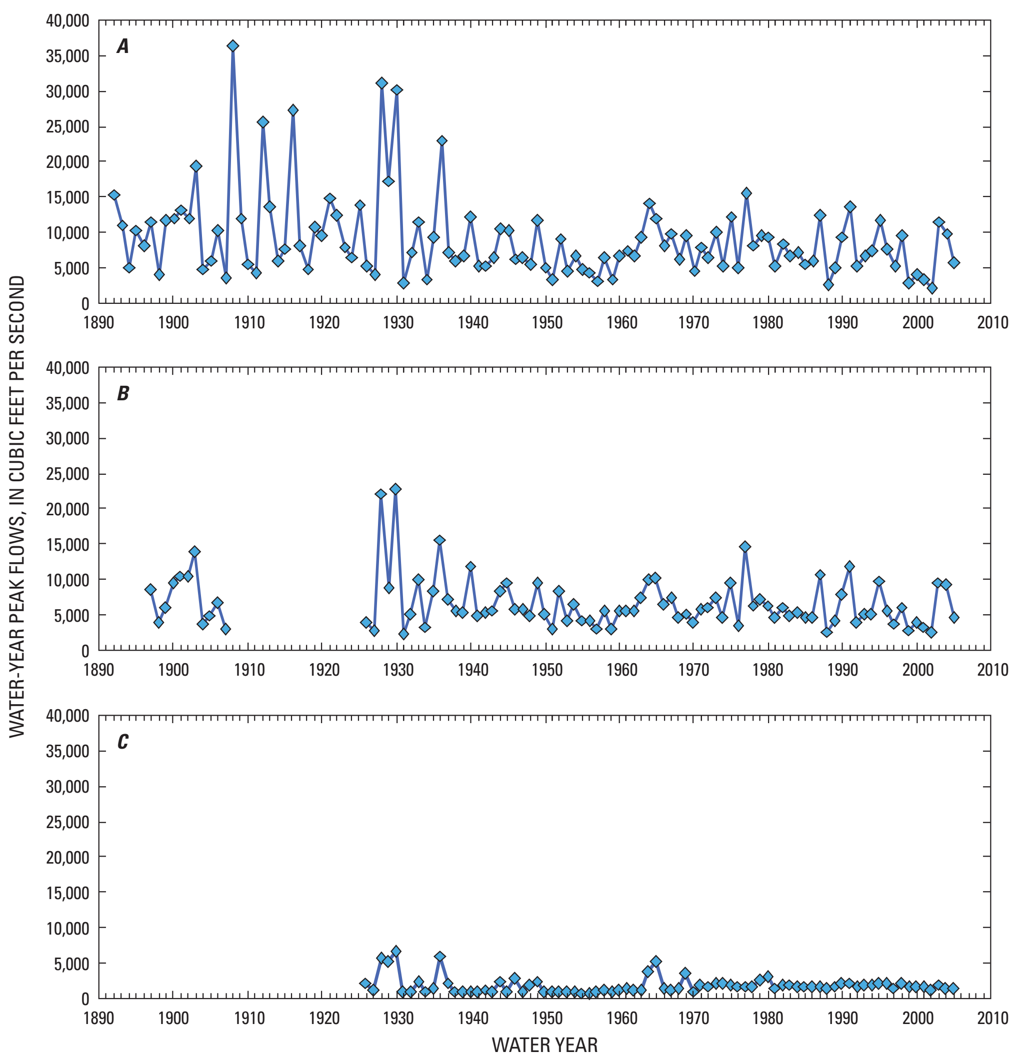

Figure 14. Maximum water-year peak flows for the period of record at the *(A)* Congaree River Columbia, *(B)* Broad River Richtex, and *(C)* Saluda River Columbia streamgaging stations.

Piedmont of Georgia also was determined to be useful for making such an assessment. Both of the Broad River basins are located primarily in the Piedmont Physiographic Province. The USGS has been collecting streamflow data at Broad River Carlton since 1913 (fig. 15). The National Weather Service provided peak-flow records from 1897 to 1913.

An analysis of the peak-flow data at Broad River Richtex and Broad River Carlton was made using historical streamflow data and similar periods of record as those collected on the Congaree River both prior to and after construction of the Saluda Dam. As previously mentioned, peak flows are defined as the highest instantaneous flow for an independent event at a streamflow gage in a given water year. For the historical review and analysis of streamflow in the Saluda, Broad (Georgia and South Carolina), and Congaree River basins, data from the following USGS streamgaging stations were used: Saluda River Columbia, Broad River Alston, Broad River Richtex, Congaree River Columbia, and Broad River Carlton (fig. 2; table 1). Analyses indicate that the difference in the recurrence-interval flows at Congaree River Columbia computed using streamflow data collected before and after the construction of the Saluda Dam (fig. 13) may have more to do with varying climatic conditions than regulation of the Saluda River.

A comparison of the water-year maximum peak flows for Congaree River Columbia, Saluda River Columbia, and Broad River Alston shows that the Congaree River peak flows are highly correlated to the Broad River Richtex peak flows (fig. 14). As previously stated, the peak flows at Saluda River Columbia measured after water year 1930 reflect regulated conditions on the Saluda River (South Carolina Water Resources Commission, 1983). As can be seen in figure 14, the three largest peaks at Congaree River Columbia occurred in water years 1908, 1928, and 1930, respectively. The next three largest floods occurred in water years 1916, 1912, and 1936, respectively. Given that regulation tends to reduce the large peaks on a river, one might conclude that the completion of the Saluda Dam in 1930 is the main reason why only one major flood (1936) has occurred at Congaree River Columbia since that time. Unfortunately, the Broad River streamgaging station in South Carolina (Broad River Alston and Broad River Richtex) was inactive from water years 1908 to 1925. Nonetheless, it is reasonable to assume based on the strong graphical correlation between Congaree River Columbia and Broad River Richtex that there were also major floods on the Broad River in 1908, 1912, and 1916. As previously mentioned, the 1908 flood was noted as the most extensive flood of record in South Carolina (Paulson and others, 1991).

Broad River Carlton is on an unregulated stream in the Savannah River basin, has a drainage basin of 760 mi^2, and is completely located in the Piedmont Province of Georgia (fig. 2). The streamgaging station is located in Madison County, GA, which is approximately due west of Columbia, SC. Noted as being the largest flood at that site since 1888, the largest flood of record occurred on August 25, 1908. The next two largest floods occurred in water years 1902 and 1912,

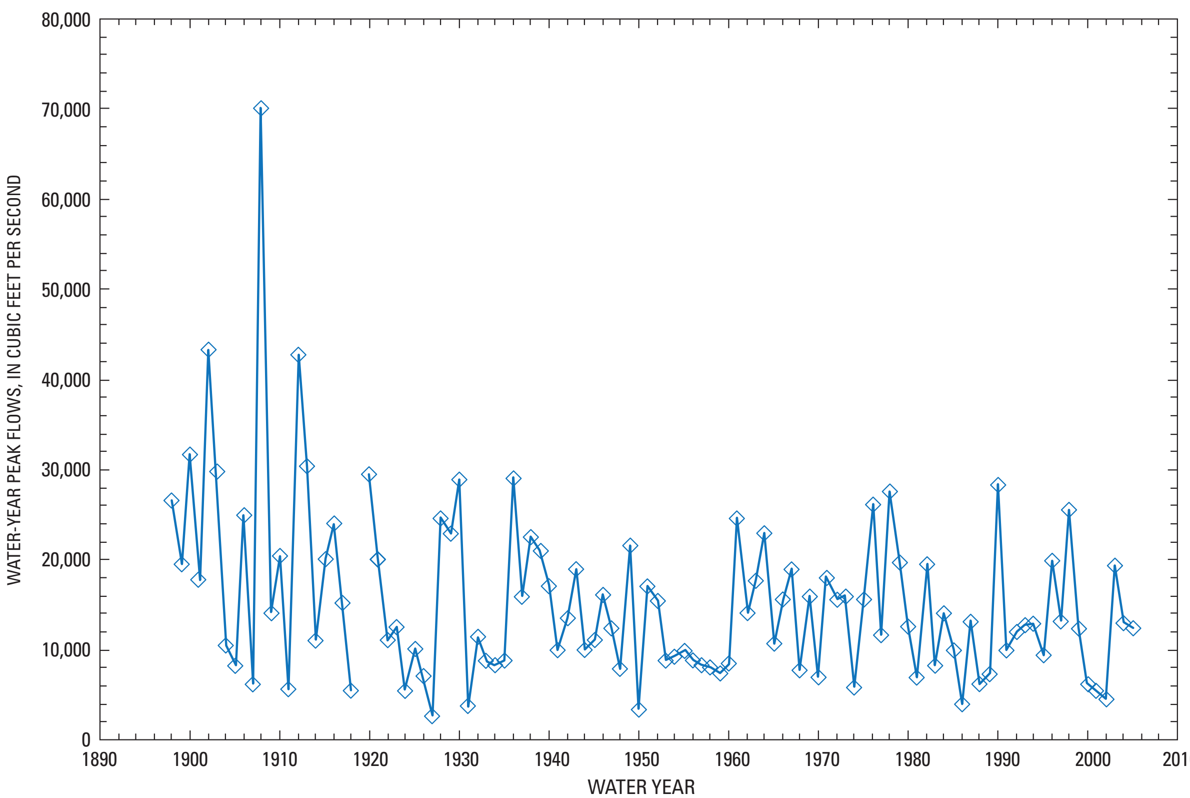

Figure 15. Maximum water-year peak flow for the period of record (1897–2005) at the Broad River Carlton streamgaging station.

respectively. At Congaree River Columbia and Broad River Carlton, there are 107 years in which both streamgages were operated concurrently. Of those 107 years, there were 47 years in which the peaks occurred within plus or minus 8 days of each other. Another 16 peaks occurred within 1 month of each other indicating similar climatic characteristics between the two basins and giving additional validity for comparing the two stations.

For comparison purposes, a Pearson Type III distribution with log transformation of the peak flows (log-Pearson Type III) was used to compute flood-frequency statistics for Congaree River Columbia, Broad River Richtex, and Broad River Carlton (Hydrology Subcommittee of the Interagency Advisory Committee on Water Data, 1982). Two periods were analyzed for each station: (1) beginning of record to 1930 and (2) 1931 to 2005. The breakpoint of 1930 was chosen to perform a similar analysis as was done by Whetstone (1982) on peak-flow data collected before and after the construction of the Saluda Dam. Results from the analyses are shown in figure 16. It should be noted that typically the recurrence-interval scale is plotted using a probability scale but is being shown here using a logarithmic scale.

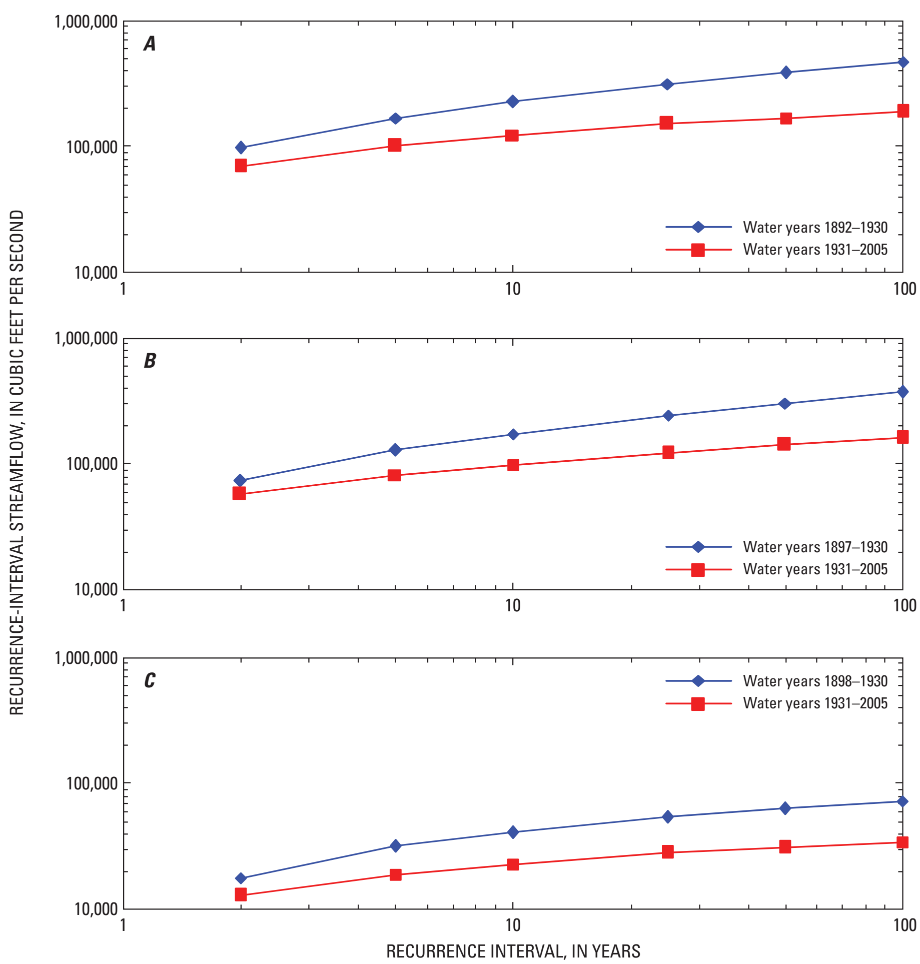

Figure 16. Recurrence-interval streamflows for two periods at the *(A)* Congaree River Columbia, *(B)* Broad River Richtex, and *(C)* Broad River Carlton streamgaging stations.

The percentage differences in the 100-year recurrence interval flows for the two periods for Congaree River Columbia, Broad River Richtex, and Broad River Carlton were 151, 133, and 112 percent, respectively (fig. 16; table 4). With respect to estimating the magnitude and frequency of floods at a streamgaging station, these graphs and the percentage differences highlight the importance of record length and the influence of large floods when doing a log-Pearson Type III analysis. The comparisons also support the conclusion that the significant differences between the pre-and post-regulation recurrence-interval flows as noted in Whetstone's (1982) report are more related to climatic variability than to regulation of the Saluda River.

Regression Analysis Using Historical Peak-Flow Data

To quantify how regulation on the Saluda River has affected peak flows on the Congaree River, regression techniques were used to develop pre- and post-regulation relations between the peak flows at Congaree River Columbia and Broad River Richtex. Because of the uncertainty that construction of the Saluda Dam may have had on the water year 1929 and 1930 peaks, those data from the Broad and Congaree Rivers were excluded from the analysis. For the period from 1897 to 1928, which defines the relation between the peak flows on the Congaree and Broad Rivers as they were prior to regulation on the Saluda River, there were 14 years for which peak flows were measured concurrently at both the Congaree River Columbia and Broad River Richtex. After review of the peak-flow data, the water year 1899 peaks were excluded from the regression because of uncertainty in the Broad River value. A record-extension regression method called Maintenance of Variance Extension (MOVE) was used to extend the peak-flow record from the short unregulated period (1897–1928) at Congaree River Columbia based on the longer unregulated period (1897–2005) at Broad River Richtex (Hirsch, 1982). Hirsch (1982) compared four record-extension methods and found that the MOVE.2 regression technique was the most effective in terms of producing a time series with properties (such as variance and extreme order statistics) most like those of the records they are intended to represent. The MOVE.2

Table 4. Recurrence-interval flows computed for two periods at the Congaree River Columbia, Broad River Richtex, and Broad River Carlton streamgaging stations.

[ft^3/s, cubic feet per second]

Recurrence interval, in years	Congaree River Columbia: Recurrence-interval flow (ft^3/s) (1892–1930)	Congaree River Columbia: Recurrence-interval flow (ft^3/s) (1931–2005)	Congaree River Columbia: Percent difference	Broad River Richtex (South Carolina): Recurrence-interval flow (ft^3/s) (1897–1930)	Broad River Richtex (South Carolina): Recurrence-interval flow (ft^3/s) (1931–2005)	Broad River Richtex (South Carolina): Percent difference	Broad River Carlton (Georgia): Recurrence-interval flow (ft^3/s) (1898–1930)	Broad River Carlton (Georgia): Recurrence-interval flow (ft^3/s) (1931–2005)	Broad River Carlton (Georgia): Percent difference
2	97,400	68,400	42.4	70,500	58,100	27.4	17,000	12,300	38.2
10	224,000	122,000	83.6	170,000	100,000	75.0	39,600	22,000	80.0
50	386,000	167,000	131	305,000	142,000	115	61,000	29,800	105
100	470,000	187,000	151	379,000	161,000	133	70,100	33,000	112

regression method was used to estimate peak flows for water years 1931–2005 at Congaree River Columbia based on the relation between stations Broad River Richtex and Congaree River Columbia as it existed prior to regulation (1897–1928). The correlation coefficient between the measured unregulated peaks at the two stations is 0.98, indicating a very strong relation between the peak flows for the unregulated period (fig. 17).

Peak flows for water years 1931–2005 were estimated at Congaree River Columbia using the regression relation shown in figure 17 and the measured peak flows at the Broad River Richtex streamgaging station. The estimated peaks, therefore, represent conditions as they would have existed at Congaree River Columbia for unregulated conditions on the Saluda River. The frequency distribution for the "unregulated" condition at Congaree River Columbia was determined from a log-Pearson Type III analysis using the estimated peaks for the Congaree River streamgage and was compared with results from a similar analysis using the measured peaks (fig. 18).

