Simulation of Unsteady Flow in the Roanoke River from Near Oak City to Williamston, North Carolina

United States Geological Survey Water-Supply Paper 2408–A

Prepared in cooperation with the Division of Water Resources of the North Carolina Department of Environment, Health, and Natural Resources and the U.S. Army Corps of Engineers

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Chapter A

Simulation of Unsteady Flow in the Roanoke River from Near Oak City to Williamston, North Carolina

By A.G. STRICKLAND and JERAD D. BALES

Prepared in cooperation with the Division of Water Resources of the North Carolina Department of Environment, Health, and Natural Resources and the U.S. Army Corps of Engineers

U.S. GEOLOGICAL SURVEY WATER-SUPPLY PAPER 2408

HYDRODYNAMICS AND SOLUTE TRANSPORT IN NORTH CAROLINA ESTUARIES

U.S. DEPARTMENT OF THE INTERIOR
BRUCE BABBITT, Secretary

U.S. GEOLOGICAL SURVEY
GORDON P. EATON, Director

UNITED STATES GOVERNMENT PRINTING OFFICE: 1994

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Library of Congress Cataloging in Publication Data

Strickland, A.G., 1953–
Simulation of unsteady flow in the Roanoke River from near Oak City to Williamston, North Carolina / by A.G. Strickland and Jerad D. Bales.
p. cm. — (Hydrodynamics and solute transport in North Carolina estuaries ; Ch. A) (U.S. Geological Survey water-supply paper ; 2408–A)
"Prepared in cooperation with the Division of Water Resources of the North Carolina Department of Environment, Health, and Natural Resources, and the U.S. Army Corps of Engineers."
Includes bibliographical references.
1. Stream measurements—Roanoke River (Va. and N.C.)—Simulation methods 2. Stream measurements—North Carolina—Simulation methods. 3. Unsteady flow (Fluid dynamics)—Simulation methods. I. Bales, Jerad. II. Geological Survey (U.S.) III. North Carolina. Division of Water Resources. IV. United States. Army. Corps of Engineers. V. Title. VI. Series. VII. Series: U.S. Geological Survey water-supply paper ; 2408–A.
GC512.N8H93 1994 Ch. A
[GB1225.N8]
551.46'148 s—dc 20
[551.48'3'0975616] 93–12403
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CONVERSION FACTORS, TEMPERATURE, AND VERTICAL DATUM

Multiply	By	To obtain SI metric unit
	Length	
inch (in)	25.4	millimeter
	2.54	centimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
	Area	
square mile (mi^2)	2.590	square kilometer
	Volume per unit time (includes flow)	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
cubic foot per second per square mile [$(ft^3/s)/mi^2$]	0.01093	cubic meter per second per square kilometer

Temperature: In this report temperature is given in degrees Fahrenheit (°F), which can be converted to degrees Celsius (°C) by the following equation:

$$(°F-32) \times 5/9 = °C$$

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

Definition and abbreviations used in this report:

Water year—The period October 1 through September 30, determined by the calendar year in which it ends.
h—Hours.
in/yr—Inch per year.
min—Minutes.

Simulation of Unsteady Flow in the Roanoke River from Near Oak City to Williamston, North Carolina

By A.G. Strickland *and* Jerad D. Bales

Abstract

A one-dimensional, unsteady-flow model was calibrated, validated, and applied to a 30.4-mile reach of the Roanoke River between State Highway 42–11 bridge near Oak City (river mile 67.0) and U.S. Highway 17–13 bridge (river mile 36.6) at Williamston, North Carolina. The model was calibrated and validated for water levels ranging from 5.62 to 16.44 feet at river mile 67.0 and for flows ranging from about 2,000 to 12,000 cubic feet per second. For model calibration, the mean absolute difference between 22 measured and simulated flows was 3.4 percent. The mean absolute difference between nine measured and simulated flows obtained in the validation process was 3.3 percent.

The sensitivity of model results to small changes in computational time step, momentum coefficient, numerical scheme weighting factors, resistance coefficients, and boundary values was evaluated. The model, which was calibrated at a time step of 15 minutes, was unstable at a computational time step of 30 minutes, but results were insensitive to changes in the momentum coefficient and the numerical scheme weighting factors. Results were somewhat sensitive to small changes in the resistance coefficients and boundary values.

The model was used to compute daily mean flows at river miles 67.0, 59.2, and 36.6 for water years 1988–90. Flows were calculated for the range of conditions for which the model was calibrated and validated. After adjustment for inflow from the intervening drainage area between river miles 137.0 and 67.0, simulated monthly mean flows at river mile 67.0 were within 5 percent of flows measured at Roanoke Rapids (river mile 137.0) for months in which mean flows were less than about 14,000 cubic feet per second.

INTRODUCTION

The Roanoke River (fig. 1) is one of North Carolina's most important surface-water resources. The Roanoke River drainage basin includes 9,666 mi^2 in southern Virginia and northern North Carolina, and the annual average flow from the Roanoke River into Albemarle Sound is estimated to be about 8,900 ft^3/s (Giese and others, 1985). Interest in the resource has increased because of the creation of the Roanoke River National Wildlife Refuge, the decline of the striped bass and herring fisheries in the river (Manooch and Rulifson, 1989), the potential for increased wastewater discharges to the river, and proposals for the transfer of additional water out of the Roanoke basin.

Giese and others (1985) estimated that conditions in Albemarle Sound affect flows in the Roanoke River as far upstream as Hamilton, which is about 59 river miles from the mouth of the river (fig. 2). Consequently, standard stream-gaging techniques, which are based on a unique and fairly stable relation between stage and discharge at a selected site, cannot be used to determine flow rates in the Roanoke River downstream from about Hamilton. Flow models, however, can be used to compute continuous records of discharge at sites where standard stream-gaging techniques are not applicable.

Because of the need for continuous records of flow in the Roanoke River downstream from

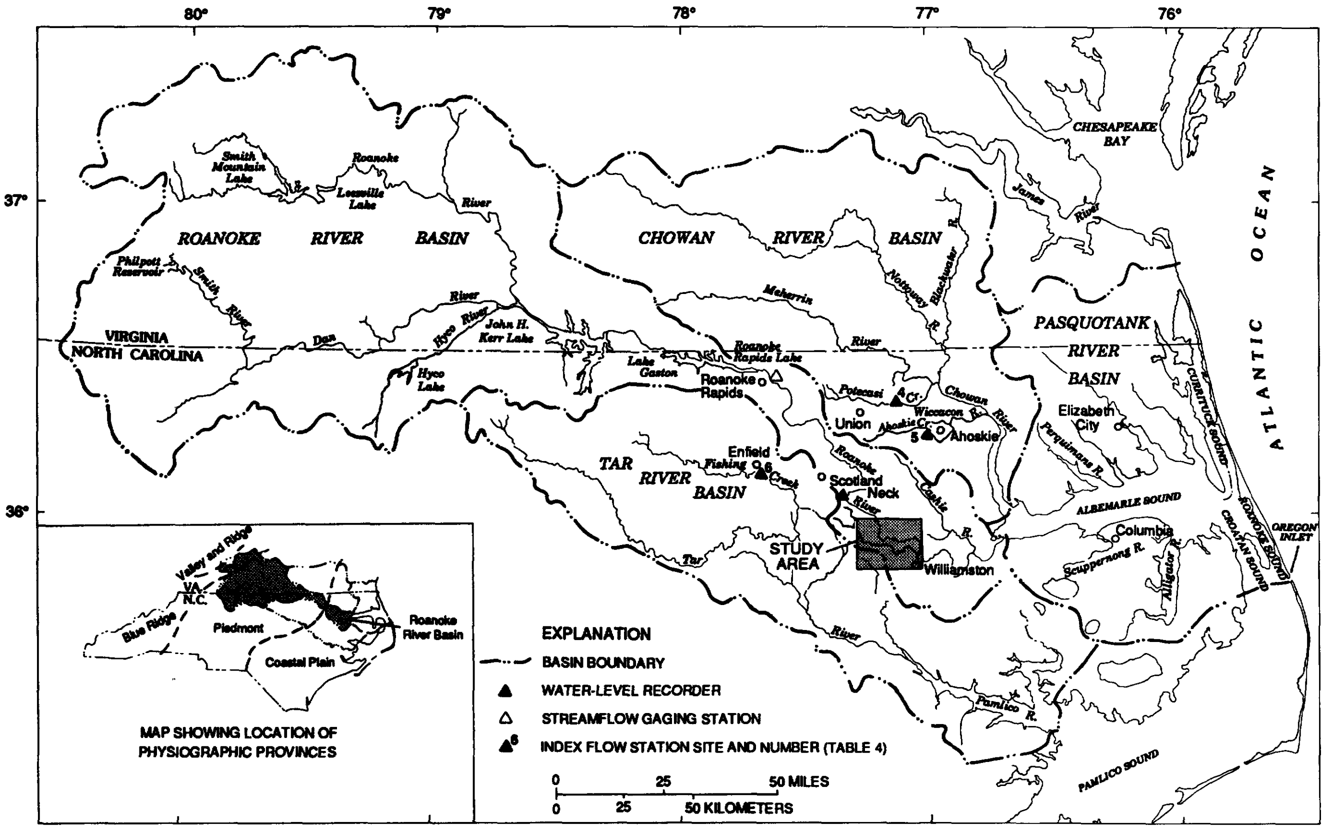

Figure 1. Location of study area, Roanoke River and adjacent basins, and selected streamflow gaging stations outside of study area.

Hamilton, the U.S. Geological Survey (USGS), in cooperation with the Division of Water Resources, North Carolina Department of Environment, Health, and Natural Resources, initiated a study in 1988 to determine flow rates in the reach of the Roanoke River between river mile 67.0 (site 1) at State Highway 42–11 bridge near Oak City and river mile 36.6 (site 3) at U.S. Highway 17–13 bridge near Williamston (fig. 2). In 1990, the U.S. Army Corps of Engineers provided funding to complete the investigation. A one-dimensional, unsteady-flow model was implemented to compute flows from observations of water level at the study reach boundaries. Bales and others (1993) presented preliminary modeling results for the study reach, as well as plans for extending the model to the mouth of the Roanoke River.

Purpose and Scope

This report documents the development and application of a one-dimensional, unsteady-flow model for computing flows in the 30.4-mi reach of the Roanoke River between State Highway 42–11 bridge near Oak City and U.S. Highway 17–13 bridge near Williamston. The report presents model construction, calibration, and validation, as well as the results of an analysis of model sensitivity to changes in input parameters. The model is used to simulate daily mean flows at the study reach boundaries and at river mile 59.2 (site 2) near Hamilton for the period October 1, 1988, through September 30, 1990.

Development and implementation of the flow model consisted of data collection for model construction and operation; model calibration, validation, and sensitivity testing; and model application. Data required to properly calibrate, validate, and operate the model include (1) continuous records of flows or water levels at the upstream boundary of the study reach, (2) continuous records of water levels at the downstream boundary, (3) local inflow rates, (4) channel geometry throughout the study reach, and (5) water-level records and flow rates at selected locations within the study reach.

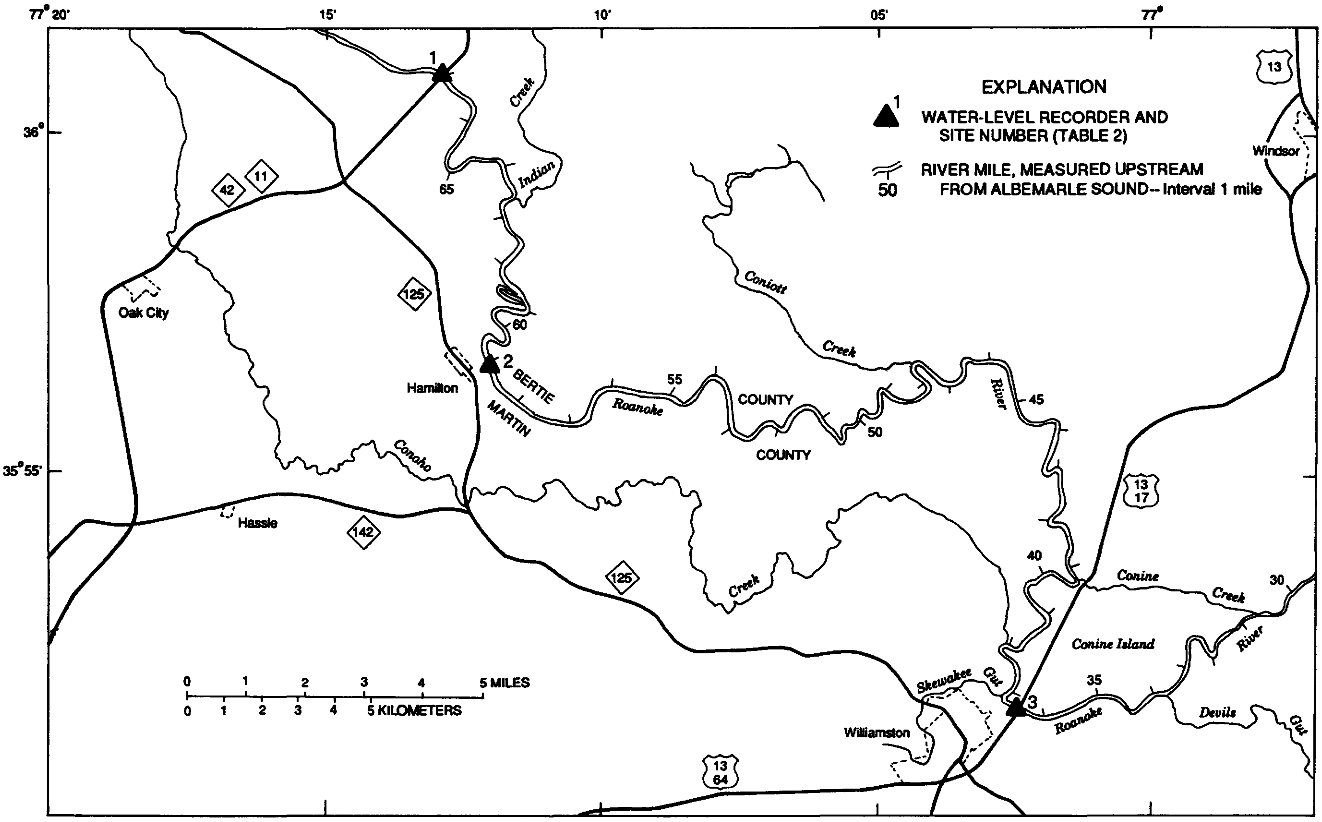

Figure 2. Study area and selected water-level recorders.

Model calibration is accomplished by adjusting model parameters until model results agree with observations (Ditmars and others, 1987). The model is considered validated if model results agree with observations distinct from those used for model calibration without further adjustment of model parameters (Ditmars and others, 1987). The model is assumed to be valid over the range of conditions used in the calibration and validation process. Sensitivity testing is the determination of the effects on model results of small changes in model parameters or input data.

The validated model was applied to the study reach to compute daily mean flows for the period October 1, 1988, through September 30, 1990. Roanoke River flows were computed for three locations by using observed water levels at the study reach boundaries and estimates of intervening drainage area inflows obtained from measurements at nearby index stations.

Acknowledgments

This study was conducted in cooperation with the Division of Water Resources within the North Carolina Department of Environment, Health, and Natural Resources, and the U.S. Army Corps of Engineers, Wilmington District. The Corps of Engineers, Wilmington District, supplied data on channel geometry and, along with Virginia Electric and Power Company, provided information on planned releases from Roanoke Rapids Lake, which facilitated the scheduling of field activities.

STUDY AREA

The study area is in the Coastal Plain province of North Carolina and consists of the subbasin of the Roanoke River between river mile 67.0 at State Highway 42–11 bridge near Oak City and river mile 36.6 at U.S. Highway 17–13 bridge near

Williamston (fig. 2). This area includes Conoho Creek and the head of Conine Creek through which some water bypasses a segment of the Roanoke (fig. 2). Conoho Creek is the largest tributary to the Roanoke River in the study area and has a drainage area of 120 mi^2, which represents 47 percent of the 257-mi^2 subbasin that drains directly to the Roanoke in the study area. Drainage areas and river miles (measured upstream from Albemarle Sound) at selected locations within the study area are provided in table 1. For this report, the study reach is defined as the 30.4-mi reach of the Roanoke River between river miles 67.0 and 36.6.

Other streams that drain to the Roanoke River in the study area are relatively small, and their basins have little topographic relief. Land-surface elevations within the study area are generally less than 50 ft above sea level.

Climate in the region is mild and moderately humid. The annual mean temperature at Williamston is about 60 °F, and mean annual precipitation is about 50 in. Annual precipitation totals vary greatly from year to year, ranging from less than 40 in/yr to more than 75 in/yr. However, precipitation is relatively uniform throughout the year, with the highest amounts typically occurring in July, August, and September. Evapotranspiration rates average about 34 in/yr and vary less from year to year than precipitation amounts vary (Wilder and others, 1978). On the average, about 30 percent of the total precipitation that occurs in the study area reaches streams through either surface runoff or ground-water discharge (Wilder and others, 1978).

The study area is characterized primarily by agricultural land use and extensive bottomland hardwood forest. Some of the land is artificially drained by ditches and canals to facilitate development. The bottomland hardwood forest along the Roanoke River is considered the largest intact and least disturbed ecosystem of its kind in the mid-Atlantic region (Manooch and Rulifson, 1989). Water use in the Roanoke basin was summarized by Treece (1990) and Treece and others (1990).

Data-Collection Network

Data collection for the investigation included (1) continuous measurements of water level, (2) measurements of discharge, and (3) measurements of channel geometry and flood-plain topography. Ungaged inflow to the study reach from the intervening drainage area was estimated from flow records at three nearby streamflow gaging stations.

In addition to the water-level recorders in the study reach (fig. 2 and table 2), continuous records of water level are also obtained upstream at river mile 97.0 near Scotland Neck and at river mile 137.0 near Roanoke Rapids (fig. 1). All water-level data are referenced to sea level. Flow at Roanoke Rapids is computed from a stage-discharge relation. No additional continuous records of Roanoke River flow are available downstream from river mile 137.0.

Between 1987 and 1991, 37 discharge measurements were made in the study reach (table 3). Because there typically is no large tidal variation in water levels and flow in the study reach, continuous measurements of discharge throughout a tidal period were not required.

