COST EFFECTIVENESS OF THE U.S. GEOLOGICAL SURVEY STREAM-GAGING PROGRAM IN ALABAMA

By Hillary H. Jeffcoat

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ABSTRACT

This report documents the results of a study of the cost effectiveness of the stream-gaging program in Alabama. Data uses and funding sources were identified for the 72 surface-water stations (including dam stations, slope stations, and continuous-velocity stations) operated by the U.S. Geological Survey in Alabama with a budget of $393,600. Of these, 58 gaging stations were used in all phases of this analysis at a funding level of $328,380.

For the current policy of operation of the 58-station program, the average standard error of estimation of instantaneous discharge is 29.3 percent. This overall level of accuracy could be maintained with a budget of $319,800 by optimizing routes and implementing some policy changes. The maximum budget considered in the analysis was $361,200; this analysis gave an average standard error of estimation of 20.6 percent. The minimum budget considered was $299,360; this analysis gave an average standard error of estimation of 36.5 percent.

The study indicates that a major source of error in the stream-gaging records is lost or missing data that results from failure of the streamside equipment. If perfect equipment were available, the standard error in estimating instantaneous discharge under the current program and budget could be reduced to 18.6 percent. This can also be interpreted to mean that the streamflow data records have a standard error of this magnitude during times when the equipment is operating properly.

INTRODUCTION

The U.S. Geological Survey is the principal Federal agency collecting surface water data in the Nation. The data are collected in cooperation with State and local governments and other Federal agencies. In 1983 the Geological Survey operated approximately 8,000 continuous-record gaging stations throughout the Nation. Some of these records extend from the turn of the century. Any long-term activity, such as the collection of surface-water data, needs to be reexamined at intervals, if not continuously, because of changes in objectives, technology, or external constraints. The last systematic nationwide evaluation of the streamflow-information program was completed in 1970 and is documented by Benson and Carter (1973). The Geological Survey presently (1986) is undertaking another nationwide analysis of the stream-gaging program that will be completed by 1988 with 20 percent of the program being analyzed each year. The objective of this analysis and report is to define and document the most cost-effective means of obtaining and providing streamflow information.

The first phase of the analysis identifies the principal uses of the data and relates these uses to funding sources for every continuous-record gaging station. Gaged sites for which data are no longer needed are identified, as are deficient or unmet data demands. In addition, gaging stations are categorized as to whether the data are available to users in a real-time sense, on a provisional basis, or at the end of the water year.

The second phase of the analysis is to identify less costly alternate methods of obtaining and providing the needed information; among these are flow-routing models and statistical methods. The stream-gaging activity no longer is considered just a network of measuring points, but rather an integrated information system in which data are provided both by measurements and synthesis.

The final phase of the analysis involves the use of Kalman-filtering and mathematical-programming techniques to define strategies for operation of the necessary stations that minimize the uncertainty in the streamflow records for given operating budgets. Kalman-filtering techniques are used to compute uncertainty functions (relating the standard errors of computation or estimation of streamflow records to the frequencies of visits to the gaging stations) for all stations in the analysis. A steepest-descent optimization program uses these uncertainty functions, information on practical stream-gaging routes, the various costs associated with stream gaging, and the total operating budget to identify the visit frequency for each station that minimizes the overall uncertainty in the streamflow records. The stream-gaging program that results from this analysis will meet the expressed water-data needs in the most cost-effective manner.

The standard errors of estimate given in the report are those that would occur if daily discharges were computed through the use of methods described in this study. No attempt has been made to estimate standard errors for discharges that are computed by other means. Such errors could differ from the errors computed in the report. The magnitude and direction of the differences would be a function of methods used to account for shifting controls and for estimating discharges during periods of missing records.

This report is organized into five sections; the first being an introduction to the stream-gaging activities in Alabama. The middle three sections each contain discussions of an individual phase of the analysis. Because of the sequential nature of the phases and the dependence of subsequent phases on the previous results, conclusions are made at the end of each of the middle three sections. The study, including all phase summaries, is summarized in the final section.

History of the Stream-Gaging Program in Alabama

In 1896 the United States Geological Survey began systematically collecting stream discharge data in Alabama. The initial investigations consisted of discharge measurements of a few large streams at stations maintained in cooperation with the Geological Survey of Alabama, the United States Army Corps of Engineers, and the United States Weather Bureau. During 1900-05 the network expanded to 12 gaging stations which was operated almost exclusively to obtain data on the amount of water flowing in the streams. These data were intended to provide a basis for estimating discharge at all seasons of the year for the development of "water power" in Alabama. The network remained practically static until the major floods of the 1930's produced an awareness of the need for additional streamflow information, and a rapid enlargement of the stream gaging program in Alabama. Additional program enlargement resulted from the expanding operations of the Corps of Engineers and Tennessee Valley Authority. A partial-record program was added to the regular program during the period 1944-52 to collect low-flow and crest-stage information. The streamflow program was further expanded in the mid-1950's to obtain flood information on small streams (1 to 15 square miles). In 1970 the stream-gaging program included 82 daily-discharge sites, 46 crest-stage partial-record sites, 31 small-stream rainfall-flood hydrograph sites, 6 flood hydrograph sites, and 284 low-flow partial-record sites.

A systematic network evaluation was conducted in 1971 in which accuracy criteria were described in quantitative terms and applied to the accumulated data from the network. In addition, consideration of alternative means to meet accuracy goals for each type of information were explored. Recommendations from this evaluation identified 25 gaging stations with sufficient record to meet the established accuracy goals and thus were recommended to be discontinued or reduced to partial-record status. Further recommendations included establishing 12 new daily-discharge stations. These recommendations were implemented during the period 1975-77. Subsequent minor adjustments were made yearly, based primarily on cooperator needs and financial support.

The number of continuous-record stream-gaging stations operated in Alabama is shown in figure 1.

Current Stream-Gaging Program in Alabama

During 1983, 72 daily-discharge, 6 stage-only, and 5 crest-stage stations were operated by the U.S. Geological Survey in Alabama. Of these stations, 58 were included in all three phases of this investigation. The network of streamflow stations contains nine stations where navigation structures are located. At another site discharge is determined using a continuous, electromagnetic current meter. The cost for operating the 58 streamflow stations during 1983 was $328,380.

The responsibility for data collection and records computation for all the network stations is shared by the District Office in Tuscaloosa, the Subdistrict Office in Montgomery, and the Field Headquarters in Cullman. The location of these offices and the assigned areas of responsibility are shown in figure 2.

Selected hydrologic data, including drainage area, period of record, and mean annual flow, for the 72 stations are given in table 1. The official U.S. Geological Survey eight-digit downstream order number, station name, and map identification number are also given in table 1.

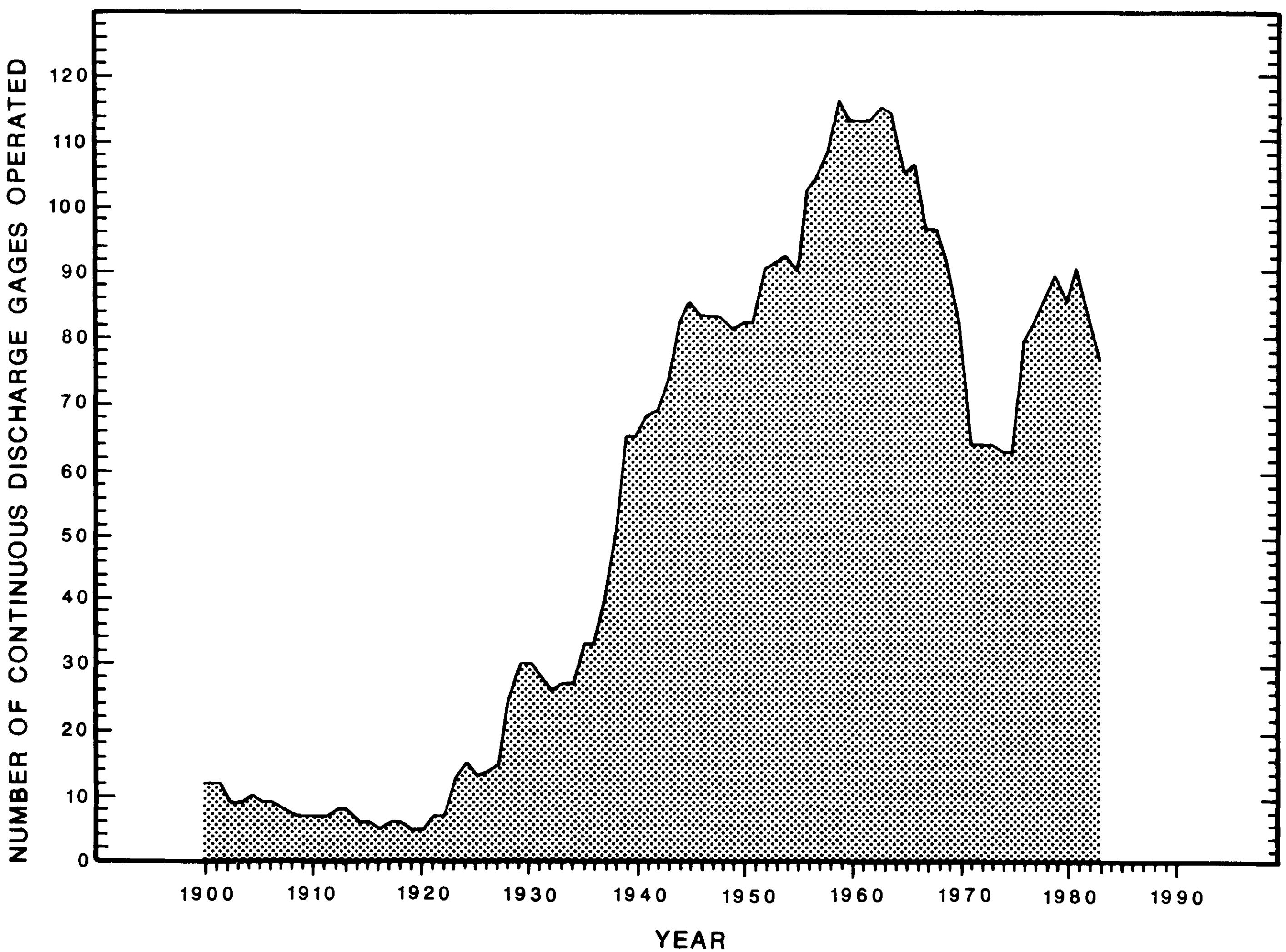

Figure 1. -- History of continuous stream gaging in Alabama.

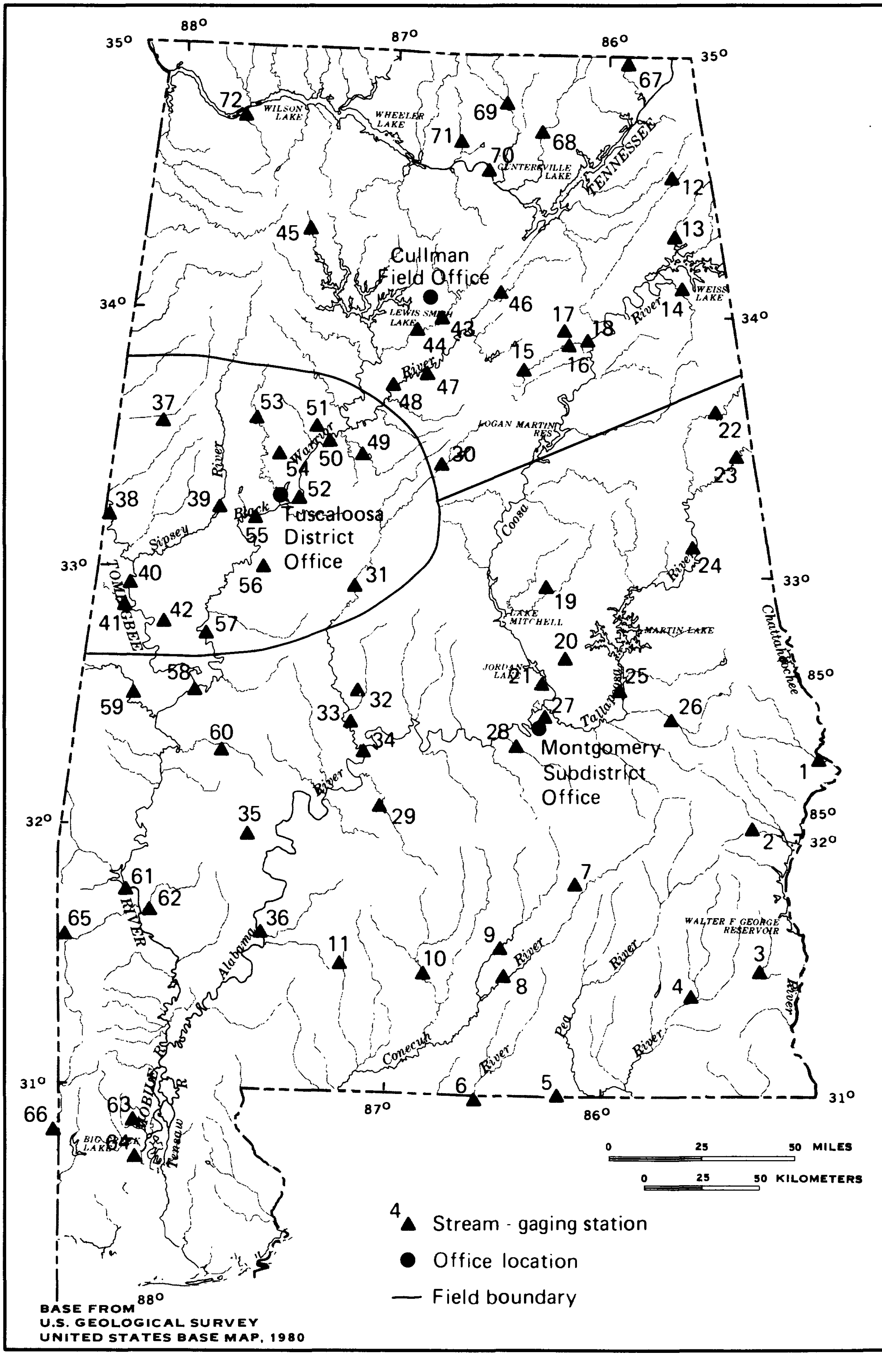

Figure 2. -- Location of gaging stations, office, and areas of responsibility.

Table 1.--Drainage area, period of record, and mean annual flow for selected stations in the Alabama surface-water program

Map index number	Station number	Station name	Drainage area (mi^2)	Period of record	Mean annual flow (ft^3/s)
1	02342500	Uchee Creek nr Ft Mitchell	325	1946-	447
2	02342933	So. Fork Cowikee Creek nr Batesville	114	1963-71, 1972-74[a], 1974-	135
3	02343300	Abbie Creek nr Haleburg	144	1958-71, 1974-	213
4	02361000	Choctawhatchee River nr Newton	683	1906-08, 1921-27, 1935-	983
5	02364570	Panther Creek nr Hacoda	26.5	1974-	51.3
6	02369800	Blackwater Creek nr Bradley	86.8	1967-	153
7	02371200	Indian Creek nr Troy	8.88	1958-68, 1969-70[a], 1970-	13.3
8	02371500	Conecuh River at Brantley	492	1937-	680
9	02372250	Patsaliga Creek nr Brantley	439	1974-	724
10	02373000	Sepulga River nr McKenzie	464	1937-67, 1968-70[a],1967[b], 1974-	684
11	02374500	Murder Creek nr Evergreen	170	1937-	287
12	02398195	Mills Creek nr Chesterfield	9.56	1978-	21.2
13	02399200	Little River nr Blue Pond	194	1958-67, 1967-70[ab], 1970-	500
14	02400100	Terrapin Creek at Ellisville	258	1962-67, 1967-79[a], 1980-	400
15	02401370	Big Canoe Creek nr Springville	45.0	1978-	95.1
16	02401390	Big Canoe Creek nr Ashville	148	1965-	280
17	02401460	Gulf Creek nr Ashville	14.2	1978-	30.6
18	02401470	Little Canoe Creek nr Steele	22.3	1982-	c
19	02408540	Hatchet Creek below Rockford	263	1980-	c
20	02410000	Paterson Creek nr Central	4.95	1953-	6.99
21	02411000	Coosa River at Jordan Dam	10,200	1912-14, 1925-	16,540
22	02412000	Tallapoosa River nr Heflin	444	1952-	703
23	02413300	Little Tallapoosa River nr Newell	401	1975-	649
24	02414500	Tallapoosa River at Wadley	1,660	1923-	2,584

See footnote at end of table.

Table 1.--Drainage area, period of record, and mean annual flow for selected stations in the Alabama surface-water program--Continued

Map index number	Station number	Station name	Drainage area (mi^2)	Period of record	Mean annual flow (ft^3/s)
25	02418500	Tallapoosa River below Tallassee	2,230	1928-	4,859
26	02419000	Uphapee Creek nr Tuskegee	220	1939-70, 1971-74[a], 1974-	439
27	02420000	Alabama River nr Montgomery	15,100	1927-	24,170
28	02421000	Catoma Creek nr Montgomery	298	1952-71, 1972-74[a], 1974-	368
29	02422500	Mulberry Creek at Jones	208	1938-70, 1970-74[a], 1974-	319
30	02423425	Cahaba River nr Cahaba Heights	201	1975-	312
31	02424000	Cahaba River at Centreville	1,029	1901-08, 1929-32, 1935-	1,621
32	02424940	Oakmulgee Creek nr Augustin	215	1975-	193
33	02425000	Cahaba River nr Marion Junction	1,768	1938-54, 1968-	2,919
34	02425200	Big Swamp Creek nr Orrville	37.8	1972-	51.2
35	02427700	Turkey Creek at Kimbrough	114	1958-	141
36	02428400	Alabama River at Claiborne L&D	21,500	1975-	37,200
37	02442500	Luxapallila Creek at Millport	241	1954-59, 1980-	328
38	02444160	Tombigbee River at Aliceville L&D	5,750	1980	c
39	02446500	Sipsey River nr Elrod	518	1928-32, 1939-71, 1978-	768
40	02448475	Tombigbee River nr Gainesville L&D	7,220	1978-	14,037
41	02448500	Noxubee River nr Geiger	1,140	1939-40, 1944-65, 1966-	1,571
42	02449245	Brush Creek nr Eutaw	42.7	1975-	72.3
43	02450000	Mulberry Fork nr Garden City	365	1928-	678
44	02450180	Mulberry Fork nr Arkadelphia	487	1976-	914
45	02450250	Sipsey Fork nr Grayson	90.1	1966-	171
46	02455000	Locust Fork nr Cleveland	303	1936-	528
47	02456330	Crooked Creek nr Morris	16.2	1975-	29.2
48	02456500	Locust Fork at Sayre	885	1928-31, 1941-	1,460

See footnotes at end of table.

Table 1.--Drainage area, period of record, and mean annual flow for selected stations in the Alabama surface-water program--Continued

Map index number	Station number	Station name	Drainage area (mi^2)	Period of record	Mean annual flow (ft^3/s)
49	02462000	Valley Creek nr Oak Grove	145	1954-58, 1965, 1979-	340
50	02462500	Black Warrior River at Bankhead L&D	3,990	1976-	7,332
51	02462600	Blue Creek nr Oakman	5.32	1959-65, 1976-	9.62
52	02462950	Black Warrior River at Holt L&D	4,230	1976-	7,673
53	02464000	North River nr Samantha	223	1938-54, 1968-	388
54	02464146	Turkey Creek nr Tuscaloosa	6.16	1981	c
55	02465000	Black Warrior River at Northport	4,828	1894-1902, 1928-	7,971
56	02465493	Elliots Creek nr Moundville	31.2	1976-	48.3
57	02466030	Black Warrior River at Warrior Dam	5,800	1976-	10,620
58	02467000	Tombigbee River at Demopolis L&D	15,400	1928-	23,100
59	02467500	Sucarnoochee River at Livingston	606	1938-	819
60	02468500	Chickasaw Bogue nr Linden	258	1945-46, 1966-	359
61	02469761	Tombigbee River at Coffeeville L&D	18,500	1960-	30,060
62	02469800	Satilpa Creek nr Coffeeville	166	1957-70, 1971-74[a], 1975-	230
63	02471001	Chickasaw Creek nr Kushla	125	1951-	275
64	02471065	Montlimar Creek at US 90 at Mobile	8.57	1963-67, 1975-	23.6
65	02479431	Pond Creek nr Deer Park	20.5	1976-	41.1
66	02479560	Escatawpa Creek nr Agricola, Miss.	556	1973-	1,334
67	03572110	Crow Creek at Bass	131	1975-	296
68	03574500	Paint Rock nr Woodville	320	1935-	688
69	03575000	Flint River nr Chase	342	1929-	551
70	03575500	Tennessee River at Whitesburg	25,610	1924-	43,570
71	03575830	Indian Creek nr Madison	49.0	1959-66, 1966-75[a], 1975-	62.6
72	03589500	Tennessee River at Florence	30,810	1894-	51,780

a/ Annual maximum discharge computed and published.
b/ Annual low-flow measurement made and published.
c/ No mean annual flow published; less than 5 years streamflow record.

Acknowledgment

The author thanks Peggy S. Reese for her assistance during this investigation. She provided valuable support in implementing the various computer programs used to optimize the cost-effectiveness of collecting streamflow data in Alabama.

USES, FUNDING, AND AVAILABILITY OF CONTINUOUS STREAMFLOW DATA

The relevance of a gaging station is defined by the uses that are made of the data that are produced by the station. The uses of the data from each stream-gaging station in the Alabama program were identified by a survey of known data users. The survey documented the relative importance of each gage. Yearly cooperator meetings were used to document the relative importance and use of the data from individual gages and also to identify gaging stations that may be considered for discontinuation. Data uses identified by the survey were categorized into nine classes, defined below. The sources of funding for each gage and the frequency at which data are provided to the users also were compiled (table 2).

Data-Use Classes

The following definitions were used to categorize each known use of streamflow data for each gaging station:

Regional Hydrology

For data to be useful in defining regional hydrology, a gaged stream needs to be largely unaffected by manmade storage or diversion. In this class of uses, the effects of man on streamflow are not necessarily small, but the effects are limited to those caused primarily by land-use and climate changes. Large amounts of manmade storage may exist in the basin provided the outflow is uncontrolled. These stations are useful in developing regionally transferable information about the relations between basin characteristics and streamflow.

Twenty-seven stations in the Alabama network are classified in the regional hydrology data-use category. Three of the stations, Conecuh River at Brantley (02371500), Cahaba River at Centreville (02424000), and Paint Rock River near Woodville (03574500), are classified as index reporting stations for the national monthly publication, Water Resources Review. There are two hydrologic benchmark stations in Alabama, Blackwater Creek near Bradley (02369800) and Sipsey Fork near Grayson (02450250), which are used to indicate hydrologic conditions in watersheds relatively free of manmade alteration. Nine of the regional hydrology stations are used to report current hydrologic conditions. The locations of the gaging stations that provide information about regional hydrology are given in figure 3.

