FLOOD FREQUENCY OF THE SAVANNAH RIVER AT AUGUSTA, GEORGIA

By Curtis L. Sanders, Jr., Harold E. Kubik, Joseph T. Hoke, Jr., and William H. Kirby

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ABSTRACT

A flood-frequency study of the Savannah River at Augusta, Georgia (02197000) was made to provide information on floods of various probabilities of occurrence. The study was complicated by the fact that the Savannah River upstream of Augusta has been regulated since water year 1952 by one or more of three large Federal multi-purpose dams. Although the period of record, available for analysis of regulated conditions was 34 years, the pre-impoundment period was important to the flood-frequency analysis because it included a number of large floods that, even when adjusted for regulation, exceed all floods since water year 1952. A reservoir routing model was used to adjust nine such floods for the effects of regulation by the dams. The model results also were used to develop a relation for estimating regulated peak discharges for additional unregulated floods as far back as 1796 that could not be modeled because of lack of data. The one-percent chance exceedance flood for current (1990) reservoir operation criteria on the Savannah River at Augusta was computed to be 180,000 cubic feet per second.

INTRODUCTION

Increased development of the Savannah River flood plain and greater interest in managing development to minimize damages caused by floods have emphasized the need for reliable information on flood frequency of the Savannah River at Augusta, Georgia. The U.S. Geological Survey (USGS) and the U.S. Army Corps of Engineers (COE) jointly made a study to provide such information.

Although peak discharges for major floods since 1796 at this site have been documented, the flood-frequency analysis was complicated because the Savannah River upstream from Augusta has been regulated since water year 1952 due to construction of three large Federal multi-purpose projects: Hartwell Dam, Richard B. Russell Dam, and J. Strom Thurmond Dam (formerly called Clarks Hill). These reservoirs have changed the statistical characteristics of flooding on the river, and the regulated flow records are those most directly relevant to present and future conditions.

The analysis could not be based solely on the regulated period of record, however, because the period since regulation began has been exceptionally free of large storms such as those that occurred prior to regulation. Most of those large storms were caused by infrequent climatic events, including hurricanes.

The record of floods prior to commencement of regulation in 1951 could not be combined directly with the record of regulated floods. Instead, to compile a homogeneous record for statistical analysis, it was necessary to use hydraulic simulation models to determine the effects of reservoir regulation on flood magnitudes. Using these models, the regulated post-1951 flood records were converted into equivalent de-regulated records which could be combined with the pre-1952 observed unregulated floods. In addition, the models were used to simulate the effects of regulation on nine unregulated floods for which sufficient data were available for computation. In this way, a homogeneous record of unregulated flows and a homogeneous record of regulated flows were developed for statistical analysis.

The extended record of unregulated floods was analyzed by standard procedures of flood-frequency analysis. The resultant unregulated flood frequency curve is representative of flood hydrology on the basin in the long term in the absence of regulation. The unregulated frequency curve was combined with relations between corresponding regulated and unregulated flood magnitudes to derive a frequency curve representative of regulated conditions. In addition, an independent graphical frequency analysis of the regulated data was performed.

Purpose and Scope

The purpose of this report is to provide discharges for floods of selected percent chances of exceedance for the Savannah River at Augusta (station number 02197000) based on current reservoir operating criteria (1990) (COE, 1974).

This report presents the results of the flood-frequency analysis and describes procedures used in the analysis to:

- generate unregulated-peak discharge data during periods when regulated flow conditions existed;
- generate regulated peak discharge data for major floods during periods when unregulated conditions existed; and
- develop the flood-frequency relation from the adjusted data.

The flood-frequency data presented in this report for regulated conditions are based on 1990 reservoir operating procedures. This analysis may not apply if substantial changes are made in the operation of the three large reservoirs upstream of Augusta.

Description of Study Area

The Seneca and Tugaloo Rivers, which originate in the Blue Ridge physiographic province, join within Lake Hartwell. The Savannah River flows from 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 (Cooke, 1936). The city of Augusta is on the Fall Line, which separates these two provinces. The slope of the river ranges from an average of about 3 feet per mile in the Piedmont to less than 1 foot per mile in the Coastal Plain.

Upstream from the Fall Line, three large Federal multi-purpose dams (Hartwell Lake, Richard B. Russell Lake, and J. Strom Thurmond Lake, formerly Clarks Hill Lake) provide hydropower, water supply, recreational facilities and a limited degree of flood control (table 1). J. Strom Thurmond Dam is responsible for most of the flow regulation that affects the Savannah River at Augusta. J. Strom Thurmond Dam and Lake will hereafter be referenced as Thurmond Dam and Lake. Richard B. Russell Lake and Dam will hereafter be referenced as Russell Lake and Dam. Stevens Creek Dam, built in 1916 and located between Thurmond Dam and Augusta, impounds a minor run-of-the-river reservoir compared to the three major reservoirs. Stevens Creek dam and other dams upstream of Hartwell Lake have little impact on flood discharges at Augusta.

Table 1.--Characteristics of major reservoirs on the Savannah River upstream of Augusta, Georgia

[mi^2, square miles]

Lake	Month and year filling began[1]	Drainage area (mi^2)	Storage (1,000 acre-feet) Flood	Conservation	Total
Hartwell	Feb. 1961	2,088	293,000	1,416,000	2,843,000
Richard B. Russell	Oct. 1984	2,900	140,000	127,000	1,026,000
J. Strom Thurmond	Dec. 1951	6,144	390,000	1,045,000	2,900,000

[1]Partial filling due to construction could have occurred prior to this date.

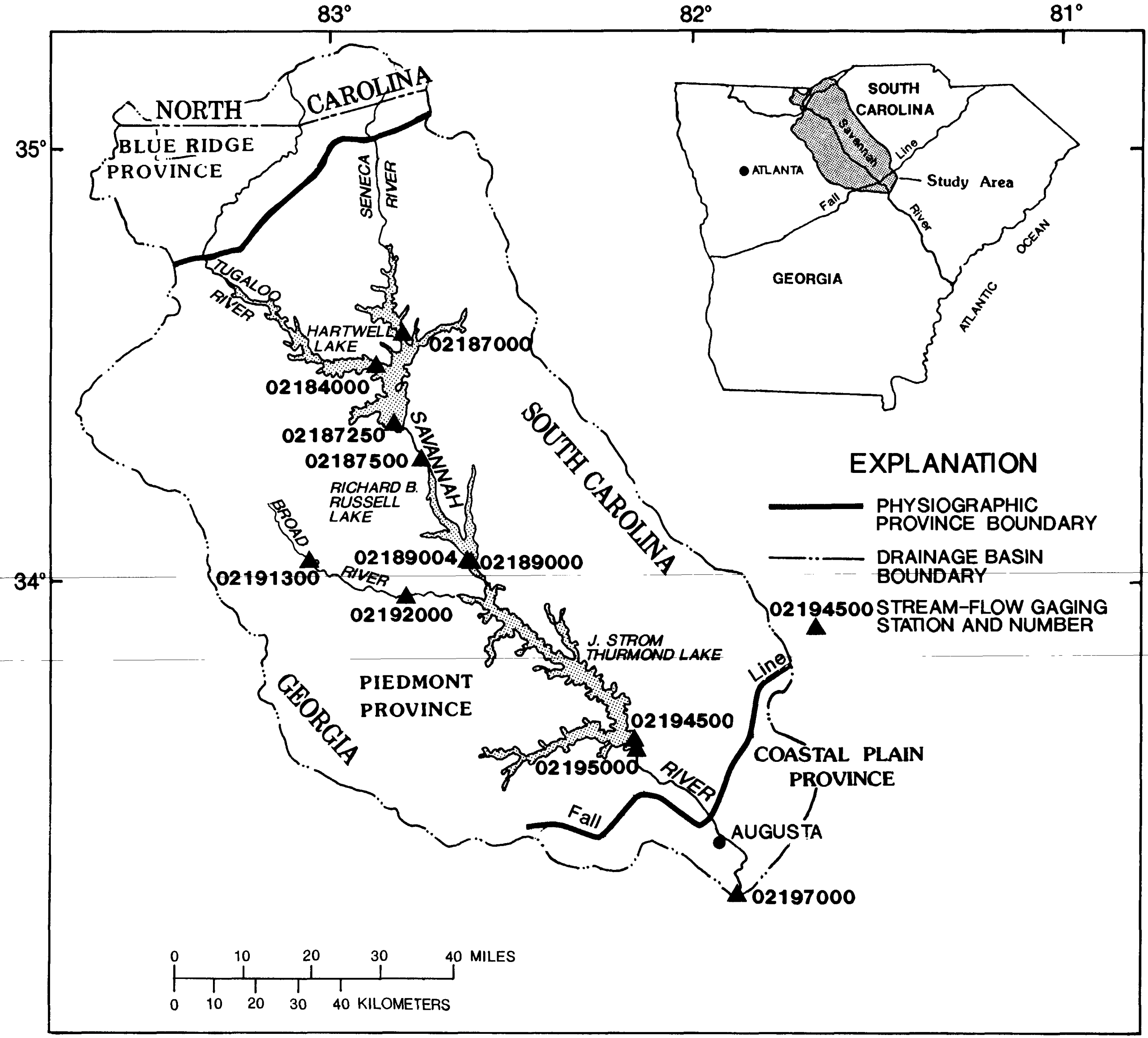


Figure 1.--Location of study area and location of gaging stations in the study area.

Previous Studies

The first comprehensive listing of floods of the Savannah River was published in U.S. House of Representatives Executive Documents No. 1 and 213 in 1890. Updated listings of floods in Georgia, along with frequency relations, were published by Carter (1951); Bunch and Price (1962); and Price (1979). A similar USGS report for South Carolina (Whetstone, 1982) lists peak discharges for the Savannah River at Calhoun Falls, Augusta and Clyo, and provides unregulated flood-frequency information based on the period prior to 1952 and regulated flood-frequency information based on the period 1952-79.

The USGS tabulated peak discharges for floods prior to 1962 for several gaging stations in the Savannah River basin (Speer and Gamble, 1964). The COE (1971) developed flood profiles for the Savannah River downstream of Augusta for recurrence intervals of 5, 10, 15, 50, and 100 years. Other studies that provide information on peak discharges and floods are documented in several House Documents presented in the reference section of this report. Other useful reports include: two by Emigh (1914 and 1929) of the Weather Bureau, reports by Patterson (1889) and Phillips (1892); and several reports by the COE (1929, 1945, 1952, 1953 and 1974). An unsteady-flow computer model has been used by the USGS to determine flood profiles between Augusta and Clyo for 4 historic floods of various magnitudes (McDonald and Sanders, 1987).

Acknowledgments

The assistance of Rachel Brewer, city clerk of Augusta, Ga., in locating historic information pertaining to floods in Augusta, is gratefully acknowledged. The authors are also indebted to the Federal Energy Regulatory Commission, which provided additional information regarding floods in Augusta, and to Dr. Edward Cashin, a professor of Augusta College, who has been extremely helpful in providing information regarding the history of Augusta.

AVAILABLE FLOOD RECORDS

Some information is available on floods in Augusta as early as 1722 and for flood stages, as early as 1796. A stage of 40 feet (ft) for the flood of 1796 was first published by the U.S. Weather Bureau (USWB) (Emigh, 1914). A stage gage was established on the Savannah River in Augusta at 5th Street about 1835; the datum of the gage and for the city was the low water of 1835.

Daily stage readings were published for the Savannah River at Augusta from 1875 to July 1952 by the National Weather Service (formerly U.S. Weather Bureau). Stages were recorded continuously from about 1927 to 1936 at 5th or 13th Streets in Augusta, except for short periods when the recorder was removed due to bridge construction or relocation of the gage. A staff gage was used when the recorder was not operated. The gage was located at 5th Street from 1927 to 1932, and at 13th Street from October 1, 1932, to September 30, 1936. On July 4, 1934, a staff gage was established on the Savannah River near Butler Creek, 13 miles downstream at a different datum, and used until July 30, 1936. A water stage recorder was operated at the Butler Creek site from October 1, 1936 to November 10, 1948, when the gage was moved 0.2 miles upstream to its present location at the New Savannah Bluff Lock and Dam. The station name (Savannah River at Augusta, Ga.) and station number (02197000), have not changed, and peak discharges at the four sites are considered equivalent.

Peak discharges prior to 1912 were determined using a stage-discharge rating established by discharge measurements made during the 1890's and early 1900's. The COE first published discharges for the major floods in U.S. House of Representatives Executive Documents No. 1 and 213 and the U.S. Weather Bureau published discharges for the major floods in 1891. The USGS listed the peak stages and discharges for the floods of 1840, 1852, 1865, 1876, and 1888, and maximum daily stages and discharges for "all the large floods" from 1840 to 1905, (Murphy, 1906). The USGS published peak stages and discharges for the Savannah River in 1951 (Carter, 1951).

Carter (1951) indicates that discharges for all floods above 225,000 ft^3/s (cubic feet per second) are known (either by direct measurement or indirect calculations). Newspapers and other publications (listed in References) used to verify the occurrences of floods indicate that, in addition to the floods used in the analysis described in this report, notable floods also occurred on the Savannah River in 1722, 1741, 1793, 1820, 1824, 1830, 1833, 1851, 1854, 1870 and 1875. The Augusta Gazette (Chronicle) newspaper began publication in October, 1785. It appears that the newspaper (its name changed several times over the years) reported any major flooding of the city.

Flood data for all floods of the Savannah River at Augusta used in this analysis are listed in table 2 and plotted in figure 2. The flood data are presented by water year. A water year is the 12-month period October 1 through September 30, and is designated by the calendar year in which it ends. Other gaging stations in the study area with records of stage and discharge used in this study are listed in table 3 and shown in figure 1.

Table 2.--Annual peak stages and discharges for the Savannah River at Augusta, Ga. (02197000) for the period 1796 - 1985

[ft, feet; ft³/s, cubic feet per second]

Water year	Date	Stage (ft)	Discharge (ft^3/s)	Water year	Date	Stage (ft)	Discharge (ft^3/s)	Water year	Date	Stage (ft)	Discharge (ft^3/s)
[1]1796	Jan. 17	40	360,000	1909	June 5	28.7	87,300	1947	Jan. 22	23.97	86,000
1840	May 28	37.8	270,000	1910	Mar. 2	26.4	69,800	1948	Feb. 10	23.90	83,200
[2]1852	Aug. 29	37.4	250,000	1911	Apr. 14	19.1	32,8D0	1949	Nov. 30	26.61	154,000
[3]1864	Jan. 1	34.9	185,000	1912	Mar. 17	36.8	234,000	1950	Oct. 9	20.10	32,500
1865	Jan. 11	36.9	240,000	1913	Mar. 16	35.1	156,000	1951	Oct. 22	22.32	46,300
1876	Dec. 30	28.6	86,400	1914	Dec. 31	24.3	48,000	[6]1952	Mar. 6	21.53	39,300
1877	Apr. 14	31.4	119,000	1915	Jan. 20	28.2	61,000	1953	May 8	20.80	35,200
1878	Nov. 23	23.5	51,500	1916	Feb. 3	31.0	82,400	1954	Mar. 30	17.39	25,500
1879	Aug. 3	22.0	44,000	1917	Mar. 6	29.2	68,000	1955	Apr. 15	16.77	23,900
1880	Dec. 16	30.1	102,000	1918	Jan. 30	25.5	45,500	1956	Apr. 12	14.70	18,600
1881	Mar. 18	32.2	130,000	1919	Dec. 24	35.0	128,000	1957	May 7	14.08	18,000
1882	Sept.12	29.3	93,300	1920	Dec. 11	35.4	133,000	1958	Apr. 18	22.91	66,300
1883	Jan. 22	30.8	111,000	1921	Feb. 11	35.1	129,000	1959	June 8	18.65	28,500
1884	Apr. 16	28.0	81,000	1922	Feb. 16	32.0	92,000	1960	Feb. 14	20.58	34,900
1885	Jan. 26	27.5	77,000	1923	Feb. 28	28.0	59,700	[7]1961	Apr. 2	20.56	34,800
1886	May 21	32.5	135,000	1924	Sept.22	28.0	59,700	1962	Jan. 9	20.09	32,500
1887	July 31	34.5	173,000	1925	Jan. 20	36.5	150,000	1963	Mar. 23	19.52	31,300
1888	Sept.11	38.7	303,000	1926	Jan. 20	27.3	55,300	1964	Apr. 9	24.16	87,100
1889	Feb. 19	33.3	149,000	1927	Dec. 30	24.0	39,000	1965	Dec. 27	20.62	34,600
1890	Feb. 27	22.9	48,500	1928	Aug. 17	40.4	226,000	1966	Mar. 6	21.50	39,300
1891	Mar. 10	35.5	197,000	1929	Sept 27	46.3	343,000	1967	Aug. 25	18.10	26,500
1892	Jan. 20	32.8	140,000	1930	Oct. 2	45.1	350,000	1968	Jan. 12	20.94	35,900
1893	Feb. 14	25.0	60,000	1931	Nov. 17	19.9	26,100	1969	Apr. 21	22.24	45,600
1894	Aug. 7	24.0	54,000	1932	Jan. 9	30.4	93,800	1970	Apr. 1	17.68	25,200
1895	Jan. 11	30.4	106,000	1933	Oct. 18	30.3	92,600	1971	Mar. 5	23.30	63,900
1896	July 10	30.5	107,000	1934	Mar. 5	28.5	73,200	1972	Jan. 20	20.36	33,700
1897	Apr. 6	29.3	93,300	1935	Mar. 15	27.4	63,700	1973	Apr. 8	21.63	40,200
1898	Sept. 2	31.3	117,000	1936	Apr. 8	41.2	258,000	1974	Feb. 23	20.13	32,900
1899	Feb. 8	31.0	113,000	1937	Jan. 4	30.1	91,400	1975	Mar. 25	22.24	45,600
1900	Feb. 15	32.7	138,000	1938	Oct. 21	30.1	91,400	1976	June 5	20.27	33,300
1901	Apr. 4	31.8	124,000	1939	[4]Mar. 2	[5] 24.10	90,900	1977	Apr. 7	20.50	34,200
1902	Mar. 1	34.6	175,000	1940	Aug. 15	29.40	239,000	1978	Jan. 26	21.98	43,100
1903	Feb. 9	33.2	147,000	1941	July 8	22.89	53,300	1979	Feb. 27	21.13	37,300
1904	Aug. 10	25.5	63,000	1942	Mar. 23	24.56	105,000	1980	Mar. 31	22.33	47,200
1905	Feb. 14	25.8	64,800	1943	Jan. 20	25.10	117,000	1981	Feb. 12	14.70	17,700
1906	Jan. 5	29.6	96,600	1944	Mar. 22	25.53	128,000	1982	Jan. 2	19.39	30,700
1907	Oct. 5	23.6	52,000	1945	Apr. 27	23.16	64,000	[8]1983	Apr. 10	23.21	66,100
1908	Aug. 27	38.8	307,000	1946	Jan. 9	24.43	97,200	1984	Mar. 5	20.35	34,000
								1985	Feb. 7	17.89	25,700

Note: [1] Flood of January 17, 1796, reached a stage of about 40 feet (at site and datum of Fifth Street gage), marked by local residents; discharge approximately 360,000 ft³/s, by slope conveyance study. Little information exists and the data are considered approximate. Data furnished by the U.S. Army Corps of Engineers.

[2] A horizontal line in "Water year" column indicates discontinuous record.

[3] U.S. House of Representatives Document No. 64.

[4] Lines across the "Date" and "Discharge" columns indicate a change in the site that significantly affects the stage-dischage relation.

[5] A line across the "Stage" column indicates a change in gage datum and means that the stages above and below the line are not comparable.

[6] Filling of Thurmond Lake began in December 1951.

[7] Filling of Hartwell Lake began in February 1961.

[8] Filling of Russell Lake began in October 1984.

Table 3.--Drainage areas and periods of record for gaging stations in the Savannah River basin from which stage and discharge data were obtained

Station number	Site or station	Drainage area, square miles	Period of record
02184000	Tugaloo River near Hartwell, Ga.	909	1925-1927 1940-1960
02187000	Seneca River near Anderson, S.C.	1,026	1928-1959
02187250	Hartwell Lake near Hartwell, Ga.	2,088	1959-current year
02187500	Savannah River near Iva, S.C.	2,231	1950-current year
02189000	Savannah River near Calhoun Falls, S.C.	2,876	1896-1898 1899-1900 1930-1932 1938-1982
02189004	Richard B. Russell near Calhoun Falls, S.C.	2,900	1984-current year
02191300	Broad River above Carlton, Ga.	760	1898-1988
02192000	Broad River near Bell, Ga.	1,430	1926-1932 1937-current year
02194500	Thurmond Lake near Clarks Hill, S.C.	6,150	1951-current year
02195000	Savannah River near Clarks Hill, S.C.	6,150	1940-1954
02197000	Savannah River at Augusta, Ga.	7,508	1883-1891 1896-1906 1925-current year

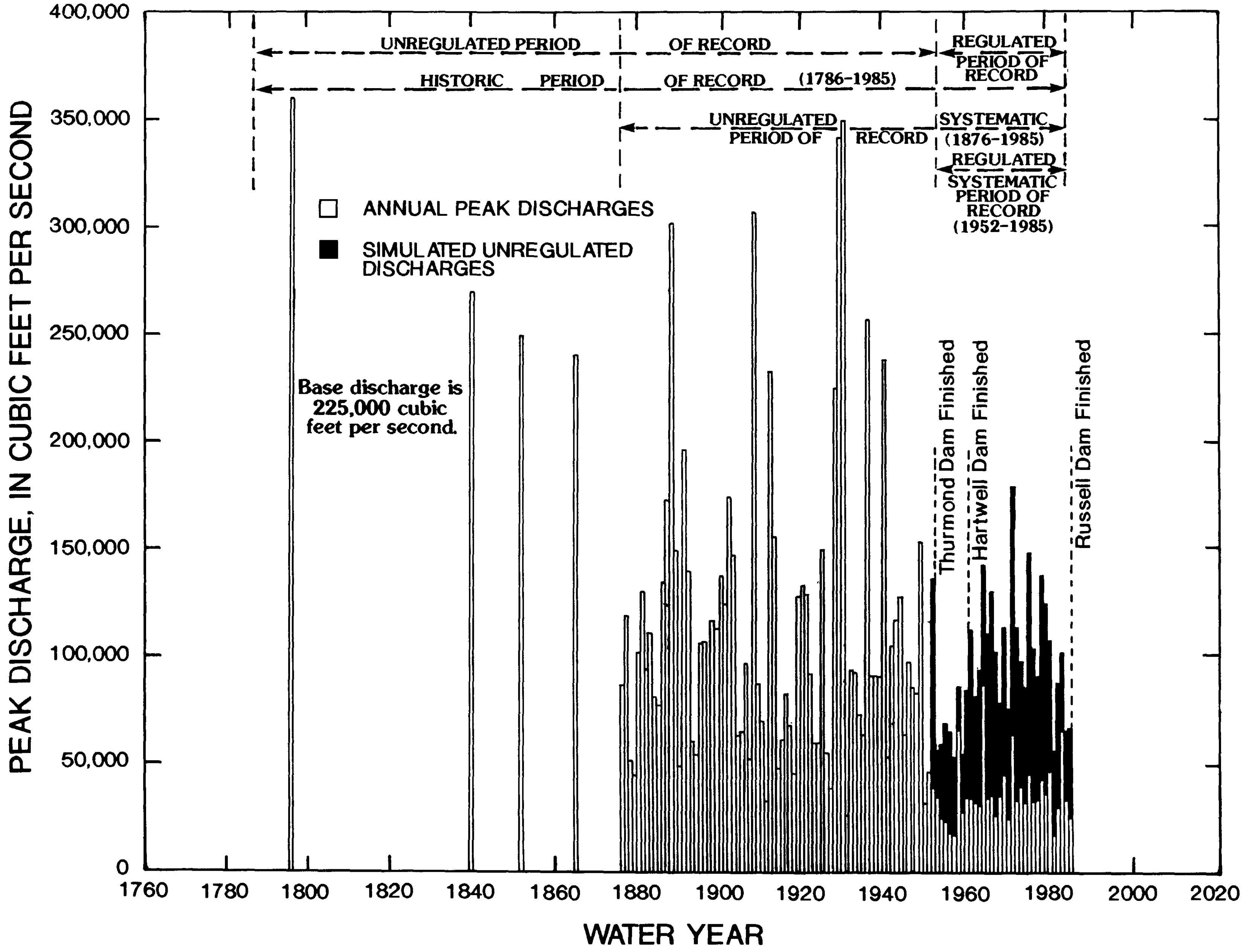


Figure 2.--Annual peak discharges and simulated unregulated peak discharges for the Savannah River at Augusta, Ga. (02197000) for 1786-1985.

Based on information currently (1990) available, the range of uncertainty for the stage of the flood of 1796 extends from 37 to 41 ft, with a corresponding range of discharge from 240,000 ft^3/s to 410,000 ft^3/s. The published stage of 40 feet and discharge of 360,000 ft^3/s were used in the frequency analysis of this report. The first reference to a stage of 40 ft appeared in House Executive Document No. 23, dated January 1881. Other references that show a stage of 40 ft are Emigh (1914), COE (1929), House Document No. 64 (1935), and Carter (1951). Carter (USGS, written commun., 3/23/50) indicates that in 1930 the COE had knowledge of a high-water mark for the 1796 flood and had determined the discharge by a slope-conveyance computation; no records of the high-water mark or the computation are available at this time (1990).

Publications prior to House Document No. 64 (1935) list various values for peak stages for several early floods on the Savannah River at Augusta. Most publications indicate that the gage at the 5th street bridge was read routinely from 1 to 4 times daily (Hall and Hall, 1907). During floods the gage was read more frequently. Therefore, the differences may be because some publications may show observed stage and other publications may show the interpolated peak stage based on more than one observed stage. These floods and the peak stages published prior to 1951 and those used in this report are listed in table 4.

APPROACH

Peak discharges for 5 historic and for floods in water years 1876-1985 as given in table 2 consist of unregulated peak discharges prior to 1952 and regulated peak discharges since 1952.

To determine the one-percent chance exceedance flood, a flood in which the peak discharge has a one-percent chance of being exceeded in any year, it is desirable to use the longest period of record possible (Interagency Advisory Committee on Water Data, 1982).

The period of record used for a flood-frequency analysis can have a substantial effect on the discharge for a given probability of exceedance; for example, the one-percent chance exceedance flood computed for the Broad River near Carlton, Ga. for the period 1898-1985 is 49 percent greater than that computed for the period 1952-85 (fig. 3). Similarly, the one-percent chance exceedance flood computed for the Savannah River near Calhoun Falls, S.C. for the period 1900-1960 is 18 percent greater than that computed for the period 1931-60 (fig. 4). These differences would be even greater if the large floods that occurred during the eighteenth and nineteenth centuries were included. The peak discharges for neither river were subject to significant regulation during these periods.

Table 4.--Published peak stages for early floods of the Savannah River at Augusta, Ga. (02197000)

[dashes indicate no data]

Flood	U.S. House of Represen-tatives Executive Document No. 213 1890	Murphy 1906	Emigh 1914	U.S. House of Represent-tatives Document No. 615 1916	Corps of Engineers 1929	U.S. House of Represent-tatives Document No. 64 1935	Carter 1951	This report 1990
1796	--	--	40	39.5	40	40.0	40	[1]40
1840	37.5	37.8	37.8	37.8	37.8	37.8	37.8	37.8
1852	36.8	36.8	37.4	37.4	37.4	37.4	37.4	37.4
1864	34.0	--	34.9	34.9	34.9	34.9	--	34.9
1865	36.4	36.4	36.9	36.9	36.9	36.9	36.9	36.9
1888	38.7	38.7	38.7	38.8	38.7	38.7	38.7	38.7
1908	--	--	38.8	38.9	38.8	38.8	38.8	38.8

[1]An analysis of the flood frequency in this report includes discharges for stages of 37, 40, and 41 feet for the flood of 1796.

