SIMULATED FLOOD DISCHARGES AND ELEVATIONS FOR THE SAVANNAH RIVER, SOUTH CAROLINA AND GEORGIA, USING AN UNSTEADY STREAMFLOW MODEL

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CONVERSION FACTORS AND ABBREVIATIONS OF UNITS

The following factors may be used to convert the inch-pound units published herein to the International System of Units (SI).

Multiply inch-pound units	By	To obtain SI units
foot (ft)	0.3048	meter (m)
foot per second (ft/s)	0.3048	meter per second (m/s)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
cubic foot per second (ft^3/s)	0.0283	cubic meter per second (m^3/s)
mile (mi)	1.609	kilometer (km)

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 "Mean Sea Level of 1929."

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ABSTRACT

A linear implicit finite-difference model that uses the continuity and momentum equations was used to simulate unsteady streamflow along a 126-river mile reach of the Savannah River. Streamflow records from the gaging stations at Augusta, Georgia, the upstream boundary, and Clyo, Georgia, the downstream boundary, for the years 1952-79, were used for calibration purposes. Data for 1952-70 from the stream-gaging station at Millhaven, 74 river miles downstream from Augusta, along with the 1952-79 discharge data from the station at Clyo, were used to verify the model. Maximum annual flood discharges and elevations for intermediate locations along the reach were also simulated by the model.

INTRODUCTION

Development of the Savannah River flood plain is increasing and State and local planners need additional site specific information to effectively manage this development. The Savannah District of the U.S. Army Corps of Engineers has received an increasing number of requests for flood discharges and elevations on the Savannah River from Augusta, Georgia, to Clyo, Georgia, a reach of approximately 126 miles. These requests for data are the result of increased interest in potential development near this important waterway, but little or no reliable flood profile data currently exist for this reach of the Savannah River. Estimates in the past have been made on straight line profiles between data points determined at Augusta and Clyo. Improved profile and peak discharges in this report will help the Savannah District answer data requests, as well as aid in the planning of flood plain and reservoir regulation activities.

Purpose and Scope

The purpose of this study is to provide flood elevations and discharges affected by reservoir regulation for intermediate locations on a reach of 126 river miles (80 airline miles) of the Savannah River from Augusta to Clyo, Georgia.

Elements of the study include: (1) calibration of an unsteady-flow model; and (2) generation of water-surface elevation and discharge data at numerous cross sections within the study reach through the use of the model.

Description of Study Area

The Seneca and Tugaloo Rivers join within the Hartwell Reservoir to form the Savannah River. The Savannah River flows from the Hartwell Dam to the Atlantic Ocean, forming the State boundary between South Carolina and Georgia (fig. 1). The river transects two physiographic provinces, the Piedmont and the Coastal Plain. The flood plain in the vicinity of Augusta, Georgia, is approximately 2.5 miles wide and increases to widths of more than 4 miles upstream from Clyo, Georgia. The slope of the river ranges from an average of 3 feet per mile in the Piedmont to less than 1 foot per mile in the Coastal Plain.

Upstream from the Fall Line, three major impoundments, Lake Hartwell, Lake Richard B. Russell, and Clarks Hill Lake, regulate flow and reduce flooding hazards downstream. The drainage area upstream from Clarks Hill Hill Lake is 6,150 mi^2. The drainage area at the Augusta streamflow gaging station is 7,508 mi^2, and the drainage area at the Clyo streamflow gaging stations is 9,850 mi^2. In the reach from Clarks Hill Lake to the Augusta gage, the drainage area per mile of stream length is 27.0 mi^2/mi; whereas, in the reach between the Augusta and Clyo gages the ratio is 18.6 mi^2/mi. The drainage area per mile of stream length decreases in the downstream direction.

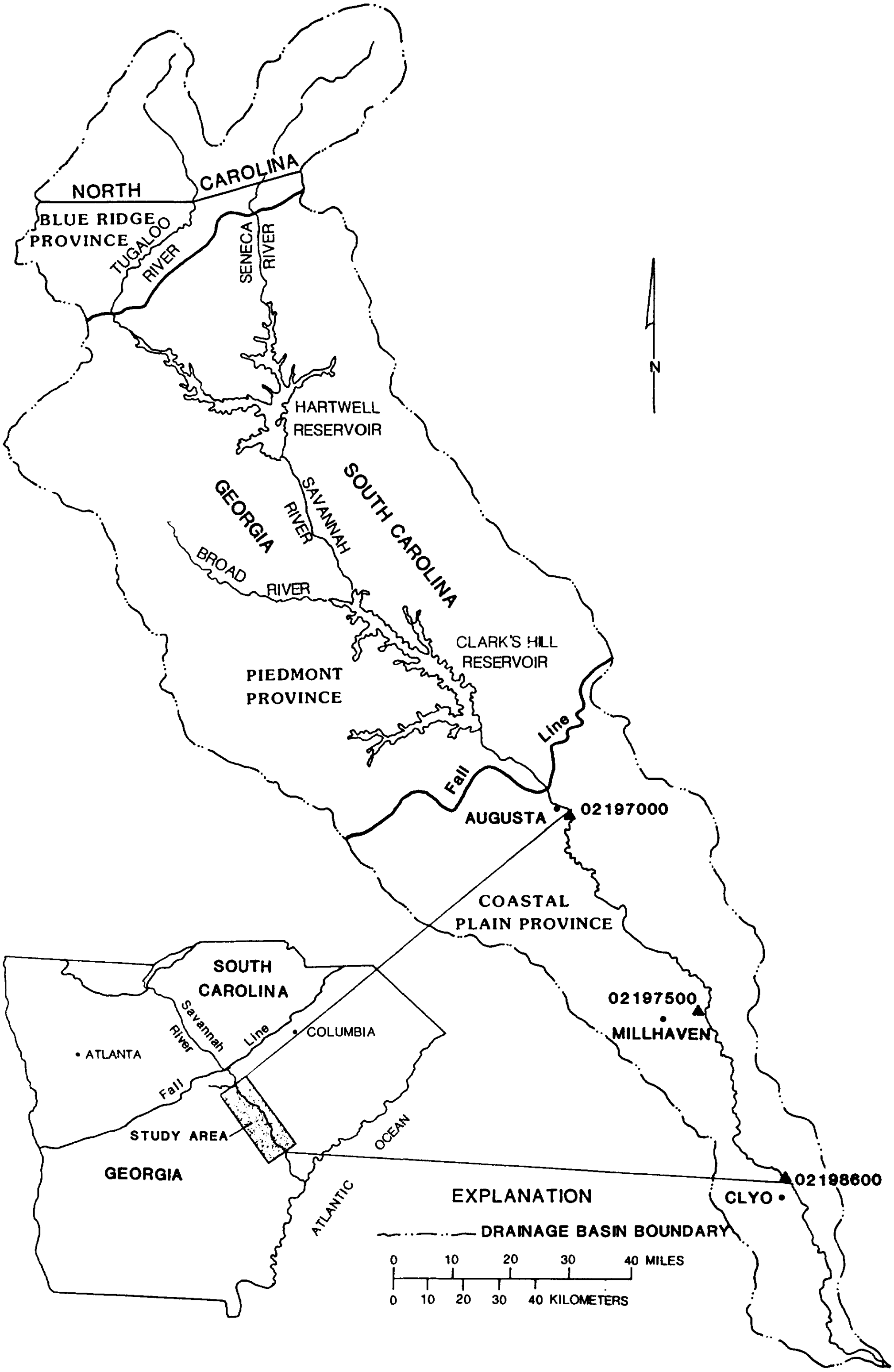

Figure 1.--Location of study area.