Table 2.--Data use, funding, and frequency of availability

Map index no.	Station no.	Regional hydrology	Hydrologic systems	Legal obligations	Planning and design	Project operation	Hydrologic forecasts	Water-quality monitoring	Research	Other	Federal program	OFA program	Coop program	Other non-Federal	Data avail-ability
1	02342500	*	1								*				A
2	02342933		1									2			A
3	02343300		3					4					5		A
4	02361000	*	1,3				6				*				A, P, T
5	02364570	*	1,3										7		A
6	02369800	*	1,8,9								*				A, P
7	02371200	*	1								*				A
8	02371500	*	1,9										7		A, P
9	02372250		3										7		A
10	02373000	*	10										7		A
11	02374500	*	1										7		A
12	02398195				11									12	A
13	02399200	*	1										7	12	A
14	02400100		13					4						12	A
15	02401370				11									12	A
16	02401390		13											12	A
17	02401460				11									12	A
18	02401470				11									12	A

Table 2.--Data use, funding, and frequency of availability--Continued

Map index no.	Station no.	Regional hydrology	Hydrologic systems	Legal obligations	Planning and design	Project operation	Hydrologic forecasts	Water-quality monitoring	Research	Other	Federal program	OFA program	Coop program	Other non-Federal	Data avail-ability
19	02408540	*	1,9					4					5		A, P
20	02410000								14				7		A
21	02411000		13			12	6							12	A, P, T
22	02412000	*	1				6						7		A, P, T
23	02413300	*	1										7		A
24	02414500		13				6							12	A, P, T
25	02418500		13			12	6							12	A, P, T
26	02419000		15										7		A
27	02420000		15					16,17				2			A, T
28	02421000		15					4					5		A
29	02422500		15										7		A
30	02423425		18				6	4					5		A, P, T
31	02424000	*	1,9				6				*				A, T, P
32	02424940		15					4					5		A
33	02425000		15				6					2			A, P, T
34	02425200				11									12	A
35	02427700	*	1,9										7		A

Table 2.--Data use, funding, and frequency of availability--Continued

Map index no.	Station no.	Regional hydrology	Hydrologic systems	Legal obligations	Planning and design	Project operation	Hydrologic forecasts	Water-quality monitoring	Research	Other	Federal program	OFA program	Coop program	Other non-Federal	Data avail-ability
36	02428400					19	6					2			A, P, T
37	02442500		15									2			A
38	02444160					19	6					2			A, P, T
39	02446500		15									2			A, T
40	02448475					19	6					2			A, P, T
41	02448500		15									2			A
42	02449245		15										7		A
43	02450000		9,15									2			A
44	02450180		15					4					5		A, P
45	02450250	*	8								*				A
46	02455000	*	15									2			A
47	02456330		20										7		A
48	02456500		15				6					2			A, T
49	02462000		16						21			2			A
50	02462500					19	6					2			A, P, T
51	02462600		20					4	22			23			A
52	02462950					19	6					2			A, P, T
53	02464000	*	24					4				2			A
54	02464146		20					4,17	22			23			A

Table 2.--Data use, funding, and frequency of availability--Continued

Map index no.	Station no.	Regional hydrology	Hydrologic systems	Legal obligations	Planning and design	Project operation	Hydrologic forecasts	Water-quality monitoring	Research	Other	Federal program	OFA program	Coop program	Other non-Federal	Data avail-ability
55	02465000		15				6	17				2			A, P, T
56	02465493	*	15										7		A
57	02466030					19	6	16				2			A, P, T
58	02467000					19	6					2			A, P, T
59	02467500	*	1,9				6	4					5		A, P, T
60	02468500		15										5		A
61	02469761					19	6	16				2			A, P, T
62	02469800	*	9										7		A
63	02471001	*	1										7		A
64	02471065								25			2			A
65	02479431	*											7		A
66	02479560	*						16					5		A
67	03572110	*											7		A
68	03574500	*	9								*				A
69	03575000	*	1										7		A
70	03575500					26	6					26			A, P, T
71	03575830	*	1,9										7		A
72	03589500					26	6					26			A, P, T

Table 2.--Data use, funding, and frequency of data availability--Continued

1 Long term index
2 U.S. Army Corps of Engineers
3 Water supply assessment southeast Alabama (GSA)
4 Contributes to statewide water quality monitoring (GSA, ADEM)
5 Geological Survey of Alabama
6 Flood forecasting - U.S. National Weather Service
7 Alabama Department of Environmental Management (ADEM)
8 Hydrologic Benchmark Station
9 Current water conditions report - Statewide distribution
10 Assessment - Major tributary draining three county area in south Alabama (ADEM)
11 Alabama Power Company - collection of basic records, planning hydropower system (CBR)
12 Alabama Power Company - electric power generation system operation
13 Federal Energy Regulatory Commission - licensing requirements
14 Small streams research - Alabama Highway Department
15 Determination of inflow between control structure and downstream gage (Alabama Power Company and Corps of Engineers)
16 National Stream Quality Accounting Network (NASQAN) station
17 Sediment station
18 Assessment near Birmingham wastewater treatment plant (ADEM, GSA)
19 Mobile Corps of Engineers control structure, multi purpose operation
20 Assessment impact of coal strip mining (GSA, ADEM)
21 Impact of urbanization (Birmingham)
22 Coal hydrology
23 Bureau of Land Management
24 Water supply for city of Tuscaloosa
25 Impact of urbanization (Mobile)
26 Tennessee Valley Authority control structure, electric power generation

A Data published on an annual basis
P Provisional data
T Data transmitted by telemetry

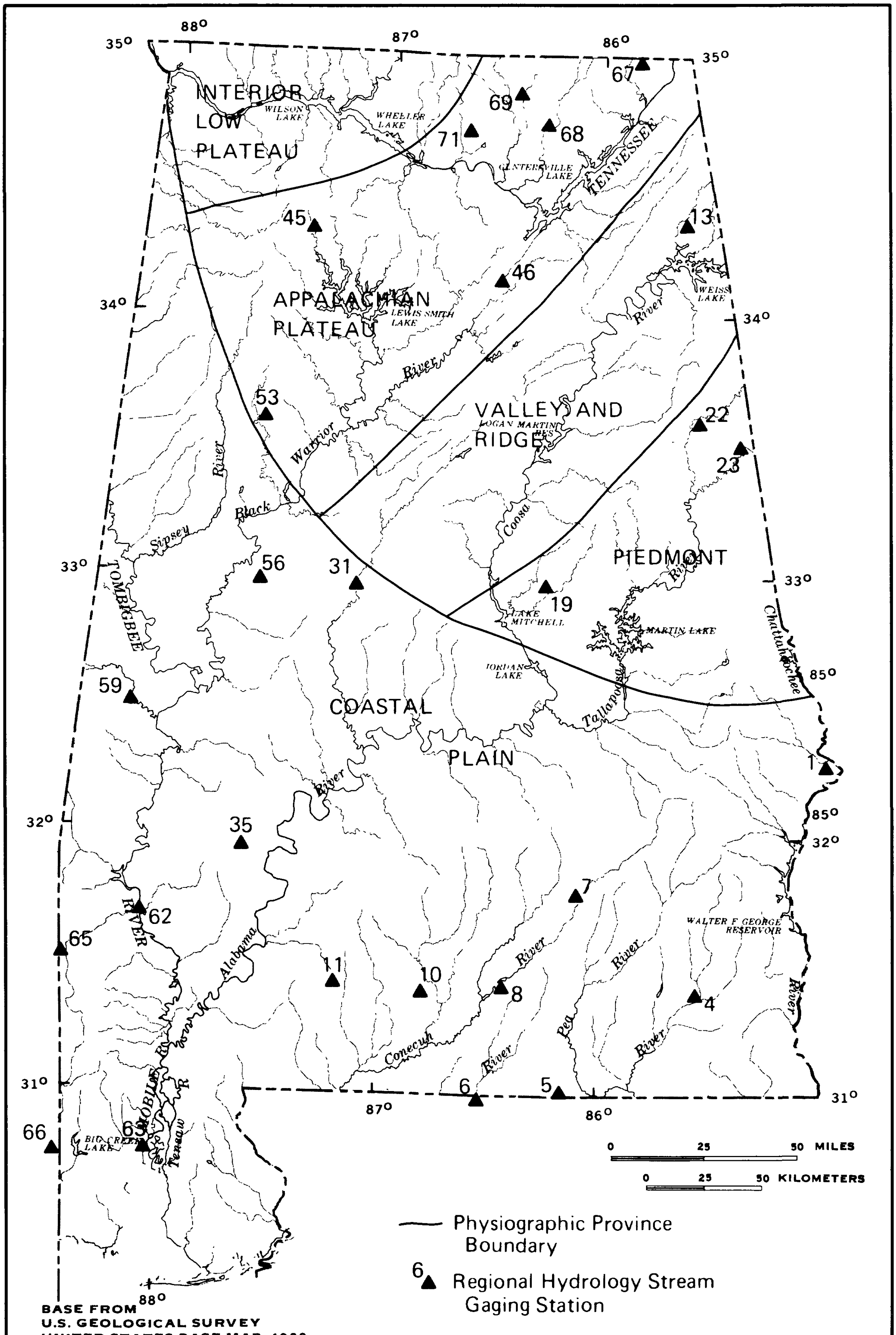

Figure 3. -- Location of regional hydrology stream gages and physiographic provinces.

Hydrologic Systems

Stations that can be used for hydrologic accounting, that is, to define current hydrologic conditions and the sources, sinks, and fluxes of water through hydrologic systems including regulated systems, are designated as hydrologic-systems stations. They include diversions and return flows and stations that are useful for defining the interaction of water systems.

The benchmark and index stations are included in the hydrologic systems category because they account for current and long-term conditions of the hydrologic system that they gage. Federal Energy Regulatory Commission (FERC) stations also are included.

The data collected at the five FERC stations are used to monitor flow conditions between structures to satisfy downstream flow requirements determined by FERC.

Legal Obligations

Some stations provide records of flows for the verification or enforcement of existing treaties, compacts, and decrees. The legal-obligation category contains only those stations that the U.S. Geological Survey is required to operate to fulfill a legal responsibility. There are no stations in the Alabama program that exist to fulfill a legal responsibility of the Geological Survey.

Planning and Design

Gaging stations in this category provide data to be used for the planning and design of a specific project or group of structures. For example, streamflow data are needed for the design of dams, reservoir storage, flood control, levees, floodwalls, navigation systems, water supplies, hydropower plants, or waste-treatment facilities. Currently there are five gaging stations in this category.

Project Operation

Data from gaging stations in this category are used, on an ongoing basis, to assist water managers in making operational decisions such as reservoir releases, hydropower operations, or diversions. The project-operation use generally implies that the data are routinely available to the operators on a rapid reporting basis. For projects on large streams, data may be needed only every few days.

There are 12 stations in the Alabama program that are used to aid operators in the management of reservoirs and control structures that are part of multipurpose projects of flood control, recreation, navigation and low-flow augmentation.

Hydrologic Forecasts

Gaging stations in this category provide information for hydrologic forecasting by agencies other than the U.S. Geological Survey. These might be flood forecasts for a specific river reach, or periodic (daily, weekly, monthly, or seasonal) flow-volume forecasts for a specific site or region. The hydrologic-forecast use generally implies that the data are routinely available to the forecasters on a rapid reporting basis. On large streams, data may be needed only every few days.

Stations in the Alabama program that are included in the hydrologic forecast category are those used for flood forecasting and for forecasting inflows to reservoirs that are a part of the hydropower generating and flood control systems. Data are used by the National Weather Services's Flood Forecast Office in Birmingham and the U.S. Army Corps of Engineers to predict flood flows and reservoir inflows downstream. Currently there are 21 gaging stations in this category.

Water-Quality Monitoring

Gaging stations where regular water-quality or sediment-transport monitoring is being conducted are designated as water-quality-monitoring stations.

Two such stations in the 1983 water-year program are designated benchmark stations, and five are National Stream Quality-Accounting Network (NASQAN) stations. Water-quality samples from benchmark stations are used to indicate water-quality characteristics of streams that have been and probably will continue to be relatively free of the effects of man. NASQAN stations are part of a countrywide network designed to assess water-quality trends of significant streams.

Research

Gaging stations in this category provide data for a particular research or water-investigations study. Typically, these are only operated for a few years. Two gaging stations classified in this category, Patterson Creek near Central (02410000) and Valley Creek near Oak Grove (02462000), were operated as part of a highway research project that has been completed; however, another cooperator has continued the support. Two other gaging stations, Blue Creek near Oakman (02462600) and Turkey Creek near Tuscaloosa (02464146) are operated as part of a coal hydrology research project. Gaging station Montlimar Creek at Mobile (02471001) is operated as part of an urban hydrology research project.

Funding

The four sources of funding for the streamflow-data program are:

1. Federal program.--Funds that have been directly allocated to the U.S. Geological Survey.

2. Other Federal Agency program.--Funds that have been transferred to the U.S. Geological Survey by other Federal agencies.

3. State-Federal cooperative program.--Funds that come jointly from U.S. Geological Survey cooperative-designed funding and from a non-Federal cooperating agency. Cooperating-agency funds may be in the form of direct services or cash.

4. Other non-Federal.--Funds that are provided entirely by a non-Federal agency or a private concern under the auspices of a Federal agency. In this study, funding from municipal and private concerns was limited to operation of water supply, waste-treatment projects, and legal requirements for water use. Funds in this category are not matched by U.S. Geological Survey cooperative funds.

In all four categories, the identified sources of funding pertain only to the collection of streamflow data; sources of funding for other activities, particularly collection of water-quality samples at the gaging station, may not necessarily be the same as those identified herein. Five entities currently are contributing funds to the Alabama stream-gaging program.

Frequency of Data Availability

Data availability refers to the times at which the streamflow data may be provided to the users. In this category, three distinct possibilities exist. Data can be provided by direct-access telemetry equipment for immediate use, by periodic release of provisional data, or in publication format through the annual data report for Alabama (U.S. Geological Survey, 1984). These three categories are designated T, P, and A, respectively, in table 2. In the current Alabama program, data for all 72 stations are made available through the annual report, data from 23 stations are available by telemetry, and data for 5 stations are released on a provisional basis.

Data-Use Presentation

Data-use and ancillary information are presented for each continuous-record gaging station in table 2. The entry of an asterisk in the table indicates that the station is used by the Geological Survey for regional hydrology purposes, and (or) the station is operated from Federal funds appropriated directly to the Survey.

Conclusions Pertaining to Data Uses

A review of the data in table 2 indicates that a majority of the 72 stations are multi-use. Although the original purpose of establishing gaging stations was to provide information for a singular use, many stations provide information for other uses. Twenty-four stations provide information simultaneously to the two categories of regional hydrology and hydrologic systems.

Another major segment of the network are those stations identified in the category of hydrologic forecasts. This category contains stations with combined data uses by the National Weather Service for flood forecasting and other agencies for water management at control structures. There are 21 stations in this category, 11 of which are located at control structures. Excluding the 11 stations at control structures, the 2 slope stations on the Tennessee River, and the electromagnetic velocity meter station, 58 stations will be used for the remainder of the analysis.

This analysis does not provide a measure of how well the existing network meets the accuracy goals for regional streamflow estimates established by Benson and Carter (1973). A follow-up analysis is planned to evaluate the existing network's ability to provide optimum regional flow information for Alabama. The analysis of this phase recommends that all 72 stations be continued. Indications are that cooperator support will be lost for coal hydrology stations (Blue Creek near Oakman 02462600 and Turkey Creek near Tuscaloosa 02464146).

ALTERNATIVE METHODS OF DEVELOPING STREAMFLOW INFORMATION

The second phase of the analysis of the stream-gaging program is to investigate alternative methods of providing daily streamflow information in lieu of operating continuous streamflow stations. The objective of this phase is to identify gaging stations where alternative technology, such as flow routing or statistical methods, could provide information about daily mean streamflow in a more cost-effective manner than operating the streamflow stations. No guidelines exist concerning suitable accuracies for particular uses of the data; therefore, judgment was required in deciding whether the accuracy of the estimated daily flows would be suitable for the intended purpose. The uses of data from a station will affect whether or not that station could be discontinued. For example, those stations for which flood hydrographs are required in a real-time sense, such as hydrologic forecasts and project operation, are not candidates for the alternative-method approach. Likewise, there might be a legal obligation to operate a gaging station that would preclude using alternative methods. The primary candidates for alternative methods are stations that are operated upstream or downstream of other stations on the same stream. The accuracy of the alternative method at these sites may be suitable because of the significant redundancy of flow information between sites. Similar watersheds, for example those located in the same physiographic and climatic area, also may have potential for alternative methods.

Desirable attributes of a proposed alternative method are: (1) the proposed method needs to be computer oriented and easy to apply, (2) the proposed method needs to have an available interface with the U.S. Geological Survey's WATSTORE Daily-Values File (Hutchison, 1975) in order to facilitate the calibration of the proposed method, (3) the proposed method needs to be technically sound so it will be able to provide data of suitable accuracy, and be generally acceptable to the hydrologic community, and (4) the proposed method needs to permit easy evaluation of the accuracy of the simulated streamflow records. Because of the short duration of this analysis, only two methods were considered. The above criteria were used to select two alternative methods for consideration, a flow routing model and multiple regression analysis.

Description of Flow-Routing Model

Hydrologic flow-routing methods use the law of conservation of mass and the relation between the storage in a reach and the outflow from the reach. The hydraulics of the system are not considered. The method usually requires only a few parameters and treats the reach in a lumped sense without subdivision. Usually, the input is a discharge hydrograph at the upstream end of the reach and the output is a discharge hydrograph at the downstream end. Several different types of hydrologic routing are available such as Muskingum, Modified Puls, Kinematic Wave, and the unit-response flow-routing method. The latter method was selected for this analysis. This method uses two techniques --storage continuity (Sauer, 1973) and diffusion analogy (Keefer, 1974; Keefer and McQuivey, 1974). These concepts are discussed below.

The unit-response flow-routing method was selected because it fulfilled the criteria noted above. Computer programs for the unit-response method can be used to route streamflow from one to more upstream locations to a downstream location. Downstream hydrographs are produced by the convolution of upstream hydrographs with their appropriate unit-response functions. This method can only be applied at a downstream station where an upstream station exists on the same stream. An advantage of this model is that it can be used for regulated stream systems. Reservoir-routing techniques are included in the model so flows can be routed through reservoirs if the operating rules are known. Calibration and verification of the flow-routing model is achieved using historic upstream and downstream hydrographs and estimates of tributary inflows. The convolution subroutine of the model treats a stream reach as a linear one-dimensional system in which the system output (downstream hydrograph) is computed by multiplying (convoluting) the ordinates of the upstream hydrograph by the unit-response function and lagging them appropriately. The model has the capability of combining hydrographs, multiplying a hydrograph by a ratio, and changing the timing of a hydrograph. In this analysis, the model is only used to route an upstream hydrograph to a downstream point. Routing can be accomplished using hourly data, but only daily data are used in this analysis.

Three options are available for determining the unit-(system) response function. Selection of the appropriate option depends primarily on the variability of wave celerity (travel time) and dispersion (channel storage) throughout the range of discharges to be routed. Adequate routing of daily flows usually can be accomplished using a single unit-response function (linearization about a single discharge) to represent the system response. However, if the routing coefficients vary significantly with discharge, linearization about a low-range discharge results in overestimated high flows that arrive late at the downstream site; whereas, linearization and a high-range discharge results in low-range flows that are underestimated and arrive too soon. A single unit-response function may not provide acceptable results in such cases. Therefore, the option of multiple linearization (Keefer and McQuivey, 1974), which uses a family of unit-response functions to represent the system response, is available.

Determination of the system's response to the input at the upstream end of the reach is not the total solution for most flow-routing problems. The convolution process makes no accounting of flow from the intervening area between the upstream and downstream locations. Such flows may be totally unknown or estimated by some combination of gaged and ungaged flows. An estimating technique that should prove satisfactory in many instances is the multiplication of known flows at an index gaging station by a factor (for example, a drainage-area ratio).

The objective in either the storage-continuity or diffusion analogy flow-routing method is to calibrate two parameters that describe the storage-discharge relationship in a given reach and the travel time of flow passing through the reach. In the storage-continuity method, a response function is derived by modifying a translation-hydrograph technique developed by Mitchell (1962) to apply to open channels. A triangular pulse (Sauer, 1973) is routed through reservoir-type storage and then transformed by a summation-curve technique to a unit response of desired duration. The two parameters that describe the routing each are K_s, a storage coefficient that is the slope of the storage-discharge relation, and W_s, the translation-hydrograph time base. These two parameters determine the shape of the resulting unit-response function.

In the diffusion-analogy theory, the two parameters requiring calibration in this method are K_o, a wave-dispersion or damping coefficient, and C_o, the floodwave celerity. K_o controls the spreading of the wave (analogous to K_s in the storage-continuity method) and C_o controls the travel time (analogous to W_s in the storage-continuity method). In the single-linearization method, only one K_o and C_o value are used. In the multiple-linearization method, C_o and K_o are varied with discharge so a table of wave celerity (C_o) versus discharge (Q) and a table of dispersion coefficient (K_o) versus discharge (Q) are used.

In both the storage-continuity and diffusion-analogy methods, the two parameters are calibrated by trial and error. The analyst needs to decide if suitable parameters have been derived by comparing the simulated discharge to the measured discharge.

Description of Regression Analysis

Simple- and multiple-regression techniques also can be used to estimate daily flow records. Regression equations can be computed that relate daily flows at a single station to daily flows at a combination of upstream, downstream, and tributary stations. This statistical method is not limited, like the flow-routing method, to stations where an upstream station exists on the same stream. The explanatory variables in the regression analysis can be stations from different watersheds, or downstream and tributary watersheds.

The regression method has many of the same attributes as the flow-routing method in that it is easy to apply, provides indices of accuracy, and is generally accepted as a good tool for estimation. The theory and assumptions of regression analysis are described in several textbooks such as Draper and Smith (1966) and Kleinbaum and Kupper (1978). The application of regression analysis to hydrologic problems is described and illustrated by Riggs (1973) and Thomas and Benson (1970). Only a brief description of regression analysis is provided in this report.

A linear regression model of the following form was used for estimating daily mean discharges:

$$Y_i = B_o + \sum_{j=1}^{P} B_j X_j + E_i$$

where

Y_i = daily mean discharge at station i (dependent variable),
X_j = daily mean discharges at nearby stations (explanatory variables),
B_o and B_j = regression constant and coefficients, and
E_i = the random error term.

The above equation is calibrated (B_o and B_j are estimated) using measured values of Y_i and X_j. These measured daily mean discharges can be retrieved from the WATSTORE Daily Values File. The values of X_j may be discharges measured on the same day as discharges at station i or may be the previous or future days, depending on whether station j is upstream or downstream of station i. Once the equation is calibrated and verified, future values of Y_i are estimated using measured values of X_j. The regression constant and coefficient (B_o and B_j) are tested to determine if they are significantly different from zero.

The regression equation (model) should be fitted (calibrated) using data from one period of time and then verified or tested on data using a different period of time to obtain a measure of the true predictive accuracy. Both the calibration and verification period needs to be representative of the range of flows that could occur at station i. The equation should be verified by: (1) plotting the residuals E_i (difference between simulated and measured discharges) against the dependent and all explanatory variables in the equation, and (2) plotting the simulated and measured discharges versus time. These tests are intended to identify if: (1) the linear model is appropriate or whether some transformation of the variables is needed, and (2) there is any bias in the equation such as overestimating low flows. These tests might indicate, for example, that a logarithmic transformation is desirable, that a nonlinear regression equation is appropriate, or that the regression equation is biased in some way.

Categorization of Gaging Stations by their Potential for Alternative Methods

From an analysis of funding and data uses presented in table 2, five basins were selected in which alternative methods would be investigated. The five basins selected for this phase of investigation are the Big Canoe Creek, Tallapoosa River, Cahaba River, Mulberry Fork of Black Warrior River, and Locust Fork of Black Warrior River (fig. 4). Both flow-routing and regression techniques were used for each of the five basins. Streamflows for all streams are unregulated and, except for the Tallapoosa and Cahaba River basins, each contains two main-stem gaging stations. Streamflow data available for this phase of the analysis are summarized in table 3.

Evaluation of the alternative methods is based on a comparison of the computed and observed discharge. Under the heading "Accuracy of field data and computed results" in "Water Resources Data of Alabama, 1984," the following categories of accuracy and their meanings are stated. "Excellent" means that 95 percent of the daily discharges are within 5 percent; "good" within 10 percent; "fair" within 15 percent; and "poor" greater than 15 percent.

Flow-Routing Analysis

Big Canoe Creek at Ashville

The purpose of this flow-routing analysis is to investigate the potential of using the single-linearization diffusion-analogy model, described by Doyle and others (1983), to simulate daily mean discharges at station 02401390, Big Canoe Creek at Ashville. A sketch of the Big Canoe Creek study area is presented in figure 5. In this application, as with the other systems that were modeled, the desired product is the best model for the entire flow range. The Ashville gage is located 14.7 miles downstream from the gage near Springville. The drainage area at the Ashville gage is more than three times the drainage area at the upstream site; there are no gages within the intervening area. The Springville gage has been operating only since 1978.

To simulate the daily mean discharges, flows were routed from Springville to Ashville and then increased by the drainage-area ratio of the two stations to account for the increase in flow from the intervening area.

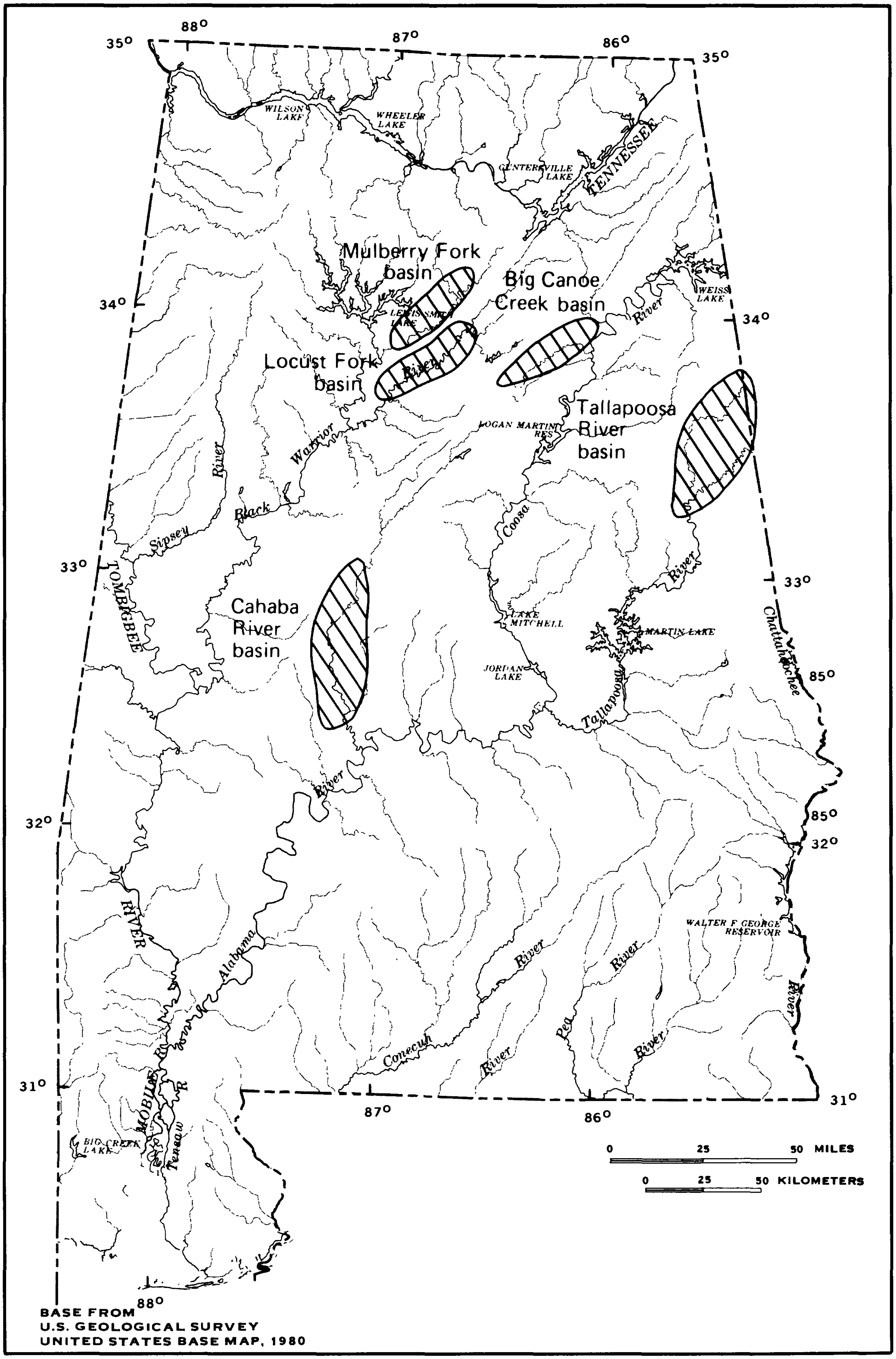

Figure 4. -- Study areas for alternative methods of providing streamflow information.