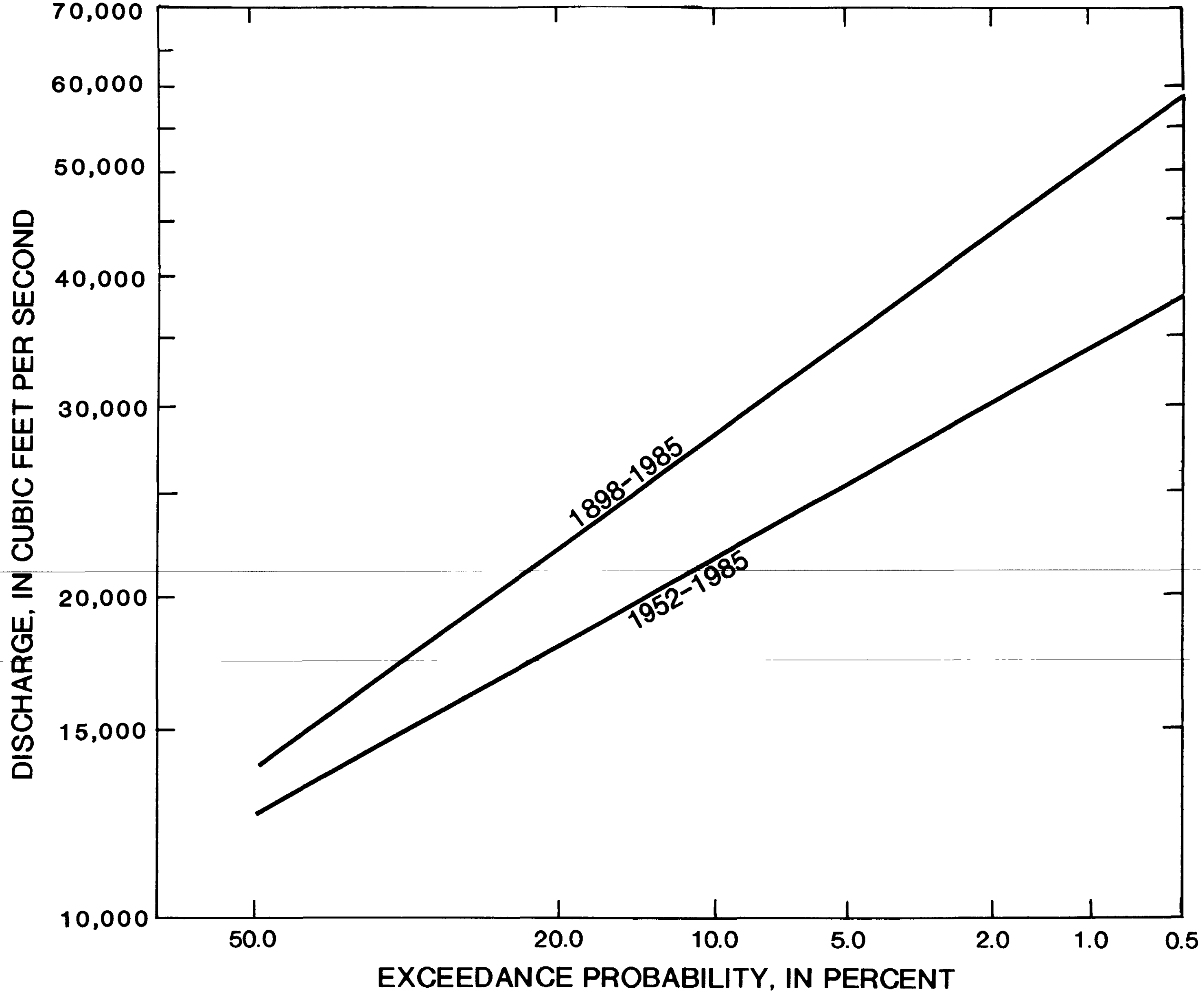


Figure 3.--Flood-frequency relations based on two different periods of record for the Broad River above Carlton, Ga. (02191300)

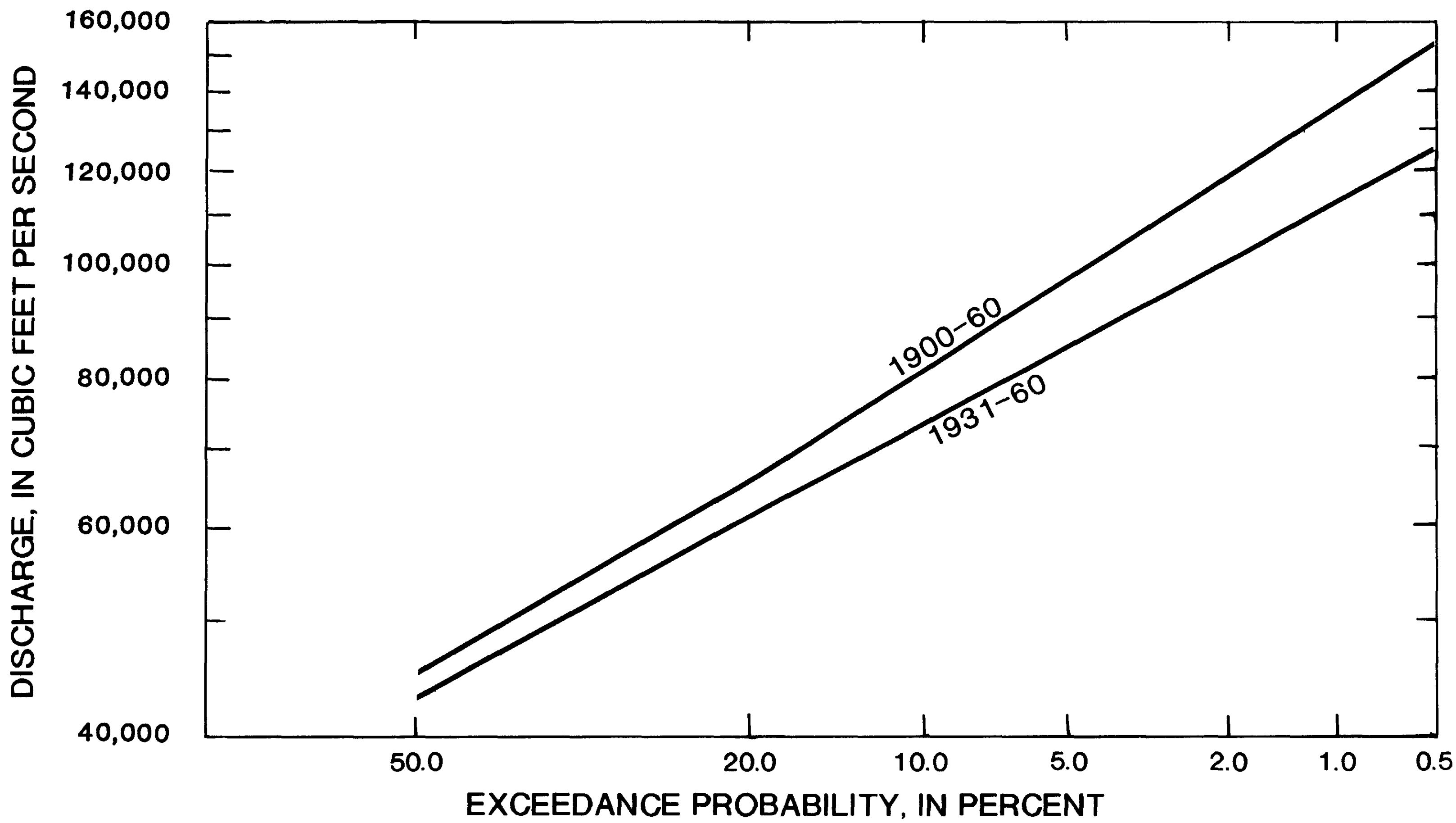


Figure 4.--Flood-frequency relations based on two different periods of record for the Savannah River near Calhoun Falls, S.C. (02189000).

The analysis used in this report utilizes the period of record from 1786 through 1985 and includes the combined regulation capability of Thurmond, Hartwell and Russell Dams, and is based on 1990 dam operating criteria (COE, 1974). The period of record commences with the water year (1786) in which the Augusta Chronicle commenced publication, because the Chronicle apparently reported any significant flooding of Augusta for the period of record.

The approach used in the analysis was:

A. Peak discharges for regulated conditions for 1952-85 were converted to peak discharges for unregulated conditions using a streamflow routing model and inflow hydrographs estimated from daily streamflow and reservoir storage data.

B. Peak discharges for nine major unregulated floods were converted to peak discharge for regulated conditions, using a reservoir routing model, current reservoir operation criteria, streamflow routing parameters, inflow hydrographs, and simulated initial lake elevations. The inflow hydrographs were developed using a rainfall-runoff model or using hydrographs of the Broad River near Bell, Ga. (02192000) or above Carlton, Ga. (02191300) adjusted for relative drainage area size, storm rainfall amounts, and calibration residuals. Hypothetical regulated peak discharges were also developed using the unregulated discharges multiplied by factors of 1.25, 1.50, and 2.00.

   Initial lake elevations were determined for the beginning of major floods using a reservoir routing model and daily flows computed from daily discharge data at gaging stations. Median daily lake elevations were used when inflow data were not available for use in the reservoir routing model.

C. A relation between regulated and unregulated peak discharges was graphically established using the data from steps A and B.

D. A flood-frequency relation for unregulated conditions was developed by fitting a Pearson Type III distribution to the logarithms of the unregulated peak discharges. A systematic record period of 1876-1985, a historical period of 1786-1985, and a historical flood threshold of 225,000 ft^3/s were used. For an explanation of the significance of these flood-frequency parameters, see Hydrology Subcommittee Bulletin 17B (Interagency Committee on Water Data, 1982).

E. The flood-frequency relation for unregulated conditions was converted to a flood-frequency relation for regulated conditions using total probability methods and the relation between regulated and unregulated peak discharges.

F. Frequency plotting positions were computed for the highest 10 regulated peak discharges above a historic threshold discharge of 90,000 ft^3/s using a historic period of 1786-1985 and for the measured regulated peak discharges for water years 1952-85, historically adjusted to match the longer period. The 10 highest discharges were either simulated or obtained from the regulated-unregulated frequency relation.

G. The final regulated flood frequency relation was obtained by averaging the independent estimates developed in steps E and F.

SIMULATED PEAK DISCHARGES

The regulated peak discharges for water years 1952-85 were converted to unregulated peak discharges using daily lake stage and storage data, daily discharge data and the streamflow routing capabilities of the HEC-1 computer program (COE, 1985). Unregulated peak discharges for floods during water years 1908, 1912, 1928, March and September 1929, 1930, 1936, 1940, and 1949, were converted to regulated peak discharges using estimated daily, hourly, and bi-hourly hydrographs, streamflow routing parameters, 1990 lake operation criteria and the HEC-5 reservoir-routing computer program (COE, 1982).

The lake system and areas A-E for which hydrographs were computed are shown in figure 5 and schematically in figure 6. Hydrographs for areas A and C were combined for use in simulating unregulated peak discharges for water years 1952-85, regulated peak discharges for the 1936 flood, and initial lake elevations for 1927-85. The inflow hydrographs for each of the areas represent the flow contributed by the area to the river or lake. The "local inflow" of an area is the difference between the flow from an immediate upstream area and the outflow from the area in question.

Regulated discharges for the Savannah River at Augusta for 1952-85 were converted to unregulated discharges by routing of inflows using the HEC-1 streamflow model (COE, 1985). HEC-1 has rainfall-runoff modeling capability, which was used to generate hourly inflow hydrographs for the 1936 flood.

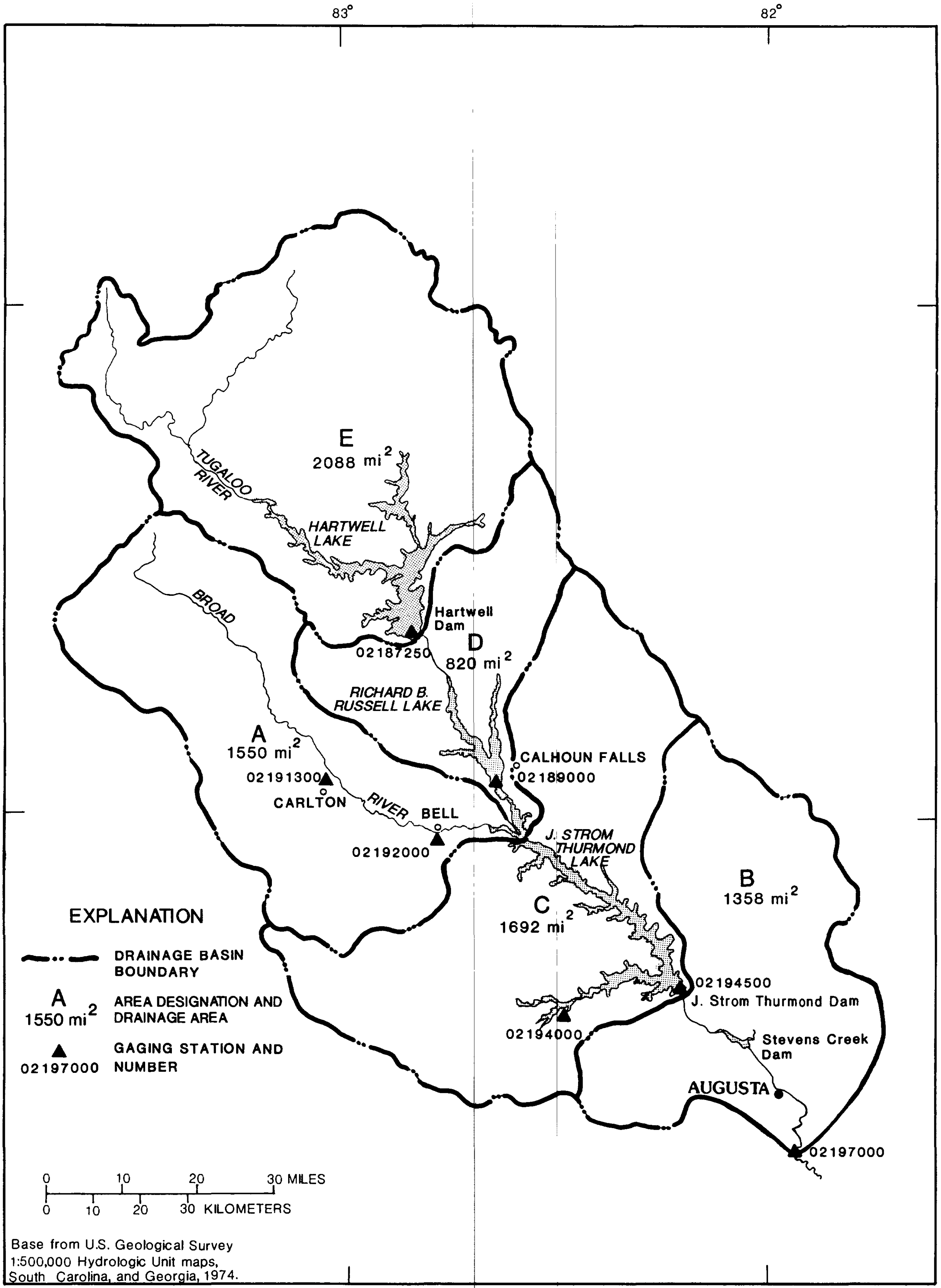


Figure 5.--Areas, drainage areas, and gaging stations used in estimating unregulated inflow hydrographs.

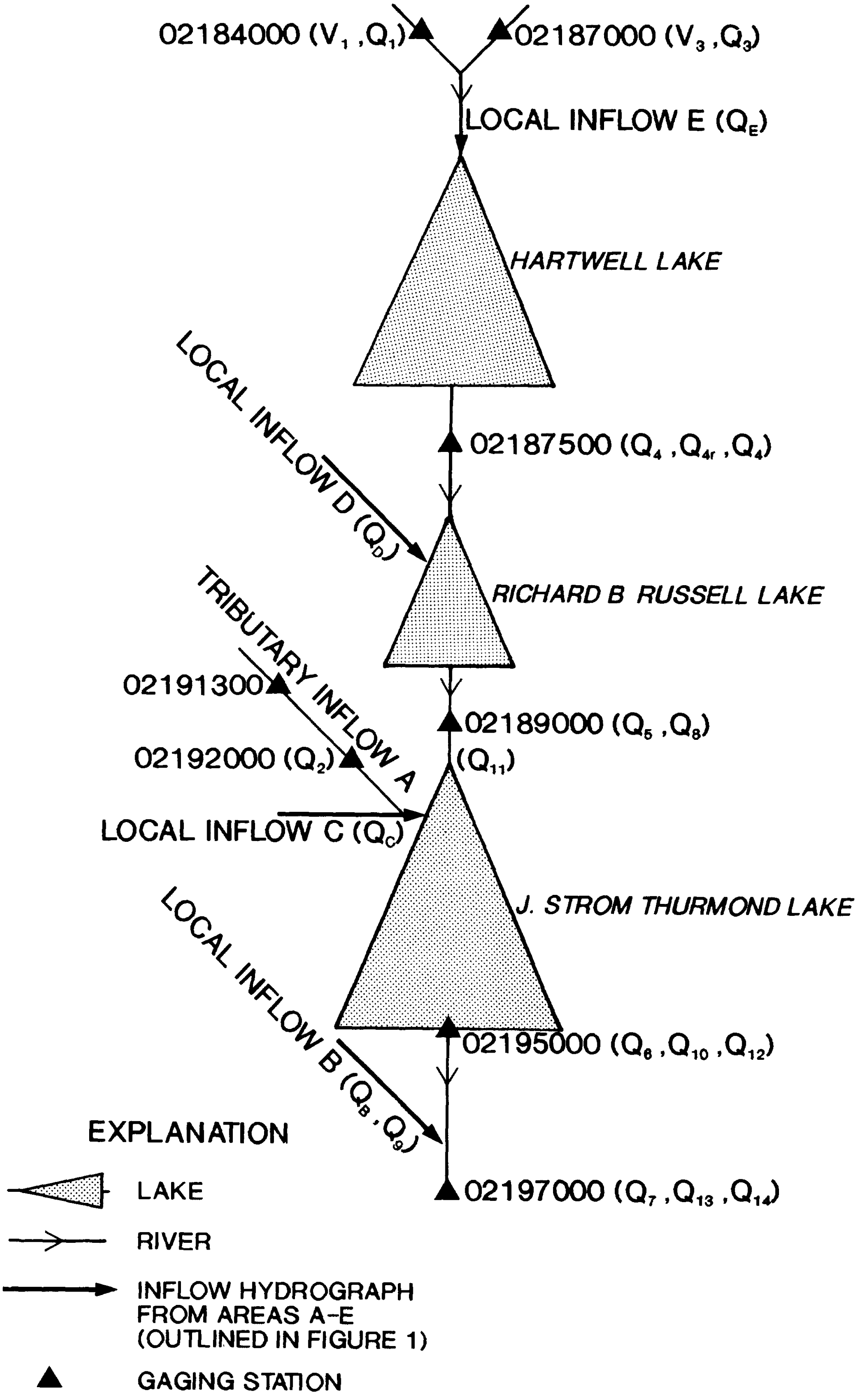


Figure 6.--Schematic diagram of the study area.

The HEC-1 computer program is a generalized hydrologic program developed by the COE Hydrologic Engineering Center (HEC) to simulate the surface-runoff response of a river basin to precipitation by representing the basin as an interconnected system of hydrologic and hydraulic components (COE, 1985). Input to the HEC-1 computer program consisted of routing parameters, inflow hydrographs, precipitation data, and interception/infiltration parameters. The HEC-1 program supports a variety of hydrologic computation procedures. In this study, the Soil Conservation Service (SCS) curve number method was used to compute rainfall excess, the unit hydrograph method was used to compute discharge from rainfall excess and the Muskingum method was used for flood routing in channels.

A reservoir routing model, HEC-5 (COE, 1982), was used to route daily inflow hydrographs through the three reservoirs to establish initial lake elevations for hourly hydrographs for eight floods, which were routed through the system using the HEC-5 model.

The HEC-5 computer program is a generalized hydrologic reservoir computer program developed by the COE Hydrologic Engineering Center to simulate operation of reservoirs for flood-control purposes during a single flood or for conservation purposes (such as maintenance of minimum flows for water supply) and for period-of-record routings (COE, 1982). The HEC-5 model was developed to assist in planning studies for evaluation of proposed reservoirs, and to assist in sizing the flood control and conservation storage requirements for a specified project. The program allows simulation of the sequential operation of a system of reservoirs of any configuration for short-interval historic or synthetic floods. For detailed information, refer to the users manual (COE, 1982).

Input to the HEC-5 model consisted of routing parameters, stage-storage relations for reservoirs, reservoir operation rules and constraints, system configuration, inflow hydrographs, and initial pool elevations.

The Muskingum method for channel routing was used to route hydrographs through channel reaches and through each reservoir to the dam. The Muskingum method approximates outflow from a channel reach as a linear function of inflows at current and previous time steps. Flow was routed through the dams using reservoir storages, reservoir operation criteria (COE, 1974), and flow constraints at downstream locations.

HEC-5 was modified to accommodate the complex channel flow capacity criteria specified in plate A-7-1 of the "Reservoir Regulation Manual, Savannah River Basin," (COE, 1974).

Requirements for releases from Thurmond Dam include:

1) maintenance of minimum weekly average flow of 3,600 ft^3/s for water supply and hydropower generation,

2) variation of operating channel flow capacity at Augusta from 20,000 ft^3/s to 30,000 ft^3/s, depending on pool elevations,

3) releases in excess of 30,000 ft^3/s to prevent dam overtopping, and

4) maintenance of discharge at Augusta equal to maximum local inflow during periods of falling reservoir stages during floods to lower lake levels as quickly as possible.

Unregulated Peak Discharges

Regulated peak discharges were converted to unregulated peak discharges by the following methodology:

1. For water years 1952-85, daily inflow hydrographs were estimated using peak discharge, daily discharge, and daily lake elevation data. Local inflows were computed from the hydrologic storage equation, Local Inflow = Outflow - Upstream Inflow + Change in Storage. Where there were no reservoirs in the areas where local inflows were computed, the changes in storage was assumed to be zero. Where the areas included reservoirs, changes in storage were computed using measured lake elevations and relations of lake storage to lake elevation (COE, 1974). Negative daily local inflows sometimes resulted using the change-in-storage method, most likely because of non-equilibrium conditions at the time of day when reservoir elevations were measured. These negative inflows were set at a representative minimum flow. In such cases, all hydrograph ordinates were multiplied by a constant to adjust the computed volume to equal the measured volume. Inflow hydrographs were transferred to other locations in proportion to drainage area ratios.

2. The daily inflow hydrographs were converted to 2-hour hydrographs by interpolation, and then routed through the regulated river system to ensure that flood volumes were preserved.

3. The 2-hour inflow hydrographs were then routed through the stream system without the reservoirs, using HEC-1, to simulate unregulated hydrographs and peak discharges for the water years 1952-85 (fig. 2 and table 5).

Table 5.--Measured regulated and simulated unregulated peak discharges for the Savannah River at Augusta, Ga. (02197000) for the period 1952-1985

[ft³/s, cubic feet per second]

Water year	Measured regulated discharge (ft³/s)	Simulated unregulated discharge (ft³/s)
1952	39,300	137,000
1953	35,200	56,400
1954	25,500	59,100
1955	23,900	68,400
1956	18,600	65,200
1957	18,000	53,400
1958	66,300	86,100
1959	28,500	54,900
1960	34,900	84,700
1961	34,800	113,000
1962	32,500	81,700
1963	31,300	94,000
1964	87,100	143,000
1965	34,600	111,000
1966	39,300	131,000
1967	26,500	102,000
1968	35,900	79,000
1969	45,600	114,000
1970	25,200	74,300
1971	63,900	180,000
1972	33,700	114,000
1973	40,200	98,000
1974	32,900	86,000
1975	45,600	149,000
1976	33,300	104,000
1977	34,200	90,900
1978	43,100	138,000
1979	37,300	125,000
1980	47,200	108,000
1981	17,700	56,100
1982	30,700	88,000
1983	66,100	102,000
1984	34,000	65,600
1985	25,700	66,300

Regulated Peak Discharges

Regulated discharges were simulated for flood events during water years 1908, 1912, 1928, March and September 1929, 1930, 1936, 1940 and 1949 by:

1. Assuming initial lake elevations for the 1908 and 1912 floods to be equal to median daily lake levels at Hartwell and Thurmond Lakes and the rule curve elevation for Russell Lake.

2. Estimating daily inflow hydrographs into each lake for the period 1927-1951.

3. Simulating daily lake elevations for the period 1927-1951 using the daily inflow hydrographs and the HEC-5 model to provide initial lake elevations for the floods being routed.

4. Estimating hourly inflow hydrographs for the floods being routed, using a rainfall-runoff model or using hydrographs of the Broad River near Bell, Ga. (02192000) or above Carlton, Ga. (02191300) adjusted for relative drainage area size, storm rainfall amounts, and calibration residuals. Hypothetical regulated peak discharges were also developed using the unregulated discharges multiplied by factors of 1.25, 1.50, and 2.00.

5. Calibrating the HEC-5 model using hydrographs from gaging stations on the Savannah River.

6. Routing the calibrated inflow hydrographs to Augusta using the HEC-5 model with regulated conditions.

Computation of Daily Lake Inflow Hydrographs for the Period 1927-51

Daily lake inflow hydrographs were estimated for 1927-51 and used with the HEC-5 program to estimate initial pool elevations for floods in water years 1928, 1929, 1930, 1936, 1940, and 1949, for which hourly hydrographs were available. The procedure used to compute daily inflow hydrographs depended on available data.

Local inflows were computed from the hydrologic storage equation as explained previously. Some hydrographs were computed by multiplying daily discharges collected at other sites on the same stream in an area by the ratios of the drainage areas of the sites.

During the subtraction process, negative flows were occasionally computed. These negative flows were eliminated by the following steps:

1. computing the annual means of the unadjusted daily values,

2. adjusting all flows below a reasonable minimum flow to the minimum flow,

3. computing the annual means of the adjusted daily flows, and

4. preserving measured annual volume, by multiplying the adjusted daily flows of step 2 by the ratios of the annual means of the unadjusted values to the annual means of the adjusted annual means in step 3.

Equations for computing daily inflows are listed in table 6.

Simulation of Initial Pool Elevations

Initial pool elevations for the 1928, March and September 1929, 1930, 1936, 1940, and 1949 water-year floods were determined by routing the daily inflow hydrographs through the reservoirs using HEC-5. Current requirements for flood control, hydropower, and conservation storage were incorporated into the model. Hydropower production loads were used according to Southeastern Power Administration contract requirements. Storage rule curves obtained from the Reservoir Regulation Manual (COE, 1974) for Thurmond and Hartwell Lakes and the Interim Reservoir Regulation Criteria (COE, written commun., 1983) for Russell Lake. Channel capacity at Augusta was set according to Plate A.7.1 of the Reservoir Regulation Manual (COE, 1974). Initial pool elevations for Hartwell and Thurmond Lakes for the 1908 and 1912 floods were estimated using median daily lake elevations for periods preceding the flood dates for years 1963-85 (Hartwell) and 1971-85 (Thurmond), excluding 1981. Records for calendar year 1981 for both lakes and prior to 1971 for Thurmond Lake were excluded because of uncharacteristically low lake elevations. The rule-curve elevation was used for Russell Lake. Initial pool elevations are listed in table 7.