DESCRIPTION OF MODEL

The streamflow simulation model selected for this study is the U.S. Geological Survey model known as J879 (Land, 1978). The model uses a linear implicit finite-difference technique that arranges the coefficients of the continuity and momentum equations into a pentadiagonal matrix and computes the solutions. The model is designed to simulate one-dimensional, subcritical, gradually varied, unsteady flow.

The initial discharge conditions, velocity and water depth at time = 0, are computed by a steady-state step-backwater subprogram. Beginning with the next time step, the model simulates the movement of a flood wave down the channel and computes discharge and elevation at each cross section as functions of time.

These discharge and elevation computations are derived from data provided at the upstream and downstream boundaries. The model contains numerous options for entering data at the boundaries. The upstream boundary condition may be any one of the following: (1) water-surface elevation, (2) depth, (3) discharge with depth obtained from a rating curve, or (4) discharge with self-setting depth. However, the self-setting depth option is not recommended for the upstream boundary condition because depth and velocity are used to drive the model. The downstream boundary condition may be entered as: (1) constant depth, (2) self-setting depth, (3) variable depth, or (4) water-surface elevation.

A major step in applying the model is to design a cross-section network that geometrically represents the stream. The designation of the distance between cross sections and the length of time step are important considerations, because the model computes discharge and water-surface elevations at each cross section at the time interval specified. The Courant equation (Courant and Reese, 1952) is used to relate the distance between cross sections (Δ_x) and the length of the time step (Δ_t). The Courant number (K) is a dimensionless factor that expresses the number of times the Courant conditions are exceeded. When K is equal to 1, computation stability is best; but computational errors remain small if K is below 10 and are negligible if K is less than 5. The Courant equation is as follows:

$$K = \frac{(|U| + \sqrt{gy})\Delta_t}{\Delta_x} \quad , \qquad (1)$$

where:

$|U|$ = absolute value of average velocity in cross section, in feet per second;

g = acceleration due to gravity, in feet per second squared;

y = depth, in feet;

Δ_t = time step, in seconds; and

Δ_x = distance between cross-sections, in feet.

The roughness coefficient can be input as a constant or varied linearly with depth. However, the roughness coefficient for a cross section is a composite value because the model will not allow lateral subdivision of the cross section based on differences in roughness. This limitation is compensated for by varying the effective flow width at the cross section. Thus, a 1-mile wide cross section may have an effective flow width of only 0.75 mile. For a further explanation of input to the model, refer to Land (1978).

INPUT DATA

Cross-section information and flood hydrograph data are major inputs into the model. The cross-section data for defining the geometry of the main channel were obtained from U.S. Army Corps of Engineers' Savannah River navigation charts. The flood plain cross-section elevations were obtained from U.S. Geological Survey 7-1/2-minute topographic maps. One hundred and twenty-six cross sections were delineated to facilitate modeling of flow between the gaging stations. For each cross section the following information was entered into the digital model:

River mile,
Topography,
Elevation of lowest point in channel,
Symmetry coefficient, and
Roughness coefficient.

Model documentation and descriptions of these parameters are presented by Land (1978).

Water-surface elevation and discharge data for the 28 years of regulated flow were available for model input and verification of modeling results. Similar data were available for the floods of September and October 1929, which occurred prior to flow regulation by the Hartwell and Clarks Hill reservoirs. Flood hydrograph data associated with the maximum annual peak discharge at the three stream-gaging stations (table 1) in the study reach were tabulated and included in the data base.

Table 1.--Stream-gaging stations used in this study

Station number	Station name	River mile*	Period of record
02197000	Savannah River at Augusta, Ga.	187.1	1952-79
02197500	Savannah River near Millhaven, Ga.	118.5	1952-70
02198500	Savannah River near Clyo, Ga.	60.9	1952-79

*River mile established by the U.S. Army Corps of Engineers.

CALIBRATION

The boundary conditions used in the model were (1) discharge, with depth determined from a rating curve at the upstream end and (2) water-surface elevation at the downstream end for floods that occurred during the period 1952-79. The most accurate model simulation results were obtained using these boundary conditions because the model was provided with as much controlled data as possible. The self-setting depth option was used for the downstream boundary condition for the floods of 1929.

The distance (Δ_x) between cross sections and length of time step (Δ_t) were selected based on the limits of the value of K (Courant and Reese, 1952) and the rate of change of discharge relative to time. As discussed in a previous section, the Courant equation relates Δ_x and Δ_t to produce a value of K that must be equal to or less than 10 and equal to or greater than 1. A time step interval of 10 to 20 minutes and a distance between cross sections of approximately 1 mile were determined to be necessary to insure stability in the model.

Time Calibration

Maximum annual peak discharges for the period 1952-79 ranged from 18,600 to 87,000 ft^3/s at the Augusta station and from 14,000 to 83,800 ft^3/s at the Clyo station. Simulated regulated peak discharges for the flood of September-October 1929 at Augusta and Clyo were 245,000 ft^3/s and 201,000 ft^3/s, respectively. The three storm events used for unsteady flow calibration were the March 1956 flood with a peak discharge at Augusta of 13,500 ft^3/s, the April 1969 flood with a peak discharge of 45,600 ft^3/s, and the April 1964 flood with a peak discharge of 87,100 ft^3/s. Flood hydrograph discharges and the appropriate rating curve were input at the upstream boundary and water-surface elevations from the flood hydrograph were input at the downstream boundary.

During initial model calibration attempts, simulated peak discharges arrived late, even after decreasing the roughness coefficient to unrealistically low values (less than 0.001). The simulated peaks arrived late because the large floods (above a discharge of 23,000 ft^3/s) are not confined to a meandering channel, but cut across meanders. The routing of water using the flood path reduced the travel distance from 126 miles to approximately 81 miles. The travel distance was reduced 22 miles (31 percent) in the reach from Augusta to Millhaven and 24 miles (41 percent) in the reach from Millhaven to Clyo. The number of cross sections was also reduced to 81, resulting in one cross section approximately each flood-path mile. A plan view of the meandering river channel for a reach near Millhaven, Ga., and the superimposed flood route used in the model is shown in figure 2.

