COST EFFECTIVENESS OF THE STREAM-GAGING PROGRAM IN SOUTH CAROLINA

By A. Carroll Barker, Benjamin C. Wright, and Curtis S. Bennett III

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 85-4210

Columbia, South Carolina

1985

UNITED STATES DEPARTMENT OF THE INTERIOR

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GEOLOGICAL SURVEY

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CONVERSION FACTORS AND ABBREVIATIONS OF UNITS

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

Multiply inch-pound units	By	To obtain SI units
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
cubic foot (ft^3)	0.02832	cubic meter (m^3)
	Flow	
foot per second (ft/s)	0.3048	meter per second (m/s)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)

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ABSTRACT

This report documents the cost effectiveness of the stream-gaging program in South Carolina for the 1983 water year. Data uses and funding sources were identified for the 76 continuous stream gages currently being operated in South Carolina. The budget of $422,200 for collecting and analyzing streamflow data also includes the cost of operating stage-only and crest-stage stations. The streamflow records for one stream gage can be determined by alternate, less costly methods, and should be discontinued. The remaining 75 stations should be maintained in the program for the foreseeable future.

The current policy for the operation of the 75 stations including the crest-stage and stage-only stations would require a budget of $417,200 per year. The average standard error of estimation of streamflow records is 16.9 percent for the present budget with missing record included. However, the standard error of estimation would decrease to 8.5 percent if complete streamflow records could be obtained. It was shown that the average standard error of estimation of 16.9 percent could be obtained at the 75 sites with a budget of approximately $395,000 if the gaging resources were redistributed among the gages.

A minimum budget of $383,500 is required to operate the program; a budget less than this does not permit proper service and maintenance of the gages and recorders. At the minimum budget, the average standard error is 18.6 percent. The maximum budget analyzed was $850,000, which resulted in an average standard error of 7.6 percent.

INTRODUCTION

The U.S. Geological Survey is the principal Federal agency collecting streamflow data in the nation. The collection of these data is a major activity of the Water Resources Division of the U.S. Geological Survey. The data are collected in cooperation with State and local governments and other Federal agencies. The U.S. Geological Survey is presently (1985) operating approximately 8,000 continuous-record gaging stations throughout the nation. Some of these records extend back to the turn of the century. Any activity of long standing, such as the collection of streamflow data, should be reexamined at intervals, if not continuously, because of changes in objectives, technology, or external constraints. The most recent systematic nationwide evaluation of the stream-gaging program was completed in 1970 (Benson and Carter, 1973). The U.S. Geological Survey is presently undertaking another nationwide analysis of the stream-gaging program that will be completed over a 5-year period with 20 percent of the program being analyzed each year.

The objective of this analysis is to define and document the most cost-effective means of furnishing streamflow information for South Carolina. For every continuous-record gaging station, the analysis identifies the principal uses of the data and relates these uses to funding sources. Stations 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 aspect of the analysis is to identify less costly alternate methods of furnishing the needed information; among these are flow-routing models and statistical methods. The stream-gaging program no longer is considered a network of observation points, but rather an integrated information system in which data are provided by both observation and synthesis.

The final part 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 stream gages 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 computation of streamflow. The stream-gaging program that results from this analysis will meet the expressed water-data needs in the most cost-effective manner.

This report is organized into five sections; the first section is an introduction to the stream-gaging activities in South Carolina and to the study itself. The middle three sections each contain discussions of an individual step of the analysis. Because of the sequential nature of the steps and the dependence of subsequent steps on the previous results, summaries of conclusions are given at the end of each of the middle three sections. The complete study is summarized in the final section.

History of the Stream-Gaging Program in South Carolina

The program of streamflow investigations by the U.S. Geological Survey in South Carolina has grown rather steadily through the years as Federal and State interest in water resources has increased (fig. 1). Streamflow records have been obtained in South Carolina by the U.S. Geological Survey since 1883, when a gaging station providing a daily discharge record was established on the Savannah River near Augusta, Georgia. River stages had been collected and published by the U.S. Weather Bureau as early as 1875 at the same site. In 1900, discharge records were collected at two stations in the State, and the program remained at this level until 1906. Between 1906 and 1930 the number of stations fluctuated from 0 in 1910 to 14 in 1930. Collection of these streamflow records was the responsibility of the U.S. Geological Survey's office in Asheville, North Carolina.

On November 1, 1930, the South Carolina District WRD of the U.S. Geological Survey Cooperative programs were begun with the South Carolina State Highway Department (now the South Carolina Department of Highways and Public Transportation), several Federal Power Commission licensees, and the U.S. Army Corps of Engineers. Three new gaging stations were constructed in 1934 through a cooperative agreement with the Soil Erosion Service (now the Soil Conservation Service) of the U.S. Department of Agriculture. Six additional gaging stations were established in 1938 at the request of the U.S. Army Corps of Engineers. By 1951, the South Carolina District operated 55 gaging stations and in 1969 there were 64 stations.

The formation of the South Carolina Research, Planning and Development Board in 1946 (now the South Carolina State Development Board) established a low-flow partial record program. The network provided low-flow data at sites that were not gaged regularly, but were considered as potential industrial locations.

The data collection program was further expanded in 1966 to investigate flood frequencies on small streams for the South Carolina Department of Highways and Public Transportation. The network consisted of 56 partial-record stations that were equipped with dual digital stage-rainfall recorders.

Carter and Benson (1970) proposed an approach for evaluating stream-gaging programs. A study by Armbruster (1970) described the development of the South Carolina stream-gaging program needed to meet the needs of future water-data users. There were 64 stations at the time of the study. Eleven stations were discontinued and one station was added after the study was completed. Between 1970 and 1983, 27 stations were added and 15 were eliminated from the South Carolina stream-gaging program. Currently, there are 76 continuous stream gages in operation in South Carolina.

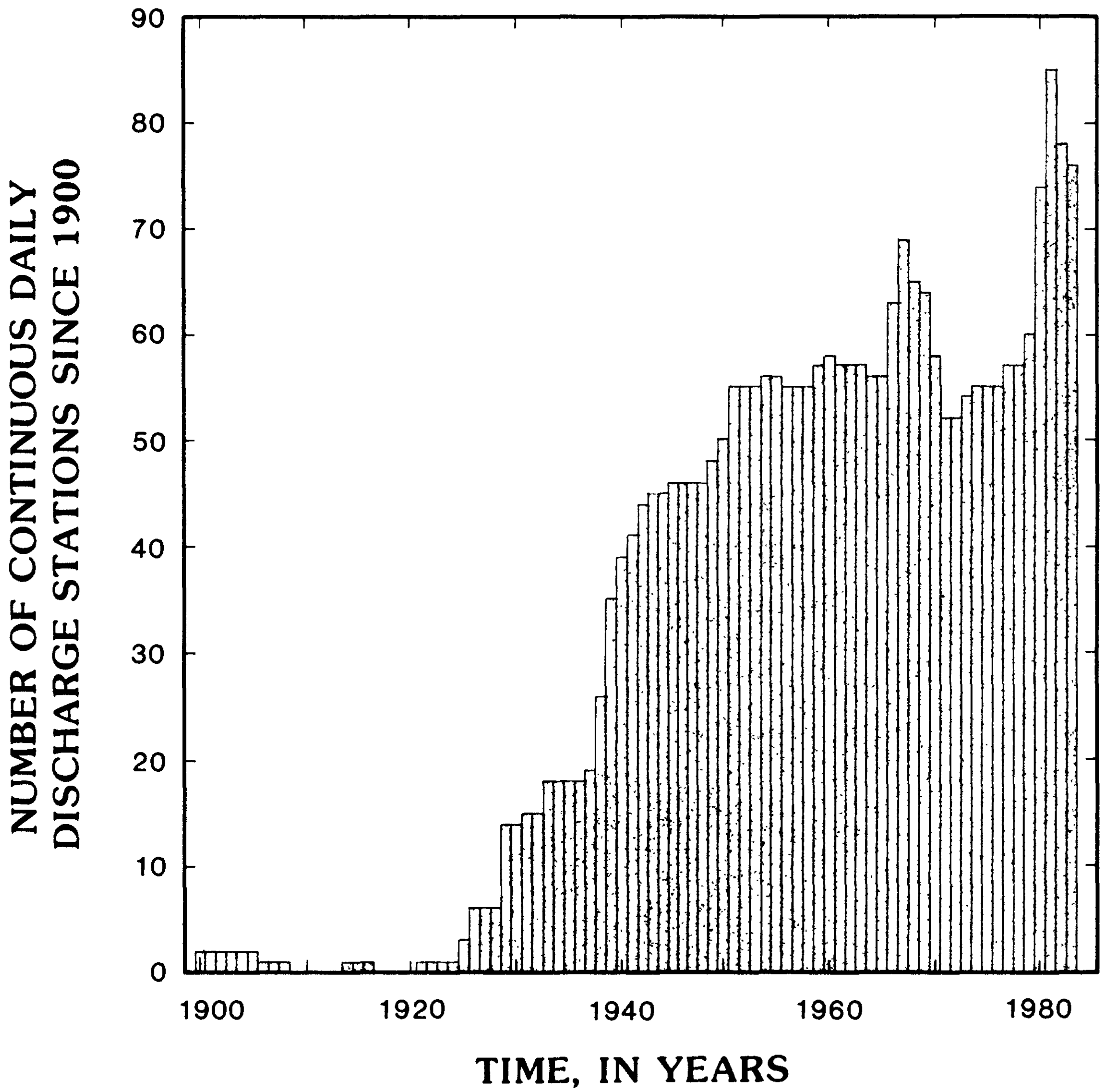

Figure 1.--History of continuous stream gaging in South Carolina

Current South Carolina Stream-Gaging Program

The locations of the 76 stream gages currently operated by the South Carolina District of the U.S. Geological Survey and their distribution in various physiographic provinces of the state are shown in figure 2. Eighteen gages are located in the lower Coastal Plain, 29 are located in the inner Coastal Plain, 27 are located in the Piedmont, and 2 are located in the Blue Ridge Province. The location of stations for other than continuous stream-gaging only are shown in figure 3.

The cost of operating the 76 stream gages, the 16 stage-only stations, and the 40 crest-stage stations in fiscal year 1983 was $422,200.

Selected hydrologic data, including drainage area, period of record, and mean annual flow for the 76 stations are given in table 1. Station identification numbers used throughout this report are the U.S. Geological Survey eight-digit downstream order station number except in figures 2 and 3, where the first two digits (02) of the standard U.S. Geological Survey station number are omitted. Table 1 also provides the official names and identification numbers of these stations.