Table 6.--Equations for computing daily inflow hydrographs

Period (inclusive)	Equations for computing daily discharge
	to Hartwell Lake
October 1927 - June 1928	$Q_{E1} = K_1\ Q_{4r}\ (D_h/D_i)$
July 1928 - January 1940	$Q_{E2} = Q_3(V_4\ D_h/V_3D_i)$
February 1940 - September 1950	$Q_{E3} = (Q_1+Q_3)\ (V_4\ D_h/D_i(V_1+V_3))$
October 1950 - June 1961	$Q_{E4} = Q_4\ D_h/D_i$
	to Russell Lake
October 1927 - May 1930	$Q_{D1} = Q_{E1}\ (D_r-D_h)/D_h$
April 1930 - April 1932	$Q_{D2} = Q_5-Q_8$
May 1932 - March 1938	$Q_{D1} = Q_E\ (D_r-D_h)/D_h$
April 1938 - January 1961	$Q_{D2} = Q_5-Q_8$
	to Thurmond Lake
October 1927 - March 1930	$Q_{C1} = Q_7-Q_9-Q_{10}$
April 1930 - April 1832	$Q_{C2} = Q_7-Q_9-Q_{11}$
May 1932 - March 1938	$Q_{C1} = Q_7-Q_9-Q_{10}$
April 1938 - May 1940	$Q_{C2} = Q_7-Q_9-Q_{10}$
June 1940 - June 1954	$Q_{C3} = Q_{12}-Q_{10}$
	to the reach of the Savannah River between Thurmond Dam and the Savannah River at Augusta, Georgia (02197000)
October 1927 - May 1940	$Q_{B1} = K_1\ Q_7$
June 1940 - June 1954	$Q_{B2} = Q_7-Q_{14}$

where

D_h is the drainage area for Hartwell Lake near Hartwell, Ga. (02187250); in mi^2.

D_i is the drainage area for the Savannah River near Iva, S.C. (02187500), in mi^2.

D_r is the drainage area for the Richard B. Russell Lake near Calhoun Falls, S.C. (02189004), in mi^2.

K_1 is an adjustment factor (1.05) to preserve volumes.

K_2 is an average of factors (K_3) computed by the equation:

$$K_3 = \frac{Q_{13} - Q_{12}}{Q_7}$$

Q_{B1-2} is the daily mean discharge from area B to the Savannah River at Augusta (02197000) in ft^3/s.

Q_{C1-3} is the daily mean discharge from areas A and C at Thurmond Dam, in ft^3/s.

Q_{D1-2} is the daily mean discharge from area D at Russell Dam, in ft^3/s.

Q_{E1-2} is the daily mean discharge from area E to Hartwell Lake, in ft^3/s.

Q_1 is the daily mean discharge for the Tugaloo River near Hartwell, Ga. (02184000) in ft^3/s;

Q_2 is the daily mean discharge for the Broad River near Bell, Ga. (02192000) in ft^3/s;

Q_3 is the daily mean discharge for the Seneca River near Anderson, S.C. (02187000) in ft^3/s;

Q_4 is the daily mean discharge for the Savannah River near Iva, S.C. (02187500) in ft^3/s;

Q_{4r} is the daily mean discharge for the Savannah River near near Iva, in ft^3/s, computed from the regression equation: $Q_{4r} = 39.99\ Q_2^{0.664}$

Q_5 is the daily mean discharge for Savannah River near Calhoun Falls, S.C. (02189000)in ft^3/s;

Q_6 is the daily mean discharge for Savannah River near Clarks Hill, S.C. (02195000) in ft^3/s;

Q_7 is the daily mean discharge for the Savannah River at Augusta, Ga. (02197000), in ft^3/s;

Q_8 is the daily mean discharge as determined by routing the Hartwell inflows to the Savannah River near Calhoun Falls, S. C. (02189000) using the HEC-1 Model, in ft^3/s;

Q_9 is the daily mean discharge for the reach of the Savannah River between Thurmond Dam and the Savannah River at Augusta (02197000), in ft^3/s;

Q_{10} is the daily mean discharge as determined by routing the Hartwell and Russell inflows to Thurmond Dam using the HEC MATHPK program (Robert Carl, written commun.), in ft^3/s;

Q_{11} is the daily mean discharge, to Thurmond Lake as determined by routing the flow of the Savannah River at Calhoun Falls, S.C. (02189000) to Thurmond Lake using the HEC MATHPK program, in ft^3/s;

Q_{12} is the daily mean discharge, for the Savannah River near Clarks Hill, S.C. (02195000), in ft^3/s;

Q_{13} is the daily mean discharge as determined by routing the flow of the Savannah River near Clarks Hill, S.C. (02195000) to the Savannah River at Augusta, Ga. (02197000), by the HEC-1 program in ft^3/s;

Q_{14} is the daily mean discharge as determined by routing the flow of the Savannah River near Clarks Hill, S. C. (02195000) to the Savannah River at Augusta, (02197000), by the HEC MATHPK program, in ft^3/s;

V_1 is the accumulated daily discharge for the Tugaloo River near Hartwell, Ga. (02184000), in ft^3/s;

V_3 is the accumulated daily discharge for the Seneca River near Anderson, S.C. (02187000), in ft^3/s.

V_4 is the accumulated daily discharge for the Savannah River near Iva, S.C. (02187500), in ft^3/s.

Table 7.--Simulated initial lake elevations prior to major floods

Beginning flood date	Initial lake elevation (feet)		
	Hartwell	Russell	Thurmond
Aug. 21, 1908	658.6	475.0	329.7
Mar. 14, 1912	657.8	475.0	328.6
Aug. 13, 1928	660.0	475.0	330.3
Sept. 25, 1929	657.2	474.1	327.7
Mar. 24, 1936	659.0	475.0	328.5
Aug. 12, 1940	648.8	472.0	321.5
Nov. 26, 1948	656.4	475.0	327.5

Computation of Hourly Inflow Hydrographs

For the 1908, 1912, 1928, March and September 1929, 1930, 1940, and 1949 water-year floods, measured hydrographs were available for the following stations: Broad River near Bell, Ga. (02192000), Broad River above Carlton, Ga. (02191300), Savannah River near Calhoun Falls, S.C. (02189000), and Savannah River at Augusta, Ga. (02197000). The peak discharges for the eight floods for which measured hourly hydrographs were available occurred on the following dates:

Calendar date	Water year
August 27, 1908	1908
March 17, 1912	1912
August 17, 1928	1928
March 6, 1929	1929
September 27, 1929	1929
October 2, 1929	1930
August 15, 1940	1940
November 30, 1948	1949

Hereafter, these floods will be identified by month and (or) water year rather than by calendar date.

Regulated peak discharges at Augusta for the eight floods were estimated using measured hourly hydrographs and rainfall maps to estimate initial hourly hydrographs for five areas of the Savannah River upstream of Augusta, labeled A through E in figures 5 and 6. Shapes of the initial hourly hydrographs were derived from hydrographs of the Broad River above Carlton and near Bell. The initial hourly hydrographs were then adjusted for timing and discharge residuals at Augusta, and routed through the reservoirs using the HEC-5 reservoir flow-routing model. This method of determining hourly hydrographs is described as "hydrograph method" in this report.

The rainfall-runoff option of the HEC-1 model was used to simulate inflow hydrographs for the 1936 flood because measured discharge data were not available for the Savannah River near Calhoun Falls, S.C. (02189000). This method of determining inflow hydrograph is described as "rainfall-runoff method" in this report.

Hypothetical inflow hydrographs were computed by multiplying the discharges of the inflow hydrographs by factors of 1.25, 1.50, and 2.00. The hypothetical inflow hydrographs were used to determine the effects of regulation for floods larger than were actually experienced.

Hydrograph Method

Initial hydrograph shapes for areas of the Savannah River drainage basin upstream of Augusta were determined in the hydrograph method by using observed hydrographs for the Broad River, adjusted by relative drainage areas and rainfall volume. Hydrographs for areas B and C were refined further by adding prorated residuals between the computed hydrograph and the measured hydrograph of the Savannah River at Augusta. Hydrographs for areas C, D, and E were subsequently adjusted to shapes greater in discharge and shorter in time to account for the effect of shorter travel times through the reservoirs. Stevens Creek Reservoir was assumed to have negligible impact on large floods in the Savannah River, compared to the much larger flow regulation effected by Hartwell Lake, Russell Lake, and Thurmond Reservoir.

Area A.--An hourly hydrograph for area A, the Broad River drainage basin upstream from its mouth, beginning with construction of a "shape" hydrograph, was computed as described below:

1. The shapes of the hydrographs for the Broad River above Carlton, Ga., (760 mi^2) (square miles) and near Bell, Ga., (1,430 mi^2) were assumed to be representative of the shape of initial hourly hydrographs for areas A, B, C, and D, which range from 820 mi^2 to 1,692 mi^2. The Carlton hydrographs were used for the 1908 and 1912 floods because records were not available for the Bell gage. Hydrographs for the 1928, 1929, 1930, 1940, and 1949 floods were estimated using measured hydrographs at Bell.

2. Measured hydrograph discharges were multiplied by the factor Ry, and measured hydrograph times were multiplied by the factor Rx, to maintain a direct relation between volume and R (the drainage area ratio) where:

$$R = A_B/A_G,$$

$$Ry = R^{0.58}, \text{ and}$$

$$Rx = R/R^{.58},$$

and

A_B is the drainage area of the Broad River at its mouth, in mi² (table 3),

A_G is the drainage area for the Broad River above Carlton, Ga. (02191300) or near Bell, Ga. (02192000), in mi², and

$^{0.58}$ is the average slope of the relation of flood discharge of selected frequencies to drainage area, (Price, 1979 p. 17).

R is the ratio of the drainage area of the Broad River at its mouth to the drainage area above Carlton, Ga. (02191300) or near Bell, Ga. (02192000).

Ry is the drainage area adjustment factor for the hydrograph discharge. Peak discharges at two sites vary directly with the 0.58 exponent of the ratio of their respective drainage areas. The exponent of 0.58 is based on the slope of the regression between peak discharge for selected recurrence intervals and drainage area, as determined by Price (1979, p. 17).

Rx is the drainage area adjustment factor for the hydrograph time base. Hydrograph volumes were determined to vary directly with drainage area ratio on the average.

3. Operation (2) broadened the hydrograph and moved the centroid and peak later in time. The hydrographs were adjusted so that the hydrographs at the mouth occurred 20 hours later than at the Broad River above Carlton or 8 hours later than at the Broad River near Bell as projected from concurrent hydrographs at the two stations.

Discharges of the "shape hydrographs" constructed for the mouth of the Broad River were then multiplied by R_A to adjust for rainfall volume, assuming that flood volumes vary directly with the ratio of rainfall volumes upstream of the two sites and runoff and loss rates are similar. The following equations were used:

$$V_A = V_G(P_G A_G + P_A (A_B - A_G))/P_G A_G, \text{ and}$$

$$R_A = V_A/V_S,$$

where

V_A is the hydrograph volume at the mouth of the Broad River, in ft^3/s-hrs, adjusted for rainfall and drainage area,

V_G is the hydrograph volume at the gaging station, in ft^3/s-hrs,

V_S is the volume of the "shape hydrograph", in ft^3/s-hrs,

P_G is the average rainfall, in inches, for the drainage area upstream of the Broad River above Carlton, Ga. (02191300) or near Bell, Ga. (02192000) as derived from rainfall given in table 8 and from rainfall maps shown in figures 7-16.

P_A is the average rainfall, in inches, for the drainage area between the Broad River above Carlton, or near Bell and the mouth of the Broad River, derived and tabulated as described for P_G,

A_G as previously described, and

R_A is the ratio of the hydrograph volume at the mouth of the Broad River (adjusted for rainfall and drainage area) to the volume of the "shape hydrograph."

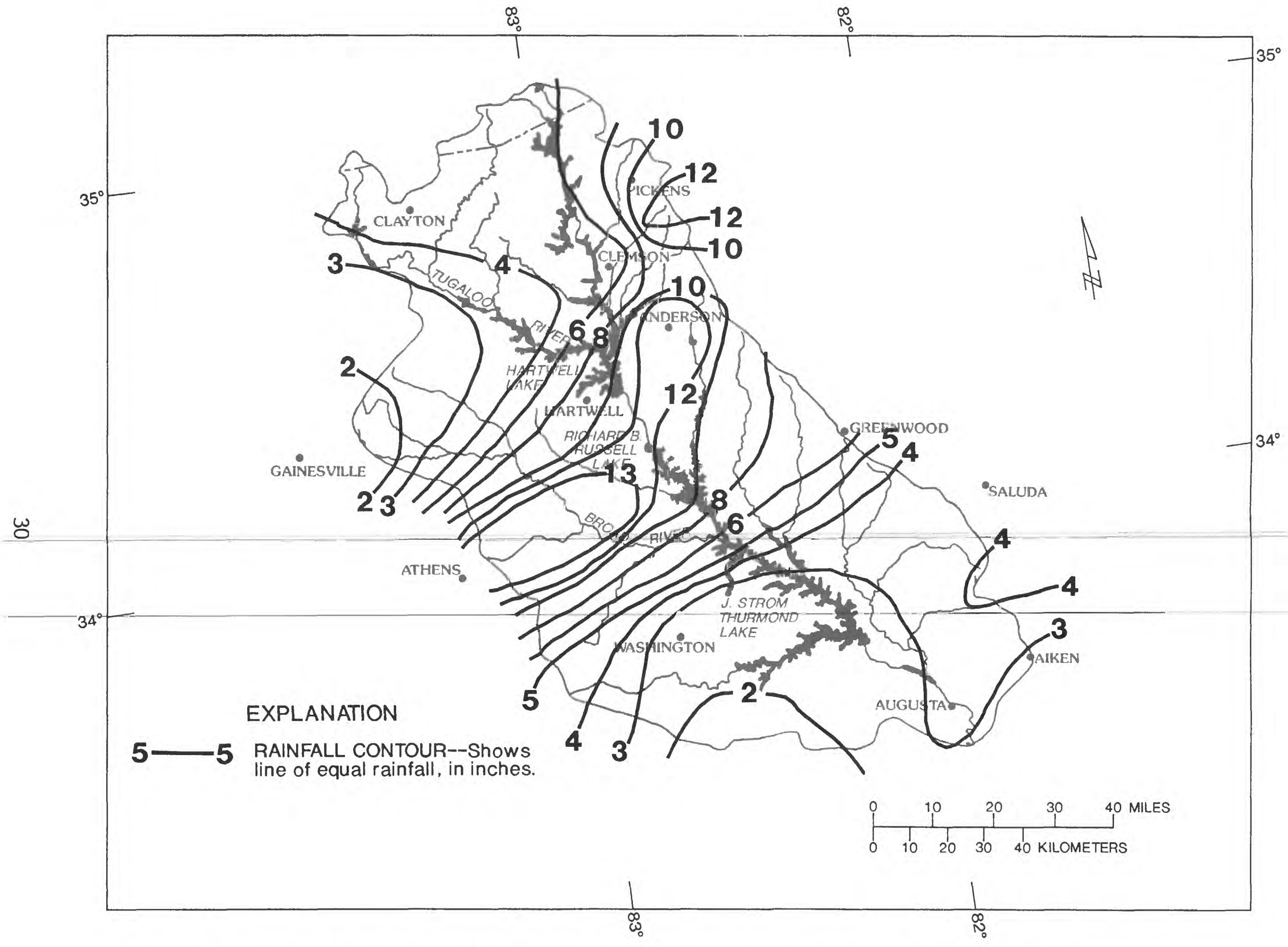


Figure 7.-- Lines of equal rainfall for Savannah River basin upstream from Augusta, Ga. for storm of August 23-26, 1908.

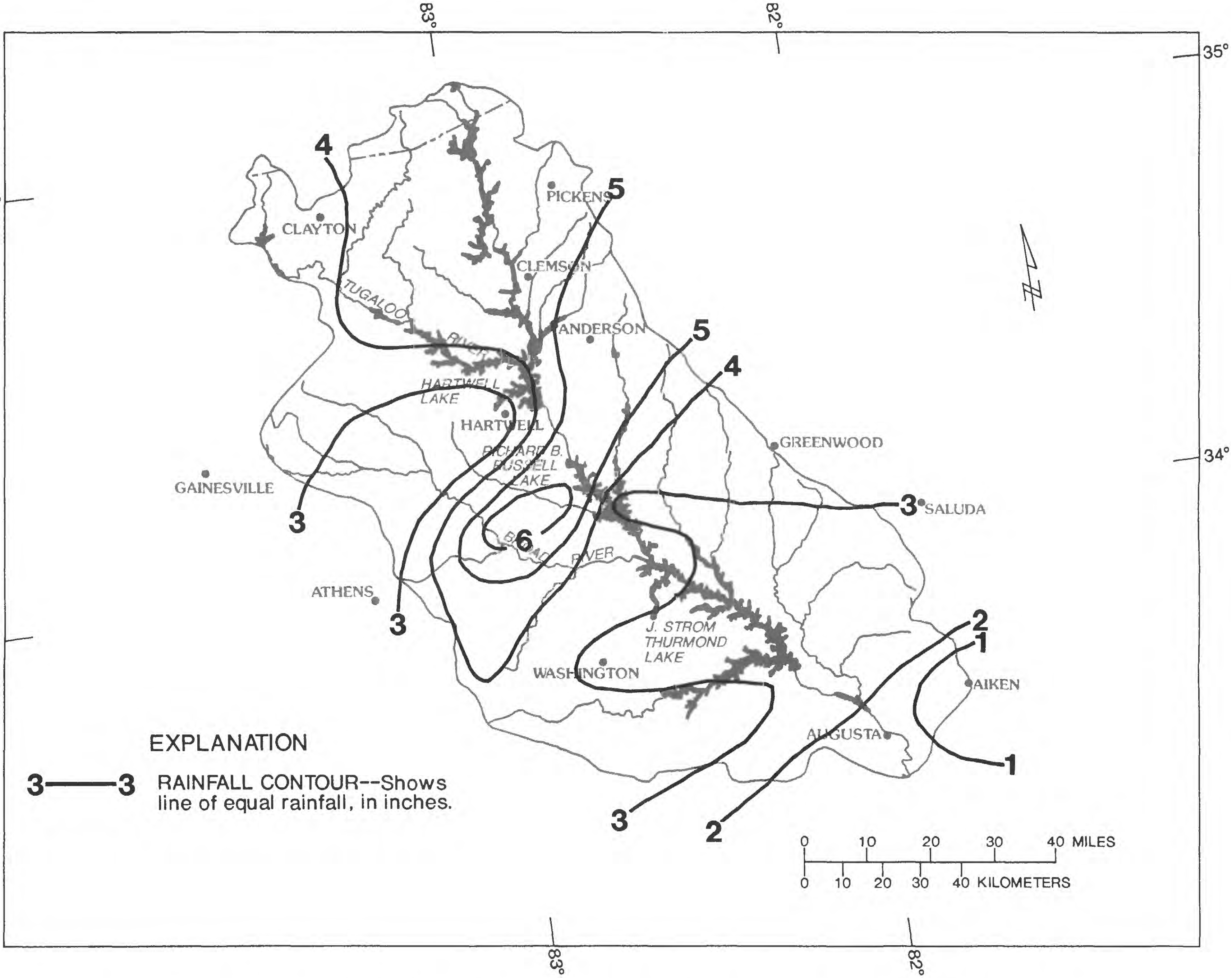


Figure 8.--Lines of equal rainfall for Savannah River basin upstream from Augusta, Ga. for storm of March 14-16, 1912.

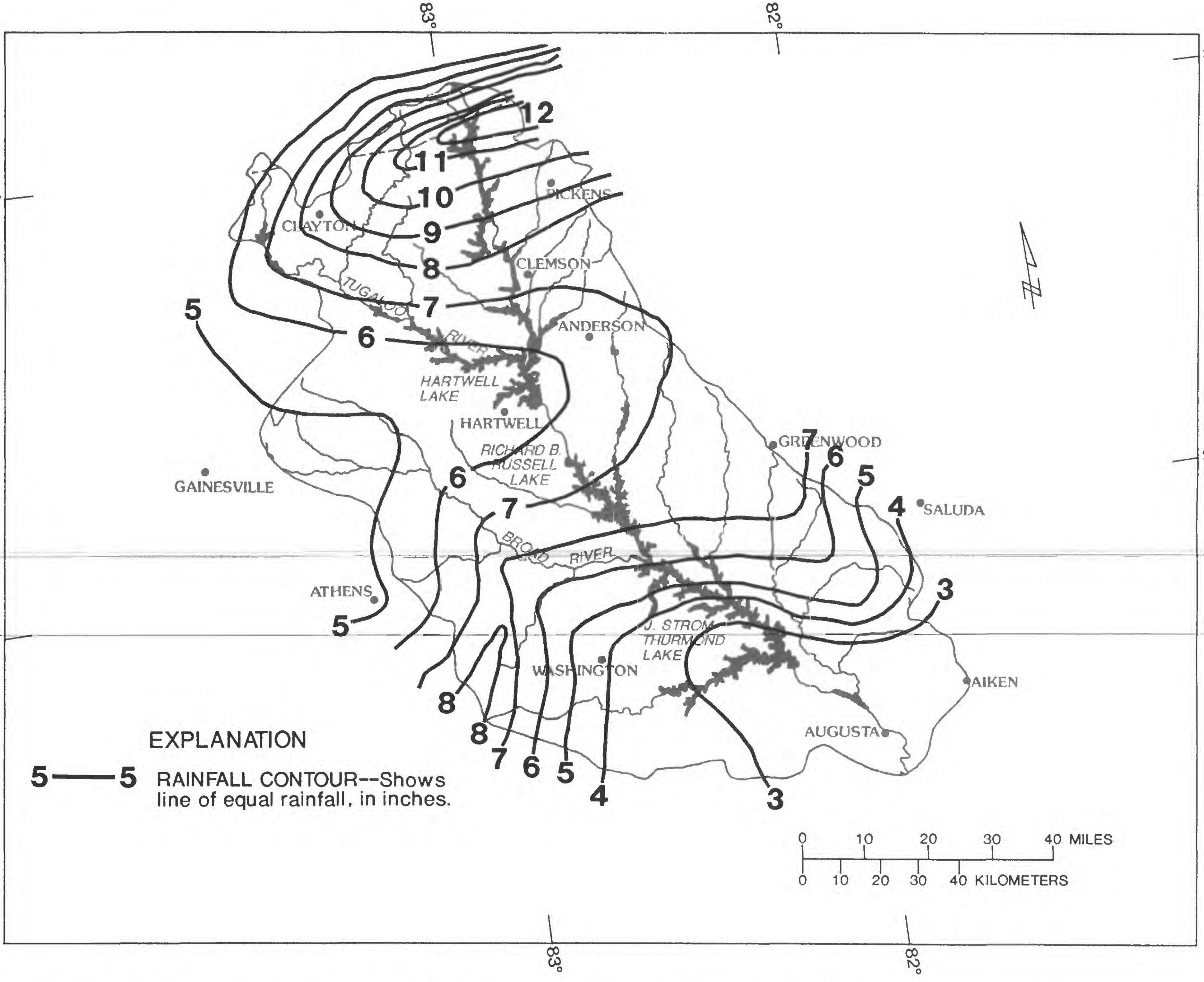


Figure 9.--Lines of equal rainfall for Savannah River basin upstream from Augusta, Ga. for storm of August 1928.

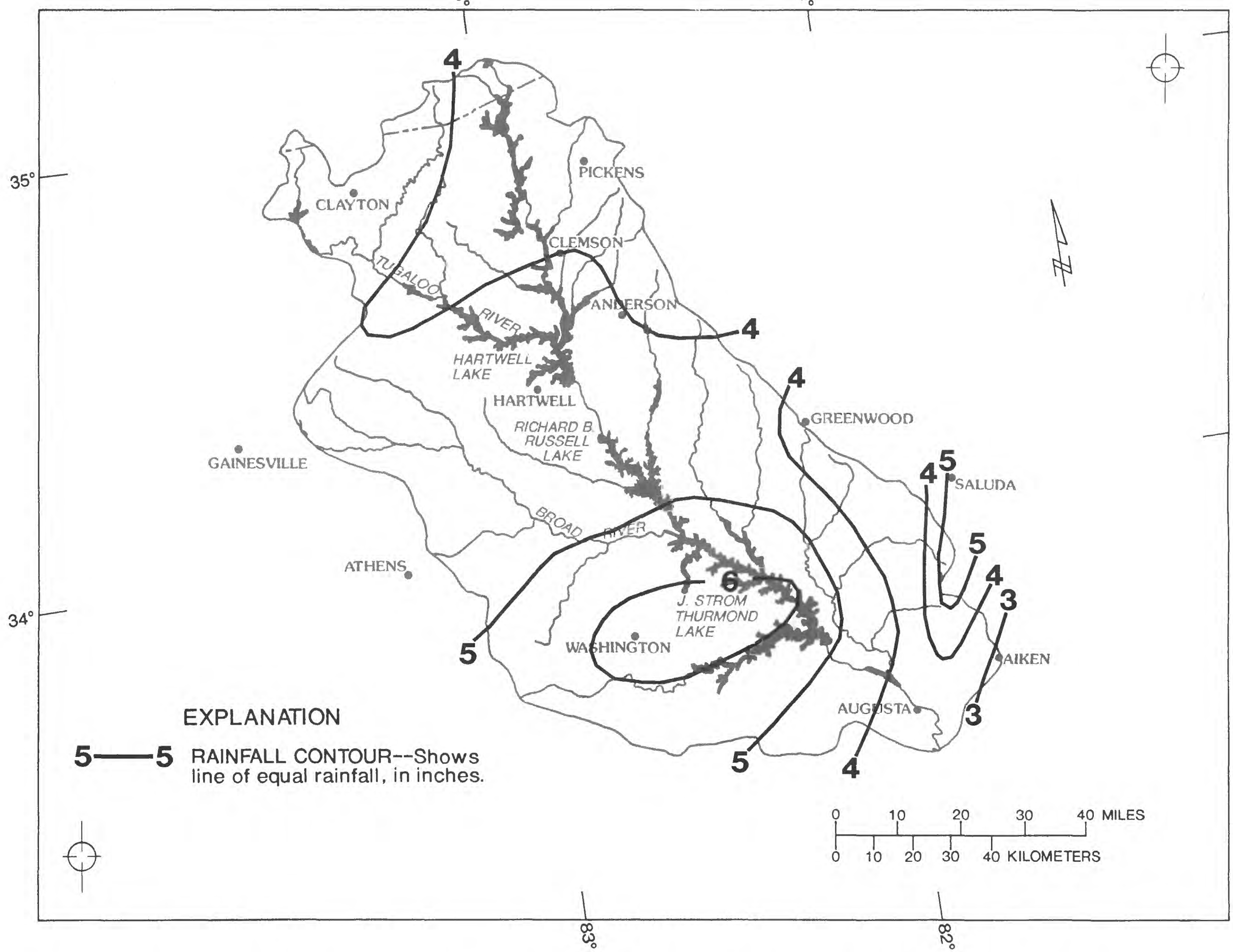


Figure 10.--Lines of equal rainfall for Savannah River basin upstream from Augusta, Ga. for storm of February 26 to March 3, 1929.