Channel cross-sectional data were obtained for more than 40 sites along the study reach, although not all of the available cross-sectional geometry data were used in the model. Some of the cross sections were from previous surveys by the U.S. Army

Table 1. Drainage areas and river miles at selected locations within the study area

[–, not applicable]

Site number	Location (fig. 2)	Drainage area (mi^2)	River mile
1	Roanoke River at State Highway 42–11 bridge near Oak City.	8,813	67.0
2	Roanoke River near Hamilton	8,886	59.2
–	Roanoke River at head of Conine Creek.	8,936	40.8
–	Mouth of Conoho Creek	120	37.9
3	Roanoke River at U.S. Highway 17–13 bridge near Williamston.	9,070	36.6

Table 2. Continuous water-level data-collection sites within the study reach

Site number (fig. 2)	Station number[1]	Location (fig. 2)	Latitude	Longitude
1	02081022	River mile 67.0	36°00′50″	77°12′55″
2	02081022	River mile 59.2	35°56′50″	77°12′10″
3	02081054	River mile 36.6	35°51′40″	77°02′20″

[1] U.S. Geological Survey downstream order number.

Table 3. Discharge measurements and channel section data for Roanoke River and selected tributaries, 1987–91

[Times are shown in military time; ft^3/s, cubic feet per second; ft^2, square feet; –, data not available]

Date	Time	Flow (ft^3/s)	Water level (ft above sea level)	Channel width (ft)	Channel cross section area (ft^2)
River mile 67.0 (site 1)					
7–15–87	1125–1230	2,620	4.22	261	3,620
12–16–87	1430–1535	10,800	14.06	320	6,675
5–04–90	0935–1055	8,520	12.10	305	5,300
6–22–90	1005–1130	11,400	16.44	317	6,600
6–26–90	1655–1815	5,590	9.03	288	4,320
6–28–90	1055–1300	9,780	12.76	306	5,380
6–29–90	1255–1405	8,100	12.26	303	5,230
7–06–90	1025–1205	4,150	5.62	274	3,190
River mile 59.2 (site 2)					
3–12–90	1315–1445	[1]10,300	14.33	270	5,480
3–13–90	0920–1035	8,170	12.74	320	5,885
5–04–90	1225–1345	8,480	10.24	317	5,120
6–27–90	1230–1355	[1]7,820	9.31	254	3,860
6–29–90	1050–1145	[1]8,780	10.70	256	4,215
7–06–90	1400–1530	[1]4,140	4.32	248	2,610
River mile 40.8					
6–26–90	1120–1305	5,280	–	272	4,380
7–05–90	1420–1555	2,010	–	263	3,330
8–13–91	1110–1235	3,320	–	258	3,830
Head of Conine Creek					
6–26–90	0915–1035	220	–	54	410
3–20–91	0915–1000	600	–	60	500
8–13–91	1110–1200	100	–	50	260
Mouth of Conoho Creek					
3–20–91	1110–1215	525	–	66	540
8–13–91	0850–0955	290	–	67	345
River mile 36.6 (site 3)					
3–14–90	0845–1020	10,700	6.95	271	5,390
3–16–90	0915–1125	9,000	5.76	268	5,110
5–04–90	1515–1615	8,730	5.15	269	4,940
6–26–90	0855–1020	6,510	4.62	265	4,800
6–26–90	1100–1210	6,550	4.56	265	4,810
6–26–90	1455–1600	6,800	4.56	265	4,790
6–27–90	0800–0950	7,230	4.70	266	4,760
6–29–90	0820–0925	8,990	5.32	268	4,980
7–05–90	1655–1810	2,180	1.47	257	3,960
8–01–90	0955–1100	3,850	2.18	262	4,260
3–20–91	1310–1425	10,800	6.55	272	5,390
3–22–91	1330–1500	12,000	6.86	275	5,400
8–13–91	0820–1020	3,630	2.60	267	4,300
8–13–91	1735–1820	3,660	2.43	272	4,230
8–15–91	0910–1110	2,970	2.18	270	4,180

[1]Discharge measurement was made within 500 ft of site 2.

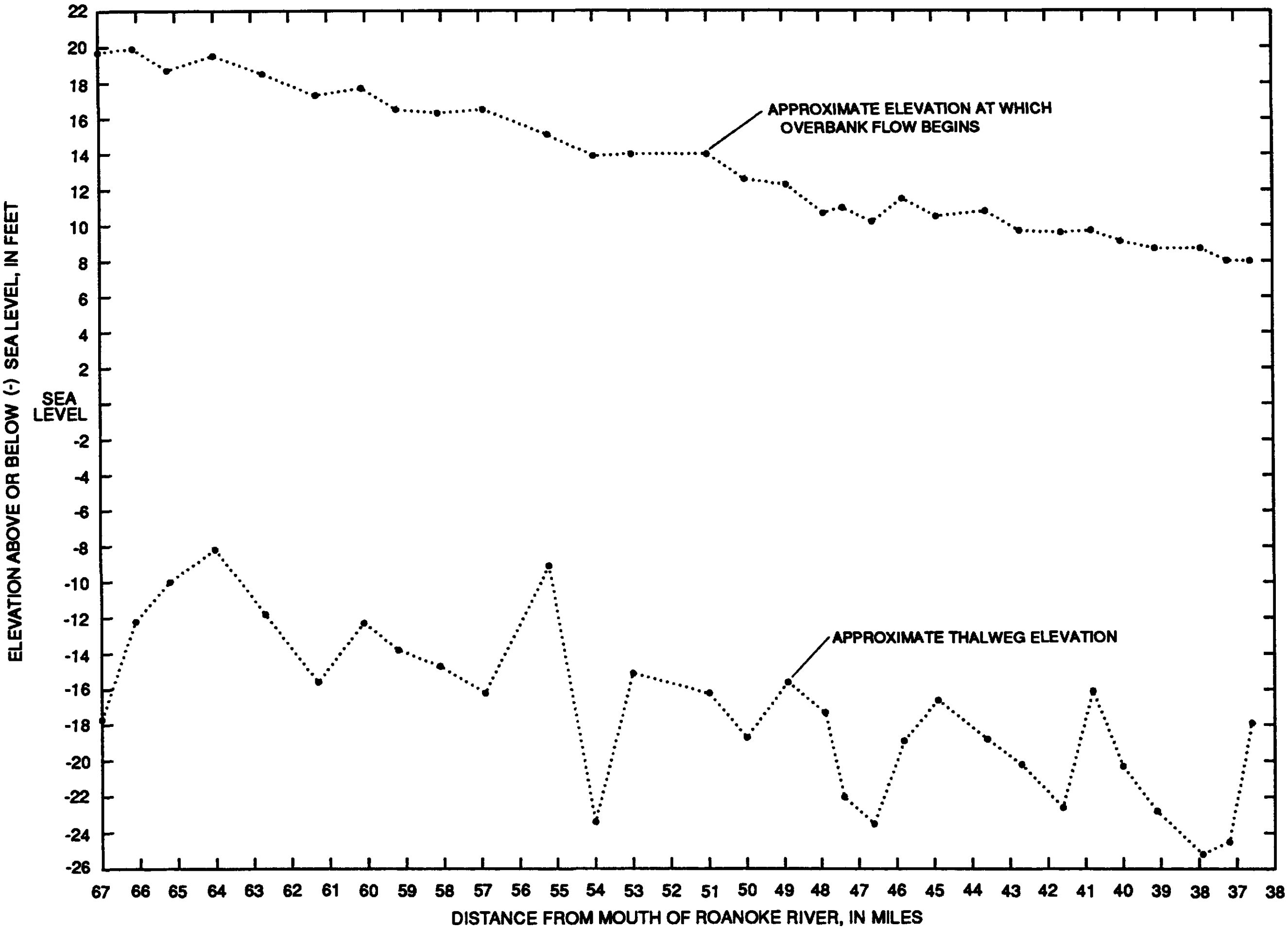

Figure 3. Approximate elevation at which overbank flow begins and thalweg elevation within the study reach.

Table 4. Streamflow gaging stations used for local inflow estimation
[mi², square miles]

Site number (fig. 1)	Station number[1]	Stream and location (fig. 1)	River basin	Drainage area (mi²)	Latitude	Longitude
4	02053200	Potecasi Creek near Union	Chowan	225	36°22′14″	77°01′36″
5	02053500	Ahoskie Creek at Ahoskie	Chowan	63.3	36°16′48″	77°00′00″
6	02083000	Fishing Creek near Enfield	Tar	526	36°09′03″	77°41′35″

[1] U.S. Geological Survey downstream order number.

Corps of Engineers, but most of the cross sections used in the model were surveyed by the USGS. The channel thalweg elevation ranges from about 8 to 25 ft below sea level (fig. 3). The approximate elevation at which overbank flow begins ranges from about 8 to about 20 ft above sea level (fig. 3). Typical channel geometry at six locations is shown in figure 4.

Three continuous-record gaging stations (table 4; fig. 1) were used as index stations to estimate daily mean ungaged inflow from the 257-mi² subbasin that drains directly to the study reach. Two of the index stations are located in the Chowan River basin northeast of the study area. The third station is in the Tar River basin southwest of the study area. Land use upstream of each of the index stations is

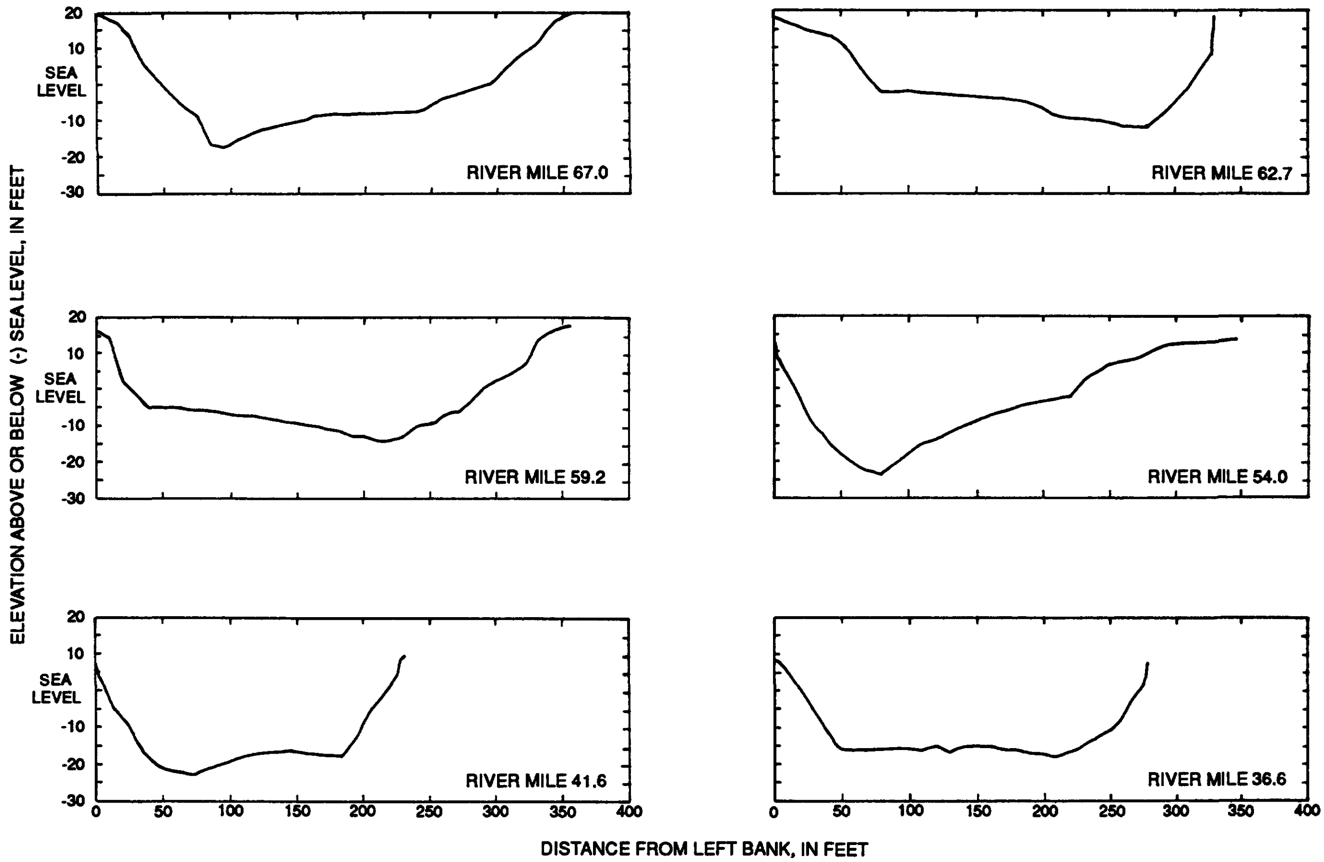

Figure 4. Channel geometry of the Roanoke River at selected locations within the study reach.

similar to that in the study reach subbasin. Ahoskie Creek, which has been channelized, is representative of the small number of channelized streams that drain to the study reach.

Hydrologic Conditions

Construction of a series of three reservoirs (John H. Kerr Lake, Lake Gaston, and Roanoke Rapids Lake) on the Roanoke River upstream of Roanoke Rapids first affected flows in the Roanoke in August 1950 (Manooch and Rulifson, 1989). (However, small hydroelectric projects affected flows in the Roanoke River as early as 1902.) Roanoke Rapids Lake, the reservoir farthest downstream on the Roanoke River, was completed in 1955. Since that time, releases from this reservoir have been the primary control on flows in the study reach. Nevertheless, local inflows and conditions in Albemarle Sound also affect flows in the Roanoke River.

Daily flow durations at river mile 137.0 (at Roanoke Rapids) for the periods 1913–50 (prior to reservoir construction) and 1955–89 (after completion of the reservoirs) differed significantly in the high-flow range (fig. 5). Between 1913 and 1950, for example, daily mean flows of 30,000 ft^3/s were exceeded about 3 percent of the time, whereas daily mean flows of that magnitude were seldom exceeded after 1955. This difference between the pre- and postimpoundment flow durations at the extremely high flows partially reflects the flood control function of John H. Kerr Lake. Daily mean flows of about 4,500 to 20,000 ft^3/s occurred more often between 1955 and 1989 than from 1913 to 1950, but daily mean flows of less than about 4,500 ft^3/s occurred less often during the 1955–89 period than during the 1913–50 period. The more frequent occurrence of flows of about 1,000 and 2,000 ft^3/s during the postimpoundment period relative to the preimpoundment period likely reflects reservoir releases made to meet instream flow requirements.

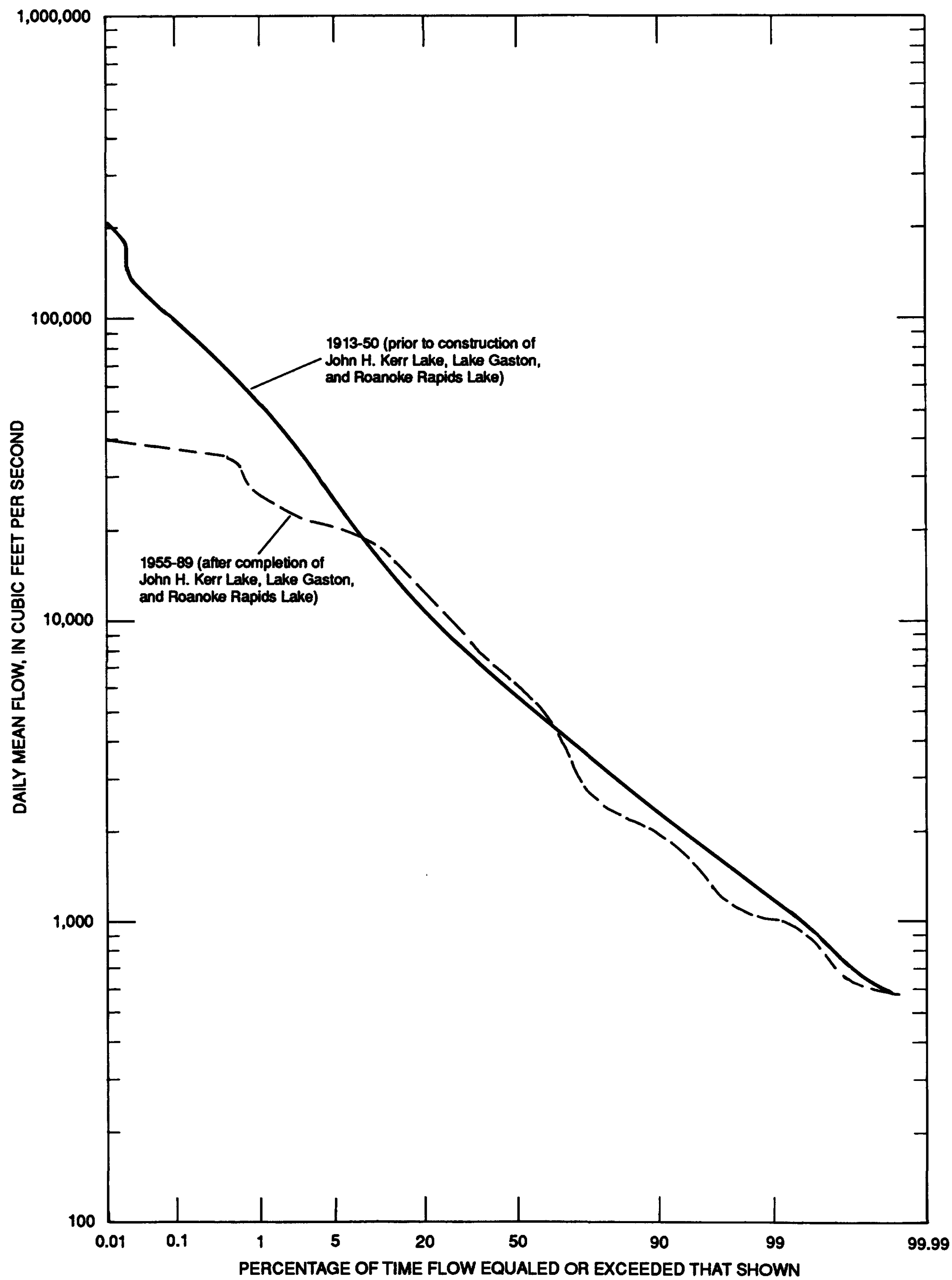

Figure 5. Flow-duration curves for the Roanoke River at river mile 137.0 for the periods 1913–50 and 1955–89.