As shown in figure 18, the magnitude and frequency of floods have been affected by regulation of the Saluda River but not to the extent implied in Patterson and others (1985; figs. 13 and 18; table 4). For the 2-year to 100-year recurrence-interval flows, the percentage differences between the measured peak flows (regulated) and the estimated peak flows (unregulated) at Congaree River Columbia for water years 1931–2005

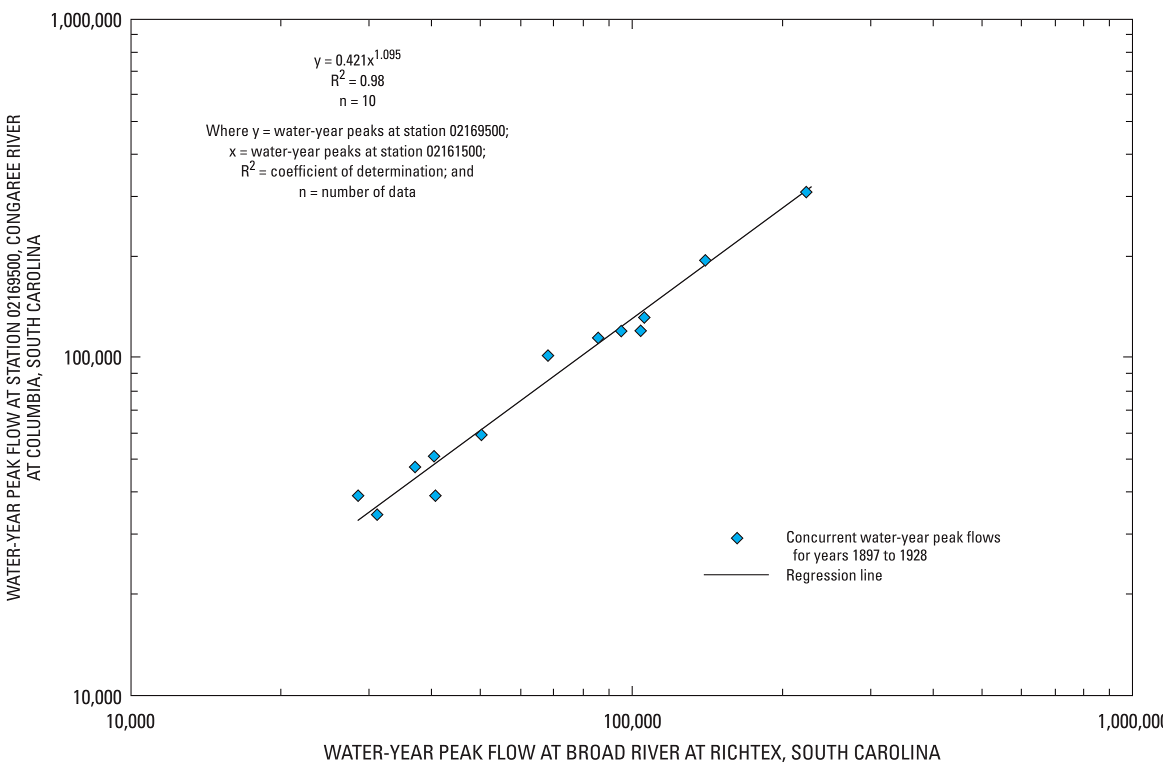

Figure 17. Regression relation between concurrent peak flows for water years 1897–1928 at the Congaree River Columbia and Broad River Richtex streamgaging stations.

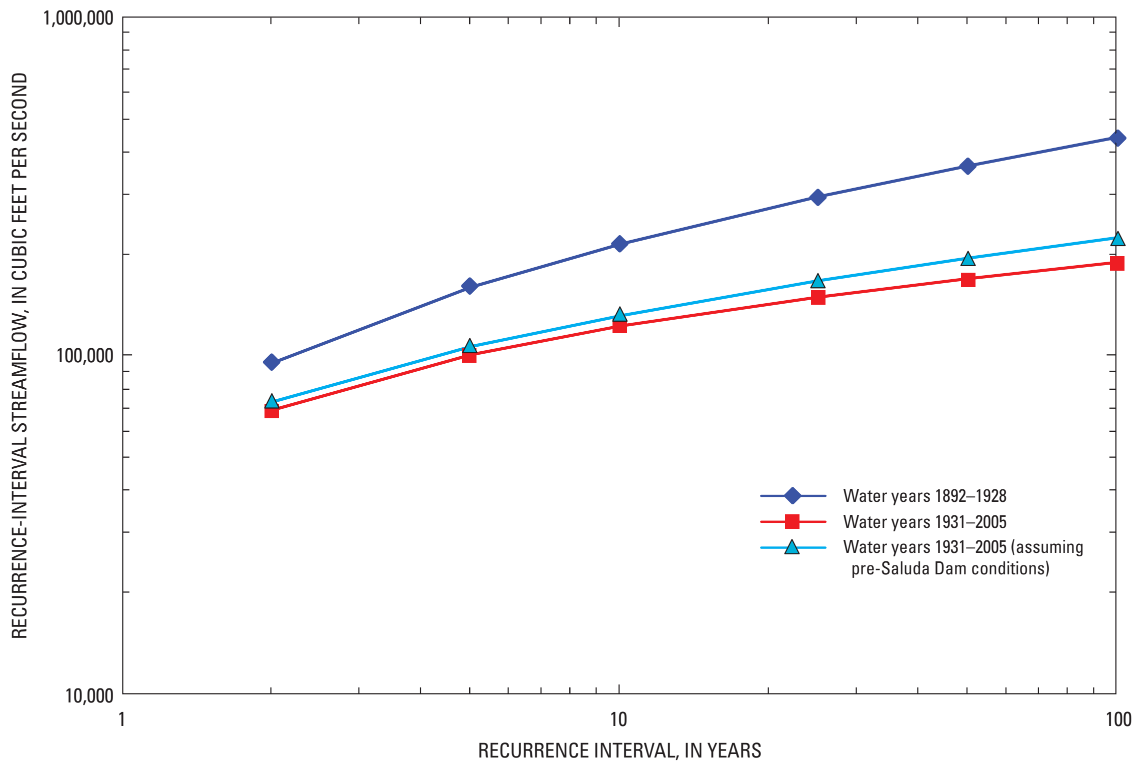

Figure 18. Recurrence-interval streamflows at the Congaree River Columbia streamgaging station computed using measured peak-flow data for water years 1892–1930 (unregulated) and 1931–2005, and using simulated peak-flow data for water years 1931–2005 assuming pre-Saluda Dam conditions (simulated unregulated).

ranged from 6.1 to 17.6 percent (table 5), respectively. These percentage differences are comparable to the standard error of prediction for the regression equation used to estimate the unregulated peak flows at Congaree River Columbia for the period from 1931 to 2005. Thus, the analysis indicates that the Saluda Dam has caused about an 18- percent decrease in the magnitude of the 100-year recurrence-interval flood estimate at Congaree River Columbia. Consequently, the more significant decrease in the 100-year recurrence-interval flood estimate based on peak-flow data from before the construction of the Saluda Dam as compared to the flood estimate after the construction of the Saluda Dam appears to be related to climate variability. These conclusions are supported by comparisons discussed in the previous section (fig. 16; table 4) from flood estimates using similar periods at Broad River Richtex and Broad River Carlton. Those comparisons show

Table 5. Recurrence-interval flows at Congaree River Columbia for measured and estimated peak flows.

[ft³/s, cubic feet per second]

Recurrence interval, in years	Recurrence-interval flows from measured, unregulated peak-flow data for water years 1892–1928 (ft³/s)	Recurrence-interval flows from measured, regulated peak-flow data for water years 1931–2005 (ft³/s)	Recurrence-interval flows from estimated, unregulated peak-flow data from water years 1931–2005 (ft³/s)	Percent difference in recurrence-interval flows from the measured, regulated peak-flow data and estimated, unregulated peak-flow data
2	94,600	68,400	72,600	6.1
5	159,000	100,000	106,000	6.0
10	212,000	122,000	131,000	7.4
25	291,000	148,000	165,000	11.5
50	360,000	167,000	192,000	15.0
100	436,000	187,000	220,000	17.6

that similar differences can be attributed to the major floods that occurred in the early 1900s, the magnitudes of which have not been experienced in these basins in the last seven to eight decades.

As part of an investigation by Koman (2003) of the hydrologic effect of dams on the Saluda River, the issue of regional climate variability was addressed. Koman (2003) analyzed monthly rainfall data from two precipitation gages in the study area—Little Mountain and Laurens, South Carolina (fig. 2). The analysis was based on precipitation data from 1926 to 2001. A precipitation anomaly value was computed for each month and then analyzed by year. The results showed that no significant change in the precipitation volumes had occurred since 1926. The results may have been different had precipitation data for several decades prior to 1926 been included.

A detailed analysis of climate variability was beyond the scope of this investigation. However, a cursory review was made of precipitation data from the U.S. Historical Climatology Network for several gages in or around the study area. The gages reviewed were Little Mountain, Winnsboro, and Blackville, South Carolina (fig. 2). The period of record available for each gage was 1893–2005, 1887–2005, and 1892–2005, respectively. A graphical review of the maximum monthly precipitation by year was made. For all three gages, it appears that the period before 1930 showed overall higher maximum monthly precipitation values than the period after 1930 (fig. 19). In addition, a simple linear regression through the data shows a distinct downward trend for the Winnsboro and Blackville stations and a slight downward trend at the Little Mountain station. If the Little Mountain data are analyzed for the period from 1893 to 1930, however, there is a distinct upward trend (fig. 20).

In August 2001, the Federal Emergency Management Agency (FEMA) issued letters of final determination for the Congaree River flood hazard study (Federal Emergency Management Agency, 2001). For that study, the 100-year recurrence-interval flood estimate was determined using data through 1998. Statistical techniques were used to estimate “regulated” peak flows for the unregulated period on the

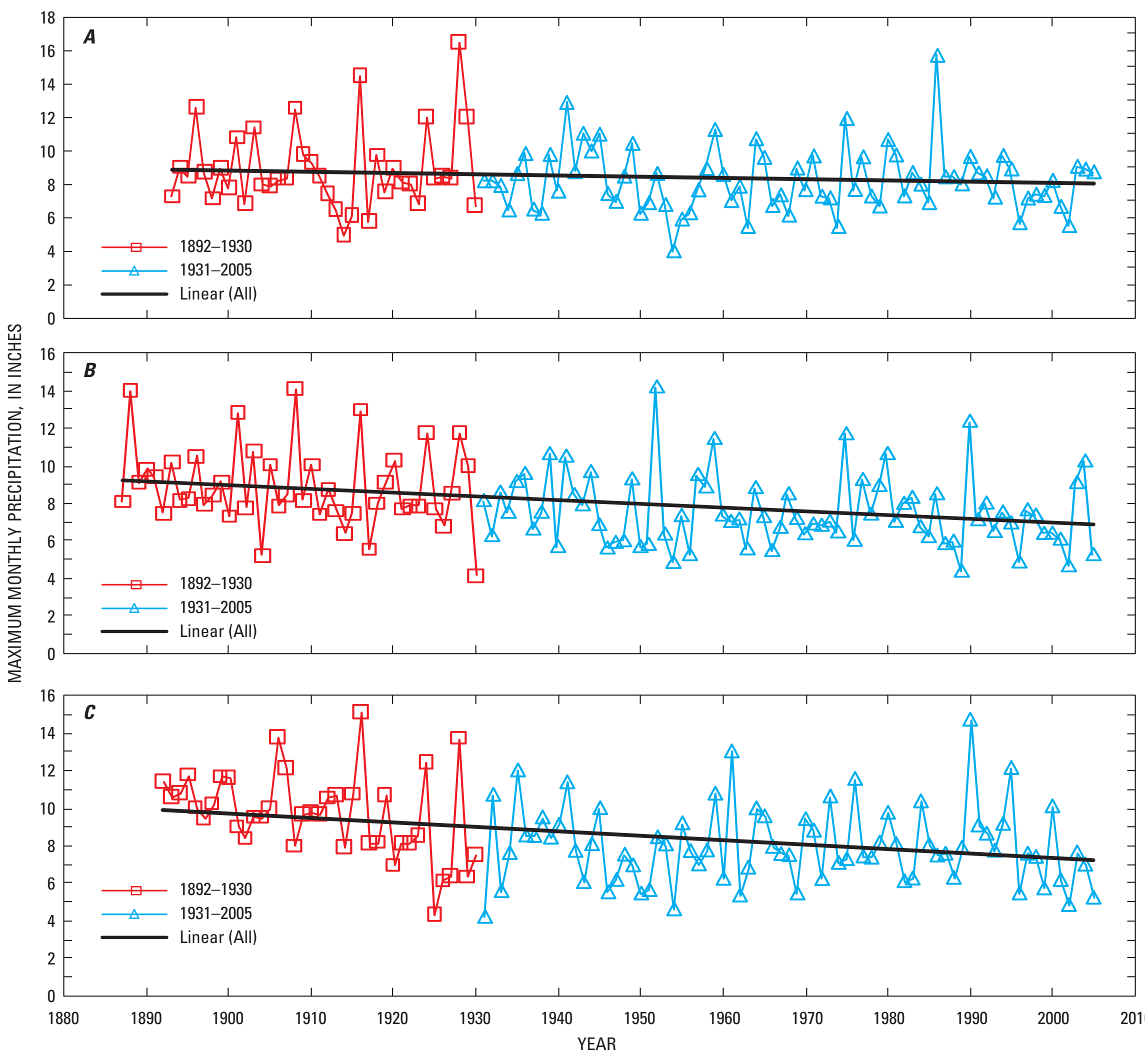

Figure 19. Maximum monthly precipitation by year at *(A)* Little Mountain, *(B)* Winnsboro, and *(C)* Blackville, South Carolina.

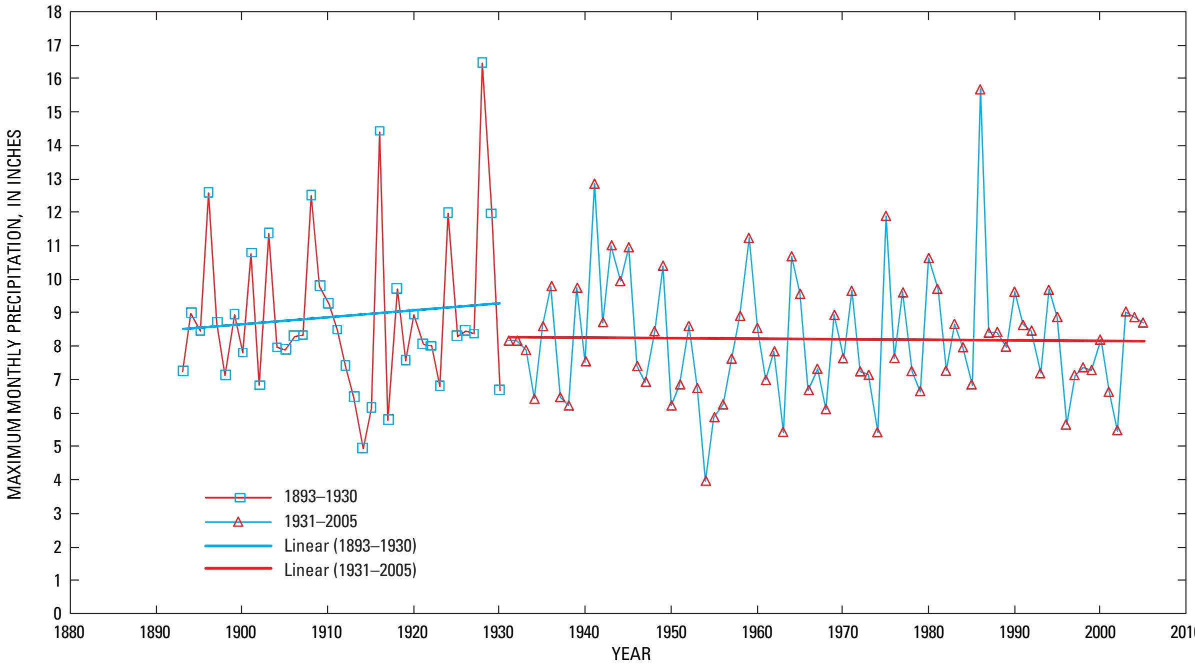

Figure 20. Maximum monthly precipitation at Little Mountain, South Carolina.

Congaree River. Those estimated regulated peaks were combined with the measured regulated peaks to form a regulated period of record for 1892–1998. The 100-year flood estimate using those data was determined to be 292,000 ft³/s. For comparison purposes, the unregulated data from 1892 to1929 were combined with the unregulated regression estimates of peak flows for the period from 1931 to 2005, and a log-Pearson Type III analysis was done to estimate the 100-year recurrence-interval flood for "unregulated" conditions. That 100-year flood estimate was 315,000 ft³/s, a 7.9-percent increase from the regulated 100-year flood estimate documented in the FEMA study. These differences are well within the 95-percent confidence limits of the estimates and also are within the uncertainty of the statistical analyses used in the estimations of the regulated and unregulated peak flows. Once again, this indicates that regulation of the Saluda River has not significantly altered the magnitude of the largest floods on the Congaree River.

Analysis of Surface-Water Daily Gage Heights

To evaluate the effect of the controlled releases on the Congaree River stage in the vicinity of the CNP, data-mining techniques, including ANN models, were applied to the long-term hydrologic database. Artificial neural network based models have been successfully developed for complex estuarine systems along the Georgia and South Carolina coast (Roehl and others, 2000; Conrads and others, 2002, 2003, 2006). The type of ANN model used for this analysis was the multilayered perceptron described by Jensen (1994), which is a multivariate, nonlinear regression method based on machine learning. A brief description of ANN models can be found in Appendix 2.