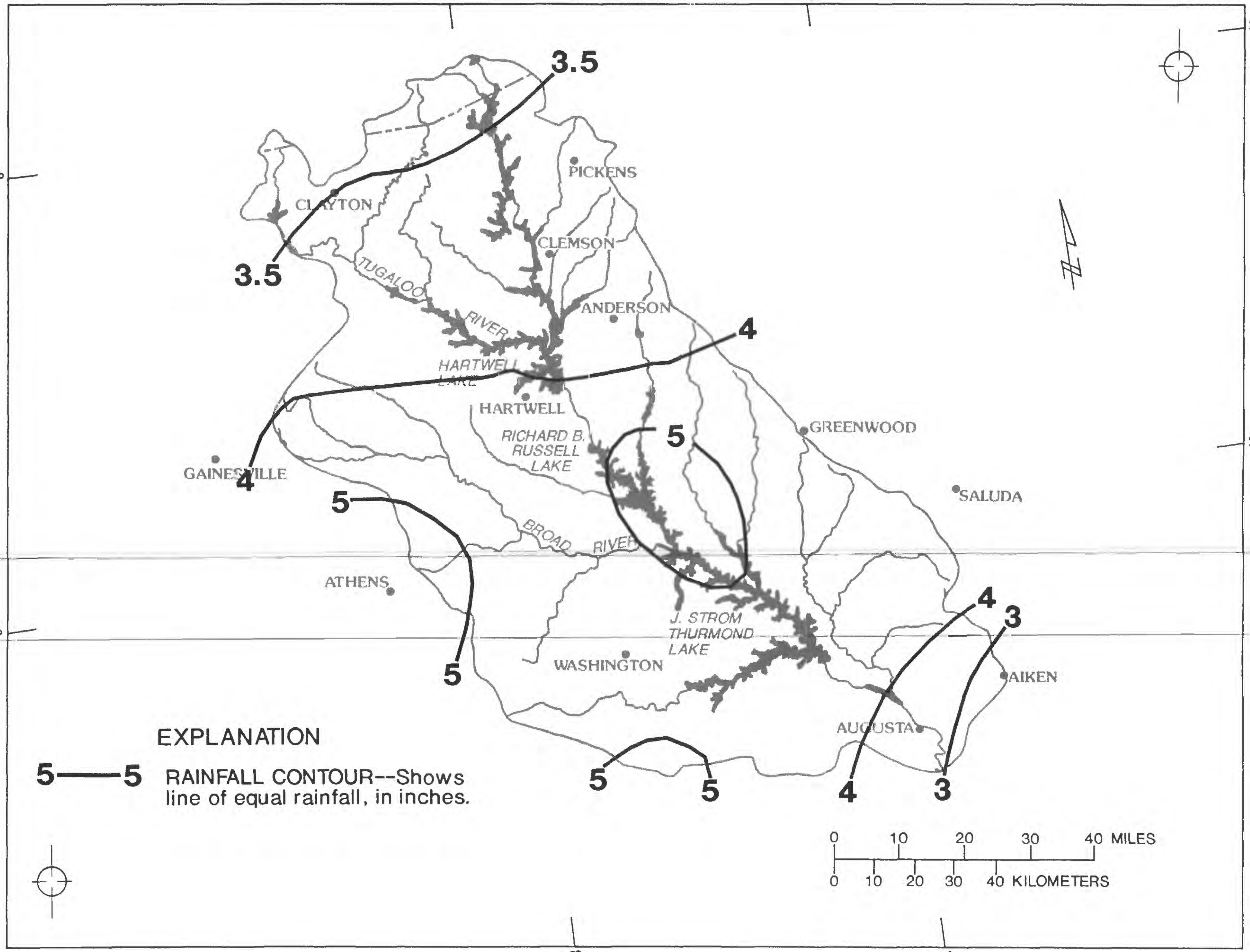


Figure 11.--Lines of equal rainfall for Savannah River basin upstream from Augusta, Ga. for storm of March 3-6, 1929.

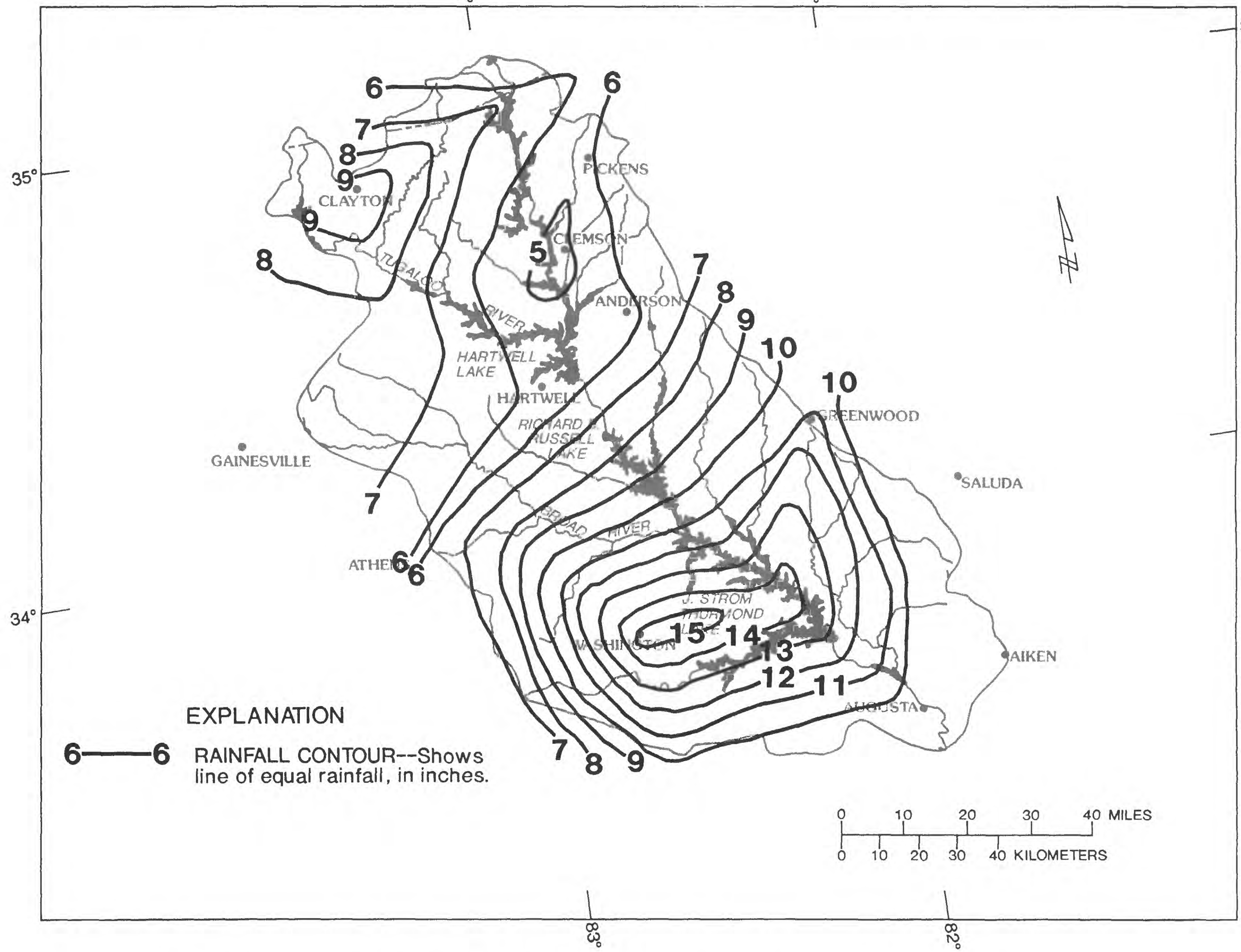


Figure 12.--Lines of equal rainfall for Savannah River basin upstream from Augusta, Ga. for storm of September 25-27, 1929.

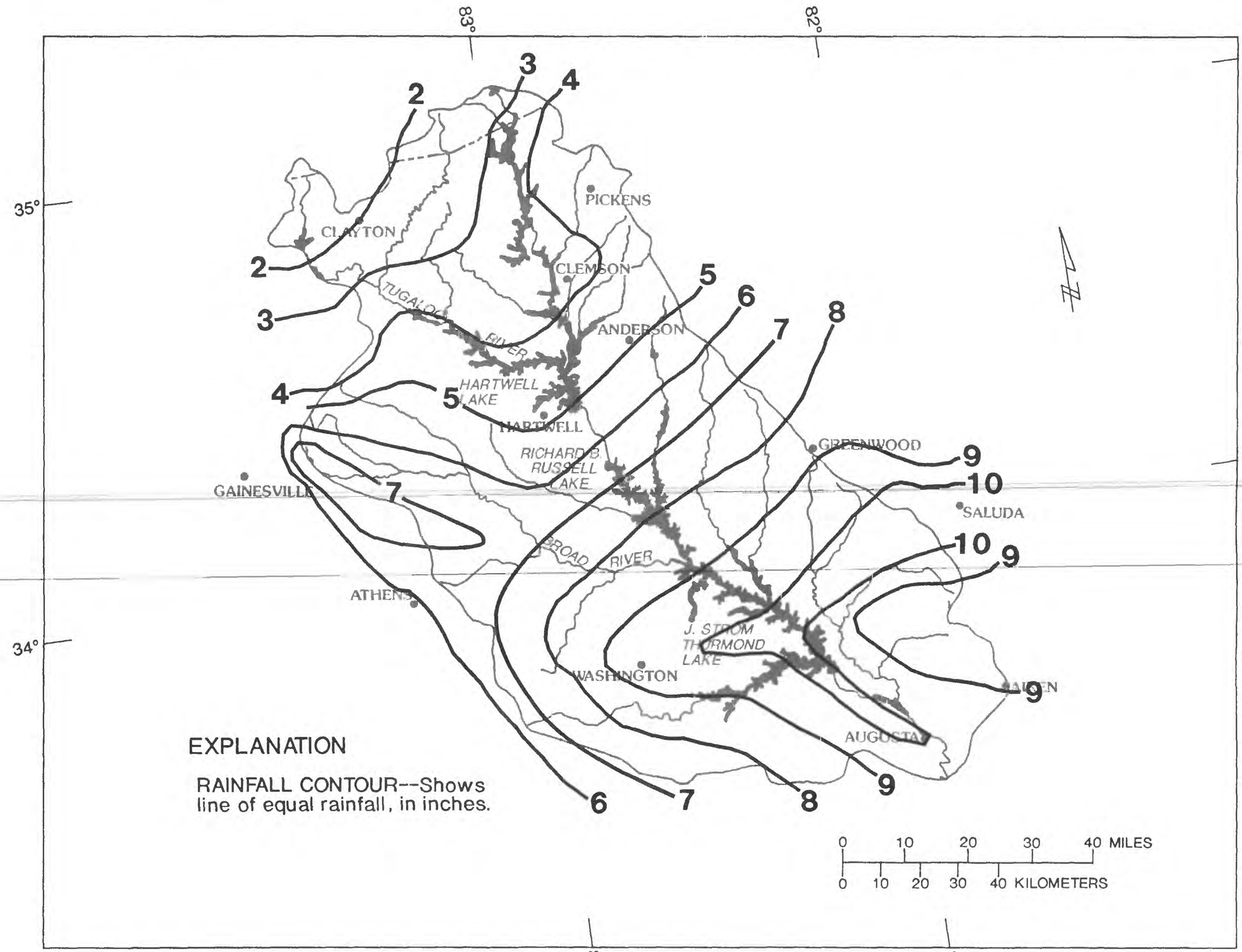


Figure 13.--Lines of equal rainfall for Savannah River basin upstream from Augusta, Ga. for storm of September 29 to October 2, 1929.

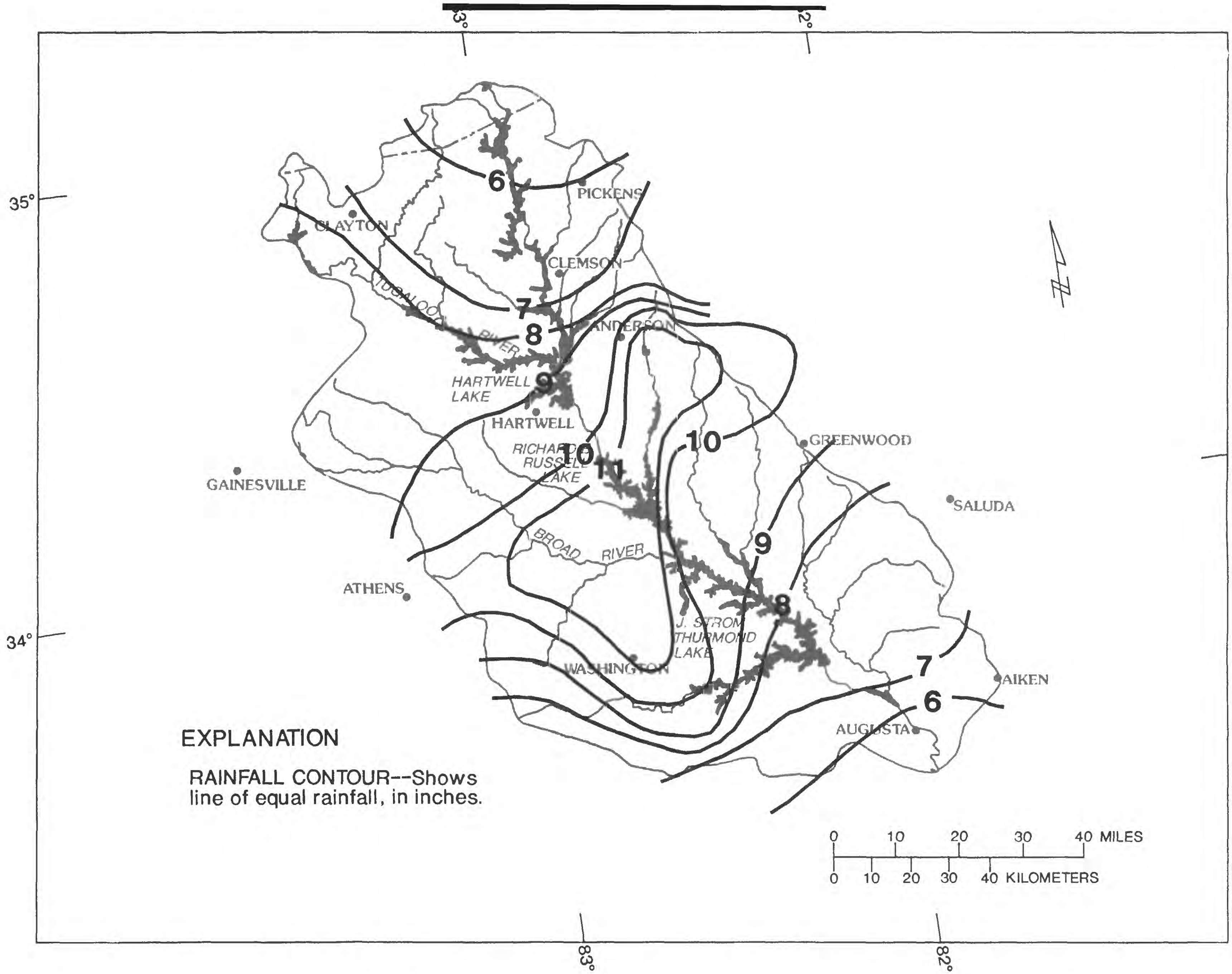


Figure 14.--Lines of equal rainfall for Savannah River basin upstream from Augusta, Ga. for storm of April 1-9, 1936.

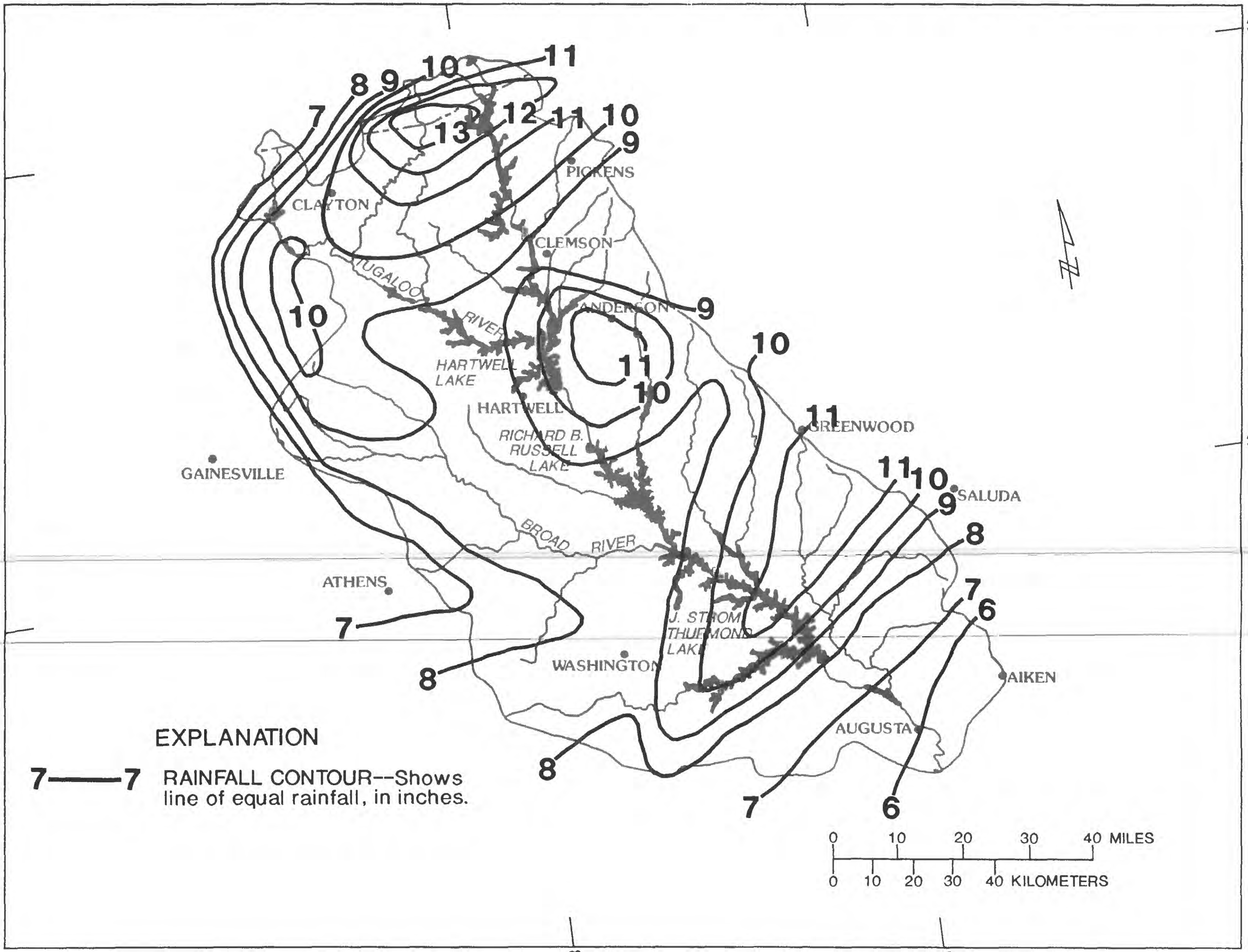


Figure 15.--Lines of equal rainfall for Savannah River basin upstream from Augusta, Ga. for storm of August 11-15, 1940.

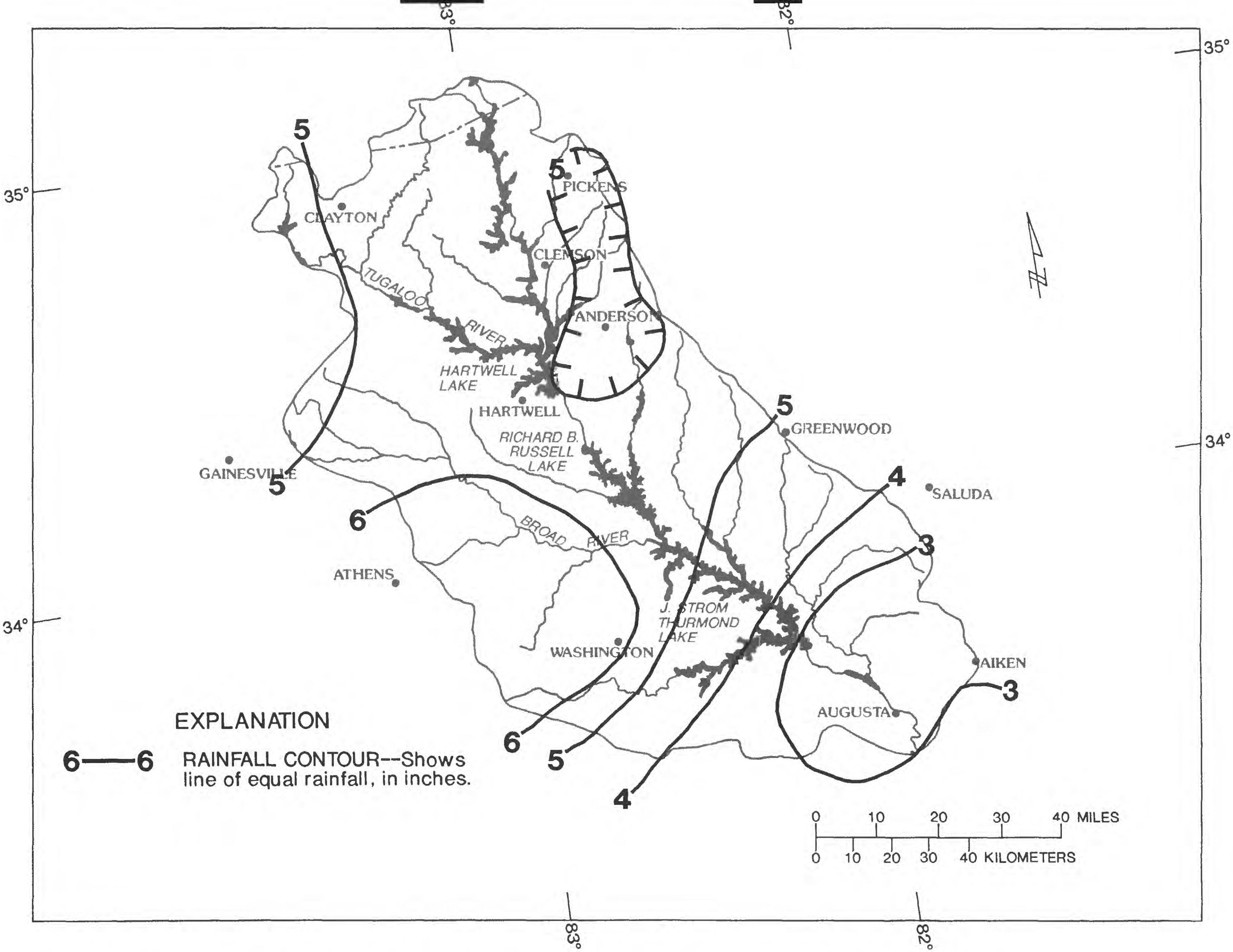


Figure 16.--Lines of equal rainfall for Savannah River basin upstream from Augusta, Ga. for storm of November 26-29, 1948.

Table 8.--Areal rainfall amounts for the floods of 1908, 1912, 1928, 1929, 1930, 1936, 1940, and 1949 water years

[dashes indicate no data]

Area	Amount of rainfall for indicated flood, in inches								
	Aug. 1908	Mar. 1912	Aug. 1928	Mar.[1] 1929	Sept. 1929	Oct. 1930	Apr.[2] 1936	Aug. 1940	Nov. 1949
A, mouth of Broad River to station 02191300	10.28	4.28	--	--	--	--	--	--	--
A, upstream of station 02191300	4.85	3.25	--	--	--	--	--	--	--
A, mouth of Broad River to station 02192000	--	--	6.43	5.26, 4.98	10.88	8.50	11.30	8.60	6.04
A, upstream of station 02192000	--	--	5.85	4.67, 4.48	8.04	6.68	9.91	8.32	6.03
B, station 02197000 to Thurmond Dam	3.23	2.34	3.91	4.26, 4.16	10.25	9.42	7.10	8.58	3.21
C, Thurmond Dam to downstream of Broad River	4.49	3.36	5.22	5.36, 4.75	11.80	8.62	9.26	9.18	5.22
D, Upstream of Broad River to Hartwell Dam	11.42	4.83	6.50	4.43, 4.32	7.29	6.23	10.08	9.53	5.08
E, Upstream of Hartwell Dam	7.12	4.25	8.00	4.08, 3.69	6.69	3.48	7.20	9.44	5.09

[1]Rainfall amounts for floods of March 1 and 6, 1929.

[2]Rainfall-runoff method rather than hydrograph method was used for computing inflow hydrographs.

The hydrograph for the Broad River at its mouth for the 1908 flood was not adjusted for rainfall, because the large difference between rainfall amounts downstream and upstream of the Carlton gage resulted in unrealistic hydrograph simulations.

Area D.--Hourly hydrographs for area D were created by first creating a "shape hydrograph" from measured hydrographs for the Broad River above Carlton or near Bell as was done for the Broad River at its mouth. Discharges of the "shape hydrograph" were then multiplied by a ratio (R_D), using the equations:

$$V_D = V_G P_D A_D / P_G A_G, \text{ and}$$

$$R_D = V_D / V_S,$$

where

V_D is the hydrograph volume for area D, in ft^3/s-hrs,

P_D is the average rainfall volume, in inches, for the drainage area D,

A_D is the drainage area of area D, in mi^2, and

A_G, V_G, P_G, and V_S are as previously defined.

Rainfall adjustments were not made for the 1908 and 1912 floods because the large difference between rainfall amounts for the area upstream of the Broad River above Carlton and rainfall for area D resulted in hydrographs with volumes too large in comparison with observed hydrographs for the Savannah River near Calhoun Falls.

The initial hydrographs for area D (and also areas C and E) were shortened in time and increased in discharge, to reflect the effect of shorter travel times through the reservoir compared to travel time for natural conditions. Pre-and post-reservoir 6-hour unit hydrographs developed by the COE (1969) and an average time of rainfall excess of 12 hours for the drainage basin between Russell and Hartwell dams were used to make the adjustments, according to the following methodology:

1. Twelve-hour unit hydrographs were generated for pre- and post-reservoir conditions. The post-reservoir hydrograph was computed for a minimum flood-pool elevation of 475 feet above sea level for Russell Lake.

2. Discharges of the pre-reservoir hydrograph were multiplied by a flow factor of 1.25 because the average discharge of the 12-hour unit hydrographs for post-reservoir conditions was 25 percent greater than the average discharge for pre-reservoir conditions.

3. The bases of the hydrographs were shortened to preserve volumes, by dividing the time increments by 1.25.

4. The time difference between peak flows of the pre- and post-reservoir 12-hour unit hydrographs was 6 hours, and the timing of the peaks of the revised hydrographs was adjusted to maintain the same time differential.

Area E.--Hourly hydrographs for area E were computed by subtracting the hydrographs for area D from the observed hydrographs for the Savannah River near Calhoun Falls, S.C. (02189000) and adjusting the resultant hydrograph 7 hours earlier. Routing by the Muskingum method indicated that there was very little attenuation of the inflow hydrograph between Hartwell Dam and Russell Dam. The hydrographs for area D were moved from zero to four hours later to avoid computation of negative discharges.

The hydrographs for area E were adjusted to reflect the effects of shorter travel times through the reservoir as was done for area D, using unit hydrograph information developed by the COE (1952). The average time of rainfall excess was 18 hours at Hartwell Dam. After developing 18-hour unit hydrographs and a flow ratio of 1.17, the hydrographs were adjusted, as previously explained. The timing of the peaks of the revised hydrograph peaks were adjusted to maintain a 9-hour differential, the time difference between peak flows of the pre- and post-reservoir 18-hour unit hydrographs.