Bales and others (1993) evaluated the effects of releases from Roanoke Rapids Lake dam on downstream water levels and concluded that, under some conditions, water levels at site 3 (the downstream boundary of the study reach) respond within about 12 h to sustained (a day or longer) changes in releases from Roanoke Rapids Lake. However, short-duration (6 h or less) changes, such as those that occur during hydropower peaking operations, typically do not have a noticeable effect on water level downstream from site 2.

The effects of Albemarle Sound on water levels in the study reach were observed as far upstream as site 2, although these effects could extend farther upstream. For example, the measured flow at site 2 on March 13, 1990, was 8,170 ft^3/s at a water level of 12.74 ft (table 3). However, on June 29, 1990, the measured flow was higher (8,780 ft^3/s) at a lower water level (10.70 ft) than on March 13. This observation is further evidence of the need for a flow model to compute discharge in the study reach.

According to Wilder and others (1978) and Krug and others (1990), the long-term average annual runoff in the vicinity of the study reach is about 14 in., or 1.03 $(ft^3/s)/mi^2$. Consequently, the long-term average runoff at site 3 for the 257-mi^2 subbasin, which drains directly to the study reach, is about 265 ft^3/s. Between river mile 137.0, just downstream from Roanoke Rapids Lake, and site 1, at the upstream boundary of the study reach, the long-term average runoff into the Roanoke River is about 440 ft^3/s.

The natural levee along the Roanoke River is breached by numerous drainage canals and a few small creeks, especially near the downstream end of the study reach. These channels provide conduits for water to move out of the river and into the flood plain during high-water levels. As water levels fall, water slowly drains from the flood plain into the canals and streams and eventually back into the river. This process is different from water spilling over the top of the bank during high flows.

BRANCH-NETWORK FLOW MODEL

A one-dimensional, unsteady-flow model (Schaffranek and others, 1981) was used to compute flows in the study reach. The model is capable of simulating flows in response to wind, as well as flows in a network of channels. The model has been applied to streams, rivers, and canals representing a wide range of physical and hydrologic conditions (Schaffranek, 1989). Typical applications include those made to the Columbia River, Wash. (Schaffranek and others, 1981); the tidally influenced lower Calcasieu River, La. (Arcement, 1988); and the Detroit River, Mich., which consists of a series of interconnected channels linking Lake Erie and Lake St. Clair (Schaffranek and others, 1981).

The flow model is based on the cross-sectionally averaged (or one-dimensional), nonlinear momentum and continuity equations for unsteady flow in channels. The governing equations include the assumptions that (1) the water density is essentially homogeneous throughout the study reach; (2) the hydrostatic pressure distribution prevails; (3) the channel slope is sufficiently mild so that the flow remains subcritical; and (4) a flow-resistance coefficient is used to account for energy losses. Because the governing equations are cross-sectionally averaged, bidirectional flow (either across the channel or in the vertical plane) at a cross section cannot be simulated by the model. Upstream and downstream flow within the study reach, however, can be computed by the model. The governing equations are solved for the two unknowns—water level and flow—by using a weighted, four-point, implicit finite-difference scheme. Development and use of the model require information on channel geometry and synchronous, precisely timed data at the boundaries of the study reach.

The study reach must be accurately described in order to implement the flow model. The model requires that the study reach be described as a series of branches, segments, junctions, and cross sections or computational points (fig. 6). Locations at which two or more channels join or where local inflows must be accommodated are internal junctions. Locations at which a single branch is begun or terminated are external junctions. User-supplied boundary conditions (time sequence of water level or flow) are required at external junctions; inflows or losses within the study reach are also required as boundary conditions. Channel reaches between junctions are called branches, which can be further subdivided into segments. Selection of segments is based on variability in cross-sectional geometry and computational considerations. Model results are provided at the end points of all segments.

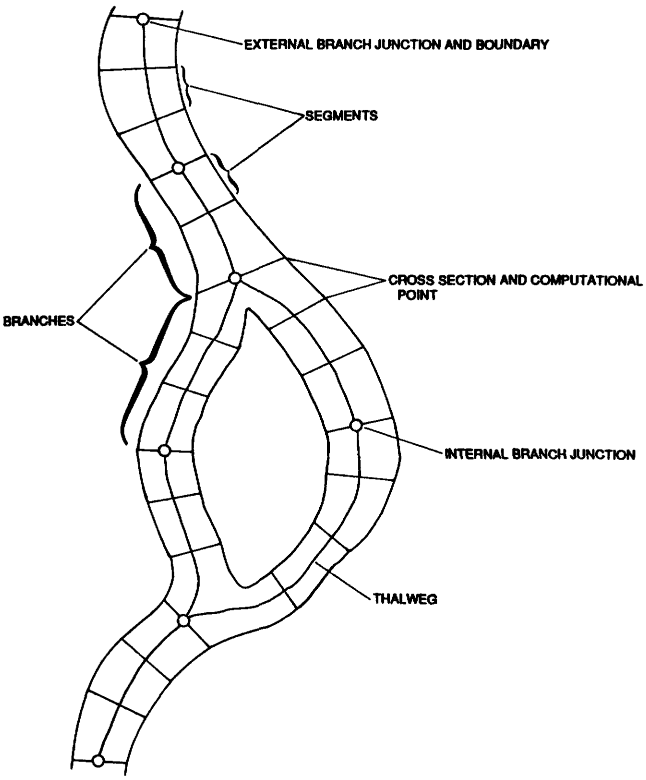

Figure 6. Idealized branch-network model diagram.

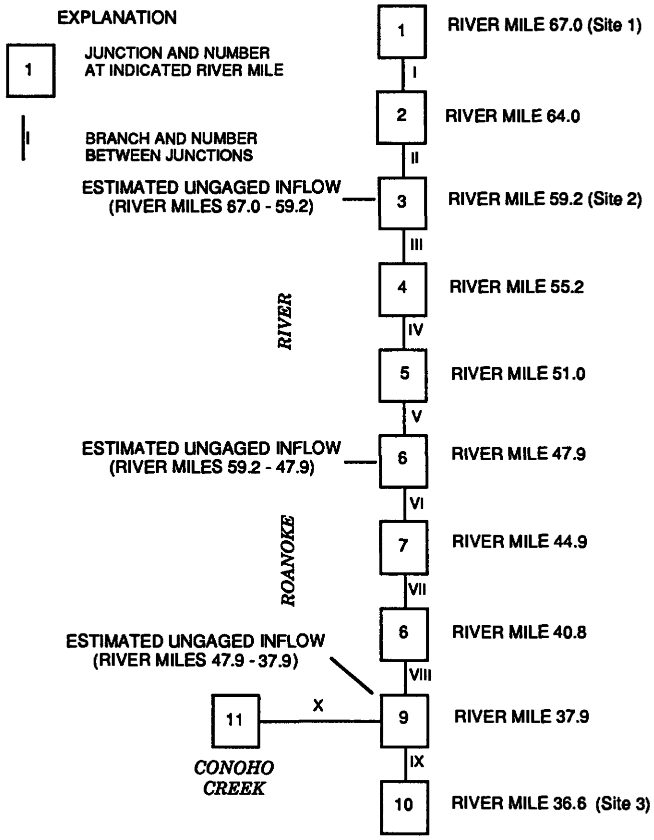

Figure 7. Model schematization of the study reach.

SIMULATION OF UNSTEADY FLOW IN THE ROANOKE RIVER

Implementation of the unsteady-flow model for the Roanoke River began with segmenting the study reach into a series of branches, junctions, and cross sections. Model parameters were initially estimated, and then adjusted, during model calibration so that close agreement between simulated and measured water level and flow was obtained. Following extensive testing of the model during the calibration, validation, and sensitivity analysis phases, the model was used, along with observed boundary conditions, to compute flow records at three locations within the study reach.

Model Schematization

The model of the study reach was schematized by using 10 branches (fig. 7) and 38 cross sections (table 5). The main stem of the river is represented by 9 branches and 32 cross sections, an arrangement which is equivalent to approximately one cross section per river mile. Ungaged inflow from the intervening drainage area is input at junctions 3, 6, and 9 (river miles 59.2, 47.9, and 37.9, respectively). Conoho Creek is described by using one branch (branch X) and six cross sections. Because the head of Conine Creek is within the study reach but the mouth of the creek is downstream from the study reach (fig. 2), flow lost from the study reach through Conine Creek cannot be included in this model. However, Bales and others (1993) described plans and preliminary results for a model that extended from river mile 67.0 to river mile 19.2 and that included Conine Creek as an additional branch in the model. This planned extension of the model might better simulate the effects of Conine Creek on flow in the Roanoke River.

The study reach was initially represented by using three branches. The number of branches was increased until preliminary model results were satisfactory and no changes in model results were observed from increasing the number of branches further. The locations of the cross sections used to represent river geometry in the model were selected to best describe average conditions in the river.

Table 5. Summary of branches and cross sections used in the flow model

Branch (fig. 7)	Branch length (ft)	Junction	Cross section	River mile	Approximate elevation at which overbank flow begins (ft above sea level)	Location (fig. 7)
				Roanoke River		
I	15,840	1	1	67.0	19.7	Site 1
			2	66.1	19.9	
			3	65.2	18.7	
		2	4	64.0	19.5	
II	25,340	2	4	64.0	19.5	
			5	62.7	18.5	
			6	61.3	17.3	
			7	60.1	17.7	
		3	8	59.2	16.5	Site 2
III	21,120	3	8	59.2	16.5	Intervening drainage area inflow input
			9	58.1	16.3	
			10	56.9	16.5	
			11	56.0	15.5	
		4	12	55.2	15.1	
IV	22,180	4	12	55.2	15.1	
			13	54.0	13.9	
			14	53.0	14.0	
			15	52.0	14.0	
		5	16	51.0	14.0	
V	16,370	5	16	51.0	14.0	
			17	50.0	12.6	
			18	48.9	12.3	
		6	19	47.9	10.7	
VI	15,840	6	19	47.9	10.7	Intervening drainage area inflow input
			20	47.4	11.0	
			21	46.6	10.2	
			22	45.8	11.5	
		7	23	44.9	10.5	
VII	21,650	7	23	44.9	10.5	
			24	43.6	10.8	
			25	42.7	9.7	
			26	41.6	9.6	
		8	27	40.8	9.7	
VIII	15,310	8	27	40.8	9.7	
			28	40.0	9.1	
			29	39.1	8.7	
		9	30	37.9	8.7	
IX	6,860	9	30	37.9	8.7	Intervening drainage area inflow input
			31	37.2	8.0	
		10	32	36.6	8.0	Site 3
				Conoho Creek		
X	53,860	11	33	[1]10.2	9.6	
			34	[1]5.5	9.6	
			35	[1].75	8.7	
			36	[1].50	8.7	
			37	[1].25	8.7	
		9	38	37.9	8.7	Mouth of Conoho Creek

[1] Miles upstream from mouth of Conoho Creek.

Some adjustments of cross section location and number of cross sections used within the model were made during the preliminary simulations. Model results were not particularly sensitive to these changes in location and number of cross sections. However, a rigorous analysis of spatial convergence, in which effect on model results of the number and spacing of cross sections in the model is evaluated, was not conducted.

Because discharge measurements were not available for conditions during which overbank flows occurred, the model was constructed to simulate water levels and flows that are below the top of bank. Approximate elevations at which overbank flow begins are given in table 5. However, because the natural levee along the study reach is breached by numerous small drainage canals and a few creeks, water may move into and out of the flood plain, even during periods when water levels in the river are below the top of bank.

Preliminary model results and field observations indicated that storage and release of water from the flood plain were not being simulated properly by the model. Because most of the flood-plain storage is downstream from about river mile 50 and because the Conoho Creek basin contains a large part of the storage volume, all the flood-plain storage in the study reach was lumped into the branch representing Conoho Creek (branch X), which enters the Roanoke River at river mile 37.9. The storage section of branch X has a surface area of 29 mi^2 at an elevation of 8 ft and is connected to the main stem of the Roanoke River by a relatively small channel so that water will move into and out of the storage section slowly, thus mimicking flood-plain processes.

Calibration

Model calibration is required to adapt the general branch-network flow model to the specific application in the study reach. Calibration is accomplished by adjusting model parameters until model results agree with observations. Essentially all components of the model schematization are subject to adjustment during model calibration. Components that are directly measurable and physically well defined are, however, typically less subject to adjustment than are those that might not be directly measured.

Prior to model calibration, the computational time step was selected. A time step of 15 min gave the most satisfactory compromise between computational cost and model accuracy. Fifteen-minute interval input data from upstream and downstream boundary water-level recorders were linearly interpolated from hourly observations. Water-level variations were sufficiently gradual to permit such interpolation without loss of accuracy.

Factors that were subject to adjustment during calibration of the flow model include the following:

- *Channel geometry*. Cross sections in the main stem of the river were based on direct measurements. Elevations relative to mean sea level were obtained by (1) measuring channel geometry, including stream banks, and referencing measurements to water surface; (2) determining water-surface elevation at water-level recorders upstream of and downstream from measurement sections at the time of the measurement; and (3) linearly interpolating between the elevations at the two recorders to obtain water-surface elevation at the measurement section. Adjustments to cross-sectional area at some sections were required during the calibration process, but adjustments were generally made at higher elevations where direct measurements of cross-sectional geometry were more difficult. Adjustments to the Conoho Creek storage section (branch X) were also required to obtain the desired effects on flow in the main stem.

  Although gage datums were established by surveys to the nearest benchmark, calibration results indicated that the gage datum at site 1 was different from the datum at sites 2 and 3. After several trials, a positive 0.6-ft datum correction to the water-level readings made at site 1 provided improved results. Because of the relatively large distances between gages, no attempt was made to determine gage datums at each site relative to the other sites by surveying from gage to gage. Existing gage datums are part of the State network of benchmarks, but some of the benchmarks at gage sites were established more than 50 yr ago.
- *Resistance coefficient*. The resistance coefficient accounts for the extraction of energy from the main flow by turbulence generated at the streambed. Resistance coefficients were initially estimated by using handbook values and the Manning flow equation. The coefficients were then adjusted to minimize differences between observed and computed

water level and discharge. Within the calibrated model, the resistance coefficients are specified as a function of water-surface elevation at each cross section. The coefficients range from 0.034 to 0.049, with the higher values generally applying to the lower water levels.

- *Momentum coefficient.* The momentum coefficient accounts for the effects of nonuniform velocity distributions on flows. A value of 1.06, which is typical for turbulent flows in natural channels (Holtschlag, 1981; Schaffranek and others, 1981), was used.
- *Weighting factors for numerical solution.* Two factors are used in the numerical solution of the governing equations (Schaffranek and others, 1981). Theta controls the amount of numerical dampening in the solution, and chi affects the phase lag in the solution. Based on experience in other applications (Schaffranek, 1989), theta and chi were each set to 0.75.

Flows and water levels within the study reach are required prior to initiating model computations. A linearly sloping water surface and a constant flow throughout the reach were assumed as initial conditions at the beginning of each set of computations. Because the assumed initial conditions were not exact, model results for the first day of each simulation period were considered to be unreliable and were not used. Tests indicated that the 24-h "warm-up" period was more than sufficient time for removing the effects of the initial conditions from the study reach.

Boundary conditions at external junctions (junctions 1, 10, and 11) are required for model operation. Observed records of water level from site 1 and site 3 provided the upstream and downstream water-level boundary conditions at junctions 1 and 10, respectively. Boundary conditions at junction 11 were fulfilled by specifying a zero discharge at the upstreammost extent of branch X.

Inflow boundary conditions were supplied at junctions 3, 6, and 9. Because inflow from the intervening drainage area to the study reach is time-varying and ungaged, data from three nearby index stations (table 4) were used to estimate inflow to the study reach. Daily mean flow per square mile of drainage area was determined for each of the three index stations. These values were averaged to provide an estimate of daily mean inflow per square mile of intervening drainage area at each of the inflow boundaries (junctions 3, 6, and 9).

Model calibration was completed for three sets of arbitrarily selected water-level conditions. Water levels above about 9 ft at site 2 were designated as high water-level conditions; midrange water levels were between about 9 ft and 6 ft; and low water levels were less than about 6 ft.

Simulated water levels were compared with water levels measured at site 2. Simulated and observed water levels for the period June 25 through July 6, 1990, when water levels varied as much as 8 ft, are shown in figure 8 and are typical of the results obtained in all tests. Overall, the difference between simulated and observed water levels was less than 0.5 ft and usually less than 0.2 ft. The simulated and observed depths of flow differed by less than 5 percent.

Likewise, simulated and measured flows were compared for the period June 25 through July 6, 1990 (fig. 9), as well as for the period August 11–15, 1991 (fig. 10). Simulated flows are in close agreement with measured values (table 6). Measurements included flows from 2,010 to 10,700 ft^3/s. (The measurement made on March 12, 1990, at site 2, listed in table 3, was not used for calibration or validation because flow was over the top of bank at site 3.) The maximum difference between a measured and simulated value was 15 percent. The mean absolute difference between the 22 measured and simulated values was 3.4 percent, and the root mean square error was 5.0 percent. The average error was 0.5 percent, indicating that there was also no bias toward under- or oversimulation of flow (fig. 11).

The simulated results in figure 9 also depict the attenuation of peak flows within the study reach. The peak flow at site 1 was 10,100 ft^3/s at 1600 on June 28; the peak flow of 9,810 ft^3/s at site 2 occurred 2.75 h later; and the peak flow at site 3 was 9,640 ft^3/s at 1015 on June 29, or 18.25 h after the occurrence of the peak 30.4 mi upstream. Finally, the simulated results indicate that a slight periodic variation can occur in flows at site 3 (July 3–5, 1990, in fig. 9; August 12–15, 1991, in fig. 10), when no such variation exists farther upstream. This condition is another indication of the effects of water-level variations in Albemarle Sound on flows in the Roanoke River.