The simulation of 75 years of "with-dam" and "without-dam" conditions were developed using a series of two cascading models in which the output from one model is used as input to a subsequent model (fig. 21). The first model, the without-dam model (fig. 21; table 6), simulated

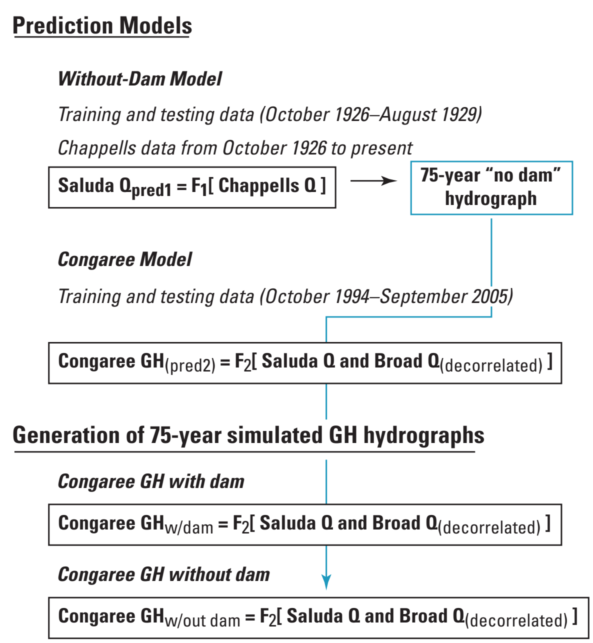

Figure 21. The without-dam streamflow model and Congaree gage-height (GH) model and the generation of the 75-year simulated hydrographs.

Table 6. Summary statistics for the surface-water models used in the study.

[HLN, hidden layer neurons; n, number of input vectors; R^2, coefficient of determination; ME, mean error; RMSE, root mean square error; PME, percent model error; ft^3/s, cubic feet per second; %, percent; ft, feet]

Model name	Output variables	Number of HLN (Appendix 2)	Range of output variable		n	R^2	ME	RMSE	PME
			Minimum	Maximum					
Training									
WithoutDam	Flow at station 02169000	1	2,320 ft^3/s	57,100 ft^3/s	26	0.89	–158.9 ft^3/s	5,459 ft^3/s	10.0%
CongareeGH	Gage height at station 02169625	3	0.55 ft	20.84 ft	1,456	0.95	-0.23 ft	0.90 ft	4.4%
Testing									
WithoutDam	Flow at station 02169000	1	255 ft^3/s	57,100 ft^3/s	1,063	0.88	–133.5 ft^3/s	2,137 ft^3/s	3.8%
CongareeGH	Gage height at station 02169625	3	0.56 ft	21.18 ft	4,502	0.95	-0.3 ft	0.86 ft	4.2%

the Saluda River streamflows at the Saluda streamgages using the without-dam dataset from October 1926 to August 1929. Two variables were used as input to the ANN model. The first variable was the 2-day moving window average (MWA) of streamflow at Saluda River Columbia. A MWA is the average of (n) values in a data sequence. The second variable was the 3-day time difference (derivative) in streamflow at Saluda River Columbia. Time derivative variables capture the trajectory, or momentum, of the system as it moves into and out of changing hydrologic conditions. The dataset was bifurcated into training and testing datasets using a zone-average filter. The filter separates the datasets into a user-specified number of zones or boxes that determines the input vectors with the highest information content and reserves those vectors for the training dataset. Using the zone-average filter, all the data are used in the test dataset and a small selected sample of the data is used for the training dataset. For the without-dam model, 26 vectors were used to train the model, and 1,063 vectors were used to test the model.

The measured and simulated values from the model are shown in figure 22. The R^2, the mean error (ME), root mean square error (RMSE), and percent model error (PME) were computed for the training and testing datasets and are listed in table 6. Model accuracy usually is reported in terms of R^2 and is a good measure of the ability of a model to capture the overall trend of the data. The ME and RMSE statistics provide a measure of the simulation accuracy of the ANN models. The ME is a measure of the bias of model simulations—whether the model over or under simulates the measured data. The ME is presented as the adjustment to the simulated values to equal the measured values. Therefore, a negative ME indicates an over simulation by the ANN model and a positive ME indicates an under simulation by the model. Mean errors near zero may be misleading because negative and positive discrepancies in the simulations can cancel each other. RMSE addresses the limitations of ME by computing the magnitude rather than the direction (sign) of the discrepancies. The units of the ME and RMSE statistic are the same as the simulated variable of the model. The PME was computed by dividing the RMSE by the range of the measured data. The model statistics for the without-dam model evaluated with the testing dataset show that the model explains 88 percent of the variability of the streamflow ($R^2 = 0.88$) and the model over simulates the measured values by an average of 133.5 ft^3/s. The magnitude of the model error over the range of the measured data, as seen in the RMSE, is 2,137 ft^3/s for a PME of 3.8 percent (table 6).

Model performance also can be evaluated by plotting the cumulative frequencies of the measured and simulated values. The ability of the without-dam model to capture frequency distribution of the measured data is shown in figure 23. The largest discrepancy in the model is the frequencies of streamflows of 3,000 ft^3/s. The data for the period indicate that these streamflows occur 71 percent of the time, and the model simulates these streamflows 64 percent of the time (fig. 23).

The second model, the Congaree gage height model (fig. 21), simulates the gage height for the Congaree CNP using streamflow inputs from the Saluda and Broad River streamgages (figs. 2, 21). The streamflow data at the two gages have similar response to regional meteorological conditions. To develop a representative empirical model, it is necessary to determine the optimal time delays of input variables, or explanatory variables, on a response variable. For the Saluda and Broad River streamflow inputs, it was determined that a 1-day delay (or lag) and a 3-day moving window average was the optimum signal transformation for the highest correlation for both streamflow inputs to the Congaree River gage height. These transformations were applied to the Saluda River and Broad River streamflow data, and the resulting time series were summed for input to the model.

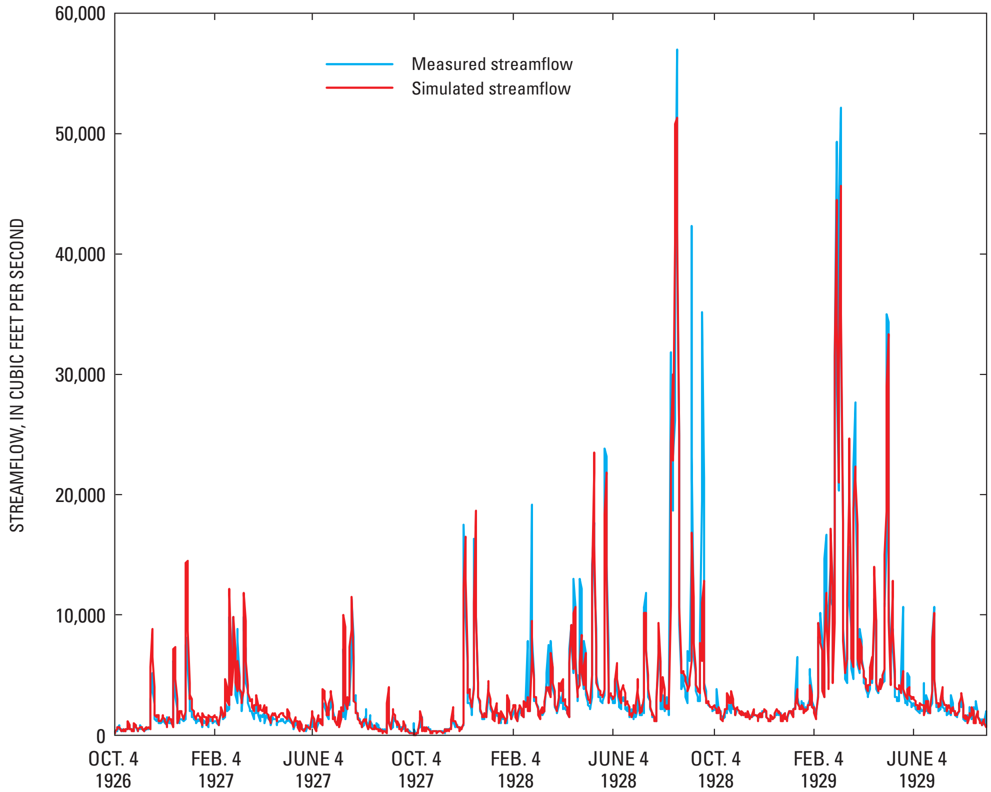

Figure 22. Measured and simmulated streamflow at Saluda River Columbia for October 1926 to August 1929.

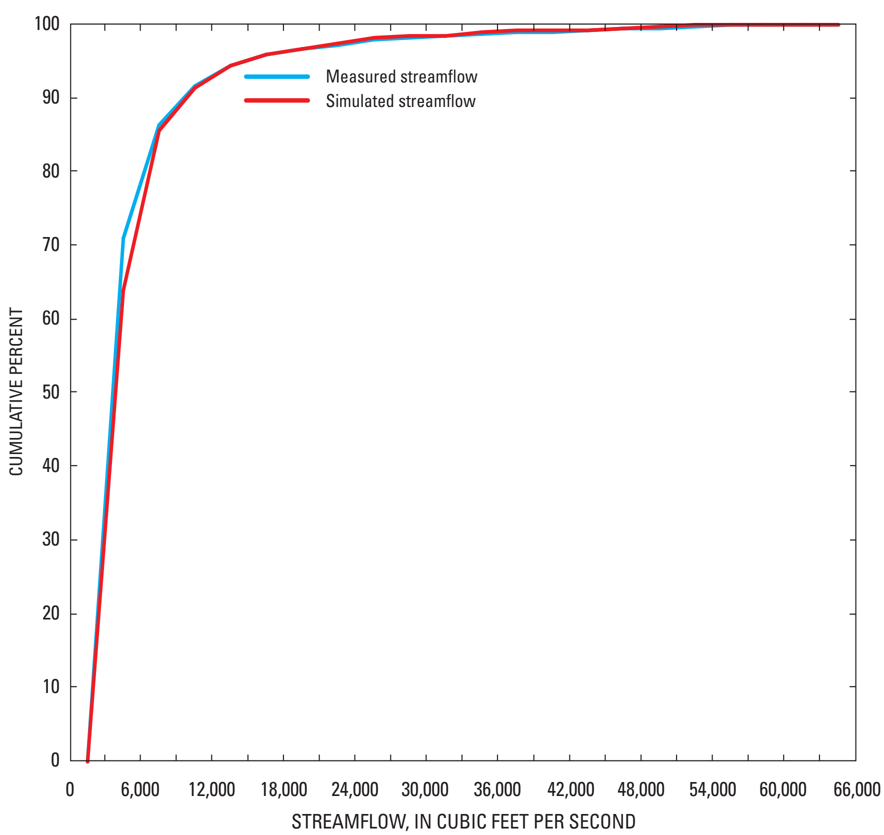

Figure 23. Measured and simulated cumulative frequency of streamflow at Saluda River Columbia for October 1926 to August 1929.

The dataset for the Congaree gage height model was randomly bifurcated into training and testing datasets. Approximately 25 percent of the data (1,456 vectors) was used to train the ANN model, and 75 percent of the data (4,502 vectors) was used to test the model. The Congaree gage height model captures the overall trend of measured data, as indicated in figure 24, but is unable to simulate the extremes of the range of gage heights, especially the low gage heights. The frequency distributions of the measured and simulated data show that the model predictions generally follow the same distribution of gage heights as the measured data but with a small over prediction (fig. 25). The inability of the model to simulate the extreme low gage heights can be seen in the frequency distribution curves where the simulated curve diverges from the measured curve around a gage height of 2.0 ft. Overall, the Congaree gage height model has a percent model error of 4.2 percent (table 6).

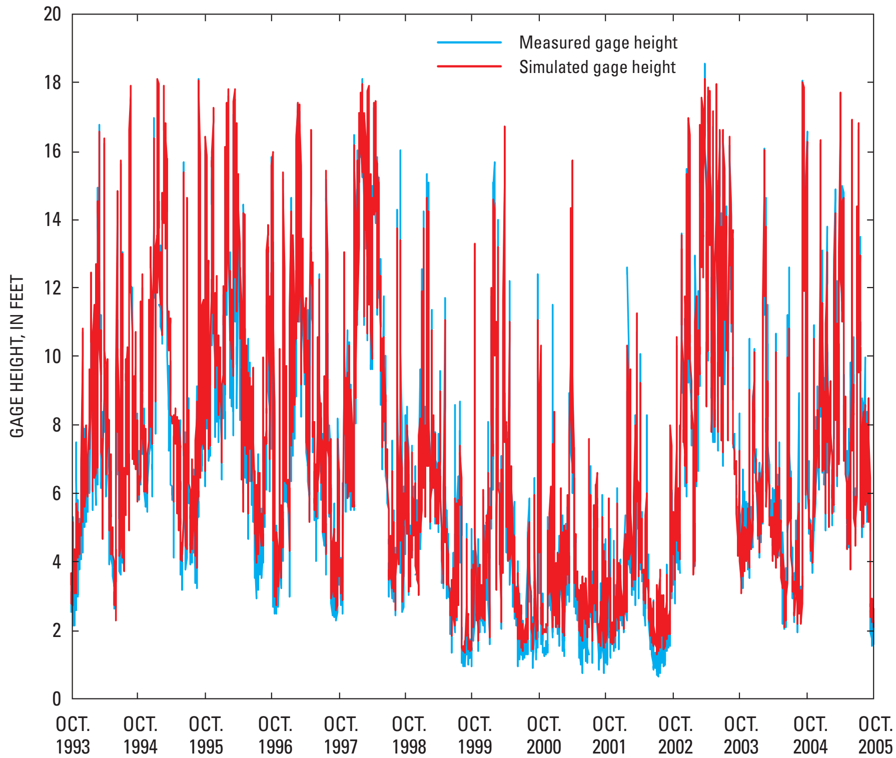

Figure 24. Measured and simulated gage height at Congaree River Congaree National Park for October 1993 to October 2005.

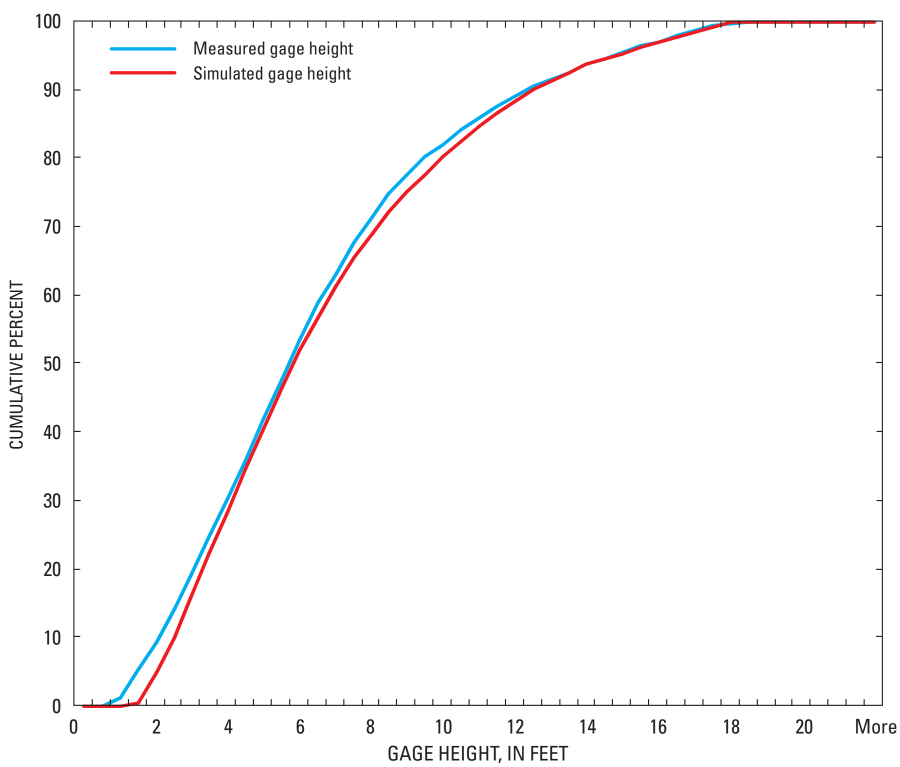

Figure 25. Measured and simulated cumulative frequency of gage height at Congaree River Congaree National Park for October 1983 to September 1989 and May 1993 to September 2005.

Long-Term Daily Gage-Height Model Results and Analysis

The models were used to evaluate the effect of the operation of the Saluda Dam on the surface-water gage heights at the CNP. Two 75-year gage-height hydrographs were generated using the measured Saluda River streamflow data (Saluda River Chappells) and a simulated hydrograph of the Saluda River streamflow data using the without-dam model scenario (fig. 21). The simulated hydrographs were compared for changes in the timing and duration of gage heights at the CNP. Regulated streamflows from hydroelectric plant operations typically modulate both the peak flows and sustained flows to meet electric power demand. The timing and peak flows of the simulated without-dam hydrograph for the Saluda River show similar behavior to the unregulated streamflows of the Broad River as indicated in a short period of the 75-year hydrograph shown in figure 26. It should be noted that the simulated without-dam hydrograph is not completely unregulated because of the regulated streamflows from the operation of the Lake Greenwood Dam.

The frequency distribution curves of the two 75-year hydrographs show the general, or overall, effect of the dam. In general, the dam has increased low to medium daily gage heights and decreased medium to high daily gage heights. Without the dam, the occurrence of low to medium daily gage heights increased and the occurrence of medium to high daily gage heights decreased (fig. 27). The two frequency curves cross at a gage height of 8.5 ft. Below this gage height, the without-dam curve shows higher percent of occurrences than the with-dam frequency curve. For example, gage heights of 5 ft occurred more frequently without the dam approximately 28.3 percent of the time or less, whereas with the dam, gage heights of 5 ft occurred approximately 23.6 percent of the time. Alternatively, 25 percent of the time or less, gage heights without the dam were approximately 5.0 ft as compared to approximately 5.5 ft with the dam. Above a gage height of 8.5 ft, the with-dam frequency curve shows a higher occurrence of gage heights. For example, 85 percent of the time or less, gages heights without the dam were approximately 13.0 ft as compared to approximately 12.3 ft with the dam.

Duration hydrographs showing the distribution of daily percentile gage heights were generated to evaluate and summarize the effect of the dam on a temporal scale (fig. 28). The gage-height duration hydrograph 5th, 50th, and 95th percentile for the with-dam and without-dam simulated data are shown in figure 28. For the 5th and 50th percentile duration hydrographs (low and medium gage heights), the dam has the effect of decreasing gage heights in the first half of the year and increasing gage heights in the second half of the year. For the 50th percentile, the decrease in gage heights can be as great as 2.17 ft (April 4) or increase gage height as much as 2.45 ft (August 31). For the 95th percentile duration hydrographs (high gage heights), the effect of the dam generally lowers the gage height throughout the year.