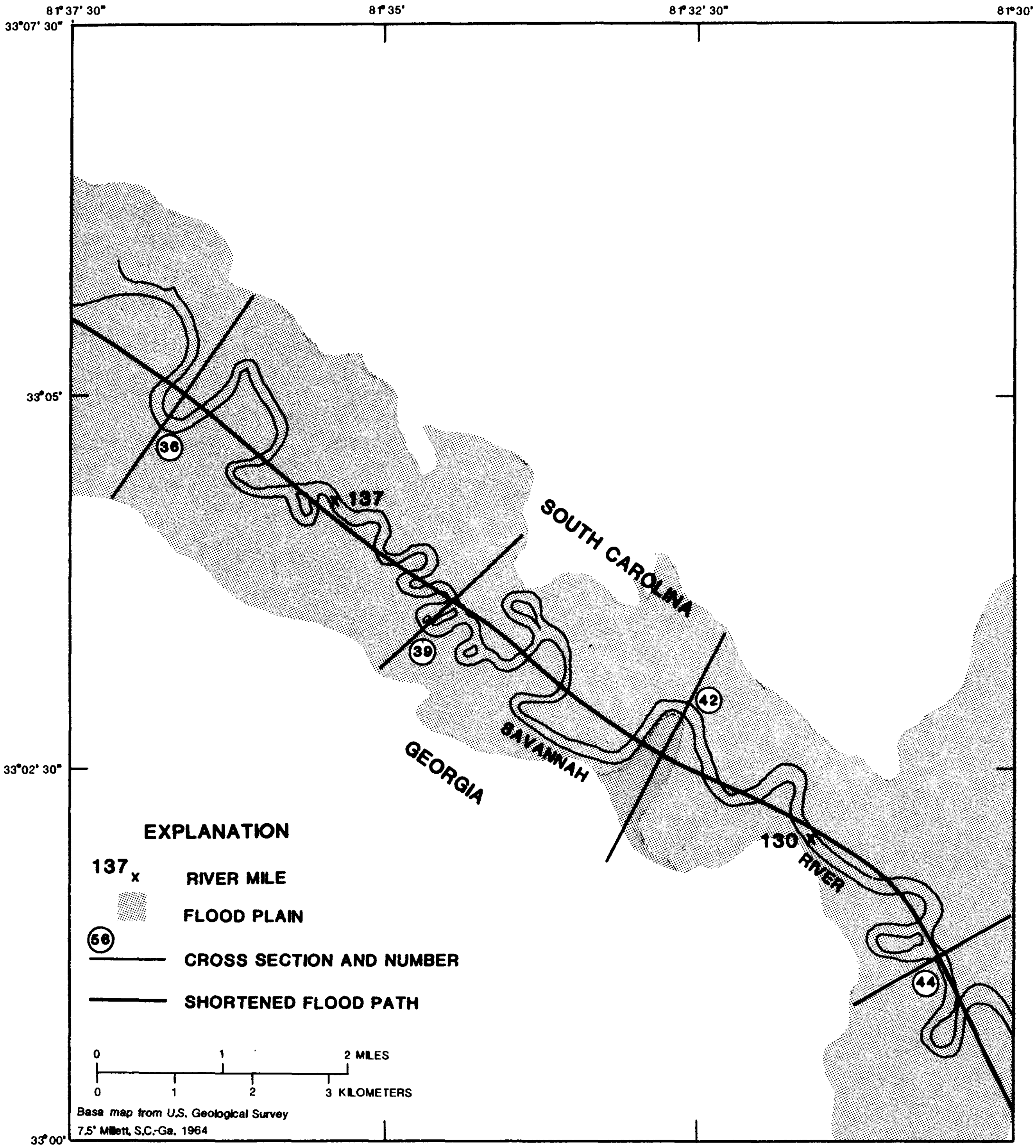

Figure 2.--Main channel, path of flood flow, and cross section locations for reach of Savannah River near Millhaven, Georgia.

Using the shortened flood path, the best fit roughness coefficients were determined through a series of simulations. The roughness coefficient can be input as (1) a constant for all water-surface elevations, (2) increased or decreased linearly as a function of water-surface elevation, or (3) constant to a specified elevation, then increasing or decreasing linearly as a function of water-surface elevation.

Each of these options was used, and the best results were obtained by using a constant roughness coefficient of 0.030 at each cross section for the 13,500 ft^3/s calibration and a constant of 0.040 at each cross section for the 45,600 ft^3/s and 87,100 ft^3/s calibrations.

The discharge at which water spills out of the main channel and into the wooded areas is approximately 23,000 ft^3/s. The attempts at calibration indicated that the best results were obtained using a constant roughness coefficient of 0.030 for those floods in which all the 20-minute time interval input discharges at Augusta are less than 23,000 ft^3/s and a constant roughness coefficient of 0.040 for those floods in which the majority of the 20-minute time interval input discharges at Augusta are greater than 23,000 ft^3/s. An increase in roughness coefficient at higher discharges appears to be consistent with the increased resistance to flow that occurs when water spreads onto the more heavily wooded areas of the channel and flood plain.

Discharge Calibration

Inflow to the Savannah River within the study reach can be simulated in the model by either a point-source tributary inflow or a distributed lateral inflow. Ideally, inflow would be added at the location, time, and rate that it actually occurred. However, the available data were not adequate to accurately determine where and when, along the 126-mile reach, the inflow occurred.

The ratio of drainage area to mile of stream length does not change significantly (less than 11 percent) for the reach from the Augusta to Millhaven streamflow gages as compared to the reach from the Millhaven to Clyo streamflow gages. Therefore, distributed lateral inflow provides a reasonably accurate means of adding water to the simulated streamflow. The inflow, referred to as QLAT, was entered along the entire length of the channel for the total time period. The units of QLAT are cubic feet per second per lateral foot of channel, and the value may be calculated directly. A different QLAT was computed for each annual storm event by the equation:

$$QLAT = \frac{V}{1,200\ (NTS)\ (CHANLEN)}$$

where: QLAT = volume of water introduced, in cubic feet per second per foot of channel;

V = difference between volume of water entering at the upstream gage and exiting at the downstream gage, in cubic feet, for the given storm;

1,200 = number of seconds in one time step;

NTS = number of time steps for that annual storm; and

CHANLEN = length of shortened flood path, in feet.

For those maximum annual floods occurring from 1952-70, QLAT was calculated for two subreaches; one from Augusta to Millhaven, the second from Millhaven to Clyo. The record at Millhaven was discontinued in 1970, and thereafter only one QLAT was calculated for the reach using the data at Augusta and at Clyo.

By including QLAT in the time-calibrated model, the fit of the simulated discharges with measured discharges was improved. Comparisons of the simulated and measured discharges at the Millhaven stream-gaging station for the calibration floods are shown in figures 3, 4, and 5.