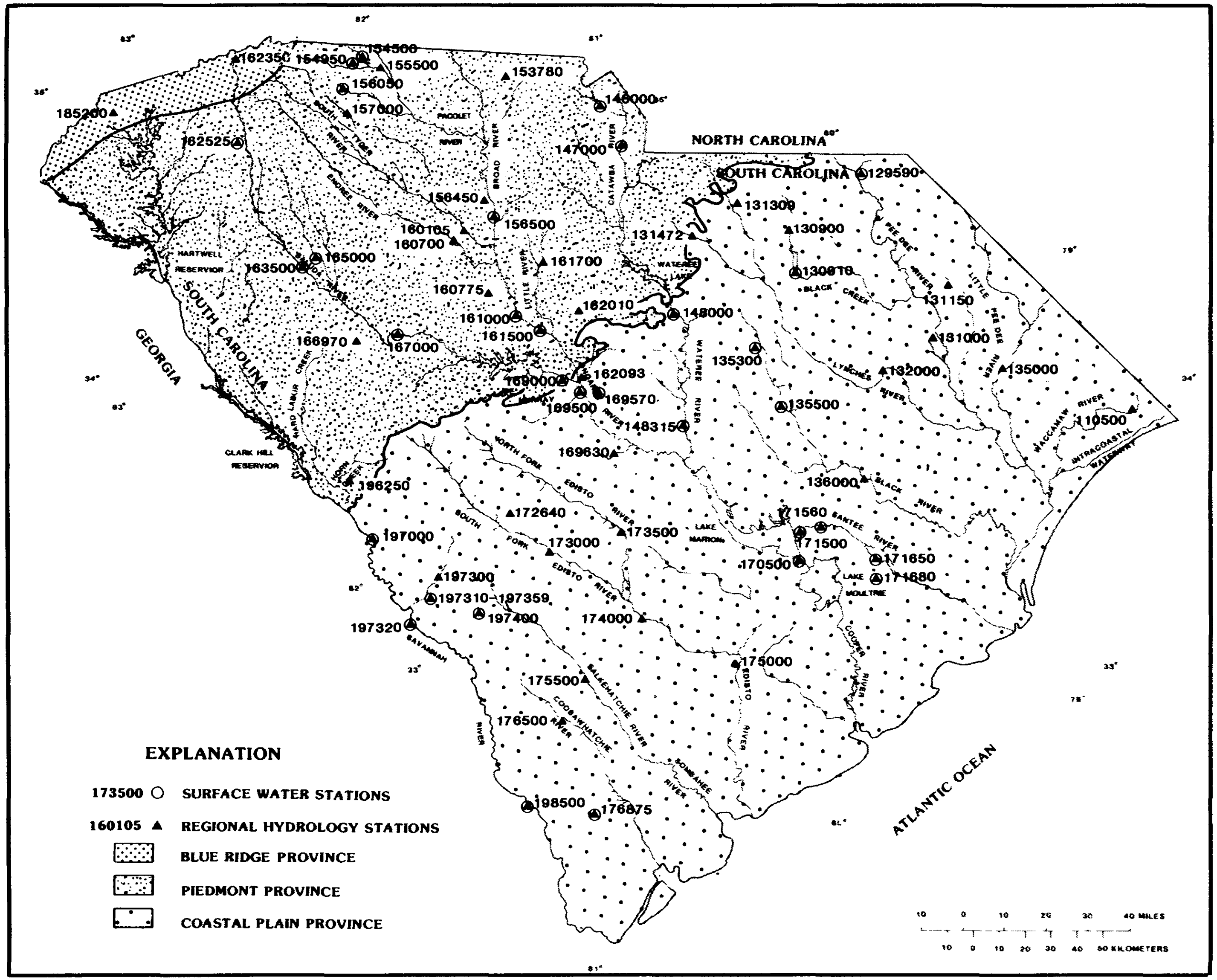

Figure 2.--Location of Stream-gaging stations in South Carolina

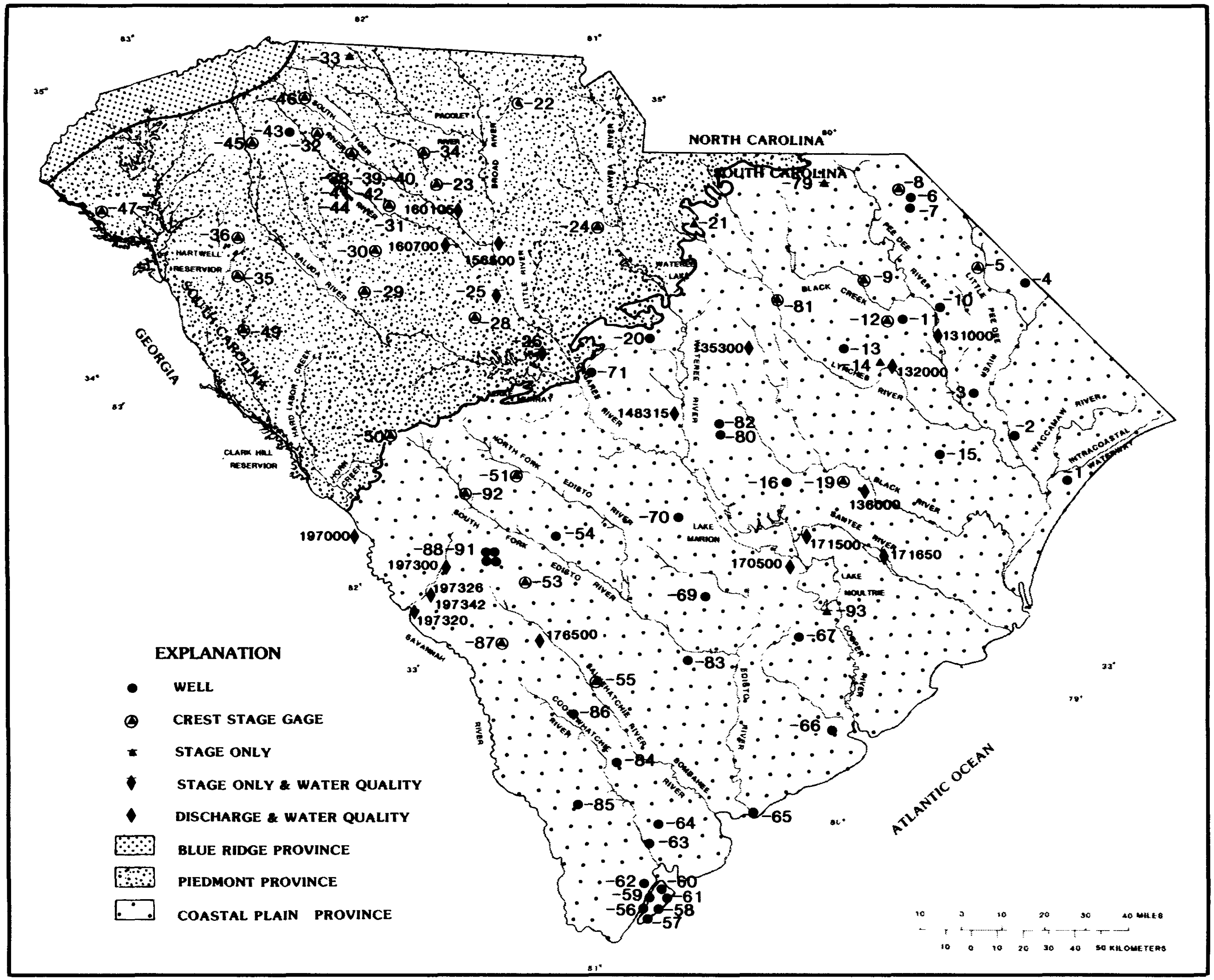

Figure 3.--Location of stations for other than stream-gaging only

Table 1.--Selected hydrologic data for stations in the South Carolina stream-gaging program

Station number	Station name	Drainage area (mi^2)	Period of record (mo/yr-mo/yr)	Mean annual flow (ft^3/s)
02110500	Waccamaw River nr Longs	1,110	03/50-	1,213
02129590	Whites Creek nr Wallace	26.4	10/79-	--*
02130900	Black Creek nr McBee	108	10/59-	167
02130910	Black Creek nr Hartsville	173	10/60-	236
02131000	Pee Dee River at Pee Dee	8,830	10/38-	9,748
02131150	Catfish Canal at Sellers	27.4	11/66-	26.8
02131309	Fork Creek at Jefferson	24.3	10/76-	25.4
02131472	Hanging Rock Creek nr Kershaw	10.1	10/80-	--*
02132000	Lynches River at Effingham	1,030	08/29-	1,025
02135000	Little Pee Dee River at Galivants Ferry	2,790	10/41-	3,197
02135300	Scape Ore Swamp nr Bishopville	96.0	07/68-	107
02135500	Black River nr Gable	401	06/51-06/66 04/72-	383
02136000	Black River at Kingstree	1,252	08/29-	930
02146000	Catawba River nr Rock Hill	3,050	09/1895-09/1903 04/42-	4,567
02147000	Catawba River nr Catawba	3,530	10/68-	5,816
02148000	Wateree River nr Camden	5,070	01/03-12/03 10/04-09/10 10/29-	6,396
02148315	Wateree River below Eastover	5,590	07/63-	--*
02153780	Clarks Fork Creek nr Smyrna	24.1	10/80-	--*
02154500	North Pacolet River at Fingerville	116	10/29-	212
02155500	Pacolet River nr Fingerville	212	10/29-	354
02156050	Lawsons Fork Creek at Dewey Plant nr Inman	6.46	10/79-	--*
02156450	Neals Creek nr Carlisle	12.3	10/80-	--*
02156500	Broad River nr Carlisle	2,790	10/38-	4,059
02157000	North Tyger River nr Fairmont	44.4	10/50-	66.2
02160105	Tyger River nr Delta	759	10/73-	1,168
02160700	Enoree River at Whitmire	444	10/73-	610
02160775	Hellers Creek nr Pomaria	8.16	10/80-	--*
02161000	Broad River at Alston	4,790	10/80-	--*
02161500	Broad River at Richtex	4,850	10/25-	6,214
02161700	West Fork Little River nr Salem Crossroads	25.5	10/80-	--*
02162010	Cedar Creek nr Blythewood	48.9	11/66-	48.4
02162093	Smith Branch at North Main St. at Columbia	5.67	10/76-	22.6
02162350	Middle Saluda River nr Cleveland	21.0	10/80-	--*

Table 1.--Selected hydrologic data for stations in the South Carolina stream-gaging program--Continued

Station number	Station name	Drainage area (mi^2)	Period of record (mo/yr-mo/yr)	Mean annual flow (ft^3/s)
02162525	Hamilton Creek nr Easley	1.60	10/80-	--*
02163500	Saluda River nr Ware Shoals	581	10/38-	1,027
02165000	Reedy River nr Ware Shoals	236	03/39-	352
02166970	Ninety-Six Creek nr Ninety-Six	17.4	10/80-	--*
02167000	Saluda River at Chappells	1,360	10/26-	1,974
02169000	Saluda River nr Columbia	2,520	08/25-	2,901
02169500	Congaree River at Columbia	7,850	10/39-	9,326
02169570	Gills Creek at Columbia	59.6	09/66-	76.1
02169630	Big Beaver Creek nr St. Mathews	10.0	07/66-	14.0
02170500	Lakes Marion-Moultrie Div. Canal nr Pineville	--	10/43-	14,930
02171500	Santee River nr Pineville	14,700	04/42-	2,235
02171560	Santee River nr Russellville	14,800	10/79-	--*
02171650	Santee River below St. Stephens	14,900	10/70-	2,875
02171680	Wedboo Creek nr Jamestown	17.4	09/66-	11.3
02172640	Dean Swamp Creek nr Salley	31.2	10/80-	--*
02173000	South Fork Edisto River nr Denmark	720	08/31-09/71 10/80-	792
02173500	North Fork Edisto River at Orangeburg	683	10/38-	798
02174000	Edisto River nr Branchville	1,720	10/45-	2,033
02175000	Edisto River nr Givhans	2,730	01/39-	2,678
02175500	Salkehatchie River nr Miley	341	02/51-	351
02176500	Coosawatchie River nr Hampton	203	02/51-	184
02176875	Great Swamp nr Ridgeland	48.8	10/78-	--*
02185200	Little River nr Walhalla	72.0	03/67-	190
02196250	Horn Creek nr Colliers	13.9	10/80-	--*
02197000	Savannah River nr Augusta, Ga.	7,508	10/1883-12/1891 01/1896-12/1906 01/1925-	10,200
02197300	Upper Three Runs nr New Ellenton	87.0	06/66-	111
02197310	Upper Three Runs above Road C at SRP (Savannah River Plant)	176	06/74-	209
02197315	Upper Three Runs at Road A at SRP	203	06/74-01/78 10/78-	268
02197320	Savannah River nr Jackson	--	10/71-	--†
02197326	Beaverdam Creek at 400-D at SRP	0.73	06/74-	84.4
02197330	Site no. 1 at SRP	0.13	08/67-	1.44
02197332	Site no. 2 at SRP	0.30	09/67-	1.53
02197334	Site no. 3 at SRP	5.95	09/67-	7.73
02197336	Site no. 4 at SRP	6.96	08/67-	8.80

Table 1.--Selected hydrologic data for stations in the South Carolina stream-gaging program--Continued

Station number	Station name	Drainage area (mi^2)	Period of record (mo/yr-mo/yr)	Mean annual flow (ft^3/s)
02197338	Site no. 5 at SRP	0.28	09/67-	2.47
02197339	Site no. 5B at SRP	--	10/80-	--*
02197340	Site no. 6 at SRP	7.53	09/67-	12.7
02197342	Site no. 7 at SRP	12.5	09/67-	17.9
02197344	Four Mile Creek at Road A-12.2 at SRP	22.0	11/76-	--*
02197348	Pen Branch at Road A-13.2 at SRP	21.2	11/76-	--*
02197359	Steel Creek at Old Hattiesville Bridge (SRP)	34.4	03/74-	--†
02197400	Lower Three Runs nr Snelling	59.3	03/74-	95.6
02198500	Savannah River nr Clyo, Ga.	9,850	10/29-09/33 10/37-	12,100

*No mean annual flow published, less than 5 years of streamflow record.

†No mean annual flow published, streamflow records are not continuous.

USES, FUNDING, AND AVAILABILITY OF CONTINUOUS STREAMFLOW DATA

The relevance of a stream gage is defined by the uses that are made of the data that are produced from the gage. The uses of the data from each gage in the South Carolina program were identified by a survey of known data users. The survey documented the importance of each gage and identified gaging stations that may be considered for discontinuation.

Data uses identified by the survey were categorized into eight classes, which are defined below. The sources of funding for each gage and the frequency at which data are provided to the users were also compiled.

Data-Use Classes

The following definitions were used to categorize each known use of streamflow data for each gage.

Regional Hydrology

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

Thirty-two stations in the South Carolina network are classified in the regional hydrology data-use category. Four of the stations are special cases in that they are designated bench-mark or index stations. There are two hydrologic bench-mark stations in South Carolina which serve as indicators of hydrologic conditions in watersheds relatively free of manmade alteration. Two index stations, located in different regions of the State, are used to indicate current hydrologic conditions. The locations of stream gages that provide information about regional hydrology are also given in figure 2.

Hydrologic Systems

Stations that can be used for 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 bench-mark and index stations are included in the hydrologic systems category because they are accounting for current and long-term conditions of the hydrologic systems that they gage. There are 48 hydrologic-systems stations in South Carolina.

Planning and Design

Gaging stations in this category are used for the planning and design of a specific project (for example, a dam, levee, floodwall, navigation system, water-supply diversion, hydropower plant, or waste-treatment facility) or group of structures. The planning and design category includes those stations that were instituted for such purposes and for which this purpose is still valid.

Currently, 13 stations in the South Carolina program are being operated for planning or design purposes.

Project Operation

Gaging stations in this category are used, on an ongoing basis, to assist water managers in making operational decisions regarding 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 only be needed every few days.

There are 38 stations in the South Carolina program that are used to aid operators in the management of reservoirs and control structures that are part of hydropower production systems.

Hydrologic Forecasts

Gaging stations in this category are regularly used to provide information for hydrologic forecasting. Such information might include 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 only be needed every few days.

Nine stations in the South Carolina program are included in the hydrologic forecasting category. They are used for flood forecasting by the U.S. National Weather Service (NWS) and other agencies.

Water-Quality Monitoring

Gaging stations where regular water-quality or sediment-transport monitoring is being conducted or stations where streamflow data are used to support the interpretation of these parameters are designated as water-quality monitoring sites.

Two such stations in the program are designated bench-mark stations and seven are National Stream Quality Accounting Network (NASQAN) stations. Water-quality samples from bench-mark stations are used to indicate water-quality characteristics of streams that have been and probably will continue to be relatively free of manmade influence. NASQAN stations are part of a nation-wide network designed to assess water-quality trends of significant streams. Other water-quality stations are shown in table 2.

(Text continues on page 25)

Table 2.--Use of data from stream gaging stations in SC.

1. Flood Forecasting, U.S. National Weather Service
2. U.S. Army Corps of Engineers, Charleston District
3. Carolina Power and Light Company
4. South Carolina Water Resources Commission
5. NASQAN station
6. Caro-Knit, Inc.

Station number	Data use									Funding				Frequency of data available
	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	
02110500	*					1				*	2			AT
02129590				3								4		A
02130900	*				3							4		AT
02130910					3							4		AT
02131000						1	5				2			AT
02131150	*									*	2			A
02131309	*				6							6		A

Table 2.--Use of data from stream gaging stations in SC (continued)

1. Flood Forecasting, U.S. National Weather Service
2. U.S. Army Corps of Engineers, Charleston District
4. South Carolina Water Resources Commission
5. NASQAN station
7. South Carolina Department of Health and Environmental Control
8. Long-term index gaging station
9. Milliken Corporation
10. Hydrologic bench mark station

Station number	Data use: Regional hydrology	Data use: Hydrologic systems	Data use: Legal obligations	Data use: Planning and design	Data use: Project operation	Data use: Hydrologic forecasts	Data use: Water-quality monitoring	Data use: Research	Data use: Other	Funding: Federal program	Funding: OFA program	Funding: Coop program	Funding: Other non-Federal	Frequency of data available
02131472	*	7		7								7		A
02132000	8	8				1	5, 9			*				AT
02135000	*					1				*	2	4		AT
02135300	10	10					10			*				A
02135500	*										2			A
02136000	*					1	5			*				ATP

Table 2.--Use of data from stream gaging stations in SC (continued)

1. Flood Forecasting, U.S. National Weather Service
4. South Carolina Water Resources Commission
7. South Carolina Department of Health and Environmental Control
9. Milliken Corporation
11. Federal Energy Regulatory Commission hydropower licensing requirements
12. Duke Power Company
13. Bowater-Carolina Corporation
14. South Carolina Electric and Gas Company
15. City of Spartanburg

Station number	Data use									Funding				Frequency of data available
	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	
02146000		11											12	A
02147000					13							4		A
02148000		11				1							12	AT
02148315					14		14					4		AT
02153780	*	7		7								7		A
02154500					15							15		A
02155500					15							15		A
02156050					9							4		A

Table 2.--Use of data from stream gaging stations in SC (continued)

4. South Carolina Water Resources Commission
7. South Carolina Department of Health and Environmental Control
11. Federal Energy Regulatory Commission hydropower licensing requirements
14. South Carolina Electric and Gas Company

Station number	Data use									Funding				Frequency of data available
	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	
02156450	*	7		7								7		A
02156500		11			14		14						14	AT
02157000	*	4										4		A
02160105	*	14			14		14					4		AT
02160700	*	14			14		14					4		AT

Table 2.--Use of data from stream gaging stations in SC (continued)

4. South Carolina Water Resources Commission
7. South Carolina Department of Health and Environmental Control
14. South Carolina Electric and Gas Company
16. South Carolina Department of Highways and Public Transportation

Station number	Data use									Funding				Frequency of data available
	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	
02160775	*	7		7								7		A
02161000					14							4		AT
02161500		14											14	A
02161700	*	7		7								7		A
02162010	*									*				A
02162093	*			16								16		A
02162350	*	7		7								7		A

Table 2.--Use of data from stream gaging stations in SC (continued)

1. Flood Forecasting, U.S. National Weather Service
4. South Carolina Water Resources Commission
7. South Carolina Department of Health and Environmental Control
11. Federal Energy Regulatory Commission hydropower licensing requirements
12. Duke Power Company
14. South Carolina Electric and Gas Company
17. Platt-Saco-Lowell Corporation

Station number	Data use									Funding				Frequency of data available
	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	
02162525					17							4		A
02163500		11			12								12	A
02165000		11			12								12	A
02166970	*	7		7								7		A
02167000		11			14 12	1							14 12	AT
02169000		11			14								14	A

Table 2.--Use of data from stream gaging stations in SC (continued)