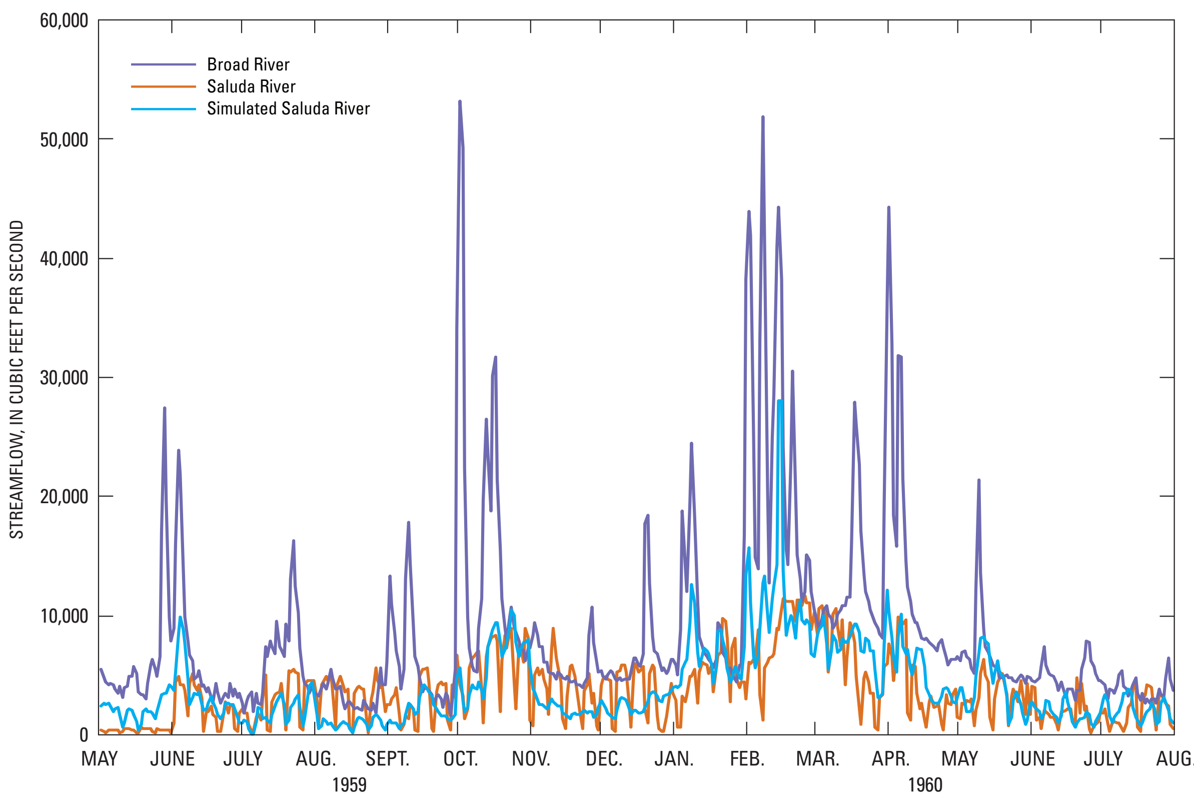

Figure 26. Measured streamflow at the Broad and Saluda Rivers and simulated streamflow for the Saluda River without the dam for May 1, 1959, to July 31, 1960.

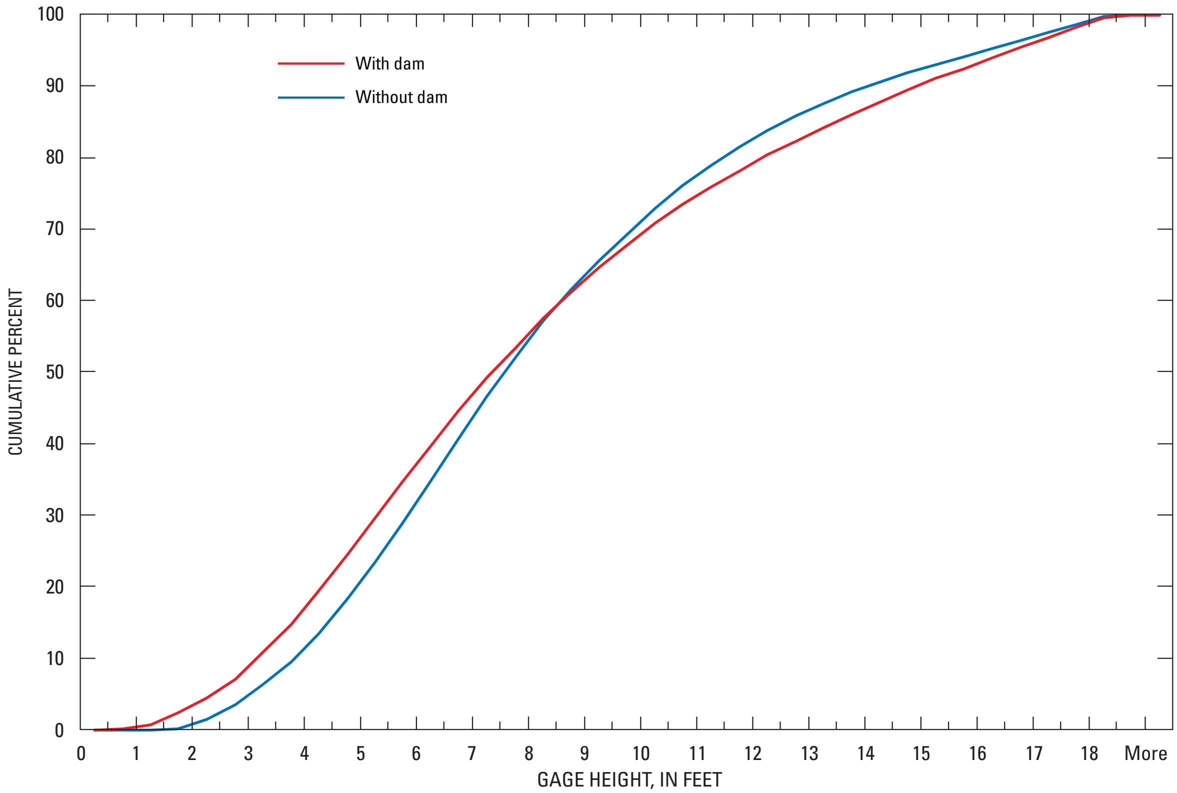

Figure 27. Frequency distribution curves for daily simulated gage heights at Congaree River Congaree National Park for October 1, 1929, to September 30, 2005.

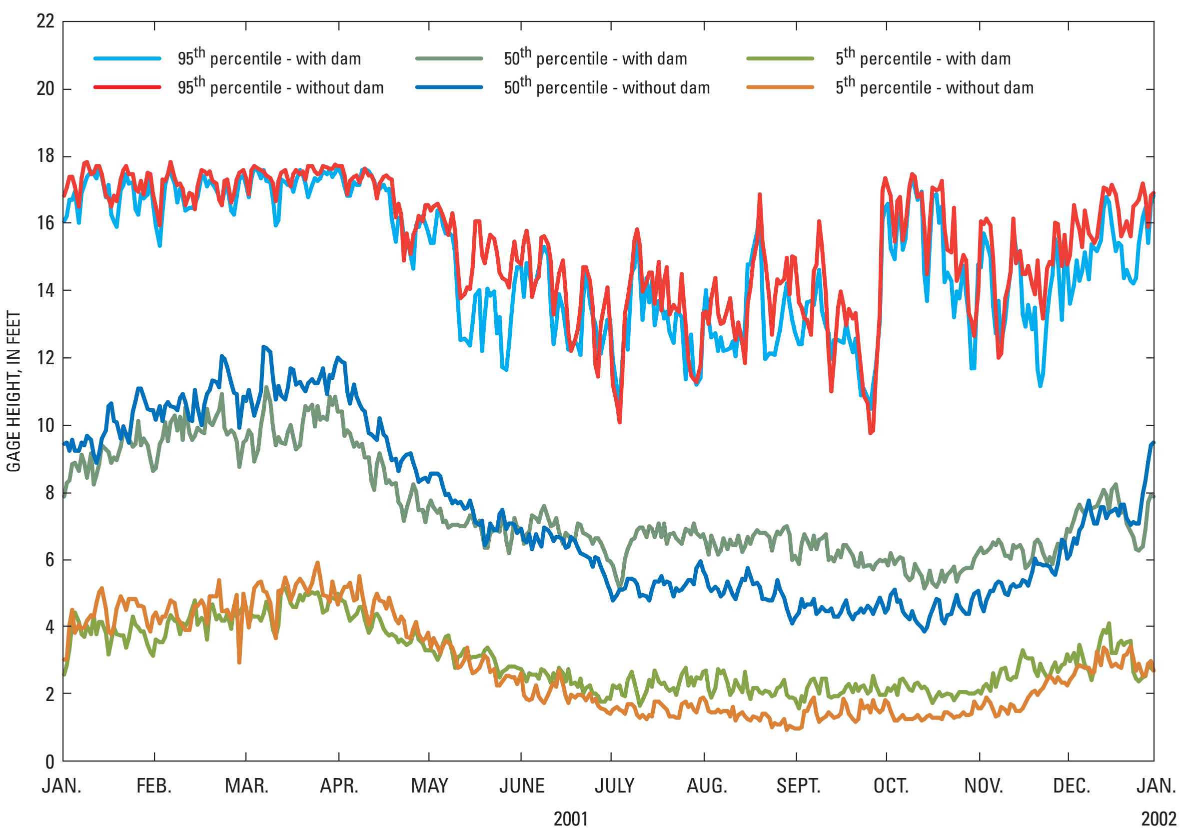

Figure 28. Daily duration hydrographs showing the 95th, 50th, and 5th percentiles for simulated gage heights with and without the dam at Congaree River Congaree National Park.

Hydroecological Indices

Differences in gage-height characteristics also can be analyzed by determining hydroecological indices of the with-dam and without-dam hydrographs. The ecological importance of streamflow characteristics and the ecological integrity of natural streamflow conditions has been researched by Richter and others (1996) and Poff and others (1997). Typically, hydroecological indices characterizing the magnitude, frequency, duration, timing, and rate of change of streamflows of pre-impoundment and post-impoundment streamflow records are computed and compared. Rather than compute the indices on the limited pre- and post-impoundment streamflow hydrographs, the simulated 75-year hydrographs were used to compute hydroecological indices using the National Hydroecological Integrity Assessment Software (Henriksen and others, 2006). Of the 171 indices computed by the software, 56 were selected to quantify the change in the magnitude, frequency, duration, and timing of the two simulated gage-height hydrographs.

The monthly minimums, means, and maximum gage heights were determined for the 75-year hydrographs, and the percentage change from the without-dam to the with-dam condition was computed to evaluate differences in temporal magnitude (table 7). Similar to the percentile plots shown in figure 28, the monthly mean values indicate that the dam decreased mean gage heights between December and May by as much as 10 percent, whereas the monthly mean gage heights with the dam increased by as much as 18.5 percent between the months of June and November. Two indices were generated that characterize the frequency of the magnitude of low- and high-flow events. The average number of events below the 25th percentile and the average number of events above the 75th percentile per year increased 26.5 and 22.6 percent, respectively, from the without-dam condition.

Table 7. Average monthly change from a without-dam condition for minimum, mean, and maximum gage heights for the 75-year simulation period.

Month	Minimum change from without-dam condition (percent)	Mean change from without-dam condition (percent)	Maximum change from without-dam condition (percent)
January	–12.7	–7.4	–3.8
February	–11.1	–7.2	–3.6
March	–11.1	–9.2	–3.1
April	–14.3	–10.0	–6.0
May	–6.2	–7.2	–7.9
June	4.4	3.8	–1.1
July	15.6	12.6	5.1
August	22.2	15.8	5.5
September	23.1	18.5	6.7
October	19.7	13.6	6.3
November	10.9	8.3	3.1
December	–0.8	–1.5	–4.3

The dam also had the effect of increasing the duration of minimum n-day gage heights and decreasing the duration of the maximum n-day gage heights (table 8). Minimum 1-, 3-, 7-, 30-, and 90-day gage heights increased from 13.9 to 23.9 percent, whereas maximum 1-, 3-, 7-, 30-, and 90-day gage heights decreased from 1.5 to 7.2 percent.

Table 8. Average change in minimum and maximum 1-, 3-, 7-, 30-, and 90-day gage height duration from a without-dam condition for the 75-year simulation period.

Duration	Minimum change from without-dam condition (percent)	Maximum change from without-dam condition (percent)
1-day	22.6	–1.5
3-day	23.1	–1.9
7-day	23.9	–3.8
30-day	21.7	–6.6
90-day	13.9	–7.2

Four indices characterize the timing of the minimum and maximum gage heights and the variability of minimum and maximum gage heights (table 9). The variability in the timing is determined from the coefficient of variation between the Julian date and value (minimum or maximum). The day of the minimum and maximum gage height changes by less than 6 days from the without-dam condition. The largest change, 12 days, occurred with the timing of the minimum variability.

Table 9. Average change in the timing of the annual minimum and maximum gage heights and minimum and maximum variability from a without-dam condition for the 75-year simulation period.

	Julian date		
Gage heights	With dam	Without dam	Absolute change, in days
Minimum	260.8	257.5	3.3
Minimum variability	49.6	37.3	12.3
Maximum	45.0	50.2	5.2
Maximum variability	62.1	65.5	3.4

Overall, the dam has had more of an effect of raising low water levels in the Congaree River than on decreasing high water levels. The operation of the dam has had more of an effect on raising water levels within the channel of the Congaree River than in decreasing the inundation of the flood plain. The raising of water levels within the channel will affect the gradient controlling the ground-water/surface-water interactions between the river channel and the flood-plain aquifer.

Analysis of Ground-Water Dynamics

Two aspects of the dynamic interaction of the Congaree River and the ground water of the CNP flood plain were investigated—the inundation of the flood plain during high-water events on the Congaree River and the effects of the regulated streamflow from the Saluda Dam on ground-water elevations of the CNP flood plain. The timing of the rising of the surface-water and ground-water elevations was examined to discern whether flooding occurred from surface water over-flowing the flood plain or from fully saturated ground water rising above the land surface. The effects of the Saluda Dam on the ground-water dynamics were analyzed using a similar approach to the daily surface-water gage height analysis using the 75-year with-dam and without-dam simulation and ANN models of selected observation wells.

Flooding

The water-level data shown in figure 12 are a snapshot in time and do not indicate the dynamics of the pathway of material during the initial inundation of floodwaters and the potential for mobilization of materials either from the river or from the flood-plain deposits. The timing of the rise of river-water levels and ground-water elevations is important for understanding the transport of constituents in the flood plain. If ground-water elevations rise prior to the riverine water, constituents in the porewater of the flood-plain deposits can be mobilized and transported to the river. If the river levels rise prior to the ground water, the river water can transport sediments and nutrients to the flood plain and potentially can recharge the local flood-plain aquifer system. During extreme low-water conditions, the aquifer system discharges to the river and during extreme high-water conditions, the flooded surface water saturates the aquifer system.

To analyze the flooding dynamics of the flood plain, water-level data for two sets of streamgages and nearby observation wells were plotted to evaluate the timing of the rising floodwaters of September 2004. One set of gages was the Congaree River CNP and the proximal wells RIC-701 and RIC-342 (figs. 1, 29*A*). The second set of gages was Cedar Creek and the nearby well RIC-346 (figs. 1, 29*B*). The wells near the Congaree River CNP all lagged the rising river stages, indicating for this area of the CNP flood plain during flooding conditions there is a net movement of river materials into the flood plain (fig. 29*A*). The lag in the rise of ground water at RIC-701 was greater than 10 hours, and the lag in the rise at RIC-342 was greater than 2 days. The hydrographs in figure 29 also show the differences in the ground-water response of the Group 1 and Group 2 wells. The receding limb of the flood hydrograph for the Group 1 well closest to the river, RIC-701, shows a similar response and approximately equal rates of recession. The rate of recession of the more interior Group 2 well, RIC-342, shows a much lower recession rate on the receding limb, indicating an extended delay in the release of ground water into the river. The hydrographs for the Cedar Creek gage and RIC-346 show that ground water typically lags the rise of the surface- water system by greater than 2 days and does not reach the magnitude of the water level of Cedar Creek (fig. 29*B*).

Development of Ground-Water Artificial Neural Network Models

To evaluate the effects of the Saluda Dam releases on the ground-water dynamics in the CNP, ANN models were developed for selected wells in each of the three classes of wells (fig. 10) from the cluster analysis described previously. The ground-water elevation response to the river water levels is attenuated as the water travels through the various flow paths in the flood plain (figs. 11, 30). To capture the dynamic response of the ground-water elevations and develop accurate models, various signals, or variables, were computed from the gage-height record, including moving window averages (MWA), lagged variables, and time derivatives and used for candidate input variables to the models. Often there is a time delay between an input variable and a response variable. Lagged variables capture these time delays by shifting the signal back in time by a specified time increment. Time-derivative variables, such as the 7-day change in gage height, or the 5-day change in 3-day MWA, captures the trajectory of the system as it moves into and out of changing hydrologic conditions. The input variables to the models are listed in table 10.

The models for the Group 1 wells (RIC-699, RIC-700, and RIC-701) responded relatively rapidly to the changing river stages. The models used two inputs, the 2- or 3-day MWA of gage height at Congaree CNP and the time derivative of the 7-day change in gage heights (table 10). The same statistics used to evaluate the surface-water ANN models were used to evaluate the ground-water ANN models (table 11). For the Group 1 models, less than 15 percent of the data was used to train the models. The remainder of the data was used to test, or evaluate, the models. The R^2 for the testing datasets was greater than 0.96, and the percent model error ranged from 3.3 to 3.6 percent (table 11). Plots of the measured and simulated daily ground-water elevations show that the models are able to capture the overall trend of the data and the dynamic variability (fig. 30). The RIC-700 model over simulates the low ground-water elevations during the summer and fall of 2004. The over simulation also can be seen in the frequency distribution plot and the small difference between the measured and simulated curves (fig. 30).