Simulated flow at the mouth of Conoho Creek (branch X), which serves as the model storage reservoir, ranged from −573 to 2,246 ft^3/s during the June 25 through July 6, 1990, calibration period. As flow (and water levels) in the main stem of the river

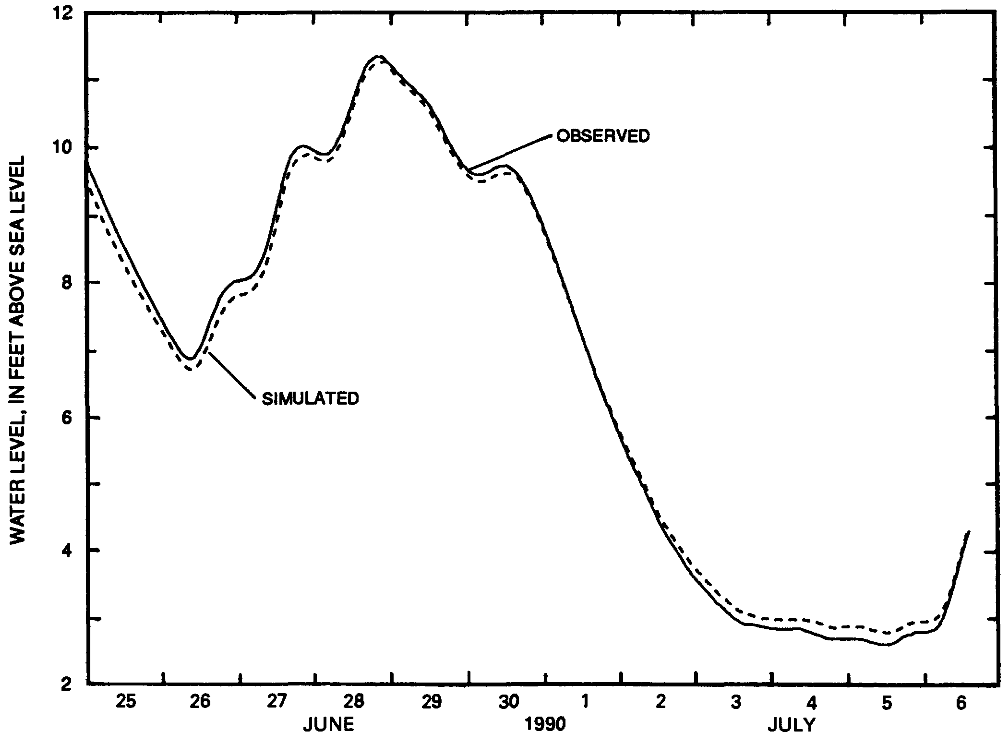

Figure 8. Simulated and observed water levels in the Roanoke River at site 2 for model calibration period June 25 through July 6, 1990.

fell on June 25, the flow out of branch X decreased, and on June 27, water began flowing out of the river and into branch X (fig. 9). During the low-flow period from July 3–6, the simulated branch X storage reservoir had virtually no effect on flows in the river.

Validation

The model was validated by using boundary data different from that used for calibration, but representing the same range of water-level conditions as was used for calibration. Model parameters were not adjusted during the validation process.

Nine pairs of measured and simulated flows were used for model validation (table 6 and fig. 11). Observed and simulated water levels at site 2 differed by less than 0.5 ft, as was the case for calibration. The average absolute difference between measured and simulated flows obtained in the validation process was 3.3 percent, and the root mean square error was 4.1 percent. With an average error of 1.1 percent, there was no evident bias toward under- or oversimulation.

The model has been calibrated and validated for water levels ranging from about 6 to 16 ft at site 1, for water levels from about 1.5 to 7.0 ft at site 3, and for flows between about 2,000 and 12,000 ft^3/s. The model may be used with caution for conditions that do not differ substantially from conditions for which the model was calibrated and validated. However, because peak flows in the study reach are probably in excess of 20,000 ft^3/s (based on flows measured at river mile 137.0), there is a need for additional data collection, model calibration, and model validation if the model is to be used to simulate high-flow conditions.

Sensitivity Analysis

Sensitivity analysis consists of evaluating the sensitivity of model results to changes in (1) computational time step, (2) momentum coefficient, (3) numerical scheme weighting factors (chi and theta), (4) resistance coefficients, and (5) boundary gage datum. Sensitivity testing for the Roanoke River model was conducted by using data collected during June 25–29, 1990 (figs. 8 and 9), and during August 13–15, 1991 (fig. 10).

The model was calibrated and validated by using a 15-min computational time step. The model was then operated at other time steps. Both chi and

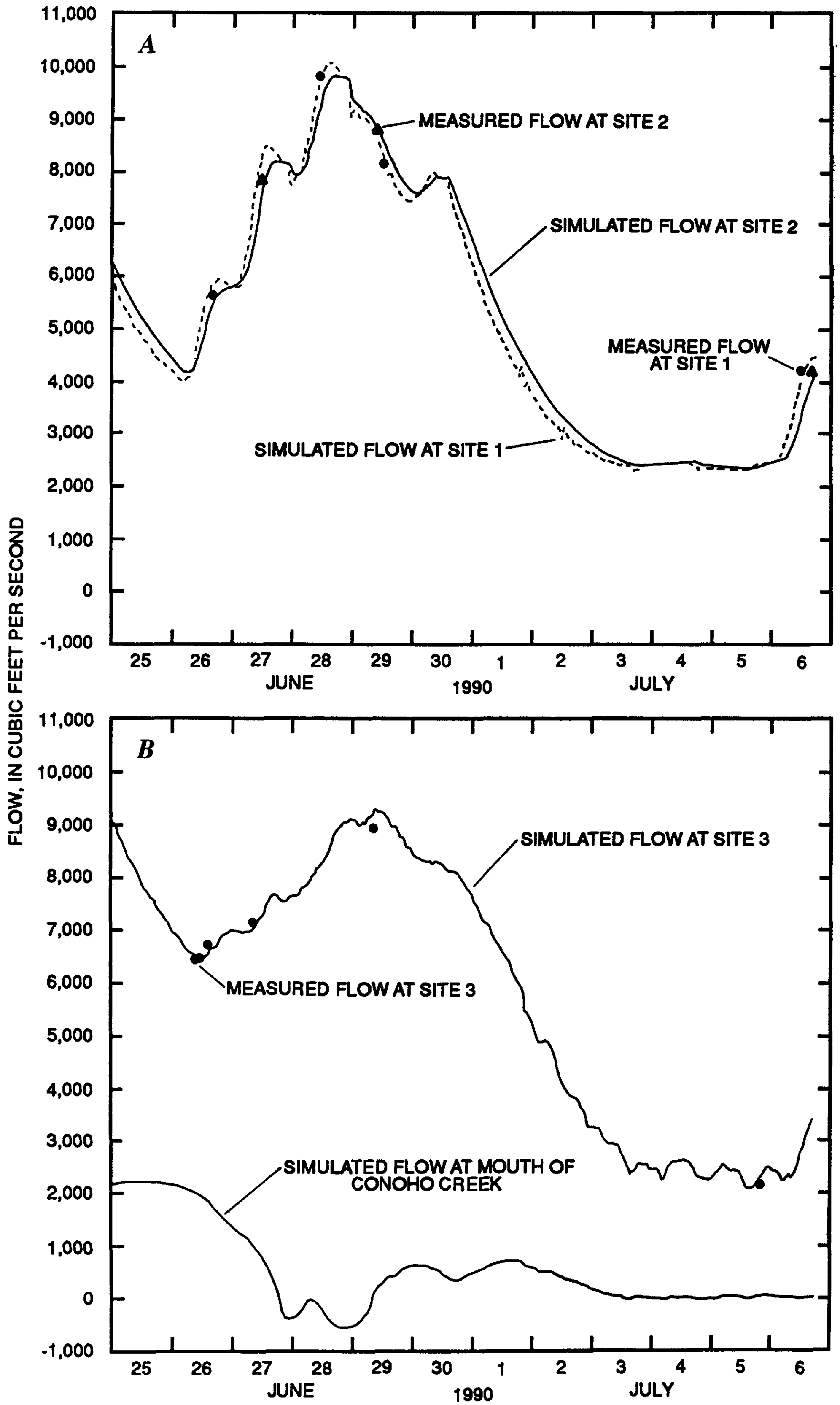

Figure 9. Simulated and measured flows for the period June 25 through July 6, 1990, at (*A*) Roanoke River sites 1 and 2 and (*B*) Roanoke River site 3 and mouth of Conoho Creek.

Table 6. Measured and simulated flows in the Roanoke River for model calibration and validation

[Time is shown in military time; ft³/s, cubic feet per second]

River mile	Date	Time	Water-level condition[1]	Measured flow (ft³/s)	Simulated flow (ft³/s)	Percent difference
			Model calibration			
67.0	6–26–90	1730	low	5,590	5,830	−4
67.0	6–28–90	1200	midrange	9,780	9,660	1
67.0	6–29–90	1330	midrange	8,100	8,190	−1
67.0	7–06–90	1115	low	4,150	4,060	2
59.2	3–13–90	1000	high	8,170	9,100	−11
59.2	6–27–90	1315	midrange	7,820	7,660	2
59.2	6–29–90	1115	midrange	8,780	8,760	0
59.2	7–06–90	1445	low	4,140	3,940	5
40.8	6–26–90	1215	midrange	5,280	4,490	15
40.8	7–05–90	1505	low	2,010	2,150	−7
40.8	8–13–91	1150	low	3,320	3,280	1
36.6	3–14–90	0930	high	10,700	9,840	8
36.6	3–16–90	1015	high	9,000	8,880	1
36.6	6–26–90	0945	midrange	6,510	6,560	−1
36.6	6–26–90	1130	midrange	6,550	6,470	1
36.6	6–26–90	1530	midrange	6,800	6,640	2
36.6	6–27–90	0900	midrange	7,230	7,090	2
36.6	6–29–90	0900	midrange	8,990	9,230	−3
36.6	7–05–90	1730	low	2,180	2,260	−4
36.6	8–13–91	0920	low	3,630	3,650	−1
36.6	8–13–91	1800	low	3,660	3,700	−1
36.6	8–15–91	1010	low	2,970	2,890	3
			Model validation			
67.0	7–15–87	1200	low	2,620	2,550	3
67.0	12–16–87	1500	high	10,800	10,300	4
67.0	5–04–90	1015	midrange	8,520	8,580	−1
67.0	6–22–90	1045	high	11,400	11,700	−3
59.2	5–04–90	1315	midrange	8,480	8,600	−1
36.6	5–04–90	1545	midrange	8,730	8,150	7
36.6	8–01–90	1030	low	3,850	3,610	6
36.6	3–20–91	1345	high	10,800	10,800	0
36.6	3–22–91	1415	high	12,000	12,600	−5

[1] Low water-level condition refers to water levels at site 2 less than about 6 ft; midrange, to water levels at site 2 between about 6 and 9 ft; and high, to water levels at site 2 above about 9 ft.

theta were maintained at the calibrated values of 0.75. Flows were simulated at site 3 by using time steps of 5, 15, and 30 min for June 25–29, 1990; results are shown for June 26–29 (fig. 12). Model results oscillate at a time step of 30 min, but there is virtually no difference between results obtained by using 5- and 15-min time steps. Changes in the magnitude of theta might affect the oscillations in the solution at the 30-min time step.

The sensitivity of model results to changes in the momentum coefficient was also evaluated by using data from the period June 25–29, 1990. Results were insensitive to changes in the momentum coefficient within the range of 1.0 to 1.10. The model was calibrated and validated by using a momentum coefficient of 1.06.

The effects of changes in the numerical-scheme weighting factors, chi and theta, on model results were evaluated by using data from June 25–29, 1990. In addition to the calibrated values of chi = 0.75 and theta = 0.75, four other combinations of chi and theta were evaluated: (1) chi = 0.6 and theta = 1.0; (2) chi = 1.0 and theta = 0.6; (3) chi = 1.0 and theta = 1.0; and (4) chi = 0.6 and theta = 0.6. At the selected time step of 15 min, simulated flows at sites 1, 2, and 3 were insensitive to these changes in chi and theta, as were the simulated water levels at site 2.

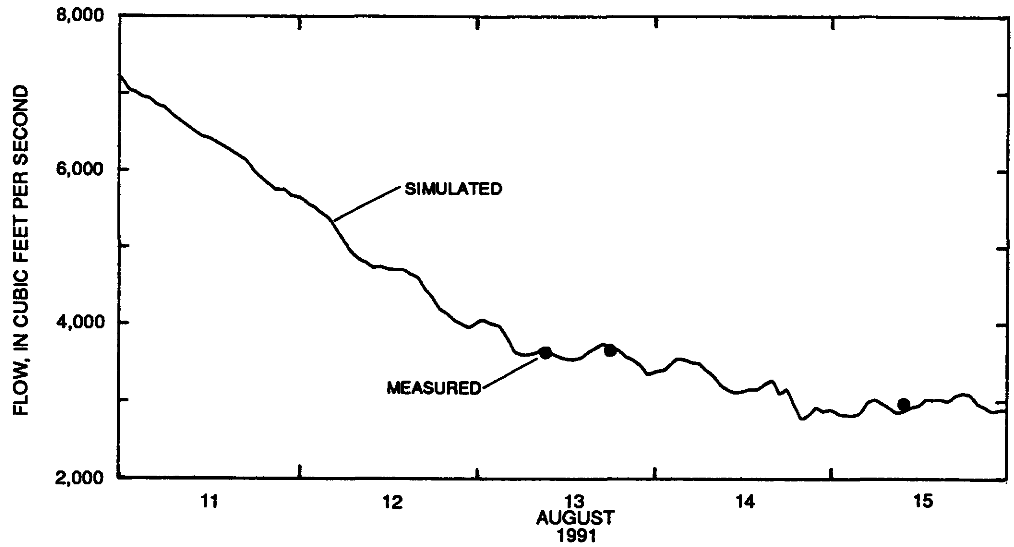

Figure 10. Simulated and measured flows in the Roanoke River at site 3 for the period August 11–15, 1991.

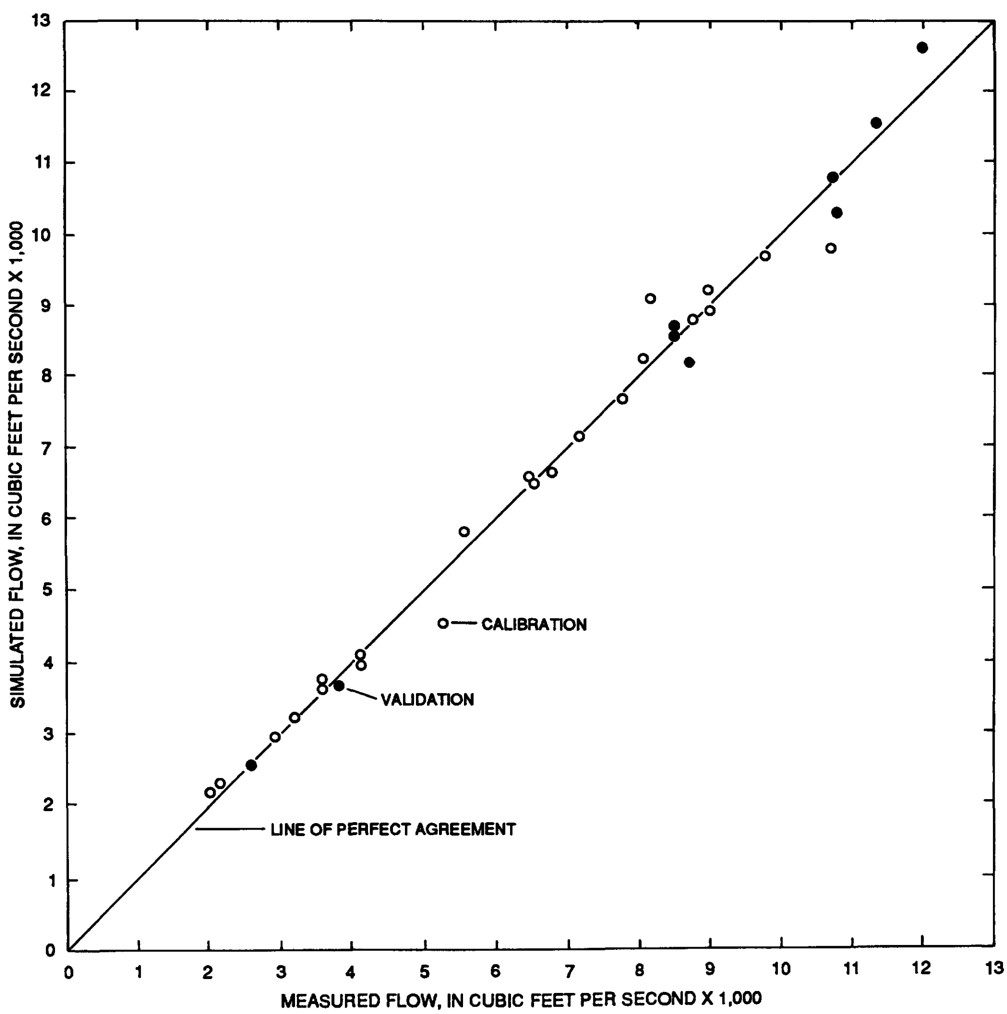

Figure 11. Relation of simulated and measured flows in the Roanoke River study reach.

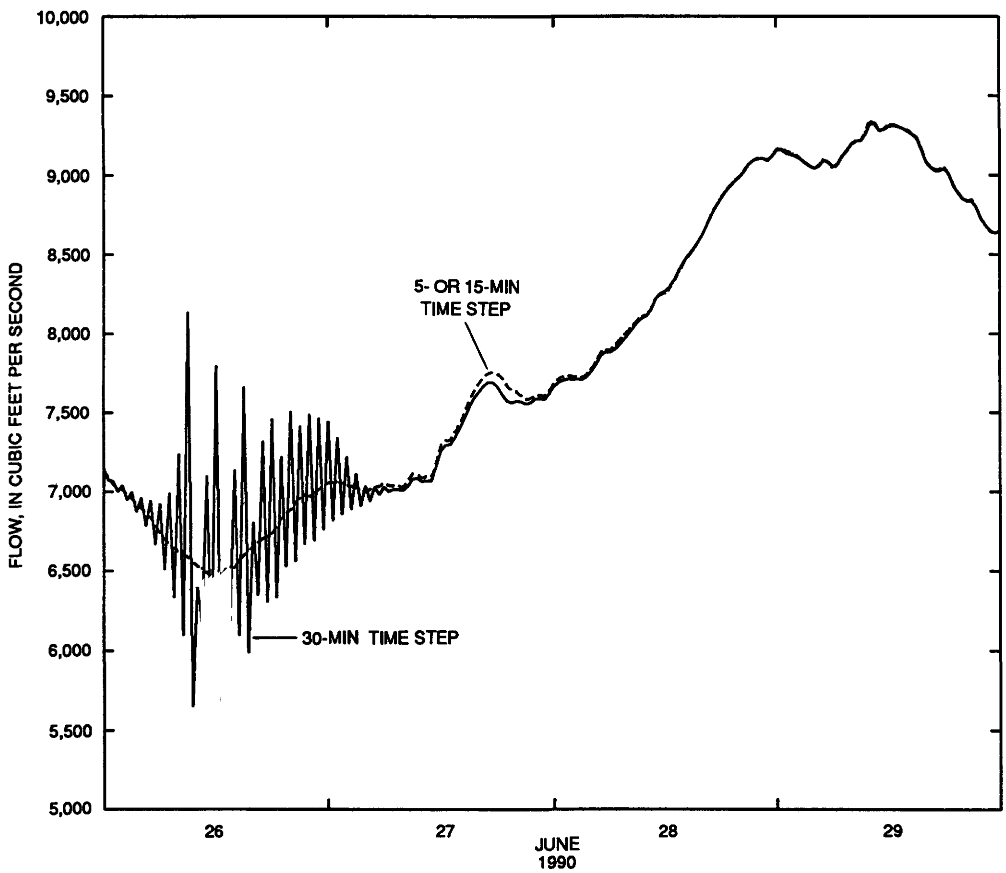

Figure 12. Simulated flows in the Roanoke River at site 3 for the period June 26–29, 1990, using a 5- , 15- , and 30-min computational time step.