Areas B and C.--As shown in figure 5 and 6, area B lies between Thurmond Dam and the Savannah River at Augusta. Area C lies between Thurmond Dam and downstream of the confluence at the Savannah and Broad Rivers. Hourly hydrographs were computed for areas B and C by the following method:

1. "Shape hydrographs" were created for areas B and C using the same methodology as described for area D. Volumes of these hydrographs (V_{SB} and V_{SC}) were computed.

2. Volumes were computed for the inflow hydrographs, based on volumes of hydrographs of the Broad River at its mouth and of the Savannah River near Calhoun Falls and Augusta adjusted by drainage area ratios and average rainfall amounts as shown by the equations:

$$V_{DIF} = V_{AUG} - V_A - V_{DE},$$

$$V_B = V_{DIF}\, P_B\, A_B/(P_B\, A_B + P_C\, A_C), \text{ and}$$

$$V_C = V_{DIF}\, P_C\, A_C/(P_B\, A_B + P_C\, A_C),$$

where

V_{DIF} is the total volume of runoff in ft^3/s-hours, for areas B and C;

V_{AUG} is the volume of runoff in ft^3/s-hours, of the measured unregulated hydrograph for the Savannah River at Augusta (02197000);

V_A is the volume of runoff, in ft^3/s-hours, of area A;

V_{DE} is the total volume of runoff, in ft^3/s-hours, of areas D and E combined from measured discharges for the Savannah River near Calhoun Falls;

V_B and V_C are the volumes of runoff, in ft^3/s-hours, of areas B and

P_B and P_C are the average rainfalls, in inches, of areas B and C, respectively; and

A_B and A_C are the drainage areas, in mi^2, of areas B and C, respectively.

3. The "shape hydrographs" were then adjusted for volume by multiplying the discharges by the following ratios:

$$R_B = V_B/V_{SB}$$

$$R_C = V_C/V_{SC}$$

where

$V_{SB,SC}$ = volume of runoff, in ft^3/s-hours, of the "shape hydrographs" for areas B and C, respectively.

4. The hydrographs developed in step 3 and the hydrographs for areas A and D-E were then routed downstream to Augusta using HEC-1 and compared with the measured hydrograph at that location. Muskingum routing coefficients used in the model are given in table 9.

Table 9.--Muskingum routing parameters used in the HEC-5 model for the Savannah River from Hartwell Dam near Hartwell, Ga. (02187250) to the Savannah River near Augusta, Ga. (02197000)

Reach	Natural conditions			Regulated conditions		
	X	K (hours)	Number of sub-reaches	X	K (hours)	Number of sub-reaches
For all floods:						
Hartwell Dam to Russell Dam	0.2	7.5	5	0.0	4.0	1
Russell Dam to Broad River	0.2	3.0	3	0.2	3.0	3
For the 1908, 1912, 1928, 1929, and 1930 floods:						
Broad River to Thurmond Dam	0.2	9.0	6	0.0	6.0	1
Thurmond Dam to Augusta, Ga.	0.2	10.0	5	0.2	10.0	5
For the 1940 and 1948 floods:						
Broad River to Thurmond Dam	0.2	15.0	5	0.0	6.0	1
Thurmond Dam to Augusta, Ga.	0.2	16.0	8	0.2	16.0	8

Note: X = constant which expresses the relative importance of inflow and outflow in determining storage.

K = constant which is the ratio of storage to discharge, expressed in hours.

5. Hydrographs for areas B and C were then shifted as much as 6 hours earlier or later, except for the 1928 flood for which both hydrographs were shifted 12 hours earlier in time. For the 1940 and 1949 floods, the Muskingum "K" routing coefficient was adjusted to achieve a "best fit" of the routed hydrograph to the measured hydrograph of the Savannah River at Augusta. The Muskingum "K" routing coefficient is about equal to the travel time of the flood through the reach. The value of "K" was increased by 6 hours for the unregulated flood of 1940 because the flood was a two-peak event, and the travel time of the second flood was lengthened because travel of the second flood was impeded by the presence of the first flood in the lower reaches. The value of "K" was increased by 6 hours for the 1949 unregulated flood because that flood was of much lower magnitude than the other floods, and its travel time would be greater because of greater flow resistance and length of travel.

6. An adjustment was made to the hydrographs for areas B and C to distribute residuals between the routed and measured hydrographs, based on the following:

   (a) Drainage areas A, B, and C are nearly the same (fig. 5). Therefore, area A was used to define a preliminary "shape" hydrograph for areas B and C.

   (b) Area A is longer and narrower than areas B and C (fig. 5), and, therefore, the final hydrographs for areas B and C would be expected to be shorter in time and greater in discharge than a "shape hydrograph" derived from area A.

   (c) The "shape hydrograph" derived from area A does not reflect differences in rainfall distribution within areas B and C.

   (d) The residuals between the routed hydrograph and the measured hydrograph for the Savannah River at Augusta are assumed to reflect the differences described in (6b) and (6e) and are used to refine the hydrographs developed in step 5.

Hydrographs for areas B and C were adjusted for residuals by the following method:

1. The hydrograph for area C was moved downstream to the Savannah River at Augusta by advancing it in time by 10 hours for hydrographs measured at 5th Street in Augusta and 11 hours for hydrographs measured at the present Butler Creek site. Routing was not necessary, because the Muskingum routing showed very little hydrograph attenuation for the reach.

2. The hydrograph for area C was then combined with the hydrograph for area B.

3. Residuals were computed by:

   a. Simulating the hydrograph for the Savannah River at Augusta using the hydrographs of areas B and C unadjusted for residuals, the Broad River hydrograph at its mouth, and the Savannah River hydrograph upstream of Broad River.

   b. Subtracting the simulated hydrograph from the measured hydrograph at Augusta to obtain the residuals.

4. The residual for each specific time was then prorated by the ratio of the discharge of area B (or C) to the summed discharge of areas B and C and added to the discharge of area B (or C) according to the following equations:

$$Q_T = Q_B + Q_C,$$

$$R_B = R_T\, Q_B/Q_T,$$

$$R_C = R_T\, Q_C/Q_T,$$

$$Q_{FB} = Q_B + R_B, \text{ and}$$

$$Q_{FC} = Q_C + R_C,$$

where

Q_T is the total discharge, in ft^3/s, for a specific time on the hydrograph;

Q_B and Q_C are the discharges, in ft^3/s, for areas B and C, respectively;

R_T is the residual discharge, in ft^3/s;

R_B and R_C are the prorated residual discharges, in ft^3/s, for areas B and C, respectively;

Q_{FB} and Q_{FC} are the discharges, in ft^3/s, at areas B and C, respectively adjusted for residual discharge.

Except for the 1928 flood, the resulting hydrographs looked reasonable in comparison with the measured Augusta hydrographs. The Broad River hydrograph was not well suited for the 1928 flood, because the residual adjustment resulted in a double peak for the hydrographs for areas B and C. Therefore, these hydrographs were manually smoothed and verified by steps 5 and 6 that follow.

5. The adjusted hydrograph for area C was then moved to Thurmond Dam by moving it 10 or 11 hours earlier depending on the location of the Augusta gage.

6. All hydrographs were then routed to Augusta for a final comparison with the measured hydrograph. Minor negative flows computed at the beginning and ending tails of the hydrographs were adjusted to a minimum value.

As previously described for areas D and E, the hydrograph for area C was adjusted in shape to reflect the effects of shorter travel times through the reservoir, using unit hydrograph information developed by the COE (1945). However, post-reservoir 6-hour unit hydrographs were not available for area C. The unit hydrograph was determined by deriving hydrographs for the lake area and non-lake area from the pre-reservoir hydrograph, consistent with the methods used for Hartwell and Russell Lakes, and combining them with unit tributary hydrographs using accelerated travel times. The average time of rainfall excess was 36 hours for the Savannah River basin at Thurmond Dam. After developing 36-hour unit hydrographs and a flow ratio of 1.13, the hydrographs were adjusted as previously explained. The time difference between pre- and post-reservoir hydrographs was adjusted to 12 hours to agree with the relative timing of the unit hydrograph peaks.

The computed inflow hydrographs for the eight floods are shown in figures 17-24. The simulated regulated hydrographs and the measured unregulated hydrographs for the Savannah River at Augusta are shown in figures 25-32. Peak discharges simulated for regulated conditions are listed in table 10.

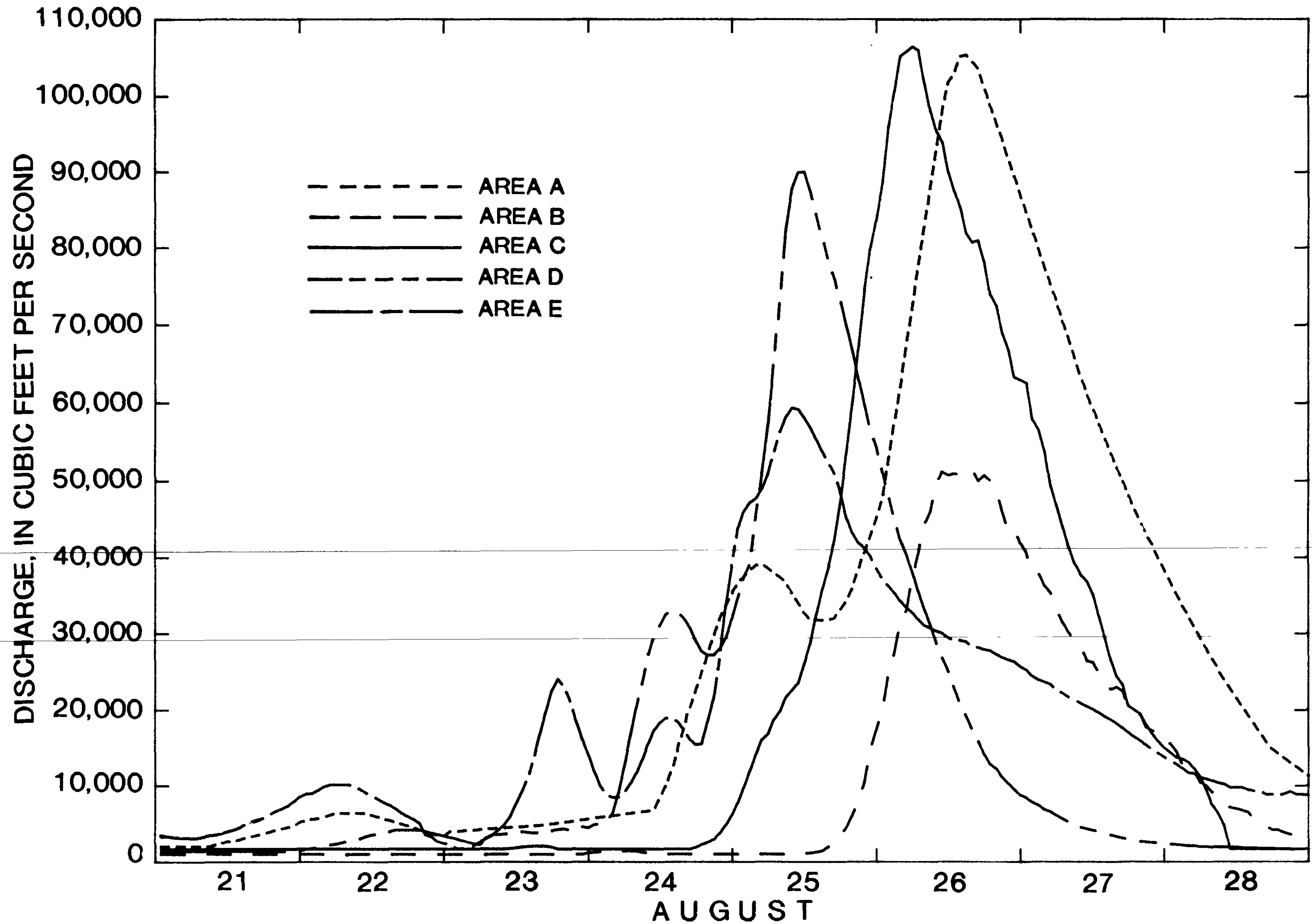


Figure 17.--Estimated inflow hydrographs for areas A-E for flood of August 1908.

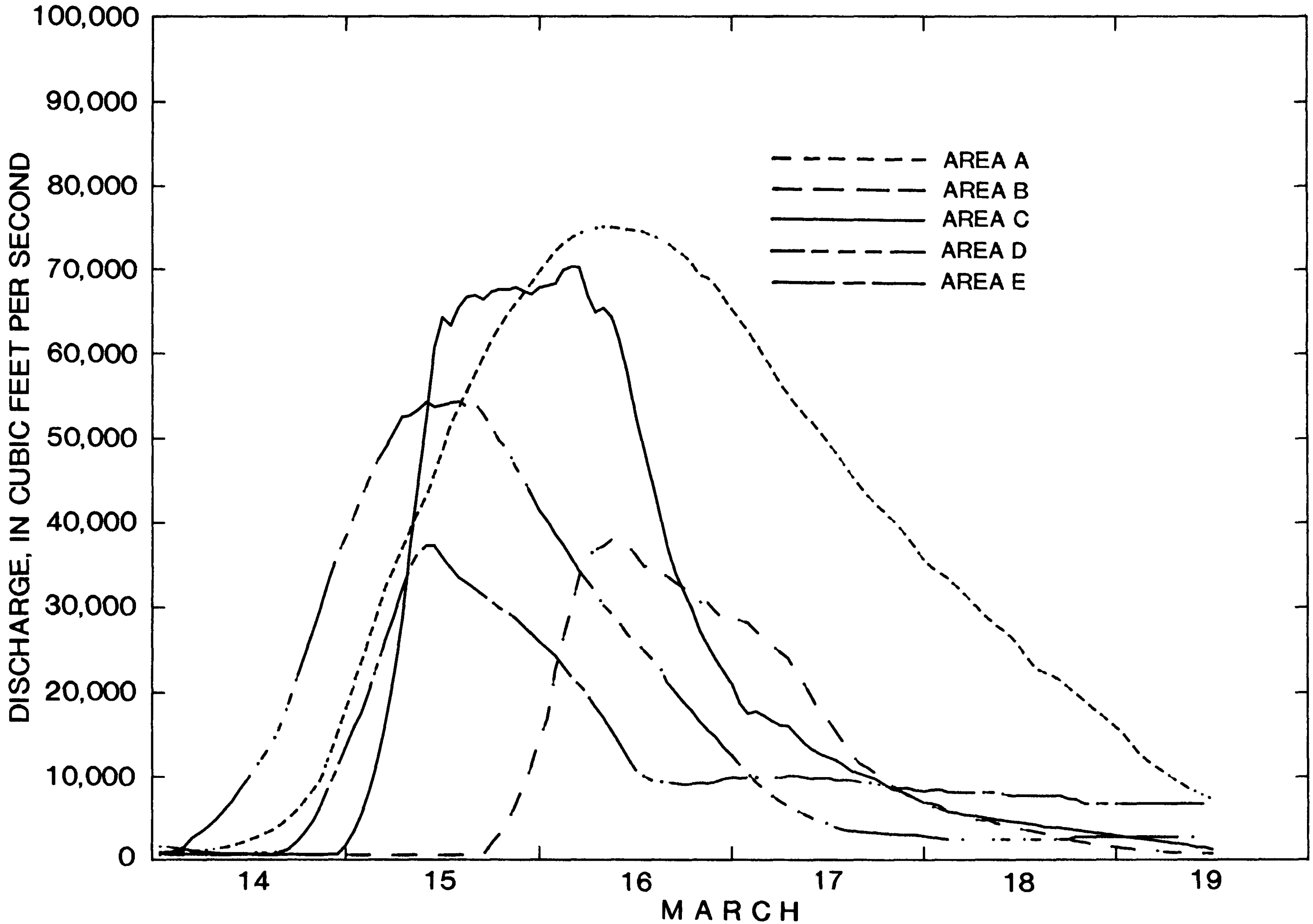
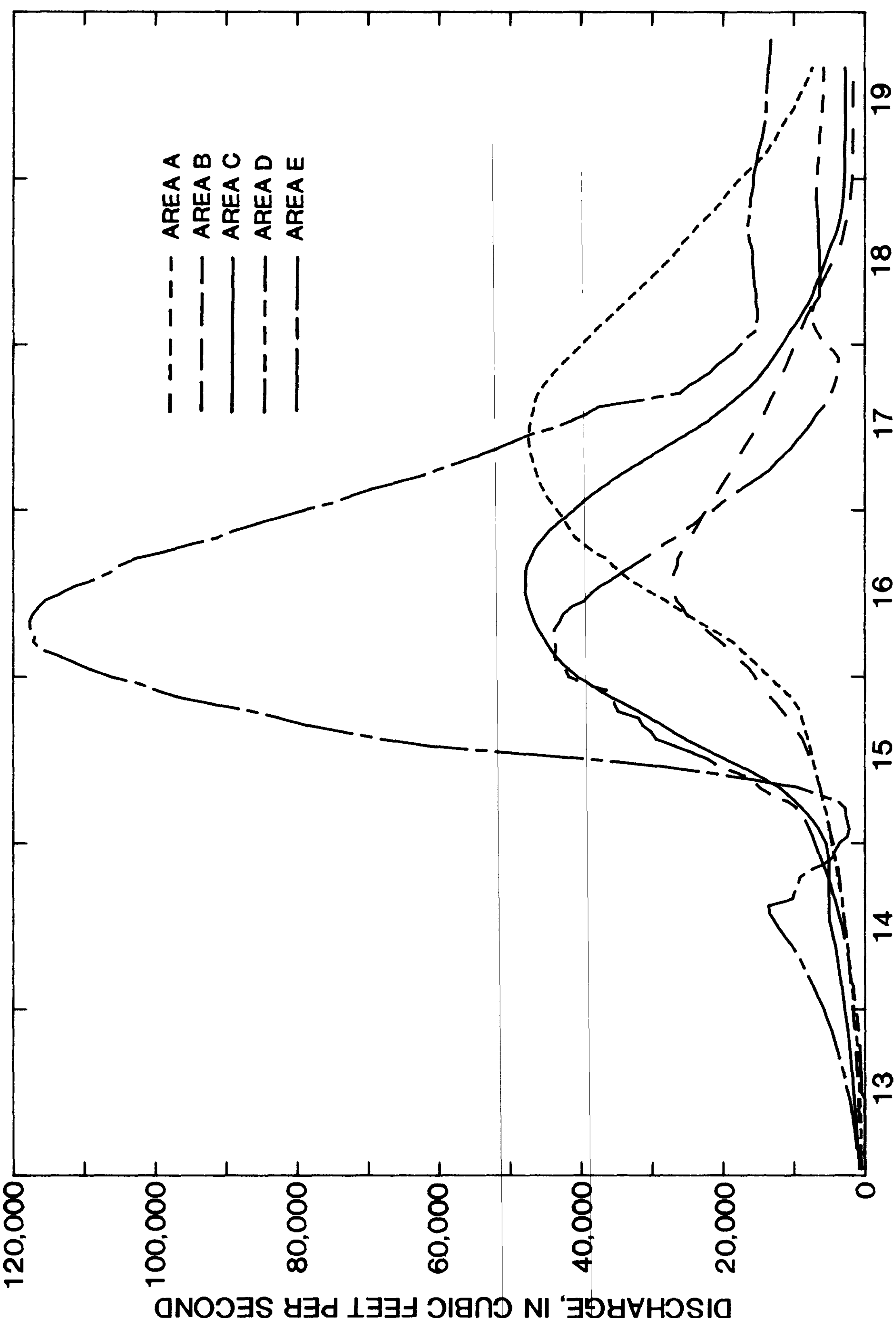


Figure 18.--Estimated inflow hydrographs for areas A-E for flood of March 1912.


AREA A
AREA B
AREA C
AREA D
AREA E
DISCHARGE, IN CUBIC FEET PER SECOND
120,000
100,000
80,000
60,000
40,000
20,000
0
AUGUST
13
14
15
16
17
18
19

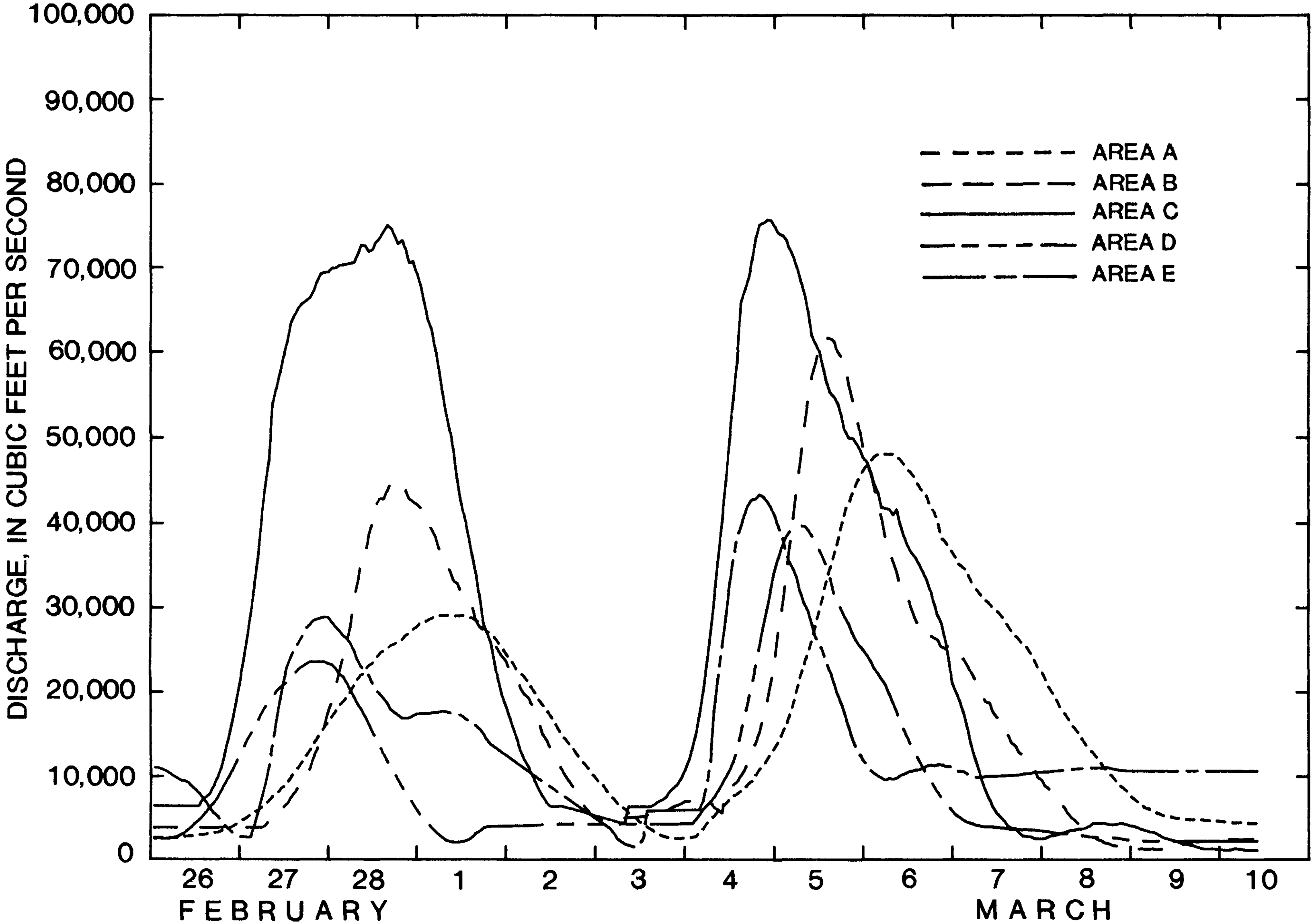


Figure 20.--Estimated inflow hydrographs for areas A-E for flood of February to March 1929.

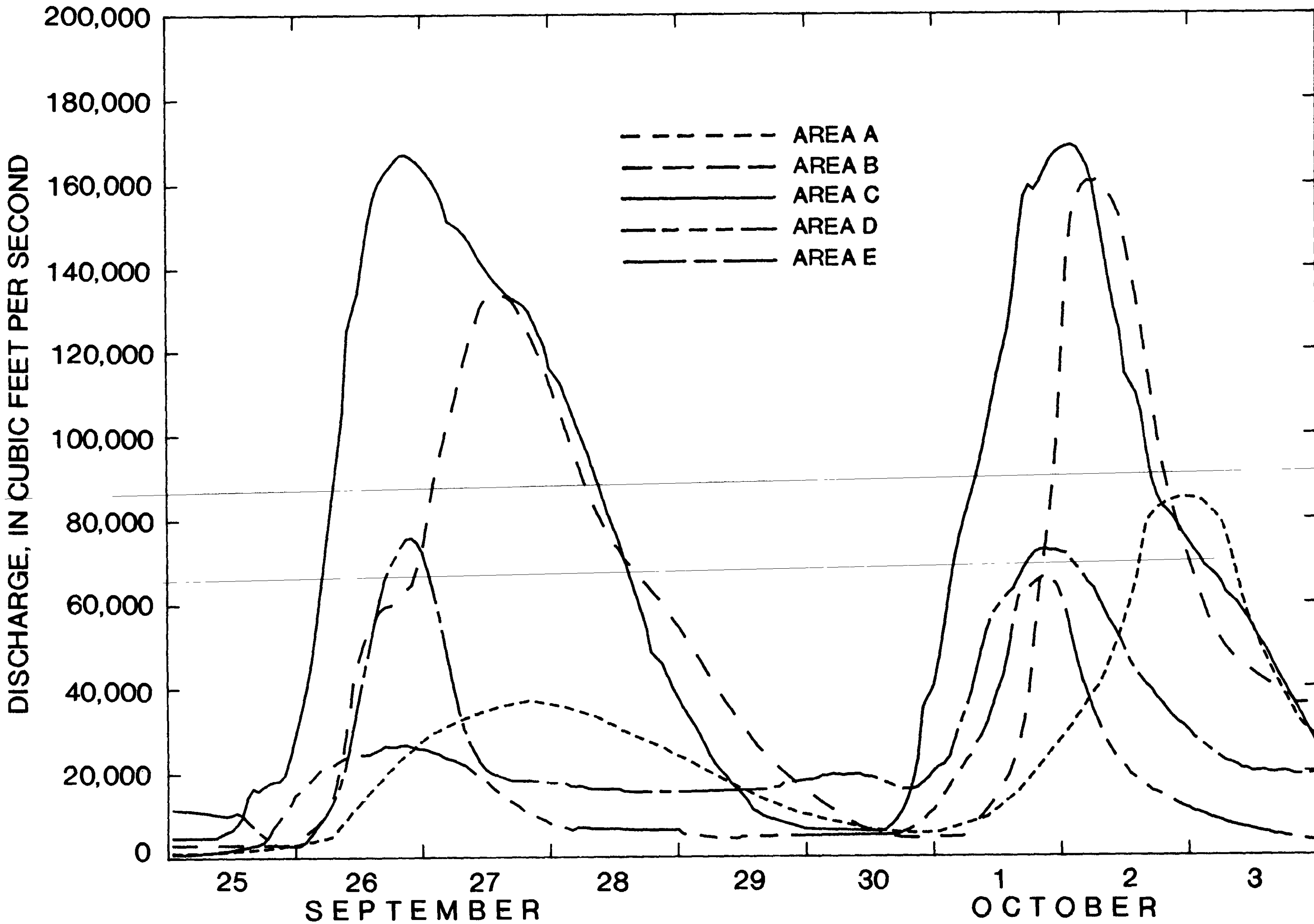


Figure 21.--Estimated inflow hydrographs for areas A-E for floods of September and October 1929.