The ground-water response in the Group 2 wells (RIC-342 and RIC-703) is attenuated as compared to the Group 1 wells and this is reflected in the inputs to the ANN models. For these models, the MWA of gage height ranged from 5 to 10 days (table 10). In addition, two or three time derivatives of gage height were used to capture temporal changes in the trajectory of hydrologic conditions. For these

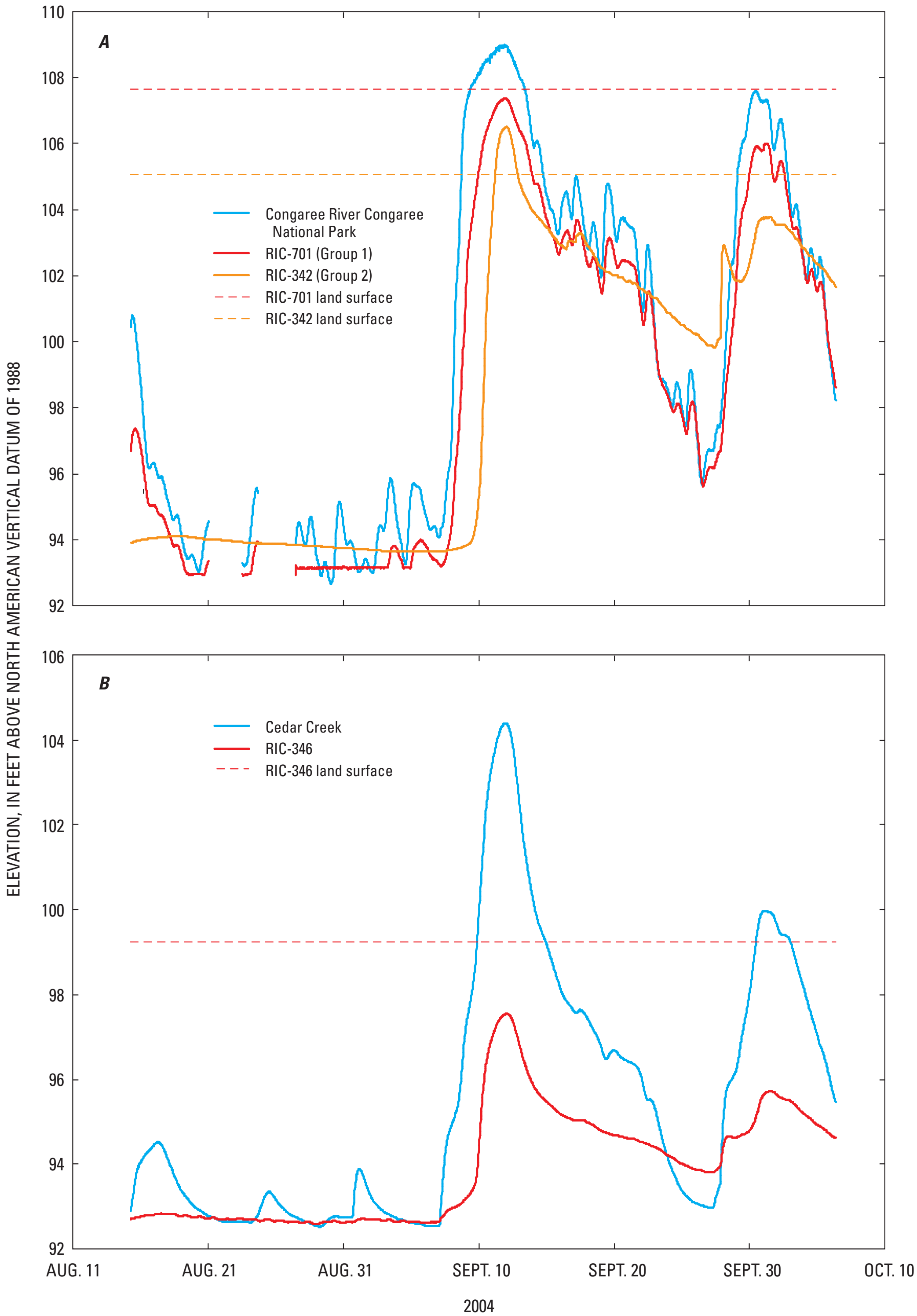

Figure 29. Water-level elevations for *(A)* Congaree River Congaree National Park and observation wells RIC-701 and RIC-342, and *(B)* Cedar Creek and observation well RIC-346 in the Congaree National Park flood plain for August 15 to October 6, 2004.

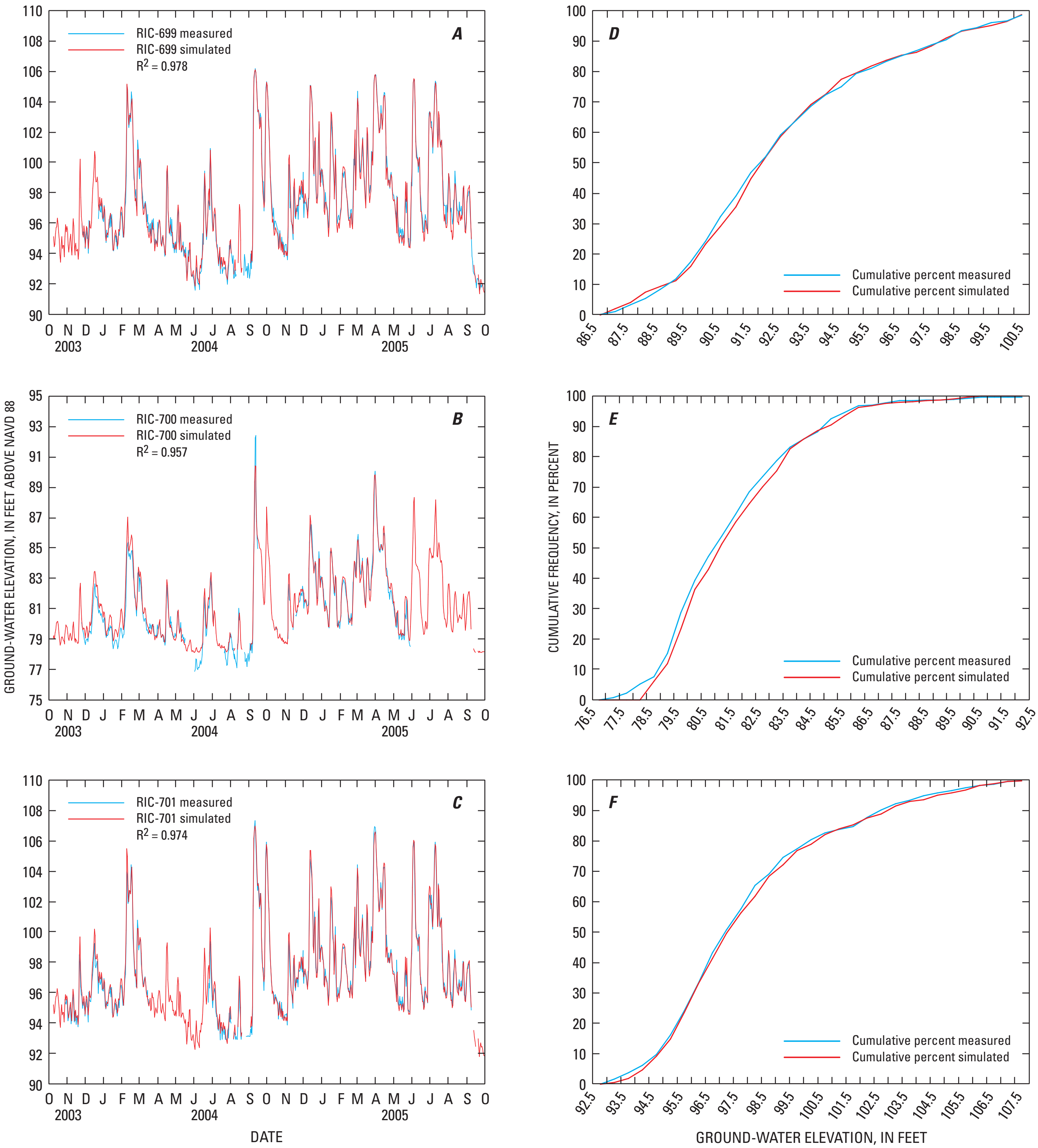

Figure 30. Measured and simulated ground-water elevations for Group 1 observtion wells *(A)* RIC-699, *(B)* RIC-700, and *(C)* RIC-701, and measured and simulated cumulative frequency distributions for observation wells *(D)* RIC-699, *(E)* RIC-700, and *(F)* RIC-701.

Table 10. Variables used in the ground-water artificial neural network models.

[MWA, moving window average]

Model	Inputs	Description
	Group 1 models	
gw_699	GHA2	2-day MWA of gage height
	GHDI7	7-day change in gage height
gw_700	GHA3	3-day MWA of gage height
	GHDI7	7-day change in gage height
gw_701	GHA2	2-day MWA of gage height
	GHDI7	7-day change in gage height
	Group 2 models	
gw_342	GHA10	10-day MWA of gage height
	GHA3DI5	5-day change in 3-day MWA of gage height
	GHA5DI10	10-day change in 5-day MWA of gage height
	GHA20DI15	15-day change in 20-day MWA of gage height
gw_703	GHA5	5-day MWA of gage height
	GHA20DI10	10-day change in 20-day MWA of gage height
	GHA20DI45	10-day change in 45-day MWA of gage height
	GHA3DI5	5-day change in 3-day MWA of gage height
	GHA5DI10	10-day change in 5-day MWA of gage height
	Group 3 models	
gw_341	MONTH	numerical value for month of the year
	GHA38(001)	38-day MWA of gage height lagged 1-day
	GHA3DI5	5-day change in 3-day MWA of gage height
	GHA10DI5	15-day change in 10-day MWA of gage height
gw_702	MONTH	numerical value for month of the year
	GHA35	35-day MWA of gage height
	GHA3DI5	5-day change in 3-day MWA of gage height
	GHA10DI5	15-day change in 10-day MWA of gage height
	GHA3	3-day MWA of gage height
gw_704	GHA14	14-day MWA of gage height
	GHA3DI5	5-day change in 3-day MWA of gage height
	GHA20DI15	15-day change in 20-day MWA of gage height

Table 11. Summary statistics for the ground-water models used in the study.

[USGS, U.S. Geological Survey; HLN, hidden layer neurons; Min, minimum; Max, maximum; n, number of vectors; R^2, coefficient of determination; ME, mean error; SSE, sum of squares error; MSE, mean square error; RMSE, root mean square error; PME, percent model error; %, percent]

USGS well identifier	Model name	Number of HLN (fig. 19)	Range of output variable		n	R^2	Statistics				
			Min, water level	Max, water level			ME, water level	SSE, water level	MSE, water level	RMSE, water level	PME
Group 1 wells training											
RIC-699	gw_699	3	87.04	100.78	70	0.994	0.027	6.77	0.097	0.32	2.3%
RIC-700	gw_700	4	77.48	90.64	75	0.981	–0.166	12.65	0.169	0.42	3.2%
RIC-701	gw_701	3	93.09	106.97	72	0.990	–0.098	9.43	0.131	0.37	2.6%
Group 2 wells training											
RIC-342	gw_342	2	93.68	105.00	325	0.904	–0.052	195.77	0.602	0.78	6.9%
RIC-703	gw_703	3	83.51	91.27	252	0.880	0.026	51.36	0.204	0.45	5.8%
Group 3 wells training											
RIC-341	gw_341	3	95.27	104.45	256	0.868	0.040	114.21	0.446	0.67	7.3%
RIC-702	gw_702	2	86.58	98.86	282	0.828	–0.350	331.51	1.176	1.09	8.9%
RIC-704	gw_704	2	88.38	100.22	287	0.879	–0.077	285.93	0.996	1.00	8.5%
Group 1 wells testing											
RIC-699	gw_699	3	87.04	100.78	631	0.98	0.024	151.05	0.239	0.49	3.6%
RIC-700	gw_700	4	76.87	92.42	445	0.96	–0.237	118.75	0.267	0.52	3.3%
RIC-701	gw_701	3	92.94	107.38	569	0.97	–0.104	136.19	0.239	0.49	3.4%
Group 2 wells testing											
RIC-342	gw_342	2	93.71	106.53	328	0.89	–0.053	236.97	0.722	0.85	6.7%
RIC-703	gw_703	3	83.51	91.30	254	0.81	–0.038	83.68	0.329	0.58	7.4%
Group 3 wells testing											
RIC-341	gw_341	3	95.35	105.26	223	0.85	–0.00003	119.70	0.537	0.74	7.4%
RIC-702	gw_702	2	86.57	99.05	256	0.80	–0.398	332.20	1.298	1.14	9.2%
RIC-704	gw_704	2	88.46	100.60	282	0.85	–0.067	360.26	1.278	1.13	9.3%

models, approximately half the data was used to train the models and half to test, or evaluate, the models. The R^2 for the testing dataset for these models was greater than 0.81, and the PME was less than 7.4 percent (table 11). Plots of the measured and simulated daily ground-water elevations show that the models are able to capture the overall trend of the data, but models are not able to capture the dynamic variability as well as the Group 1 models (fig. 31). The cumulative frequency distribution plots show that the RIC-342 (fig. 31*C*) models simulated the overall occurrence of ground-water elevations more accurately than the RIC-703 model (fig. 31*D*).

The Group 3 wells, RIC-341, RIC-702, and RIC-704, used a MWA of gage heights that ranged from 14 and 38 days (table 10). In addition, two time derivatives of gage heights were used to capture temporal changes in the trajectory of hydrologic conditions. For two of the models (gw_341 and gw_702) an additional input variable for month of the year was used to capture some of the seasonal variability. These models had an average sensitivity to the "month" variable of approximately 5 percent. For these models, approximately half the data was used to train the models and half to test, or evaluate, the models. The R^2 for the testing datasets for these models was greater than 0.80, and the PME ranged from 7.4 to 9.3 percent (table 11). Plots of the measured and simulated daily ground-water elevations show that the models are able to capture the overall trend of the data (fig. 32), but the Group 3 models are not able to capture the dynamic variability as well as the Group 1 and Group 2 models (figs. 30, 31). The cumulative frequency distribution plots show that the models capture the overall shape of the frequency distribution of the measured data but generally under simulate the ground-water elevation occurrences for a portion of the range of ground-water elevations (fig. 32).

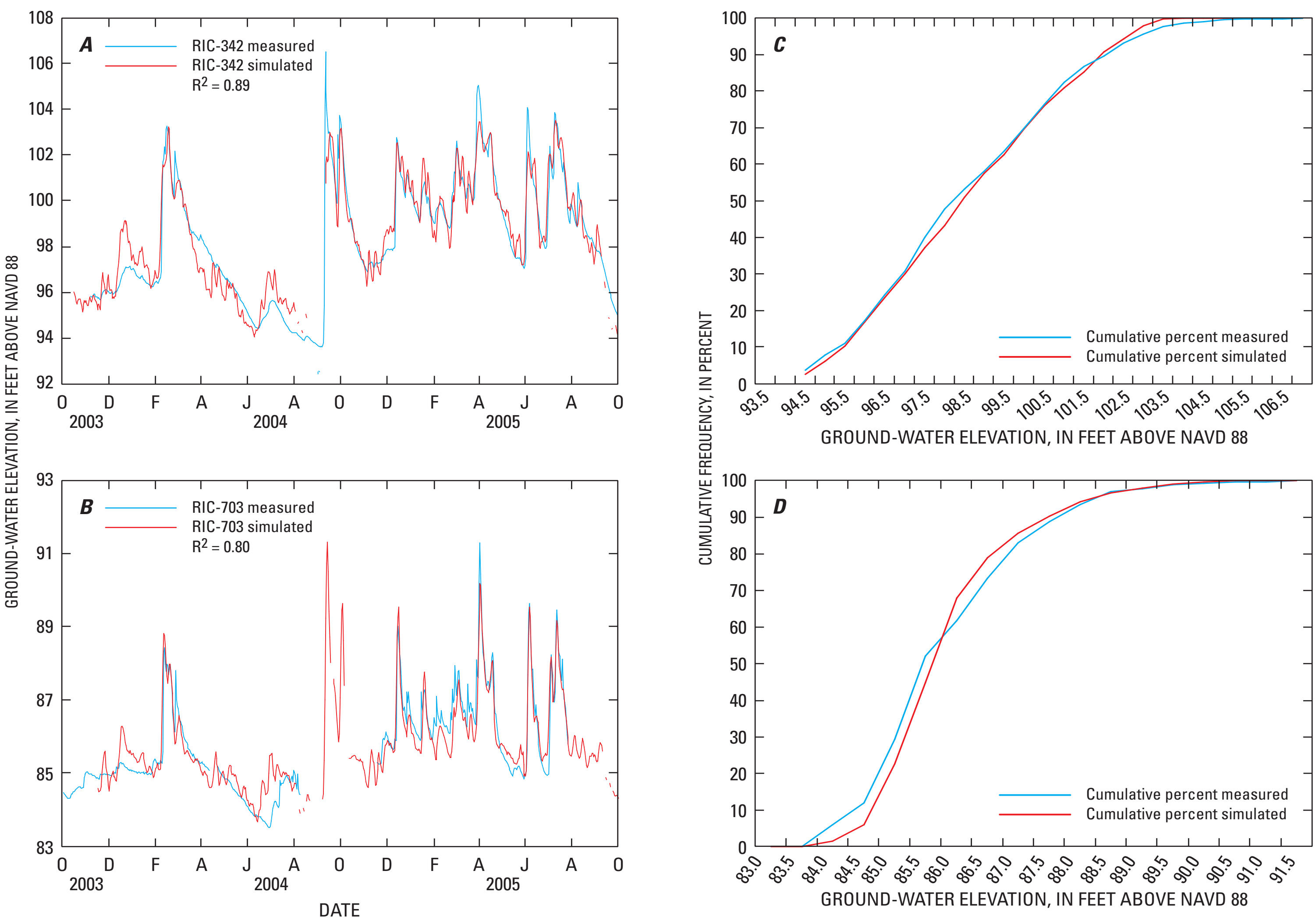

Figure 31. Measured and simulated ground-water elevations for Group 2 observation wells *(A)* RIC-342 and *(B)* RIC-703, and measured and simulated cumulative frequency distributions for observation wells *(C)* RIC-342 and *(D)* RIC-703.