The effect of reasonably small changes in the resistance coefficients on model results was demonstrated by using the June 25–29, 1990, boundary data. Results are shown for site 3 for June 26–29 (fig. 13). All resistance coefficients were increased by 10 percent, and flows at site 3 were computed. Likewise, all resistance coefficients were reduced by 10 percent, and flows at the same site were simulated. An increase in the resistance coefficients resulted in a general decrease in simulated flows as compared with the flows simulated by using the unadjusted resistance coefficients (fig. 13). The minimum flow on June 26 was reduced from 6,450 to 5,990 ft^3/s, and the maximum flow on June 29 was reduced from 9,340 to 8,470 ft^3/s. A 10-percent decrease in the resistance coefficients resulted in an increase of the minimum flow to 6,990 ft^3/s, and an increase of the maximum flow during the period to 10,400 ft^3/s.

Changes in the resistance coefficients did not affect the time of occurrence of the minimum flow on June 26, or of the maximum flow on June 29. However, changes in the resistance coefficients did affect the time of occurrence of the peak flow on June 27; the increased resistance coefficients delayed the time of peak flow occurrence by 2.5 h.

Finally, given the uncertainty about gage datums, the downstream boundary gage datum was adjusted to determine the sensitivity of model results to changes in the downstream datum. Because low flows are more sensitive than medium or high flows to the changes in water-surface slope that result from adjusting the downstream datum, boundary data from the low-flow period of August 13–15, 1991, were used for this sensitivity test. Flows simulated by using a gage datum adjusted by a positive 0.5 ft were lower than those simulated by using the unadjusted datum (fig. 14). Likewise, flows simulated by using the negatively adjusted datum were higher than those simulated by using the unadjusted datum. For some times, datum adjustment did not appear to affect the time of occurrence of peak

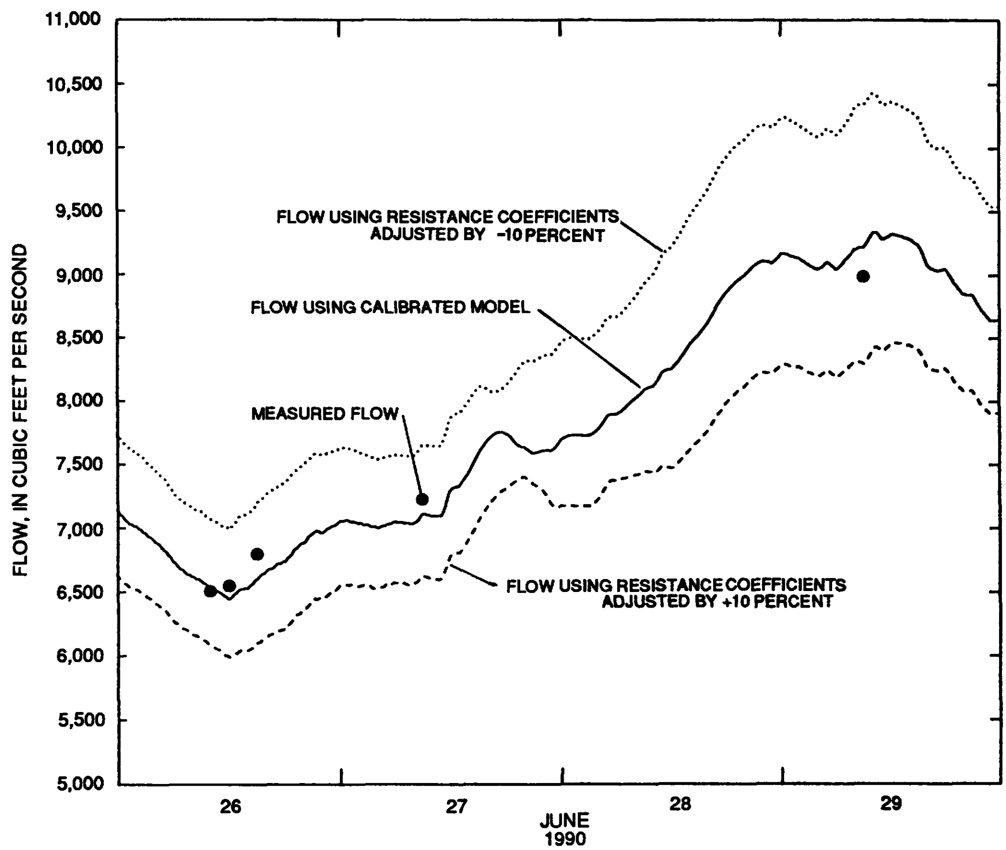

Figure 13. Simulated flows in the Roanoke River at site 3 for the period June 26–29, 1990, using calibrated model, resistance coefficients increased by 10 percent, and resistance coefficients reduced by 10 percent.

flows (August 13), but at other times, the time of peak flow occurrence was altered by datum adjustment (August 14).

In summary, model results are insensitive to changes in the momentum coefficient and the numerical scheme weighting factors, chi and theta, at the 15-min computational interval. Model results oscillate at a 30-min computational time step, but there is virtually no difference in results obtained by using either a 5- or a 15-min time step. The magnitude and timing of simulated flows are sensitive to changes in the resistance coefficients and to changes in the downstream boundary gage datum.

Model Application

The validated unsteady-flow model was used to compute daily mean flow at site 1 (tables 7–9; fig. 15), site 2 (tables 10–12; fig. 16), and site 3 (tables 13–15; fig. 17) for the water years 1988–90. During this period, measured flows at river mile 137.0 ranged from 912 ft^3/s on March 18, 1988, to 28,200 ft^3/s on June 20, 1989. Boundary data were recorded water levels at sites 1 and 3. For water years 1988–90, water levels ranged from 20.52 to 1.33 ft at site 1 and from 8.56 to −0.35 ft at site 3. Ungaged inflows from the intervening drainage area were estimated from records at the three index stations (sites 4–6). Total estimated ungaged inflow to the study reach varied from 10 to 2,500 ft^3/s during the 3-yr period, demonstrating the importance of including in the model ungaged inflow from the 257-mi^2 subbasin that drains directly to the study reach.

Flows were computed for all times when boundary water levels were available. Flows for days during which the mean water level at the upstream boundary was greater than 17 ft, which was about the upper limit used in model calibration, were omitted from tables 7–15 because of uncertainty about model accuracy for conditions of overbank flow. Days for which the mean water level at

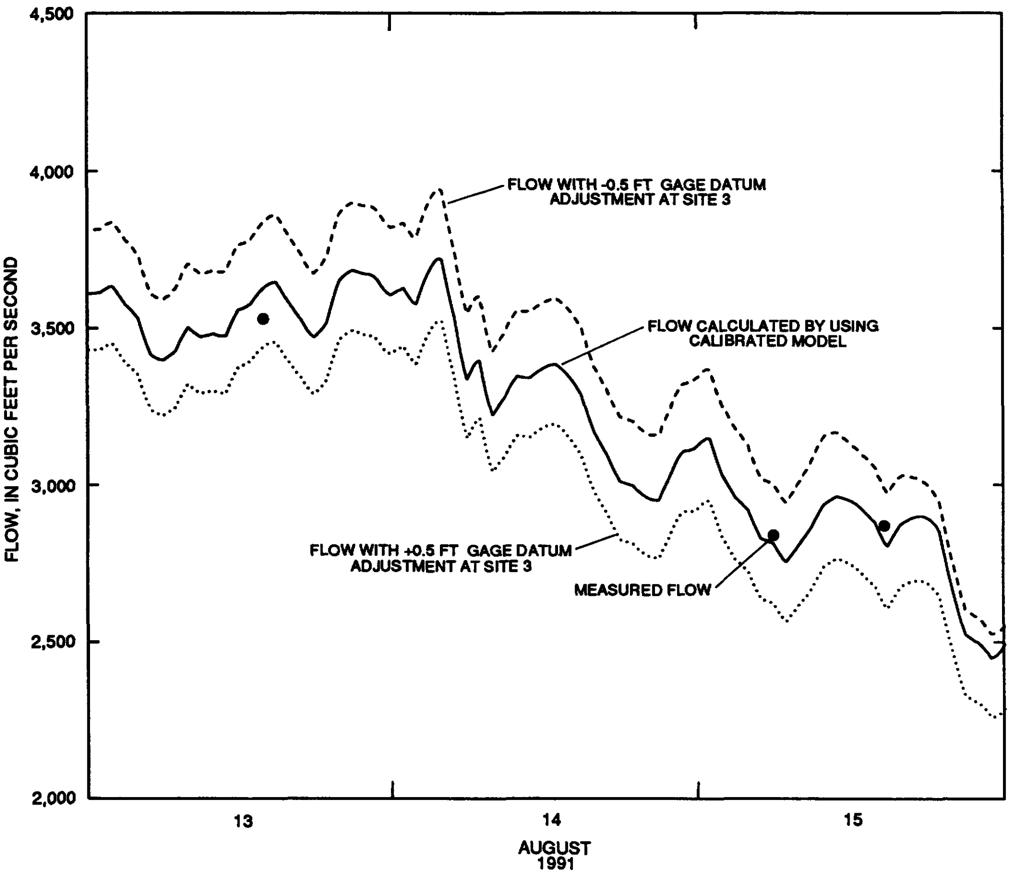

Figure 14. Simulated flows in the Roanoke River at site 3 for the period August 13–15, 1991, using calibrated model, gage datum increased by 0.5 ft, and gage datum reduced by 0.5 ft.

the downstream boundary was less than 1.5 ft, which was the lower limit in model calibration, are identified. These lower simulated flows are included in the tables, even though they are out of the range of conditions for which the model was calibrated, because there are no major changes in channel geometry at these low water levels. As will be shown, flows simulated for boundary water levels not much beyond the range of conditions for which the model was calibrated and validated might be reliable.

Monthly mean flows at river mile 67.0 were estimated for comparison with model-simulated monthly mean flows at the same site (table 16). Monthly mean flows at river mile 67.0 were estimated as the sum of monthly mean flow at river mile 137.0, where a streamflow gaging station is located, and estimated ungaged inflow from the 429-mi^2 subbasin between river miles 137.0 and 67.0, as determined from the monthly mean flows at the three index stations (table 4). Simulated monthly mean flows for all months having boundary water-level data, including months for which daily mean water levels at the upstream boundary exceeded 17 ft, were included in the comparison.

For the 26 months with estimated monthly mean flows of less than 14,000 ft^3/s, the mean absolute difference between the estimated and simulated monthly mean flows is 5 percent, and the mean difference is 2 percent, thus indicating that there is no strong bias toward over- or undersimulation in this flow range. However, simulated monthly mean flows were consistently less than estimated monthly mean flows for months when estimated mean flows were greater than 14,000 ft^3/s (fig. 18). Estimated and simulated monthly mean flows were also in good agreement for low-flow months when some daily mean water levels at the downstream boundary were less than 1.5 ft, which was the minimum used in model calibration. Although flow data available for model calibration and validation ranged from about 2,000 to 12,000 ft^3/s, these results indicate

Table 7. Simulated daily mean flow in the Roanoke River at site 1 for water year 1988

[Location of site 1 shown in figure 2; flow measured in cubic feet per second; —, boundary water levels not available to simulate flow, invalid calendar day, or insufficient values to determine mean]

Day	1987			1988								
	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.
1	8,510	3,080	7,760	([1])	4,810	3,920	[2]1,560	5,830	8,490	[2]2,320	3,670	[2]2,450
2	6,420	[2]2,120	10,700	11,800	5,870	2,920	[2]1,630	5,820	9,040	[2]2,210	2,660	[2]2,460
3	6,420	[2]1,870	10,300	([1])	7,070	[2]2,500	[2]1,780	5,790	—	[2]2,060	2,320	[2]2,180
4	5,940	[2]2,680	9,570	([1])	10,400	[2]1,900	[2]1,850	5,870	—	[2]2,020	2,270	[2]2,080
5	4,310	3,130	9,130	([1])	11,800	[2]1,700	[2]2,080	7,460	—	[2]2,030	2,270	[2]2,150
6	8,420	[2]2,860	9,010	([1])	10,400	[2]1,640	[2]2,190	8,560	—	[2]2,020	2,300	[2]2,170
7	10,800	[2]3,210	8,930	([1])	7,850	[2]1,560	[2]2,210	—	—	[2]1,990	[2]2,300	[2]2,110
8	11,600	[2]2,400	8,950	([1])	6,540	[2]1,560	[2]2,210	—	—	[2]1,990	[2]2,430	[2]2,040
9	10,500	[2]1,760	8,840	11,800	9,540	[2]1,600	[2]2,890	—	—	[2]2,020	2,860	[2]2,050
10	7,160	[2]1,470	8,700	10,700	8,540	[2]2,620	[2]3,070	—	—	[2]2,030	4,940	[2]2,130
11	4,820	[2]1,420	8,880	10,800	7,830	9,310	2,740	—	—	[2]2,030	4,640	[2]2,300
12	3,810	[2]6,400	9,640	11,300	7,550	7,240	2,600	7,120	—	[2]2,050	3,640	[2]2,840
13	[2]2,920	6,820	10,000	11,300	11,200	3,940	5,570	7,010	—	[2]2,080	3,220	[2]2,430
14	6,240	4,460	9,650	11,500	11,800	2,450	9,010	6,410	—	[2]2,100	2,840	4,130
15	7,420	2,570	9,840	11,400	10,400	[2]3,690	8,340	6,450	—	[2]2,050	[2]2,350	7,460
16	11,100	[2]1,910	10,300	9,910	10,000	6,350	7,270	6,630	—	[2]2,040	[2]3,010	6,060
17	8,690	[2]1,570	9,970	7,870	11,500	5,520	6,880	7,370	—	[2]4,010	[2]3,040	3,910
18	5,050	[2]1,500	10,500	5,840	10,800	3,670	6,420	7,790	—	6,190	[2]3,590	2,650
19	3,730	[2]2,150	11,900	5,370	8,040	[2]2,280	6,420	6,850	—	3,690	3,790	[2]2,320
20	3,530	5,450	12,300	4,730	4,760	[2]4,010	7,840	6,710	—	2,630	2,760	4,440
21	3,190	8,980	12,300	4,450	3,520	5,570	8,090	7,410	—	[2]2,310	2,470	6,070
22	[2]2,720	9,490	9,480	6,640	6,820	3,440	8,330	7,120	—	[2]2,270	[2]2,490	5,650
23	[2]3,290	5,390	9,190	10,400	9,100	[2]2,180	8,030	6,830	—	[2]2,310	[2]2,460	4,370
24	2,640	5,980	11,400	11,600	7,990	[2]1,670	7,690	6,760	—	[2]2,260	[2]2,350	3,620
25	[2]2,350	6,200	11,000	8,350	8,110	[2]1,530	6,960	7,350	—	[2]2,200	[2]2,250	2,970
26	[2]2,280	7,700	10,300	9,310	10,800	[2]1,520	6,570	7,010	—	[2]2,120	[2]2,200	[2]2,500
27	[2]3,420	11,500	11,000	12,200	7,550	[2]1,580	6,330	6,730	—	[2]2,160	2,610	[2]2,390
28	3,080	9,040	11,900	12,300	4,230	[2]1,600	6,240	6,640	[2]2,370	[2]2,230	2,710	[2]2,290
29	[2]4,430	6,180	12,200	10,700	3,290	[2]1,590	6,090	6,080	[2]2,250	[2]2,240	2,420	[2]2,190
30	6,280	6,250	([1])	9,460	—	[2]1,630	5,920	5,640	2,270	[2]2,280	2,330	[2]2,180
31	4,180	—	([1])	7,540	—	[2]1,620	—	5,490	—	4,300	2,260	—
Mean	5,650	4,520	—	—	8,210	3,040	5,160	—	—	2,460	2,820	3,150

[1] Daily mean water level at upstream boundary exceeded 17 ft; simulated flow not reliable.

[2] Flow considered reliable although daily mean water level at downstream boundary was less than 1.5 ft and was outside calibrated range.

that the unsteady-flow model may be used to reliably estimate flows in the study reach for all flows less than about 14,000 ft^3/s.

SUMMARY

The Roanoke River is one of North Carolina's most important surface-water resources. The Roanoke River drainage basin includes 9,666 mi^2 in southern Virginia and northern North Carolina. Because conditions in Albemarle Sound affect flows in the Roanoke River at least 59 mi upstream from the mouth of the river, standard streamflow-gaging techniques cannot be used to determine flows in the lower 59 mi of the river. Consequently, an investigation was initiated in 1988 to determine flows in a 30.4-mi reach of the Roanoke River downstream from State Highway 42–11 bridge near Oak City.