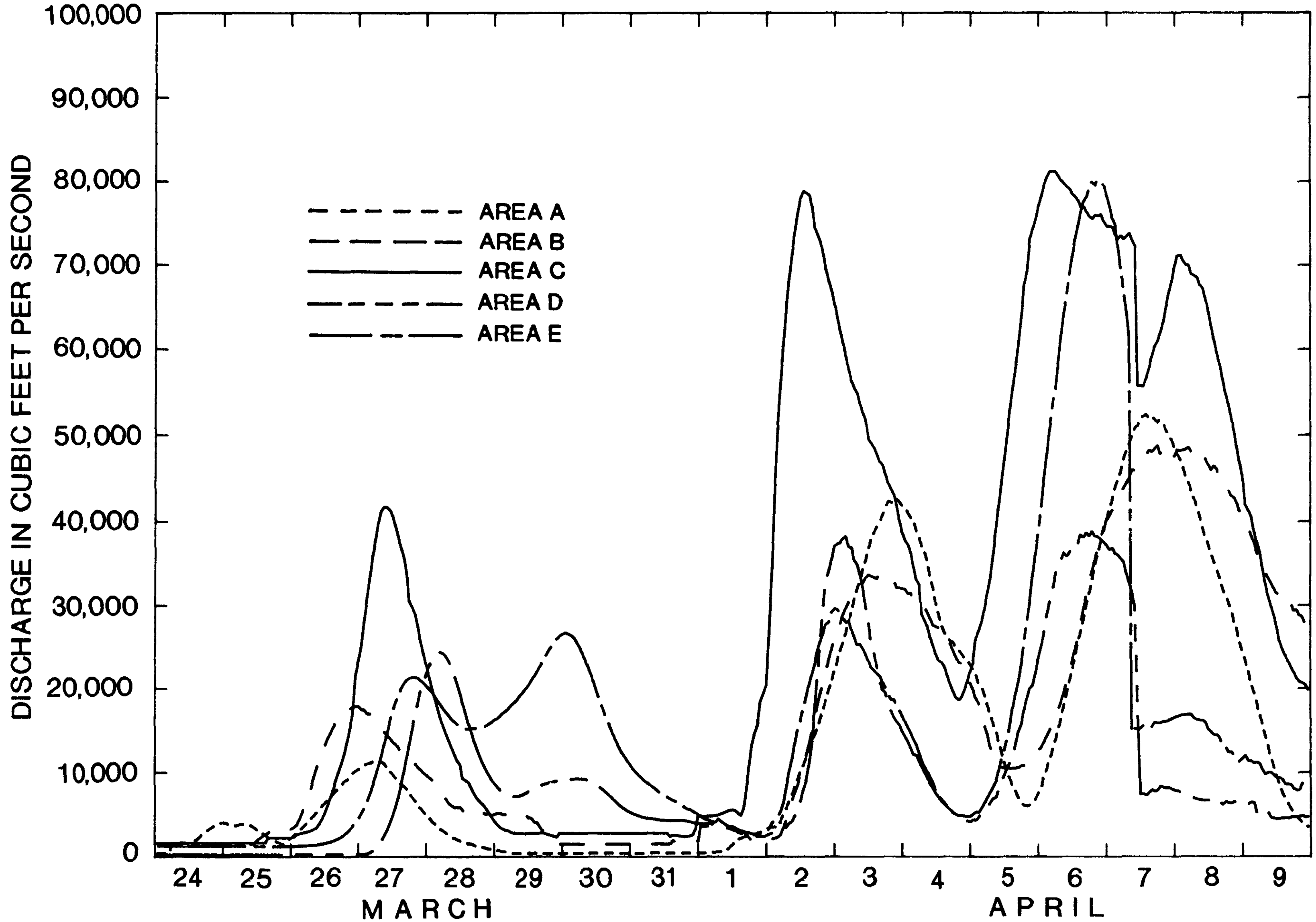


Figure 22.--Estimated inflow hydrographs for areas A-E for flood of April 1936.

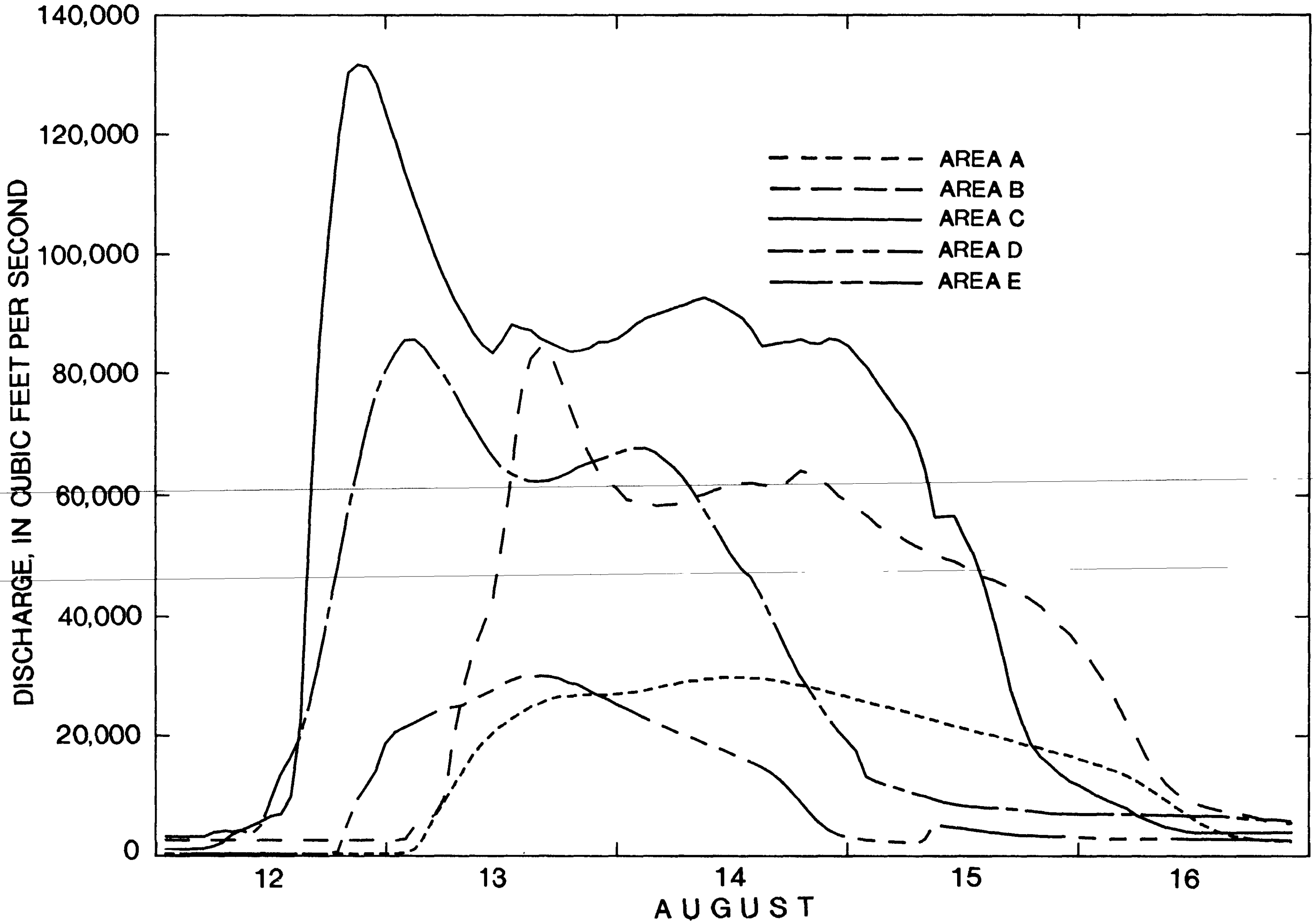


Figure 23.--Estimated inflow hydrographs for areas A-E for flood of August 1940.

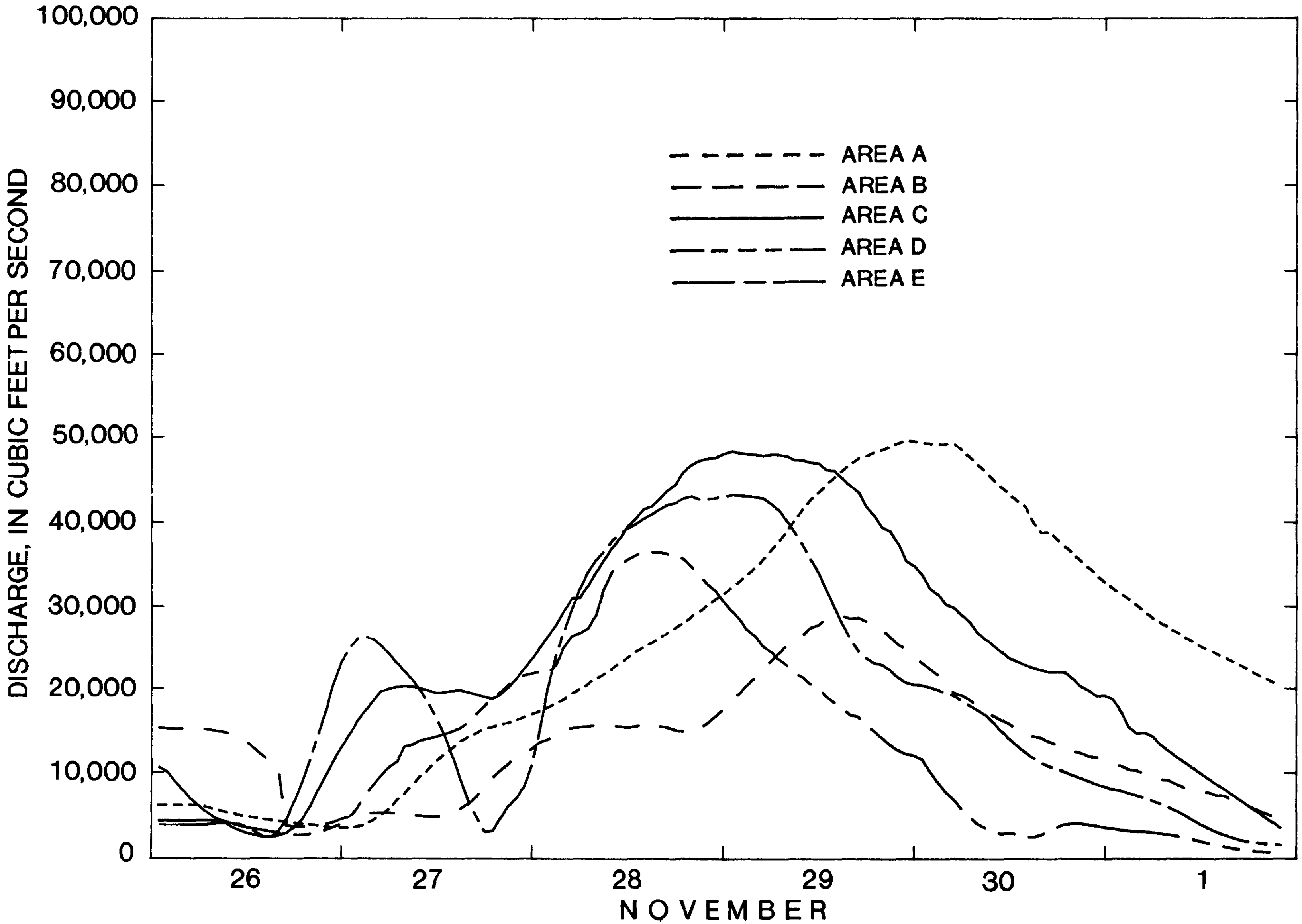


Figure 24.--Estimated inflow hydrographs for areas A-E for flood of November 1948.

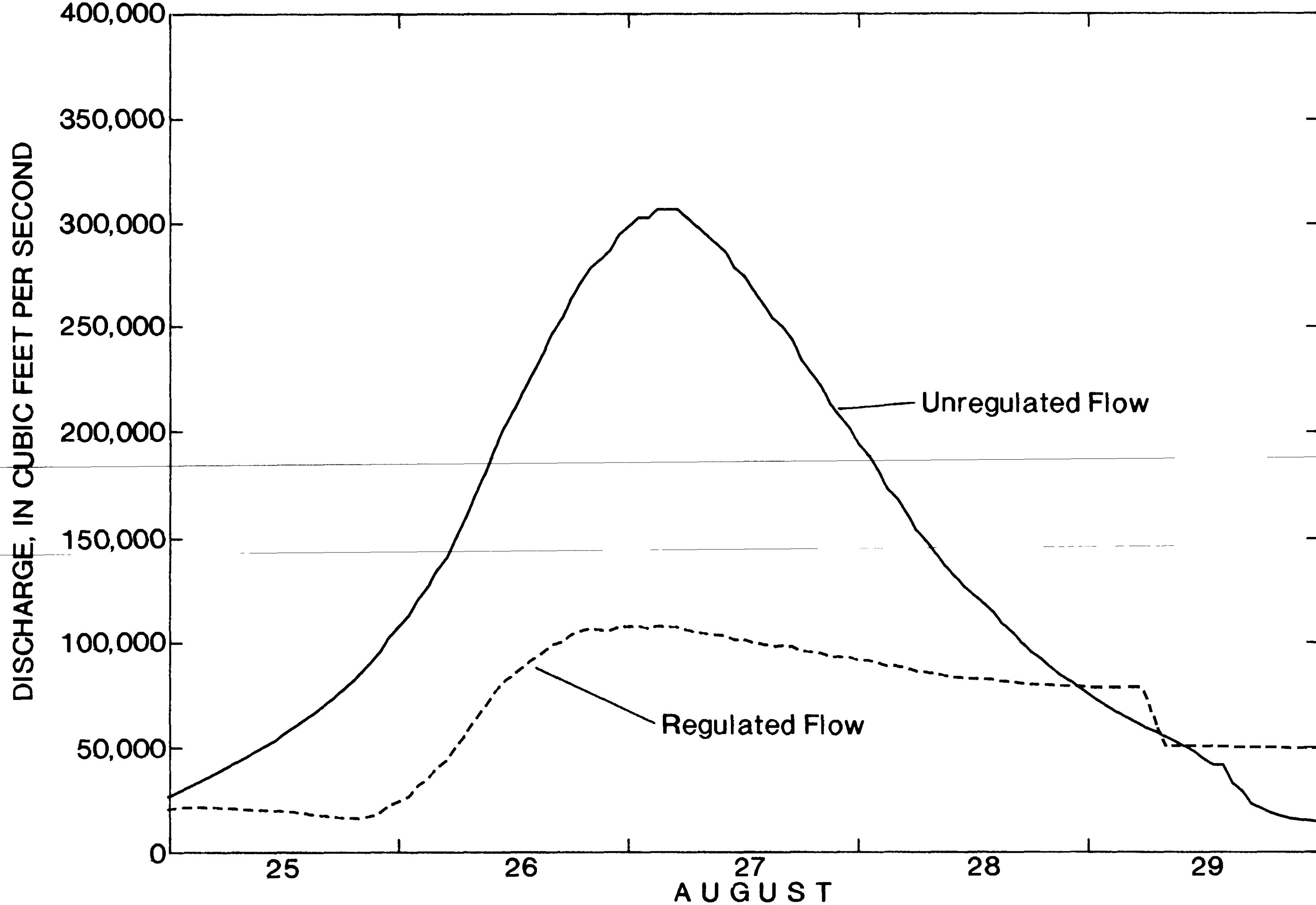


Figure 25.--Measured flood hydrograph for unregulated conditions and simulated hydrograph for the regulated conditions for the Savannah River at Augusta, Ga. (02197000) for flood of August 1908.

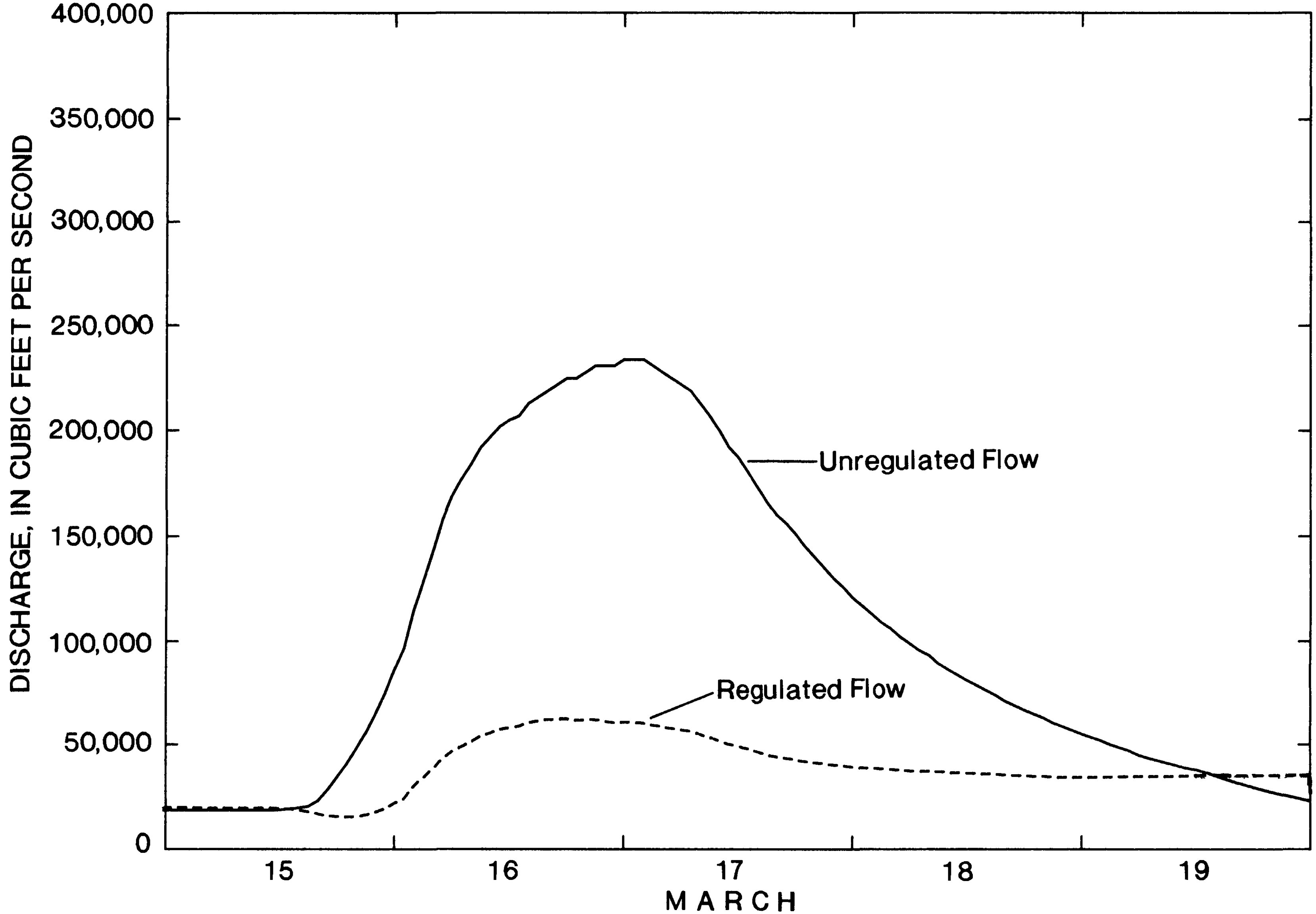


Figure 26.--Measured flood hydrograph for unregulated conditions and simulated hydrograph for the regulated conditions for the Savannah River at Augusta, Ga. (02197000) for flood of March 1912.

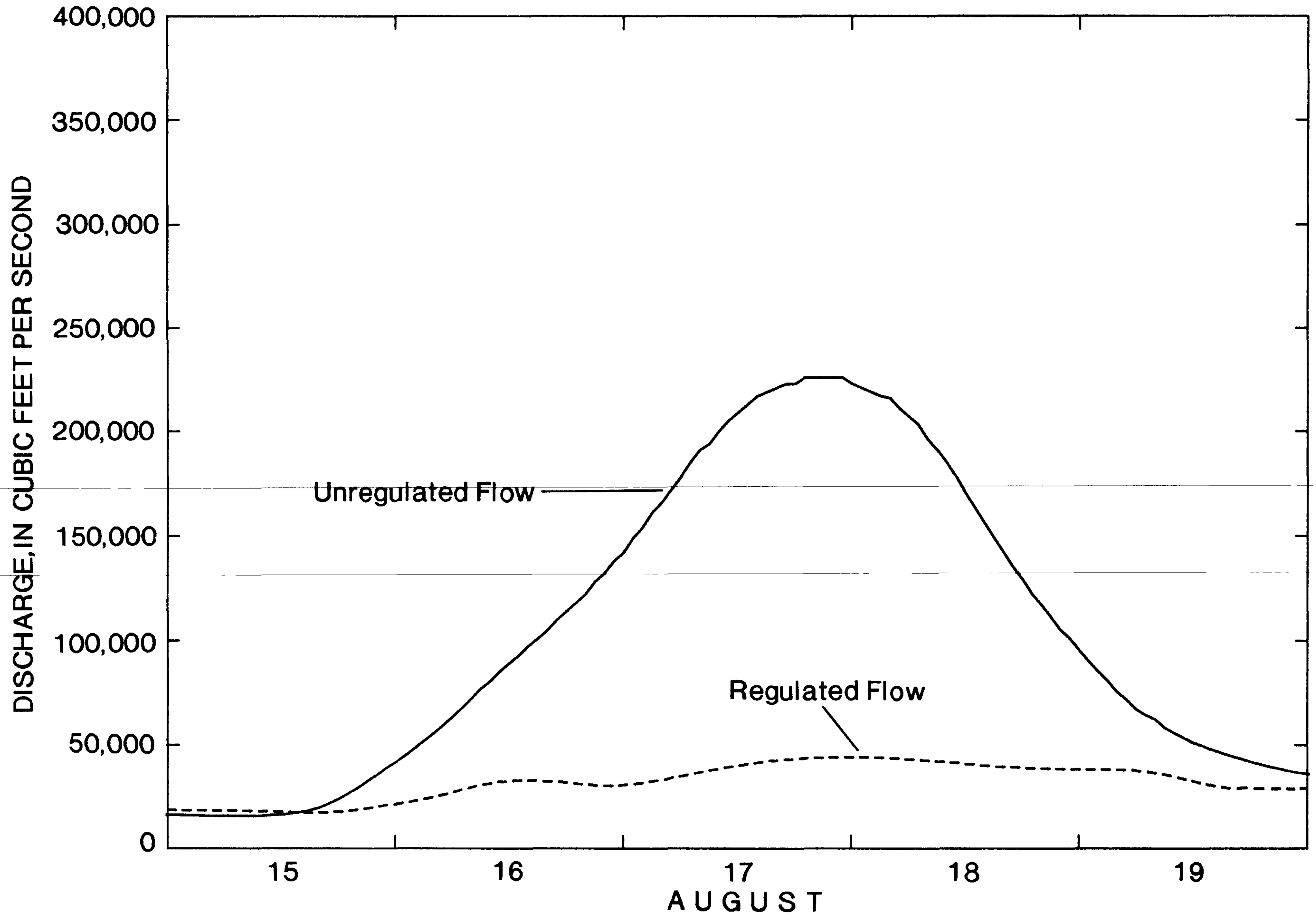


Figure 27.--Measured flood hydrograph for unregulated conditions and simulated hydrograph for the regulated conditions for the Savannah River at Augusta, Ga. (02197000) for flood of August 1928.

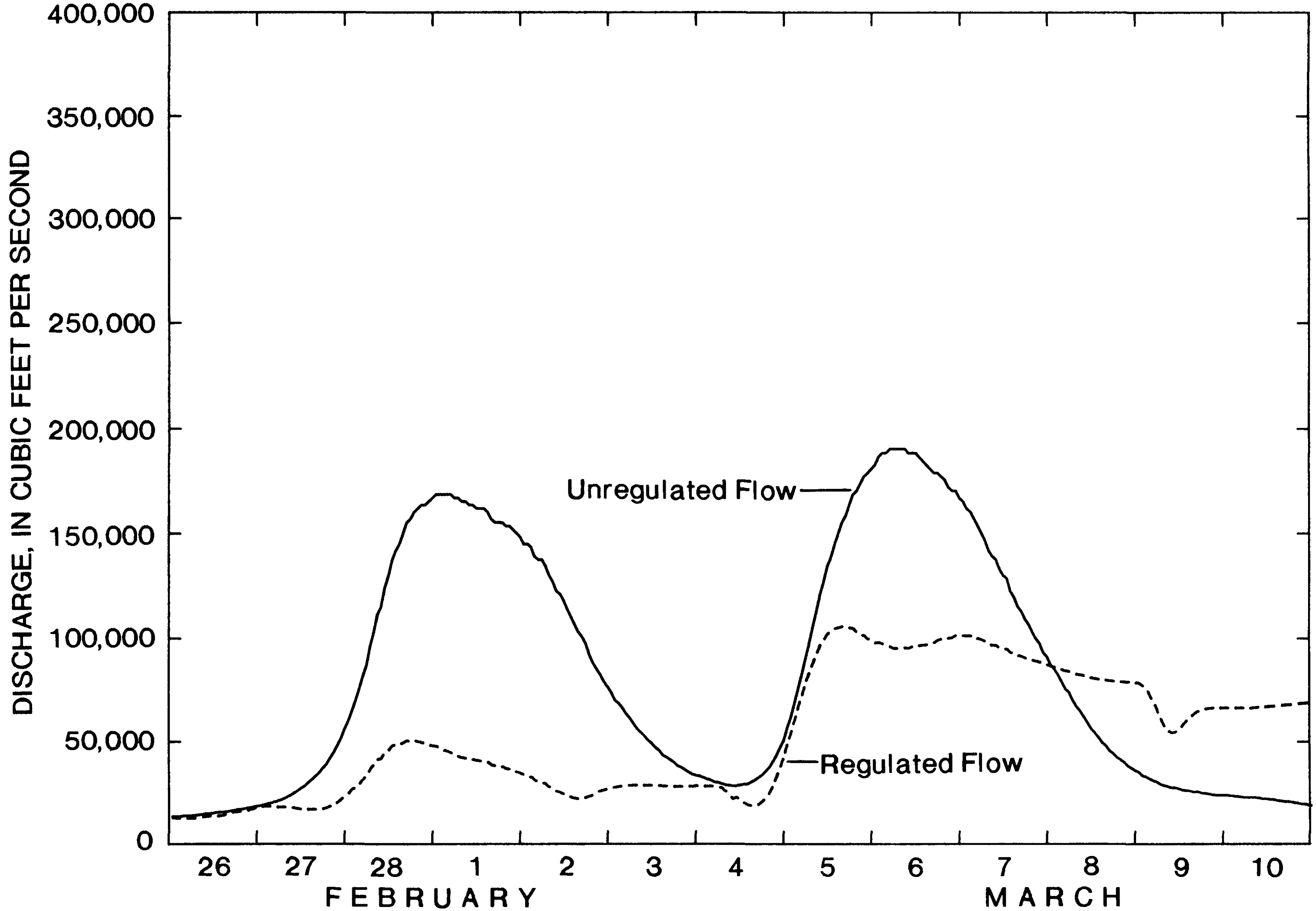


Figure 28.--Measured flood hydrographs for unregulated conditions and simulated hydrographs for the regulated conditions for the Savannah River at Augusta, Ga. (02197000) for flood of March 1929.