2. U.S. Army Corps of Engineers, Charleston District
5. NASQAN station
7. South Carolina Department of Health and Environmental Control
11. Federal Energy Regulatory Commission hydropower licensing requirements
18. South Carolina Public Service Authority
19. National Park Service

Station number	Data use: Regional hydrology	Hydrologic systems	Legal obligations	Planning and design	Project operation	Hydrologic forecasts	Water-quality monitoring	Research	Other	Funding: Federal program	OFA program	Coop program	Other non-Federal	Frequency of data available
02169500					18							18		AT
02169570		19									19			A
02169630	*									*				A
02170500							5			*				A
02171500		11			18		7						18	A
02171560					2						2			A
02171650							2				2			A

Table 2.--Use of data from stream gaging stations in SC (continued)

1. Flood Forecasting, U.S. National Weather Service
2. U.S. Army Corps of Engineers, Charleston District
4. South Carolina Water Resources Commission
5. NASQAN station
7. South Carolina Department of Health and Environmental Control
8. Long-term index gaging station
20. City of Charleston

Station number	Data use									Funding				Frequency of data available
	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	
02171680				2							2			A
02172640	*	7		7								7		A
02173000	*	4		4								4		A
02173500	8	8				1				*				AT
02174000	*	2									2			A
02175000	*				20	1	5					20		AT

Table 2.--Use of data from stream gaging stations in SC (continued)

2. U.S. Army Corps of Engineers, Charleston District
4. South Carolina Water Resources Commission
5. NASQAN station
7. South Carolina Department of Health and Environmental Control
10. Hydrologic bench mark station
21. Soil Conservation Service
22. U.S. Army Corps of Engineers, Savannah District
23. U.S. Department of Energy

Station number	Data use									Funding				Frequency of data available
	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	
02175500	*	2									2			A
02176500	*	2					5				2			A
02176875								21			21			A
02185200	*	4						4				4		A
02196250	*	7		7								7		A
02197000					22		23				22			AT
02197300	10	23 10			23		10			*				A

Table 2.--Use of data from stream gaging stations in SC (continued)

23. U.S. Department of Energy

Station number	Data use: Regional hydrology	Hydrologic systems	Legal obligations	Planning and design	Project operation	Hydrologic forecasts	Water-quality monitoring	Research	Other	Funding: Federal program	OFA program	Coop program	Other non-Federal	Frequency of data available
02197310		23			23						23			A
02197315		23			23						23			A
02197320		23			23		23				23			AT
02197326		23			23		23				23			AT
02197330		23			23						23			A
02197332		23			23						23			A

Table 2.--Use of data from stream gaging stations in SC (continued)

23. U.S. Department of Energy

Station number	Data use									Funding				Frequency of data available
	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	
02197334		23			23						23			A
02197336		23			23						23			A
02197338		23			23						23			A
02197339		23			23						23			A
02197340		23			23						23			A
02197342		23			23		23				23			A

Table 2.--Use of data from stream gaging stations in SC (continued)

1. Flood Forecasting, U.S. National Weather Service
2. U.S. Army Corps of Engineers, Charleston District
3. Carolina Power and Light Company
4. South Carolina Water Resources Commission
5. NASQAN station
6. Caro-Knit, Inc.
7. South Carolina Department of Health and Environmental Control
8. Long-term index gaging station
9. Milliken Corporation
10. Hydrologic benchmark station
11. Federal Energy Regulatory Commission hydropower licensing requirements
12. Duke Power Company
13. Bowater-Carolina Corporation
14. South Carolina Electric and Gas Company
15. City of Spartanburg
16. South Carolina Department of Highways and Public Transportation
17. Platt-Saco-Lowell Corporation
18. South Carolina Public Service Authority
19. National Park Service
20. City of Charleston
21. Soil Conservation Service,
22. U.S. Army Corps of Engineers, Savannah District
23. U.S. Department of Energy

Research

Gaging stations in this category are operated for a particular research or water-investigations study. Typically, these are only operated for a few years. Two stations in the South Carolina program are used in the support of research activities.

Funding

The four sources of funding for the stream-gaging program are as follows:

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

2. Other Federal Agency (OFA) program.--Funds that have been transferred to the U.S. Geological Survey by OFA's.

3. Coop program.--Funds that come jointly from U.S. Geological Survey (joint-funding agreement) 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 private concerns was limited to licensing and permitting requirements for hydropower development by the Federal Energy Regulatory Commission. Funds in this category are not matched by the U.S. Geological Survey through joint-funding agreements.

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, that might be carried out at the site are not necessarily the same as those identified herein.

Fifteen entities currently are contributing funds to the South Carolina stream-gaging program.

Data Availablity

Data availability refers to the times at which the streamflow data may be furnished to the users. In this category, three distinct possibilities exist. Data can be furnished by direct-access telemetry equipment for immediate use, by periodic release of provisional data, or in publication format through the annual data report published by the U.S. Geological Survey for South Carolina (U.S. Geological Survey, 1982). These three categories are designated T, P, and A, respectively, in table 2.

Data-Use Presentation

Data-use and ancillary information are presented for each continuous gaging station in table 2. An asterisk in the table indicates that the station is used by the U.S. 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

All sites in the South Carolina District are operated for a specific purpose, as noted in the Date-use table (Table 2). Thirty-two stations are classified in the regional hydrology data-use category, 48 in the hydrologic-systems category, and 13 in the planning and design category. Thirty-eight stations are designated for the project operation category, nine in the hydrologic forecast category, and seven are used for water-quality monitoring. Only two stations are used for research activities. Of the 76 stations in operation, 54 have multi-purpose data-uses.

ALTERNATIVE METHODS OF DEVELOPING STREAMFLOW INFORMATION

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

All stations in the South Carolina stream-gaging program were categorized as to their potential for utilization of alternative methods, and selected methods were applied at four stations. The categorization of gaging stations and the application of the specific methods are described in subsequent sections of this report. This section briefly describes the two alternative methods that were used in the South Carolina analysis and documents why these specific methods were chosen.

Because of the short time frame of this analysis, only two methods were considered. Desirable attributes of a proposed alternative method are:

1. The proposed method should be computer oriented and easy to apply.

2. The proposed method should have an available interface with the U.S. Geological Survey WATSTORE Daily Values File (Hutchinson, 1975).

3. The proposed method should be technically sound and generally acceptable to the hydrologic community.

4. The proposed method should permit easy evaluation of the accuracy of the simulated streamflow records.

The desirability of the first attribute above is obvious. Second, the interface with the WATSTORE Daily Values File is needed to easily calibrate the proposed alternative method. Third, the alternative method selected for analysis must be technically sound or it will not be able to provide data of suitable accuracy. Fourth, the alternative method should provide an estimate of the accuracy of the streamflow to judge the adequacy of the simulated data. The above selection criteria were used to select two methods--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. The input is usually a discharge hydrograph at the upstream end of the reach, and the output is usually a discharge hydrograph at the downstream end. Several different types of hydrologic routing are available such as the 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 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 or 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 observed upstream and downstream hydrographs and estimates of tributary inflows. The convolution 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 upon the variability of wave celerity (traveltime) and dispersion (channel storage) throughout the range of discharges to be routed. Adequate routing of daily flows can usually be accomplished using a single unit-response function (linearization about a single discharge) to represent the system response. However, if the routing coefficients vary drastically with discharge, linearization about a low-range discharge results in overestimated high flows that arrive late at the downstream site; whereas, linearization about 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. The third option available is the single unit-response storage-continuity routing model.

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 range from partially gaged to totally ungaged and can be 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 relation 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 reach are K_s, a storage coefficient which 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 are K_0, a wave dispersion or damping coefficient, and C_0, the flood wave celerity. K_0 controls the spreading of the wave (analogous to K_s in the storage-continuity method), and C_0 controls the travel time (analogous to W_s in the storage-continuity method). In the single linearization method, only one K_0 and C_0 value is used. In the multiple linearization method, C_0 and K_0 are varied with discharge so a table of wave celerity (C_0) versus discharge (Q) and a table of dispersion coefficient (K_0) versus discharge (Q) are used.

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

Description of Regression Analysis

Simple- and multiple-regression techniques can also be used to estimate daily flow records. Regression equations can be computed that relate daily flows (or their logarithms) at a single station to daily flows at a combination of upstream, downstream, and/or 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 developed for estimating daily mean discharges in South Carolina:

$$y_i = B_0 + \sum_{j=1}^{p} B_j \, x_j + e_i$$

where:

y_i = daily mean discharge at station i (dependent variable),

B_0 and B_j = regression constant and coefficients,

x_j = daily mean discharges at nearby stations (explanatory variables), and

e_i = the random error term.

The above equation is calibrated (B_0 and B_j are estimated) using observed values of y_i and x_j. These observed daily mean discharges can be retrieved from the WATSTORE Daily Values File. The values of x_j may be discharges observed on the same day as discharges at station i or may be for 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 observed values of x_j. The regression constant and coefficients (B_0 and B_j) are tested to determine if they are significantly different from zero. A given station j should only be retained in the regression equation if its regression coefficient (B_j) is significantly different from zero. The regression equation should be calibrated using one period of time and then verified or tested on a different period of time to obtain a measure of the true predictive accuracy. Both the calibration and verification period should be representative of the range of flows that could occur at station i. The equation should be verified by plotting: (1) the residuals e_i (difference between simulated and observed discharges) against the dependent and all explanatory variables in the equation, and (2) the simulated and observed discharges versus time. These tests are used to determine: (1) if the linear model is appropriate or whether some transformation of the variables is needed, and (2) if 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. In this report these tests indicated that a linear model with y_i and x_j, in cubic feet per second, was appropriate. The application of linear-regression techniques to four stations in South Carolina is described in a subsequent section of this report.

It should be noted that the use of a regression relation to synthesize data at a discontinued gaging station entails a reduction in the variance of the streamflow record relative to that which would be computed from an actual record of streamflow at the site. The reduction in variance expressed as a fraction is approximately equal to one minus the square of the correlation coefficient that results from the regression analysis.

Categorization of Stream Gages by Their Potential for Alternative Methods

An analysis of the data uses presented in table 2 identified four stations at which alternative methods for providing the needed streamflow information could be applied. These four stations are Catawba River near Catawba (02147000), Broad River at Richtex (02161500), North Fork Edisto River at Orangeburg (02173500), and Edisto River near Branchville (02174000). Based on the capacities and limitations of the methods and data availability, flow-routing techniques were used only at the Richtex and Branchville gaging stations. Regression methods were applied to all four stations.

Richtex Flow-Routing Analysis

The purpose of this flow-routing analysis is to investigate the potential for use of the unit-response model for streamflow routing to simulate daily mean discharges in the Broad River at Richtex. In this application, a best-fit model for the entire flow range is the desired product. Gaging station data available for this analysis are summarized in table 3.

Table 3.--Gaging stations used in the Richtex flow-routing analysis

Station number	Station name	Drainage area (mi^2)	Period or record
161000	Broad River at Alston	4,790	October 1980 to present
161500	Broad River at Richtex	4,850	October 1925 to present

The Richtex gage is located 9.0 miles downstream from the next upstream station at Alston. This reach is subjected to regulation at low and medium flows by powerplants upstream at the Parr Shoals Dam. The ungaged drainage area between Alston and Richtex is 60 mi^2 or 1.2 percent of the total drainage area contributing to the Richtex site. Although the ungaged percentage of drainage area in this reach is relatively small, the Richtex gage has a history of requiring corrections to recorded gage heights to adjust for intake lags. For this reason, the records at the Richtex station have been rated poor for the water years used in simulation. An additional limitation in this analysis is the short period of streamflow data at the Alston gage. Because records for 1983 water year were not complete, only the 1981 and 1982 water years were used for calibration.

To simulate daily mean discharges, the approach was to route the flow from Alston to Richtex using the diffusion analogy method with a single linearization. The intervening flow was estimated by using Alston as the index station and multiplying its daily mean discharges by an intervening drainage area factor. The total discharge at Richtex was the summation of the routed discharge from Alston plus the estimated intervening flow.

To route flow from Alston to Richtex, it was necessary to determine the model parameters C_0 (flood wave celerity) and K_0 (wave dispersion coefficient). The coefficients C_0 and K_0 are functions of channel width (W_0) in feet, channel slope (S_0) in feet per foot, the slope of the stage-discharge relation (dQ_0/dY_0) in square feet per second, and the discharge (Q_0) in cubic feet per second representative of the reach in question and are determined as follows:

$$C_0 = (1/W_0)\ (dQ_0/dY_0) \qquad (1)$$

$$K_0 = Q_0/(2\ S_0\ W_0)\ . \qquad (2)$$

The discharge, Q_0, for which initial values of C_0 and K_0 were linearized was the mean daily discharge for the Alston and Richtex gages as published for the 1982 water year (U.S. Geological Survey, 1982). The channel width, W_0, was determined from width-discharge relations plotted from actual measurements. Channel slope, S_0, was calculated by adjusting gage heights from discharge measurements to a common datum, calculating the difference between upstream and downstream elevations and dividing by the channel length. The slope of the stage-discharge relations, dQ_0/dY_0, was determined from the rating curves at each gage by using a 1-foot increment that bracketed the mean discharge, Q_0. The difference in the discharge through the 1-foot increment then represents the slope of the function at that discharge. The model parameters as determined by the methods described above are listed in table 4.

Table 4.--Selected reach characteristics used in the Richtex flow-routing analysis

Site	Q_0 (ft^3/s)	W_0 (ft)	S_0 (ft/ft)	dQ_0/dY_0 (ft^2/s)	C_0 (ft/s)	K_0 (ft^2/s)
Alston	5,710	477	5.64×10^{-4}	2,440	5.12	10,610
Richtex	6,130	541		2,940	5.43	10,050

For the first routing trial, average values for the model parameter C_0 = 5.28 and K_0 = 10,330 were used. To simulate the intervening flow, a drainage area ratio was calculated by dividing the ungaged drainage area by the drainage area of the Alston gage. This ratio (60/4,790 = 0.013) was then multiplied by flows at Alston to simulate input from the ungaged intervening drainage as a first estimate. However, a factor was necessary to adjust Q_0 for intervening drainage area in lieu of the drainage area ratio for calibration of the model.

Using the only two complete water years of data at Alston as a calibration data set, several trials were made adjusting the parameters C_0, K_0, and the intervening drainage area factor. The best-fit single linearization model was determined to be that with $C_0 = 4.75$, $K_0 = 10{,}330$, and an ungaged intervening drainage area factor of 0.10. Several attempts were made to improve the model using multiple linearization, but no increase in accuracy was obtained.

A summary of the simulation errors of daily mean discharge at Richtex for two water years, 1981-82, is given in table 5. There was no consistency of errors for any particular season or range of flows. Therefore, no trends were available to suggest any sound reasoning for the cause of error.

Table 5.--Simulation errors of the routing model for Richtex flow-routing analysis

Mean absolute error for 730 days = 7.54 percent
Mean negative error (318 days) = -8.05 percent
Mean positive error (412 days) = 7.14 percent
Total volume error = -0.87 percent
54 percent of the total observations had errors $\leq$ 5 percent
79 percent of the total observations had errors $\leq$ 10 percent
86 percent of the total observations had errors $\leq$ 15 percent
91 percent of the total observations had errors $\leq$ 20 percent
94 percent of the total observations had errors $\leq$ 25 percent
6 percent of the total observations had errors > 25 percent

Table 6.--Gaging stations used in the Branchville flow-routing analysis

Station number	Station name	Drainage area (mi^2)	Period of record
173000	South Fork Edisto River near Denmark	720	August 1931 to September 1971 and October 1980 to present
173500	North Fork Edisto River	683	October 1938 to present
174000	Edisto River near Branchville	1,720	October 1945 to present

Branchville Flow-Routing Analysis

The unit-response method was also applied to Edisto River near Branchville (02174000) to determine the potential of the model to accurately estimate daily mean discharges. Gaging station data available for this analysis are summarized in table 6.