This report documents the development and application of a one-dimensional, unsteady-flow model for computing flows in the Roanoke River between State Highway 42–11 bridge near Oak City (river mile 67.0) and U.S. Highway 17–13 bridge at Williamston (river mile 36.6). The report presents model construction, calibration, validation, and results of sensitivity testing. The model is used to

Table 8. Simulated daily mean flow in the Roanoke River at site 1 for water year 1989

[Location of site 1 shown in figure 2; flow measured in cubic ft per second; —, boundary water levels not available to simulate flow, invalid calendar day, or insufficient values to determine mean]

Day	1988			1989								
	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.
1	[1]2,210	[1]1,990	5,980	2,950	5,510	([2])	([2])	8,270	([2])	([2])	5,760	3,830
2	[1]2,140	5,030	3,340	[1]1,850	5,870	([2])	([2])	10,200	([2])	([2])	8,410	3,330
3	[1]2,100	4,010	[1]2,160	[1]1,440	6,100	([2])	11,500	([2])	([2])	([2])	12,700	4,060
4	[1]2,130	3,260	[1]1,620	[1]2,760	3,920	([2])	10,400	([2])	11,700	([2])	([2])	3,890
5	[1]2,210	4,570	[1]1,730	[1]3,260	[1]2,490	([2])	9,650	([2])	9,320	([2])	([2])	3,150
6	[1]2,170	3,340	[1]3,730	[1]2,960	[1]1,810	([2])	9,870	([2])	7,740	([2])	([2])	5,650
7	[1]2,310	2,460	3,600	[1]2,330	[1]2,560	([2])	10,800	([2])	6,500	([2])	([2])	8,220
8	[1]3,150	[1]2,520	3,430	[1]2,780	3,820	([2])	11,600	([2])	7,040	([2])	([2])	7,210
9	[1]2,440	3,720	4,950	2,780	[1]3,340	([2])	12,200	([2])	9,400	([2])	11,400	5,910
10	[1]1,840	7,370	5,830	[1]1,990	8,260	([2])	([2])	([2])	10,200	([2])	8,390	6,780
11	[1]1,660	6,410	5,950	[1]2,390	7,950	([2])	([2])	([2])	10,200	([2])	7,660	7,130
12	[1]1,670	4,740	5,480	[1]3,250	4,140	([2])	([2])	([2])	10,000	([2])	9,390	5,580
13	[1]2,070	2,940	10,600	3,780	[1]2,400	([2])	([2])	([2])	11,200	([2])	8,490	4,580
14	[1]3,100	[1]2,390	11,400	8,290	[1]2,010	([2])	([2])	([2])	12,700	([2])	8,020	4,620
15	3,880	[1]3,010	9,890	7,060	[1]1,920	([2])	([2])	([2])	([2])	11,500	8,610	6,870
16	3,790	5,860	9,780	4,070	[1]1,840	([2])	([2])	([2])	([2])	9,040	5,650	5,350
17	3,450	5,620	10,200	4,070	[1]1,910	([2])	([2])	([2])	([2])	7,800	7,100	3,720
18	[1]2,370	7,160	10,400	7,530	[1]6,800	([2])	([2])	([2])	([2])	11,200	8,840	3,470
19	[1]1,910	8,940	9,180	7,080	9,640	([2])	([2])	([2])	([2])	([2])	8,730	10,000
20	[1]1,870	10,400	6,850	4,860	5,750	([2])	([2])	([2])	([2])	([2])	6,960	([2])
21	[1]3,060	7,260	4,560	2,730	3,840	([2])	11,800	([2])	([2])	([2])	5,510	([2])
22	3,810	4,710	2,590	[1]1,710	4,170	([2])	11,600	([2])	([2])	([2])	4,130	([2])
23	3,110	7,860	[1]1,660	[1]1,370	10,800	([2])	11,200	([2])	([2])	10,700	3,130	([2])
24	2,790	6,720	[1]1,370	[1]1,330	([2])	([2])	10,700	([2])	([2])	8,730	6,060	([2])
25	3,880	3,410	[1]1,330	[1]2,060	([2])	([2])	10,800	([2])	([2])	10,600	5,990	11,200
26	2,650	[1]1,900	[1]1,300	[1]3,850	11,300	([2])	9,810	([2])	9,500	11,900	3,800	8,640
27	[1]2,070	[1]1,390	[1]1,240	6,620	10,000	([2])	9,510	([2])	11,600	12,300	2,920	9,350
28	[1]1,920	[1]1,520	[1]1,360	3,830	10,200	([2])	9,290	([2])	([2])	12,000	2,590	13,100
29	[1]1,830	[1]4,330	[1]1,680	[1]2,300	—	([2])	7,810	([2])	([2])	10,500	3,750	([2])
30	[1]1,690	7,240	[1]5,710	[1]2,270	—	([2])	7,590	([2])	([2])	10,600	4,810	([2])
31	[1]1,700	—	5,450	[1]2,430	—	([2])	—	([2])	—	8,510	4,200	—
Mean	2,480	4,740	4,980	3,480	—	—	—	—	—	—	—	—

[1] Flow considered reliable although daily mean water level at downstream boundary was less than 1.5 ft and was outside calibrated range.

[2] Daily mean water level at upstream boundary exceeded 17 ft; simulated flow not reliable.

simulate daily mean flows at the study reach boundaries and at river mile 59.2 for the period October 1, 1988, through September 30, 1990.

The study area is in the Coastal Plain province of North Carolina and consists of the 257-mi^2 subbasin of the Roanoke River between river miles 67.0 and 36.6. Conoho Creek, which has a drainage area of 120 mi^2, is the largest tributary to the Roanoke River in the study area. The study reach is defined as the 30.4-mi reach of the Roanoke River between river miles 67.0 and 36.6.

Data collection for the investigation included (1) continuous measurements of water level, (2) measurements of discharge, and (3) measurements of channel geometry and flood-plain topography. Water-level recorders were located at river mile 67.0 (site 1), river mile 59.2 (site 2), and river mile 36.6 (site 3). Thirty-seven discharge measurements were made in the study reach between 1987 and 1991. Channel geometry was measured at more than 40 locations. Ungaged inflow from the 257-mi^2 subbasin that drains directly to the study reach was estimated from flow records at three nearby gaging stations.

The model used to compute flows in the study reach is capable of simulating flows in response to

Table 9. Simulated daily mean flow in the Roanoke River at site 1 for water year 1990

[Location of site 1 shown in figure 2; flow measured in cubic feet per second; —, boundary water levels not available to simulate flow, invalid calendar day, or insufficient values to determine mean]

Day	1989			1990								
	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.
1	([1])	6,240	9,800	—	—	([1])	9,540	8,210	([1])	4,770	3,750	5,290
2	([1])	6,930	6,360	—	—	([1])	9,140	7,370	([1])	3,040	3,660	3,400
3	([1])	9,540	3,770	—	—	([1])	11,200	7,230	([1])	2,410	3,100	2,610
4	([1])	9,740	4,770	—	—	([1])	([1])	8,620	([1])	[2]2,370	2,790	2,380
5	([1])	7,270	10,400	—	—	([1])	([1])	9,160	([1])	[2]2,350	3,410	[2]2,260
6	([1])	5,100	9,220	—	—	([1])	([1])	8,890	([1])	3,740	3,580	2,220
7	([1])	5,800	7,900	—	—	([1])	([1])	8,670	([1])	5,870	2,740	4,260
8	([1])	9,880	7,700	—	([1])	([1])	([1])	8,290	([1])	4,260	2,790	8,580
9	([1])	12,100	11,300	—	([1])	([1])	([1])	8,630	([1])	3,080	3,590	8,090
10	([1])	10,500	12,700	—	([1])	([1])	([1])	9,040	([1])	4,520	6,360	5,660
11	([1])	7,920	10,900	—	([1])	([1])	([1])	9,200	([1])	5,200	5,620	4,530
12	([1])	4,980	11,400	—	([1])	10,700	([1])	9,910	([1])	3,700	6,640	3,320
13	([1])	3,800	10,200	—	([1])	8,600	([1])	11,100	([1])	3,080	6,100	2,540
14	([1])	5,760	9,920	—	([1])	6,860	([1])	11,500	([1])	2,860	6,970	2,330
15	([1])	6,420	11,100	—	([1])	6,350	([1])	12,000	([1])	2,600	8,180	2,280
16	([1])	5,260	10,300	—	([1])	7,160	([1])	12,700	([1])	2,490	5,880	2,200
17	([1])	5,790	11,700	—	([1])	4,890	([1])	([1])	([1])	6,650	3,840	2,210
18	([1])	8,760	12,200	—	([1])	4,640	([1])	([1])	([1])	12,300	2,890	[2]2,410
19	([1])	10,300	12,700	—	([1])	7,330	([1])	([1])	([1])	12,900	2,760	2,280
20	([1])	11,200	([1])	—	([1])	13,300	([1])	([1])	([1])	([1])	2,400	2,250
21	([1])	9,750	([1])	—	([1])	([1])	([1])	11,700	([1])	([1])	[2]2,350	2,270
22	([1])	10,700	—	—	([1])	([1])	([1])	10,800	11,700	([1])	[2]2,200	2,200
23	([1])	12,900	—	—	([1])	([1])	([1])	10,400	10,600	12,000	3,010	[2]2,200
24	([1])	([1])	—	—	([1])	([1])	11,300	10,100	7,370	8,970	3,980	[2]2,440
25	([1])	([1])	—	—	([1])	([1])	10,400	9,860	4,870	5,780	3,730	[2]2,570
26	([1])	10,400	—	—	([1])	([1])	9,570	9,750	4,950	5,030	3,430	[2]2,270
27	([1])	6,990	—	—	([1])	11,500	9,100	10,800	7,410	7,290	2,930	[2]2,220
28	([1])	5,950	—	—	([1])	10,200	8,800	11,800	9,150	6,620	7,710	[2]2,180
29	([1])	6,550	—	—	—	10,100	8,600	([1])	8,310	4,880	11,400	[2]3,130
30	9,650	9,290	—	—	—	11,600	8,470	([1])	7,400	3,860	9,920	4,040
31	7,360	—	—	—	—	11,800	—	([1])	—	3,330	8,130	—
Mean	—	—	—	—	—	—	—	—	—	—	4,700	3,220

[1] Daily mean water level at upstream boundary exceeded 17 ft; simulated flow not reliable.

[2] Flow considered reliable although daily mean water level at downstream boundary was less than 1.5 ft and was outside calibrated range.

wind and flow in a network of channels. The model, which has been applied to a wide range of physical and hydrologic conditions, is based on the cross-sectionally averaged (or one-dimensional) nonlinear momentum and continuity equations for unsteady flow in channels.

The study reach was schematized by using 10 branches and 38 cross sections. The main stem of the river is represented by 9 branches and 32 cross sections, and Conoho Creek, the largest tributary to the Roanoke River in the study reach, is described by using 1 branch and 6 cross sections. Daily mean ungaged inflow determined from three nearby index stations was input to the model at river miles 59.2, 47.9, and 37.9.

The model was calibrated and validated for water levels ranging from 5.62 to 16.44 ft at river mile 67.0, and for flows from about 2,000 to 12,000 ft^3/s. For model calibration, the mean absolute difference between 22 measured and simulated flows was 3.4 percent. The mean absolute difference between nine measured and simulated flows obtained in the validation process was 3.3 percent.

The sensitivity of model results to small changes in computational time step, momentum coefficient, numerical scheme weighting factors,

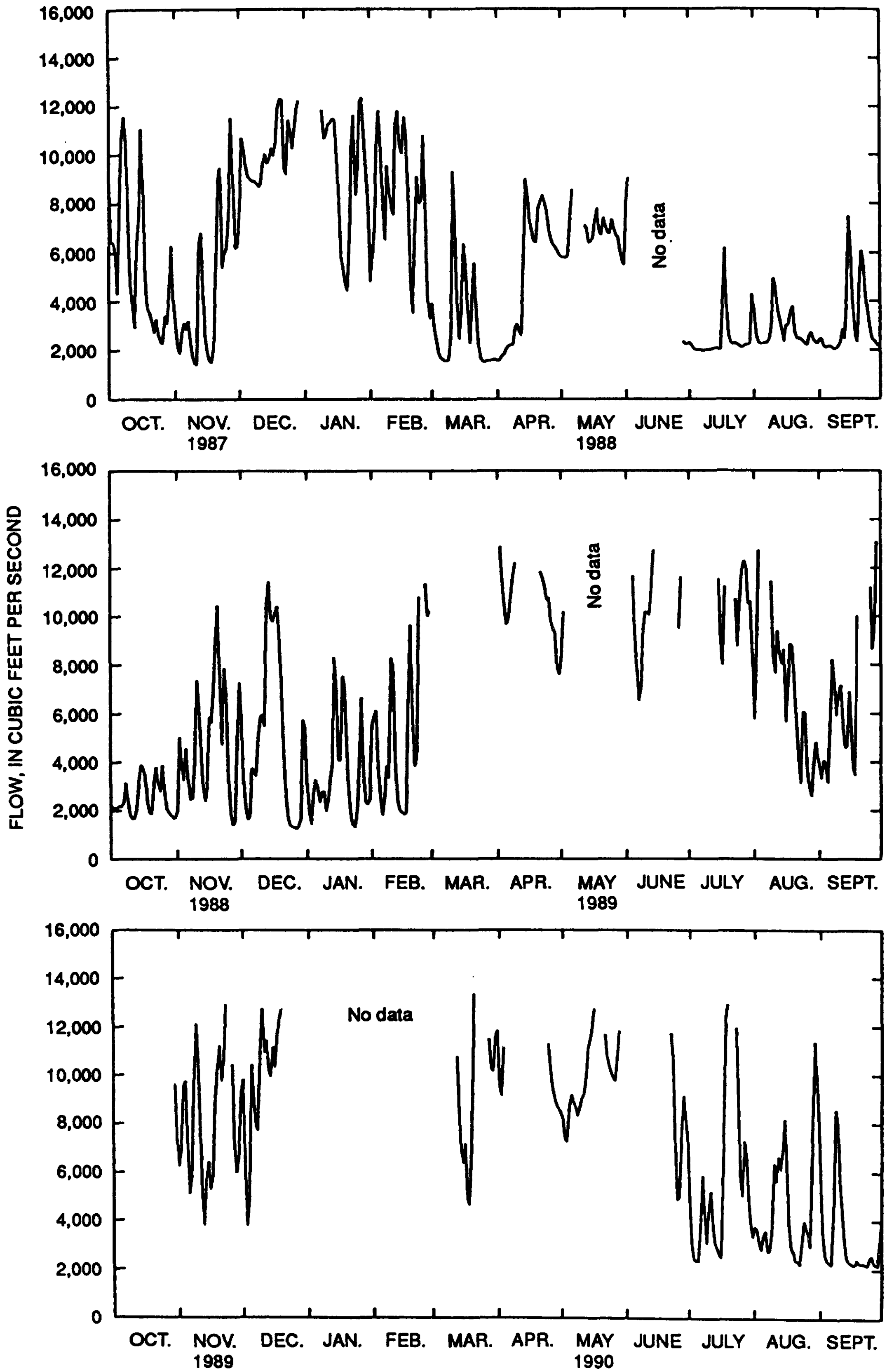

Figure 15. Simulated daily mean flow in the Roanoke River at site 1 for water years 1988–90.

Table 10. Simulated daily mean flow in the Roanoke River at site 2 for water year 1988

[Location of site 2 shown in figure 2; flow measured in cubic feet per second; —, boundary water levels not available to simulate flow, invalid calendar day, or insufficient values to determine mean]

Day	1987			1988								
	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.
1	8,720	3,300	7,390	([1])	5,180	3,950	[2]1,600	5,860	7,980	[2]2,370	3,880	[2]2,420
2	6,690	[2]2,290	10,500	11,900	5,600	3,060	[2]1,630	5,850	9,150	[2]2,270	2,810	[2]2,490
3	6,300	[2]1,880	10,400	([1])	7,050	[2]2,640	[2]1,780	5,810	—	[2]2,090	2,360	[2]2,240
4	6,250	[2]2,420	9,680	([1])	9,910	[2]2,020	[2]1,830	5,850	—	[2]2,030	2,290	[2]2,080
5	4,450	3,240	9,190	([1])	11,900	[2]1,750	[2]2,080	7,230	—	[2]2,050	2,280	[2]2,130
6	7,750	[2]2,800	9,040	([1])	10,800	[2]1,710	[2]2,220	8,530	—	[2]2,060	2,320	[2]2,180
7	10,600	[2]3,240	8,950	([1])	8,310	[2]1,600	[2]2,240	—	—	[2]2,000	[2]2,300	[2]2,160
8	11,400	[2]2,560	8,960	([1])	6,690	[2]1,550	[2]2,250	—	—	[2]2,000	[2]2,410	[2]2,060
9	10,800	[2]1,880	8,880	12,000	9,280	[2]1,640	[2]2,790	—	—	[2]2,020	2,720	[2]2,030
10	7,640	[2]1,520	8,710	10,900	8,820	[2]2,170	[2]3,070	—	—	[2]2,040	4,680	[2]2,170
11	5,140	[2]1,470	8,870	10,800	7,940	8,510	2,800	—	—	[2]2,040	4,660	[2]2,290
12	4,000	[2]5,260	9,560	11,300	7,680	7,770	2,580	7,160	—	[2]2,050	3,900	[2]2,800
13	[2]3,080	7,130	10,000	11,400	10,900	4,390	4,950	7,060	—	[2]2,080	3,230	[2]2,530
14	5,600	4,820	9,720	11,500	12,100	2,720	8,770	6,540	—	[2]2,130	2,960	3,590
15	7,190	2,870	9,800	11,500	10,600	[2]3,170	8,520	6,430	—	[2]2,050	[2]2,440	7,190
16	10,700	[2]2,020	10,300	10,200	10,300	6,260	7,400	6,630	—	[2]2,040	[2]2,800	6,340
17	9,230	[2]1,610	10,100	8,190	11,400	5,670	6,980	7,280	—	[2]3,340	[2]3,160	4,270
18	5,480	[2]1,520	10,300	6,110	11,200	4,030	6,510	7,820	—	6,300	[2]3,330	2,840
19	3,910	[2]1,910	11,800	5,570	8,600	[2]2,530	6,430	7,020	—	4,030	3,930	[2]2,350
20	3,550	4,970	12,300	4,970	5,270	[2]3,390	7,730	6,720	—	2,820	2,890	3,920
21	3,300	8,380	12,300	4,570	3,750	5,730	8,230	7,400	—	[2]2,380	2,540	5,880
22	[2]2,800	9,780	9,990	6,280	6,200	3,790	8,390	7,210	—	[2]2,280	[2]2,520	5,900
23	[2]3,200	5,770	9,130	10,100	9,120	[2]2,410	8,140	6,900	—	[2]2,340	[2]2,510	4,480
24	2,750	5,930	11,100	11,700	8,160	[2]1,770	7,820	6,780	—	[2]2,340	[2]2,370	3,760
25	[2]2,410	6,240	11,300	8,840	7,980	[2]1,580	7,120	7,310	—	[2]2,280	[2]2,270	3,110
26	[2]2,220	7,260	10,400	9,020	10,600	[2]1,530	6,660	7,090	—	[2]2,150	[2]2,210	[2]2,580
27	[2]3,320	11,200	10,700	11,900	8,150	[2]1,620	6,410	6,770	—	[2]2,170	2,500	[2]2,410
28	3,150	9,530	12,000	12,400	4,670	[2]1,650	6,290	6,670	[2]2,520	[2]2,250	2,750	[2]2,300
29	[2]3,850	6,500	12,200	11,100	3,380	[2]1,620	6,170	6,200	[2]2,320	[2]2,280	2,450	[2]2,200
30	6,430	6,210	([1])	9,670	—	[2]1,650	5,960	5,710	2,280	[2]2,260	2,350	[2]2,190
31	4,420	—	([1])	7,930	—	[2]1,660	—	5,500	—	3,930	2,300	—
Mean	5,690	4,520	—	—	8,330	3,080	5,180	—	—	2,470	2,840	3,160

[1] Daily mean water level at upstream boundary exceeded 17 ft; simulated flow not reliable.