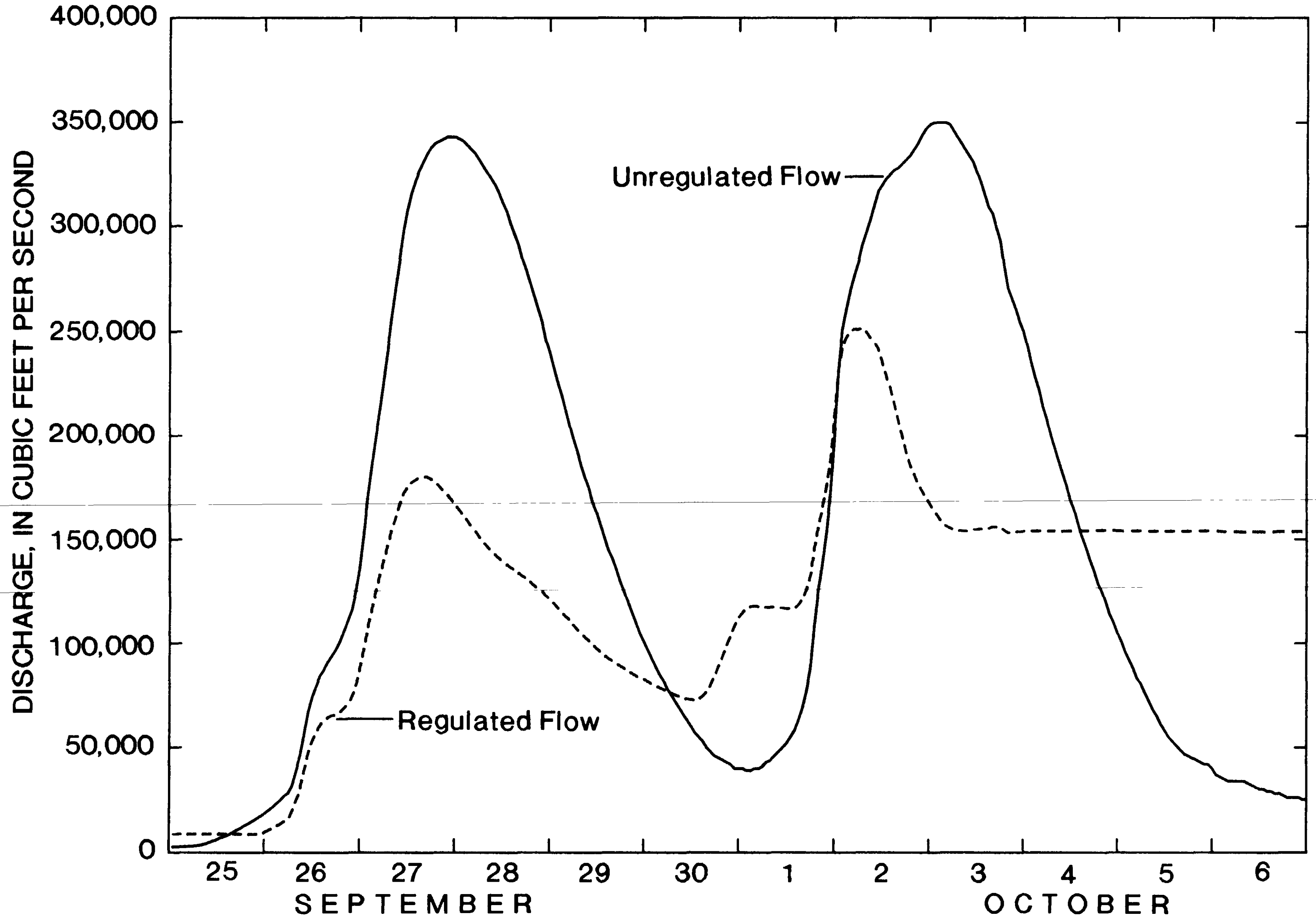


Figure 29.--Measured flood hydrographs for unregulated conditions and simulated hydrograph for the regulated conditions for the Savannah River at Augusta, Ga. (02197000) for floods of September and October 1929.

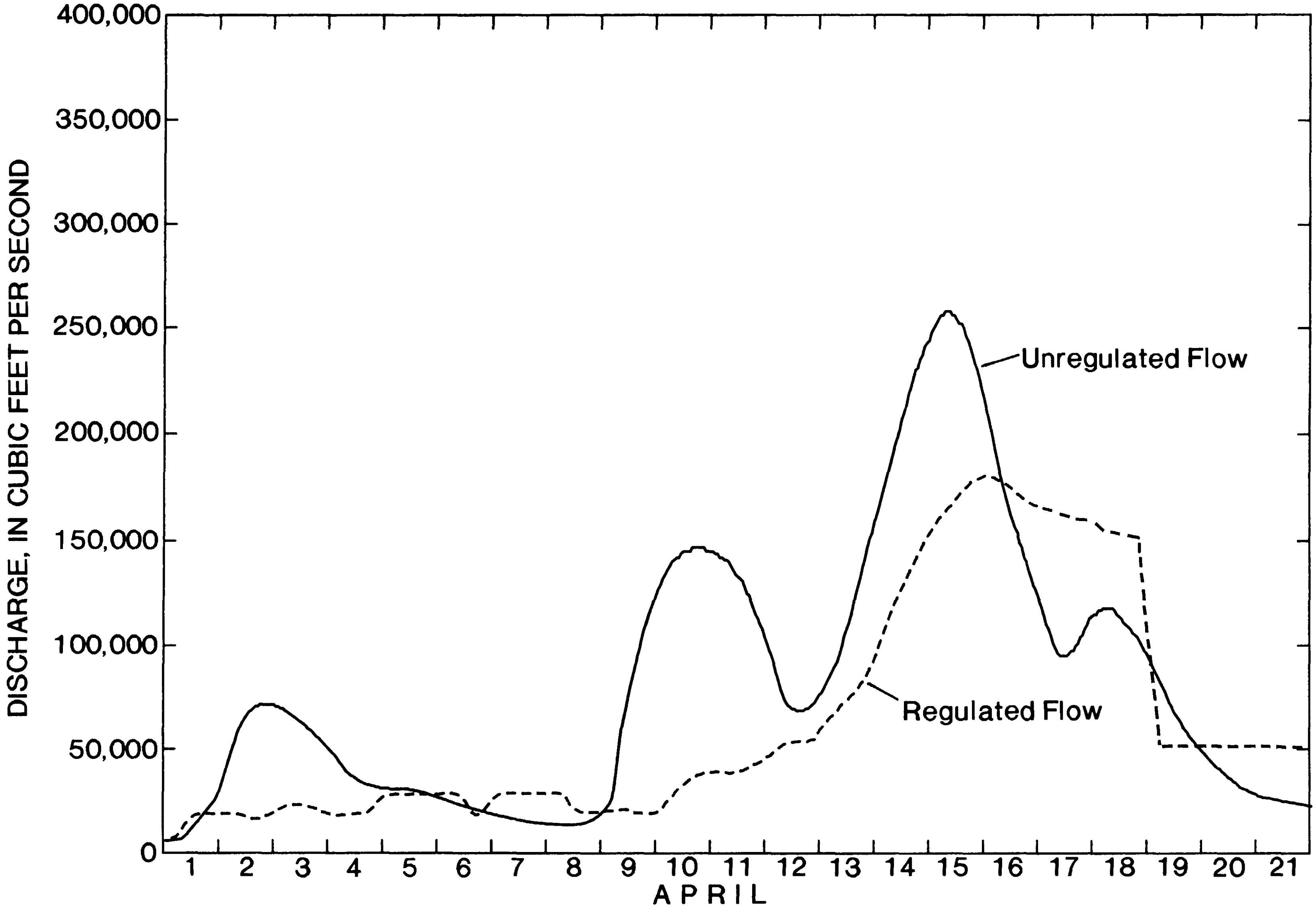


Figure 30.--Measured flood hydrographs for unregulated conditions and simulated hydrographs for the regulated conditions for the Savannah River at Augusta, Ga. (02197000) for flood of April 1936.

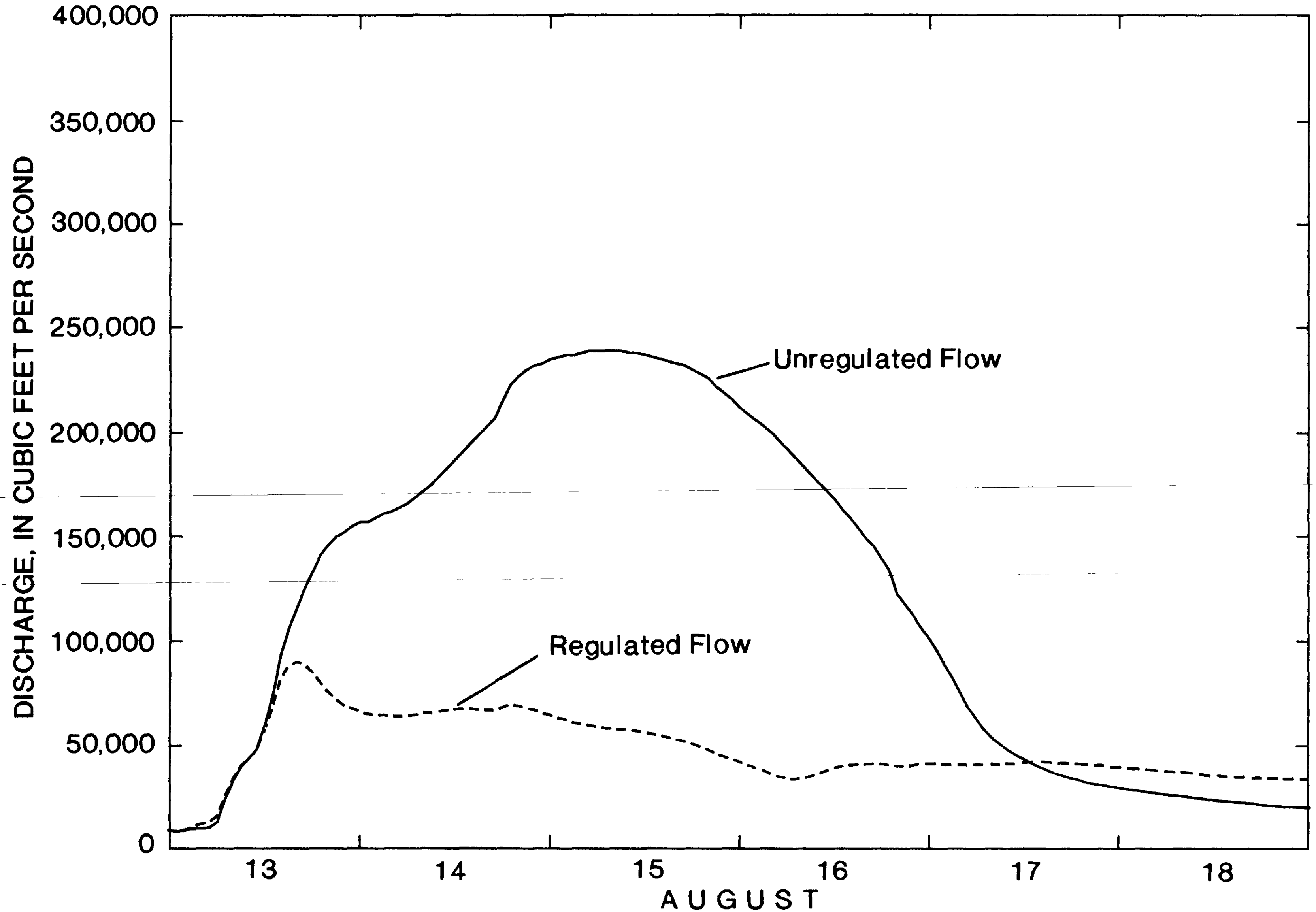


Figure 31.--Measured flood hydrographs for unregulated conditions and simulated hydrographs for the regulated conditions for the Savannah River at Augusta, Ga. (02197000) for flood of August 1940.

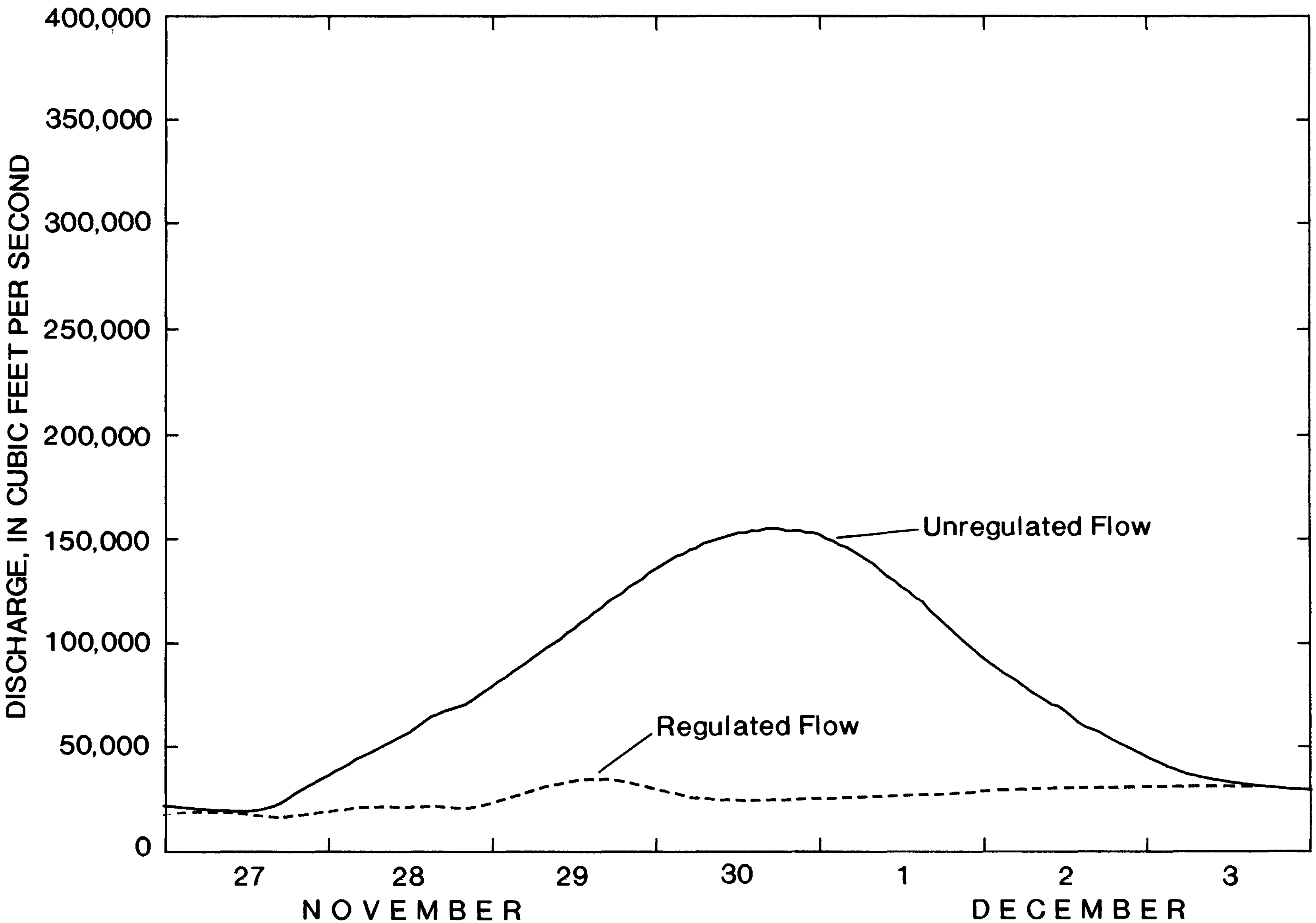


Figure 32.--Measured flood hydrographs for unregulated conditions and simulated hydrographs for the regulated conditions for the Savannah River at Augusta, Ga. (02197000) for flood of November to December 1948.

Table 10.--Measured and simulated regulated and unregulated peak discharges for the Savannah River at Augusta, Ga. (02197000)

[ft^3/s, cubic feet per second; dashes indicate no data]

Month	Water year	[1]Amplification factor	Unregulated discharge (ft^3/s)	Regulated discharge (ft^3/s)
January	1796	--	[2]360,000	[4]191,000
May	1840	--	[2]270,000	[4]118,000
August	1852	--	[2]250,000	[4]105,000
January	1865	--	[2]240,000	[4]99,700
September	1888	--	[2]303,000	[4]143,000
August	1908	--	[2]307,000	[3]108,000
August	1908	1.25	[3]383,000	[3]153,000
August	1908	1.50	[3]459,000	[3]202,000
August	1908	2.00	[3]613,000	[3]331,000
March	1912	--	[2]234,000	[3]62,700
March	1912	1.25	[3]291,000	[3]92,800
March	1912	1.50	[3]349,000	[3]120,000
March	1912	2.00	[3]465,000	[3]187,000
August	1928	--	[2]226,000	[3]44,200
August	1928	1.25	[3]282,000	[3]66,400
August	1928	1.50	[3]339,000	[3]102,000
August	1928	2.00	[3]452,000	[3]182,000
March	1929	--	[2]190,000	[3]106,000
March	1929	1.25	[3]343,000	[3]134,000
March	1929	1.50	[3]286,000	[3]167,000
March	1929	2.00	[3]381,000	[3]247,000
September	1929	--	[2]343,000	[3]180,000
September	1929	1.25	[3]429,000	[3]237,000
September	1929	1.50	[3]514,000	[3]298,000
September	1929	2.00	[3]686,000	[3]421,000
October	1930	--	[2]350,000	[3]252,000
October	1930	1.25	[3]437,000	[3]328,000
October	1930	1.50	[3]524,000	[3]400,000
October	1930	2.00	[3]699,000	[3]491,000

Table 10.--Measured and simulated regulated and unregulated peak discharges for the Savannah River at Augusta, Ga. (02197000)--Continued

[ft^3/s, cubic feet per second; dashes indicate no data]

Month	Water year	[1]Amplification factor	Unregulated discharge (ft^3/s)	Regulated discharge (ft^3/s)
April	1936	--	[2]258,000	[3]181,000
April	1936	1.25	[3]322,000	[3]265,000
April	1936	1.50	[3]386,000	[3]346,000
April	1936	2.00	[3]515,000	[3]488,000
August	1940	--	[2]239,000	[3] 90,200
August	1940	1.25	[3]299,000	[3]111,000
August	1940	1.50	[3]358,000	[3]134,000
August	1940	2.00	[3]478,000	[3]203,000
November	1949	--	[2]154,000	[3] 34,700
November	1949	1.25	[3]194,000	[3] 52,700
November	1949	1.50	[3]232,000	[3] 78,400
November	1949	2.00	[3]310,000	[3]129,000
March	1952	--	[3]137,000	[2] 39,300
May	1953	--	[3] 56,400	[2] 35,200
March	1954	--	[3] 59,100	[2] 25,500
April	1955	--	[3] 68,400	[2] 23,900
April	1956	--	[3] 65,200	[2] 18,600
May	1957	--	[3] 53,400	[2] 18,000
April	1958	--	[3] 86,100	[2] 66,300
June	1959	--	[3] 54,900	[2] 28,500
February	1960	--	[3] 84,700	[2] 34,900
April	1961	--	[3]113,000	[2] 34,800
January	1962	--	[3] 81,700	[2] 32,500
March	1963	--	[3] 94,000	[2] 31,300
April	1964	--	[3]143,000	[2] 87,100
April	1964	1.25	[3]197,000	[3]154,000
April	1964	1.50	[3]236,000	[3]190,000
April	1964	2.00	[3]315,000	[3]266,000

Table 10.--Measured and simulated regulated and unregulated peak discharges for the Savannah River at Augusta, Ga. (02197000)--Continued

[ft³/s, cubic feet per second; dashes indicate no data]

Month	Water year	[1]Amplification factor	Unregulated discharge (ft³/s)	Regulated discharge (ft³/s)
December	1965	--	[3]111,000	[2]34,600
March	1966	--	[3]131,000	[2]39,300
August	1967	--	[3]102,000	[2]26,500
January	1968	--	[3]79,000	[2]35,900
April	1969	--	[3]114,000	[2]45,600
April	1970	--	[3]74,300	[2]25,200
March	1971	--	[3]180,000	[2]63,900
January	1972	--	[3]114,000	[2]33,700
April	1973	--	[3]98,000	[2]40,200
February	1974	--	[3]86,000	[2]32,900
March	1975	--	[3]149,000	[2]45,600
June	1976	--	[3]104,000	[2]33,300
April	1977	--	[3]90,900	[2]34,200
January	1978	--	[3]138,000	[2]43,100
February	1979	--	[3]125,000	[2]37,300
March	1980	--	[3]108,000	[2]47,200
February	1981	--	[3]56,100	[2]17,700
January	1982	--	[3]88,000	[2]30,700
April	1983	--	[3]102,000	[2]66,100
May	1984	--	[3]65,600	[2]34,000
February	1985	--	[3]66,300	[2]25,700

[1]Factor by which inflow hydrographs were multiplied to synthesize larger floods.

[2]Discharge was measured.

[3]Discharge was simulated by computer modeling.

[4]Discharge was simulated from relation of regulated discharge to unregulated discharge.

Rainfall-Runoff Method

A rainfall-runoff model (HEC-1) was used to simulate hourly hydrographs for the 1936 flood upstream from Thurmond Dam. Discharge data were not available for the Savannah River at Calhoun Falls and for the Broad River near Bell, therefore, the hydrographs to Hartwell, Russell, and Thurmond Lakes were simulated using HEC-1. Hydrographs for the reach from Thurmond Dam (02195000) to Augusta are from the Savannah District Reservoir Regulation Manual Plate A-25 (COE, 1974).

Daily rainfall data for 20 gages in the Savannah River basin upstream from Thurmond Dam for January through April 1936 were obtained from the NWS. Using these data, Thiessen polygons were determined to estimate the areal distribution of rainfall over the basin. The daily rainfall data were adjusted to hourly values and linearly interpolated.

Models were developed for each area using the SCS unit hydrograph method (SCS, 1972; McCuen, 1982) in HEC-1. SCS curve numbers for the areas ranged from 62 to 99. A curve number of 99 was used for rainfall on lakes. Hourly rainfall values were input and weighted according to the Thiessen polygons. Inflow hydrographs to each of the three lakes were computed using HEC-1 for the period of heaviest rainfall, mid-March to mid-April.

The unregulated inflows were routed to Augusta using the Muskingum routing method. The simulated unregulated discharges were compared to measured discharges and adjustments were made to HEC-1 parameters as necessary to calibrate the models. Once the models were calibrated, regulated discharges were simulated using the unregulated inflow hydrographs and the HEC-5 model with reservoir storage and current operation data. The simulated regulated hydrograph and the measured unregulated hydrograph are shown in figure 30. The peak discharge for regulated conditions is listed in table 10.

RELATION OF REGULATED TO UNREGULATED PEAK DISCHARGES

Regulated peak discharges were related to unregulated discharges using measured and simulated data for the floods of 1908, 1912, 1928, March and September 1929, 1930, 1936, 1940, 1949, and 1952-85.

The relation was determined graphically (fig. 33) from data listed in table 10.

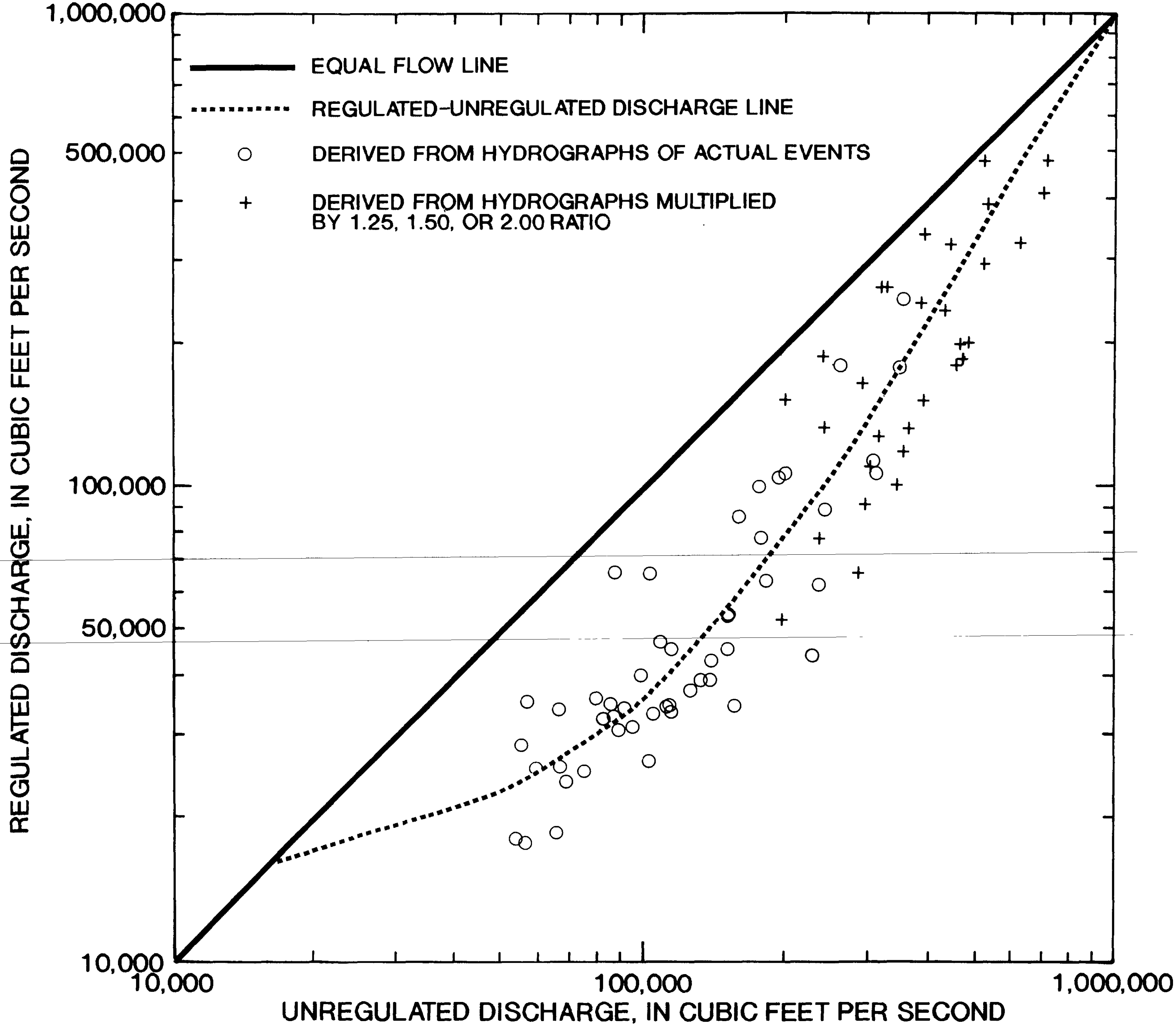


Figure 33.--Relation between regulated peak discharges and unregulated peak discharges for the Savannah River at Augusta, Ga. (02197000).

The data in figure 33 show that the reservoirs have little effect on the extremely large floods because reservoir storage is small compared to the flood volume. The scatter in the points in figure 33 is caused by differences in initial pool elevations, flood volumes, and timing of inflow hydrographs. The relation in figure 33 reflects average conditions for a wide range of flood flows. The logarithmic residuals from the curve of relation are normally distributed with a mean and standard deviation of -.016 and 0.145 respectively.