The Branchville gage is 13.0 miles downstream from the confluence of the South Fork Edisto River and the North Fork Edisto River. The Denmark gage (02173000) is located 23.6 miles upstream from the confluence on the South Fork Edisto River and the Orangeburg gage (02173500) is located 22.1 miles upstream from the confluence on the North Fork Edisto River. The intervening ungaged drainage area between the two upstream sites and Branchville is 317 mi^2, or 18 percent of the total drainage area contributing to the Branchville site. The reaches used in this analysis are not subjected to any regulation.

The approach used in this analysis was to route the flows from the two upstream stations, Denmark and Orangeburg, merge them at the confluence, and route the combined flow to Branchville. The single linearization option was first used in this diffusion analogy. The intervening flow was accounted for by using Orangeburg as the index station and multiplying its daily mean discharges by a drainage area ratio. The total discharge at Branchville was the summation of the routed discharge from Denmark, the routed discharge from Orangeburg, and the estimated intervening flow.

Although the routing parameters C_0 and K_0 were determined by using the same techniques applied in the Richtex analysis, some points should be noted. The discharge, Q_0, for which initial values of C_0 and K_0 were linearized was the mean daily discharge for each of the stations as published for the 1981 water year (U.S. Geological Survey, 1981). Also, channel slopes were calculated for the following three reaches: Denmark to the confluence, Orangeburg to the confluence, and the confluence to Branchville. These results are summarized in table 7.

Table 7.--Selected reach characteristics used in the Branchville flow-routing analysis

Site	Q_0 (ft^3/s)	W_0 (ft)	S_0 (ft/ft)	dQ_0/dY_0 (ft^2/s)	C_0 (ft/s)	K_0 (ft^2/s)
Denmark	565	73	4.20×10^{-4}	333	4.56	9,210
Orangeburg	583	85	3.87×10^{-4}	200	2.35	8,860
Branchville	1,322	173	3.76×10^{-4}	301	1.74	10,200

For the first routing trial, the C_0 and K_0 parameters above were used for each of the three individual reaches. To simulate the intervening flow, a drainage area ratio was calculated by dividing the ungaged drainage area by the drainage area of the Orangeburg gage. The discharges at Orangeburg were then multiplied by this drainage area ratio (317/683 = 0.46) to simulate input from the ungaged intervening drainage as a first estimate. A drainage area factor to adjust the discharge at the downstream gage was also used in this reach for calibration of the model.

Calibration and verification of the model requires concurrent observed streamflow data at both the system input and output sites. The water years of 1981 through 1983 were used as a calibration set since they were the most recent record of the Denmark gage. Several trials were made by adjusting the C_0, K_0, and drainage area factor for each of the three reaches. The best fit single linearization model yielded these values: $C_0 = 2.00$, $K_0 = 9{,}210$ to route flow from Denmark to the confluence, $C_0 = 0.75$, $K_0 = 8{,}860$ to route flow from Orangeburg to the confluence, and $C_0 = 0.50$, $K_0 = 10{,}200$ to route flow from the confluence to Branchville. Further refinement of this model found the best-fit value of the intervening drainage area factor to be 0.27. The flow at Orangeburg was then multiplied by this value. Attempts were made to improve the model by using multiple linearization and trying other combinations of index stations. None of the alternatives resulted in a better model for the calibration data set.

A summary of the simulation errors of daily mean discharge at Branchville for the three water years, 1981-83, is given in table 8.

Table 8.--Simulation errors of the routing model for Branchville flow-routing analysis

Mean absolute error for 1,095 days	=	9.15 percent
Mean negative error (696 days)	=	-11.13 percent
Mean positive error (399 days)	=	5.70 percent
Total volume error	=	-9.67 percent

40 percent of the total observations had errors ≤ 5 percent

65 percent of the total observations had errors ≤ 10 percent

76 percent of the total observations had errors ≤ 15 percent

87 percent of the total observations had errors ≤ 20 percent

96 percent of the total observations had errors ≤ 25 percent

4 percent of the total observations had errors > 25 percent

After reviewing the 3-year simulation of flow at Branchville, it was observed that significant errors occurred during each of the winter seasons. The model indicated consistently large negative errors (simulated values too low) during periods of higher flows. This may be attributed to inaccuracies in estimating intervening flows due to the large amount of rainfall that occurred during the months of January, February, and March for each of the water years used in the simulation. The daily hydrograph for the winter period for 1982 is given in figure 4.

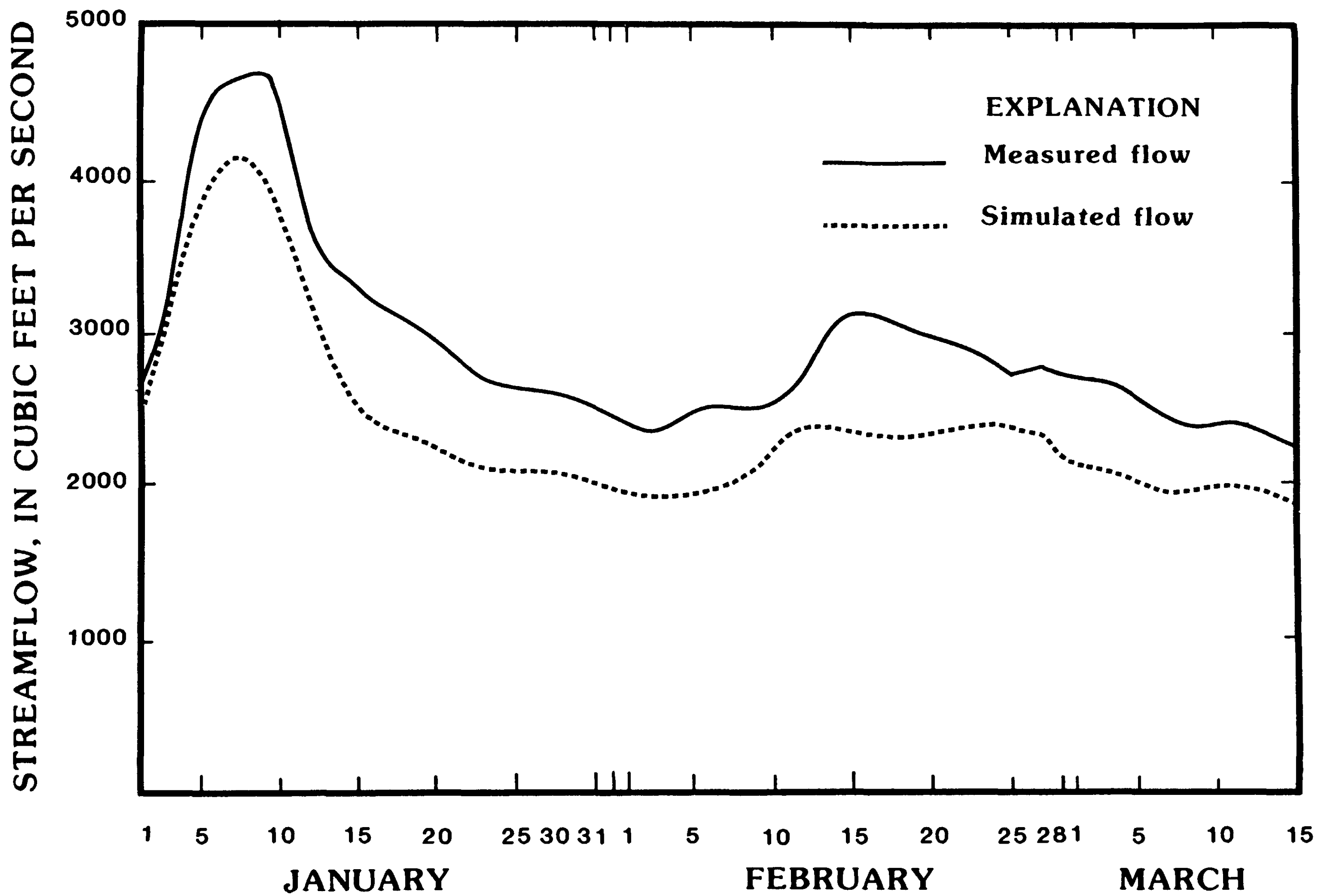

Figure 4.--Daily Hydrograph, Edisto River near Branchville, winter 1982

Regression Analysis Results

Linear regression techniques were applied to four selected stations. The streamflow record for each station considered for simulation (the dependent variable) was regressed against streamflow records at other stations (explanatory variables) during a given period of record (the calibration period). Best-fit linear regression models were developed and used to provide a daily streamflow record that was compared to the observed streamflow record. The percent difference between the simulated and actual record for each day was calculated. The results of the regression analysis for each station are summarized in table 9.

The streamflow record at Catawba River near Catawba (02147000) was not reproduced with an acceptable degree of accuracy using regression techniques. Only 32 percent of the simulation data were within 10 percent of the actual record for the period of calibration. These results occurred when daily mean discharges at Catawba River near Rock Hill (02146000) were used as the explanatory variable. This poor simulation is probably due to the regulation of flows at both the Catawba and Rock Hill stations. Rock Hill and Catawba are located 3.5 miles and 18.3 miles, respectively, downstream from Lake Wylie Dam. After a review of the 1981-83 water year hydrographs for both stations, it was observed that the flow fluctuated significantly during the routing interval of 24 hours. Because daily mean discharges were used for calibration, it was assumed that the model was not sensitive enough to detect this volatile change of flow.

The more successful simulations of streamflow records occurred at the Orangeburg, Branchville, and Richtex stations. As in the Catawba analysis, these stations were also regressed against other stations within the same basin. However, there was little or no regulation present for the above stations. The dependent streamflow records were regressed against records obtained from upstream or adjacent sites.

The streamflow record for Orangeburg was simulated by regressing its daily mean discharges against those at Denmark. As mentioned before, the South Fork Edisto flows adjacent to the North Fork Edisto until they converge to form the Edisto River. The Denmark and Orangeburg gages are located on the South Fork Edisto River and the North Fork Edisto River, respectively, and they are approximately the same distance from the confluence. After several combinations of lagged and unlagged flows, it was determined that a direct unlagged correlation produced the most accurate results. The regression model for Orangeburg simulated the actual record within 10 percent error for 59 percent of the calibration period and within 5 percent error for 32 percent of the period.

Another regression analysis was performed to simulate the daily mean flows for Branchville. This regression model included two explanatory variables--the lagged flow at Denmark and the lagged flow at Orangeburg. Several trials were performed and it was determined that a 3-day lag applied to flows of both upstream stations generated the most accurate results. The simulation data for Branchville were within 10 percent of the actual flows for 62 percent of the calibration period and within 5 percent error for 34 percent of the period.

Table 9.--Summary of calibration for regression modeling of daily mean streamflow at selected stations in South Carolina

Station number and name	Model	Percentage of simulated flow within 5% of actual	Percentage of simulated flow within 10% of actual	Calibration period (water years)
02147000 Catawba	$Q_{1470} = 499.47 + 1.041\ (Q_{1460})$	18.9	32.0	1981-83
02161500 Richtex	$Q_{1615} = 162.01 + 1.028\ (Q_{1610})$	52.9	73.4	1981-82
02173500 Orangeburg	$Q_{1735} = 154.09 + 0.793\ (Q_{1730})$	31.6	59.4	1981-83
02174000 Branchville	$Q_{1740} = -236.45 + 1.415\ (LAG3Q_{1730}) + 1.460\ (LAG3Q_{1735})$	34.0	61.7	1981-83

The probable reason that both the Orangeburg and Branchville simulations are not more accurate is that some flow is diverted directly above the Orangeburg station to provide the city of Orangeburg with a municipal water supply.

The most successful regression modeling for all of the four selected stations was that for the Richtex station. Daily mean discharges were simulated for Richtex by using discharge at Alston as the explanatory variable. No lag of flow was necessary to obtain the optimum regression model. The analysis for Richtex yielded these results: 73 percent of the calibration period was within 10 percent of the actual flows and 53 percent of the period was within 5 percent error. Streamflow regulation and intake lags are probably the reasons for the inaccuracy in the model.

Conclusions Pertaining to Alternative Methods of Data Generation

The simulated data from both the flow-routing and regression methods for the Branchville stream gage were not sufficiently accurate to suggest these methods in lieu of operating a continuous-record gaging station. The same was true for the regression results for Catawba and Orangeburg. At the Richtex station, both the flow-routing and regression methods provided streamflow data that are accurate enough for its intended usage. In describing the accuracy of streamflow records, "fair" means that about 95 percent of the daily discharges are within 15 percent; "poor" means that daily discharges have less than "fair" accuracy (U.S. Geological Survey, 1982). The records simulated by both the regression and flow-routing models are rated poor. However, because the Richtex records used in simulation are also rated poor, it is suggested that the models are suitable alternatives to the operation of a continuous-record station at Richtex.

In summary, the Catawba, Branchville, and Orangeburg stations should remain in operation and will be included in the next step of this analysis. After reviewing the simulated and observed record for both models at the Richtex station, it has been determined that it would be more cost effective to discontinue the operation of this station. Therefore, the Richtex site will be removed from further consideration in this report.

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

In a study of the cost effectiveness of a network of stream gages operated to determine water consumption in the Lower Colorado River basin, a set of techniques called K-CERA was developed (Moss and Gilroy, 1980). Because of the water-balance nature of that study, the measure of effectiveness of the network was chosen to be the minimization of the sum of variances of errors of estimation of annual mean discharges at each site in the network. This measure of effectiveness tends to concentrate stream-gaging effort on the larger, less stable streams where potential errors are greatest. While such a tendency is appropriate for a water-balance network, in the broader context of the multitude of uses of the streamflow data collected in the U.S. Geological Survey's stream-gaging program, this tendency causes undue concentration on large streams. Therefore, the original version of K-CERA was extended 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, and average instantaneous discharge in percentage. The use of percentage errors does not unduly weight activities at large streams to the detriment of records on small streams. In addition, the 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 all continuous-record 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 stream gage increases. A procedure for dealing with the missing record has been developed and was incorporated into this study.

Brief descriptions of the mathematical program used to optimize cost effectiveness of the data-collection activity and of the application of Kalman filtering (Gelb, 1974) to the determination of the accuracy of a stream-gaging record are presented below. For more detail on either the theory or the applications of K-CERA, see Moss and Gilroy (1980) and Gilroy and Moss (1981).

Description of Mathematical Program

The program, called "The Traveling Hydrographer," attempts to allocate among stream gages 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 stream gages 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 stream gages and the least-cost travel that takes the hydrographer from his base of operations to each of the gages and back to the base. A route will have associated with it an average cost of travel and average cost of servicing each stream gage 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 stream gage with that gage as the lone stop and return to the home base so that the individual needs of a stream gage can be considered in isolation from the other gages.

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 periodic 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 gage.

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. The mathematical-programming form of the optimization of the routing of hydrographers is as follows:

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

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 5 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, βi, are the per-trip costs of the hydrographer's travel time and any related per diem and operation, maintenance, and rental costs of vehicles. The sum of the products of βi and N_i for $i = 1, 2, \ldots, NR$ is the total travel cost associated with the set of decisions $N = (N_1, N_2, \ldots, N_{NR})$.

The unit-visit cost, α_j, is comprised of the average service and maintenance costs incurred on a visit to the station plus the average cost of making a discharge measurement. The set of minimum visit constraints is denoted by the row λ_j, $j = 1, 2, \ldots, MG$, where MG is the number of stream gages. The row of integers M_j, $j = 1, 2, \ldots, MG$ 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 X_j for all j if $\underline{N}$ is to be a feasible solution to the decision problem.