Table 3.--Gaging stations used in the alternative-methods analysis

Map index number	Station number	Station name	Drainage area (mi^2)	Period of record
Big Canoe Creek basin				
15	02401370	Big Canoe Creek near Springville	45.0	1978-
16	02401390	Big Canoe Creek near Ashville	148	1965-
Tallapoosa River basin				
22	02412000	Tallapoosa River near Heflin	444	1952-
23	02413300	Little Tallapoosa River near Newell	401	1975-
24	02414500	Tallapoosa River at Wadley	1,660	1923-
Cahaba River basin				
31	02424000	Cahaba River at Centreville	1,029	1901-08, 1929-32, 1935-
32	02424940	Oakmulgee Creek near Augustin	215	1975-
33	02425000	Cahaba River near Marion Junction	1,768	1938-54, 1968-
Mulberry Fork basin				
43	02450000	Mulberry Fork near Garden City	365	1928-
44	02450180	Mulberry Fork near Arkadelphia	487	1976-
Locust Fork basin				
46	02455000	Locust Fork near Cleveland	303	1936-
48	02456500	Locust Fork at Sayre	885	1928-31, 1941-

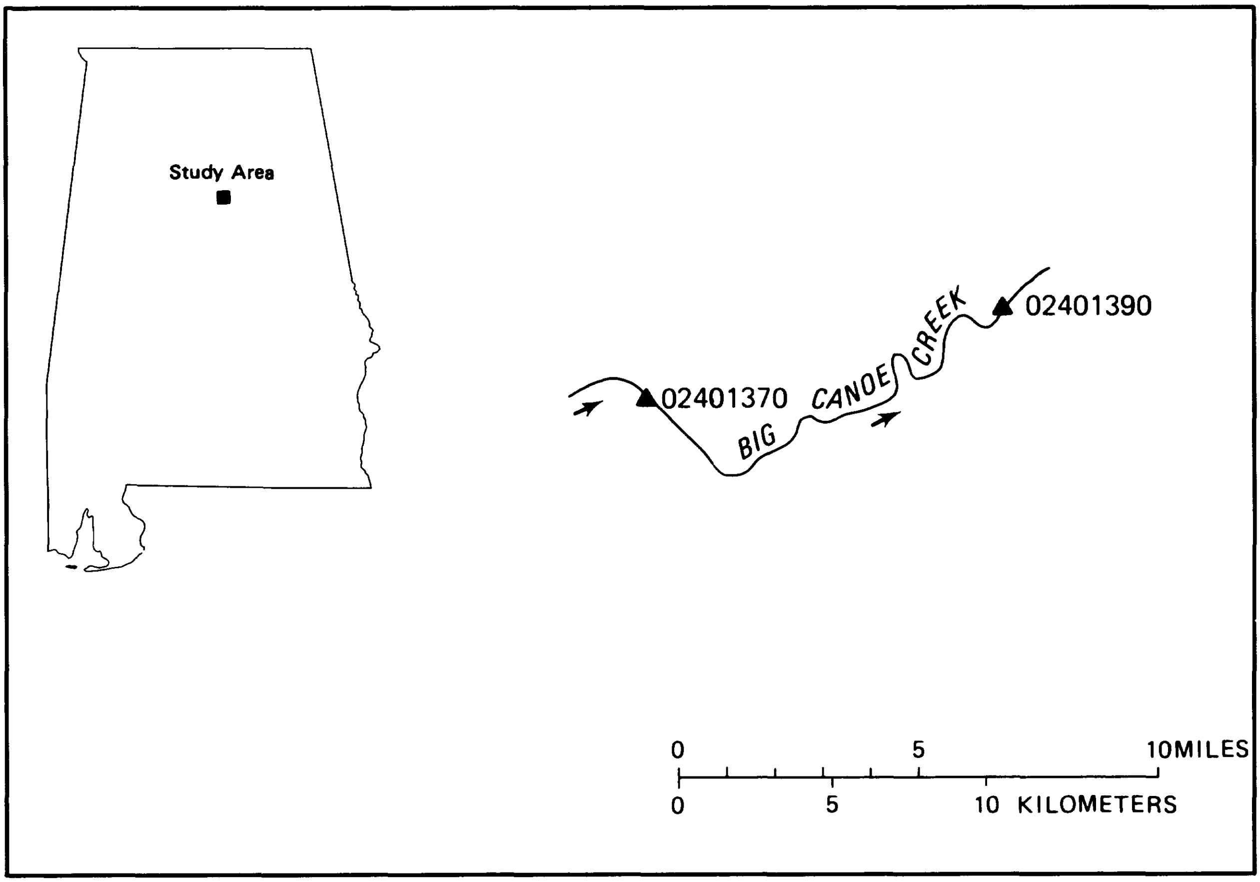

Figure 5. -- Big Canoe Creek study area.

To route flow from Springville to Ashville, it was necessary to determine the model parameters C_o (floodwave celerity) and K_o (wave-dispersion coefficient). The coefficients C_o and K_o are functions of channel width (W_o) in feet, channel slope (S_o) in feet per foot (ft/ft), the slope of the stage discharge relation (dQ_o/dY_o) in square feet per second (ft^2/s), the discharge (Q_o) in cubic feet per second (ft^3/s) representative of the reach in question and are determined as follows.

$$C_o = \frac{1}{W_o} \frac{dQ_o}{dY_o}$$

$$K_o = \frac{Q_o}{2S_oW_o}$$

Using the 1980 water year data for calibration, several trials were made adjusting values of K_o, C_o, and intervening drainage area factors. The calibration process resulted in a best-fit single-linearization model. Final calibrated values for C_o and K_o for the flow-routing analyses are presented in table 4. Observed flow data for water years 1981 and 1982 were used for verification. A summary of the simulation of mean daily discharge at Ashville is given in table 5. Figure 6 is a comparison of the observed and simulated discharge for the Ashville gage.

Table 4.--Calibrated model parameters for the basins used in flow routing analysis

Basin	Map index number	Station number	Length (mi)	Model parameters C_o (ft/s)	Model parameters K_o (ft^2/s)
Big Canoe	15	02401370	14.7	2.40	1,580
Tallapoosa	22	02412000	61.5	6.00	10,000
	23	02413300		6.00	9,690
Cahaba	31	02424000	59.8	2.89	5,110
Mulberry Fork	43	02450000	20.6	8.00	10,000
Locust Fork	46	02455000	64.7	8.00	10,000

Table 5.--Results of routing models for basins in alternative methods analysis

Station	Mean error of daily discharge (in percent)	Volume error (in percent)	Percent of days with error not more than indicated percent				
			5	10	15	20	25
02401390 (16)[A] Big Canoe Creek							
calibration	18.6	-24.0	15	28	48	63	73
verification	24.1	-30.1	9	22	36	49	61
02414500 (24) Tallapoosa River							
calibration	11.1	-4.8	31	56	77	85	92
verification	13.5	1.1	7	53	68	80	87
02425000 (33) Cahaba River							
calibration	13.3	.4	31	54	74	84	88
verification	12.4	-6.1	29	54	71	84	89
02450180 (44) Mulberry Fork							
calibration	33.7	1.4	1	43	55	64	71
verification	19.9	14.0	21	37	55	67	78
02456500 (48) Locust Fork							
calibration	27.6	-2.1	15	28	40	51	58
verification	36.8	7.8	4	24	33	45	56

[A] Map index number

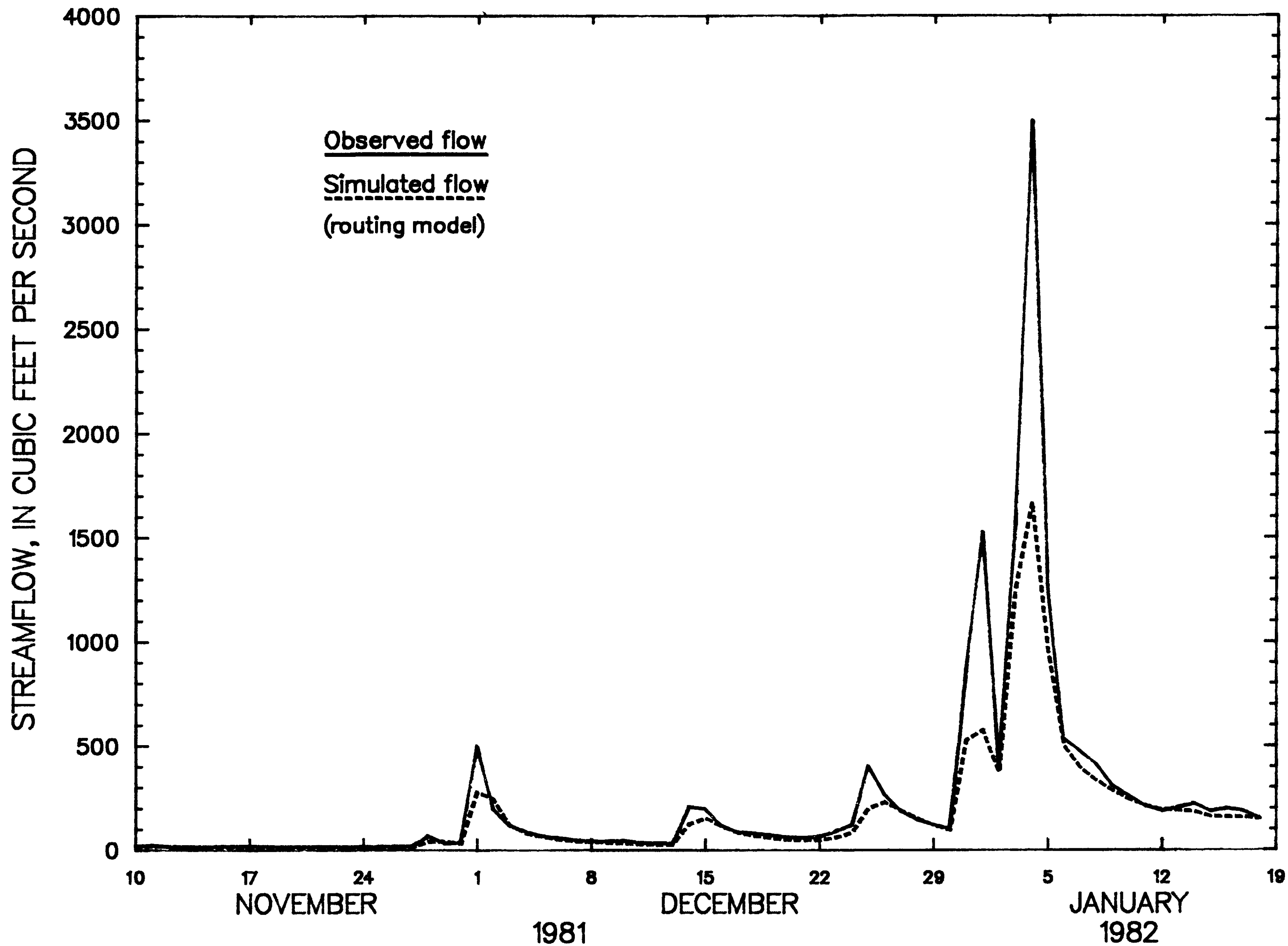

Figure 6. -- Daily hydrograph Big Canoe Creek at Ashville.

Tallapoosa River at Wadley

A sketch of the Tallapoosa study area is presented in figure 7. Gaging station data available for this analysis are identified in table 3.

The Wadley gage is located 61.5 miles downstream from the Heflin gage. The intervening drainage area between Heflin and Wadley is 1,216 mi^2, or 63 percent of the total drainage area at Wadley. A gaging station is located on the Little Tallapoosa River near Newell (02413300) which represents 33 percent of the drainage area between Heflin and Wadley.

For this analysis the approach was to route the flow downstream from Heflin to Wadley using the diffusion analogy method with single linearization. The intervening drainage area is accounted for by routing the flow downstream from the Newell gage to the mouth, adjusting the value by drainage area ratio, and combining with the routed flow from Heflin.

Using calibration procedures described in the previous section, final calibrated parameters of C_0 and K_0 were determined and are presented in table 4. Observed flow data for water years 1981 and 1982 were used for verification. A summary of the simulation of mean daily discharge at Wadley is given in table 5. Figure 8 is a comparison of the observed and simulated discharge for the Wadley gage.

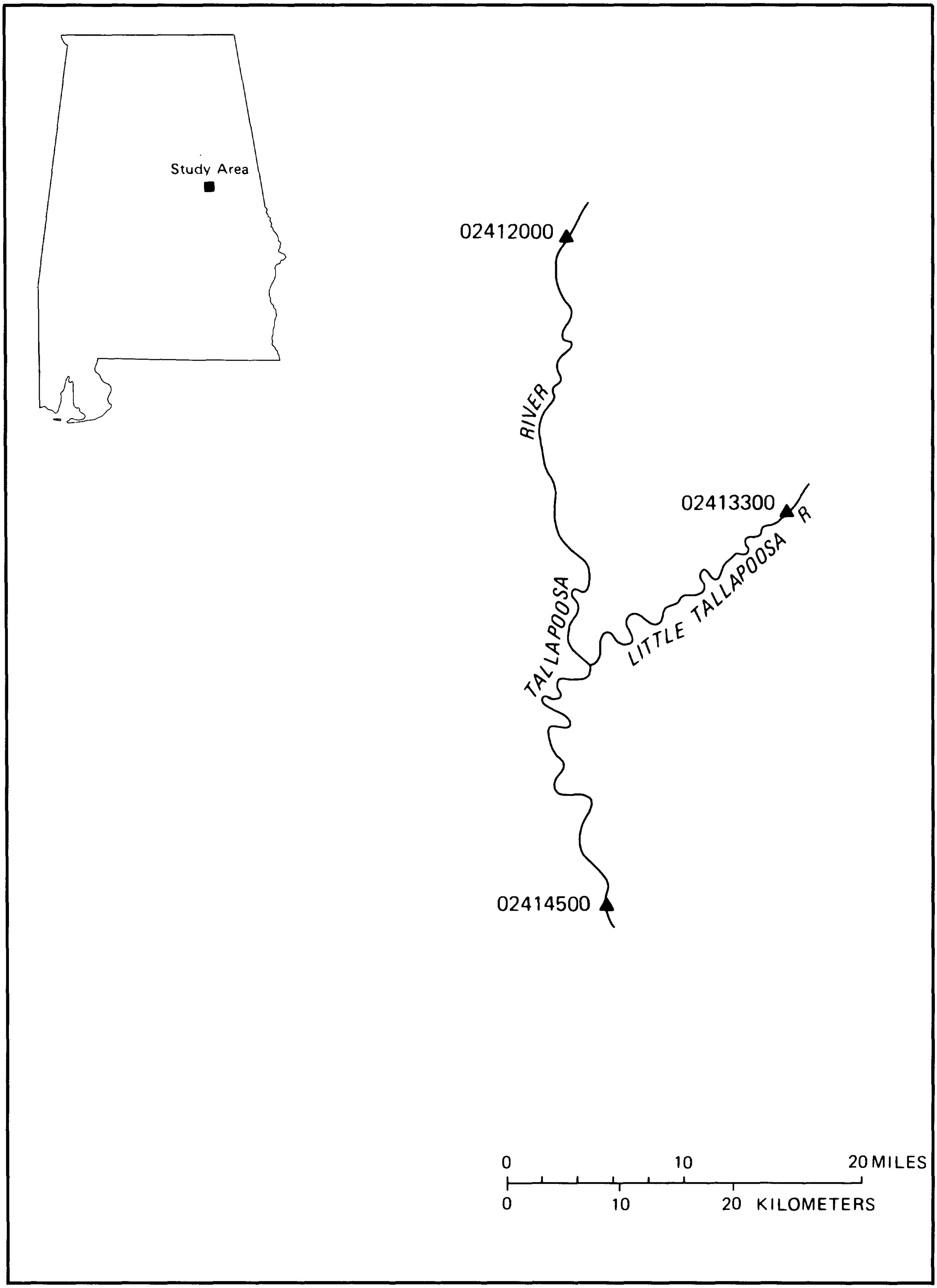

Figure 7. -- Tallapoosa River study area.

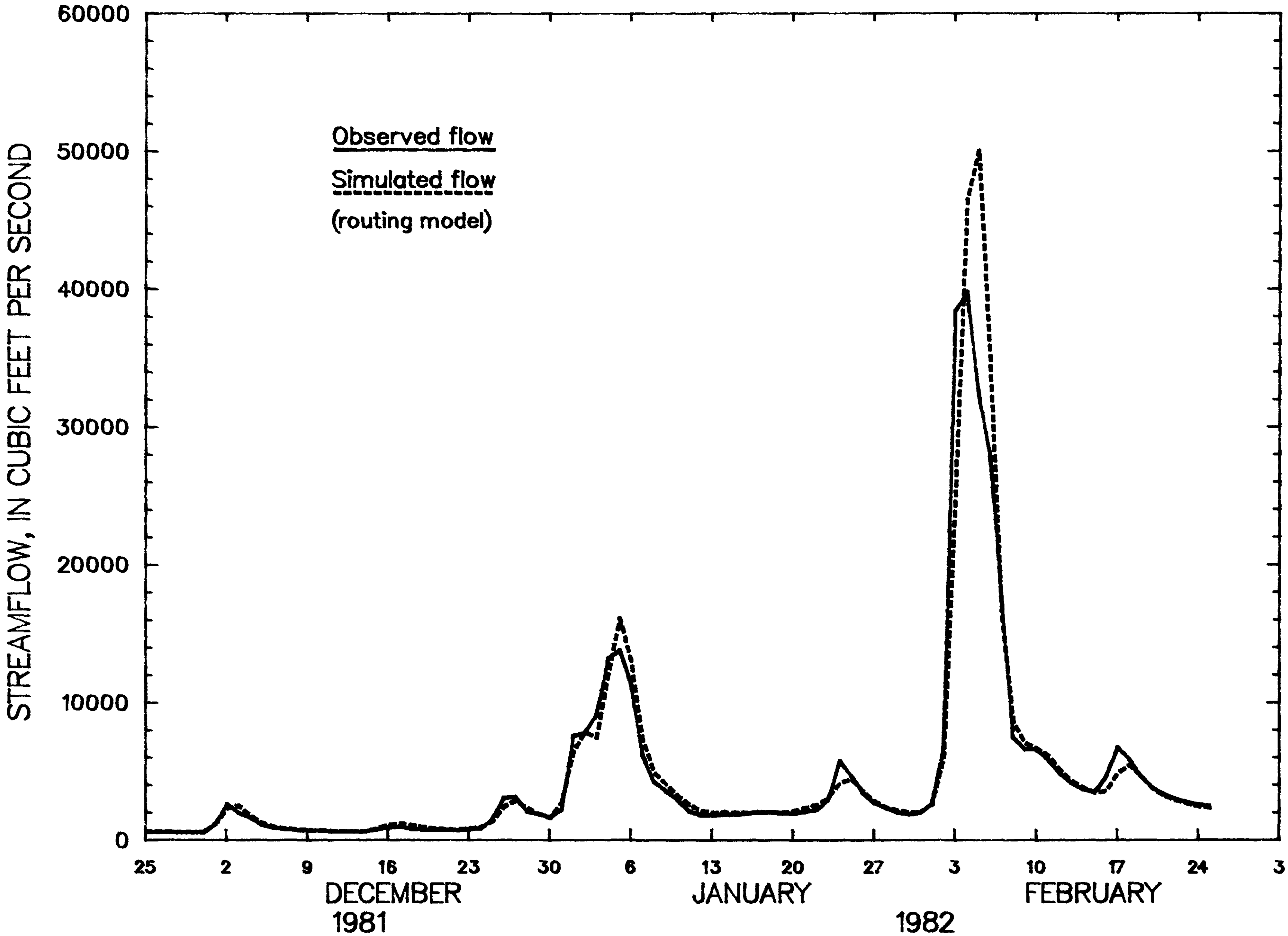

Figure 8. -- Daily hydrograph Tallapoosa River at Wadley.

Cahaba River near Marion Junction

A sketch of the Cahaba River study area is presented in figure 9. Gaging station data available for this analysis are identified in table 3. The Marion Junction gage is located 59.8 miles downstream from the Centreville gage. The intervening drainage between Centreville and Marion Junction is 739 mi^2, or 41.8 percent of the total drainage area at the Marion Junction gage. A gaging station is located on Oakmulgee Creek near Augustin (02424940) which represents 29.8 percent of the drainage area between Centreville and Marion Junction.

For this analysis the approach was to route the flow downstream from Centreville to Marion Junction using the diffusion analogy method with single linearization. The intervening drainage area is accounted for by routing the flow downstream from the Augustin gage to the mouth, adjusting the flow by drainage area ratio, and combining with the routed flow from Centreville.

Using calibration procedures described in a previous section, final calibrated parameters of C_0 and K_0 are presented in table 4. Observed flow data for water years 1981 and 1982 were used for verification. A summary of the simulation of mean daily discharge near Marion Junction is given in table 5. Figure 10 is a comparison of the observed and simulated discharge for the Marion Junction gage.

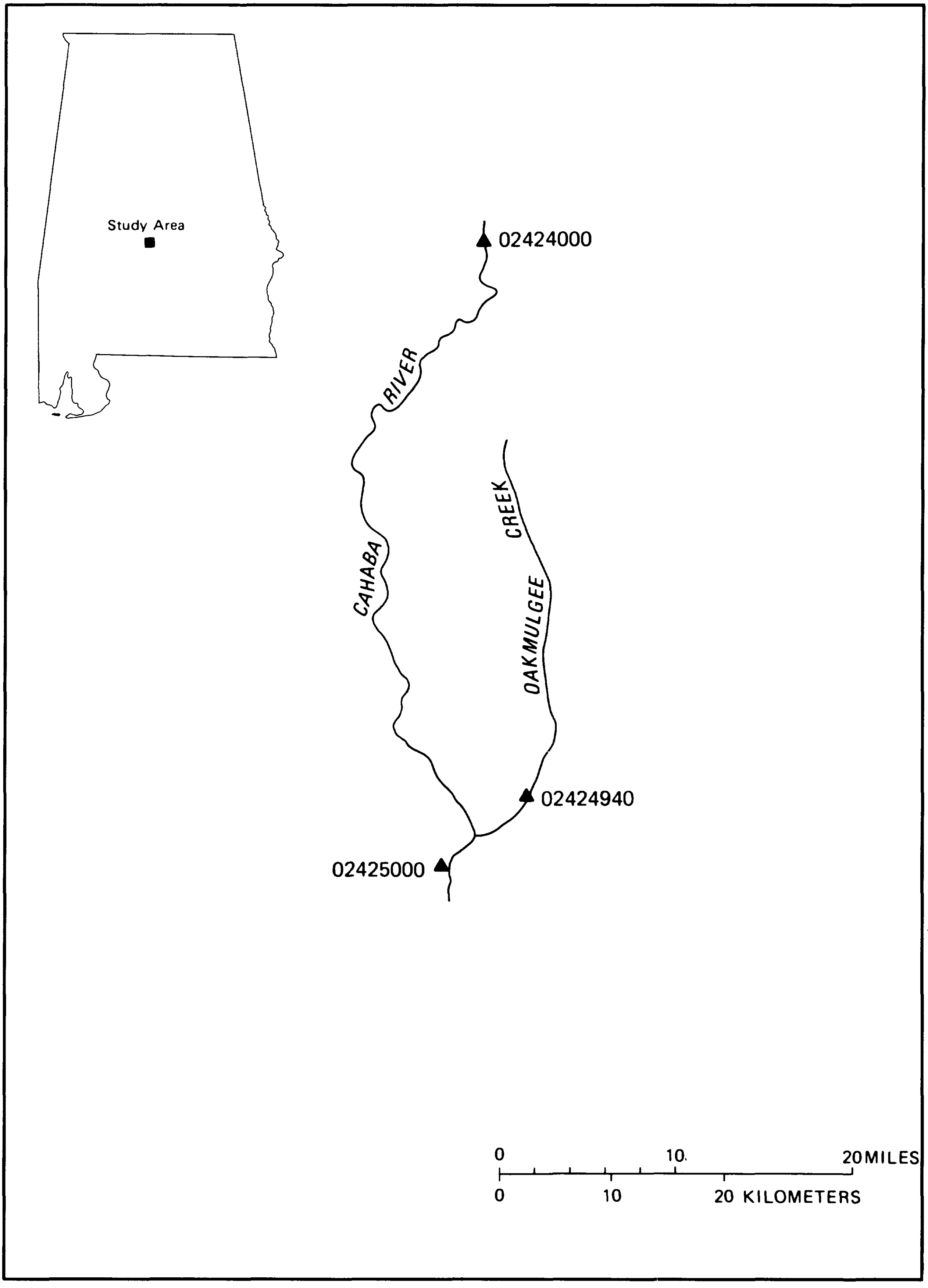

Figure 9. -- Cahaba River study area.