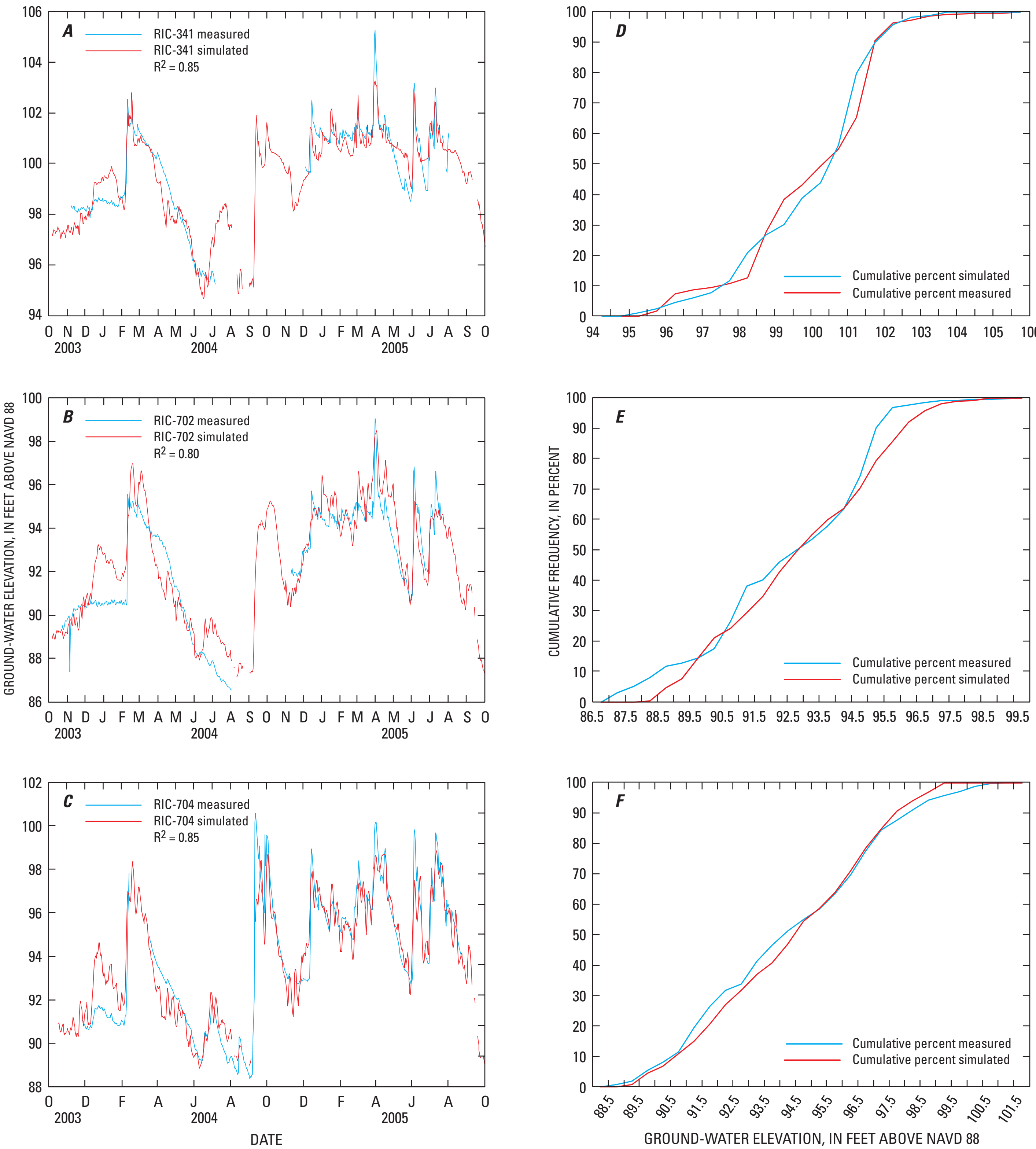

Figure 32. Measured and simulated ground-water elevations for Group 3 observation wells *(A)* RIC-341, *(B)* RIC-702, and *(C)* RIC-704, and measured and simulated cumulative frequency distributions for observation wells *(D)* RIC-341, *(E)* RIC-702, and *(F)* RIC-704.

Long-Term Daily Ground-Water Level Elevation Results and Analysis

A similar approach for evaluating the effect of the operation of the Saluda Dam on the daily surface-water gage heights at the CNP was used to evaluate the effect on ground-water levels. Two 75-year hydrographs were generated for the modeled Group 1, 2, and 3 wells using the with-dam and without-dam hydrographs generated for the Congaree CNP gage. The simulated hydrographs were then evaluated using cumulative frequency distribution plots and duration hydrographs of the 5th, 50th, and 95th percentiles to quantify the effect the operation of Saluda Dam has had on ground-water elevations in CNP (figs. 33–35).

The cumulative frequency distribution curves for Group 1, 2, and 3 observation wells illustrate that a general divergence between the with-dam and without-dam simulations occurs in the low to mid ground-water elevations between the 0 percent and 50 percent range (figs. 33–35). This result indicates that the operations of Saluda Dam have generally increased the magnitude of the lower ground-water elevations for a given frequency. Similar to the cumulative frequency distribution graph for Congaree CNP (fig. 27), three of the cumulative frequency distribution curves—RIC-699, RIC-703, and RIC-341—show a decrease in the frequency of high ground-water elevation. At these observation wells, ground-water elevations begin to diverge at the 70 percent, 40 percent, and 60 percent range, respectively, indicating that the operations of the dam have decreased the frequencies of these higher ground-water elevations. Overall, the operations of the dam have had a greater effect on raising low ground-water elevations than decreasing high ground-water elevations.

To evaluate the effect of the Saluda Dam on the daily and seasonal ground-water elevations, duration hydrographs were generated for the 5th, 50th, and 95th percentiles (figs. 33–35). As one would expect, the overall effect of the Saluda Dam on the ground-water elevations is similar, to the effect on the gage heights in the river. As with the surface-water analysis, the effect of the dam can be seen in the majority of the 50th percentile duration hydrographs. In general, these graphs show that with-dam ground-water elevations have decreased from the without-dam ground-water elevations during the first half of the year and have increased from the without-dam ground-water elevations during the second half of the year. Some of the duration hydrographs show that the dam has had no effect for certain periods of the year. For example, the 5th percentile duration hydrograph for RIC-700 (fig. 33*B*) shows little difference between the with-dam and without-dam low water-levels from June to November. For RIC-341 (fig. 35*A*), the 50th percentile duration hydrographs show little effect of the dam from January to May although the 5th percentile duration hydrograph indicates the dam has caused a decrease in low ground-water elevations from February to June and a rise in ground-water elevations from July to January.

The percentile duration hydrographs also are presented as box and whisker plots in figure 36 and summarized in table 12. For the majority of wells, the median values for the 95th percentile are higher without the dam than with the dam. Conversely, all the median values for the 5th percentiles are lower without the dam than with the dam. The maximum 5th, 50th, and 95th percentiles for the ground-water elevations for all the observation wells are equal to or lower for with-dam ground-water elevations than for without-dam elevations, indicating surface-water regulation by the Saluda Dam has lowered the high ground-water elevations in the CNP flood plain even for the 5th percentile values. The range of differences in the maximums ranged from no change (RIC-341—difference in 50th percentile) to 1.75 ft (RIC-341—difference in the 5th percentile; table 12). However, minimum 5th, 50th, and 95th percentiles for ground-water elevations for all observation wells are equal to or higher for with-dam ground-water elevations than for without-dam elevations, indicating that the lower ground-water elevations may have increased due to the regulation of the Saluda Dam. The differences in the minimums ranged from no change (RIC-700—difference in 5th percentile) to 1.90 ft (RIC-702—difference in the 50th percentile). For the majority of the wells, the changes in the minimum ground-water elevations were larger than the changes in the maximum ground-water elevations.

The range of ground-water elevations represents the difference in ground-water elevations between the lowest and highest simulated ground-water elevation for a specified percentile at a given observation well. For all observation wells, the simulated range is lower for the with-dam ground-water elevations. The maximum range in ground-water elevations for the 5th, 50th, and 95th were –2.23 ft (RIC-341), –2.61 ft (RIC-702), and –1.3 ft (RIC-342), respectively (table 12).

Overall, the operation of the dam has had more of an effect of raising low and median ground-water elevations than on lowering high ground-water elevations. In addition to the surficial ground-water elevations being higher, the interannual range in surficial ground-water elevations has decreased. A shift in the seasonal surficial ground-water elevations (lower in the first half of the year and higher in the second half of the year) and a decrease in the range of ground-water elevations may have an effect on the root zone of the swamp and an ecological effect on the vegetative community structure.

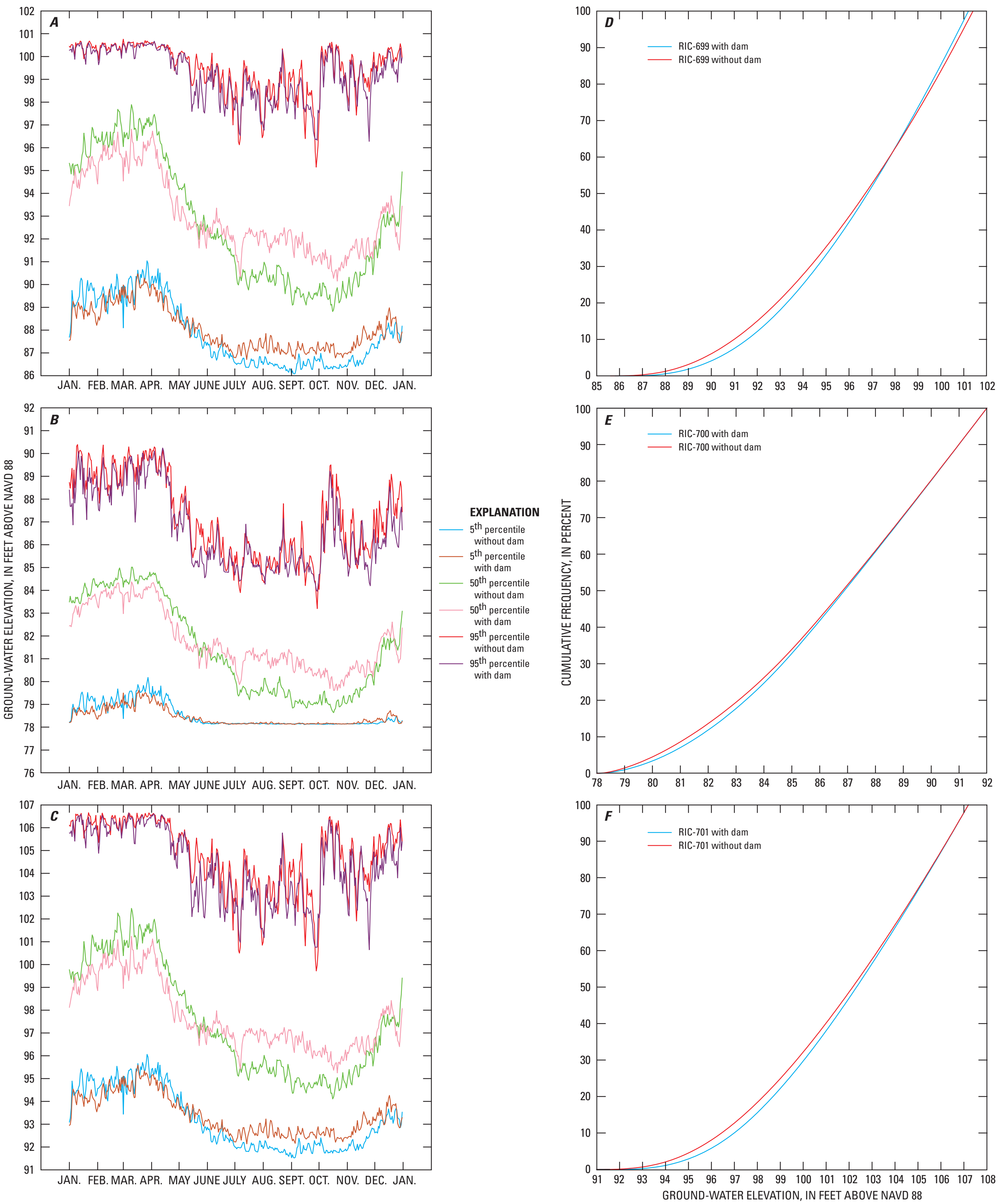

Figure 33. Duration hydrographs and cumulative frequency distribution for simulated 75-year daily mean ground-water elevation calculated for Group 1 observation wells RIC-699 *(A* and *D)*, RIC-700 *(B* and *E)*, and RIC-701 *(C* and *F)* for the with-dam and without-dam river gage heights at Congaree River Congaree National Park.

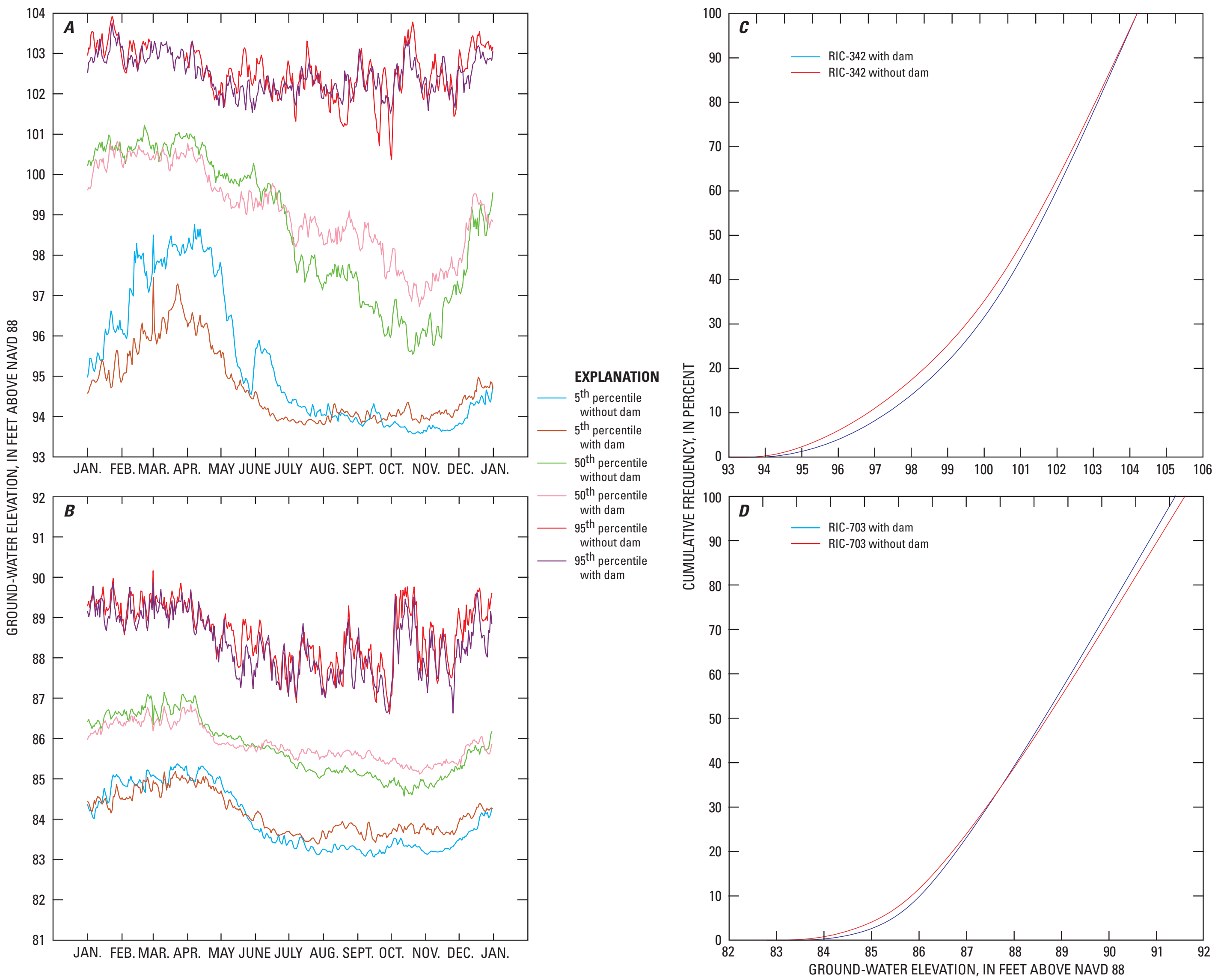

Figure 34. Duration hydrographs and cumulative frequency distribution for simulated 75-year daily mean ground-water elevation calculated for Group 2 observation wells RIC-342 *(A* and *C)* and RIC-703 *(B* and *D)* for the with-dam and without-dam river gage heights at Congaree River Congaree National Park.