[2] Flow considered reliable although daily mean water level at downstream boundary was less than 1.5 ft and was outside calibrated range.

resistance coefficients, and boundary values was evaluated. The model, which was calibrated at a time step of 15 min, was unstable at a computational time step of 30 min, but results were insensitive to changes in the momentum coefficient and the numerical scheme weighting factors. Results were somewhat sensitive to small changes in the resistance coefficients and boundary values.

The model was used to compute daily flows at river mile 67.0 (site 1), river mile 59.2 (site 2), and river mile 36.6 (site 3) for water years 1988–90. For flows less than 14,000 ft^3/s, simulated monthly mean flows at river mile 67.0 were within 5 percent of monthly mean flows observed at river mile 137.0, after adjustment for ungaged inflow between river miles 137.0 and 67.0. These results indicate that the model can be used to reliably compute flows in the study reach for all flows less than about 14,000 ft^3/s.

Table 11. Simulated daily mean flow in the Roanoke River at site 2 for water year 1989

[Location of site 2 shown in figure 2; flow measured in cubic feet per second; —, boundary water levels not available to simulate flow, invalid calendar day, or insufficient values to determine mean]

Day	1988			1989								
	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.
1	[1]2,210	[1]1,950	6,390	3,330	5,080	([2])	([2])	8,690	([2])	([2])	6,130	3,870
2	[1]2,150	4,570	3,760	[1]2,070	5,820	([2])	([2])	10,500	([2])	([2])	7,710	3,480
3	[1]2,100	4,340	[1]2,370	[1]1,510	6,160	([2])	11,800	([2])	([2])	([2])	12,400	3,810
4	[1]2,160	3,390	[1]1,700	[1]2,420	4,280	([2])	10,700	([2])	12,000	([2])	([2])	4,080
5	[1]2,210	4,420	[1]1,680	[1]3,350	[1]2,770	([2])	9,870	([2])	9,630	([2])	([2])	3,210
6	[1]2,190	3,590	[1]3,440	[1]3,030	[1]1,950	([2])	10,200	([2])	7,990	([2])	([2])	5,130
7	[1]2,220	2,630	3,660	[1]2,430	[1]2,290	([2])	11,300	([2])	6,700	([2])	([2])	8,040
8	[1]3,110	[1]2,510	3,430	[1]2,650	3,820	([2])	12,100	([2])	6,900	([2])	([2])	7,350
9	[1]2,590	3,360	4,740	2,900	[1]3,480	([2])	12,600	([2])	9,250	([2])	11,900	6,060
10	[1]1,910	7,050	5,600	[1]2,130	7,260	([2])	([2])	([2])	10,200	([2])	8,720	6,490
11	[1]1,670	6,590	6,070	[1]2,270	8,480	([2])	([2])	([2])	10,200	([2])	7,680	7,320
12	[1]1,680	5,070	5,380	[1]3,200	4,650	([2])	([2])	([2])	10,100	([2])	9,310	5,720
13	[1]2,010	3,210	9,730	3,690	[1]2,710	([2])	([2])	([2])	11,000	([2])	8,720	4,850
14	[1]2,910	[1]2,490	11,700	7,670	[1]2,080	([2])	([2])	([2])	12,700	([2])	7,890	4,390
15	3,820	[1]2,780	10,000	7,540	[1]1,960	([2])	([2])	([2])	([2])	11,700	8,800	6,650
16	3,730	5,520	9,670	4,540	[1]1,840	([2])	([2])	([2])	([2])	9,360	6,010	5,710
17	3,610	5,660	10,300	3,800	[1]1,940	([2])	([2])	([2])	([2])	8,130	6,800	3,960
18	[1]2,550	6,850	10,300	7,280	[1]5,620	([2])	([2])	([2])	([2])	10,800	9,040	3,440
19	[1]1,960	8,720	9,460	7,270	9,860	([2])	([2])	([2])	([2])	([2])	9,200	8,740
20	[1]1,850	10,400	7,070	5,280	6,240	([2])	([2])	([2])	([2])	([2])	7,580	([2])
21	[1]2,830	7,710	5,010	3,100	4,380	([2])	12,000	([2])	([2])	([2])	5,950	([2])
22	3,750	5,000	2,930	[1]1,910	4,650	([2])	11,700	([2])	([2])	([2])	4,520	([2])
23	3,250	7,240	[1]1,840	[1]1,450	10,300	([2])	11,400	([2])	([2])	11,100	3,370	([2])
24	2,750	7,220	[1]1,420	[1]1,360	([2])	([2])	10,800	([2])	([2])	8,940	5,440	([2])
25	3,820	3,880	[1]1,340	[1]1,880	([2])	([2])	10,800	([2])	([2])	10,300	6,330	11,600
26	2,850	[1]2,140	[1]1,340	[1]3,360	12,000	([2])	10,100	([2])	9,970	11,800	4,140	8,990
27	[1]2,150	[1]1,460	[1]1,260	6,490	10,500	([2])	9,510	([2])	11,400	12,300	3,060	9,000
28	[1]1,950	[1]1,460	[1]1,340	4,280	10,700	([2])	9,570	([2])	([2])	12,100	2,660	12,800
29	[1]1,860	[1]3,680	[1]1,580	[1]2,550	—	([2])	8,080	([2])	([2])	10,700	3,490	([2])
30	[1]1,740	7,000	[1]4,870	[1]2,250	—	([2])	7,800	([2])	([2])	10,600	4,730	([2])
31	[1]1,700	—	5,830	[1]2,350	—	([2])	—	([2])	—	8,850	4,350	—
Mean	2,490	4,730	5,010	3,530	—	—	—	—	—	—	—	—

[1] Flow considered reliable although daily mean water level at downstream boundary was less than 1.5 ft and was outside calibrated range.

[2] Daily mean water level at upstream boundary exceeded 17 ft; simulated flow not reliable.

Table 12. Simulated daily mean flow in the Roanoke River at site 2 for water year 1990

[Location of site 2 shown in figure 2; flow measured in cubic feet per second; —, boundary water levels not available to simulate flow, invalid calendar day, or insufficient values to determine mean]

Day	1989			1990								
	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.
1	([1])	6,380	10,000	—	—	([1])	10,200	8,320	([1])	5,190	3,680	5,740
2	([1])	6,830	6,890	—	—	([1])	9,440	7,530	([1])	3,320	3,740	3,700
3	([1])	9,310	4,210	—	—	([1])	11,300	7,210	([1])	2,510	3,190	2,730
4	([1])	9,870	4,220	—	—	([1])	([1])	8,500	([1])	[2]2,390	2,830	2,440
5	([1])	7,740	10,000	—	—	([1])	([1])	9,180	([1])	[2]2,340	3,240	[2]2,310
6	([1])	5,350	9,470	—	—	([1])	([1])	8,970	([1])	3,430	3,680	2,220
7	([1])	5,650	8,060	—	—	([1])	([1])	8,740	([1])	5,650	2,850	3,720
8	([1])	9,350	7,660	—	([1])	([1])	([1])	8,370	([1])	4,630	2,780	8,050
9	([1])	11,900	11,000	—	([1])	([1])	([1])	8,600	([1])	3,210	3,390	8,370
10	([1])	10,900	13,100	—	([1])	([1])	([1])	9,030	([1])	4,210	6,180	5,960
11	([1])	8,410	11,600	—	([1])	([1])	([1])	9,240	([1])	5,250	5,800	4,710
12	([1])	5,420	11,700	—	([1])	11,100	([1])	9,820	([1])	3,970	6,560	3,560
13	([1])	3,970	10,900	—	([1])	8,930	([1])	11,100	([1])	3,120	6,220	2,650
14	([1])	5,490	10,300	—	([1])	7,150	([1])	11,500	([1])	2,950	6,770	2,370
15	([1])	6,440	11,500	—	([1])	6,380	([1])	12,000	([1])	2,670	8,110	2,290
16	([1])	5,520	10,800	—	([1])	7,280	([1])	12,700	([1])	2,550	6,330	2,220
17	([1])	5,720	11,800	—	([1])	5,220	([1])	([1])	([1])	5,590	4,170	2,210
18	([1])	8,390	12,400	—	([1])	4,780	([1])	([1])	([1])	11,900	3,040	[2]2,410
19	([1])	10,200	12,800	—	([1])	6,850	([1])	([1])	([1])	12,900	2,840	2,300
20	([1])	11,200	([1])	—	([1])	13,000	([1])	([1])	([1])	([1])	2,450	2,240
21	([1])	10,000	([1])	—	([1])	([1])	([1])	11,800	([1])	([1])	[2]2,400	2,290
22	([1])	10,400	—	—	([1])	([1])	([1])	10,900	11,800	([1])	[2]2,230	2,210
23	([1])	12,900	—	—	([1])	([1])	([1])	10,600	10,800	12,300	2,880	[2]2,220
24	([1])	([1])	—	—	([1])	([1])	11,500	10,300	7,810	9,360	4,100	[2]2,390
25	([1])	([1])	—	—	([1])	([1])	10,500	9,980	5,190	6,190	3,900	[2]2,590
26	([1])	11,000	—	—	([1])	([1])	9,720	9,810	4,840	5,060	3,630	[2]2,320
27	([1])	7,510	—	—	([1])	11,600	9,210	10,700	7,120	6,940	3,080	[2]2,230
28	([1])	6,120	—	—	([1])	10,300	8,880	11,700	8,970	6,900	6,600	[2]2,200
29	([1])	6,520	—	—	—	10,200	8,660	([1])	8,560	5,090	11,400	[2]2,870
30	9,950	8,920	—	—	—	11,600	8,510	([1])	7,530	4,080	10,200	3,970
31	7,700	—	—	—	—	12,200	—	([1])	—	3,370	8,370	—
Mean	—	—	—	—	—	—	—	—	—	—	4,730	3,250

[1] Daily mean water level at upstream boundary exceeded 17 ft; simulated flow not reliable.

[2] Flow considered reliable although daily mean water level at downstream boundary was less than 1.5 ft and was outside calibrated range.

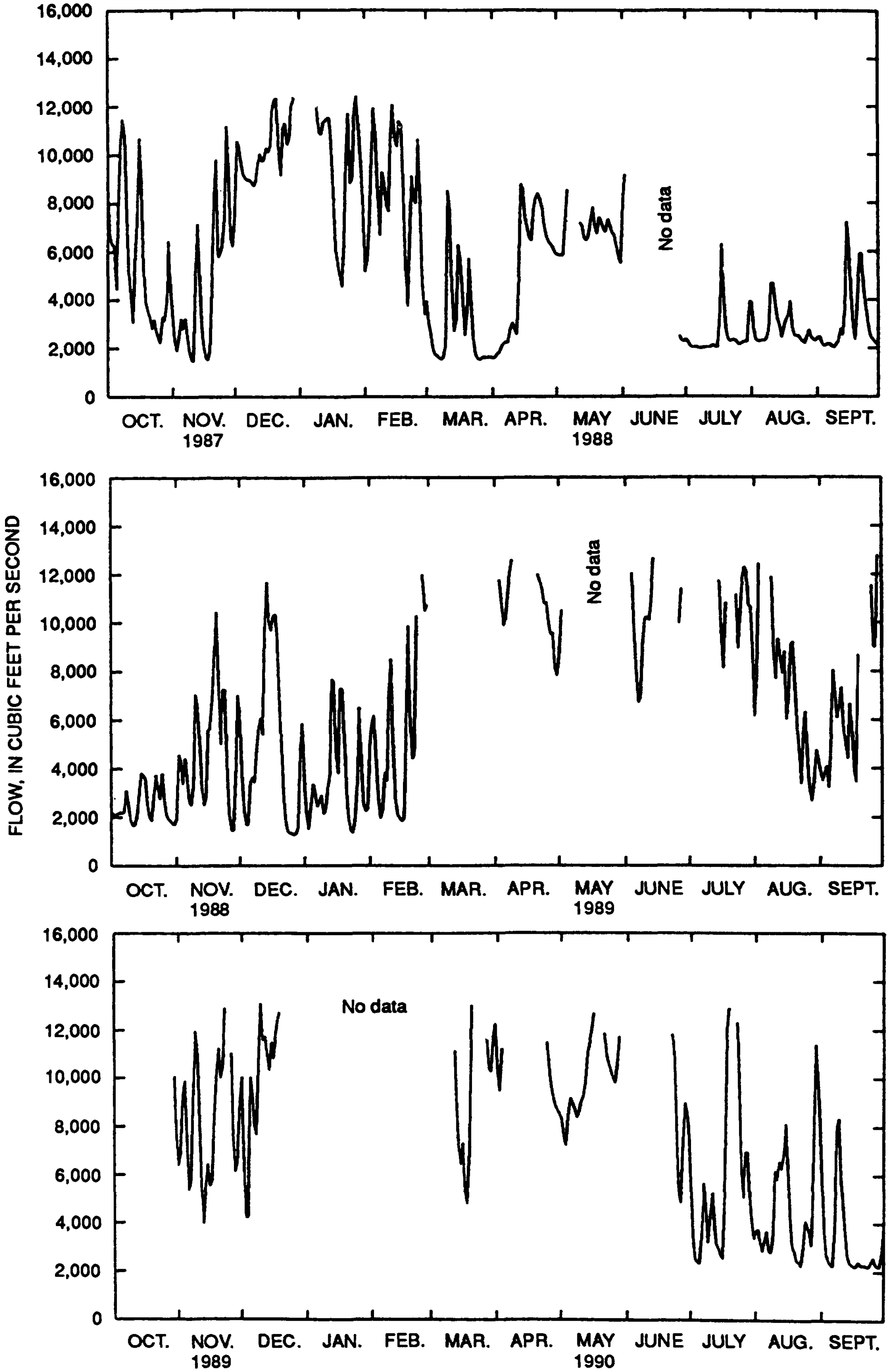

Figure 16. Simulated daily mean flow in the Roanoke River at site 2 for water years 1988–90.

Table 13. Simulated daily mean flow in the Roanoke River at site 3 for water year 1988

[Location of site 3 shown in figure 2; flow measured in cubic feet per second; —, boundary water levels not available to simulate flow, invalid calendar day, or insufficient values to determine mean]

Day	1987			1988								
	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.
1	10,300	3,760	6,910	(1)	7,300	3,930	[2]1,740	5,900	6,820	[2]2,560	4,180	[2]2,440
2	8,750	[2]2,570	9,350	12,100	5,950	3,390	[2]1,640	5,980	8,660	[2]2,310	3,080	[2]2,520
3	7,660	[2]1,890	9,900	(1)	6,740	[2]2,900	[2]1,780	5,900	—	[2]2,090	2,400	[2]2,310
4	7,620	[2]2,100	10,000	(1)	8,660	[2]2,230	[2]1,770	5,810	—	[2]2,040	2,340	[2]2,050
5	5,550	3,270	9,670	(1)	11,100	[2]1,860	[2]2,170	6,580	—	[2]2,170	2,270	[2]2,110
6	6,330	[2]2,940	9,240	(1)	11,100	[2]1,940	[2]2,230	8,090	—	[2]2,180	2,470	[2]2,220
7	9,370	[2]3,160	8,990	(1)	10,000	[2]1,600	[2]2,370	—	—	[2]1,960	[2]2,280	[2]2,330
8	10,500	[2]2,790	8,990	(1)	8,190	[2]1,520	[2]2,440	—	—	[2]2,060	[2]2,420	[2]2,110
9	10,800	[2]2,070	9,010	12,800	8,500	[2]1,700	[2]2,650	—	—	[2]1,990	2,480	[2]1,870
10	9,330	[2]1,550	8,780	12,200	9,290	[2]1,780	[2]2,970	—	—	[2]2,070	4,150	[2]2,350
11	6,830	[2]1,790	8,870	11,800	8,630	6,540	2,790	—	—	[2]2,080	4,780	[2]2,350
12	4,880	[2]3,440	9,190	11,900	8,270	8,390	2,490	7,210	—	[2]1,960	4,360	[2]2,690
13	[2]3,550	7,190	9,720	11,800	9,940	5,710	4,020	7,270	—	[2]2,170	3,300	[2]2,660
14	4,440	5,570	9,830	11,800	11,500	3,470	7,860	6,910	—	[2]2,190	3,130	2,820
15	6,780	3,490	9,630	11,900	11,000	[2]2,760	8,480	6,500	—	[2]2,050	[2]2,660	6,350
16	9,130	[2]2,210	10,200	11,300	10,900	5,690	7,870	6,690	—	[2]2,070	[2]2,480	6,910
17	9,680	[2]1,630	10,500	9,920	10,900	5,910	7,290	6,890	—	[2]2,500	[2]3,350	5,090
18	7,110	[2]1,560	10,100	8,180	11,400	4,640	6,920	7,590	—	5,970	[2]2,950	3,210
19	4,690	[2]1,760	10,900	7,160	10,300	[2]3,090	6,150	7,550	—	4,760	4,040	[2]2,440
20	3,640	4,100	11,400	6,020	7,750	[2]2,530	7,430	6,830	—	3,230	3,090	3,080
21	3,470	7,130	11,700	5,130	5,430	5,610	8,320	7,190	—	[2]2,540	2,690	5,490
22	[2]3,060	9,390	11,200	5,740	5,400	4,560	8,330	7,480	—	[2]2,290	[2]2,710	6,230
23	[2]3,000	7,270	10,000	8,750	8,320	[2]2,860	8,510	7,200	—	[2]2,420	[2]2,580	4,760
24	2,940	6,060	10,300	10,600	8,500	[2]1,980	8,220	6,930	—	[2]2,590	[2]2,370	3,970
25	[2]2,520	6,200	11,200	9,920	8,180	[2]1,700	7,750	7,050	—	[2]2,460	[2]2,310	3,410
26	[2]2,260	6,540	10,800	9,210	9,560	[2]1,570	7,090	7,370	—	[2]2,160	[2]2,210	[2]2,770
27	[2]3,040	9,520	10,400	10,600	9,380	[2]1,780	6,810	6,990	—	[2]2,200	2,330	[2]2,440
28	3,290	9,890	11,400	11,600	6,570	[2]1,790	6,570	6,810	[2]2,960	[2]2,350	2,780	[2]2,240
29	[2]3,200	7,860	11,900	11,500	4,120	[2]1,650	6,510	6,610	[2]2,390	[2]2,380	2,480	[2]2,240
30	6,140	6,570	(1)	10,600	—	[2]1,750	6,020	5,870	2,350	[2]2,270	2,450	[2]2,280
31	5,020	—	(1)	9,510	—	[2]1,710	—	5,580	—	3,260	2,440	—
Mean	5,960	4,510	—	—	8,720	3,180	5,240	—	—	2,490	2,890	3,190

[1] Daily mean water level at upstream boundary exceeded 17 ft; simulated flow not reliable.