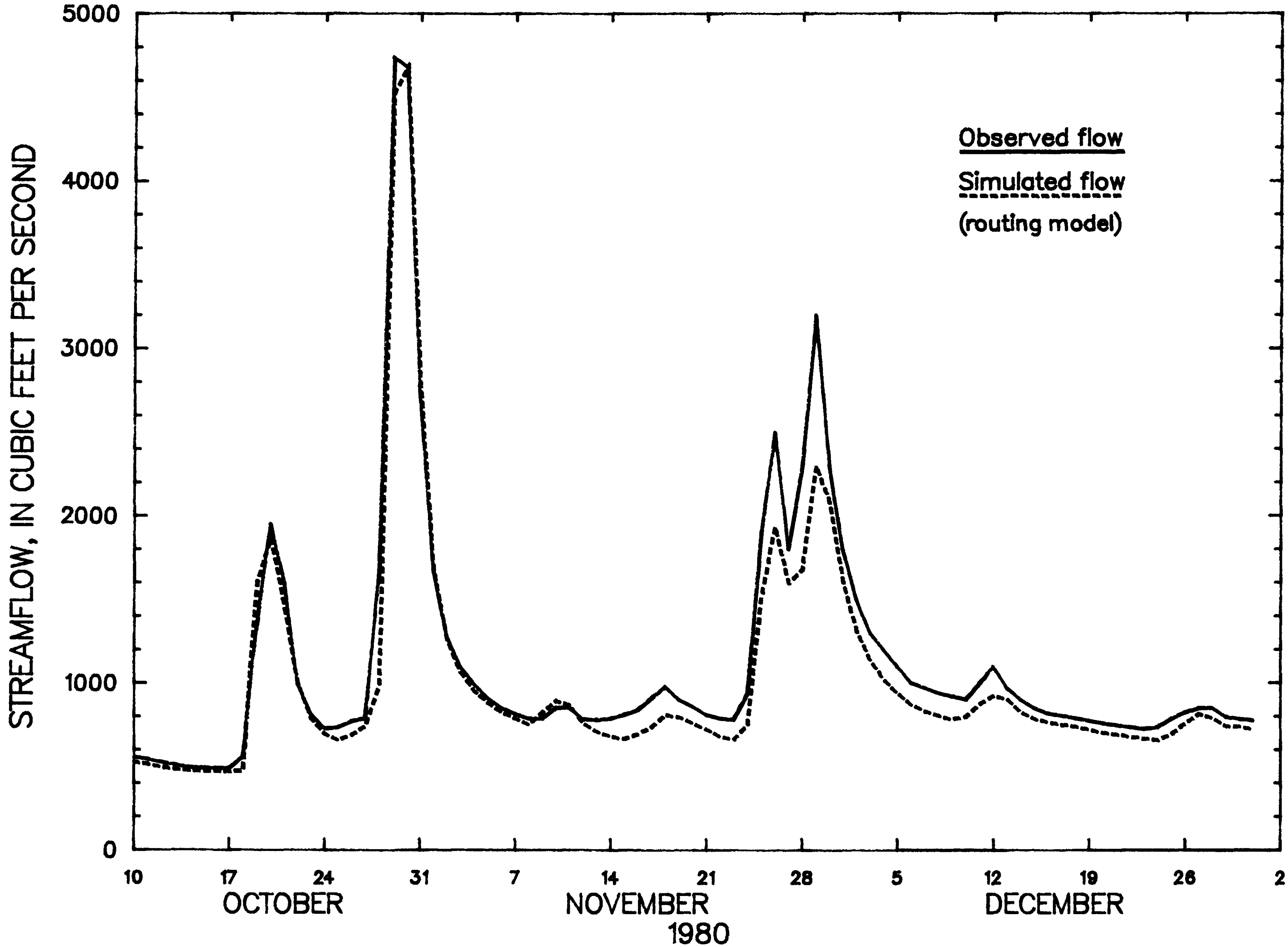

Figure 10. -- Daily hydrograph Cahaba River near Marion Junction.

Mulberry Fork near Arkadelphia

A sketch of the Mulberry Fork study area is presented in figure 11. Gaging station data available for this analysis are identified in table 3.

The Arkadelphia gage is located 20.6 miles downstream from the Garden City gage. The intervening drainage between Garden City and Arkadelphia gages is 122 mi^2, or 25.1 percent of the drainage area of the Arkadelphia gage.

For this analysis the approach was to route the flow downstream from Garden City to Arkadelphia using the diffusion analogy method with single linearization. The intervening drainage area is accounted for by increasing the routed flow to Arkadelphia by a drainage-area ratio.

Using calibration procedures described in a previous section, final calibrated parameters of C_0 and K_0 were determined, and are presented in table 4. Observed flow data for water years 1981 and 1982 were used for verification. A summary of the simulation of mean daily discharge near Arkadelphia is given in table 5. Figure 12 is a comparison of the observed and simulated discharge for the Arkadelphia gage.

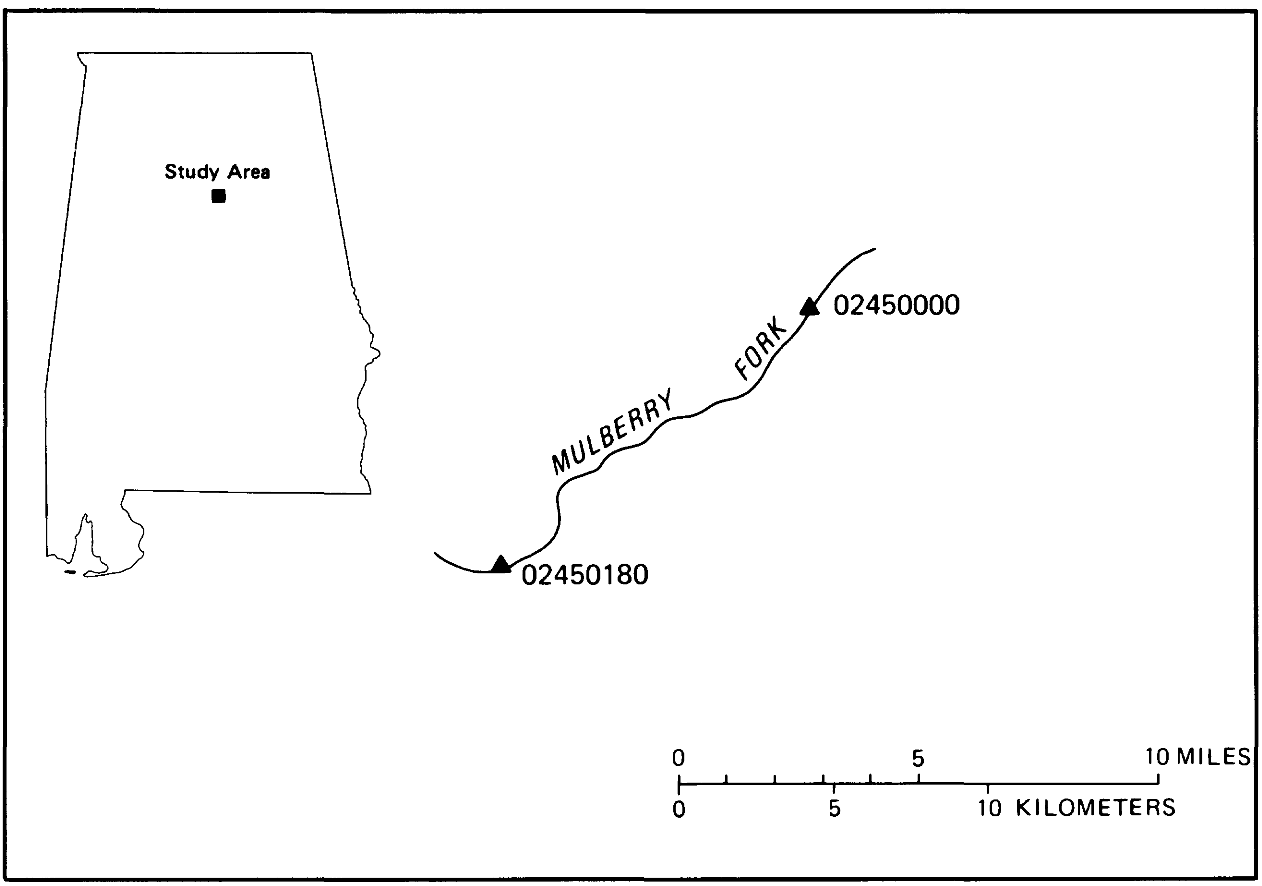

Figure 11. -- Mulberry Fork study area.

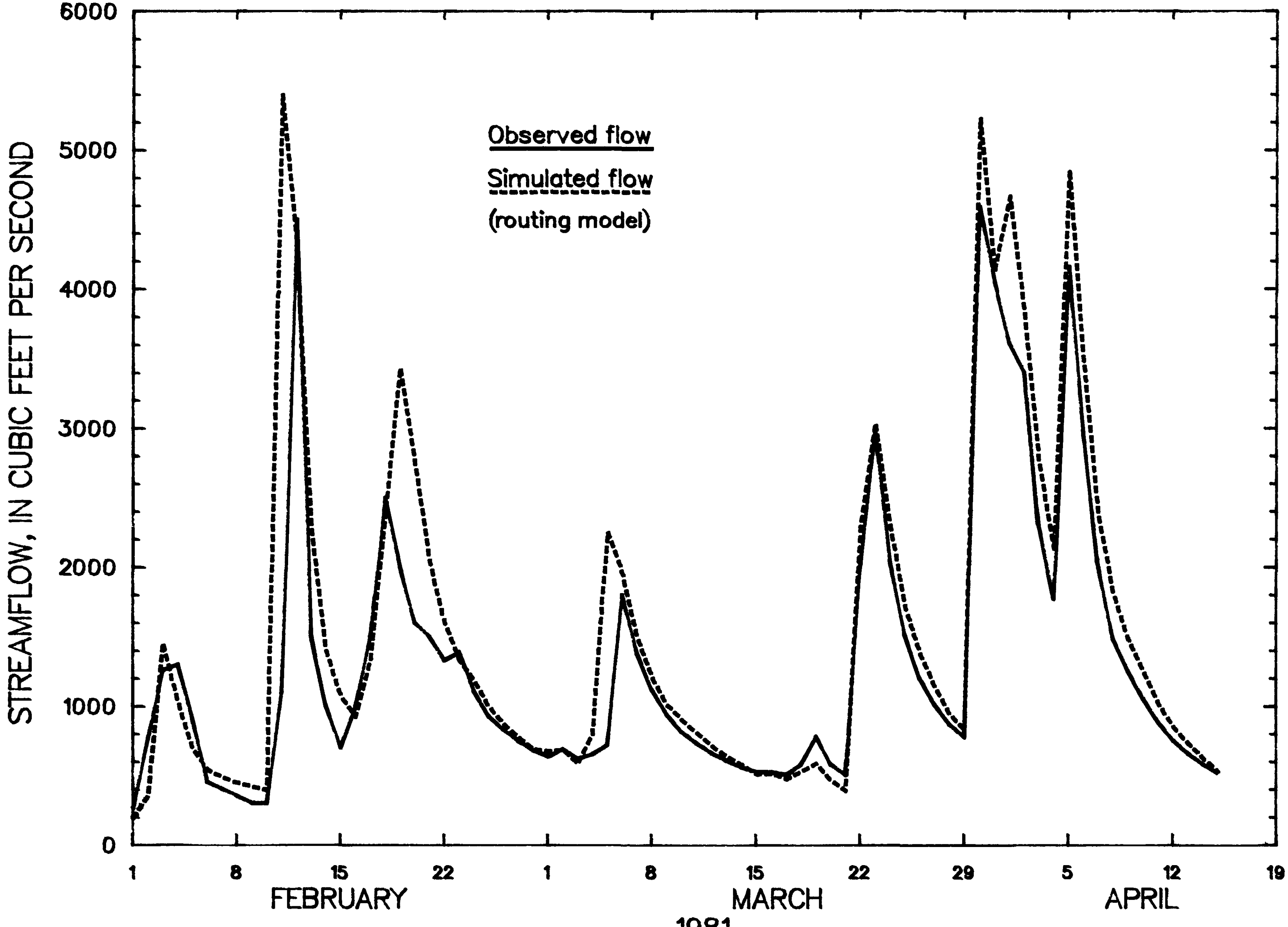

Figure 12. -- Daily hydrograph Mulberry Fork near Arkadelphia.

Locust Fork at Sayre

A sketch of the Locust Fork study area is presented in figure 13. Gaging station data available for this analysis are identified in table 3.

The Sayre gage is located 64.7 miles downstream from the Cleveland gage. The intervening drainage area between Sayre and Cleveland is 582 mi^2, or 65.8 percent of the drainage area of the Sayre gage.

For this analysis the approach was to route the flow downstream from Cleveland to Sayre using the diffusion analogy method with single linearization. The intervening drainage area is accounted for by increasing the routed flow to Sayre by a drainage-area ratio.

A relatively small drainage-area gaging station is located on Crooked Creek (02456330), drainage area 16.2 mi^2. It was not used as an index for the intervening drainage area because its flow has been altered by significant amounts of previously surface mined and reclaimed areas.

Using calibration procedures described in a previous section, final calibrated parameters of C_0 and K_0 were determined, and are presented in table 4. Observed flow data for water years 1981 and 1982 were used for verification. A summary of simulation of mean daily discharge near Sayre is given in table 5. Figure 14 is a comparison of the observed and simulated discharge for the Sayre gage.

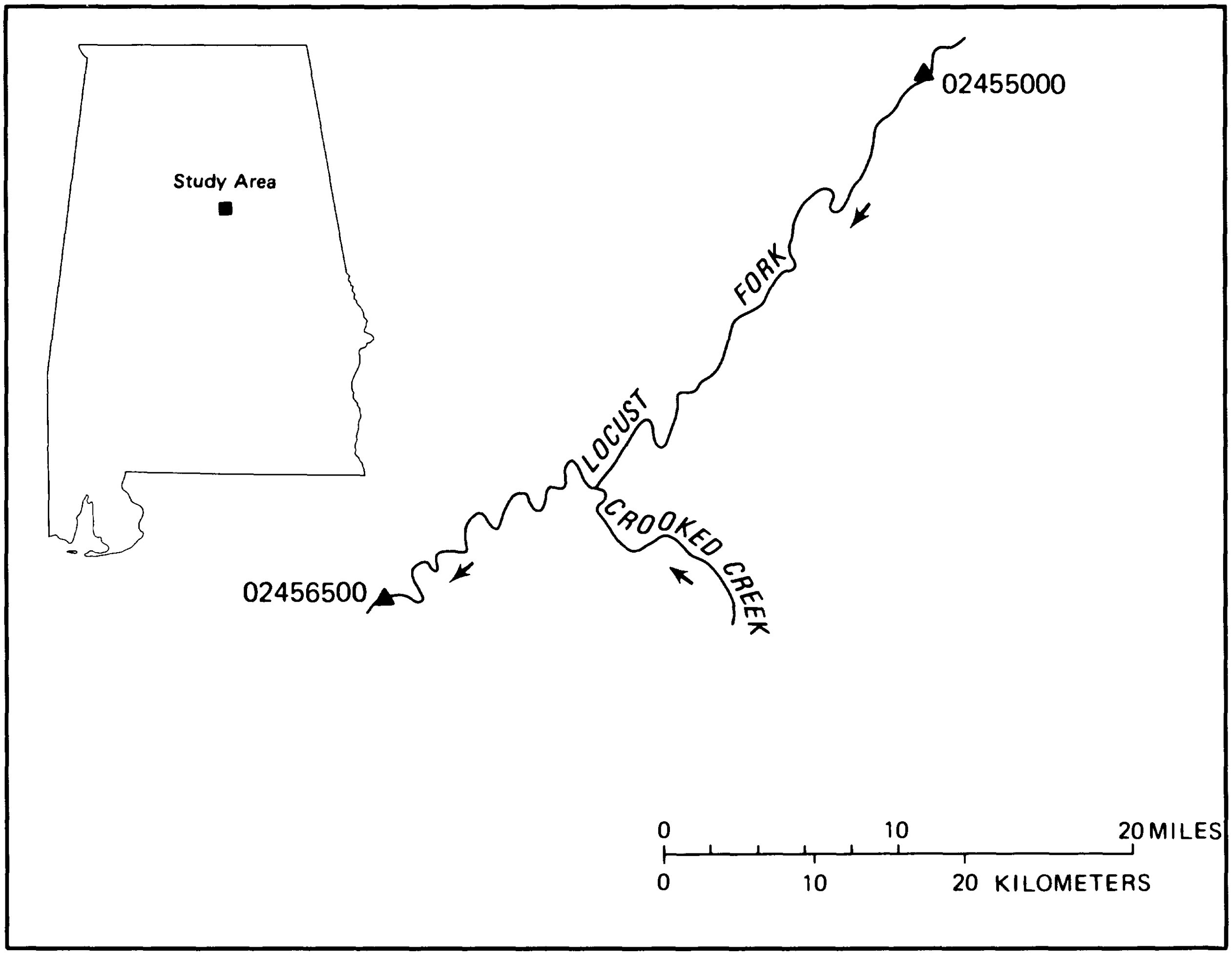

Figure 13. -- Locust Fork study area.

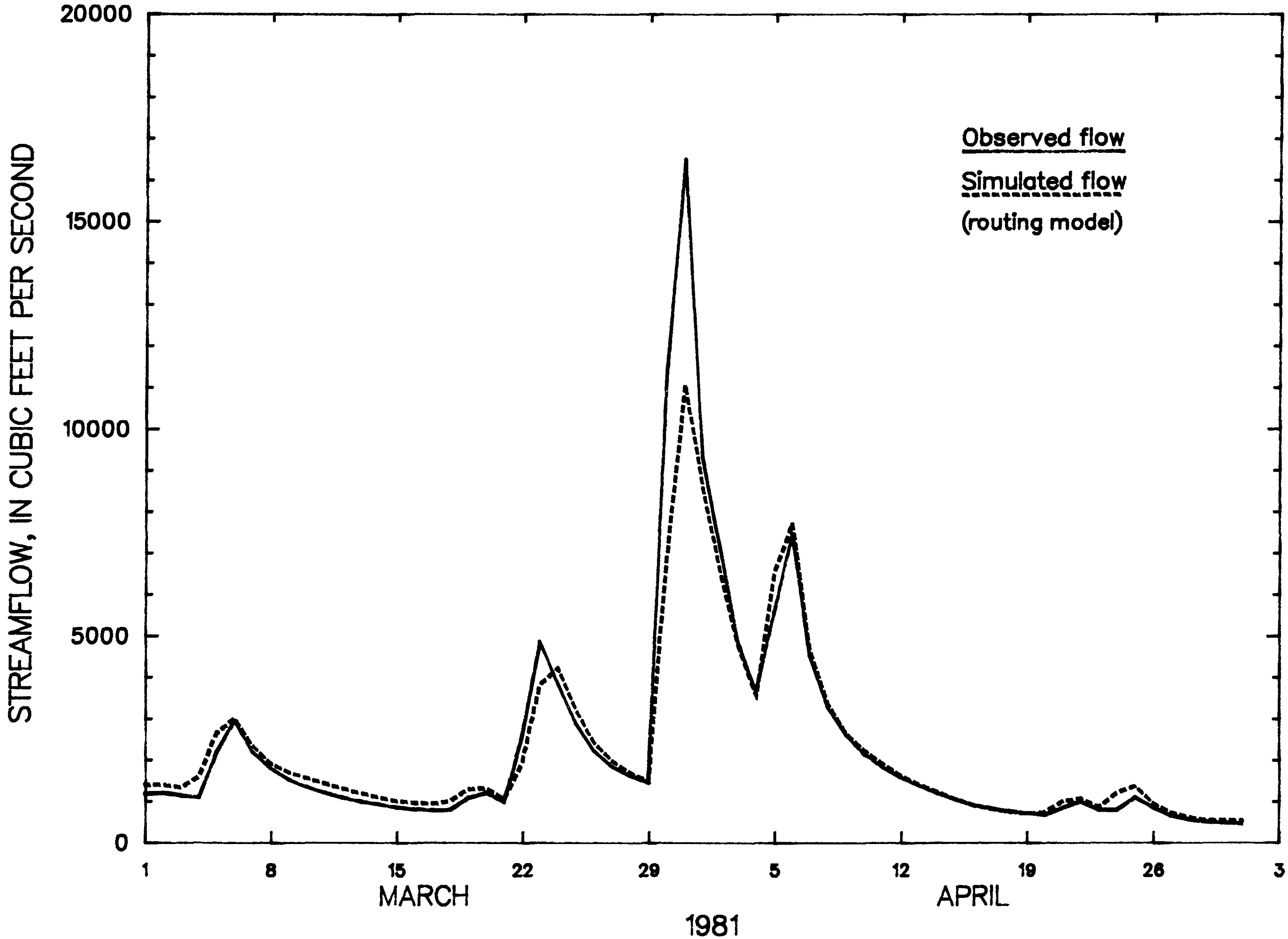

Figure 14. -- Daily hydrograph Locust Fork at Sayre.

Regression Analysis

Linear or log-linear regression techniques were applied to all five selected basins. The streamflow data for each station considered for simulation (the dependent variable) were regressed against streamflow data at other stations (explanatory variables) during a given period of record (the calibration period). Usually, the explanatory variables are streamflow data from upstream main stem and tributary gaging stations. A special explanatory variable, specified as Lag 1 Q, was defined for use in this analysis. It is the daily mean discharge at a station lagged by 1 day. Lagging the discharge in the regression equation amounts to routing the flow from the upstream site to the downstream site; the lagged discharge values account for the travel time between the two sites. Data from the 1980 water year were used for calibration and data for water years 1981 and 1982 were used for simulation. Best-fit linear regression models were developed to simulate a streamflow record that was compared to the observed streamflow record, and the percent difference between the simulated and observed record for each day was calculated. The results of the regression analysis are summarized in table 6.

The most successful regression model for all five selected basins was for the Cahaba River station (02425000). The model uses lagged values for station (02424000) and the unlagged values for tributary station (02424940). The model simulated the observed daily values within 10 percent for 65 percent of the days, and within 20 percent for 86 percent of the days. The mean error for daily values is 11.2 percent, and the total volume error is 0.3 percent. Further refinement of all the regression models may be possible with the investigation of separate high- and low-flow models. Daily hydrographs of observed and simulated flow for selected periods of record are shown in figures 15 through 19.

Conclusions Pertaining to Alternative Methods

Both flow-routing and regression models were used to simulate daily mean discharge for all five candidate stations. Neither model simulated flows of suitable accuracy to substitute for the operation of the continuous discharge station.

Using the mean error as criteria, the lowest error of 11.2 percent was produced for the Cahaba River near Marion Junction station (02425000), using the regression model, and 12.4 percent using the flow-routing model. Perhaps the relatively short period of record for stations on the Big Canoe Creek and Mulberry Fork contributed to less accurate simulations than those stations in the Tallapoosa and Cahaba basins. The least accurate in terms of mean error, 29.8 percent, was the Locust Fork station (02456500). The inability to accurately account for the intervening drainage area, which is approximately 66 percent of the total area, probably caused the large error.

In summary, all five stations considered in this section should remain in operation and will be included in the next step of this analysis.

Table 6.--Summary of regression modeling results and comparison of observed and simulated daily flows for 1981-82 water year

Station	Model equation	Mean error of daily discharge (in percent)	Volume error (in percent)	Percent of days with errors not more than indicated percent: 5	10	20	Calibration period
024013900 (16)[A] Big Canoe Creek	$\text{Log}(Q_{40139}) = 0.541 + 0.985\ \text{Log}(Q_{40137})$	20.1	10.0	17	32	66	1979-80
02414500 (24) Tallapoosa River	$\text{Log}(Q_{4145}) = 0.338 + 0.990\ \text{Log}(Q_{4120}+Q_{4133})$	14.4	1.0	23	50	80	1979-80
02425000 (33) Cahaba River	$\text{Log}(Q_{4250}) = 0.285 + 0.971\ \text{Log}(\text{Lag 1 } Q_{4240} + Q_{42494})$	11.2	.3	36	65	86	1979-80
02450180 (44) Mulberry Fork	$\text{Log}(Q_{45018}) = 0.295 + 0.925\ \text{Log}(Q_{4500})$	20.0	.7	20	39	74	1979-80
02456500 (48) Locust Fork	$\text{Log}(Q_{4565}) = 0.936 + 0.812\ \text{Log}(\text{Lag 1 } Q_{4550})$	29.8	15.2	14	25	45	1979-80

[A] Map index number

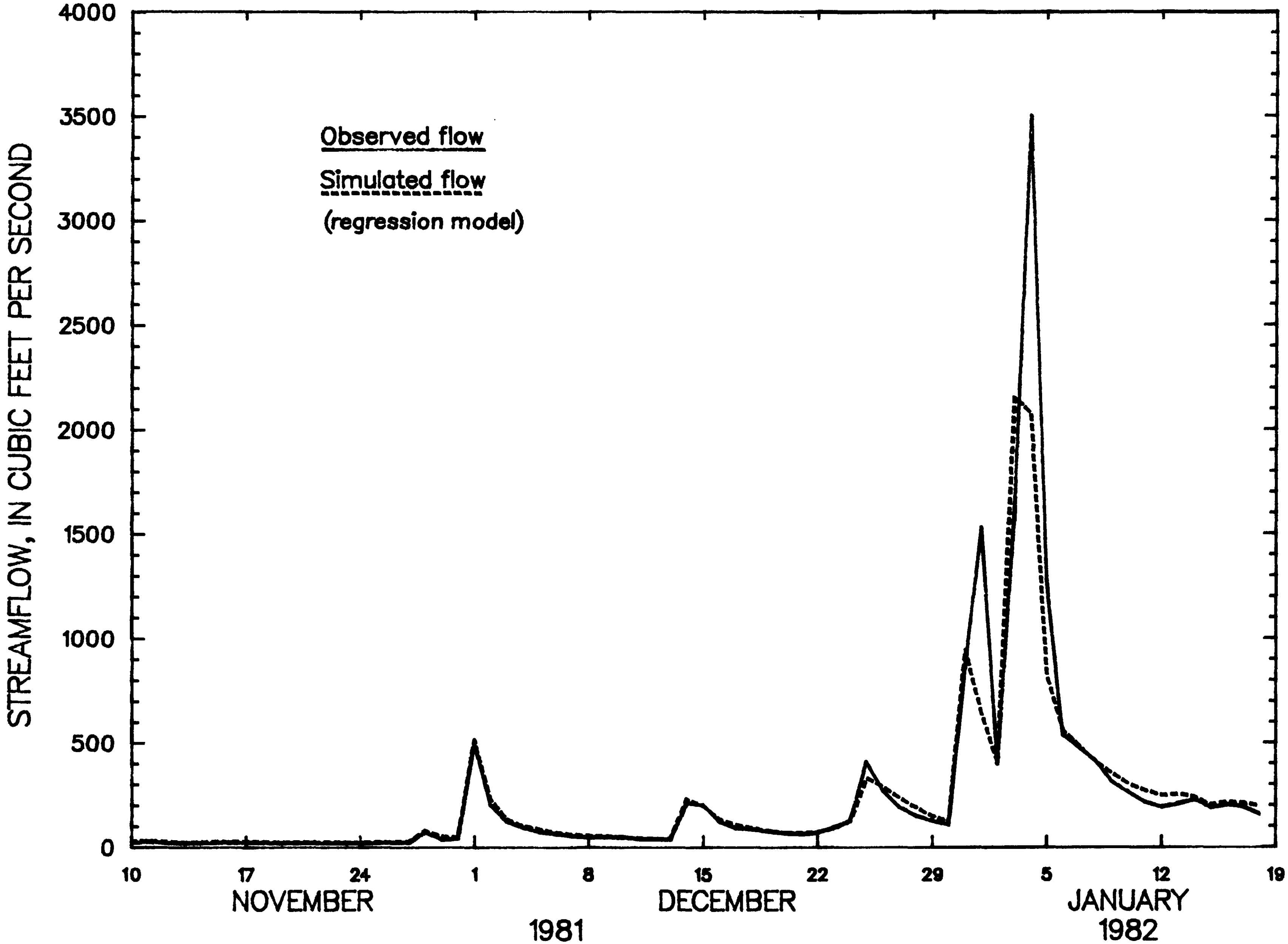

Figure 15. -- Daily hydrograph Big Canoe Creek at Ashville.