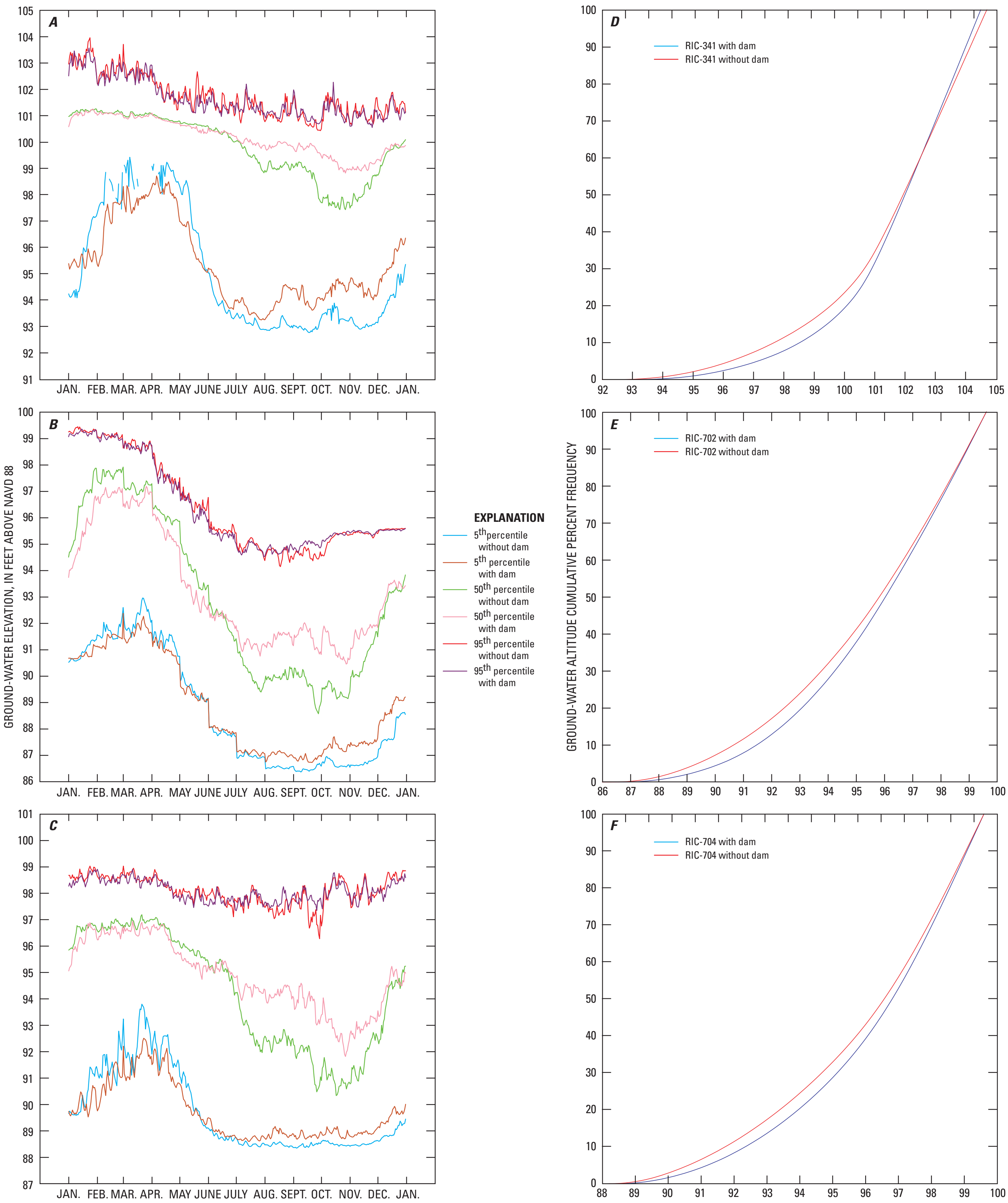

Figure 35. Duration hydrographs and cumulative frequency distribution for simulated 75-year daily mean ground-water elevation calculated for Group 3 observation wells RIC-341 *(A* and *D)*, RIC-702 *(B* and *E)*, and RIC-704 *(C* and *F)* for the with-dam and without-dam river gage heights at Congaree River Congaree National Park.

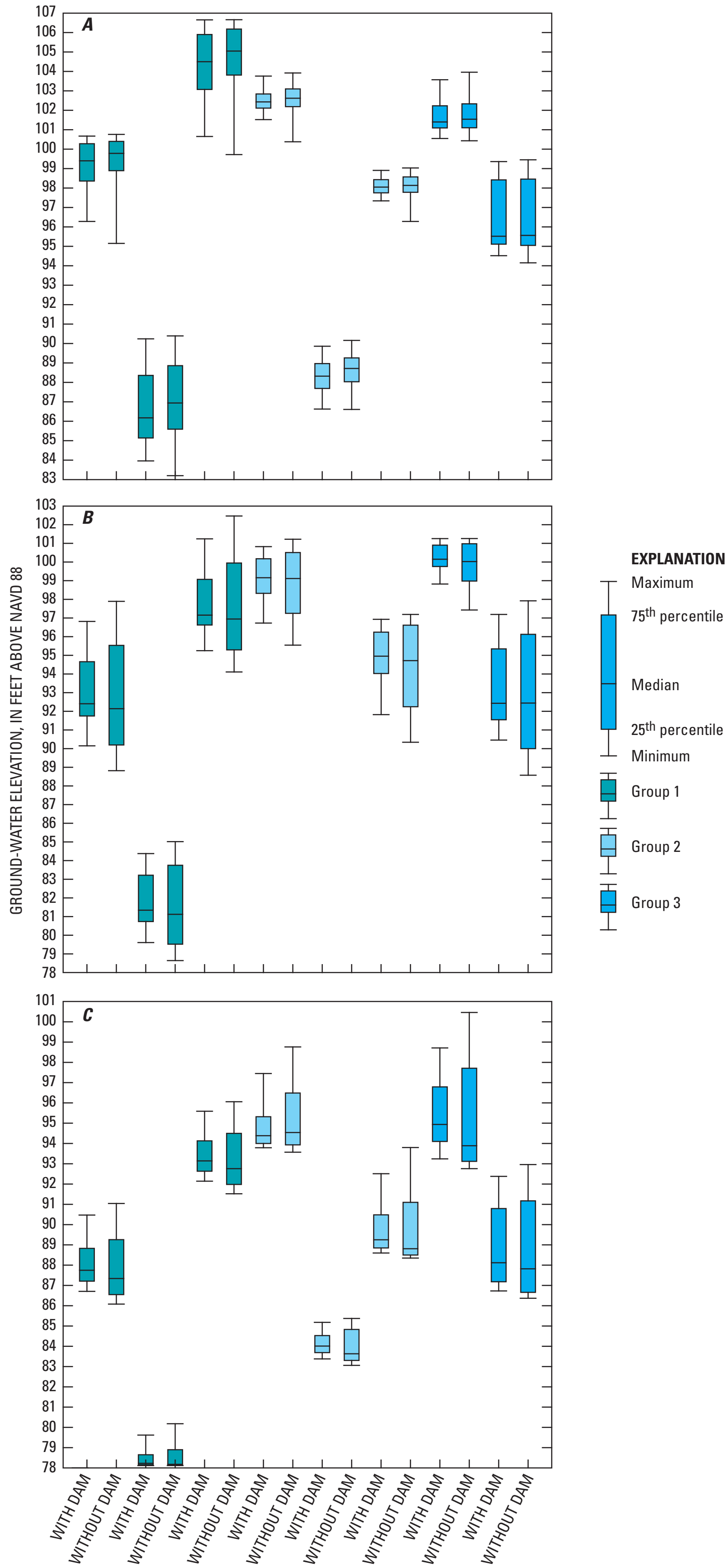

Figure 36. Box and whisker plots showing the *(A)* 95th, *(B)* 50th, and *(C)* 5th percentiles for simulated ground-water elevations with and without the dam.

Table 12. General statistics calculated for 5th, 50th, and 95th percentile water-level elevations for Group 1, 2, and 3 observation wells in the Congaree National Park using the 75-year daily ground-water elevations for the with-dam and without-dam gage heights in the Congaree River Congaree National Park.

[USGS, U.S. Geological Survey; NAVD 88, North American Vertical Datum of 1988]

USGS well identifier	Statistic	5th percentile for with-dam ground-water elevation (NAVD 88), in feet	5th percentile for without-dam ground-water elevation (NAVD 88), in feet	Differences in 5th percentiles statistics, in feet	50th percentile for with-dam ground-water elevation (NAVD 88), in feet	50th percentile for without-dam ground-water elevation (NAVD 88), in feet	Differences in 50th percentiles statistics, in feet	95th percentile for with-dam ground-water elevation (NAVD 88), in feet	95th percentile for without-dam ground-water elevation (NAVD 88), in feet	Differences in 95th percentiles statistics, in feet
Group 1 observation wells										
RIC-699	Maximum	90.47	91.04	–0.57	96.82	97.89	–1.07	100.67	100.76	–0.09
	Minimum	86.71	86.08	0.63	90.15	88.82	1.33	96.28	95.15	1.13
	Median	87.75	87.34	0.41	92.41	92.14	0.27	99.4	99.78	–0.38
	Range	3.76	4.96	–1.2	6.67	9.08	–2.41	4.39	5.61	–1.22
RIC-700	Maximum	79.62	80.18	–0.56	84.38	85.02	–0.64	90.24	90.39	–0.15
	Minimum	78.12	78.12	0	79.61	78.64	0.97	83.96	83.2	0.76
	Median	78.23	78.18	0.05	81.34	81.12	0.22	86.18	86.94	–0.76
	Range	1.5	2.06	–0.56	4.76	6.38	–1.62	6.28	7.19	–0.91
RIC-701	Maximum	95.59	96.52	–0.93	101.24	102.46	–1.22	106.65	106.66	–0.01
	Minimum	92.14	91.52	0.62	95.25	94.11	1.14	100.65	99.72	0.93
	Median	93.14	92.76	0.38	97.15	96.94	0.21	104.5	105.05	–0.55
	Range	3.45	4.54	–1.09	5.99	8.36	–2.37	6	6.94	–0.94
Group 2 observation wells										
RIC-342	Maximum	97.45	98.76	–1.31	100.82	101.22	–0.4	103.76	103.92	–0.16
	Minimum	93.79	93.57	0.22	96.73	95.54	1.19	101.52	100.38	1.14
	Median	94.38	94.54	–0.16	99.16	99.12	0.04	102.43	102.62	–0.19
	Range	3.66	5.19	–1.53	4.1	5.68	–1.58	2.24	3.54	–1.3
RIC-703	Maximum	85.18	85.37	–0.19	86.84	87.14	–0.3	89.86	90.16	–0.3
	Minimum	83.38	83.06	0.32	85.12	84.57	0.55	86.63	86.61	0.02
	Median	84.01	83.63	0.38	85.77	85.73	0.04	88.32	88.72	–0.4
	Range	1.8	2.31	–0.51	1.72	2.58	–0.86	3.23	3.55	–0.32

Table 12. General statistics calculated for 5th, 50th, and 95th percentile water-level elevations for Group 1, 2, and 3 observation wells in the Congaree National Park using the 75-year daily ground-water elevations for the with-dam and without-dam gage heights in the Congaree River Congaree National Park.—Continued

[USGS, U.S. Geological Survey; NAVD 88, North American Vertical Datum of 1988]

USGS well identifier	Statistic	5th percentile for with-dam ground-water elevation (NAVD 88), in feet	5th percentile for without-dam ground-water elevation (NAVD 88), in feet	Differences in 5th percentiles statistics, in feet	50th percentile for with-dam ground-water elevation (NAVD 88), in feet	50th percentile for without-dam ground-water elevation (NAVD 88), in feet	Differences in 50th percentiles statistics, in feet	95th percentile for with-dam ground-water elevation (NAVD 88), in feet	95th percentile for without-dam ground-water elevation (NAVD 88), in feet	Differences in 95th percentiles statistics, in feet
Group 3 observation wells										
RIC-341	Maximum	98.71	100.46	–1.75	101.26	101.26	0	103.57	103.96	–0.39
	Minimum	93.24	92.76	0.48	98.82	97.43	1.39	100.55	100.43	0.12
	Median	94.94	93.89	1.05	100.15	100.02	0.13	101.4	101.54	–0.14
	Range	5.47	7.7	–2.23	2.44	3.83	–1.39	3.02	3.53	–0.51
RIC-702	Maximum	92.38	92.96	–0.58	97.19	97.92	–0.73	99.36	99.45	–0.09
	Minimum	86.37	86.37	0	90.46	88.56	1.9	94.52	94.15	0.37
	Median	88.12	87.82	0.3	92.43	92.44	–0.01	95.52	95.56	–0.04
	Range	5.62	6.59	–0.97	6.73	9.34	–2.61	4.84	5.3	–0.46
RIC-704	Maximum	92.51	93.8	–1.29	96.93	97.19	–0.26	98.91	99.03	–0.12
	Minimum	88.6	88.35	0.25	91.82	90.34	1.48	97.34	96.28	1.06
	Median	89.25	88.81	0.44	94.95	94.72	0.23	98.05	98.14	–0.09
	Range	3.91	5.45	–1.54	5.11	6.85	–1.74	1.57	2.75	–1.18

Summary

The Congaree National Monument was established in 1976 and became South Carolina's first National Park in 2003. The U.S. Geological Survey, in cooperation with the National Park Service, Congaree National Park, studied the interaction between surface water in the Congaree River and ground water in the flood plain to determine the effect Saluda Dam operations have on water levels in the Congaree National Park.

Understanding the hydrologic and ecological effects of reservoir flow releases on downstream ecosystems is critical to balancing the social and economic benefits of hydroelectric power generation with the integrity of Congaree National Park. A common perception of the effect of the Saluda Dam on the Congaree National Park was that the dam had significantly reduced the frequency and magnitude of peak flows (and gage heights), thus jeopardizing the ecological benefits of periodic inundation of the Congaree National Park flood plain. Although not explicitly expressed in a previous study on the hydrology of the Congaree Swamp National Monument, the two flood-frequency curves for pre- and post-impoundment floods implied a large decrease in the frequency and magnitude in flood flows, affecting the understanding of many hydrologists and ecologists on the effect of the Saluda Dam.

Analysis of peak flows in this study showed the reduction in peak flows after the construction of Lake Murray and Saluda Dam was more a result of climate variability and the absence of large floods after 1930 than the operation of the dam. The analysis for this study showed that dam operations reduced the recurrence interval of the 2-year to 100-year peak flows by 6.1 to 17.6 percent, respectively. Analysis of the daily gage height of the Congaree River showed that the dam has had the effect of lowering low to medium (5th and 50th percentile) gage heights in the first half of the year (December to May) and raising low to medium gage heights in the second half of the year (June to November). The dam also has had the effect of increasing the 1-, 3-, 7-, 30-, and 90-day minimum gage heights by as much as 23.9 percent and decreasing the 1-, 3-, 7-, 30-, and 90-day maximum gage heights by as much as 7.2 percent. Analysis of the ground-water elevations in the Congaree National Park flood plain shows similar results as the gage-height analysis—the dam has had the effect of lowering high ground-water elevations and increasing low ground-water elevations.

Overall, the operation of the dam has had more of an effect on the water-surface elevations within the river banks than water-surface elevations in the flood plain. This result may have a larger effect on the subsurface water levels of the surficial flood-plain aquifer than the frequency and magnitude of inundation of the flood plain. A shift in the seasonal surficial ground-water levels (lower in the first half of the year and higher in the second half of the year) may have an effect on the root zone of the swamp and an ecological effect on the vegetative community structure.

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Appendix 1. Generalized lithologic descriptions of sediment samples examined during the installation of observation wells RIC-341, RIC-345, RIC-346, RIC-699, RIC-700, RIC-701, RIC-702, RIC-703, RIC-704, and RIC-705 in the Congaree National Park, South Carolina.