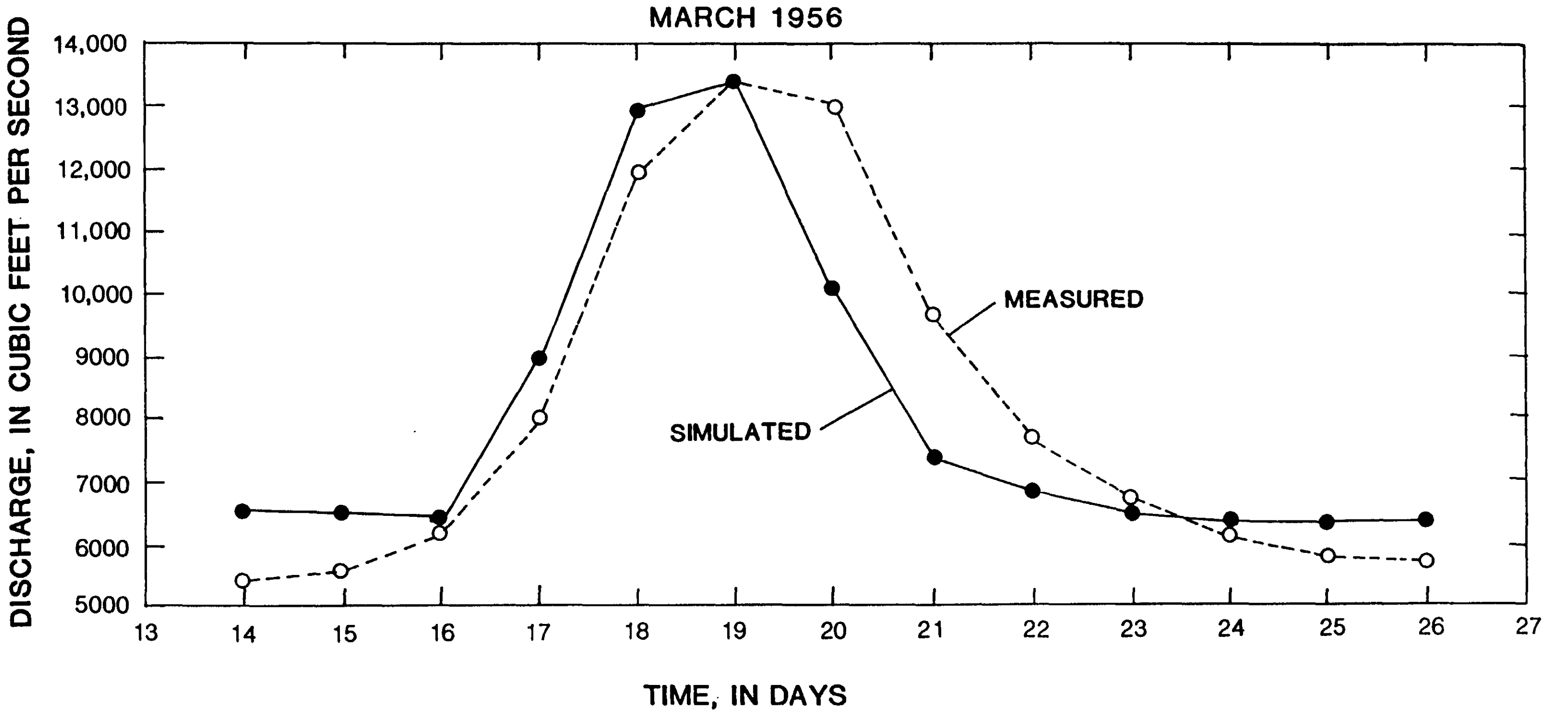

Figure 3.--Comparison of simulated and measured discharge for annual peak flood for Savannah River at Millhaven (02197500) during March 1956.

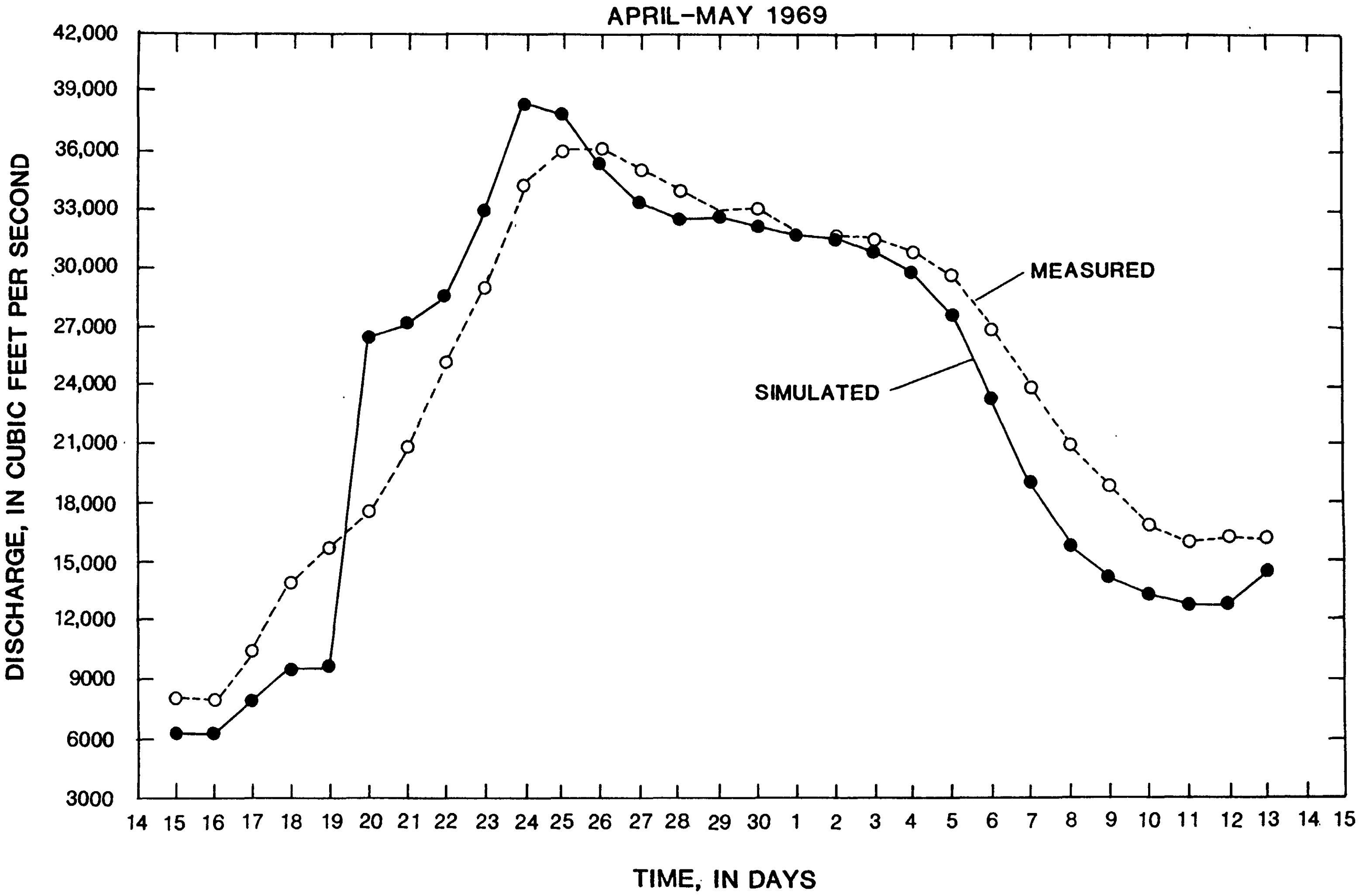

Figure 4.--Comparison of simulated and measured discharge for annual peak flood for Savannah River at Millhaven (02197500) during April-May 1969.

