COST-EFFECTIVENESS OF THE STREAM-GAGING PROGRAM IN MARYLAND, DELAWARE, AND THE DISTRICT OF COLUMBIA

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PREFACE

The collection of surface-water data is a major activity of the U.S. Geological Survey's Water Resources Division (WRD). Approximately $40 million was spent in 1985 by WRD in cooperation with State and local governments and other Federal agencies in the collection of these data. This major expenditure of funds for hydrologic data collection needs to be evaluated periodically with respect to the needs of the data users and the utility of the data. It is essential that a rigorous analysis be made of the stream-gaging program to assure maximum cost-effectiveness. The U.S. Geological Survey is undertaking a nationwide analysis of its stream-gaging program over a 5-year period. The results from such an analysis should satisfy both local and national water-data needs within budget constraints while maintaining quality control.

This report for the States of Maryland and Delaware and the District of Columbia (Md.-Del.-D.C.) is one in a series of statewide reports describing this analysis. The techniques and methods being utilized in the nationwide analysis are described and documented in this report as applied to the Md.-Del.-D.C. stream-gaging program.

Analysis of the stream-gaging program is designed to define and document the most cost-effective means of furnishing streamflow information. The stream-gaging activity is no longer considered a network of observation points, but rather an information system in which data are provided by both observation and synthesis. Alternative methods of providing streamflow information such as flow routing and statistical methods are investigated as to their cost-effectiveness, accuracy, and information content.

Recently, new techniques for evaluating the cost-effectiveness of data-collection programs have been developed. These techniques, Kalman filtering and mathematical programming, are utilized to define strategies for operating the stream-gaging program so that the uncertainty in the streamflow records is minimized. The U.S. Geological Survey first applied these techniques to a stream-gaging program in the Lower Colorado River Basin. Subsequently, the techniques have been expanded and improved, and are being applied to the present nationwide study of the Survey's stream-gaging program. No doubt these techniques will continue to be modified and improved over the duration of the study.

The analysis of the stream-gaging program is a part of the continuing effort of the U.S. Geological Survey to evaluate the Nation's water resources. The national stream-gaging program that results from this analysis should be responsive to the needs of local, State, and Federal agencies and provide streamflow information in the most cost-effective manner.

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CONVERSION FACTORS AND ABBREVIATIONS

For the convenience of readers who may prefer to use metric (International System) units rather than the inch-pound units used in this report, values may be converted by using the following factors:

Multiply inch-pound unit	By	To obtain metric unit
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.59	square kilometer (km^2)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
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 results of a cost-effectiveness study of the stream-gaging program in Maryland, Delaware, and the District of Columbia. Data uses and funding sources were identified for the 99 continuously operated stream gages being operated in Maryland, Delaware, and the District of Columbia by the U.S. Geological Survey in 1985. Data from three stream gages may not be of sufficient importance to warrant continued operation of the gages. Data collected at three other stations were identified as having uses primarily related to a short-term study. All six of these stations should be considered for discontinuation at the end of the data-collection phase of this study. The remaining 93 stations should be kept in the program for the foreseeable future.

The current (1985) policy for operation of the 99-station program requires a budget of $465,260 per year. The average standard error of estimation of streamflow records is 11.8 percent. It was shown that this overall level of accuracy at the 99 sites could be maintained with a budget of $461,000, if resources were redistributed among the gages.

A minimum budget of $448,500 is required to operate the 99-gage program; a smaller budget would not permit proper service and maintenance of the gages and recorders. At the minimum budget, with optimum operation, the average standard error would be 13.7 percent. The maximum budget analyzed was $700,000, which resulted in an average standard error of 5.3 percent.

The study indicates that a major component of error is caused by lost or missing data. If perfect equipment were available and no data were lost, the standard error for the current program and budget could be reduced to 8.0 percent. This also can be interpreted to mean that the streamflow data have a standard error of 8.0 percent during times when the equipment is operating properly.