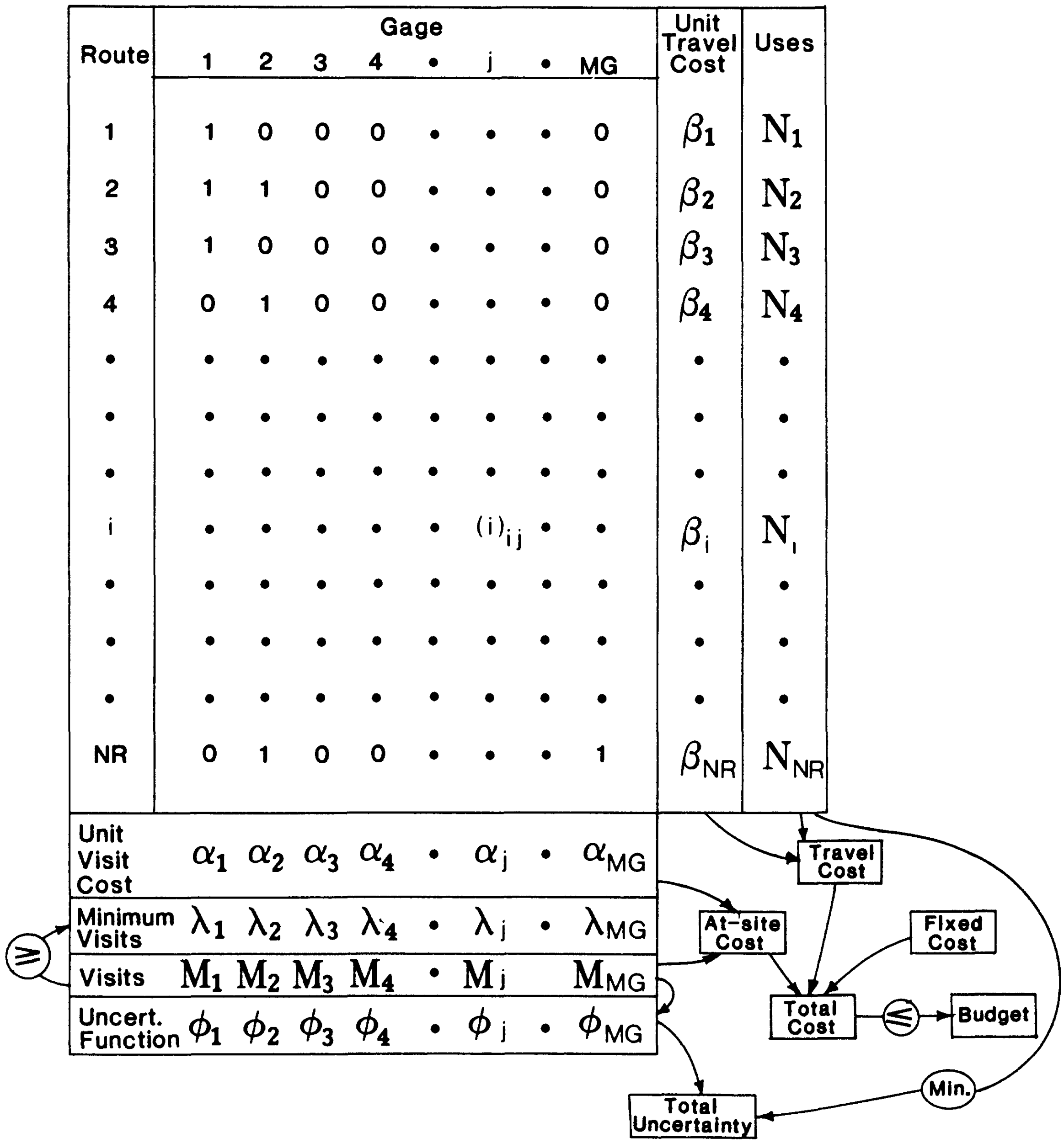

Figure 5.--Tabular form of optimization of routing of hydrographers

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, and 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 specify 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.

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:

$$\overline{V} = \varepsilon_f V_f + \varepsilon_r V_r + \varepsilon_e V_e \quad , \qquad (3)$$

with

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

where:

$\overline{V}$ is the average relative variance of the errors of streamflow estimates,

ε_f is the fraction of time that the primary recorders are functioning,

V_f is the relative variance of the errors of flow estimate 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, τ, 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:

$$f(\tau) = ke^{-k\tau}/(1-e^{-ks}) \quad , \qquad (4)$$

where:

k is the failure rate in units of 1/(days),

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,

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

(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 times between failures at both sites are independent and have negative exponential distributions with the same rate constant. It then follows that

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

(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,

$$\varepsilon_r = 1 - \varepsilon_f - \varepsilon_e$$
$$= \left[(1-e^{-ks}) + 0.5(1-e^{-2ks})\right]/(ks). \qquad (6)$$

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 the time, t, and let $q_R(t)$ be the value that would be estimated using the rating curve. Then,

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

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, $x(t) - \hat{x}(t)$, cannot be determined as well. However, the statistical properties of $x(t) - \hat{x}(t)$, 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

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

The variance of the observed residuals z(t) is

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

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 regression curve could be applied from the time of recorder stoppage until the gage 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 variance 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:

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

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

$(\bar{C}_v)^2$ is used as an estimate of V_e.

The variance, V_r, of the relative error during periods of reconstructed streamflow records is estimated on the basis of correlation between records at the primary site and records from other nearby gaged sites. The correlation coefficient, ρ_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 ρ_c^2. Thus, the relative error variance of flow estimates at the primary site obtained from secondary information will be,

$$V_r = (1-\rho_c^2)(\overline{C_v})^2 \quad . \tag{13}$$

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 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

$$\text{Probability } \left[e^{-EGS} \leq (q_c(t)/q_T(t)) \leq e^{+EGS}\right] = 0.683 \quad . \tag{14}$$

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 South Carolina

As a result of the first two parts of this analysis, it has been recommended that 75 of the currently existing stream gages in the State of South Carolina be continued in operation. These 75 stream gages were subjected to the K-CERA analysis with results that are described below.

Definition of Missing Record Probabilities

As was 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_τ 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. To estimate 1/k in South Carolina, a 5-year period of actual data collection was used. Stream gages were visited on a consistent pattern during this 5-year period and a gage could be expected to be malfunctioning 6.2 and 5.3 percent of the time based on 6-week and monthly visitations, respectively. There was no reason to distinguish between gages on the basis of their exposure or equipment, so the 6.2 and 5.3 percent lost record with 6-week and monthly visitations were used to determine a value of 1/k of 365 days, which was used to determine ε_f, ε_e, and ε_r for 71 of the 75 stream gages as a function of the individual frequencies of visit.

Four stations (02148315, 02156500, 02160105, and 02160700), however, were visited 52 times per year for water-quality monitoring and were measured for discharge only eight times on those visits. In order to optimize over the number of discharge measurements made, two uncertainty curves were stored for each of the four stations. One curve was constant due to the uncertainty contributed by lost record when the stations were visited weekly. This constant value is given by

$$V_{lost}(52) = P_c(52)V_c + Pn(52)Vn \quad , \tag{15}$$

where:

$V_{lost}(52)$ is the total variance of the error based on 52 visits per year,

$P_c(52)$ is the probability of reconstructing streamflow data from nearby sites based on 52 visits per year,

V_c is the variance of the error during periods of reconstructed streamflow records,

$Pn(52)$ is the probability of unavailable data for the reconstruction of streamflow records based on 52 visits per year,

and

Vn is the variance of the error during periods of unavailable data for reconstruction of streamflow records.

The second uncertainty curve for each of the four stations was obtained by using the process variance, the measurement variance, and the 1-day autocorrelation coefficient parameters from the rating residuals. The uncertainty from the lost record was not considered in this curve. The total uncertainty for each station was weighted from the two curves.

Definition of Cross-Correlation Coefficient and Coefficient of Variation

To compute the values of V_e and V_r of the needed uncertainty fuctions, daily streamflow records for each of the 75 stations for the last 30 years or the part of the last 30 years for which daily streamflow values are stored in WATSTORE (Hutchinson, 1975) were retrieved. For each of the stream gages that had three or more complete water years of data, the value of C_v was computed and various options, based on combinations of other stream gages, were explored to determine the maximum pc. For the 12 stations that had less than three water years of data, values of C_v and ρ_c were estimated subjectively. In addition to other nearby stream gages, some of the stations have other means by which streamflow data can be reconstructed when the primary recorder malfunctions. Eight stations are equipped with telemetry systems that operate independently from the primary recorder and are routinely queried either once or twice per day. At another station, a local resident reads and records stage once or twice daily. Two sites have an auxiliary recorder to provide backup stage record.

Analyses were performed to determine cross correlation, ρc, between daily discharges at sites with one or another of these types of auxiliary records by Fontaine and others (1983). For the case of daily or twice-daily readings of stage (observer or telemetry) a value of 0.96 or 0.99 was assigned to ρ_c, respectively. For the case of supplemental recorders at stations a value of 0.99 was assigned to ρ_c because very little record was lost.

The set of parameters for each station and the auxiliary records that gave the highest cross correlation coefficient are listed in table 10.

Kalman-Filter Definition of Variance

The determination of the variance V_f for each of the 75 stream gages required the execution of three distinct steps:

1. long-term streamflow 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 South Carolina program analysis, a single rating function was used to define the entire year for long-term ratings. Existing rating curves, in most cases, defined the long-term rating function required in the analysis. In the cases where this was not true, the shifts in the curves have been extensions at the high end of the curves or slight adjustments in the extreme low ends of the curves. In these cases, a mean curve was determined graphically.

Table 10.--Statistics of record reconstruction

Station number	C_v	p_c	Source of reconstructed records
02110500	1.1939	0.7723	135000 136000
02129590	1.3970	0.9476	136000
02130900	0.6488	0.8852	130910
02130910	0.4971	0.8967	131309 135300 130900
02131000	0.7240	0.7383	132000
02131150	1.2067	0.6387	135500
02131309	1.0065	0.6883	130900
02131472*	0.73	0.86	
02132000	0.8503	0.95	Observer; read daily
02135000	0.9114	0.7723	110500
02135300	0.8364	0.7571	135500
02135500	1.1977	0.8267	136000
02136000	1.3970	0.8267	135500
02146000	0.7649	0.8782	147000
02147000	0.6930	0.8782	146000
02148000	0.7850	0.99	Telemetry
02148315	0.4647	0.99	Telemetry
02153780*	0.73	0.86	
02154500	0.8665	0.9300	155500
02155500	0.9347	0.9300	154500
02156050	0.9776	0.8393	161500
02156450*	0.73	0.86	
02156500	0.9098	0.99	Telemetry
02157000	1.0513	0.7983	154500
02160105	0.7332	0.99	Telemetry
02160700	0.7552	0.99	Telemetry
02160775*	0.74	0.61	
02161000*	0.98	0.99	Telemetry
02161700*	0.73	0.86	
02162010	0.7460	0.6090	132000
02162093	0.6304	0.9138	173000
02162350*	0.75	0.45	
02162525*	0.75	0.45	
02163500	0.7913	0.7206	161500
02165000	0.9756	0.7431	169570
02166970*	0.74	0.61	
02167000	0.7749	0.99	Supplemental recorder at site
02169000	0.7749	0.99	Supplemental recorder at site
02169500	0.8410	0.99	Telemetry
02169570	0.9756	0.6499	169630
02169630	0.9756	0.6081	169570
02170500	0.6304	0.8652	169500
02171500	0.8665	0.4481	171560
02171560	0.9756	0.4956	171500
02171650	1.7506	0.7263	171500
02171680	1.8598	0.5070	171650

Table 10.--Statistics of record reconstruction--Continued

Station number	C_v	p_c	Source of reconstructed records
02172640*	0.63	0.92	
02173000	0.6304	0.9160	173500
02173500	0.5472	0.9346	174000
02174000	0.6239	0.9346	173500
02175000	0.8811	0.9244	174000
02175500	0.7774	0.8448	174000
02176500	1.5264	0.7432	
02176875	0.7774	0.7432	
02185200	0.7460	0.4492	174000
02196250*	0.42	0.66	
02197000	0.4545	0.99	Telemetry
02197300	0.2383	0.6096	197400
02197310	0.3005	0.8526	197315
02197315	0.3050	0.8526	197310
02197320	0.3763	0.4528	197315
02197326	0.1661	0.7466	197330
02197330	0.3771	0.3212	197310
02197332	0.4707	0.3902	197340
02197334	0.6845	0.8670	197342
02197336	0.6177	0.8998	197340
02197338	0.3483	0.4282	197340
02197339*	0.35	0.43	
02197340	0.5441	0.8998	197346
02197342	0.5991	0.8670	197334
02197344	0.5129	0.1826	197338
02197348	0.4580	0.1172	197342
02197359	0.4767	0.4637	197400
02197400	0.5327	0.5149	173000
02198500	0.7770	0.7432	197000

*Less than 3 years of data are available. Estimates of C_v and p_c are subjective.

Results of the rating analysis of many stream-gaging stations often yield ratings about which there were large amounts of variance, but some of the ratings had tight fits about the available discharge. The rating curves were developed using discharge in cubic feet per second and the residuals were converted to logarithmic units (base 10) before the autocovariance analysis.

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 autocovariance function to the time series of residuals. Measurement variance, the third parameter, was determined for individual stations. If a measurement had a rating of excellent it was assigned a value of 2 percent error. Measurements with ratings of good and fair were assumed to have errors of 5 percent and 8 percent, respectively. Poor measurements were assigned a value greater than 8 percent. These ratings were weighted and an average value was given to each station.

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 9 presents a summary of the autocovariance analysis expressed in terms of process variance and 1-day autocorrelation. Typical fits of the autocovariance functions for selected stations in South Carolina are given in figures 6 and 7.

The autocovariance parameters, summarized in table 11, and data from the definition of missing record probabilities, summarized in table 10, are used jointly to define uncertainty functions for each gaging station. The uncertainty functions give the relation of total error variance to the number of visits and discharge measurements. Uncertainty functions for the stations for which graphical fits of the autocovariance functions were previously given are presented as typical examples in figure 8. These functions are based on the assumption that a measurement was made during each visit to the station.