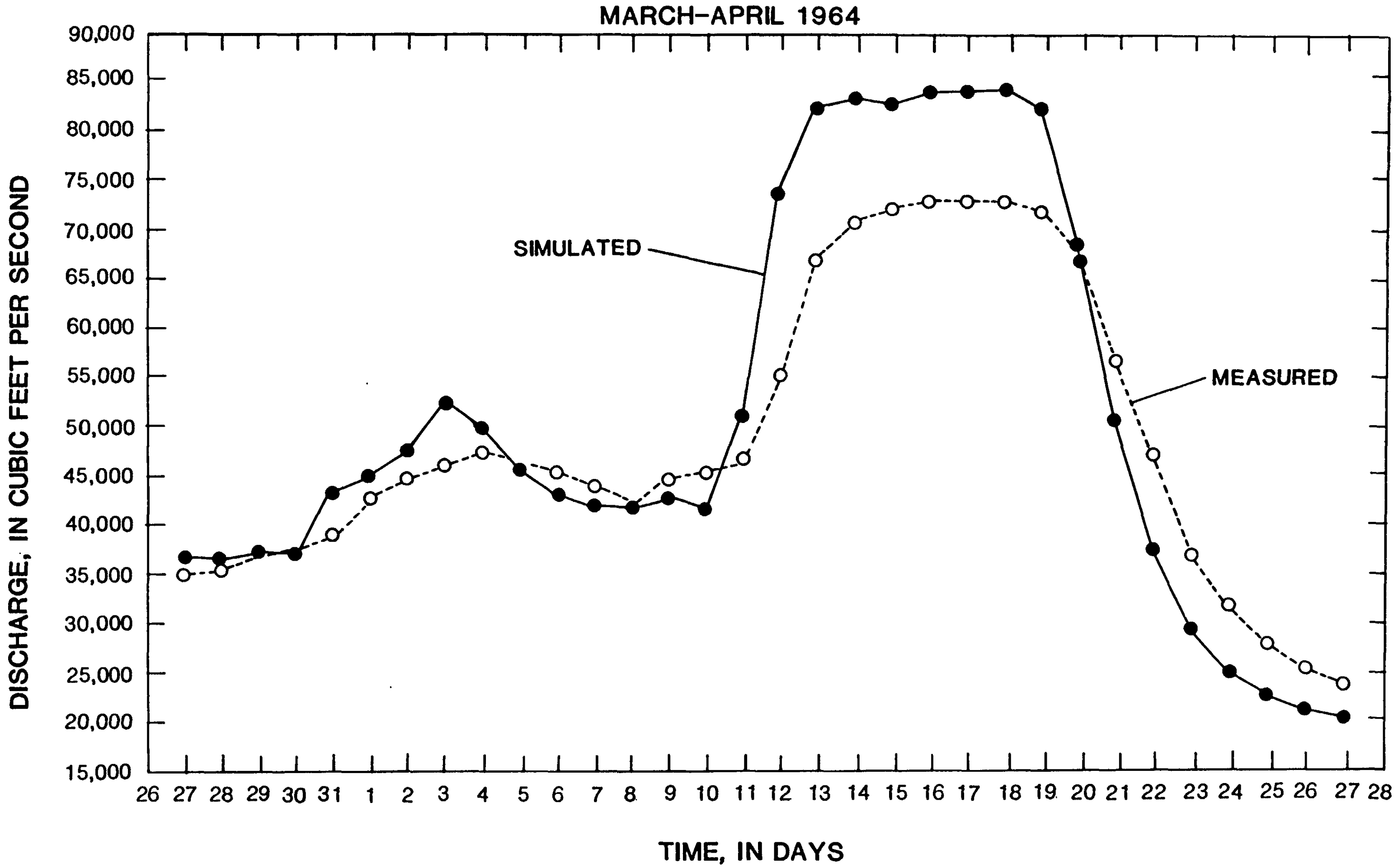

Figure 5.--Comparison of simulated and measured discharge for annual peak flood for Savannah River at Millhaven (02197500) during March-April 1964.

SIMULATION OF STREAMFLOW

The remaining 25 annual floods for the period 1952-79 and for 1929 were simulated to verify the model calibration. The discharges from the flood hydrograph for each year's maximum flow event provided the input data at the upstream boundary. Water-surface elevations from the hydrographs for the same event were used at the downstream boundary for the 1952-79 floods. These data were entered for a time period long enough for the flood wave to completely pass by the Clyo gage. In a given year, the annual maximum flood at each of the streamflow gaging stations was not always the result of the same hydrologic event.

Peak elevation and discharge were simulated at each cross section along the reach. Simulated annual maximum discharges and water-surface elevations were compared with measured discharge and water-surface elevations at the gaging stations at Millhaven and Clyo for 25 floods. Figures 6 and 7 compare measured and simulated flood-peak data (each including a 45 degree line, representing perfect agreement). The root mean-square errors associated with figures 6 and 7 (annual maximum discharge) are 6.8 and 9.5 percent, respectively.

A comparison of the simulated and measured discharges indicates a bias for the gaging station at Millhaven (fig. 6). An analysis of covariance was performed to determine if the slope of an ordinary least squares regression line fitted to the data shown in figure 6 is significantly different from 1.0 at the 5 percent level. The slope of the fitted regression is different from 1.0, indicating a bias in the simulated discharge in the vicinity of the gaging station at Millhaven. The simulated discharges range from a -9.3 percent error at 15,000 ft^3/s to a +13.9 percent at 115,000 ft^3/s.