[2] Flow considered reliable although daily mean water level at downstream boundary was less than 1.5 ft and was outside calibrated range.

Table 14. Simulated daily mean flow in the Roanoke River at site 3 for water year 1989

[Location of site 3 shown in figure 2; flow measured in cubic feet per second; —, boundary water levels not available to simulate flow, invalid calendar day, or insufficient values to determine mean]

Day	1988			1989								
	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.
1	[1]2,170	[1]1,920	7,090	4,120	4,120	([2])	([2])	9,550	([2])	([2])	8,290	4,010
2	[1]2,170	3,810	4,810	[1]2,530	5,710	([2])	([2])	10,900	([2])	([2])	7,710	3,670
3	[1]2,140	4,890	[1]2,750	[1]1,590	6,130	([2])	13,200	([2])	([2])	([2])	10,700	3,510
4	[1]2,310	3,720	[1]1,870	[1]2,110	5,070	([2])	12,400	([2])	13,200	([2])	([2])	4,320
5	[1]2,180	4,070	[1]1,770	[1]3,400	[1]3,340	([2])	11,600	([2])	11,200	([2])	([2])	3,430
6	[1]2,180	4,070	[1]2,820	[1]3,090	[1]2,190	([2])	12,200	([2])	10,100	([2])	([2])	4,290
7	[1]2,270	2,960	3,700	[1]2,620	[1]1,970	([2])	12,600	([2])	8,920	([2])	([2])	7,280
8	[1]3,030	[1]2,580	3,500	[1]2,450	3,850	([2])	13,200	([2])	8,240	([2])	([2])	7,520
9	[1]2,690	2,960	4,320	3,060	[1]3,840	([2])	13,500	([2])	8,990	([2])	12,700	6,590
10	[1]2,000	6,050	5,220	[1]2,500	5,360	([2])	([2])	([2])	9,940	([2])	10,500	6,090
11	[1]1,580	6,840	6,130	[1]2,160	8,750	([2])	([2])	([2])	10,400	([2])	9,280	7,300
12	[1]1,800	5,900	5,520	[1]3,110	6,220	([2])	([2])	([2])	10,400	([2])	9,610	6,330
13	[1]2,070	3,780	7,750	3,670	[1]3,530	([2])	([2])	([2])	10,400	([2])	9,550	5,350
14	[1]2,630	[1]2,710	10,700	6,230	[1]2,230	([2])	([2])	([2])	11,800	([2])	8,550	4,150
15	3,570	[1]2,510	10,300	8,120	[1]2,090	([2])	([2])	([2])	([2])	12,700	9,020	5,990
16	3,690	4,730	9,690	6,000	[1]1,790	([2])	([2])	([2])	([2])	11,000	7,750	6,320
17	3,840	5,660	10,200	3,900	[1]2,100	([2])	([2])	([2])	([2])	9,860	6,620	4,630
18	[1]2,810	6,240	10,100	6,380	[1]3,730	([2])	([2])	([2])	([2])	10,400	8,930	3,460
19	[1]2,090	7,900	10,000	7,430	9,190	([2])	([2])	([2])	([2])	([2])	10,000	6,390
20	[1]1,860	9,530	8,380	6,300	7,670	([2])	([2])	([2])	([2])	([2])	9,530	([2])
21	[1]2,470	8,970	6,580	3,920	5,920	([2])	13,000	([2])	([2])	([2])	7,670	([2])
22	3,660	6,440	3,950	[1]2,340	6,070	([2])	12,700	([2])	([2])	([2])	5,870	([2])
23	3,420	6,180	[1]2,200	[1]1,680	9,320	([2])	12,300	([2])	([2])	12,300	4,120	([2])
24	2,750	7,900	[1]1,510	[1]1,410	([2])	([2])	11,800	([2])	([2])	10,600	4,390	([2])
25	3,650	5,240	[1]1,370	[1]1,470	([2])	([2])	11,500	([2])	([2])	10,800	6,700	12,100
26	3,200	[1]2,590	[1]1,430	[1]2,800	12,600	([2])	11,100	([2])	12,000	11,600	5,090	10,300
27	[1]2,250	[1]1,550	[1]1,270	5,810	11,800	([2])	10,400	([2])	12,200	12,200	3,360	9,750
28	[1]1,970	[1]1,480	[1]1,330	5,260	11,700	([2])	10,500	([2])	([2])	12,300	2,830	11,600
29	[1]2,000	[1]2,790	[1]1,530	[1]3,040	—	([2])	9,640	([2])	([2])	11,600	3,120	([2])
30	[1]1,830	6,200	[1]3,460	[1]2,330	—	([2])	9,120	([2])	([2])	11,100	4,500	([2])
31	[1]1,840	—	6,250	[1]2,330	—	([2])	—	([2])	—	10,300	4,650	—
Mean	2,520	4,740	5,080	3,650	—	—	—	—	—	—	—	—

[1] Flow considered reliable although daily mean water level at downstream boundary was less than 1.5 ft and was outside calibrated range.

[2] Daily mean water level at upstream boundary exceeded 17 ft; simulated flow not reliable.

Table 15. Simulated daily mean flow in the Roanoke River at site 3 for water year 1990

[Location of site 3 shown in figure 2; flow measured in cubic feet per second; —, boundary water levels not available to simulate flow, invalid calendar day, or insufficient values to determine mean]

Day	1989			1990								
	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.
1	([1])	8,760	9,580	—	—	([1])	12,200	9,040	([1])	6,650	3,620	7,310
2	([1])	8,250	8,700	—	—	([1])	11,200	8,470	([1])	4,270	3,850	4,780
3	([1])	8,920	6,260	—	—	([1])	11,700	7,790	([1])	2,780	3,330	2,960
4	([1])	9,960	4,140	—	—	([1])	([1])	7,910	([1])	[2]2,430	2,960	2,670
5	([1])	9,320	8,210	—	—	([1])	([1])	8,900	([1])	[2]2,350	3,000	[2]2,430
6	([1])	7,310	9,230	—	—	([1])	([1])	9,030	([1])	2,970	3,740	2,160
7	([1])	6,350	8,680	—	—	([1])	([1])	9,120	([1])	5,090	3,070	2,950
8	([1])	7,800	7,770	—	([1])	([1])	([1])	8,840	([1])	5,370	2,750	6,730
9	([1])	10,400	9,910	—	([1])	([1])	([1])	8,570	([1])	3,570	3,200	8,450
10	([1])	10,800	12,500	—	([1])	([1])	([1])	8,830	([1])	3,710	5,730	6,910
11	([1])	9,870	12,100	—	([1])	([1])	([1])	9,300	([1])	5,230	6,290	5,290
12	([1])	7,630	11,900	—	([1])	12,700	([1])	9,520	([1])	4,430	6,340	4,030
13	([1])	5,470	12,200	—	([1])	11,000	([1])	10,300	([1])	3,200	6,500	2,830
14	([1])	5,190	11,700	—	([1])	9,700	([1])	10,900	([1])	3,150	6,460	2,460
15	([1])	6,180	12,000	—	([1])	8,550	([1])	11,400	([1])	2,830	7,640	2,300
16	([1])	6,360	12,200	—	([1])	8,650	([1])	12,000	([1])	2,720	7,290	2,300
17	([1])	5,890	12,000	—	([1])	7,230	([1])	([1])	([1])	4,010	5,090	2,250
18	([1])	7,360	12,600	—	([1])	5,980	([1])	([1])	([1])	9,990	3,400	[2]2,430
19	([1])	9,260	12,700	—	([1])	6,430	([1])	([1])	([1])	11,500	2,960	2,290
20	([1])	10,500	([1])	—	([1])	11,000	([1])	([1])	([1])	([1])	2,520	2,160
21	([1])	10,500	([1])	—	([1])	([1])	([1])	12,300	([1])	([1])	[2]2,560	2,380
22	([1])	10,000	—	—	([1])	([1])	([1])	11,400	12,800	([1])	[2]2,240	2,240
23	([1])	11,900	—	—	([1])	([1])	([1])	11,500	12,100	12,500	2,730	[2]2,380
24	([1])	([1])	—	—	([1])	([1])	12,700	11,200	10,100	10,800	4,420	[2]2,350
25	([1])	([1])	—	—	([1])	([1])	12,000	10,800	7,950	8,440	4,310	[2]2,520
26	([1])	12,300	—	—	([1])	([1])	11,300	10,500	6,680	6,780	4,060	[2]2,410
27	([1])	9,890	—	—	([1])	12,400	10,700	10,500	7,230	6,640	3,480	[2]2,270
28	([1])	8,200	—	—	([1])	11,600	10,100	11,200	8,340	7,300	4,780	[2]2,260
29	([1])	7,620	—	—	—	11,100	9,610	([1])	9,100	6,090	10,300	[2]2,480
30	11,600	8,180	—	—	—	11,900	9,020	([1])	8,260	4,700	10,100	3,800
31	10,100	—	—	—	—	12,900	—	([1])	—	3,450	9,280	—
Mean	—	—	—	—	—	—	—	—	—	—	4,770	3,360

[1] Daily mean water level at upstream boundary exceeded 17 ft; simulated flow not reliable.

[2] Flow considered reliable although daily mean water level at downstream boundary was less than 1.5 ft and was outside calibrated range.

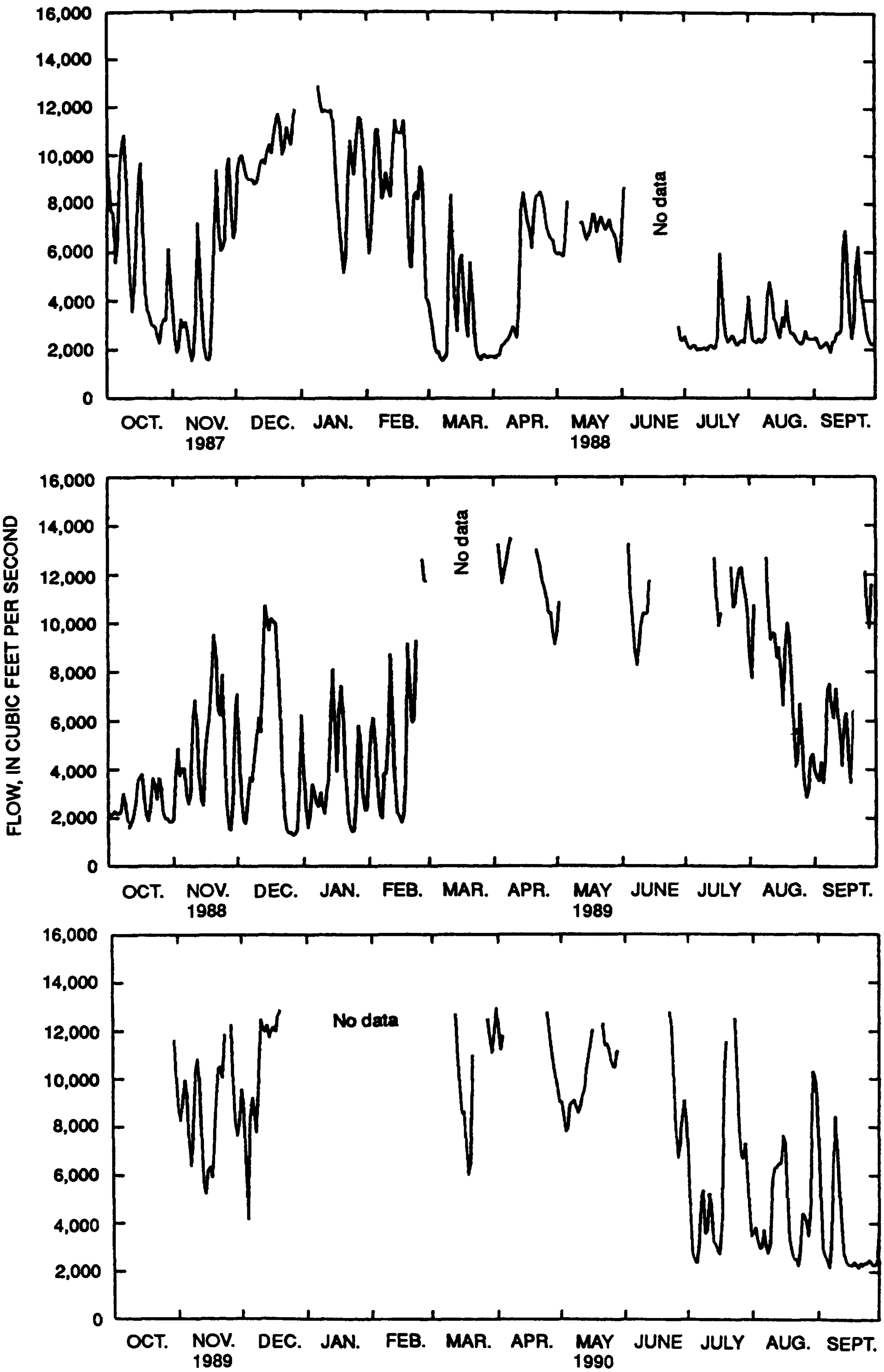

Figure 17. Simulated daily mean flow in the Roanoke River at site 3 for water years 1988–90.

Table 16. Total estimated monthly mean flow and simulated monthly mean flow in the Roanoke River at river mile 67.0 (site 1), 1987–90

[ft³/s, cubic feet per second; —, not applicable]

Year	Month	Monthly mean flow, in ft³/s				Difference, in percent, $\frac{(3)-(4)}{(3)} \times 100$
		Observed flow at river mile 137.0 (1)	Estimated ungaged inflow between river miles 137.0 and 67.0 (2)	Total estimated flow at river mile 67.0, (1)+(2) (3)	Simulated flow at river mile 67.0 (4)	
1987	Oct.	5,071	39	5,110	5,650	−11
	Nov.	4,460	60	4,520	4,520	0
	Dec.	10,380	194	10,600	[2]10,300	3
1988	Jan.	9,227	492	9,720	[2]10,400	−7
	Feb.	7,162	593	7,760	8,210	−6
	Mar.	2,470	163	2,630	3,040	−16
	Apr.	4,956	257	5,210	5,160	+1
	May	6,902	177	7,080	([1])	—
	June	4,327	290	4,620	([1])	—
	July	2,617	112	2,730	2,460	+10
	Aug.	2,891	53	2,940	2,820	+4
	Sept.	3,220	59	3,280	3,150	+4
	Oct.	2,475	47	2,520	2,480	+2
	Nov.	5,083	153	5,240	4,740	+10
	Dec.	4,812	83	4,900	4,980	−2
1989	Jan.	3,540	203	3,740	3,480	+7
	Feb.	5,703	981	6,680	[2]5,930	+11
	Mar.	15,860	2,186	18,000	[2]14,800	+18
	Apr.	10,430	1,332	11,800	[2]11,900	−1
	May	18,780	1,076	19,900	[2]15,600	+22
	June	11,710	515	12,200	[2]12,000	+2
	July	12,110	207	12,300	[2]12,400	−1
	Aug.	7,213	420	7,630	[2]7,780	−2
	Sept.	9,325	80	9,400	[2]8,240	+12
	Oct.	16,260	436	16,700	[2]15,100	+10
	Nov.	7,883	502	8,390	[2]8,420	0
	Dec.	9,540	1,021	10,600	([1])	—
1990	Jan.	15,180	716	15,900	([1])	—
	Feb.	16,970	1,107	18,100	([1])	—
	Mar.	11,530	618	12,100	[2]12,300	−2
	Apr.	14,280	845	15,100	[2]13,200	+13
	May	11,910	395	12,300	[2]10,700	+13
	June	14,020	206	14,200	[2]13,000	+8
	July	6,115	90	6,200	[2]6,000	+3
	Aug.	4,573	283	4,860	4,700	+3
	Sept.	3,111	51	3,160	3,220	−2

[1] Complete month of simulations not available because of missing boundary data.

[2] Month included days with daily mean water levels greater than 17 ft at upstream boundary; simulations for those days are not reliable.

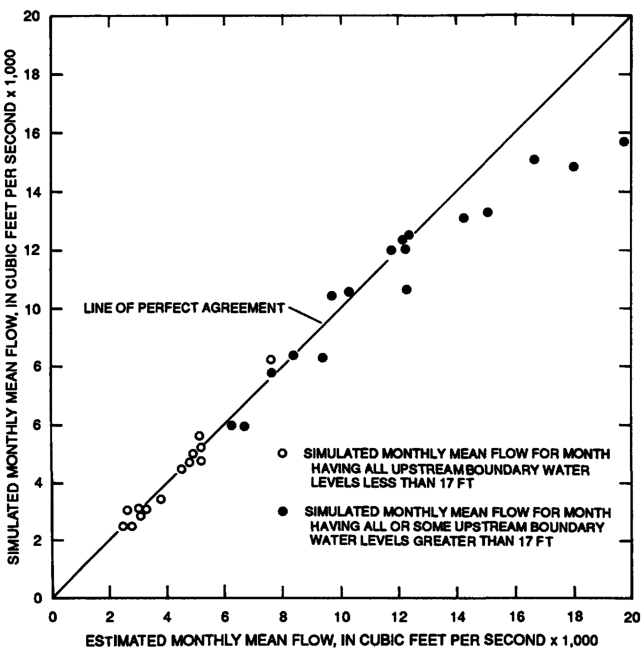

Figure 18. Relation of estimated monthly mean flow and simulated monthly mean flow in the Roanoke River at river mile 67.0 (site 1), 1987–90.

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*U.S. G.P.O.:1994-301-077:80082