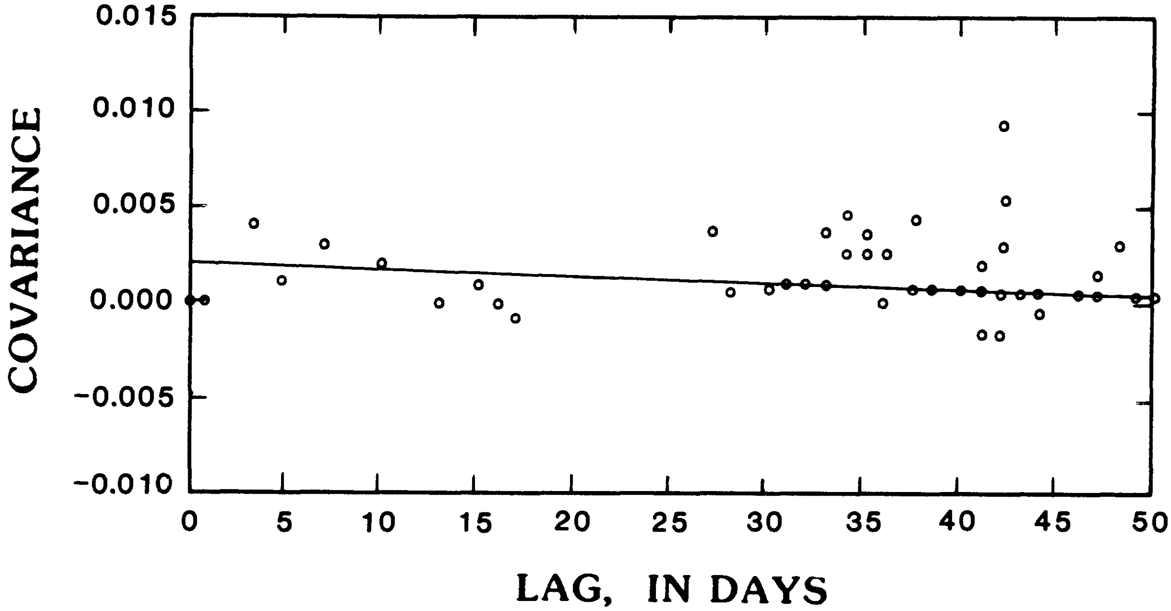

Figure 6.--Autocovariance function for station 02160700

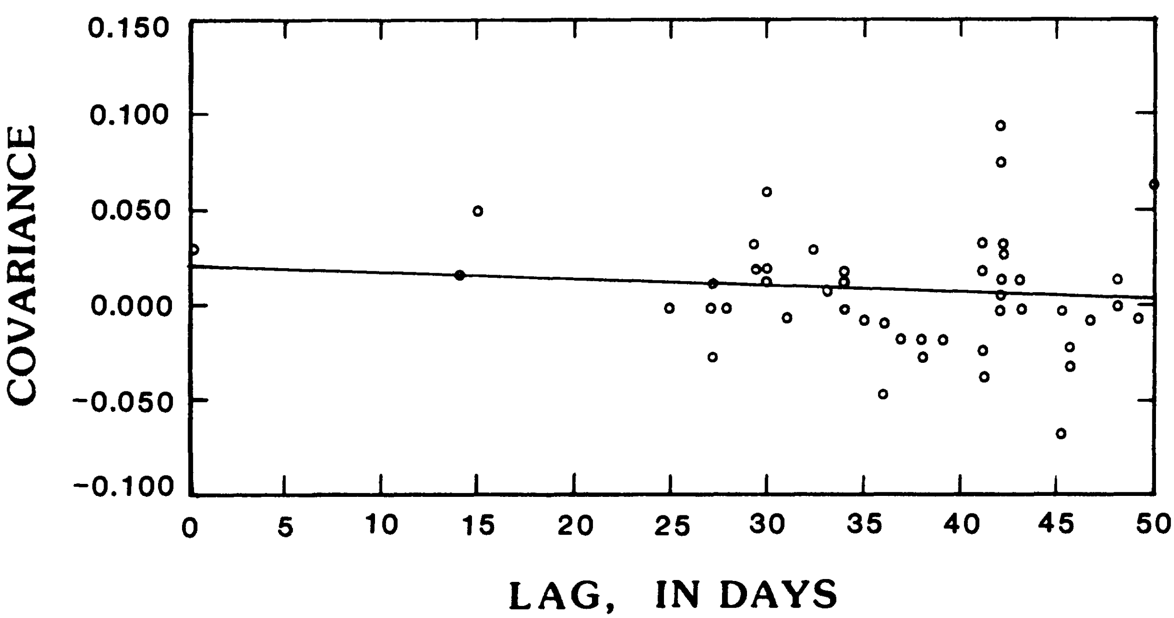

Figure 7.--Autocovariance function for station 02171680

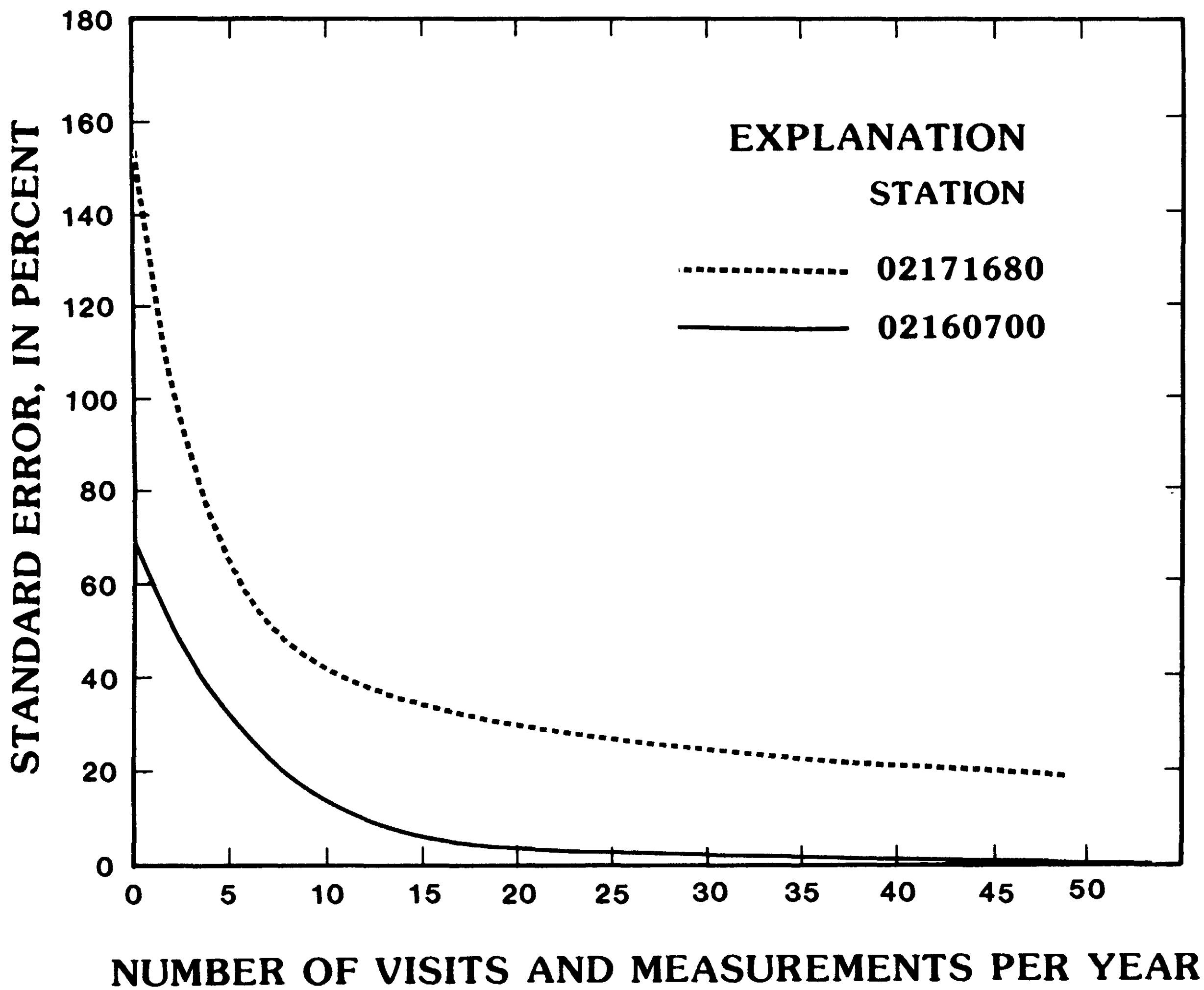

Figure 8.--Typical uncertainty function for instantaneous discharge

Table 11.--Summary of the autocovariance analysis

Station number	Rho*	Measurement variance (log base 10)^2	Process variance (log base 10)^2
02110500	0.975	7.5×10^{-5}	1.7×10^{-3}
02129590	0.974	6.4×10^{-4}	6.0×10^{-3}
02130900	0.919	8.1×10^{-4}	2.1×10^{-3}
02130910	0.986	4.7×10^{-4}	4.7×10^{-4}
02131000	0.885	1.2×10^{-3}	1.5×10^{-3}
02131150	0.982	7.8×10^{-4}	2.9×10^{-2}
02131309	0.980	6.9×10^{-4}	9.6×10^{-3}
02131472	0.985	6.0×10^{-4}	1.8×10^{-3}
02132000	0.957	4.7×10^{-4}	4.2×10^{-4}
02135000	0.975	6.6×10^{-4}	1.7×10^{-3}
02135300	0.980	6.8×10^{-4}	1.6×10^{-3}
02135500	0.985	1.1×10^{-3}	1.1×10^{-2}
02136000	0.971	7.9×10^{-4}	3.5×10^{-3}
02146000	0.971	8.1×10^{-4}	1.3×10^{-3}
02147000	0.955	8.7×10^{-4}	5.9×10^{-3}
02148000	0.982	7.3×10^{-4}	1.8×10^{-2}
02148315	0.978	5.7×10^{-4}	6.6×10^{-4}
02153780	0.997	8.6×10^{-4}	6.7×10^{-3}
02154500	0.992	4.7×10^{-4}	6.7×10^{-4}
02155500	0.983	4.7×10^{-4}	9.7×10^{-4}
02156050	0.957	6.9×10^{-4}	8.9×10^{-3}
02156450	0.961	7.1×10^{-4}	1.8×10^{-2}
02156500	0.992	4.7×10^{-4}	7.6×10^{-4}
02157000	0.987	4.7×10^{-4}	7.8×10^{-4}
02160105	0.978	5.6×10^{-4}	8.3×10^{-4}
02160700	0.986	5.7×10^{-4}	3.4×10^{-4}
02160775	0.929	8.1×10^{-4}	6.1×10^{-3}
02161000	0.979	8.5×10^{-4}	9.4×10^{-4}
02161700	0.986	7.5×10^{-4}	5.1×10^{-2}
02162010	0.992	7.9×10^{-4}	5.1×10^{-2}
02162093	0.856	8.7×10^{-4}	3.6×10^{-3}
02162350	0.988	8.6×10^{-4}	3.7×10^{-4}
02162525	0.967	6.3×10^{-4}	1.3×10^{-2}
02163500	0.977	4.7×10^{-4}	5.4×10^{-3}
02165000	0.986	6.7×10^{-4}	1.1×10^{-2}
02166970	0.977	8.7×10^{-4}	1.7×10^{-2}
02167000	0.949	7.7×10^{-4}	4.4×10^{-3}
02169000	0.955	9.9×10^{-4}	3.1×10^{-3}
02169500	0.966	6.6×10^{-4}	8.7×10^{-4}
02169570	0.980	5.9×10^{-4}	3.8×10^{-3}
02169630	0.980	4.7×10^{-4}	6.6×10^{-4}
02170500	0.894	4.9×10^{-4}	1.2×10^{-3}
02171500	0.993	5.1×10^{-4}	4.8×10^{-3}
02171560	0.980	6.4×10^{-4}	1.1×10^{-3}
02171650	0.994	5.6×10^{-4}	3.1×10^{-3}

Table 11.--Summary of the autocovariance analysis--Continued

Station number	Rho*	Measurement variance (log base 10)^2	Process variance (log base 10)^2
02171680	0.973	$1.3x10^{-3}$	$1.9x10^{-2}$
02172640	0.980	$4.9x10^{-4}$	$2.5x10^{-3}$
02173000	0.961	$6.1x10^{-4}$	$1.8x10^{-3}$
02173500	0.981	$4.9x10^{-4}$	$1.0x10^{-5}$
02174000	0.985	$9.2x10^{-4}$	$1.0x10^{-5}$
02175000	0.601	$4.7x10^{-4}$	$6.1x10^{-4}$
02175500	0.983	$6.6x10^{-4}$	$1.1x10^{-3}$
02176500	0.982	$1.3x10^{-3}$	$2.7x10^{-2}$
02176875	0.979	$1.1x10^{-3}$	$1.4x10^{-2}$
02185200	0.973	$4.7x10^{-4}$	$5.3x10^{-4}$
02196250	0.963	$6.1x10^{-4}$	$1.4x10^{-2}$
02197000	0.923	$5.9x10^{-4}$	$9.0x10^{-4}$
02197300	0.985	$4.8x10^{-4}$	$1.5x10^{-3}$
02197310	0.992	$4.7x10^{-4}$	$2.4x10^{-4}$
02197315	0.975	$5.8x10^{-4}$	$9.2x10^{-4}$
02197320	0.986	$4.7x10^{-4}$	$4.0x10^{-5}$
02197326	0.987	$5.8x10^{-4}$	$3.9x10^{-3}$
02197330	0.977	$4.7x10^{-4}$	$4.5x10^{-3}$
02197332	0.956	$6.8x10^{-4}$	$1.0x10^{-2}$
02197334	0.562	$4.7x10^{-4}$	$6.3x10^{-4}$
02197336	0.984	$7.6x10^{-4}$	$8.4x10^{-3}$
02197338	0.983	$4.7x10^{-4}$	$8.4x10^{-3}$
02197339	0.996	$6.8x10^{-4}$	$5.4x10^{-2}$
02197340	0.992	$1.2x10^{-3}$	$5.5x10^{-2}$
02197342	0.967	$5.1x10^{-4}$	$2.0x10^{-5}$
02197344	0.983	$5.9x10^{-4}$	$8.5x10^{-4}$
02197348	0.993	$4.9x10^{-4}$	$3.3x10^{-3}$
02197359	0.926	$4.7x10^{-4}$	$2.1x10^{-3}$
02197400	0.978	$9.2x10^{-4}$	$4.6x10^{-3}$
02198500	0.969	$3.0x10^{-4}$	$2.4x10^{-4}$

*One-day autocorrelation coefficient.

Determination of Routes and Costs

In South Carolina, feasible routes to service the 75 stream gages were determined after consultation with personnel in the Hydrologic Data Section of the South Carolina office and after review of the uncertainty funtions. In summary, 77 routes were selected to service all the stream gages in South Carolina. These routes included 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 gages where the levels of uncertainty indicated more frequent visits might be useful. These routes and the stations visited are summarized in table 12. Negative numbers in table 12 were assigned to stations other than stream-gaging stations, that is, water quality, stage only, crest-stage, and ground water.

The cost associated with the established routes was determined from previous expense records. Vehicle rental, mileage, maintenance, hydrographer salary, and per diem were included in the travel costs. Fixed costs to operate a gage typically include equipment rental, batteries, electricity, data processing and storage, computer charges, maintenance and miscellaneous supplies, and analysis and supervisory charges. For South Carolina, average values were applied to each station in the program for all the above categories based on past experience.

Visit costs are those associated with paying the hydrographer for the time actually spent at a station servicing the equipment and making a discharge measurement. Average visit times were calculated for each station based on an analysis of available discharge measurement data. This time was then multiplied by the average hourly salary of hydrographers in the South Carolina office to determine total visit costs.

Route costs include the vehicle cost associated with traveling the number of miles in the route, the cost of the hydrographer's time while in transit, and any per diem associated with the trip.