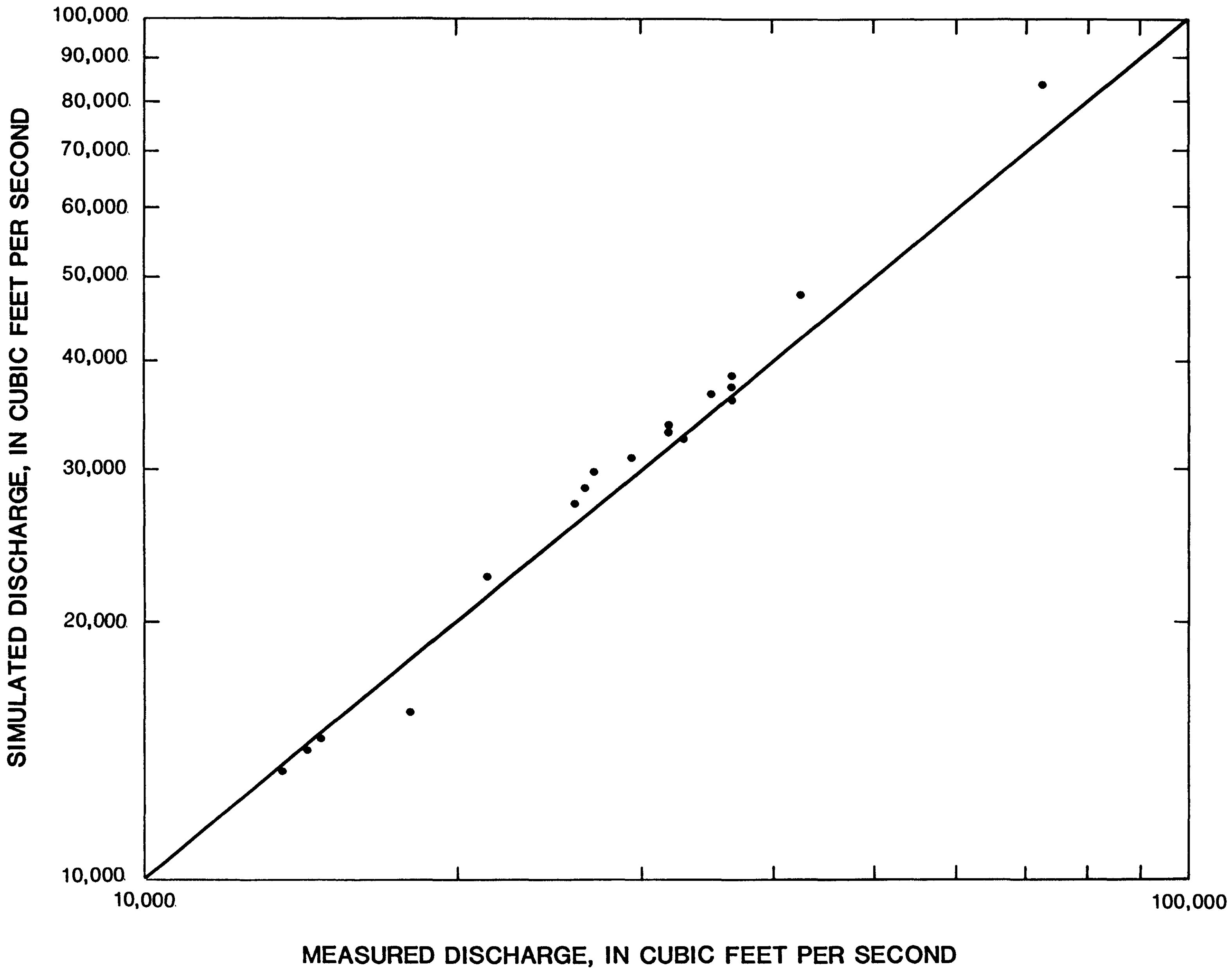

Figure 6.--Comparison of simulated and measured annual maximum peak discharge for Savannah River at Millhaven (02197500) for water years 1952-70.

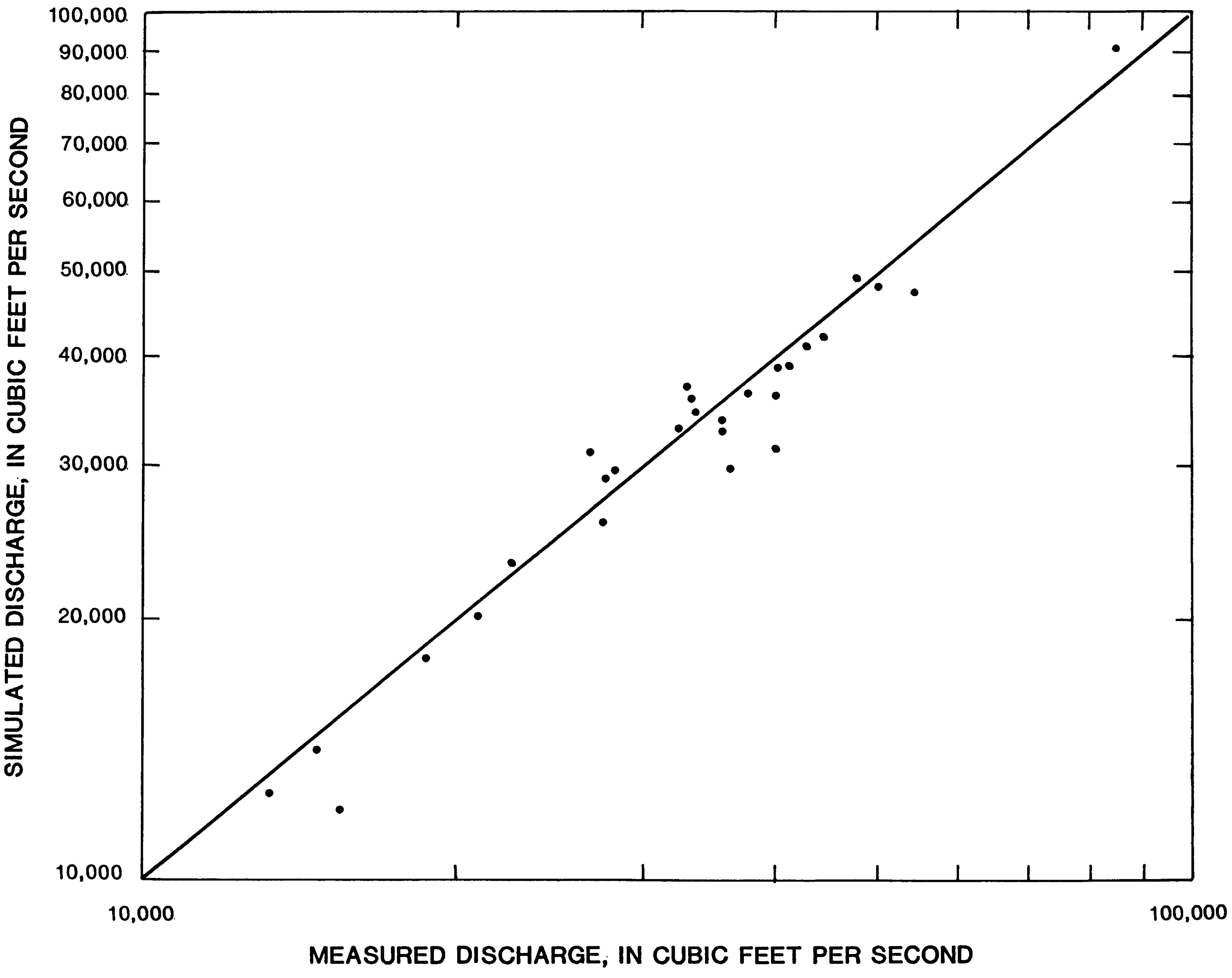

Figure 7.--Comparison of simulated and measured annual maximum peak discharge for Savannah River at Clyo (02198500) for water years 1952-79.