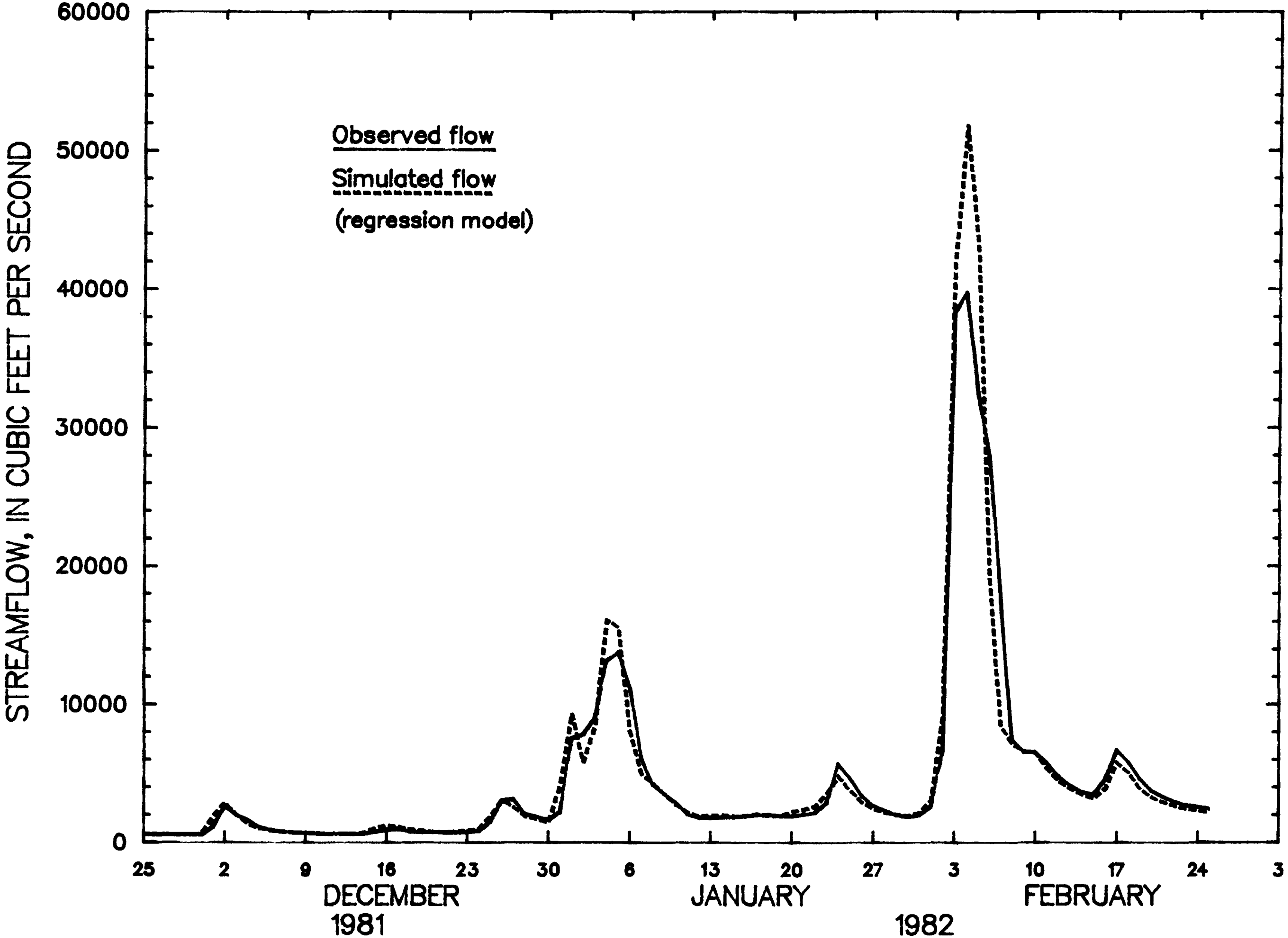

Figure 16. -- Daily hydrograph Tallapoosa River at Wadley.

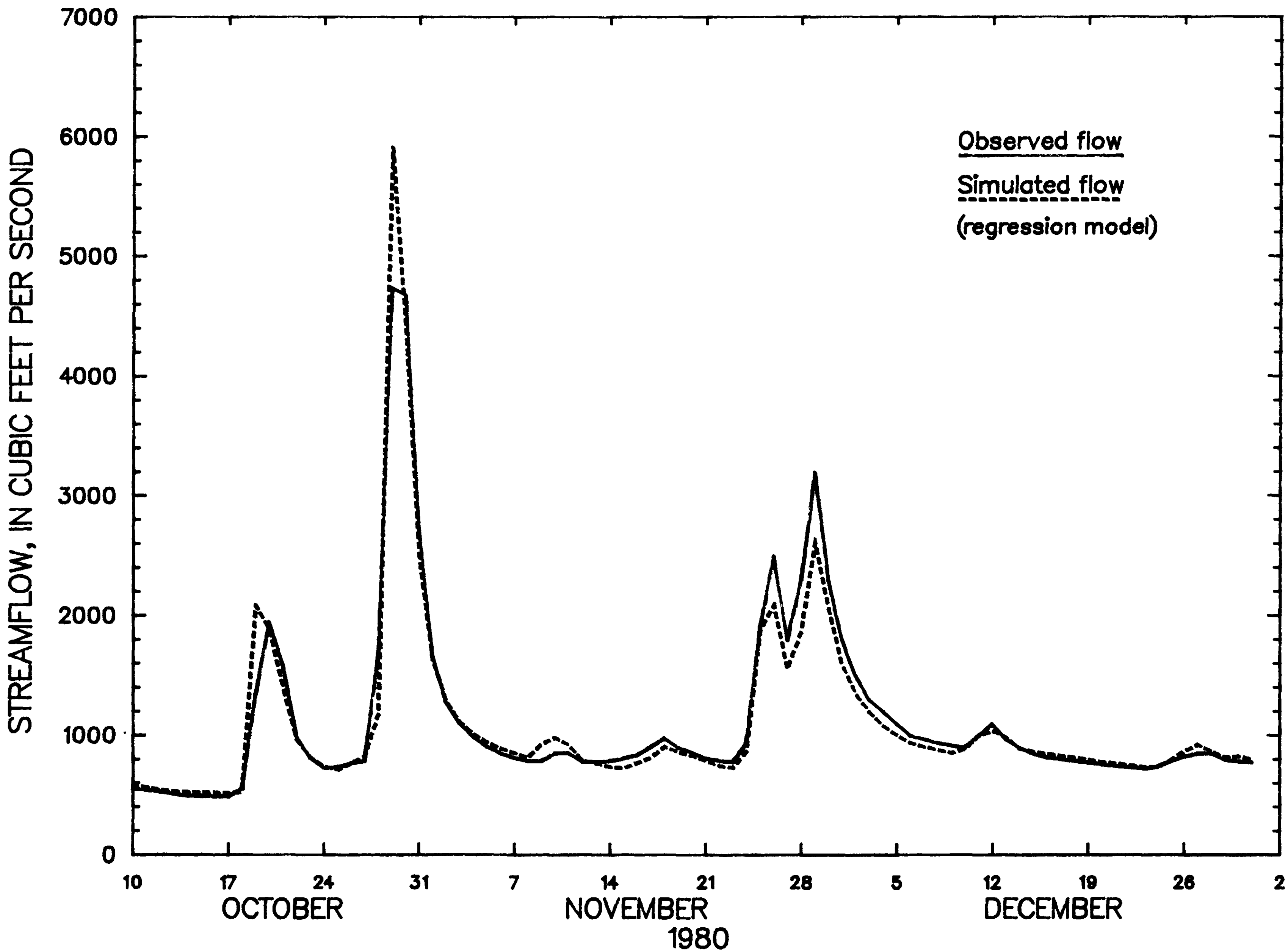

Figure 17. -- Daily hydrograph Cahaba River near Marion Junction.

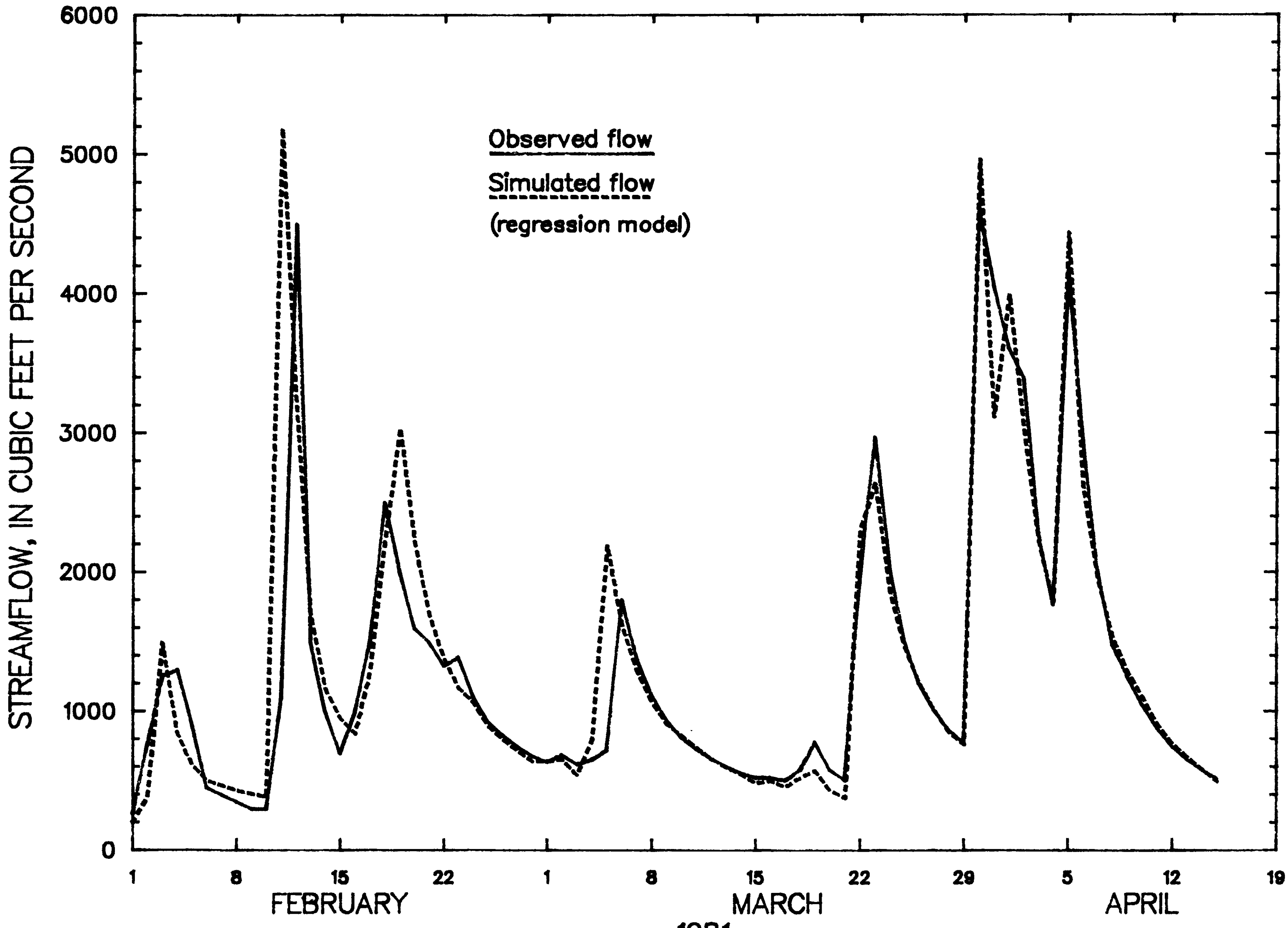

Figure 18. -- Daily hydrograph Mulberry Fork near Arkadelphia.

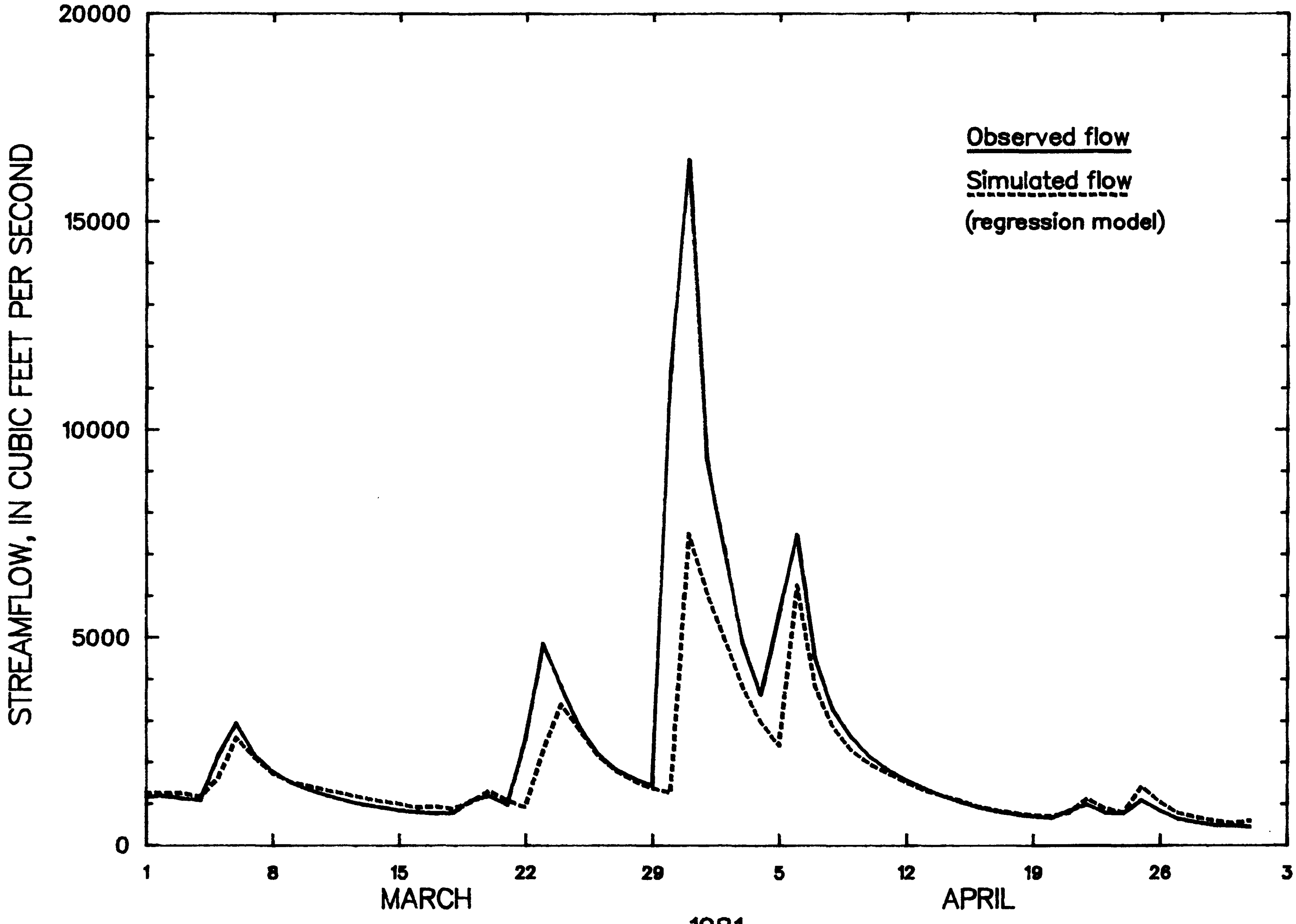

Figure 19. -- Daily hydrograph Locust Fork at Sayre.

COST-EFFECTIVE RESOURCE ALLOCATION

Introduction to Kalman-Filtering for Cost-Effective Resource Allocation (K-CERA)

A set of techniques called K-CERA were developed by Moss and Gilroy (1980) to study the cost-effectiveness of networks of gaging stations. The original application of the technique was to analyze a network of gaging stations operated to determine water consumption in the Lower Colorado River basin. Because of the water balance nature of that study, the minimization of the total variance of errors of estimation of annual mean discharges was chosen as the measure of effectiveness of the network. This total variance is defined as the sum of the variances of errors of mean annual discharge at each site in the network. This measure of effectiveness tends to concentrate stream-gaging resources on the large rivers and streams where discharge and, consequently, potential errors are greatest. Although this may be acceptable for a water-balance network, considering the many uses of data collected by the U.S. Geological Survey, concentration of effort on large rivers and streams is undesirable and inappropriate.

The original version of K-CERA was therefore altered to include as optional measures of effectiveness the sums of the variances of errors of estimation of the following streamflow variables: annual mean discharge, in cubic feet per second; annual mean discharge, in percentage; average instantaneous discharge, in cubic feet per second; or average instantaneous discharge, in percentage (Fontaine and others, 1983). The use of percentage errors effectively gives equal weight to large and small streams. In addition, instantaneous discharge is the basic variable from which all other streamflow data are derived. For these reasons, this study used the K-CERA techniques with the sums of the variances of the percentage errors of the instantaneous discharges at continuous-record gaging stations as the measure of the effectiveness of the data-collection activity.

The original version of K-CERA also did not account for error contributed by missing stage or other correlative data that are used to compute streamflow data. The probabilities of missing correlative data increase as the period between service visits to a gaging station increases. A procedure for dealing with the missing record has been developed (Fontaine and others, 1983) and was incorporated into this study.

Brief descriptions of the mathematical program used to minimize the total error variance of the data-collection activity for given budgets and of the application of Kalman filtering (Gelb, 1974) to the determination of the accuracy of a stream-gaging record are presented by Fontaine and others (1983). For more detail on either the theory or the applications of the K-CERA model, see Moss and Gilroy (1980) and Gilroy and Moss (1981).

$$\underset{\underline{N}}{\text{Minimize}}\ V = \sum_{j=1}^{MG} \phi_j \ (M_j)$$

V ≡ total uncertainty in the network

$\underline{N}$ ≡ vector of annual number times each route was used

MG ≡ number of gages in the network

M_j ≡ annual number of visits to station j

ϕ_j ≡ function relating number of visits to uncertainty at station j

Such that

Budget $\geq T_c$ ≡total cost of operating the network

$$T_c = F_c + \sum_{j=1}^{MG} \alpha_j M_j + \sum_{i=1}^{NR} \beta_i N_i$$

F_c ≡ fixed cost

α_j ≡ unit cost of visit to station j

NR ≡ number of practical routes chosen

β_i ≡ travel cost for route i

N_i ≡ annual number times route i is used (an element of $\underline{N}$)

and such that

$$M_j \geq \lambda_j$$

λ_j ≡ minimum number of annual visits to station j

Figure 20. -- Mathematical-programming form of the optimization of the routing of hydrographers.

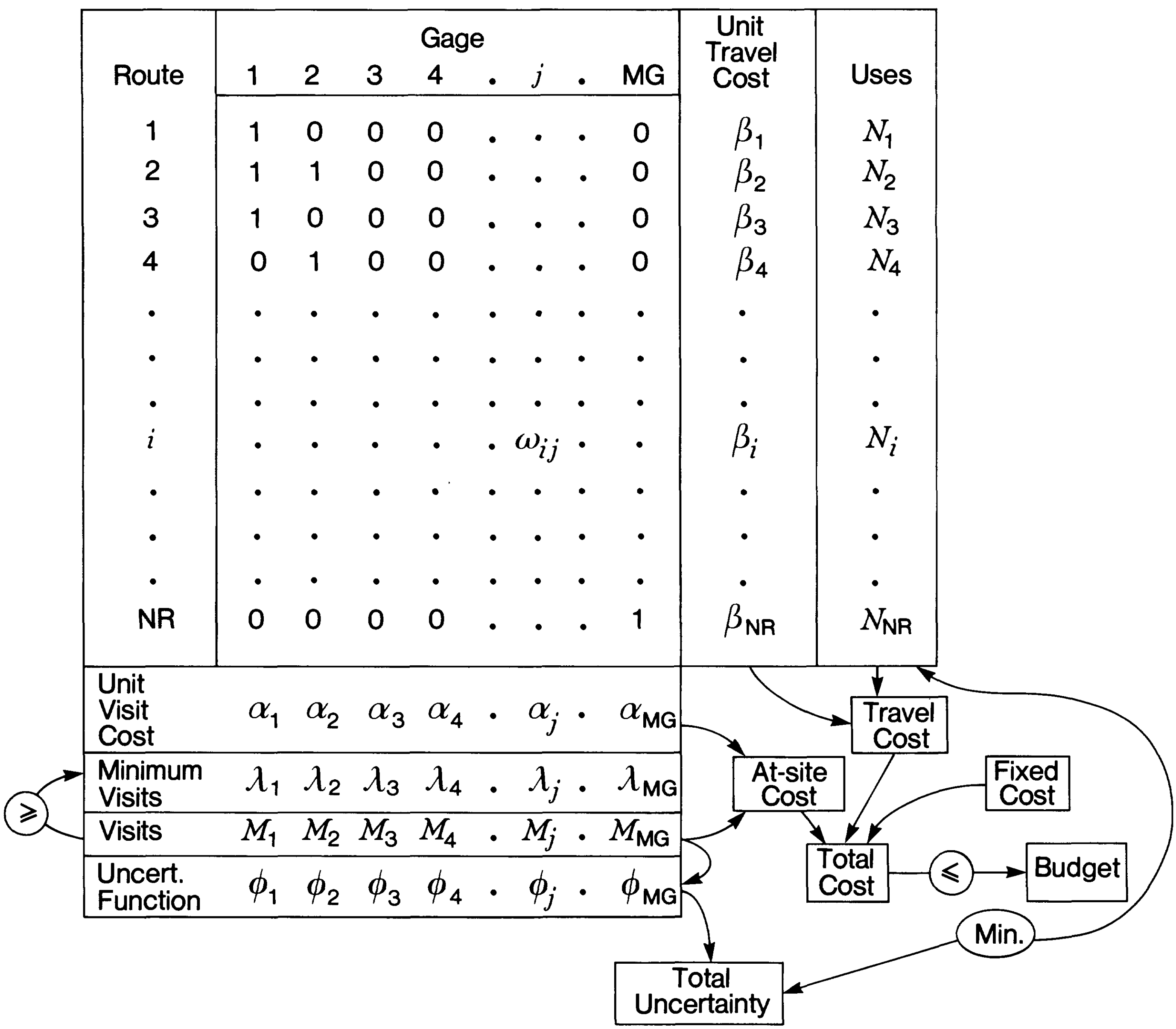

Figure 21. -- Tabular form of the optimization of the routing of hydrographers.

Description of Mathematical Program

The program, called "The Traveling Hydrographer," attempts to allocate among gaging stations a predefined budget for the collection of streamflow data in such a manner that the field operation is the most cost-effective possible. The measure of effectiveness is discussed above. The set of decisions available to the manager is the frequency of use (number of times per year) of each of a number of routes that may be used to service the gaging stations and to make discharge measurements. The range of options within the program is from zero usage to daily usage for each route. A route is defined as a set of one or more gaging stations and the least-cost travel that takes the hydrographer from his base of operations to each of the gages and back to base. A route has associated with it an average cost of travel and average cost of servicing each gaging station visited along the way. The first step in this part of the analysis is to define the set of practical routes. This set of routes frequently will contain the path to an individual station with that station as the lone stop and return to the home base so that the individual needs of a station can be considered in isolation from the other stations.

Another step in this part of the analysis is the determination of any special requirements for visits to each of the gages for such things as necessary maintenance, rejuvenation of recording equipment, or required periodic sampling of water-quality data. Such special requirements are considered to be inviolable constraints in terms of the minimum number of visits to each site.

The final step is to use all of the above to determine the number of times, N_i, that the i^{th} route for i = 1, 2, ..., NR, where NR is the number of practical routes, is used during a year such that (1) the budget for the network is not exceeded, (2) the minimum number of visits to each station is made, and (3) the total uncertainty in the network is minimized. Figure 20 represents this step in the form of a mathematical program. Figure 21 presents a tabular layout of the problem. Each of the NR routes is represented by a row of the table and each of the stations is represented by a column. The zero-one matrix (ω_{ij}) defines the routes in terms of the stations that comprise it. A value of one in row i and column j indicates that gaging station j will be visited on route i; a value of zero indicates that it will not. The unit travel costs (β_i) are the per-trip costs of the hydrographer's travel time and any related per diem and operation, maintenance, rental costs of vehicles. Also considered is the average cost of service and maintenance of recording equipment. The sum of the products of β_i and N_i for i = 1, 2, ..., NR is the total travel cost associated with the set of decisions $\underline{N} = (N_1, N_2, ..., N_{NR})$.

The unit-visit cost (α_j) is comprised of the average cost of making a discharge measurement. The set of minimum visit constraints is denoted by the row λ_j, j = a, 2, ..., MG, where MG is the number of gaging stations. The row of integers M_j, j = 1, 2, ..., MG specifies the number of visits to each station. M_j is the sum of the products of ω_{ij} and N_i for all i and must equal or exceed λ_j for all j if $\underline{N}$ is to be a feasible solution to the decision problem.

The total cost expended at the stations is equal to the sum of the products of α_j and M_j for all j. The cost of record computation, documentation, and publication is assumed to be influenced negligibly by the number of visits to the station and is included along with overhead in the fixed cost of operating the network. The total cost of operating the network equals the sum of the travel costs, the at-site costs, the fixed cost, and must be less than or equal to the available budget.

The total uncertainty in the estimates of discharges at the MG stations is determined by summing the uncertainty functions, ϕ_j, evaluated at the value of M_j from the row above it, for j = 1, 2, ..., MG.