Table 12.--Summary of the routes that may be used to visit stations in South Carolina [Negative numbers represent stations other than surface-water stations]

Route number	Stations serviced on the route						
1	-1*	02110500	-2	-3	02135000	-4	-5
	-6	-7	-8	02129590	-9	02131150	02131000
	-10	-11	-12	-13	-14	02132000	-15
	02136000	-16	-17	-18	-19	02171560	02171680
2	02110500	02135000	02131000	02131150	02129590	02132000	02136000
	02171560	02171680					
3	-1	02110500	-2	-3	02135000	-4	-5
	-6	-7	-8	-9	-10	-11	-12
	-13	-14	02132000				
4	02110500	02135000	02129590	02131150	02131000	02132000	
5	-15	02136000	-16	-17	-18	02171500	-19
	02171560	02170500	02171650	02171680			
6	02136000	02171500	02171560	02170500	02171650	02171680	
7	-1	02110500	-2	-3	02135000		
8	02135000	02131150					
9	02129590	02131150					
10	02129590	02131150	02135000				
11	02131150	02131000	02135000				
12	02135000	02131000	02132000				
13	-20	02148000	02131472	-21	02131309	02147000	02146000
	-22	02153780	-23	02156450	-24	02161700	02160775
14	02148000	02131472	02131309	02147000	02146000	02153780	02156450
	02161700	02160775					
15	02162093	02162010	-24	02131309	-21	02131472	02148000
	-20	-25					
16	02162093	02162010	02148000	02131472	02131309		
17	02161000	02160775	02160700	02160105	02156500	02161700	02162010

Table 12.--Summary of the routes that may be used to visit stations in South Carolina--Continued [Negative numbers represent stations other than surface-water stations]

Route number	Stations serviced on the route						
18	02162093	02162010	02161700	02156500	02156450	02153780	
19	02131309	02131472					
20	02146000	02147000					
21	02153780	02156450					
22	02175000	02176500					
23	-25	-26	02156500	02160105	02160700	-27	02161000
24	02162010	-28	-29	-30	-31	02157000	-32
	02156050	02154500	02155500	-33	-34		
25	02162010	02157000	02156050	02154500	02155500		
26	02162010	02161000	-28	-29	-30	-31	02157000
	02156050	02154500	02155500	-33	-34	-23	02156450
	02156500	02160105	02160700	02160775			
27	02162010	02161000	02157000	02156050	02154500	02155500	02156450
	02156500	02160105	02160700	02160775			
28	02162010	02161000	-29	-30	-31	02167000	-32
	02156050	02154500	02155500	-33	-34	-23	02160105
	02160700	02160775					
29	02162010	02161000	02167000	02156050	02154500	02155500	02160105
	02160700	02160775					
30	02162010	02161000					
31	02156050	02157000					
32	02167000	02166970	02163500	02105000	-35	-36	-37
	-38	-39	-40	-41	-42	-43	-44
	-45	02162525	-46	02162350	02185200	-47	-48
	-49	-50	02196250	02197000			
33	02167000	02166970	02163500	02165000	02162525	02162350	02185200
	02196250	02197000					
34	02167000	02166970	02163500	02165000	-35	-48	-49
	-50	02196250	02197000				

Table 12.--Summary of the routes that may be used to visit stations in South Carolina--Continued [Negative numbers represent stations other than surface-water stations]

Route number	Stations serviced on the route						
35	-39	-40	-38	-41	-42	-43	-44
	-45	02162525	-46	02162350	02185200	-47	-36
36	02165000	02163500	02166970	02167000			
37	02165000	02167000					
38	02165000	02163500					
39	02162350	02162525					
40	-51	02172640	-52	-53	02198500	-56	-57
	-58	-59	-60	-61	-62	-63	-64
	02175500	-55	02173000	-54			
41	02169630	02174000	-65	-66	-67	-68	-69
	-70						
42	02169630	02173500					
43	02169630	02173500	02174000				
44	02172640	02173000					
45	02173000	02175500					
46	02198500	02176875					
47	02173000	02198500	02176875				
48	02148000	02135300					
49	-71	-72	-73	-74	-75	-76	-77
	-78	-79	02130900	02130910	-80	-81	02135500
	-82	02169570	02162093	02169000	02169500		
50	02130900	02130910	02135500	02169570	02162093	02169000	02169500
51	02135300	02175000	-83	-84	02176500	-85	02176875
	-86						
52	02169570	02135300	02131000	02132000	02135500		

Table 12.--Summary of the routes that may be used to visit stations in South Carolina--Continued [Negative numbers represent stations other than surface-water stations]

Route number	Stations serviced on the route						
53	02197300	02197310	02197315	02197320	02197326	02197330	02197332
	02197334	02197336	02197338	02197339	02197340	02197342	02197344
	02197348	02197359	02197400	-87	-88	-89	-90
	-91	-92	-94	-95	-96	-97	
54	02197300	02197310	02197315	02197320	02197326	02197330	02197332
	02197334	02197336	02197338	02197339	02197340	02197342	02197344
	02197348	02197359	02197400				
55	02148315	-93	02170500	02171500	02171650		
56	02110500						
57	02129590						
58	02131150						
59	02135500						
60	02156450						
61	02160775						
62	02173500						
63	02162010						
64	02166970						
65	02169570						
66	02171500						
67	02171560						
68	02171650						
69	02171680						
70	02176500						
71	02176875						
72	02196250						

Table 12.--Summary of the routes that may be used to visit stations in South Carolina--Continued [Negative numbers represent stations other than surface-water stations]

Route number	Stations serviced on the route
73	02148315
74	02156500
75	02160105
76	02160700
77	02161000

K-CERA Results

The "Traveling Hydrographer Program" utilizes the uncertainty functions, appropriate cost data and route definitions to compute the most cost-effective way to operate the stream-gaging program. In this application, the first step was to simulate the current practice and determine the total uncertainty associated with it. To accomplish this, the number of visits being made to each stream gage and the specific routes being used to make these visits were fixed. In South Carolina, current practice indicates that discharge measurements are made on approximately 50 percent of the visits for 17 stations and 95 percent for 58 stations. These values were determined from past records. The resulting average error of estimation for the current practice in South Carolina is plotted as a point in figure 9 and is 16.9 percent.

The solid line on figure 9 represents the minimum level of average uncertainty that can be obtained for a given budget with the existing instrumentation and technology. The line was defined by several runs of the "Traveling Hydrographer Program" with different budgets. Constraints on the operations other than budget were defined as described below.

To determine the minimum number of times each station must be visited, consideration was given only to the physical limitations of the method used to record data. The effect of visitation frequency on the accuracy of the data and the amount of lost record is taken into account in the uncertainty analysis. Minimum visit requirements should also reflect the need to visit stations for special reasons such as water-quality sampling. Several stations in South Carolina have multiple functions, that is, stage only and quality of water, or discharge and quality of water. In South Carolina, minimum visit requirements of 4 and 12 visits per year were selected and applied to the appropriate stations.

The results in figure 9 and table 13 summarize the K-CERA analysis and are predicated on a discharge measurement being made each time that a station is visited. This is a change from the current policy under which a measurement is made on an overall average of 85 percent of the visits. It should be emphasized that figure 9 and table 11 are based on various assumptions (stated previously) concerning both the time series of shifts to the stage-discharge relation and the methods of reconstruction.

It can be seen that the current policy results in an average standard error of estimate of streamflow of 16.9 percent. This policy requires a budget of $417,200 to operate the 75-station stream-gaging program and stage-only and crest-stage stations. The range in standard errors is from a low of 2.3 percent for station 02160700, to a high of 44.8 percent for station 02171680. It is possible to obtain this same average standard error with a reduced budget of about $395,000 with a change in policy in the field activities of the stream-gaging program. This policy and budget change would result in a decrease in standard error from 2.3 to 1.2 percent at station 02160700, while the standard error at station 02171680 would decrease from 44.8 to 31.5 percent. However, these two stations would still have the extreme values of standard error.

It also would be possible to reduce the average standard error by a policy change while maintaining the same budget of $417,200. In this case, the average would decrease from 16.9 to 15.5 percent. Extremes of standard errors for individual sites would be 2.7 and 31.5 percent for stations 02160700 and 02171680, respectively.

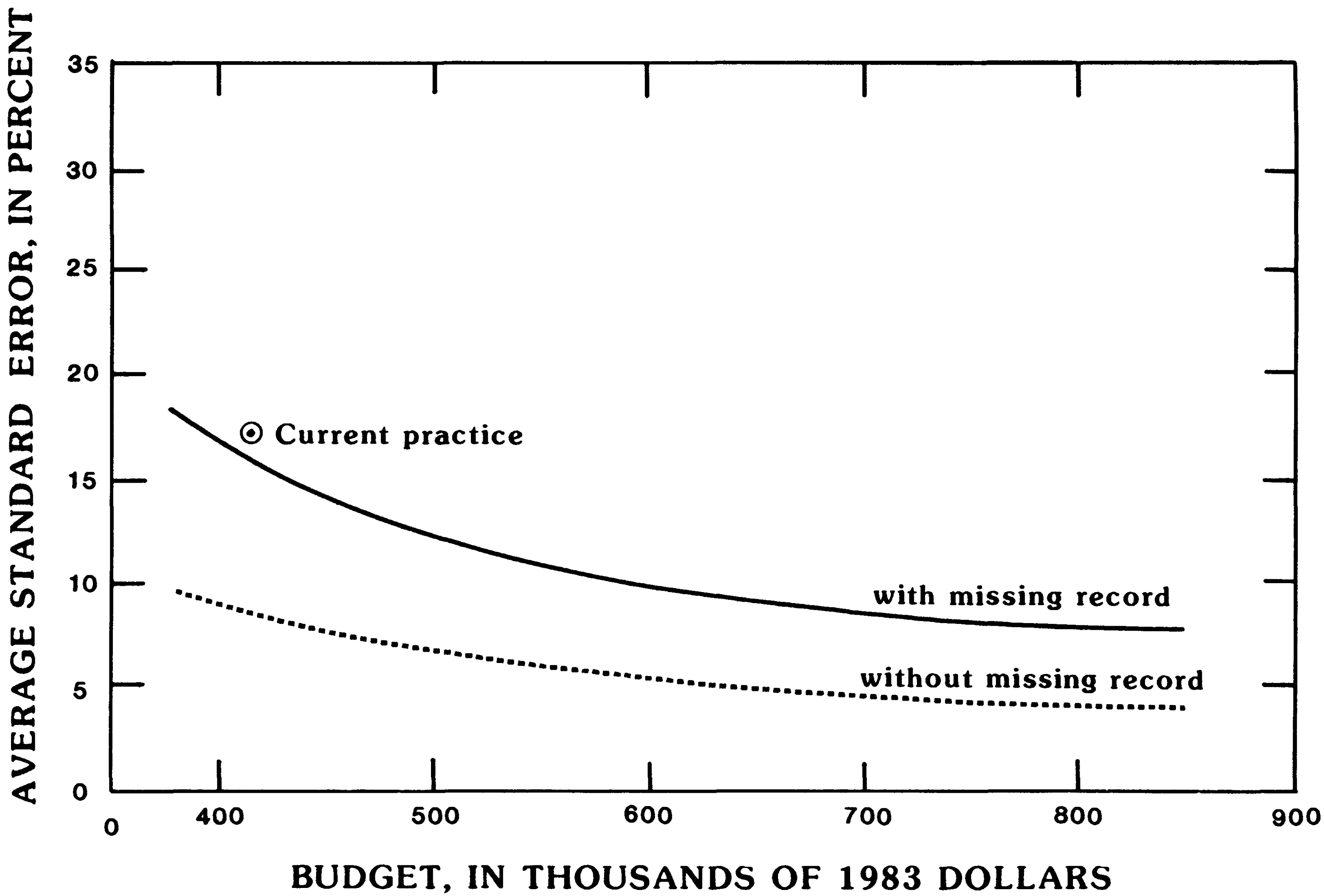

Figure 9.--Average standard error per stream-gage

Table 13.--Selected results of K-CERA analysis

Identification	Standard error of instantaneous discharge, in percent [Equivalent Gaussian spread] (Number of visits per year to site)					
	Current operation	Budget, in thousands of 1983 dollars				
		383.5	395	417.2	600	850
Average per station*	16.9 [8.5]	18.6 [9.5]	16.9 [8.9]	15.5 [8.2]	9.8 [5.3]	7.6 [4.1]
02110500	20.0 [6.6] (8)	22.8 [7.5] (6)	18.9 [6.2] (9)	18.9 [6.2] (9)	9.6 [3.1] (36)	7.0 [2.3] (69)
02129590	19.7 [17.6] (8)	22.5 [19.1] (4)	22.5 [19.1] (4)	19.2 [17.3] (9)	15.6 [14.6] (24)	11.1 [10.4] (65)
02130900	11.7 [9.8] (8)	13.9 [11.0] (4)	13.9 [11.0] (4)	12.6 [10.3] (6)	9.3 [8.1] (17)	7.0 [6.1] (37)
02130910	6.3 [2.8] (8)	8.6 [3.9] (4)	8.6 [3.9] (4)	7.2 [3.3] (6)	4.4 [2.0] (17)	3.0 [1.3] (37)
02131000	14.8 [9.3] (8)	18.7 [10.1] (4)	17.3 [9.8] (5)	13.4 [9.0] (11)	11.1 [8.4] (21)	8.9 [7.4] (47)
02131150	31.4 [23.4] (8)	31.4 [23.4] (8)	26.0 [19.0] (12)	25.0 [18.2] (13)	13.6 [9.6] (46)	10.2 [7.2] (82)
02131309	22.3 [14.3] (8)	23.6 [15.2] (7)	21.1 [13.5] (9)	19.3 [12.2] (11)	11.1 [6.8] (35)	8.3 [5.1] (64)
02131472	11.5 [5.7] (8)	12.4 [6.0] (7)	10.8 [5.3] (9)	9.8 [4.8] (11)	5.4 [2.8] (35)	4.0 [2.1] (64)
02132000	13.3 [4.7] (8)	14.1 [4.8] (7)	16.3 [5.1] (5)	11.6 [4.4] (11)	8.7 [3.8] (21)	6.2 [3.0] (6.1)
02135000	15.6 [6.7] (8)	16.6 [7.1] (7)	14.8 [6.4] (9)	12.5 [5.4] (13)	7.5 [3.3] (38)	5.5 [2.5] (70)

Table 13.--Selected results of K-CERA analysis--Continued

Identification	Standard error of instantaneous discharge, in percent [Equivalent Gaussian spread] (Number of visits per year to site)					
	Current operation	Budget, in thousands of 1983 dollars				
		383.5	395	417.2	600	850
02135300	15.3 [7.8] (8)	17.1 [8.1] (6)	16.1 [7.9] (7)	14.6 [7.6] (9)	9.2 [6.0] (30)	7.3 [5.1] (53)
02135500	20.6 [13.3] (8)	25.4 [16.7] (5)	20.6 [13.3] (8)	19.5 [12.5] (9)	11.0 [6.9] (30)	8.0 [5.0] (58)
02136000	21.5 [10.0] (8)	21.5 [10.0] (8)	22.8 [10.5] (7)	16.1 [7.6] (15)	10.3 [4.9] (38)	7.4 [3.5] (75)
02146000	10.7 [6.2] (8)	13.0 [7.3] (5)	13.0 [7.3] (5)	9.7 [5.6] (10)	7.4 [4.4] (18)	5.3 [3.2] (36)
02147000	15.6 [14.4] (8)	17.7 [16.2] (5)	17.7 [16.2] (5)	14.6 [13.4] (10)	11.7 [10.7] (18)	8.7 [7.9] (36)
02148000	16.3 [15.3] (8)	18.7 [17.3] (6)	16.3 [15.3] (8)	13.9 [13.3] (11)	8.2 [8.1] (32)	6.4 [6.3] (54)
02148315	3.7 [3.6] (8)	4.6 [4.4] (4)	4.5 [4.5] (4)	4.6 [4.5] (4)	3.8 [3.8] (7)	2.7 [2.7] (17)
02153780	11.3 [5.1] (8)	13.3 [6.0] (6)	11.3 [5.1] (8)	10.0 [4.5] (10)	8.1 [3.7] (15)	6.2 [2.9] (25)
02154500	11.2 [8.7] (8)	15.2 [12.4] (4)	13.8 [11.1] (5)	11.9 [9.4] (7)	7.5 [5.6] (19)	5.7 [4.2] (34)
02155500	9.4 [4.4] (8)	12.8 [6.0] (4)	11.6 [5.4] (5)	10.0 [4.6] (7)	6.3 [2.9] (19)	4.7 [2.2] (34)
02156050	17.4 [12.4] (8)	23.2 [17.2] (4)	19.7 [14.3] (6)	18.4 [13.2] (7)	10.8 [7.5] (22)	8.0 [5.5] (41)