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

USGS observation well identifier (fig. 1)	Latitude (degrees, minutes, seconds)	Longitude (degrees, minutes, seconds)	Sample interval depth (feet below land surface)	Generalized lithologic description	Lithologic color (Geological Society of America, 1991)
RIC-341	33° 49' 31"	80° 51' 43"	0–5	Silty, clayey fine grain sand; 50 percent fine quartz sand, 25 percent silt, 25 percent clay	Brown
			5–8	Plastic clay; 10 percent fine grain quartz sand, 10 percent silt, 80 percent clay	Mottled gray and yellow-orange
			8–10	Clayey fine grain sand; 50 percent, fine grain quartz sand, 50 percent clay	Gray to off-white
			10–22	Clayey medium grain sand; 40 percent medium grain quartz sand, 30 percent fine grain quartz sand, 30 percent clay	Gray to off-white
			22–24	Course grain sand; 40 percent coarse grain quartz sand, 40 percent medium grain quartz sand, 20 percent fine grain quartz sand	Light tan
RIC-345	33° 49' 31"	80° 49' 09"	0–3	Medium sand; 60 percent medium grain quartz sand, 20 percent fine grain quartz sand, 10 percent silt, 10 percent clay	Light tan
			3–8	Clayey sand; 40 percent medium grain quartz sand, 10 percent fine grain quartz sand, 10 percent silt, 40 percent clay; slightly micaceous	Light tan to off-white
			8–12	Slightly clayey sand; 30 percent medium grain quartz sand, 40 percent fine grain quartz sand, 10 percent silt, 20 percent clay	Light tan
			12–17	Slightly clayey medium sand; 60 percent medium grain quartz sand, 30 percent fine grain quartz sand, 10 percent clay	Light gray
			17–49	Sand; 50 percent medium grain quartz sand, 30 percent fine grain quartz sand, 20 percent clay; gravel at 24, 27, 37 to 39, 42 to 44, and 46 to 49 feet	Light gray to cream white
RIC-346	33° 49' 00"	80° 49' 38"	0–11	Silty clay; 5 percent fine grain quartz sand, 40 percent silt, 55 percent clay	Brown
			11–22	Moderately plastic silty clay; 10 percent fine grain quartz sand, 40 percent silt, 50 percent clay	Mottled light gray to orange

Appendix 1. Generalized lithologic descriptions of sediment samples examined during the installation of observation wells RIC-341, RIC-345, RIC-346, RIC-699, RIC-700, RIC-701, RIC-702, RIC-703, RIC-704, and RIC-705 in the Congaree National Park, South Carolina.—Continued

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

USGS observation well identifier (fig. 1)	Latitude (degrees, minutes, seconds)	Longitude (degrees, minutes, seconds)	Sample interval depth (feet below land surface)	Generalized lithologic description	Lithologic color (Geological Society of America, 1991)
			22–24	Clayey sand; 60 percent medium grain quartz sand, 10 percent fine grain quartz sand, 30 percent clay	Light grayish-brown
			24–28	Clayey sand; 20 percent medium grain quartz sand, 60 percent fine grain quartz sand, 20 percent clay	Light grayish-brown
			28–34	Clayey sand; 5 percent coarse grain quartz sand, 10 percent medium grain quartz sand, 60 percent fine grain quartz sand, 25 percent clay; some gravel at 28 to 29 feet	Light grayish-brown
			34–42	Slightly clayey sand; 25 percent coarse grain quartz sand, 25 percent medium grain quartz sand, 30 percent fine grain quartz sand, 10 percent silt, 10 percent clay	Light brown
			42–50	Slightly clayey sand; 40 percent coarse grain quartz sand, 30 percent medium grain quartz sand, 20 percent fine grain quartz sand, 10 percent clay	Light brown
			50–55	Gravel; 70 percent gravel, 10 percent coarse grain sand, and 20 percent medium grain sand	Light brown to gray
			55–64	Clay; 10 percent silt, 90 percent clay	Dark gray
RIC-699	33° 46' 14"	80° 47' 05"	0–3	Swamp muck; 40 percent sand, 50-55 percent clay, less than 10 percent mica	Dark yellowish brown 10 YR 4/2
			3–6	Clayey sand; 10 percent sand, 80 percent clay, 10 percent mica	Moderate brown 5 YR 3/4
			6–6.5	Sand with minor clay; 85 percent sand, 10 percent clay, 5 percent mica	Olive gray 5 YR 4/1
			6.5–7	Sandy clay; 40 percent sand, 55 percent clay, 5 percent mica	Dark greenish gray 5 GY 4/1
			7–9	Sandy clay with clayey sand lens 4 to 8 inches thick; 20-75 percent sand, 20-75 percent clay, 5 percent mica	Olive gray 5 YR 4/1

Appendix 1. Generalized lithologic descriptions of sediment samples examined during the installation of observation wells RIC-341, RIC-345, RIC-346, RIC-699, RIC-700, RIC-701, RIC-702, RIC-703, RIC-704, and RIC-705 in the Congaree National Park, South Carolina.—Continued

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

USGS observation well identifier (fig. 1)	Latitude (degrees, minutes, seconds)	Longitude (degrees, minutes, seconds)	Sample interval depth (feet below land surface)	Generalized lithologic description	Lithologic color (Geological Society of America, 1991)
			9–10	Sand with some clay; 80 percent sand, 15 percent clay, 5 percent mica	Dark greenish gray 5 GY 4/1
			10–15	Sand with some clay; 90 percent sand, 5 percent clay, less than 5 percent mica	Dark greenish gray 5 GY 4/1
RIC-700	33° 45' 48"	80° 40' 31"	0–3	Swamp muck; 10 percent sand, 85 percent clay, 5 percent mica	Moderate brown 5 YR 4/4
			3–5.5	Swamp muck; 10 percent sand, 80 percent clay, 10 percent mica, with some dark organics present	Moderate brown 5 YR 4/4
			5.5–6.5	Clayey sand; 80 percent sand, 10 percent clay, 10 percent mica	Moderate yellowish brown 10 YR 5/4
			6.5–7	Sandy clay; 30 percent sand, 60 percent clay, 10 percent mica	Moderate yellowish brown 10 YR 5/4
			7–10	Interbedded sandy clay/clayey sand; material varies between 20 percent to 70 percent sand and/or clay	Moderate yellowish brown 10 YR 5/4
			10–13	Clayey sand; 80 percent sand, 10 percent clay, 10 percent mica	Moderate yellowish brown 10 YR 5/4
RIC-701	33° 48' 34"	80° 51' 59"	0–5	Swamp muck; 20 percent sand, 70 percent clay, 10 percent mica	Moderate brown 5 YR 4/4
			5–6	Sandy clay; 20 percent sand, 70 percent clay, 10 percent mica	Dark yellowish brown 10 YR 4/2
			6–8	Sandy clay; 20 percent sand, 70 percent clay, 10 percent mica	Moderate yellowish brown 10 YR 5/4

Appendix 1. Generalized lithologic descriptions of sediment samples examined during the installation of observation wells RIC-341, RIC-345, RIC-346, RIC-699, RIC-700, RIC-701, RIC-702, RIC-703, RIC-704, and RIC-705 in the Congaree National Park, South Carolina.—Continued

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

USGS observation well identifier (fig. 1)	Latitude (degrees, minutes, seconds)	Longitude (degrees, minutes, seconds)	Sample interval depth (feet below land surface)	Generalized lithologic description	Lithologic color (Geological Society of America, 1991)
			8–9	Clayey sand; 60 percent sand, 30 percent clay, 10 percent mica	Grayish brown 5 YR 3/2
			9–11	Sandy clay; 20 percent sand, 70 percent clay, 10 percent mica	Moderate brown 5 YR 4/4
			11–14	Clayey sand; 60 percent sand, 30 percent clay, 10 percent mica	Pale brown 5 YR 5/4
			14–15.5	Clayey course sand; 75 percent sand, 20 percent clay, 5 percent mica	Pale brown 5 YR 5/4
RIC-702	33° 48' 53"	80° 47' 15"	0–6	Swamp muck; 20 percent sand, 70 percent clay, less than 10 percent mica	Pale brown 5 YR 5/4 to greenish gray 5 G 6/1
			6–9	Sandy clay; 40 percent coarse sand, 60 percent clay, no mica present	Mottled, gray, red, and brown
			9–11	Sandy clay; 20 percent coarse sand, 80 percent clay	Mottled, light olive gray 5 Y 6/1 to Light brown gray 5 YR 6/1
			11–12	Gravely clay; 40 percent gravel, 60 percent clay, no mica present	Mottled, light olive gray 5 Y 6/1 to Light brown gray 5 YR 6/1
			12–13	Gravely clay; 10 percent gravel, 90 percent clay, no mica present	Mottled, light olive gray 5 Y 6/1 to Light brown gray 5 YR 6/1
RIC-703	33° 47' 52"	80° 42' 43"	0–2.5	Swamp muck; 20 percent sand, 80 percent clay	Moderate brown 5 YR 4/4
			2.5–4	Clayey sand; 80 percent sand, 20 percent clay	Light olive gray 5 Y 6/1
			4–5.5	Coarse sand; 90 percent sand, 10 percent clay	Greenish gray 5 GY 6/1
			5.5–6	Sandy clay; 30 percent sand, 70 percent clay	Light brown 5 YR 5/6 to greenish gray 5 GY 6/1
			6–6.5	Coarse sand; 60 percent sand, 40 percent clay	Greenish gray 5 GY 6/1

Appendix 1. Generalized lithologic descriptions of sediment samples examined during the installation of observation wells RIC-341, RIC-345, RIC-346, RIC-699, RIC-700, RIC-701, RIC-702, RIC-703, RIC-704, and RIC-705 in the Congaree National Park, South Carolina.—Continued

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

USGS observation well identifier (fig. 1)	Latitude (degrees, minutes, seconds)	Longitude (degrees, minutes, seconds)	Sample interval depth (feet below land surface)	Generalized lithologic description	Lithologic color (Geological Society of America, 1991)
			6.5–7.5	Sandy clay; 10 percent clay, 90 percent sand	Greenish gray 5 GY 6/1
			7.5–11.5	Sandy clay; 20 percent sand, 80 percent clay	Medium bluish gray 5 B 5/1
			11.5–12	Sandy clay; less than 5 percent sand, 95 percent clay	Medium bluish gray 5 B 5/1
RIC-704	33° 46' 16"	80° 47' 06"	0–3.5	Swamp muck; 15 percent sand, 80 percent clay, 5 percent mica	Light brown 5 YR 6/4
			3.5–5.5	Clayey sand with some very coarse grain sand or fine grain gravel	Light brown 5 YR 6/4 to Pale yellowish brown 10 YR 6/2
			5.5–8	Plastic sandy clay	Pale yellowish brown 10 YR 6/2
			8–12	Clay, slightly sandy;	Pale yellowish brown 10 YR 6/2
			12–14	No recovery	--
RIC-705	33° 47' 41"	80° 46' 54"	0–6	Swamp muck; 10 percent sand, 90 percent clayey silt, organics present	Moderate brown 5 YR 4/4 to Pale yellowish brown 10 YR 6/2
			6–10	Clayey very fine grain sand; 80 to 90 percent sand, 10 to 20 percent clay	Medium gray to medium dark gray
			10–14.5	Clayey sand, 80 percent sand, 20 percent clay, fine to coarse sand with courser material at bottom of hole, some mica present	Medium gray to medium dark gray

Appendix 2: Description of Artificial Neural Network Models

Models generally fall into one of two categories: deterministic (or mechanistic) or empirical. Deterministic models are created from first-principles equations, whereas empirical modeling adapts generalized mathematical functions to fit a line or surface through data from two or more variables. The most common empirical approach is ordinary least squares (OLS), which relates variables using straight lines (single variable), planes (two variables), or hyper-planes (more than two variables), whether the actual relations are linear or not. Calibrating either type of model attempts to synthesize an optimal line or surface through the observed data. Calibrating models is difficult when data have substantial measurement error or are incomplete, or when the variables for which data are available provide only a partial explanation of the causes of variability. The principal advantages that empirical models have over deterministic models are that they can be developed much faster and are more accurate when the modeled systems are well characterized by data. Empirical models, however, are prone to problems when poorly applied. Overfitting and multicollinearity caused by correlated input variables can lead to invalid mappings between input and output variables (Roehl and others, 2003).

An ANN model is an empirical flexible mathematical structure capable of describing complex nonlinear relations between input and output datasets. The structure of ANN models is loosely based on the biological nervous system (Hinton, 1992). Although numerous types of ANNs exist, the most commonly used type of ANN is the multilayer perceptron (MLP) (Rosenblatt, 1958). As shown in figure A2-1, MLP ANNs are constructed from layers of interconnected processing elements called neurons, each executing a simple "transfer function." All input layer neurons are connected to each hidden layer neuron and each hidden layer neuron is connected to each output neuron. There can be multiple hidden layers, but a single layer is sufficient for most problems.

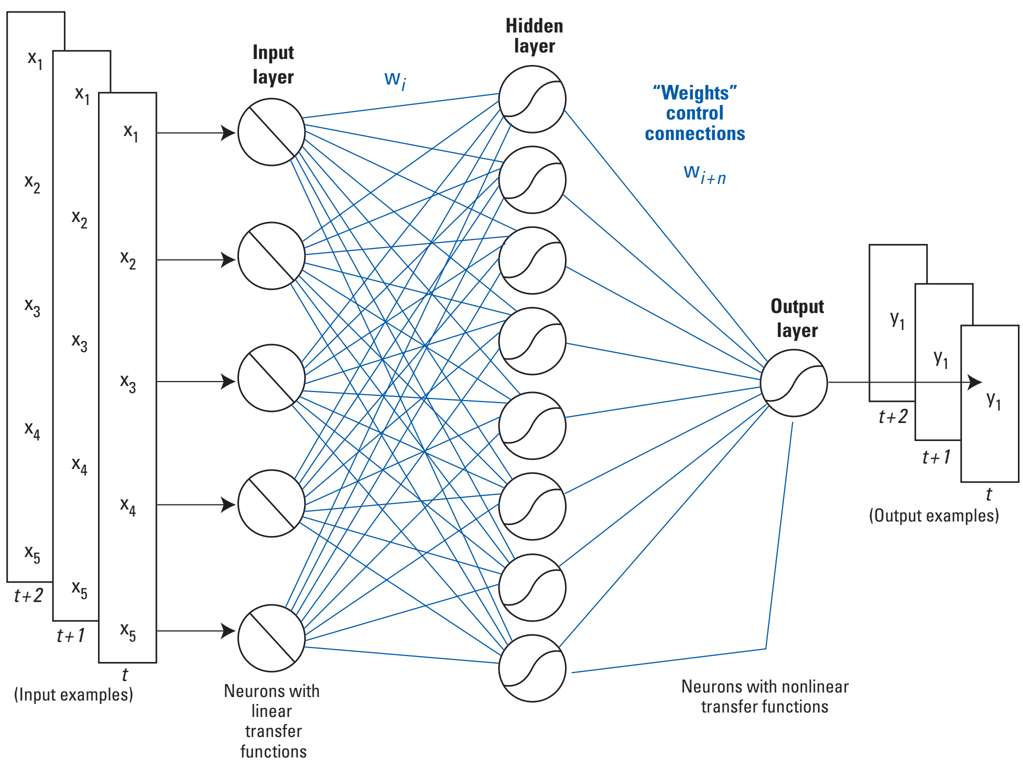

Figure A2-1. Schematic diagram showing multilayer perceptron artificial neural network architecture (Conrads and Roehl, 2007).

Typically, linear transfer functions are used to simply scale input values from the input layer to the hidden layer and generally fall within the range that corresponds to the mostly linear part of the s-shaped sigmoid transfer functions used from the hidden layer to the output layer (fig. A2-1). Each connection has a "weight" w_i associated with it, which scales the output received by a neuron from a neuron in an antecedent layer. The output of a neuron is a simple combination of the values it receives through its input connections and their weights, and the neuron's transfer function.

An ANN is "trained" by iteratively adjusting its weights to minimize the error by which it maps inputs to outputs for a dataset composed of input/output vector pairs. Simulation accuracy during and after training can be measured by a number of metrics, including R^2 and root mean square error (RMSE). An algorithm that is commonly used to train MLP ANN models is the back error propagation (BEP) training algorithm (Rumelhart and others, 1986). Jensen (1994) describes the details of the MLP ANN, the type of ANN used in this study. Multilayer perceptron ANNs can synthesize functions to fit high-dimension, nonlinear multivariate data. Devine and Roehl (2003) and Conrads and Roehl (2005) describe their use of MLP ANN in multiple applications to model and control combined manmade and natural systems including disinfection byproduct formation, industrial air emissions monitoring, and surface-water systems affected by point and nonpoint-source pollution.

Experimentation with a number of ANN architectural and training parameters is a normal part of the modeling process. For the modeling of the Saluda and Congaree Rivers, a number of candidate ANNs were trained and evaluated for their statistical accuracy and their representation of process physics. Interactions between combinations of variables also were considered. Finally, a satisfactory model can be exported for end-user deployment. In general, a high-quality simulation model can be obtained when:

- The data ranges are well distributed throughout the range of hydrologic conditions of interest,
- The input variables selected by the modeler share "mutual information" about the output variables,
- The form "prescribed" or "synthesized" for the model used to "map" (correlate) input variables to output variables is a good one. Techniques such as OLS and physics-based finite-difference models prescribe the functional form of the model's fit of the calibration data. Machine-learning techniques like ANNs synthesize a best fit to the data.

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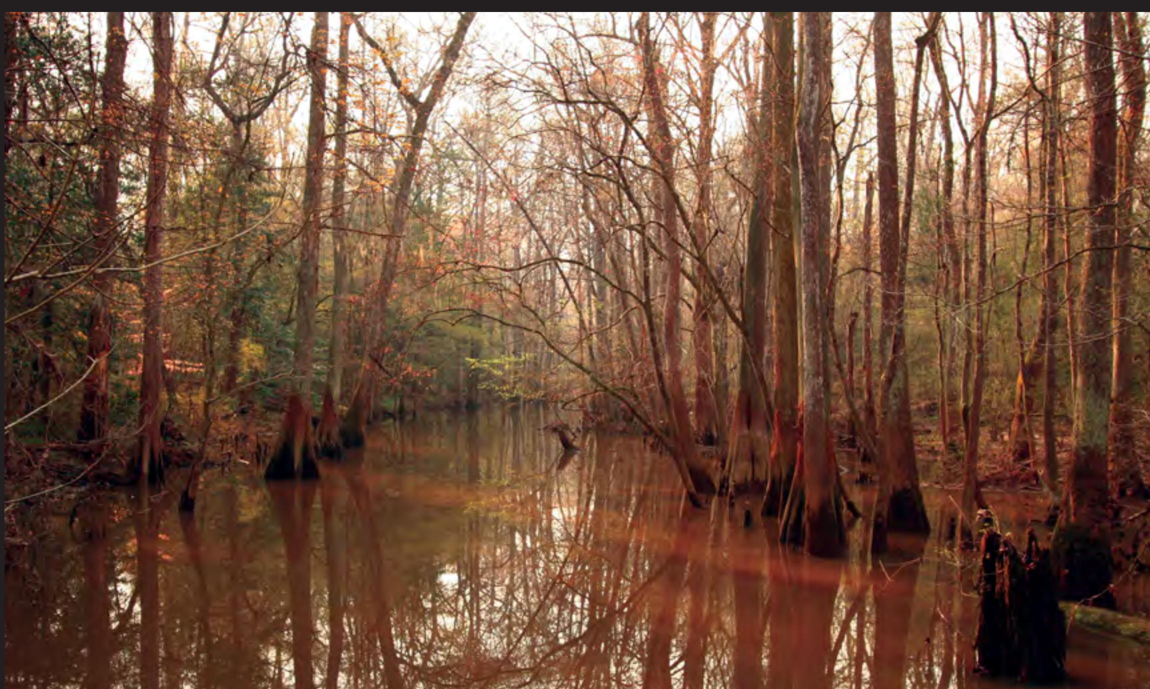

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Conrads and others—**Effects of the Saluda Dam on the Hydrology of the Congaree National Park Flood Plain, South Carolina**—Scientific Investigations Report 2008–5170