As pointed out in Moss and Gilroy (1980), the steepest-descent search used to solve this mathematical program does not guarantee a true optimum solution. However, the locally optimum set of values for $\underline{N}$ obtained with this technique specifies an efficient strategy for operating the network, which may be the true optimum strategy. The true optimum cannot be guaranteed without testing all undominated, feasible strategies.

Description of Uncertainty Functions

As noted earlier, uncertainty in streamflow records is measured in this study as the average relative variance of estimation of instantaneous discharges. The accuracy of a streamflow estimate depends on how that estimate was obtained. Three situations are considered in this study: (1) streamflow is estimated from measured discharge and correlative data using a stage-discharge relation (rating curve), (2) the streamflow record is reconstructed using secondary data at nearby stations because primary correlative data are missing, and (3) primary and secondary data are unavailable for estimating streamflow. The variances of the errors of the estimates of flow that would be employed in each situation were weighted by the fraction of time each situation is expected to occur. Thus the average relative variance would be

$$V = \varepsilon_f V_f + \varepsilon_r V_r + \varepsilon_e V_e$$

with (3)

$$1 = \varepsilon_f + \varepsilon_r + \varepsilon_e$$

where

- $\overline{V}$ is the average relative variance of the errors of streamflow estimates,
- f is the fraction of time that the primary recorders are functioning,
- V_f is the relative variance of the errors of flow estimates from primary recorders,
- ε_r is the fraction of time that secondary data are available to reconstruct streamflow records given that the primary data are missing,
- V_r is the relative variance of the errors of estimation of flows reconstructed from secondary data,
- ε_e is the fraction of time that primary and secondary data are not available to compute streamflow records, and
- V_e is the relative error variance of the third situation.

The fractions of time that each source of error is relevant are functions of the frequencies at which the recording equipment is serviced.

The time since the last service visit until failure of the recorder or recorders at the primary site is assumed to have a negative-exponential probability distribution truncated at the next service time; the distribution's probability density function is

$$f(t) = ke^{-kt}/(1-e^{-ks}) \tag{4}$$

where

k is the failure rate in units of $(day)^{-1}$,

e is the base of natural logarithms, and

s is the interval between visits to the site in days.

It is assumed that, if a recorder fails, it continues to malfunction until the next service visit. As a result,

$$\varepsilon_f = (1-e^{ks})/(ks) \tag{5}$$

(Fontaine and others, 1983, eq. 21).

The fraction of time ε_e that no records exist at either the primary or secondary sites can also be derived assuming that the time between failures at both sites are independent and have negative exponential distributions with the same rate constant. It then follows that

$$e = 1 - [2(1-e^{-ks}) + 0.5\ (1-e^{-2ks})]/(ks)$$

(Fontaine and others, 1983, eqs. 23 and 25).

Finally, the fraction of time ε_r that records are reconstructed based on data from a secondary site is determined by the equation

$$\varepsilon_r = 1 - \varepsilon_f - \varepsilon_e.$$

$$= [(1-e^{-ks}) + 0.5\ (1-e^{2ks})]/(ks) \tag{6}$$

The relative variance, V_f, of the error derived from primary record computation is determined by analyzing a time series of residuals that are the differences between the logarithms of measured discharge and the rating curve discharge. The rating curve discharge is determined from a relation between discharge and some correlative data, such as water-surface elevation at the gaging station. The measured discharge is the discharge determined by field observations of depths, widths, and velocities. Let $q_T(t)$ be the true instantaneous discharge at time t and let $q_R(t)$ be the value that would be estimated using the rating curve. Then

$$x(t) = \ln q_T(t) - \ln q_R(t) = \ln [q_T(t)/q_R(t)] \qquad (7)$$

is the instantaneous difference between the logarithms of the true discharge and the rating curve discharge.

In computing estimates of streamflow, the rating curve may be continually adjusted on the basis of periodic measurements of discharge. This adjustment process results in an estimate, $q_c(t)$, that is a better estimate of the stream's discharge at time t. The difference between the variable $\hat{x}(t)$, which is defined

$$\hat{x}(t) = \ln q_c(t) - \ln q_R(t) \qquad (8)$$

and x(t) is the error in the streamflow record at time t. The variance of this difference over time is the desired estimate of V_f.

Unfortunately, the true instantaneous discharge, $q_T(t)$, cannot be determined and thus x(t) and the difference, $\hat{x}(t) - x(t)$, cannot be determined as well. However, the statistical properties of $\hat{x}(t) - x(t)$, particularly its variance, can be inferred from the available discharge measurements. Let the observed residuals of measured discharge from the rating curve be z(t) so that

$$z(t) = x(t) + v(t) = \ln q_m(t) - \ln q_R(t) \qquad (9)$$

where

v(t) is the measurement error, and

$\ln q_m(t)$ is the logarithm of the measured discharge equal to $\ln q_T(t)$ plus v(t).

In the Kalman-filter analysis, the z(t) time series was analyzed to determine three site-specific parameters. The Kalman filter used in this study assumes that the time residuals, x(t), arise from a continuous first-order Markovian process that has a Gaussian (normal) probability distribution with zero mean and variance (subsequently referred to as process variance) equal to p. A second important parameter is β, the reciprocal of the correlation time of the Markovian process giving rise to x(t); the correlation between $x(t_1)$ and $x(t_2)$ is $\exp[-\beta|t_1-t_2|]$. Fontaine and others (1983) also define q, the constant value of the spectral density function of the white noise which drives the Gauss-Markov x-process. The parameters, p, q, and β are related by

$$\mathrm{Var}[x(t)] = p = q/(2\beta) \qquad (10)$$

The variance of the observed residuals z(t) is

$$\mathrm{Var}[z(t)] = p + r \qquad (11)$$

where r is the variance of the measurement error v(t). The three parameters, p, β, and r, are computed by analyzing the statistical properties of the z(t) time series. These three site-specific parameters are needed to define this component of the uncertainty relation. The Kalman filter utilizes these three parameters to determine the average relative variance of the errors of estimation of discharges as a function of the number of discharge measurements per year (Moss and Gilroy, 1980).

If the recorder at the primary site fails and there are no concurrent data at other sites that can be used to reconstruct the missing record at the primary site, there are at least two ways of estimating discharges at the primary site. A recession curve could be applied from the time of recorder stoppage until the recorder was once again functioning or the expected value of discharge for the period of missing data could be used as an estimate. The expected-value approach is used in this study to estimate V_e, the relative error variance during periods of no concurrent data at nearby stations. If the expected value is used to estimate discharge, the value that is used should be the expected value of discharge at the time of year of the missing record because of the seasonality of the streamflow processes. The variance of streamflow, which also is a seasonally varying parameter, is an estimate of the error variance that results from using the expected value as an estimate. Thus the coefficient of variation squared, $(C_v)^2$, is an estimate of the required relative error variance V_e. Because C_v varies seasonally and the times of failures cannot be anticipated, a seasonally averaged value of C_v is used:

$$\overline{C}_v = \left[\frac{1}{365}\sum_{i=1}^{365}\left(\frac{\sigma_i}{\mu_i}\right)^2\right]^{1/2} 100 \qquad (12)$$

where

σ_i is the standard deviation of daily discharges for the i^{th} day of the year,

μ_i is the expected value of discharge on the i^{th} day of the year, and $(\overline{C}_v)^2$ is used as an estimate of V_e.

The variance, V_r, of the relative error during the periods of reconstructed streamflow records is estimated on the basis of correlation between records at the primary site and records from other gaged nearby sites. The correlation coefficient, p_c, between the streamflows with seasonal trends removed at the site of interest and detrended streamflows at the other sites is a measure of the goodness of their linear relation. The fraction of the variance of streamflow at the primary site that is explained by data from the other sites is equal to p_c^2. Thus, the relative error variance of flow estimates at the primary site obtained from secondary information will be

$$V_r = (1-p_c^2) C_v^{-2} \qquad (13)$$

Because errors in streamflow estimates arise from three different sources with widely varying precisions, the resultant distribution of those errors may differ significantly from a normal or log-normal distribution. This lack of normality causes difficulty in interpretation of the resulting average estimation variance. When primary and secondary data are unavailable, the relative error variance V_e may be very large. This could yield correspondingly large values of $\bar{V}$ in equation (3) even if the probability that primary and secondary information are not available, ε_e, is quite small.

A new parameter, the equivalent Gaussian spread (EGS), is introduced here to assist in interpreting the results of the analyses. If it is assumed that the various errors arising from the three situations represented in equation (3) are log-normally distributed, the value of EGS was determined by the probability statement that

$$\text{Probability } [e^{-EGS} \leq (q_c(t) / q_T(t)) \leq e^{+EGS}] = 0.683 \qquad (14)$$

Thus, if the residuals, $\ln q_c(t) - \ln q_T(t)$, were normally distributed, $(EGS)^2$ would be their variance. Here EGS is reported in units of percent because EGS is defined so that nearly two-thirds of the errors in instantaneous streamflow data will be within plus or minus EGS percent of the reported values.

The Application of K-CERA in Alabama

As a result of the first two parts of this analysis, it has been recommended that all of the 1983 discharge stations operated by the Alabama District be continued. As described in phase one, 58 daily stations were operated in 1983; all will be analyzed in the final step of the study (K-CERA).

Definition of Missing Record Probabilities

As described earlier, the statistical characteristics of missing stage or other correlative data for computation of streamflow records can be defined by a single parameter, the value of k in the truncated negative exponential probability distribution of times to failure of the equipment. In the representation of f(t) as given in equation 4, the average time to failure is 1/k. The value of 1/k will vary from site to site depending upon the type of equipment at the site and upon its exposure to natural elements and vandalism. The value of 1/k can be changed by advances in the technology of data collection and recording.

An analysis of the missing record was made for the three offices in Alabama for the 5-year period 1979-83. The average lost record was computed for each station during this period. Factors considered were: type of gage (bubble gage or stilling well), availability of back-up recorder, and punch interval. The results of the lost-record analysis are summarized in table 7. Because the percentage of lost-record for the Cullman office is relatively large, several observations should be made. Of the 14 bubble-gage installations in the District-wide network, 9 are located in the Cullman office. This type of gage is particularly subject to lost record due to malfunctioning of the manometer, plugging of the air-line orifice in the stream, and complexity of the system as a whole. Also, there were more than twice the number of stations with 15-minute punch interval in the Cullman office than the other two offices. Recorders having 15-minute punch cycles are under more stress than larger punch-cycle recorders due to the extra number of times the equipment is called upon to record data.

For the Tuscaloosa office the 4.0 percent lost record and a 5-week visit frequency produced a value of 1/k of 404 days which was used to determine E_f, E_e, and E_r for each of the 10 gaging stations. For the Montgomery office, the 4.0 percent lost record and a 6-week visit frequency produced a value of 1/k of 444 days which was used similarly for each of the 30 gaging stations. For the Cullman office, the 11.0 percent lost record and a 6-week visit frequency produced a value for 1/k of 154 days which was used similarly for each of the 18 gaging stations. The majority of the Tuscaloosa stations are project stations and actually were visited more frequently than every 6 weeks due water sampling requirements.

Table 7.--Analysis of lost record for Alabama stations, water years 1979-83

			Type of equipment				
						Punch interval	
Office	Number of stations	Average lost record (in percent)	Stilling well	Bubble gage	Back-up recorder	60 min.	15 min.
Tuscaloosa	10	4	9	1	5	4	6
Montgomery	30	4	26	4	3	26	4
Cullman	18	11	9	9	7	7	11

Definition of Cross-Correlation Coefficient and Coefficient of Variation

To compute the values of V_e and V_r of the needed uncertainty functions, daily streamflow records were retrieved for each of the 58 stations having all, or part, of the last 30 years of data stored in WATSTORE (Hutchison, 1975). For each of the stations that had 3 or more complete water years of data, the cross correlation value (C_v) was computed and various options, based on combinations of other stations, were explored to determine the maximum interstation correlation (p_c).

Values of C_v and P_c were estimated subjectively for stations 0240147, 02464146, and 02479560 by comparison with surrounding stations. The largest p_c coefficient (.895) was obtained for two stations on the Tallapoosa River (0241200, 02414500). The two lowest coefficients of variation, p_c, were at stations 02410000 (.321) and 02471065 (.333), respectively. Both of these stations were originally operated as research project stations (rainfall-runoff) and were subsequently incorporated into the continuous record network. Generally, this phase of the analysis quantified the basic intuition regarding hydrographic comparison of Alabama stations. Values of C_v and P_c for each station and associated index stations used in the analysis are shown in table 8.

Kalman-Filter Definition of Variance

The determination of the variance V_f for each of the 58 gaging stations required the execution of three distinct steps: (1) long-term rating analysis and computation of residuals of measured discharges from the long-term rating, (2) time-series analysis of the residuals to determine the input parameters of the Kalman-filter streamflow records, and (3) computation of the error variance, V_f, as a function of the time series parameters, the discharge-measurement-error variance, and the frequency of discharge measurement.

In the Alabama program analysis, a common 5-year period of discharge measurements (1978-83) was used to compute residuals of the measurements from the long-term rating. The 10-year period 1973-83 was considered for use, but varying lengths of record would result from the major changes made to the network in the mid-1970's and changes during 1976-78 due to the emphasis of coal hydrology. A network of stations having the 5-year period of record 1978-83 more nearly reflect a common long term for the entire district. Also, ratings for stations operated during this period reflect the effects of two significant hydrologic events, the 1979 flood and the low-water year of 1981.

Rating curves were developed on logarithmic graph paper by plotting all measurements made during this period and fitting a curve through these points. The most recent rating in the office files was used as a guide for the scale offset, and a sufficient number of rating coordinates were selected to describe a rating table computed by logarithmic linear interpolation. A visual analysis of the residuals provided the check for a best-fit representative rating.

Table 8.--Statistics of record reconstruction

Map index number	Station number	C_v	P_c	Stations used to reconstruct records (lag days)	
1	02342500	145.5	0.856	02419000	
2	02342933	161.7	.645	02342500	02419000
3	02343300	89.8	.851	02361000	
4	02361000	101.6	.851	02343300	
5	02364570	129.3	.807	02369800	02361000
6	02369800	112.8	.807	02364570	02373800
7	02371200	118.1	.547	02372250	02371500
8	02371500	128.0	.822	02372250	02373000
9	02372250	106.6	.822	02371500	02373000
10	02373000	159.9	.824	02373800	02374500
11	02374500	91.1	.776	02373000	02373800
12	02398195	78.2	.590	02399200	
13	02399200	171.9	.845	03572900	02398195
14	02400100	81.0	.573	02401390	
15	02401370	86.5	.786	02401460	02401390
16	02401390	140.4	.673	02401370	02401460
17	02401460	111.1	.596	02401390	
18	02401470	150.0*	.850*		
19	02408540	111.0	.601	02419000	
20	02410000	196.7	.321	02408500	
22	02412000	115.0	.895	02414500	02413300
23	02413300	82.8	.795	02414500	02412000
24	02414500	96.6	.895	02412000	02413300
26	02419000	159.9	.623	02342933	
28	02421000	241.8	.616	02425200	02342933
29	02422500	100.9	.727	02424940	02425200
30	02423425	140.4	.704	02423647(-1)	
31	02424000	122.1	.684	02464000	02465493
32	02424940	90.3	.729	02425200	
33	02425000	90.9	.816	02424000	
34	02425200	137.7	.729	02424940(-2)	
35	02427700	198.8	.725	02469800	
37	02442500	84.8	.543	02464000	
39	02446500	106.6	.682	02448500	02464000
41	02448500	172.4	.682	02446500	02464000
42	02449245	145.3	.626	02465493	02424000
43	02450000	177.9	.837	02455000	02450180
44	02450180	171.0	.670	02450000	02455000
45	02450250	154.2	.617	02450000	02450180
46	02455000	164.6	.842	02456500	02450000

Table 8.--Statistics of record reconstruction--Continued

Map index number	Station number	C_v	p_c	Stations used to reconstruct records (lag days)	
47	02456330	132.9	0.646	02456000	02455000
48	02456500	150.0	.842	02455000	02450000
49	02462000	87.2	.614	02401390	02462600
51	02462600	165.6	.727	02464000	
53	02464000	160.7	.727	02462600	02424000
54	02464146	150.0*	.850*		
56	02465493	62.1	.626	02449245	02424000
59	02467500	128.1	.511	02469800(-2)	
60	02468500	219.0	.673	02469800	
62	02469800	153.0	.673	02468500	
63	02471001	98.4	.514	02469800(-1)	
64	02471065	99.0	.333	02471001	
65	02479431	127.8	.538	02469800	
66	02479560	150.0*	.850*		
67	03572110	129.1	.704	03574500	03572900
68	03574500	190.1	.740	03575000	
69	03575000	143.5	.744	03574500	03575830
71	03575830	122.3	.664	03575000	03574500

* Estimated value.

Tables 9-11 are examples of residual data for representative stations in each of the three Alabama offices. The tables show the measured discharge, the residual of the measured and predicted discharges, and the percent error.

The time series of residuals was used to compute sample estimates of q and β, two of the three parameters required to compute V_f, by determining a best fit auto-covariance function to the time series of residuals. Measurement variance, the third parameter, was determined from an assumed constant percentage standard error. For Alabama, measurement error ranges from 5 to 10 percent with the majority being 5 or 8 percent. The measurement error estimate was based on the variance of partial errors (current meter, velocity fluctuations, shape of vertical velocity curve, number of observations, and time per measurement) as outlined in Carter and Anderson (1963).

As discussed earlier, q and β can be expressed as the process variance of the shifts from the rating curve and the 1-day autocorrelation coefficient of these shifts. Table 12 presents a summary of the autocovariance analysis expressed in terms of process variance and 1-day autocorrelation.

The autocovariance parameters, summarized in table 12, and data from the definition of missing record probabilities, summarized in table 8, are used jointly to define uncertainty functions for each of the 58 gaging stations. The uncertainty functions give the relation of total error variance to the number of visits and discharge measurements. Typical examples of uncertainty functions are given in figures 22-24 for those stations for which residual data are presented in tables 9-11. These functions are based on the assumption that a measurement was made during each visit to the station.

Determination of Routes

In Alabama the responsibilities for stream gaging activities are shared by three offices located in Tuscaloosa, Montgomery, and Cullman. The Tuscaloosa office services 10 gaging stations, the Montgomery office services 30 stations, and the Cullman office services 18 stations. In addition to these gaging station activities, each office has other unique activities that dictate work load distribution. For instance, the Tuscaloosa office's work load includes other project data-collection activities. The "Traveling Hydrographer Program" was applied separately to the stream-gaging activities of each office to better analyze the efficiency of each office.

Feasible routes to service the gaging stations were determined after consultation with personnel in each office. These routes include all possible combinations that describe the current operating practice, alternatives that were under consideration as future possibilities, routes that visited certain key individual stations, and combinations that grouped proximate stations where the levels of uncertainty indicated more frequent visits might be useful. Negative station numbers (-1, -2, -3, etc.) are used to denote all of the other hydrologic data-collection sites that are serviced on these same routes. These "dummy" station numbers may represent stations that include water only, ground-water sites, crest-stage gage, water-quality collection and control structure gages. The routes and the stations visited on each are summarized in tables 13 through 15.

Table 9.--Residual data for Cahaba River at Centreville

Observation number	Date	Lag (days)	Measured discharge (ft^3/s)	Predicted discharge (ft^3/s)	Residual (ft^3/s)	Percent error
618	Oct. 4, 1978	0	224	204	20	8.9
619	Oct. 24, 1978	20	208	177	31	14.9
620	Nov. 8, 1978	15	215	196	19	8.8
621	Dec. 28, 1978	50	650	511	139	21.4
622	Jan. 29, 1979	32	1,800	1,560	240	13.3
623	Mar. 15, 1979	45	1,610	1,550	60	3.7
624	May 1, 1979	47	2,450	2,620	-170	-6.4
625	June 25, 1979	55	806	876	-70	-8.7
626	July 23, 1979	28	617	770	-153	-24.8
627	Aug. 23, 1979	31	558	703	-145	-26.0
628	Oct. 4, 1979	42	1,400	1,350	50	3.6
629	Oct. 29, 1979	25	385	514	-129	-33.5
630	Dec. 13, 1979	45	643	748	-105	-16.3
631	Jan. 28, 1980	46	2,650	2,520	130	4.9
632	Mar. 14, 1980	46	19,600	19,300	300	1.5
633	Apr. 24, 1980	41	1,590	1,540	50	3.1
634	June 10, 1980	47	697	703	-6	-.9
635	July 25, 1980	45	629	682	-53	-8.4
636	Sept. 8, 1980	45	295	373	-78	-26.4
637	Oct. 10, 1980	32	310	375	-65	-21.0
638	Nov. 19, 1980	40	445	475	-30	-6.7
639	Dec. 17, 1980	28	425	452	-27	-6.4
640	Jan. 27, 1981	41	404	436	-32	-7.9
641	Mar. 10, 1981	42	1,320	1,250	70	5.3

Table 9.--Residual data for Cahaba River at Centreville--Continued

Observation number	Date	Lag (days)	Measured discharge (ft^3/s)	Predicted discharge (ft^3/s)	Residual (ft^3/s)	Percent error
642	Apr. 21, 1981	42	694	654	40	5.8
643	June 4, 1981	44	1,220	1,020	200	16.4
644	July 14, 1981	40	305	326	-21	-6.9
645	Aug. 26, 1981	43	234	273	-39	-16.7
646	Oct. 1, 1981	36	181	219	-38	-21.0
647	Nov. 6, 1981	36	220	236	-16	-7.3
648	Dec. 8, 1981	32	274	279	-5	-1.8
649	Jan. 20, 1982	43	1,260	1,210	50	4.0
650	Feb. 25, 1982	36	1,290	1,220	70	5.4
651	Apr. 8, 1982	42	1,920	1,630	290	15.1
652	May 20, 1982	42	762	718	44	5.8
653	Aug. 5, 1982	77	632	536	96	15.2
654	Sep. 15, 1982	41	310	305	5	1.6
655	Oct. 29, 1982	44	236	242	-6	-2.5
656	Dec. 14, 1982	46	4,840	4,810	30	.6
657	Jan. 11, 1983	28	1,620	1,420	200	12.3
658	Feb. 28, 1983	48	2,480	2,420	60	2.4
659	Apr. 1, 1983	32	2,010	2,020	-10	-.5
660	May 3, 1983	32	1,600	1,460	140	8.8
661	June 13, 1983	41	859	778	81	9.4
662	July 22, 1983	39	533	496	37	6.9
663	Aug. 31, 1983	40	377	340	37	9.8

Table 10.--Residual data for Little Tallapoosa River near Newell

Observation number	Date	Lag (days)	Measured discharge (ft^3/s)	Predicted discharge (ft^3/s)	Residual (ft^3/s)	Percent error
28	Oct. 5, 1977	0	147	159	-12	-8.2
29	Nov. 17, 1977	43	449	449	0	0
30	Jan. 5, 1978	49	378	370	8	2.1
31	Feb. 22, 1978	48	471	436	35	7.4
32	Mar. 30, 1978	36	425	457	-32	-7.5
33	May 15, 1978	46	639	653	-14	-2.2
34	June 29, 1978	45	222	225	-3	-1.4
35	Aug. 2, 1978	34	225	218	7	3.1
36	Sep. 11, 1978	40	73.1	73.7	-.6	-.8
37	Oct. 17, 1978	36	60.2	63.2	-3.0	-5.0
38	Nov. 29, 1978	43	160	152	8	5.0
39	Jan. 15, 1979	47	352	323	29	8.2
40	Feb. 13, 1979	29	441	397	44	10.0
41	Mar. 28, 1979	43	486	446	40	8.2
42	May 8, 1979	41	683	641	42	6.1
43	June 14, 1979	37	341	300	41	12.0
44	July 30, 1979	46	201	193	8	4.0
45	Sep. 6, 1979	38	176	180	-4	-2.3
46	Oct. 1, 1979	25	988	974	14	1.4
47	Oct. 30, 1979	29	313	323	-10	-3.2
48	Dec. 10, 1979	41	348	341	7	2.0
49	Jan. 14, 1980	35	599	614	-15	-2.5
50	Feb. 25, 1980	42	753	747	6	.8
51	Apr. 10, 1980	45	869	907	-38	-4.4

Table 10.--Residual data for Little Tallapoosa River near Newell--Continued

Observation number	Date	Lag (days)	Measured discharge (ft^3/s)	Predicted discharge (ft^3/s)	Residual (ft^3/s)	Percent error
52	May 21, 1980	41	1,980	1,980	0	0
53	June 24, 1980	34	378	407	-29	-7.7
54	Aug. 18, 1980	55	142	133	9	6.3
55	Oct. 6, 1980	49	271	240	31	11.4
56	Nov. 13, 1980	38	166	165	1	.6
57	Dec. 18, 1980	35	210	201	9	4.3
58	Jan. 28, 1981	41	210	199	11	5.2
59	Mar. 16, 1981	47	393	354	39	9.9
60	Apr. 22, 1981	37	352	366	-14	-4.0
61	June 17, 1981	56	210	216	-6	-2.9
62	July 29, 1981	42	92.9	89.3	3.6	3.9
63	Sep. 14, 1981	47	91.6	90.9	.7	.8
64	Oct. 1, 1981	17	57.1	64.6	-7.5	-13.1
65	Nov. 18, 1981	48	103	105	-2	-1.9
66	Dec. 22, 1981	34	164	156	8	4.9
67	Feb. 4, 1982	44	8,680	8,570	110	1.3
68	Mar. 16, 1982	40	1,480	1,440	40	2.7
69	Apr. 27, 1982	42	3,960	3,880	80	2.0
70	June 22, 1982	56	249	258	-9	-3.6
71	July 21, 1982	29	481	478	3	.6
72	Sep. 9, 1982	50	113	111	2	1.8
73	Oct. 15, 1982	36	775	747	28	3.6
74	Nov. 30, 1982	46	926	924	2	.2
75	Jan. 26, 1983	57	709	673	36	5.1

Table 10.--Residual data for Little Tallapoosa River near Newell--Continued

Observation number	Date	Lag (days)	Measured discharge (ft^3/s)	Predicted discharge (ft^3/s)	Residual (ft^3/s)	Percent error
76	Mar. 15, 1983	48	669	665	4	.6
77	Apr. 25, 1983	41	1,160	1,140	20	1.7
78	June 22, 1983	58	444	475	-31	-7.0
79	Aug. 11, 1983	50	148	133	15	10.1