Table 13.--Selected results of K-CERA analysis--Continued

Identification	Standard error of instantaneous discharge, in percent [Equivalent Gaussian spread] (Number of visits per year to site)					
	Current operation	Budget, in thousands of 1983 dollars				
		383.5	395	417.2	600	850
02156450	24.9 [24.1] (8)	27.1 [26.2] (6)	26.0 [25.1] (7)	22.3 [21.6] (11)	13.0 [12.5] (37)	10.1 [9.6] (63)
02156500	3.6 [3.3] (8)	3.6 [3.6] (6)	3.6 [3.6] (6)	4.1 [3.6] (5)	3.6 [3.6] (6)	2.6 [2.6] (15)
02157000	16.1 [3.5] (8)	22.2 [5.0] (4)	18.4 [4.1] (6)	17.1 [3.8] (7)	9.9 [2.2] (22)	7.3 [1.6] (41)
02160105	4.2 [4.0] (8)	4.8 [4.7] (5)	4.8 [4.7] (5)	4.8 [4.7] (5)	3.8 [3.8] (9)	2.7 [2.7] (21)
02160700	2.3 [1.2] (8)	2.7 [0.45] (5)	1.2 [1.2] (4)	2.7 [1.2] (5)	1.2 [1.2] (4)	1.2 [1.2] (4)
02160775	21.2 [16.5] (8)	23.2 [17.6] (6)	23.2 [17.6] (6)	19.1 [15.2] (11)	11.8 [9.8] (37)	8.6 [7.1] (74)
02161000	8.8 [4.6] (8)	12.5 [5.5] (5)	12.5 [5.5] (5)	10.9 [5.2] (6)	5.6 [3.5] (15)	4.0 [2.8] (25)
02161700	27.3 [26.8] (8)	29.1 [28.5] (7)	27.3 [26.7] (8)	24.6 [24.0] (10)	24.6 [24.0] (10)	24.6 [24.0] (10)
02162010	24.9 [21.9] (8)	24.9 [21.9] (8)	20.5 [17.6] (12)	20.5 [17.6] (12)	11.3 [9.3] (41)	8.6 [7.1] (73)
02162093	14.1 [13.5] (8)	15.0 [14.2] (5)	14.6 [13.9] (6)	14.4 [13.7] (7)	12.2 [11.9] (19)	9.8 [9.5] (42)
02162350	17.1 [3.8] (8)	21.4 [4.5] (5)	19.6 [4.2] (6)	15.4 [3.6] (10)	9.7 [2.5] (26)	6.9 [1.9] (51)

Table 13.--Selected results of K-CERA analysis--Continued

Identification	Standard error of instantaneous discharge, in percent [Equivalent Gaussian spread] (Number of visits per year to site)					
	Current operation	Budget, in thousands of 1983 dollars				
		383.5	395	417.2	600	850
02162525	24.7 [19.9] (8)	29.3 [23.4] (5)	27.5 [22.1] (6)	22.6 [18.2] (10)	14.7 [11.7] (26)	10.6 [8.3] (51)
02163500	17.0 [11.2] (8)	20.7 [13.8] (5)	17.0 [11.2] (8)	15.4 [10.2] (10)	9.1 [5.9] (31)	7.0 [4.5] (53)
02165000	20.7 [14.2] (8)	25.5 [17.9] (5)	20.7 [14.2] (8)	18.7 [12.6] (10)	10.9 [7.1] (31)	7.9 [5.1] (60)
02166970	23.6 [20.0] (8)	28.5 [24.3] (5)	25.0 [21.2] (7)	21.5 [18.1] (10)	12.2 [10.0] (33)	9.4 [7.7] (57)
02167000	12.3 [12.3] (8)	13.3 [13.2] (5)	13.0 [13.0] (6)	11.6 [11.3] (10)	8.6 [8.6] (24)	6.6 [6.6] (45)
02169000	10.0 [10.0] (8)	11.7 [11.7] (4)	11.7 [11.7] (4)	10.7 [10.7] (6)	7.9 [7.9] (17)	5.8 [5.7] (37)
02169500	8.1 [5.1] (8)	13.2 [6.3] (4)	13.2 [6.3] (4)	9.9 [5.6] (6)	5.1 [3.9] (17)	3.3 [2.7] (37)
02169570	20.2 [9.0] (8)	21.4 [9.6] (7)	17.4 [7.8] (11)	18.2 [8.1] (10)	8.4 [3.8] (49)	6.4 [2.9] (86)
02169630	11.6 [3.9] (8)	14.6 [4.8] (5)	14.6 [4.8] (5)	14.6 [4.8] (5)	7.6 [2.6] (19)	5.6 [1.9] (35)
02170500	10.6 [7.9] (8)	10.0 [7.6] (10)	10.0 [7.6] (10)	10.0 [7.6] (10)	7.4 [6.0] (25)	6.1 [5.1] (41)
02171500	20.1 [6.4] (8)	18.1 [5.7] (10)	18.1 [5.7] (10)	18.1 [5.7] (10)	11.0 [3.4] (28)	8.2 [2.5] (51)

Table 13.--Selected results of K-CERA analysis--Continued

Identification	Standard error of instantaneous discharge, in percent [Equivalent Gaussian spread] (Number of visits per year to site)					
	Current operation	Budget, in thousands of 1983 dollars				
		383.5	395	417.2	600	850
02171560	21.6 [4.9] (8)	21.6 [4.9] (8)	21.6 [4.9] (8)	15.9 [3.7] (15)	10.1 [2.4] (38)	7.2 [1.7] (75)
02171650	30.3 [4.9] (8)	27.2 [4.3] (10)	26.0 [4.1] (11)	26.0 [4.1] (11)	13.6 [2.1] (41)	10.2 [1.6] (74)
02171680	44.8 [22.6] (8)	40.4 [20.4] (10)	31.5 [15.8] (17)	31.5 [15.8] (17)	16.8 [8.4] (62)	12.7 [6.4] (110)
02172640	10.0 [7.3] (8)	14.3 [9.8] (4)	14.3 [9.8] (4)	11.6 [8.3] (6)	7.3 [5.5] (15)	5.4 [4.1] (28)
02173000	9.5 [7.8] (8)	11.9 [9.6] (4)	11.1 [9.1] (5)	10.5 [8.8] (6)	6.0 [5.0] (25)	4.4 [3.6] (50)
02173500	5.9 [0.13] (12)	8.1 [0.23] (4)	8.1 [0.23] (4)	7.3 [0.20] (5)	4.4 [0.11] (15)	3.1 [0.08] (31)
02174000	5.5 [0.44] (8)	7.7 [0.62] (4)	7.7 [0.62] (4)	6.9 [0.55] (5)	5.5 [0.44] (8)	4.1 [0.33] (15)
02175000	10.0 [6.0] (8)	12.7 [6.5] (4)	12.7 [6.5] (4)	10.4 [6.1] (7)	10.0 [6.0] (8)	8.0 [5.7] (16)
02175500	11.2 [4.7] (8)	15.3 [6.5] (4)	15.3 [6.5] (4)	12.8 [6.2] (6)	9.3 [3.9] (12)	6.8 [2.9] (23)
02176500	32.8 [23.0] (8)	37.2 [26.4] (6)	29.6 [20.5] (10)	31.1 [21.7] (9)	15.0 [10.0] (41)	12.0 [8.0] (66)
02176875	21.1 [17.6] (8)	27.9 [23.4] (4)	22.3 [18.7] (7)	21.1 [17.6] (8)	12.0 [9.8] (27)	8.7 [7.1] (52)

Table 13.--Selected results of K-CERA analysis--Continued

Identification	Standard error of instantaneous discharge, in percent [Equivalent Gaussian spread] (Number of visits per year to site)					
	Current operation	Budget, in thousands of 1983 dollars				
		383.5	395	417.2	600	850
02185200	17.0 [3.9] (8)	21.1 [4.7] (5)	21.1 [4.7] (5)	15.2 [3.5] (10)	11.2 [2.7] (19)	8.7 [2.1] (32)
02196250	21.0 [20.6] (8)	25.0 [24.5] (4)	23.8 [23.4] (5)	19.5 [19.0] (10)	12.0 [11.6] (31)	8.7 [8.3] (61)
02197000	7.1 [6.3] (8)	9.0 [6.7] (4)	8.2 [6.6] (5)	6.7 [6.1] (10)	5.7 [5.5] (18)	4.7 [4.6] (33)
02197300	6.6 [5.4] (12)	6.6 [5.4] (12)	6.6 [5.4] (12)	6.6 [5.4] (12)	4.2 [3.4] (34)	3.2 [2.5] (62)
02197310	4.2 [1.8] (12)	4.2 [1.8] (12)	4.2 [1.8] (12)	4.2 [1.8] (12)	2.5 [1.1] (34)	1.8 [0.79) (62)
02197315	4.8 [4.8] (12)	4.8 [4.7] (12)	4.8 [4.7] (12)	4.8 [4.7] (12)	3.3 [3.3] (34)	2.6 [2.6] (62)
02197320	7.8 [0.91] (12)	7.8 [0.91] (12)	7.8 [0.91] (12)	7.8 [0.91] (12)	4.7 [0.56] (34)	3.5 [0.42] (62)
02197326	8.1 [8.0] (12)	8.1 [8.0] (12)	8.1 [8.0] (12)	8.1 [8.0] (12)	5.1 [5.0] (34)	3.9 [3.9] (62)
02197330	13.1 [11.0] (12)	13.1 [11.0] (12)	13.1 [11.0] (12)	13.1 [11.0] (12)	8.4 [6.9] (34)	6.3 [5.2] (62)
02197332	21.0 [19.7] (12)	21.0 [19.7] (12)	21.0 [19.7] (12)	21.0 [19.7] (12)	14.7 [13.8] (34)	11.3 [10.5] (62)
02197334	9.6 [6.1] (12)	9.6 [6.1] (12)	9.6 [6.1] (12)	9.6 [6.1] (12)	7.2 [5.7] (34)	6.4 [5.4] (62)

Table 13.--Selected results of K-CERA analysis--Continued

Identification	Standard error of instantaneous discharge, in percent [Equivalent Gaussian spread] (Number of visits per year to site)					
	Current operation	Budget, in thousands of 1983 dollars				
		383.5	395	417.2	600	850
02197336	13.6 [12.9] (12)	13.6 [12.9] (12)	13.6 [12.9] (12)	13.6 [12.9] (12)	8.6 [8.0] (34)	6.5 [6.0] (62)
02197338	14.4 [13.2] (12)	14.4 [13.2] (12)	14.4 [13.2] (12)	14.4 [13.2] (12)	9.0 [8.1] (34)	6.8 (6.1] (62)
02197339	17.3 [16.7] (12)	17.3 [16.7] (12)	17.3 [16.7] (12)	17.3 [16.7] (12)	10.6 [9.9] (34)	8.0 [7.4] (62)
02197340	23.2 [23.2] (12)	23.2 [23.2] (12)	23.2 [23.2] (12)	23.2 [23.2] (12)	14.0 [13.9] (34)	10.5 [10.4] (62)
02197342	6.9 [0.85] (12)	6.9 [0.85] (12)	6.9 [0.85] (12)	6.9 [0.85] (12)	4.2 [0.57] (34)	3.1 [0.44] (62)
02197344	12.3 [4.4] (12)	12.3 [4.4] (12)	12.3 [4.4] (12)	12.3 [4.4] (12)	7.5 [2.8] (34)	5.6 [2.1] (62)
02197348	11.7 [5.8] (12)	11.7 [5.8] (12)	11.7 [5.8] (12)	11.7 [5.8] (12)	7.1 [3.4] (34)	5.3 [2.6] (62)
02197359	13.3 [9.8] (12)	13.3 [9.8] (12)	13.3 [9.8] (12)	13.3 [9.8] (12)	9.3 [7.5] (34)	7.3 [6.1] (62)
02197400	14.7 [11.0] (12)	14.7 [11.0] (12)	14.7 [11.0] (12)	14.7 [11.0] (12)	9.3 [7.0] (34)	7.0 [5.2] (62)
02198500	13.8 [2.7] (8)	19.8 [3.6] (4)	14.8 [2.9] (7)	14.8 [2.9] (7)	7.6 [1.6] (26)	5.4 [1.2] (50)

*Square root of seasonally averaged station variance.

A minimum budget of $383,500 is required to operate the 75-discharge station program, including stage-only and crest-stage stations. A budget less than this does not permit proper service and maintenance of the gages and recorders. Stations would have to be eliminated from the program if the budget fell below this minimum. At the minimum budget, the average standard error is 18.6 percent. The minimum standard error of 2.7 percent would occur at station 02160700, while the maximum of 40.4 percent would occur at station 02171680.

The maximum budget analyzed was $850,000, which resulted in an average standard error of estimate of 7.6 percent. Thus, more than doubling the budget in conjunction with policy change would reduce the average standard error in excess of 50 percent from the current policy and current budget. For the $850,000 budget, the extremes of standard error are 24.6 for station 02161700 and 1.8 percent for station 02197310. Thus, it is apparent that significant improvements in accuracy of streamflow records can be obtained if larger budgets become available.

The analysis also was performed under the assumption that no correlative data at a stream gage were lost because of less than perfect instrumentation. The average standard errors of estimation of streamflow that could be obtained if perfectly reliable systems were available to measure and record the correlative data are 9.5 percent for the minimal operational budget of $383,500. Here, the impacts of less than perfect equipment are greatest.

At the other budgetary extreme of $850,000, under which stations are visited more frequently and the reliability of equipment should be less sensitive, average standard errors are 4.1 percent for ideal equipment. Thus, improved equipment can have a positive impact on streamflow uncertainties throughout the range of operational budgets that possibly could be anticipated for the stream-gaging program in South Carolina.

Conclusions from the K-CERA Analysis

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

1. The policy for the definition of field activities in the stream-gaging program should be altered to maintain the current average standard error of estimate of streamflow records of 16.9 percent with a budget of approximately $395,000. This shift would result in some increases and some decreases in accuracy of records at individual sites.

2. The amount of funding for stations with accuracies that are not acceptable for the data uses should be renegotiated with the data users.

3. The K-CERA analysis should be re-run with new stations included whenever sufficient information about the characteristics of new stations has been obtained.

4. Schemes for reducing the probabilities of missing record should be explored and evaluated as to their cost effectiveness in providing streamflow information. Several of these schemes are increased use of local gage observers, satellite relay of data, and backup recorder systems.

SUMMARY

Currently, 76 continuous-record stream gages are being operated in South Carolina at a cost of $422,200. Fifteen separate sources of funding contribute to this program and up to five separate uses were identified for data from a single gage.

In an analysis of the uses that are made of the data, station 02161500 was identified as having alternate methods of computing the streamflow record. Operation of this station should be discontinued. The remaining 75 stations should be maintained in the program for the foreseeable future.

The current policy for operation of the 75-discharge station program and the crest-stage and stage-only stations would require a budget of $417,200 per year. It was shown that the current overall level of accuracy of the records at these 75 sites could be maintained with approximately a $395,000 budget, including the stage-only and crest-stage gages, if the allocation of stream-gaging effort among gages was altered.

A major component of the error in streamflow records is caused by loss of primary record (stage or other correlative data) at the stream gages because of malfunctions of sensing and recording equipment. The upgrading of equipment and the development of strategies to minimize lost record appear to be key actions required to improve the reliability and accuracy of the streamflow data generated in the State.

Studies of the cost effectiveness of the 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 of reducing the probabilities of lost correlative data. Future studies also will be required because of changes in demands for streamflow information with subsequent addition and deletion of stream gages. Such changes will affect the operation of other stations in the program because of the dependence between stations of the information that is generated (data redundancy) and because of the dependence of the costs of collecting the data from which the information is derived.

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☆U.S. GOVERNMENT PRINTING OFFICE: 1986-638-694