However, the comparison of measured and simulated peak elevations at the gaging station at Millhaven indicated no significant bias (fig. 8). The root mean square error of the comparison is 0.3 feet. Therefore, water-surface elevations in the vicinity of Millhaven developed from model simulations are not significantly affected, although the associated discharge may be under-simulated by as much as 9 percent or over-simulated by as much as 14 percent.

The maximum measured peak discharge (350,000 ft^3/s) at the Augusta stream-gaging station occurred October 2, 1929, prior to regulation by Hartwell and Clarks Hill Reservoirs. This event was included to depict flood discharges and elevations for a very large flood in the study reach. The discharge hydrograph for this event was routed through Hartwell and Clarks Hill Lake Reservoirs by the U.S. Army Corps of Engineers (1974) to simulate the effect of the reservoirs on this historic flood. Reservoir control reduced the maximum peak discharge at Augusta from 350,000 ft^3/s to 245,000 ft^3/s.

The outflow hydrograph simulated by the U.S. Army Corps of Engineers was routed through the study reach using the unsteady-flow model. The model option of self-setting depth was used at the downstream boundary because water-surface elevations were not available at the gaging station at Clyo for the 1929 flood. A comparison of the simulated water-surface elevations with the measured water-surface elevations using the self-setting depth option for the 1964 flood indicated less than 0.5 foot difference.

The results of the streamflow routing for selected floods are given in table 2 (discharges) and table 3 (elevations) for several cross-section locations in the study reach. The floods selected cover the range of floods experienced in the study reach. Profiles of those flood elevations are shown in figure 9.

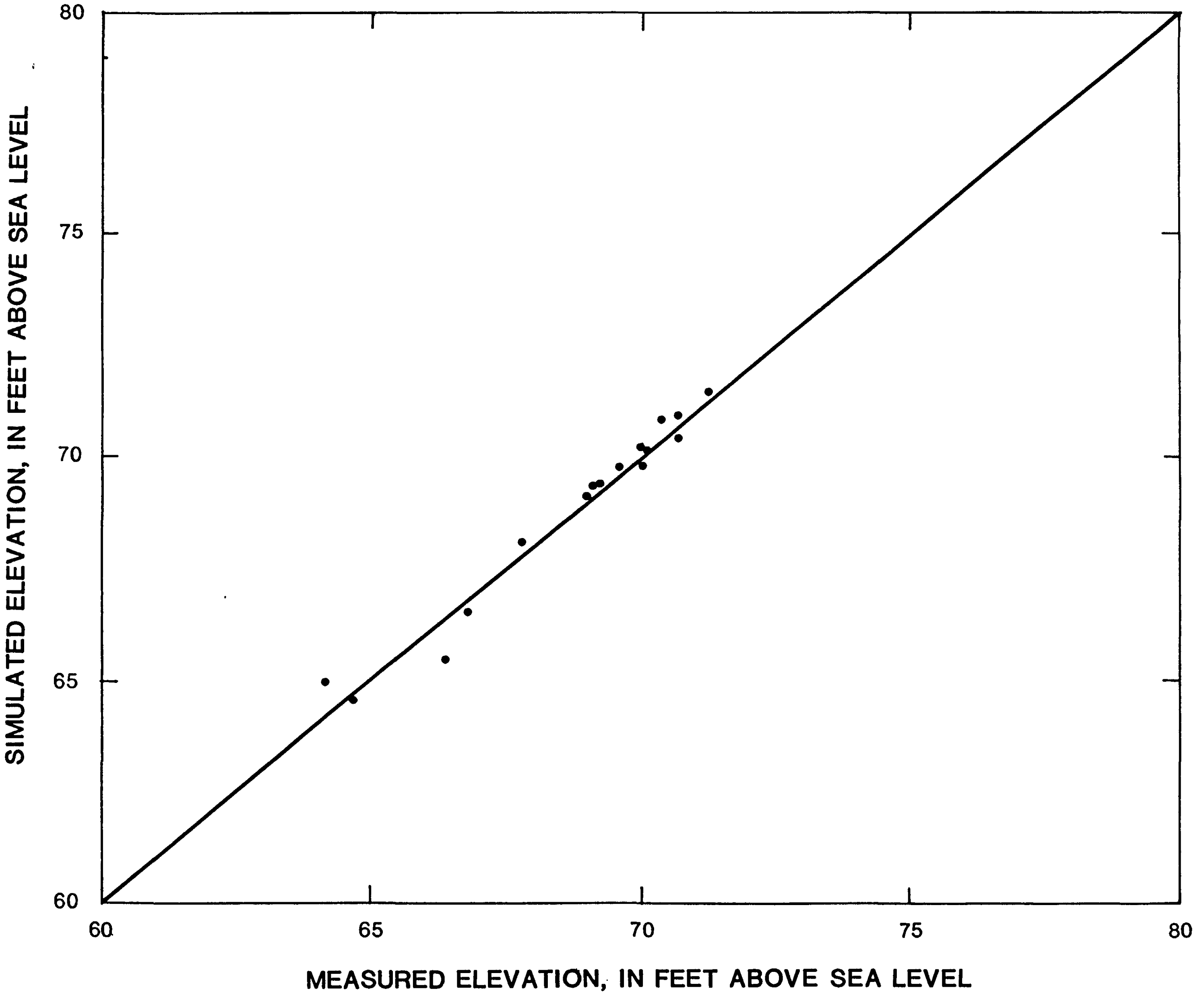

Figure 8.--Comparison of simulated and measured annual maximum peak elevation for Savannah River at Millhaven (02197500) for water years 1952-70.