Table 11.--Residual data for Terrapin Creek at Ellisville

Observation number	Date	Lag (days)	Measured discharge (ft^3/s)	Predicted discharge (ft^3/s)	Residual (ft^3/s)	Percent error
66	Oct. 29, 1980	0	692	751	-59	-8.5
67	Dec. 5, 1980	37	186	170	16	8.6
68	Jan. 14, 1981	40	134	127	7	5.2
69	Mar. 3, 1981	48	295	282	13	4.4
70	May 13, 1981	71	184	164	20	10.9
71	July 9, 1981	57	210	206	4	1.9
72	Aug. 11, 1981	33	118	109	9	7.6
73	Sep. 28. 1981	48	93.0	74.9	18.1	19.5
74	Nov. 5, 1981	38	104	104	0	0
75	Dec. 16, 1981	41	192	195	-3	-1.6
76	Feb. 4, 1982	50	2,800	2,750	50	1.8
77	Mar. 9, 1982	33	824	771	53	6.4
78	Apr. 29, 1982	51	1,880	1,850	30	1.6
79	June 9, 1982	41	217	231	-14	-6.4
80	July 28, 1982	49	155	163	-8	-5.2
81	Sept. 3, 1982	37	136	137	-1	-.7
82	Oct. 5, 1982	32	89.9	91.3	-1.4	-1.6
83	Nov. 2, 1982	28	97.5	104	-6.5	-6.7
84	Dec. 1, 1982	29	3,700	3,730	-30	-.8
85	Jan. 6, 1983	36	564	584	-20	-3.6
86	Feb. 17, 1983	42	391	407	-16	-4.1
87	Apr. 29, 1983	71	436	459	-23	-5.2
88	Aug. 10, 1983	103	130	132	-2	-1.5
89	Oct. 6, 1983	57	102	96.1	5.9	5.8

Table 12.--Summary of the autocovariance analysis

Station number	Number of measurements analyzed	RHO (1-day autocorrelation coefficient)	Measurement variance [(log base 10)^2]	Process variance [(log base 10)^2]
02342500	53	0.987	0.00047	0.00925
02342933	52	.989	.00047	.02943
02343300	53	.996	.00047	.00812
02361000	60	.982	.00047	.00152
02364570	55	.977	.00047	.00653
02369800	55	.942	.00047	.00028
02371200	53	.996	.00047	.16960
02371500	53	.970	.00047	.00159
02372250	53	.965	.00047	.00217
02373000	58	.986	.00047	.00362
02374500	53	.974	.00047	.00120
02398195	44	.973	.00047	.02231
02399200	26	.928	.00047	.08548
02400100	24	.975	.00047	.00037
02401370	37	.992	.00047	.00236
02401390	44	.982	.00047	.00335
02401460	41	.982	.00047	.23990
02401470	19	.977	.00047	.08273
02408540	31	.974	.00047	.00015
02410000	62	.994	.00047	.12010
02412000	52	.989	.00047	.00386
02413300	52	.965	.00047	.00009
02414500	54	.969	.00047	.00043
02419000	44	.951	.00047	.00878
02421000	40	.893	.00047	.04349
02422500	45	.991	.00047	.01269
02423425	53	.986	.00047	.01916
02424000	46	.982	.00047	.00233
02424940	47	.972	.00047	.00344
02425000	42	.992	.00047	.00010
02425200	41	.974	.00047	.06200
02427700	39	.989	.00047	.00970
02442500	35	.993	.00047	.01300
02446500	49	.962	.00047	.00029
02448500	52	.969	.00047	.00561
02449245	52	.983	.00047	.06124
02450000	44	.956	.00047	.00195
02450180	57	.941	.00047	.00529

Table 12.--Summary of the autocovariance analysis--Continued

Station number	Number of measurements analyzed	RHO (1-day autocorrelation coefficient)	Measurement variance [(log base 10)^2]	Process variance [(log base 10)^2]
02450250	73	0.961	0.00047	0.00894
02455000	49	.936	.00047	.00468
02456330	46	.972	.00047	.03399
02456500	49	.977	.00047	.08624
02462000	54	.985	.00047	.00188
02462600	62	.986	.00047	.05529
02464000	62	.986	.00047	.00788
02464146	48	.977	.00047	.00165
02465493	52	.976	.00047	.00189
02467500	44	.987	.00030	.00011
02468500	42	.989	.00047	.11840
02469800	45	.969	.00047	.00537
02471001	42	.981	.00047	.00028
02471065	32	.964	.00047	.00182
02479431	47	.987	.00047	.09360
02479560	43	.959	.00047	.00065
03572110	54	.986	.00047	.00829
03574500	61	.962	.00047	.06732
03575000	33	.976	.00047	.00312
03575830	47	.979	.00047	.01754

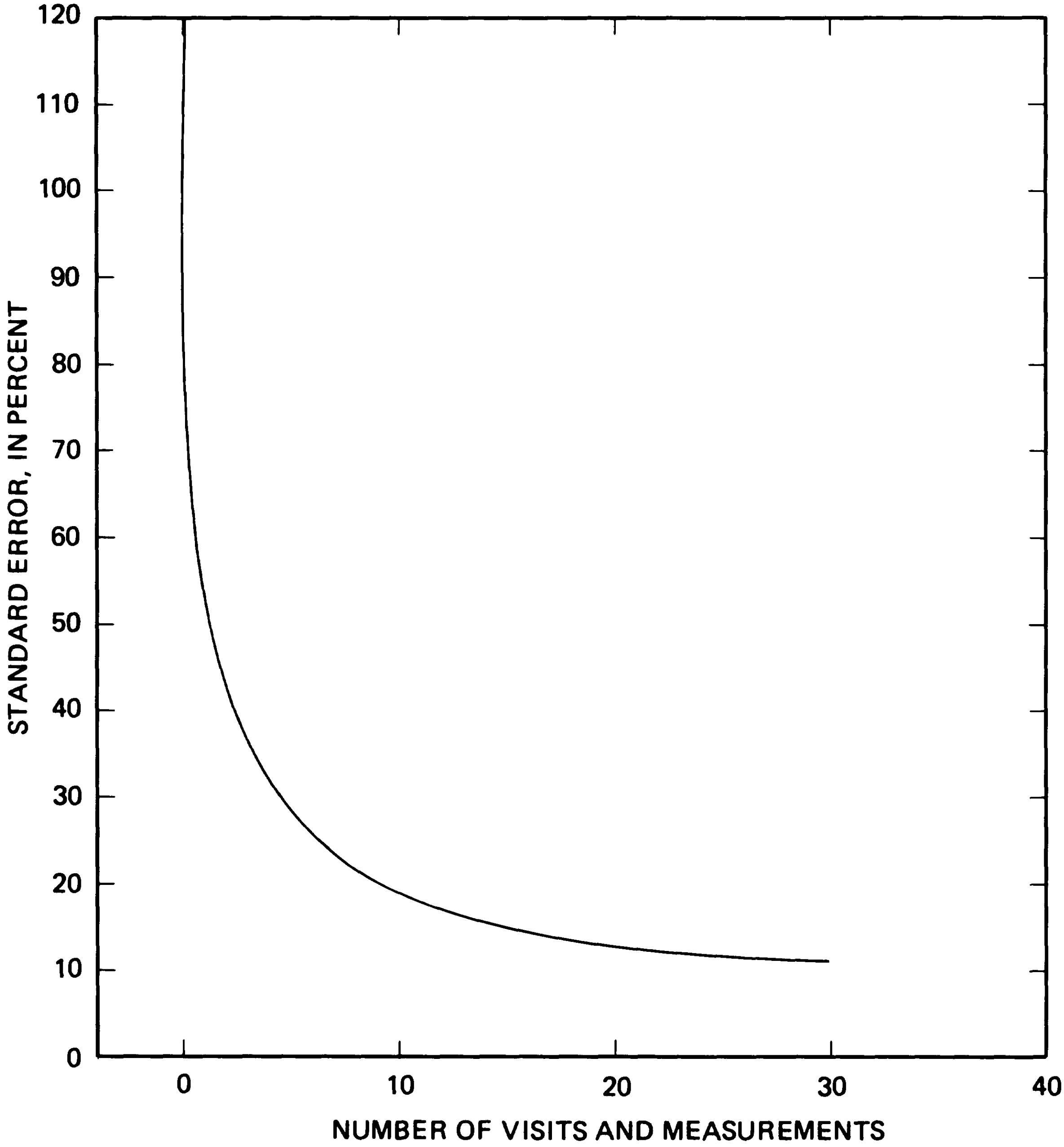

Figure 22. -- Uncertainty function for instantaneous discharge, Cahaba River at Centreville.

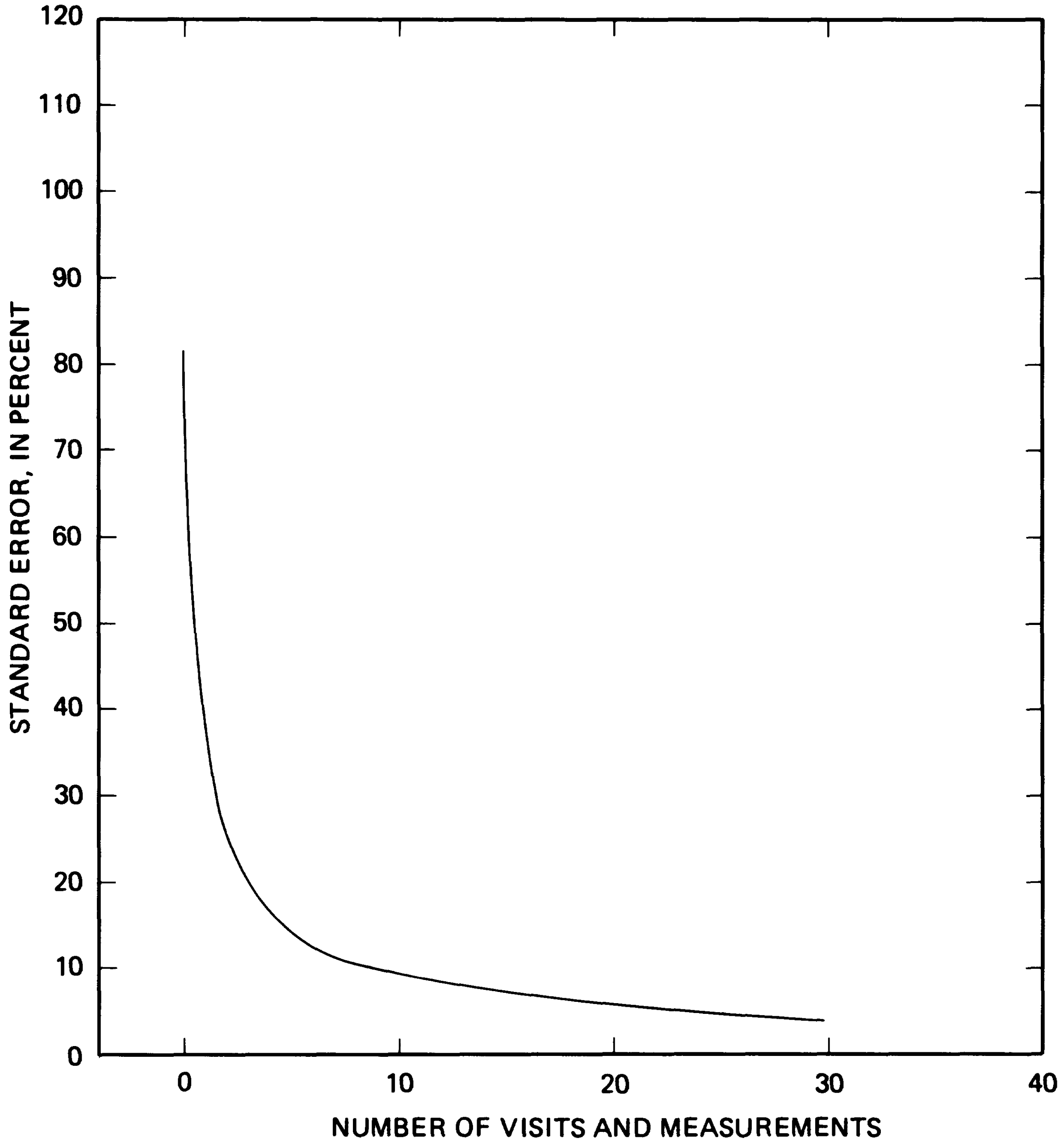

Figure 23. -- Uncertainty function for instantaneous discharge, Little Tallapoosa River near Newell.

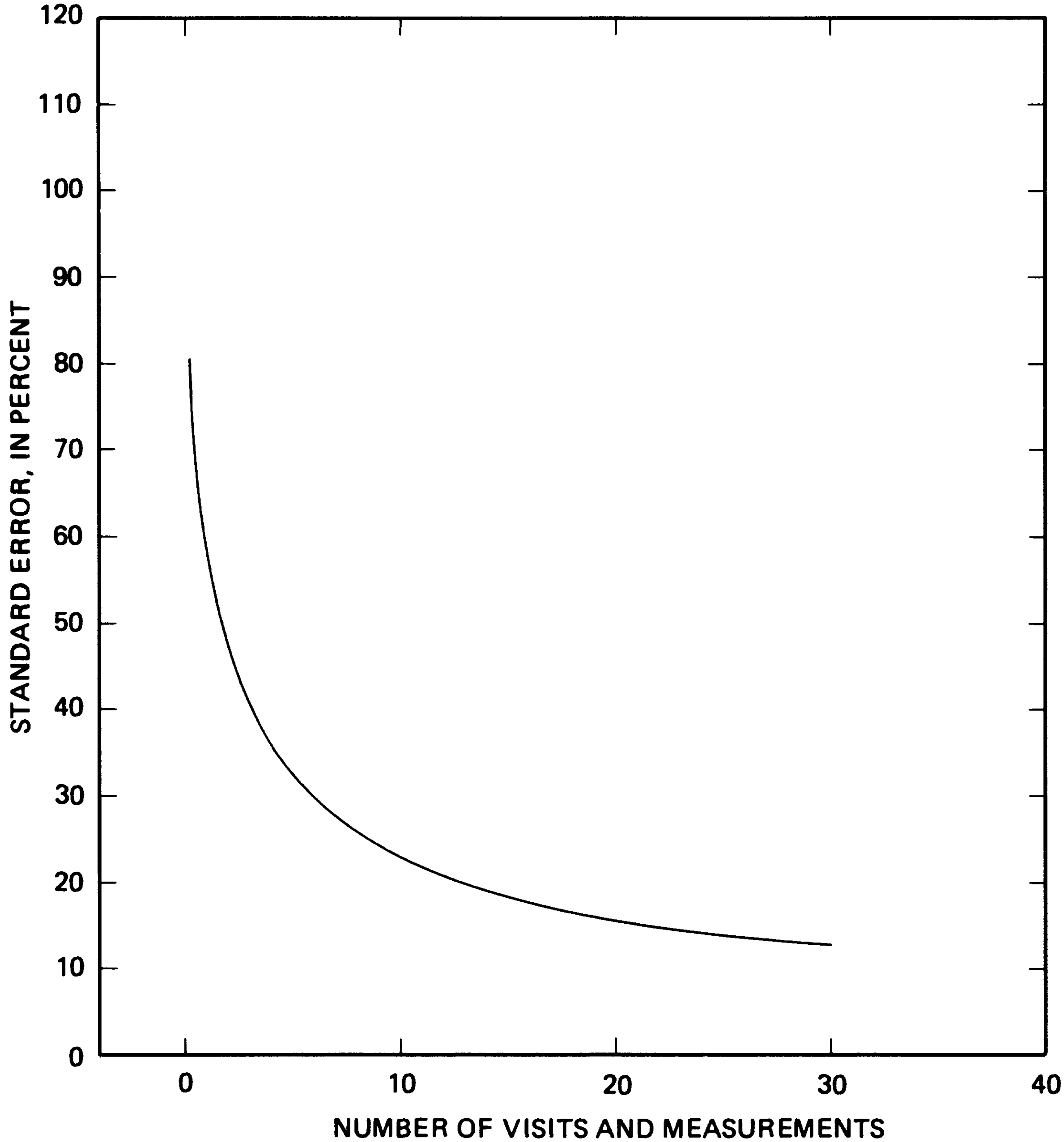

Figure 24. -- Uncertainty function for instantaneous discharge, Terrapin Creek at Ellisville.

Table 13.--Summary of the routes that may be used to visit stations in the Tuscaloosa office area of responsibility

Route number	Stations serviced on the route		
A 1	02424000	02465493	
A 2	02446500	02442500	
A 3	02448500	02449245	
A 4	02464146	02464000	02462600
A 5	02462000		

Table 14.--Summary of the routes that may be used to visit stations in the Montgomery Subdistrict office area of responsibility

Route number	Stations serviced on the route					
SEA 1	02371200	02371500	02372250	02373000	02374500	
	02369800	02364570	02361000	02343300		
BNE 1	02342933	02342500	02419000	02414500	02413300	
	02412000	-1	02408540	02410000	-2	-3
	02421000					
CSW 1	02422500	02424940	-4	02425000	02468500	
	-5	02467500	-6			
CSW 2	02471001	02479431	-7	02479560	02471065	
	-8	02425200	-9	-10	-11	02469800
	-12	02427700				
DAM 1	-8	02425200	-9			
AB	02371200					
AC	02371500					
AD	02372250					
AE	02373000					
AF	02374500					
AG	02369800					
AH	02364570					
AI	02361000					
AJ	02343300					
AM 1	02371200	02371500	02372250			
AM 2	02373000	02374500				
AM 3	02364570	02361000				
AM 4	02371200	02371500				
AM 5	02372250	02373000				
AM 6	02374500	02369800				

Table 14.--Summary of the routes that may be used to visit stations in the Montgomery Subdistrict office area of responsibility --Continued

Route number	Stations serviced on the route		
AM 7	02373000	02371200	
BB	02342933		
BC	02342500		
BD	02419000		
BE	02414500		
BF	02413300		
BG	02412000		
BH	02408540		
BI	02410000		
BJ	02421000		
BM 1	02342933	02342500	
BM 2	02419000	02414500	
BM 3	02413300	02412000	
BM 4	02408540	02410000	02421000
BM 5	02342933	02342500	02419000
BM 6	02414500	02413300	02412000
CB	02422500		
CC	02424940		
CD	02425000		
CE	02468500		
CF	02467500		
CG	02471001		
CH	02479431		

Table 14.--Summary of the routes that may be used to visit stations in the Montgomery Subdistrict office area of responsibility --Continued

Route number	Stations serviced on the route		
CI	02479560		
CJ	02471065		
CM 1	02422500	02424940	02425000
CM 2	02422500	02424940	
CM 3	02425000	02468500	
DB	02425200		
DC	02469800		
DD	02427700		
DM 1	02469800	02427700	02425200
DM 2	02425200	02427700	

Table 15.--Summary of the routes that may be used to visit stations in the Cullman field office area of responsibility

Route number	Stations serviced on the route
WA 1	03575000 03575830 -1 -2 -3 -4 02450250 -5 -6 -7 -8 -9 -10 -11
WA 2	02423425 -12 02456500
WA 3	02455000 02450180 02456330
WA 4	02450000
EA 1	02401370 02401390 02401460
EA 2	02401470 -13 -14 -15
EA 3	-16 -17 02400100 -18 02399200 02398195 03572110 03574500
WB	02450250
WC	03575000
WD	03575830
WE	02423425
WF	02456500
WH	02455000
WI	02450180
WJ	02456330
EB	02401370
EC	02401390
ED	02401460
EE	02401470
EF	02400100
EG	02399200
EH	02398195

Table 15.--Summary of the routes that may be used to visit stations in the Cullman field office area of responsibility--Continued

Route number	Stations serviced on the route			
EI	03572110			
EJ	03574500			
WM 1	03575000	03575830		
WM 2	02423425	02456500	02450000	
WM 3	02450250	03575830	03575000	
WM 4	02456330	02456500	02423425	
WM 5	02450180	02450000	02455000	
EM 1	-16	-17	02400100	-18
EM 2	02399200	02398195	03572110	
EM 3	02401470	02401390	02401460	
EM 4	02400100	02399200	02398195	
EM 5	03574500	03572110	02401470	
EM 6	02401370	02401390	02401460	
	02401470	03572110	03574500	
EM 7	02401470	02400100	03574500	
CM 1	02450250	03575830	03575000	
	03574500	03572110	02398195	
	02399200	02400100	02401470	
	02401390	02401460	02401370	
	02423425	02456500	02456330	
CM 2	03574500	03572110	02398195	
CM 3	02399200	02400100	02401470	

The costs associated with the practical routes were determined. Fixed costs to operate a gaging station typically include vehicle and equipment rental, batteries, electricity, data processing, maintenance, miscellaneous supplies, and analysis and supervising charges. For Alabama, average values were applied to each station in the program for all the above categories.

Visit costs are those associated with time actually spent making a discharge measurement. These costs vary from station to station and are a function of the difficulty and time required to make the discharge measurement. Average visit times were calculated for each station based on an analysis of discharge measurement data available. This time was then multiplied by the average hourly salary of hydrographers in the Alabama offices to determine total visit costs.

Route costs include the vehicle costs associated with driving the number of miles it takes to cover the route, the cost of the hydrographer's time while in transit, and servicing the recording equipment, and any per diem associated with the time it takes to complete the trip.

K-CERA Results

The "Traveling Hydrographer Program" utilizes the uncertainty functions along with the appropriate cost data and route definitions to compute the most cost-effective way of operating the stream-gaging program. The first step in this analysis is to determine a total uncertainty for the current operation and budget. To accomplish this, the number of visits made to each gaging station and the specific routes used to make these visits were fixed. In Alabama, current practice indicates that discharge measurements are made each time the station is visited.

The resulting average error of estimation for the current practice in the Tuscaloosa office is plotted as a point in figure 25 and is 22.3 percent. Similarly, errors of 25.1 and 40.2 for the Montgomery and Cullman offices are shown in figures 26 and 27, respectively. The solid lines on figures 25 through 27 represent the minimum average standard errors that can be obtained for given budgets at the Tuscaloosa, Montgomery, and Cullman offices, respectively, with the existing instrumentation and technology. The lines were defined by several runs of the Traveling Hydrographer Program with different budgets as presented in tables 16-18. Constraints on the operations other than budget were defined as described below.

The primary constraint in the program is the minimum number of visits to maintain the equipment in working order, which is related to the complexity and reliability of the equipment used to record data. In Alabama, the minimum visit frequency allowed is six visits per year. This value is based on the limitations of the batteries used to drive the recording equipment and the capabilities of the uptake spools on the digital recorders.

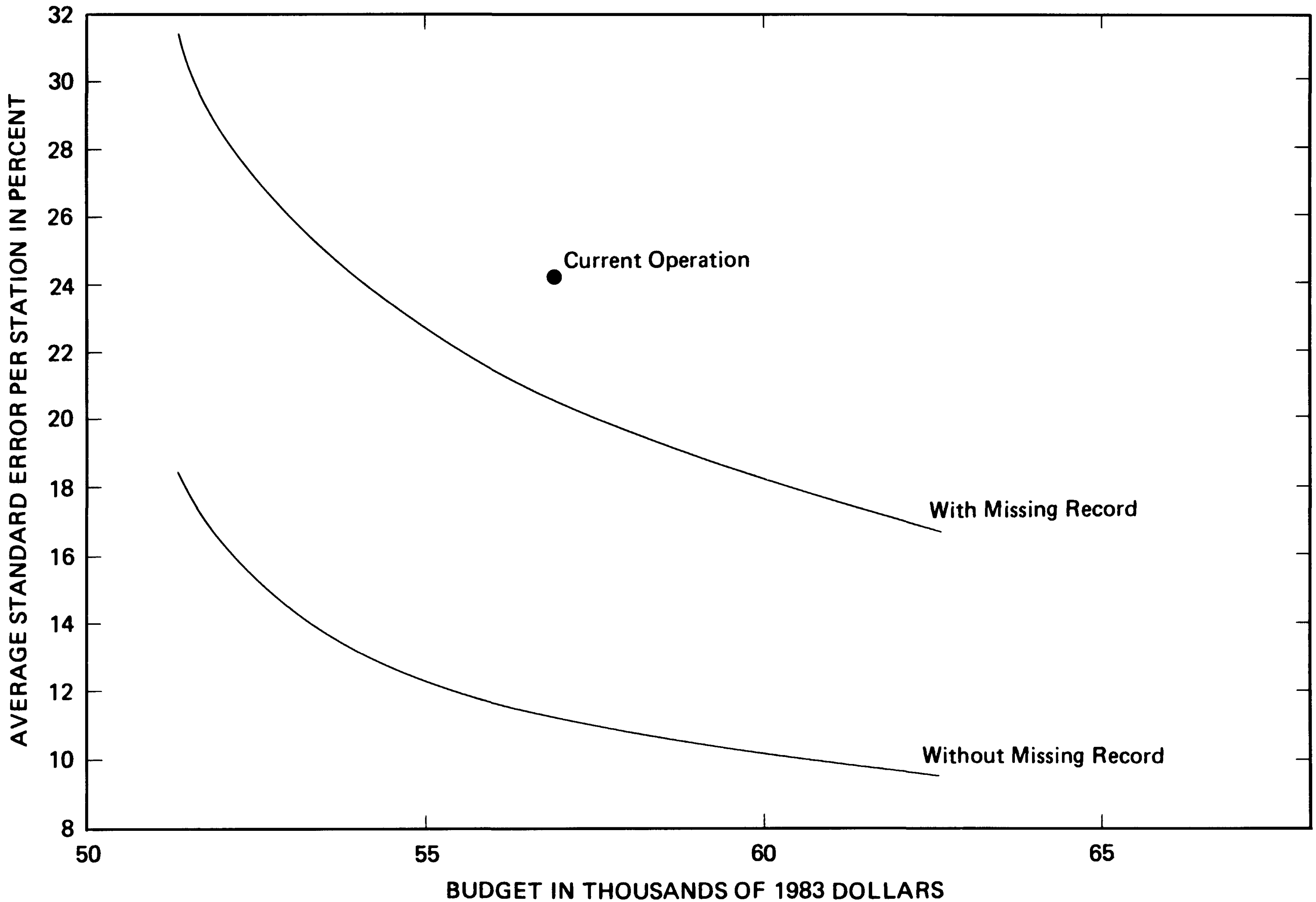

Figure 25. -- Temporal average standard error in the Tuscalōosa office.