UNREGULATED FLOOD FREQUENCY

A flood frequency curve for unregulated flow (table 11 and fig. 34) was derived from measured unregulated peak discharges at Augusta, listed in table 2 for water years 1786-1951, and from simulated unregulated peak discharges for water years 1952-85, listed in table 5, using the log-Pearson Type III method as described by the Interagency Advisory Committee on Water Data (IACWD, 1982). A systematic record period of 1876-1985 and a historic record period of 1786-1985 were used. The record of peak discharges is considered to be complete for peak discharges equal to or greater than 225,000 ft^3/s (Carter, 1951).

Reports by the COE (1929, 1974) indicate that all peak discharges above 165,000 ft^3/s were probably known for the period since 1796. Although this may be the case, if it were true it would imply that the probability of having a 54-year period (1786-1839) with only one flood (1796) exceeding 165,000 ft^3/s would be only 0.019 and that the probability of having only four such floods in the 90-year pre-systematic record (1786-1875) would be only 0.033. These probabilities are based on the occurrence of 12 floods greater than 165,000 ft^3/s in the 110-year systematic record period 1876-1985. Because it is rather unlikely that so few floods of this magnitude would have occurred during the periods considered, the possibility was considered that a higher threshold would be more appropriate. Emigh (1914) indicates that widespread flooding actually occurred at stages exceeding about 36 ft (210,000 ft^3/s); floods exceeding this level almost certainly would have been recorded. A slightly higher discharge of 225,000 ft^3/s was used as a threshold by Carter (1951). Under the hypothesis that the flood record is complete above this level, the probabilities quoted above become 0.097 and 0.22, which are considerably more likely. It is more likely, therefore, that the criteria for a complete historical record of floods above a certain threshold (IACWD, 1982) would be met if the historical flood threshold were set at 225,000 ft^3/s rather than at 165,000 ft^3/s; therefore, the higher value was used in this study.

Table 11.--Peak discharges and frequency plotting positions for unregulated conditions for the Savannah River at Augusta, Ga. (02197000)

[ft³/s, cubic feet per second]

Chronological		Ranked		
Water year	Peak discharge	Water year	Peak discharge (ft^3/s)	Frequency plotting position (percent)
1796	360,000	1796	360,000	0.50
1840	270,000	1930	350,000	1.00
1852	250,000	1929	343,000	1.49
1865	240,000	1908	307,000	1.99
1876	86,400	1888	303,000	2.49
1877	119,000	1840	270,000	2.99
1878	51,500	1936	258,000	3.48
1879	44,000	1852	250,000	3.98
1880	102,000	1865	240,000	4.48
1881	130,000	1940	239,000	4.98
1882	93,300	1912	234,000	5.47
1883	111,000	1928	226,000	5.97
1884	81,000	1891	197,000	6.68
1885	77,000	1971	180,000	7.59
1886	135,000	1902	175,000	8.51
1887	173,000	1887	173,000	9.43
1888	303,000	1913	156,000	10.35
1889	149,000	1949	154,000	11.26
1890	48,500	1925	150,000	12.18
1891	197,000	1889	149,000	13.10
1892	140,000	1975	149,000	14.01
1893	60,000	1903	147,000	14.93
1894	54,000	1964	142,800	15.85
1895	106,000	1892	140,000	16.76
1896	107,000	1900	138,000	17.68
1897	93,300	1978	138,000	18.60
1898	117,000	1952	136,900	19.52
1899	113,000	1886	135,000	20.43
1900	138,000	1920	133,000	21.35
1901	124,000	1966	131,000	22.27
1902	175,000	1881	130,000	23.18
1903	147,000	1921	129,000	24.10
1904	63,000	1919	128,000	25.02
1905	64,800	1944	128,000	25.93
1906	96,600	1979	125,000	26.85
1907	52,000	1901	124,000	27.77

Table 11.--Peak discharges and frequency plotting positions for unregulated conditions for the Savannah River at Augusta, Ga. (02197000)

[ft³/s, cubic feet per second]

Chronological		Ranked		
Water year	Peak discharge	Water year	Peak discharge (ft^3/s)	Frequency plotting position (percent)
1908	307,000	1877	119,000	28.68
1909	87,300	1898	117,000	29.60
1910	69,800	1943	117,000	30.52
1911	32,800	1969	114,000	31.44
1912	234,000	1972	114,000	32.35
1913	156,000	1899	113,000	33.27
1914	48,000	1961	113,000	34.19
1915	61,000	1883	111,000	35.10
1916	82,400	1965		
1917	68,000	1980	108,000	36.94
1918	45,500	1896	107,000	37.85
1919	128,000	1895	106,000	38.77
1920	133,000	1942	105,000	39.69
1921	129,000	1976	104,000	40.61
1922	92,000	1880	102,000	41.52
1923	59,700	1967	102,000	42.44
1924	59,700	1983	102,000	43.36
1925	150,000	1973	98,000	44.27
1926	55,300	1946	97,200	45.19
1927	39,000	1906	96,600	46.11
1928	226,000	1963	94,000	47.02
1929	343,000	1932	93,800	47.94
1930	350,000	1882	93,300	48.86
1931	26,100	1897	93,300	49.78
1932	93,800	1933	92,600	50.69
1933	92,600	1922	92,000	51.61
1934	73,200	1937	91,400	52.53
1935	63,700	1938	91,400	53.44
1936	258,000	1939	90,900	54.36

Table 11.--Peak discharges and frequency plotting positions for unregulated conditions for the Savannah River at Augusta, Ga. (02197000)--Continued

[ft³/s, cubic feet per second]

Chronological		Ranked		
Water year	Peak discharge	Water year	Peak discharge (ft^3/s)	Frequency plotting position (percent)
1937	91,400	1977	90,900	55.28
1938	91,400	1982	88,000	56.19
1939	90,900	1909	87,300	57.11
1940	239,000	1876	86,400	58.03
1941	53,300	1958	86,100	58.95
1942	105,000	1947	86,000	59.86
1943	117,000	1974	86,000	60.78
1944	128,000	1960	84,700	61.70
1945	64,000	1948	83,200	62.61
1946	97,200	1916	82,400	63.53
1947	86,000	1962	81,700	64.45
1948	83,200	1884	81,000	65.36
1949	154,000	1968	79,000	66.28
1950	32,500	1885	77,000	67.20
1951	46,300	1970	74,300	68.12
1952	136,900	1934	73,200	69.03
1953	56,400	1910	69,800	69.95
1954	59,100	1955	68,400	70.87
1955	68,400	1917	68,000	71.78
1956	65,200	1985	66,300	72.70
1957	53,400	1984	65,600	73.62
1958	86,100	1956	65,200	74.53
1959	54,900	1905	64,800	75.45
1960	84,700	1945	64,000	76.37
1961	113,000	1935	63,700	77.29

Table 11.--Peak discharges and frequency plotting positions for unregulated conditions for the Savannah River at Augusta, Ga. (02197000)--Continued

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

Chronological		Ranked		
Water year	Peak discharge	Water year	Peak discharge (ft^3/s)	Frequency plotting position (percent)
1962	81,700	1904	63,000	78.20
1963	94,000	1915	61,000	79.12
1964	142,800	1893	60,000	80.04
1965	111,000	1923	59,700	80.95
1966	131,000	1924	59,700	81.87
1967	102,000	1954	59,100	82.79
1968	79,000	1953	56,400	83.70
1969	114,000	1981	56,100	84.62
1970	74,300	1926	55,300	85.54
1971	180,000	1959	54,900	86.45
1972	114,000	1894	54,000	87.37
1973	98,000	1957	53,400	88.29
1974	86,000	1941	53,300	89.21
1975	149,000	1907	52,000	90.12
1976	104,000	1878	51,500	91.04
1977	90,900	1890	48,500	91.96
1978	138,000	1914	48,000	92.87
1979	125,000	1951	46,300	93.79
1980	108,000	1918	45,500	94.71
1981	56,100	1879	44,000	95.62
1982	88,000	1927	39,000	96.54
1983	102,000	1911	32,800	97.46
1984	65,600	1950	32,500	98.38
1985	66,300	1931	26,100	99.29

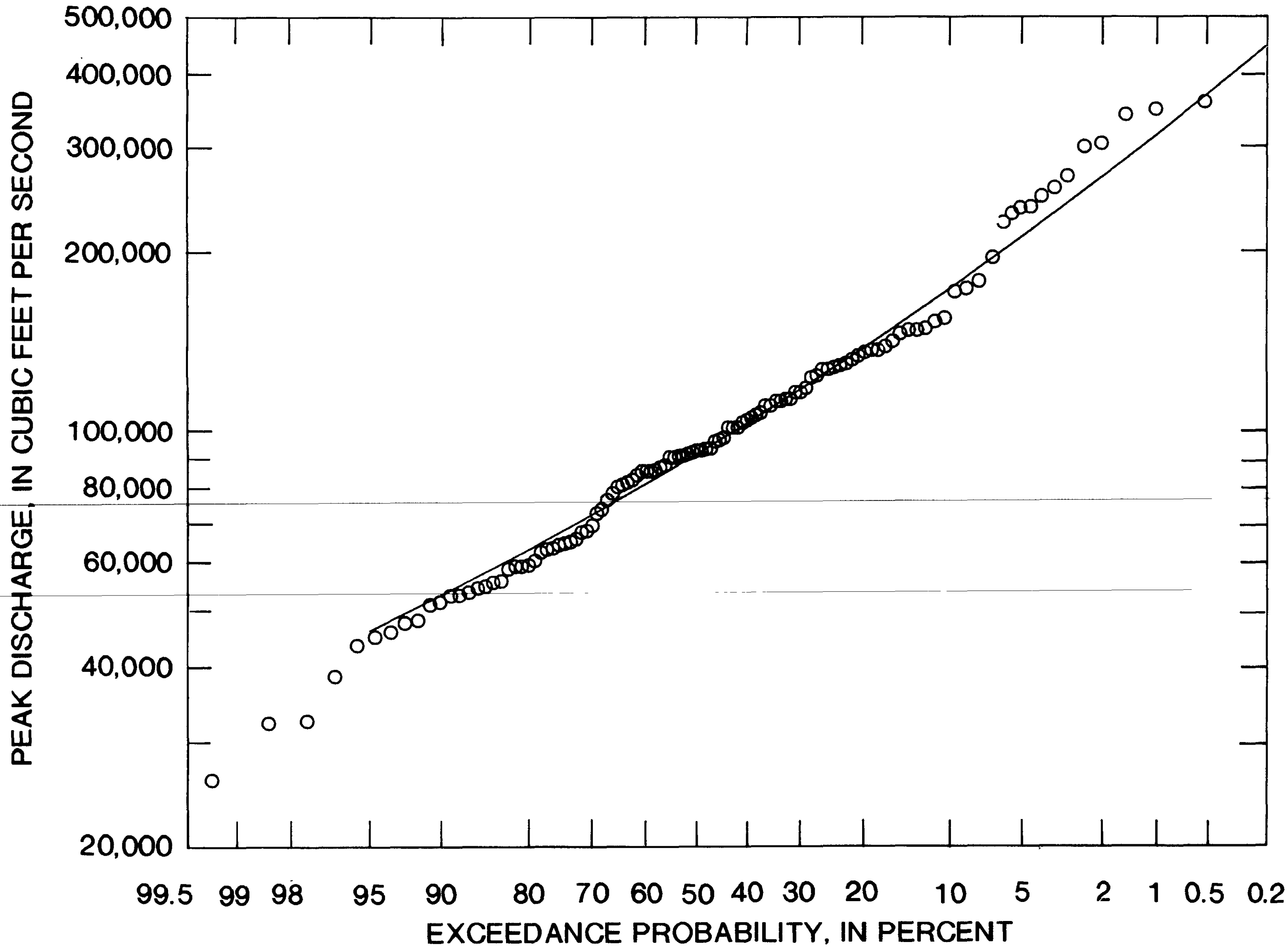


Figure 34.--Unregulated peak discharge frequency curve for the Savannah River at Augusta, Ga. (02197000).

Table 12.--Discharges of unregulated floods of selected percent chance exceedances of the Savannah River at Augusta, Ga. (02197000)

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

Percent chance of exceedance	Peak discharge (ft^3/s)
50	92,000
20	138,000
10	174,000
4	226,000
2	269,000
1	316,000
0.5	368,000
0.2	445,000

The Interagency Advisory Committee on Water Data (1982) suggests that the flood frequency relation should be tested for the sensitivity of lower exceedance probabilities to inclusion of floods that exceed the low outlier criteria by small amounts. The initially computed low outlier criterion was 20,800 ft^3/s, compared to the three smallest floods, which had peak discharges of 32,800, 26,100, and 32,500 ft^3/s for 1911, 1931, and 1950, respectively.

The estimated one-percent chance exceedance flood was insensitive to alternative values of the low-outlier criterion in the range of 35,000 to 70,000 ft^3/s. The estimated one-percent chance exceedance flood changed markedly when the criterion was lowered to include the three smallest floods. This sensitivity of the one-percent chance exceedance flood to the magnitudes of the smallest observed floods is not hydrologically reasonable; therefore, the low outlier criterion was set at 35,000 ft^3/s.

The one-percent chance exceedance flood for unregulated conditions for the Savannah River at Augusta is 316,000 ft^3/s. Peak discharges for other exceedance probabilities are listed in table 12 and shown in figure 34.

An analysis was performed to test the sensitivity of the unregulated flood frequency relation to variations in the peak stage and discharge of the 1796 flood, ranging from 37 to 41 feet and 240,000 to 410,000 ft^3/s. Discharges computed for the one-percent chance exceedance flood were three percent lower and one percent higher, respectively, for the lower and upper ranges of peak discharge estimates.

REGULATED FLOOD FREQUENCY

A regulated flood frequency relation for the Savannah River at Augusta was developed by adjusting the unregulated frequency relation for regulated conditions using the relation between regulated and unregulated peak discharges and an application of the total probability theorem. Graphical procedures and computation of probability distributions were used and the results compared. The two methods of analysis are called "total probability method" and the "plotting position method" in this report.

The unregulated flood frequency relation (fig. 34) quantifies the effect of hydrometeorological variables that determine unregulated flood occurrence and magnitude. The relation between regulated and unregulated peak discharges (fig. 33) quantifies the predictable portion of the effect of reservoir-operation variables on the regulated magnitude of a given unregulated flood. The residuals about the trend line of the regulated-unregulated relation quantify the unpredictable effect of reservoir-operation and hydrometeorological variables on the regulated magnitude of a given unregulated flood.

A graphical comparison of unregulated peak flows of the Broad River near Bell with concurrent regulated peak flows of the Savannah River at Augusta showed that regulated peak flows at Augusta for the period 1952-61 did not differ significantly from those during the 1962-85 period after Hartwell Dam was constructed. Russell Lake is considered to have little impact on flood control, because of its relatively small flood control storage. Therefore, the record 1952-85 was considered to be homogeneous with respect to the construction of Hartwell and Russell Dams.

The total probability method is based on the so-called Total Probability Theorem (Mood and others, 1974; Benjamin and Cornell, 1970) which expresses the probability of an event in terms of a sum of probabilities of constituent events. As applied to regulated flows, the Total Probability Theorem states that

$$P(Q_r > x) = \sum P(Q_u = z)\ P(Q_r > x \mid Q_u = z)$$

where Q_r is the regulated flood magnitude, Q_u is the unregulated flood magnitude, P is the probability of the indicated event, and $P(Q_r > x \mid Q_u = z)$ is the conditional probability that Q_r exceeds x, given that Q_u equals z. The sum includes all possible values of Q_u. The probability $P(Q_u = z)$ is defined by the unregulated frequency curve. The conditional probability is defined by the regulated-flood trend line and the statistics of the residuals, as follows. The relation between the regulated and unregulated floods can be expressed as

$$Q_r = H(Q_u) + \varepsilon$$

where H is the mathematical function that represents the trend line in figure 33 and ε is a random variable representing the residuals between the actual regulated flow, Q_r, and the trend line. All variables in this relation are expressed in terms of logarithms. The conditional probability then can be expressed as

$$P(Q_r > x \mid Q_u = z) = P(\varepsilon > x - H(z) \mid Q_u = z)$$

The probability distribution of ε is determined by means of statistical analysis of the residuals. This result therefore may be substituted into the Total Probability formula, with the result:

$$P(Q_r > x) = \sum P(Q_u = z)\ P(\varepsilon > x - H(z) \mid Q_u = z)$$

Because both probability terms in this formula are known, the formula can be evaluated and the probability of Q_r's exceeding x can be determined.

Evaluation of this formula was carried out numerically by a computer program (W. Kirby, USGS, written commun., 1990). For use in the program, the unregulated frequency curve was defined by its quantiles at annual exceedance probabilities of 0.5, 0.1, and 0.01; the regulated-flood trend line was defined by 14 points read off the curve in figure 33; and the probability distribution of ε was defined by the mean and standard deviation of logarithmic residuals from the trend line in figure 33. The computer program computed the regulated-flood exceedance probabilities for selected values of discharges x. The results are shown as a regulated frequency curve in figure 35. The unregulated frequency relation of figure 34 also is shown in figure 35 for comparison. These results are consistent with results of similar computations performed independently by the COE's method of coincident frequency analysis, computer program CFA (H.E. Kubik, COE, written commun., 1990).

A flood frequency relation was also computed using the Weibull probability plotting position method presented by the Interagency Committee on Water Data (1982). Regulated flood magnitudes and their frequency plotting positions are given in Table 13. A historic period of record of 1786 to 1985 and a systematic period of record of 1952-85 were used. A regulated historic threshold discharge of 90,000 ft^3/s was determined by converting the 225,000 ft^3/s unregulated historic threshold discharge to regulated discharge using the relation in figure 33. Regulated discharges for ten floods were determined above this threshold discharge from results of model simulations or from conversion of unregulated peak discharges to regulated peak discharges (table 10) using the relation in figure 33. Measured regulated peak discharges were available for water years 1952-85. Results of the plotting position method are shown in figure 35 along with the total probability results.

Comparison of the total probability and plotting-position curves as shown in figure 35 indicates agreement within about 15 percent throughout the range of probabilities of interest. This level of agreement is within the limits of uncertainty of either method. Therefore, the average results of the two methods are adopted and listed in table 14. The one-percent chance exceedance flood under 1990 reservoir operating conditions is 180,000 ft^3/s. The results of this analysis may be become inapplicable if significant changes are made in reservoir operating procedures.

A sensitivity analysis of the effects of possible inaccuracies in the 1796 peak discharge on the regulated flood-frequency relation was conducted. Variations in the 1796 discharge from 240,000 to 410,000 ft^3/s (stages 37 to 41 feet) were considered. Under these variations, discharges computed for the one-percent chance exceedance flood were -4 percent and +4 percent of the one-percent chance exceedance flood.

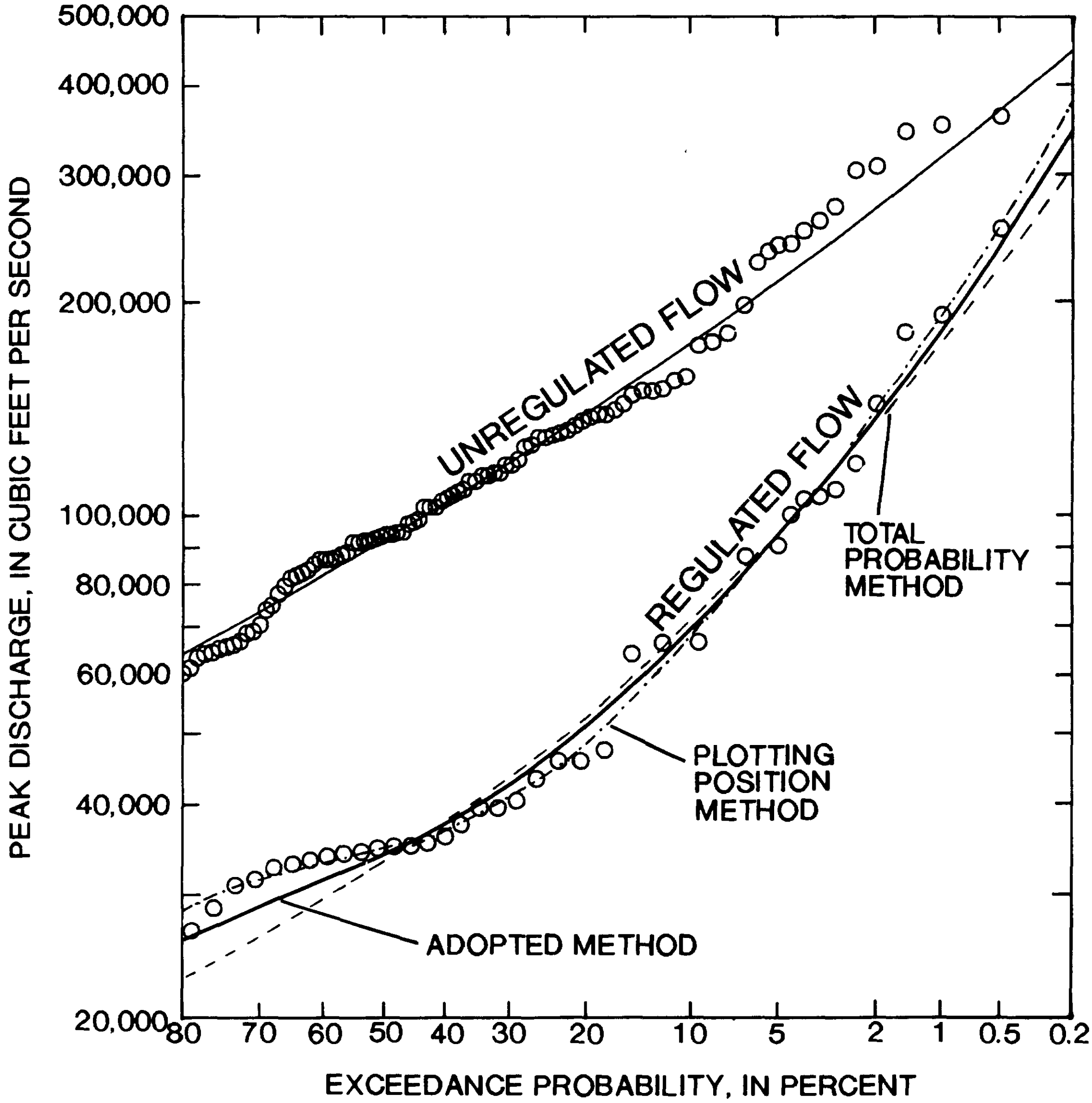


Figure 35.--Unregulated and regulated peak discharge frequency curves for the Savannah River at Augusta, Ga. (02197000).

Table 13.--Peak discharges and frequency plotting positions for regulated conditions for the Savannah River at Augusta, Ga. (02197000)

[ft³/s, cubic feet per second]

Chronological		Ranked		
Water year	Peak discharge (ft^3/s)	Water year	Peak discharge (ft^3/s)	Frequency plotting position (percent)
1796	191,000	1930	252,000	0.50
1840	118,000	1796	191,000	1.00
1852	105,000	1936	181,000	1.49
1865	99,700	1888	143,000	1.99
1888	143,000	1840	118,000	2.49
1908	108,000	1908	108,000	2.98
1929	106,000	1929	106,000	3.48
1930	252,000	1852	105,000	3.98
1936	181,000	1865	99,700	4.48
1940	90,200	1940	90,200	4.97
1952	39,300	1964	87,100	6.61
1953	35,200	1958	66,300	9.39
1954	25,500	1983	66,100	12.17
1955	23,900	1971	63,900	14.95
1956	18,600	1980	47,200	17.74
1957	18,000	1969	45,600	20.51
1958	66,300	1975	45,600	23.29
1959	28,500	1978	43,100	26.08
1960	34,900	1973	40,200	28.86
1961	34,800	1952	39,300	31.64
1962	32,500	1966	39,300	34.42
1963	31,300	1979	37,300	37.20
1964	87,100	1968	35,900	39.98
1965	34,600	1953	35,200	42.76
1966	39,300	1960	34,900	45.54
1967	26,500	1961	34,800	48.32
1968	35,900	1965	34,600	51.10
1969	45,600	1977	34,200	53.88
1970	25,200	1984	34,000	56.66
1971	63,900	1972	33,700	59.44

Table 13.--Peak discharges and frequency plotting positions for regulated conditions for the Savannah River at Augusta, Ga. (02197000)--Continued

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

Chronological		Ranked		
Water year	Peak discharge (ft^3/s)	Water year	Peak discharge (ft^3/s)	Frequency plotting position (percent)
1972	33,700	1976	33,300	62.22
1973	40,200	1974	32,900	65.00
1974	32,900	1962	32,500	67.78
1975	45,600	1963	31,300	70.56
1976	33,300	1982	30,700	73.34
1977	34,200	1959	28,500	76.12
1978	43,100	1967	26,500	78.90
1979	37,300	1985	25,700	81.68
1980	47,200	1954	25,500	84.46
1981	17,700	1970	25,200	87.24
1982	30,700	1955	23,900	90.02
1983	66,100	1956	18,600	92.80
1984	34,000	1957	18,000	95.58
1985	25,700	1981	17,700	98.36

Table 14.--Discharges of regulated floods of selected percent chance exceedances of the Savannah River at Augusta, Ga. (02197000)

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

Percent chance of exceedance	Peak discharge (ft^3/s)
50	34,500
20	51,500
10	69,000
4	105,000
2	140,000
1	180,000
0.5	240,000
0.2	345,000

SUMMARY

A flood-frequency relation was established for the Savannah River at the long-term gaging station at Augusta, Georgia (02197000) to fill an increasing need for reliable information on floods of various exceedance probabilities. The flood-frequency analysis was complicated by the fact that the Savannah River upstream of Augusta has experienced regulation of flow caused by Thurmond, Hartwell and Russell Dams, which began filling in 1951, 1961, and 1984, respectively.

In addition to the 5 historic floods, unregulated peak discharge data for the Savannah River at Augusta are available for water years 1876-1951, and regulated peak discharge data are available for 1952-85. Because it is necessary to use the longest possible period of record in flood-frequency analyses and especially because of the absence of major floods since 1951, unregulated major floods prior to 1952 were adjusted for regulation and were included in the analysis. Regulated peak discharges since 1951 were also converted to unregulated peak discharges for use in determining the unregulated flood-frequency relation.

Unregulated discharges for the 1952-85 period were simulated using daily streamflow records converted to 2-hour data and routed to Augusta (02197000) without regulation to simulate unregulated peak discharges to be included in an unregulated peak discharge data base for 1786-1985. An unregulated flood frequency relation was generated using the log-Pearson Type III method, using a historical threshold discharge of 225,000 ft^3/s and a low-outlier threshold of 35,000 ft^3/s. The one-percent chance exceedance unregulated discharge for the Savannah River at Augusta is 316,000 ft^3/s.

Nine large unregulated floods were adjusted for regulated conditions using the HEC-5 computer model and hourly inflow hydrographs estimated from discharge records at gaging stations within the basin and from rainfall-runoff modeling. Routing parameters and initial pool elevations estimated by daily flow routings or by median lake elevations were also used in the HEC-5 model. Regulated peak discharges were related to unregulated peak discharges. These relations were used to convert unregulated peak discharge to regulated peak discharges for selected unregulated floods that could not be modeled.

A flood-frequency relation for regulated conditions was developed by the graphical method using a regulated historic base discharge of 90,000 ft^3/s and by total-probability computations. The regulated one-percent chance exceedance flood for the Savannah River at Augusta for current (1990) reservoir operation methodology is 180,000 ft^3/s. The regulated flood-frequency relation may change if reservoir operation methods change.

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