Table 2.--Discharge for selected annual floods at selected locations on the Savannah River from Augusta to Clyo

Cross-section number	River mile	Discharge, in cubic feet per second, for selected floods			
		March 1956	April 1969	April 1964	September 1929
1	187.1	13,500	45,200	87,100	245,000
4	183.0	13,600	44,800	84,900	232,000
11	176.0	13,700	43,300	83,900	213,000
14	170.0	13,700	42,700	83,100	212,000
16	163.8	13,600	42,300	82,900	211,000
21	159.4	13,000	41,200	82,800	209,000
24	153.0	13,100	40,600	82,900	208,000
28	148.8	13,100	39,800	83,000	208,000
34	143.4	13,300	39,500	83,300	209,000
38	136.9	13,300	39,300	83,400	209,000
41	132.6	13,400	39,200	83,500	209,000
45	125.7	13,600	39,100	83,700	208,000
48	119.8	13,600	38,900	83,900	208,000
49	118.5	13,500	38,800	83,900	208,000
53	112.7	13,400	38,800	84,700	208,000
56	105.9	13,300	38,600	85,300	208,000
60	99.9	13,300	38,500	86,200	208,000
62	93.5	13,400	38,400	86,700	207,000
66	65.8	13,300	38,300	87,600	206,000
70	78.7	12,900	38,100	88,500	204,000
75	70.5	12,600	38,000	89,800	203,000
79	64.8	12,800	37,800	91,100	202,000
81	60.9	13,000	36,800	93,600	201,000

Table 3.--Elevations for selected annual floods at selected locations on the Savannah River from Augusta to Clyo

Cross-section number	River mile	Elevation, in feet, above sea level for selected floods			
		1956	1969	1964	1929
1	187.1	108.2	118.8	120.8	126.3
4	183.0	103.3	115.9	118.5	123.0
11	176.0	97.4	108.0	111.0	117.2
14	170.0	94.5	104.0	107.6	114.6
16	163.8	93.5	101.8	105.4	112.7
21	159.4	90.2	98.4	102.4	109.8
24	153.0	87.9	96.9	100.9	107.9
28	148.8	85.9	95.0	98.7	105.2
34	143.4	81.2	89.4	92.8	99.1
38	136.9	77.7	84.6	88.3	95.1
41	132.6	72.3	81.5	85.2	92.2
45	125.7	68.4	76.6	80.7	88.6
48	119.8	65.9	73.0	78.0	86.3
49	118.5	65.1	70.5	74.5	81.2
53	112.7	61.3	65.6	69.3	75.2
56	105.9	55.7	62.4	66.3	72.1
60	99.9	50.4	55.7	59.4	64.8
62	93.5	45.9	50.6	54.5	60.4
66	85.8	39.4	46.3	50.0	55.9
70	78.7	35.5	40.8	45.3	51.6
75	70.5	31.5	35.8	39.9	46.0
79	64.8	26.7	31.3	35.4	42.3
81	60.9	23.8	30.2	33.7	40.9

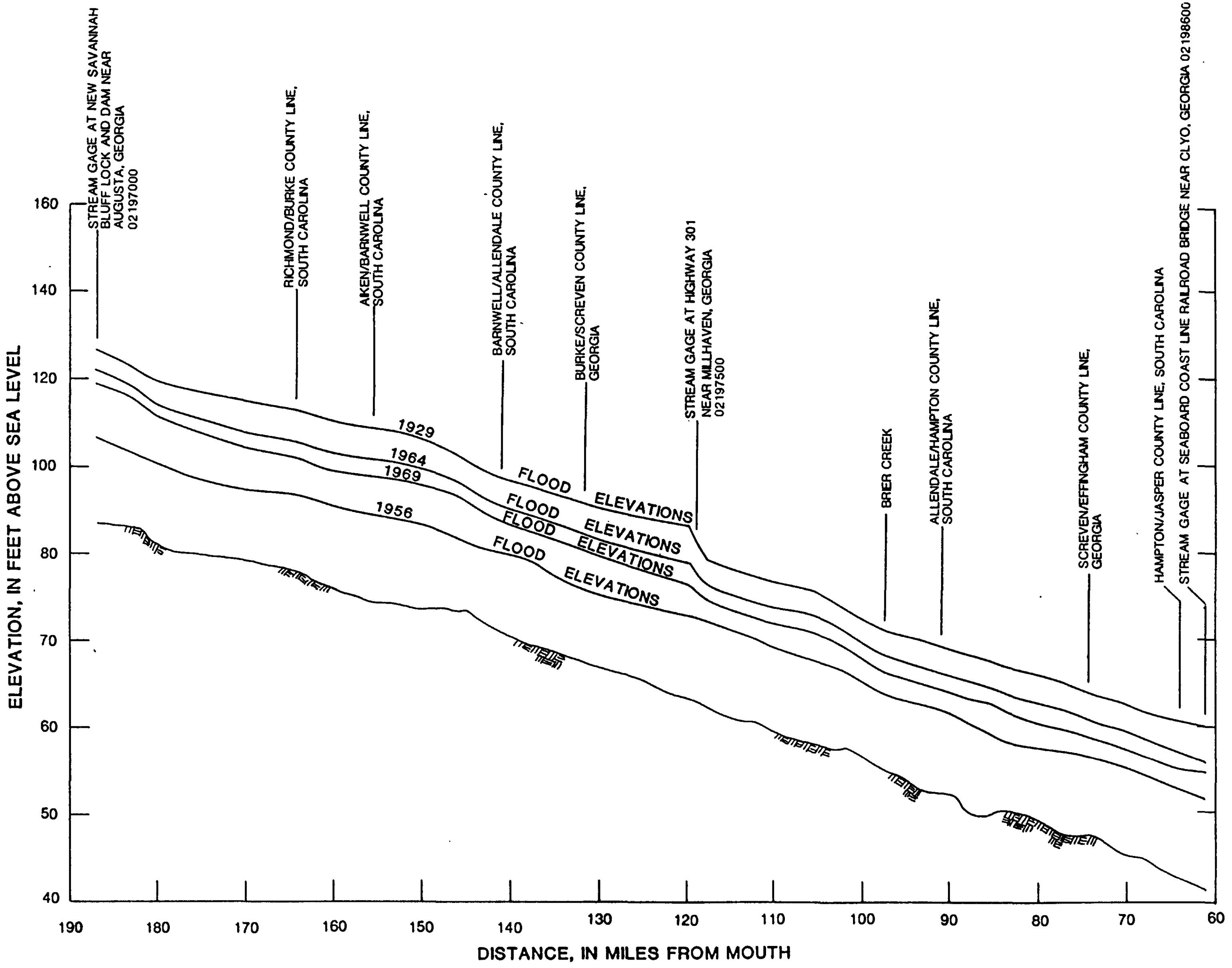

Figure 9.--Flood profiles for selected annual floods for the Savannah River from Augusta to Clyo.

SUMMARY

A linear implicit finite-difference digital model was used to route the maximum annual floods for 28 years of regulated discharge record and the 1929 historical flood (adjusted for regulation), along the reach of the Savannah River between Augusta, Georgia and Clyo, Georgia. The model was used to simulate the maximum annual flood discharges and elevations at 81 selected locations in the study reach.

Cross sections were obtained from 7-1/2-minute U.S. Geological Survey topographic maps and U.S. Army Corps of Engineers navigation charts. Flood hydrograph discharges were input at the upstream boundary (Augusta stream gage), and water-surface elevations from flood hydrographs were input at the downstream boundary (Clyo stream gage). The stage and discharge record at the stream-gaging station near Millhaven, Georgia, and the discharge record at the Clyo stream gage were used to calibrate and verify the model. Uniform lateral inflow was used to compensate for inflows from overland runoff, ground water, and tributaries. Flood elevations and discharges for the annual floods of 1956, 1969, 1964, and 1929 are presented for selected locations to depict the approximate range of floods experienced in the study reach.

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