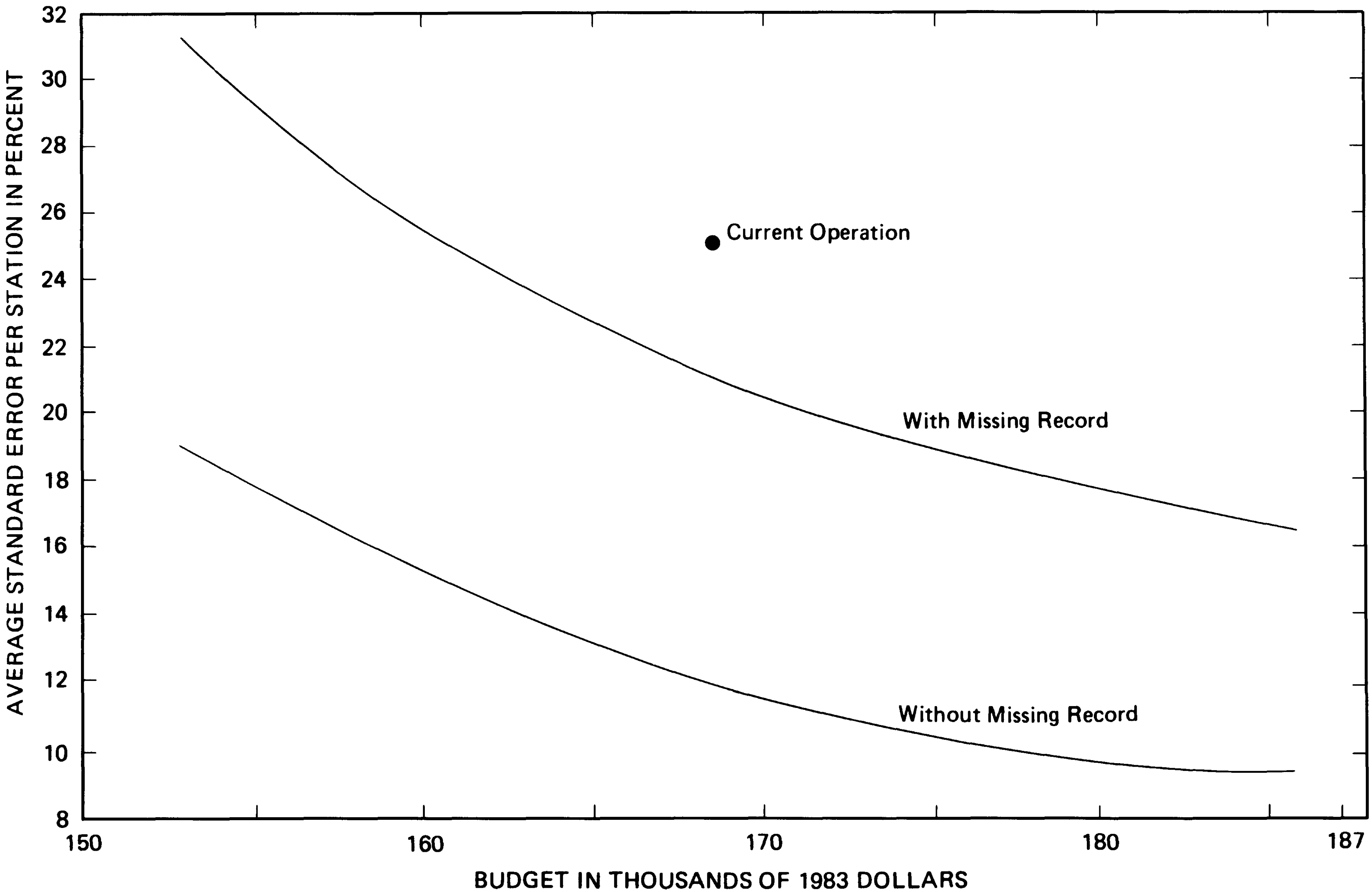

Figure 26. -- Temporal average standard error in the Montgomery office.

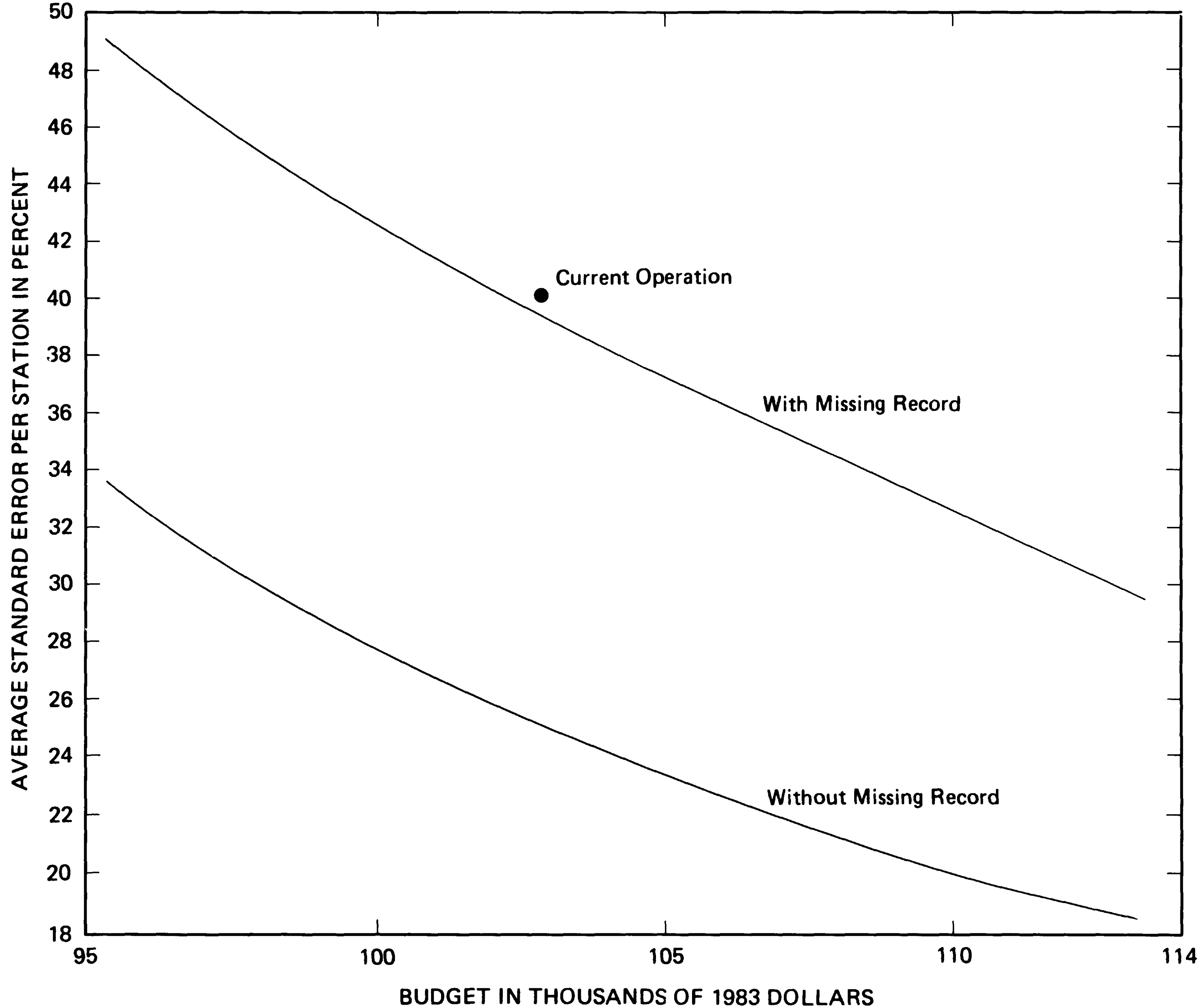

Figure 27. -- Temporal average standard error in the Cullman office.

Table 16.--Selected results of K-CERA analysis for Tuscaloosa Office

Standard error of instantaneous discharge, in percent
[Equivalent Gaussian spread (EGS)] (Number of visits per year to site)

Identification	Budget in thousands of 1983 dollars			
	Current 56.8	Minimum 51.3	Optimum 56.8	Maximum 62.5
Average SE per station	22.2	29.5	19.0	15.2
EGS for program	8.3	11.3	7.7	6.0
02424000	18.1 [5.2] (11)	24.1 [7.1] (6)	18.1 [5.2] (11)	15.0 [4.4] (16)
02442500	16.2 [8.2] (11)	21.7 [11.5] (6)	17.9 [9.2] (9)	14.0 [7.0] (15)
02446500	15.9 [2.7] (11)	21.2 [3.4] (6)	15.2 [2.6] (12)	12.2 [2.2] (19)
02448500	27.2 [11.0] (11)	36.0 [14.2] (6)	24.3 [9.9] (14)	19.1 [7.8] (23)
02449245	34.4 [27.7] (11)	45.4 [37.7] (6)	24.0 [18.8] (23)	19.2 [14.8] (36)
02462000	14.5 [4.8] (11)	19.3 [6.5] (6)	16.9 [5.6] (8)	13.4 [4.4] (13)
02462600	31.6 [23.4] (11)	41.9 [32.3] (6)	24.2 [17.5] (19)	19.9 [14.2] (28)
02464000	23.6 [9.0] (11)	31.4 [12.4] (6)	19.0 [7.2] (17)	14.9 [5.6] (28)
02464146	16.6 [5.3] (11)	22.0 [7.0] (6)	13.4 [4.4] (17)	10.5 [3.4] (28)
02465493	11.0 [5.8] (11)	14.5 [7.5] (6)	12.8 [6.6] (8)	10.2 [5.3] (13)

Table 17.--Selected results of K-CERA analysis for Montgomery Subdistrict Office

Standard error of instantaneous discharge, in percent
[Equivalent Gaussian spread (EGS)] (Number of visits per year to site)

Identification	Budget in thousands of 1983 dollars Current 168.7	Minimum 152.8	Optimum 168.7	Maximum 185.6
Average SE per station	25.1	31.3	21.2	16.9
EGS for program	8.4	11.0	8.1	6.5
02342500	17.5 [9.9] (10)	22.2 [12.9] (6)	14.9 [8.4] (14)	12.0 [6.7] (22)
02342933	28.8 [16.1] (10)	36.8 [21.3] (6)	24.5 [13.4] (14)	19.6 [10.62] (22)
02343300	10.8 [5.5] (10)	13.7 [7.2] (6)	13.7 [7.2] (6)	13.7 [7.2] (6)
02361000	11.6 [4.8] (10)	14.8 [6.0] (6)	14.8 [6.0] (6)	11.6 [4.8] (10)
02364570	15.5 [3.6] (10)	19.8 [4.4] (6)	19.8 [4.4] (6)	15.5 [3.6] (10)
02369800	13.5 [3.1] (10)	17.1 [3.6] (6)	17.1 [3.6] (6)	15.0 [3.3] (8)
02371200	29.8 [23.7] 10	38.2 [31.7] (6)	23.6 [18.4] (16)	18.9 [14.6] (25)
02371500	15.7 [6.0] (10)	20.0 [7.4] (6)	16.5 [6.3] (9)	12.2 [4.8] (17)
02372250	14.1 [7.4] (10)	17.6 [9.0] (6)	14.8 [7.8] (9)	11.0 [5.9] (17)
02373000	19.1 [5.9] (10)	24.4 [7.7] (6)	21.3 [6.6] (8)	17.5 [5.4] (12)

Table 17.--Selected results of K-CERA analysis for Montgomery Subdistrict Office --Continued

Standard error of instantaneous discharge, in percent
[Equivalent Gaussian spread (EGS)] (Number of visits per year to site)

Identification	Budget in thousands of 1983 dollars Current 168.7	Minimum 152.8	Optimum 168.7	Maximum 185.6
02374500	12.3 [5.0] 10	15.6 [6.1] (6)	14.5 [5.8] (7)	10.7 [4.8] (14)
02408540	17.8 [1.8] (10)	22.8 [2.2] (6)	16.3 [1.7] (12)	12.4 [1.5] (21)
02410000	43.4 23.8 (10)	55.6 [32.0] (6)	27.1 [14.2] (26)	21.4 [11.2] (42)
02412000	11.5 [6.0] (10)	14.6 [7.8] (6)	11.5 [6.0] (10)	11.4 [6.6] (11)
02413300	10.3 [1.5] (10)	13.1 [1.8] (6)	10.3 [1.5] (10)	9.8 [1.6] (11)
02414500	9.0 [3.2] (10)	11.4 [3.9] (6)	9.0 [3.2] (10)	8.7 [3.4] (11)
02419000	29.5 [16.6] (10)	36.6 [19.6] (6)	24.7 [14.2] (15)	19.1 [11.2] (26)
02421000	57.3 [45.7] (10)	66.3 [50.0] (6)	31.4 [26.6] (50)	24.8 [21.0] (81)
02422500	16.6 [9.9] (10)	21.1 [13.0] (6)	16.6 [9.9] (10)	13.9 [8.9] (16)
02424940	14.7 [8.5] (10)	18.3 [10.5] (6)	14.7 [8.5] (10)	12.3 [7.8] (16)

Table 17.--Selected results of K-CERA analysis for Montgomery Subdistrict Office--Continued

Standard error of instantaneous discharge, in percent
[Equivalent Gaussian spread (EGS)] (Number of visits per year to site)

Identification	Budget in thousands of 1983 dollars			
	Current 168.7	Minimum 152.8	Optimum 168.7	Maximum 185.6
02425000	18.9 [.9] (10)	24.2 [1.2] (6)	16.6 [.8] (13)	12.9 [.6] (22)
02425200	34.8 [34.5] (10)	42.4 [42.3] (6)	29.0 [28.5] (15)	22.1 [21.6] (26)
02427700	28.9 [9.2] (10)	36.9 [12.2] (6)	24.56 [7.7] (14)	18.9 [5.9] (24)
02467500	22.1 [1.2] (10)	28.2 [1.5] (6)	22.1 [1.2] (10)	18.1 [1.0] (15)
02468500	44.6 [32.6] (10)	57.1 [43.4] (6)	35.3 [25.1] (16)	27.7 [19.3] (26)
02469800	25.0 [11.1] (10)	31.5 [13.7] (6)	23.9 [10.7] (11)	18.4 [8.3] (19)
02471001	17.0 [2.1] (10)	21.7 [2.7] (6)	17.0 [2.1] (10)	12.7 [1.6] (18)
02471065	19.8 [6.9] (10)	25.0 [8.3] (6)	19.8 [6.9] (10)	14.9 [5.4] (18)
02479431	36.0 [30.6] (10)	45.9 [40.1] (6)	36.0 [30.6] (10)	26.8 [22.2] (18)
02479560	21.9 [4.4] (10)	28.0 [5.2] (6)	21.9 [4.4] (10)	16.5 [3.5] (18)

Table 18.--Selected results of K-CERA analysis for Cullman Field Office

Standard error of instantaneous discharge, in percent
[Equivalent Gaussian spread (EGS)] (Number of visits per year to site)

Identification	Budget in thousands of 1983 dollars Current 102.8	Minimum 95.3	Optimum 102.8	Maximum 113.1
Average SE per station	40.2	49.2	39.4	29.8
EGS for program	21.0	28.5	21.1	14.9
02398195	28.3 [22.5] (10)	34.5 [28.5] (6)	32.7 [26.7] (7)	24.5 [19.0] (14)
02399200	63.4 [61.6] (10)	70.9 [69.3] (6)	66.9 [65.2] (8)	48.6 [46.4] (22)
02400100	22.2 [3.1] (10)	27.9 [4.1] (6)	22.2 [3.1] (10)	17.8 [2.4] (16)
02401370	17.9 [4.5] (10)	22.6 [6.4] (6)	22.6 [6.4] (6)	17.9 [4.5] (10)
02401390	35.0 [7.9] (10)	44.0 [10.9] (6)	33.5 [7.5] (11)	25.3 [5.3] (20)
02401460	63.5 [62.2] (10)	80.0 [79.8] (6)	50.3 [48.1] (16)	38.6 [35.9] (27)
02401470	43.6 [39.9] (10)	53.4 [50.2] (6)	35.2 [31.1] (16)	27.4 [23.4] (27)
02423425	35.6 [15.9] (10)	44.7 [21.9] (6)	34.1 [15.0] (11)	26.4 [10.9] (19)
02450000	32.8 [8.4] (10)	41.0 [10.8] (6)	32.8 [8.4] (10)	25.6 [6.6] (17)
02450180	29.3 [14.9] (10)	36.0 [18.1] (6)	32.1 [16.2] (8)	23.9 [12.3] (16)

Table 18.--Selected results of K-CERA analysis for Cullman Field Office --Continued

Standard error of instantaneous discharge, in percent
[Equivalent Gaussian spread (EGS)] (Number of visits per year to site)

	Budget in thousands of 1983 dollars			
Identification	Current 102.8	Minimum 95.3	Optimum 102.8	Maximum 113.1
02450250	42.4	52.8	42.4	32.4
	[17.1]	[22.0]	[17.1]	[12.7]
	(10)	(6)	(10)	18)
02455000	32.0	39.4	33.4	26.0
	[14.4]	[17.5]	[15.0]	[12.0]
	(10)	(6)	(9)	16
02456330	41.3	50.8	43.2	30.9
	[28.8]	[37.0]	[30.4]	[20.4]
	(10)	(6)	(9)	(19)
02456500	44.7	54.8	42.9	33.3
	[40.8]	[51.7]	[38.8]	[29.0]
	(10)	(6)	(11)	(19)
03572110	31.8	39.9	35.2	26.3
	[10.9]	[15.1]	[12.5]	[8.6]
	(10)	(6)	(8)	(15)
03574500	57.6	69.6	55.4	40.7
	[45.9]	[57.0]	[43.9]	[30.8]
	(10)	(6)	(11)	(22)
03575000	32.6	41.0	32.6	26.2
	[8.5]	[11.5]	[8.5]	[6.6]
	(10)	(6)	(10)	(16)
03575830	34.0	42.4	34.0	27.4
	[18.4]	[24.7]	[18.4]	[14.2]
	(10)	(6)	(10)	(16)

The results in figures 25 through 27 and tables 16 through 18 summarize the K-CERA analysis and are predicated on a discharge measurement made each time a station is visited. These statistical errors reflect a time-series of shifts to stage-discharge relations and include methods of record reconstruction. Where a choice of assumptions was available, the assumption that would not underestimate the magnitude of the error variances was chosen.

For the Tuscaloosa office, current policy results in an average standard error of estimate for instantaneous discharge of 22.2 percent. This policy requires a budget of $56,840 to operate the 10-station stream-gaging program. The range in standard errors for individual stations is from a low of 11.0 percent for station 02465493 to a high of 34.4 at station 02449245. The top curve in figure 25 shows that it is possible to obtain the same average standard error with a reduced budget of $53,900. It also would be possible to reduce the average standard error by a policy change in route selection while maintaining the $56,840 budget. In this case, the average standard error would decrease from 22.2 to 18.6 percent.

A minimum budget of $51,260 (table 16) is required to operate the network at a six-visits-per-year level. This frequency of visits increases the potential for lost record and results in an average standard error of 29.5 percent. The maximum budget analyzed was $62,500, which resulted in an average standard error of estimate of 15.2 percent. The approximately 10 percent increase over current budget, in conjunction with some policy changes in route selection would reduce the average standard error of estimate by a third from the current budget and policy. The analysis also was performed under the assumption that current instrumentation at each gaging station and for those stations providing correlative data operated perfectly.

The curve labeled "without missing record" on figure 25, shows the average standard errors that could be obtained if perfectly reliable systems were available to measure and record the correlative data. The effects of less than perfect equipment are greatest for the minimal budget of $51,260; average standard errors at this budget increased from 16.5 to 29.5 percent. An intermediate analysis at current budget was made assigning an improved cross correlation value of 0.95. The results of increasing the reliability of the correlative data for the current operation reduced the average standard error to 15.2 percent. As indicated, larger streamflow budgets and improved equipment can have very significant positive impacts on the quality of streamflow records.

For the Montgomery office, current policy results in an average standard error of estimate of instantaneous discharge of 25.1 percent. This policy requires a budget of $168,700 to operate the 30-station stream-gaging program. The range in standard errors is from a low of 9.0 percent for station 02414500 to a high of 57.3 at station 02421000. It is possible to obtain the same average standard error with a reduced budget of $160,600 (fig. 26). It also would be possible to reduce the average standard error to 21.2 percent by a policy change while maintaining the $168,700 budget. A minimum budget of $152,800 is required to operate the network at a six-visits-per-year level. This frequency of visits increases the potential for lost record resulting in an average standard error of 31.3 percent.

The maximum budget analyzed was $185,600, which resulted in an average standard error of estimate of 16.9 percent. The approximately 10 percent increase over current budget, in conjunction with some policy changes, would reduce the average standard error of estimate by a third from the current budget and policy. The analysis also was performed under the assumption that current instrumentation at each gaging station, and for those stations providing correlative data, operated perfectly. The curve labeled "without missing record" on figure 26, shows the average standard errors that could be obtained if perfectly reliable systems were available to measure and record the correlative data. The effects of less than perfect equipment are greatest for the minimal budget of $152,800; average standard errors increase from 18.8 to 31.3 percent. An intermediate analysis at current budget was made assigning an improved cross correlation value of 0.95. The results of increasing the reliability of the correlative data for the current operation reduced the average standard error to 17.8 percent. As indicated, larger streamflow budgets and improved equipment can have very significant positive impacts on the quality of streamflow records.

For the Cullman office, current policy results in an average standard error of estimate of discharge of 40.2 percent. This policy requires a budget of $102,800 to operate the 18-station stream-gaging program. The range in standard errors is from a low of 17.9 percent for station 02401370 to a high of 63.5 at station 02401460. It is possible to obtain the same average standard error with a reduced budget of $102,100. It also would be possible to reduce the average standard error by a policy change while maintaining the $102,800 budget. In this case, the average standard error would only decrease from 40.2 to 39.4 percent. A minimum budget of $95,300 is required to operate the network at a six-visits-per-year level. This frequency of visits increases the potential for lost record resulting in an average standard error of 49.2 percent.

The maximum budget analyzed was $113,100, which resulted in an average standard error of estimate of 29.8 percent. The approximately 10 percent increase above current budget, in conjunction with some policy changes, would reduce the average standard error of estimate by 25 percent. The analysis also was performed under the assumption that current instrumentation at each gaging station and for those stations providing correlative data operated perfectly. The curve labeled "without missing record" on figure 27, shows the average standard errors that could be obtained if perfectly reliable systems were available to measure and record the correlative data. The effects of less than perfect equipment are greatest for the minimal budget of $95,300; average standard errors increase from 33.7 to 49.2 percent. An intermediate analysis was made assigning an improved cross correlation value of 0.95. The results of increasing the reliability of the correlative data for the current operation reduced the average standard error to 31.6 percent. As indicated, larger streamflow budgets and improved equipment can have very significant positive impacts on the quality of streamflow records.

Conclusions from the K-CERA Analysis

As a result of the K-CERA analysis, the following conclusions are offered.

1. Although separate analyses were made for each office, the average standard error for the total network is 29.3 percent for the current operating practice.

2. A primary goal should be to reduce the amount of lost record in the Cullman office. Using an average lost record of 4.0 percent, same as the other two offices in Alabama, the average standard error could be lowered from 40.2 percent to 28.8 percent for the current operating practice.

3. Optimization of frequency of visits in the Cullman office produced marginal results using the current budget of $102,800. However, by implementing policy changes regarding frequency of visits in the Tuscaloosa and Montgomery offices, average standard errors would remain the same with a combined budget of $217,700. This shift would result in some increases and some decreases in accuracy of records at individual stations.

4. Any funding made available from item 3 should be used to reduce the probabilities of missing record. For example, increased use of local gage observers and satellite relay of data should be explored and evaluated as to their cost-effectiveness in providing streamflow information.

5. The K-CERA analysis should be repeated when new stations are added to the network and included whenever sufficient information about the characteristics of the new station has been obtained.

SUMMARY

Currently, 72 continuous gaging stations are operated in Alabama at a cost of $393,600. Of these, 58 gaging stations were used in all the phases of this analysis at a funding level of $328,380. Seven separate sources of funding contribute to this program and four separate uses were identified for data from a single station. Conclusions from the uses and funding phase of the study are that all stations should be continued in operation and that a follow-up study is needed to provide a quantitative evaluation of the existing data network's ability to obtain optimum regional flow information for Alabama. Flow routing and regression models used at five gaging stations indicated that no daily discharge can be estimated with suitable accuracy to warrant consideration for discontinuing the station. However, use of the routing and regression techniques will improve the accuracy of the estimation of lost stage record.

The current operating budget for the 58 gaging stations is $328,380. For the current policy of operation, the average standard error of estimation of instantaneous discharge is 29.3 percent. By altering field activities and using the current budget, it would be possible to reduce the average standard error from 29.3 to 26.4 percent. It was shown that the overall level of accuracy of the records at the 58 station network could be maintained with approximately a $319,800 budget. The majority of the savings would be obtained from optimization of routes by the Tuscaloosa and Montgomery offices.

A major component of the error in streamflow records is caused by loss of primary record (stage or other correlative data) at the gaging stations because of malfunctions of sensing and recording equipment. The higher than normal lost record percentage for stations operated by the Cullman office was a major contribution to the high standard error for the gaging stations operation in that office. If upgrading of equipment and developing of strategies were made so that the percentage lost record in the Cullman office was the same as in the other two offices, the standard error would decrease from 40.2 to 27.7 percent. Efforts throughout the State should be made to reduce lost record as well as improve the transferability of the information from one station to another. Improvements in this category, to a point where the cross correlation would equal 0.95, would reduce the average standard error in the Montgomery office from 25.1 to 17.8 percent for the current budget.

Studies of the cost-effectiveness of the Alabama stream-gaging program should be continued and should include investigation of the optimum ratio of discharge measurements to total site visits for each station, as well as investigation of cost-effective ways to reduce the loss of correlative data.

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