INTRODUCTION

The U.S. Geological Survey (Survey) is the principal Federal agency collecting surface-water data in the Nation. The collection of these data is a major activity of the Water Resources Division of the Survey. The data are collected in cooperation with State and local governments and other Federal agencies. The Survey presently (1985) operates approximately 7,000 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 surface-water data, should be reexamined at intervals, if not continuously, because of changes in objectives, technology, or external constraints. The last systematic nationwide evaluation of the streamflow information program was completed in 1970 and is documented by Benson and Carter (1973). The 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 object of this analysis is to define and document the most cost-effective means of furnishing streamflow information.

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

The second phase of the analysis is to identify less costly methods of furnishing the needed information; among these are flow-routing models and statistical methods. The stream-gaging activity no longer is considered a network of observation points but rather an integrated information system in which data are provided both by 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 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 is an introduction to the stream-gaging activities in Maryland, Delaware, and the District of Columbia (Md.-Del.-D.C.) and to the study itself. The middle three sections each contain discussions of individual steps of the analysis. Because of the sequential nature of the steps and the dependence of subsequent steps on previous results, summaries of conclusions are given at the end of each middle section. The complete study is summarized in the final section.

Parts of this text have been excerpted from the prototype report for the nationwide network analyses; U.S. Geological Survey Water-Supply Paper 2244 (Fontaine and others, 1984).

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

History of the Stream-Gaging Program in Maryland, Delaware, and the District of Columbia

The U.S. Geological Survey program of surface-water investigations in Maryland, Delaware, and the District of Columbia (D.C.) began in July 1892 with the establishment of a gaging station on Rock Creek at Lyons Mill near Q Street, D.C. This site was discontinued in 1894. In June 1894, a gaging station was established on the North Branch Potomac River at Cumberland, Md., and, in February 1895, another station was put in operation at Point of Rocks, Md.

In 1896, the U.S. Geological Survey entered into a cooperative agreement with the State of Maryland to operate a stream-gaging network. By 1905, the gaging-station network had grown to 10 sites. However, State involvement gradually diminished and, by 1909, was terminated, reducing the network to two sites. From 1909 to 1923, the network remained essentially static (two to three sites). During this static period, the State of Maryland developed an interest in reestablishing the cooperative program with the Survey, and in 1924, a new cooperative agreement was signed.

With the resumption of cooperation between Maryland and the U.S. Geological Survey, the gaging-station network grew to 28 continuous-record gages by 1931, including five additional sites established when Delaware and the District of Columbia also entered into cooperative agreements with the Survey. This basic network of 28 stations gradually grew to 42 stations by 1943 as Maryland and Delaware expanded their programs to enhance their data bases for future hydraulic and hydrologic studies.

By 1950, the network had doubled in size to 87 continuous-record stations. This increase reflected increased coverage in New Castle County, Del., on the Eastern Shore of Maryland, and in southern Maryland. In addition, eight stations had been established to monitor the Baltimore City reservoir system and five others to monitor the Washington Suburban Sanitary Commission reservoir system which supplies the Washington, D.C., area. Also, in western Maryland, eight continuous-record stations had been established to monitor streamflow on the North Branch Potomac River.

The size of the network varied little during the 1950's. However, in the 1960's the network expanded again when, along with other additions, three new sites were added in Delaware and seven sites were established in Montgomery County, Md., for an urbanization study of the Rock Creek and Anacostia River basins. By 1969, the gaging-station network had reached a peak of 117 continuous-record sites.

In 1970, an evaluation of the network was made which outlined accuracy criteria for the program and examined the accumulated data in relation to these criteria. This study by Forrest and Walker (1970) proposed discontinuing 24 stations and establishing two new stations. Because of various cooperators' continuing needs for data from the 24 stations, only two of those sites were actually discontinued. However, the size of the network did decrease significantly during the 1970's as urbanization study sites in Montgomery County were discontinued at the conclusion of the study. Also, several gages were not rebuilt following their destruction, caused by Hurricane Agnes in 1972.

Between 1980 and 1985, 22 continuous-record gages were eliminated from the network. These were discontinued as cooperators' interest ceased or because project needs were met. During the same period, 12 gages were added to meet other project needs and 5 were added to assist in monitoring the Baltimore City reservoir system. The current surface-water program (1985) is composed of 86 continuous-record stations in Maryland, 12 in Delaware, and 1 in D.C. All are operated by the U.S. Geological Survey.

The numbers of continuous-record stream gages operated through the history of the program are presented in figure 1.

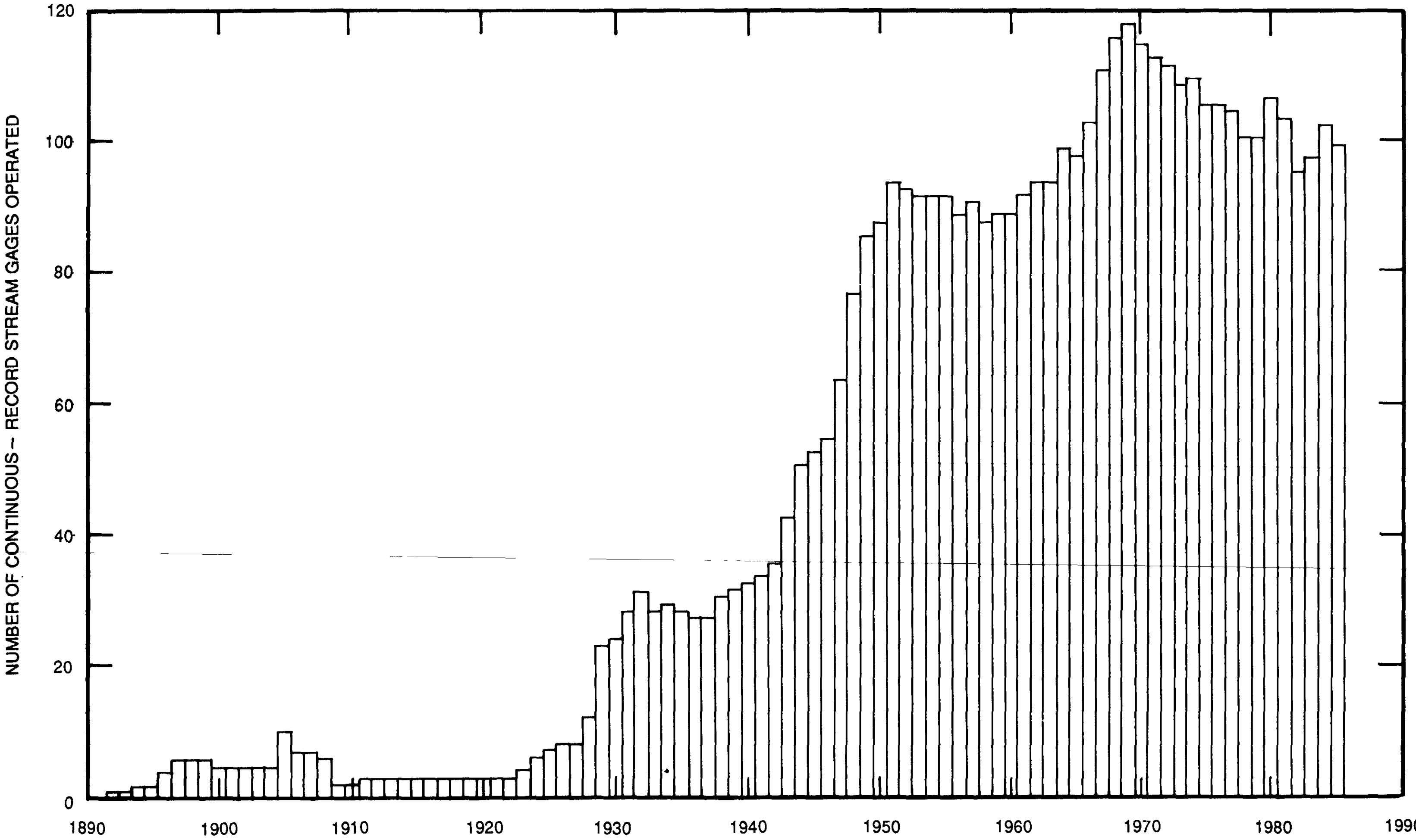
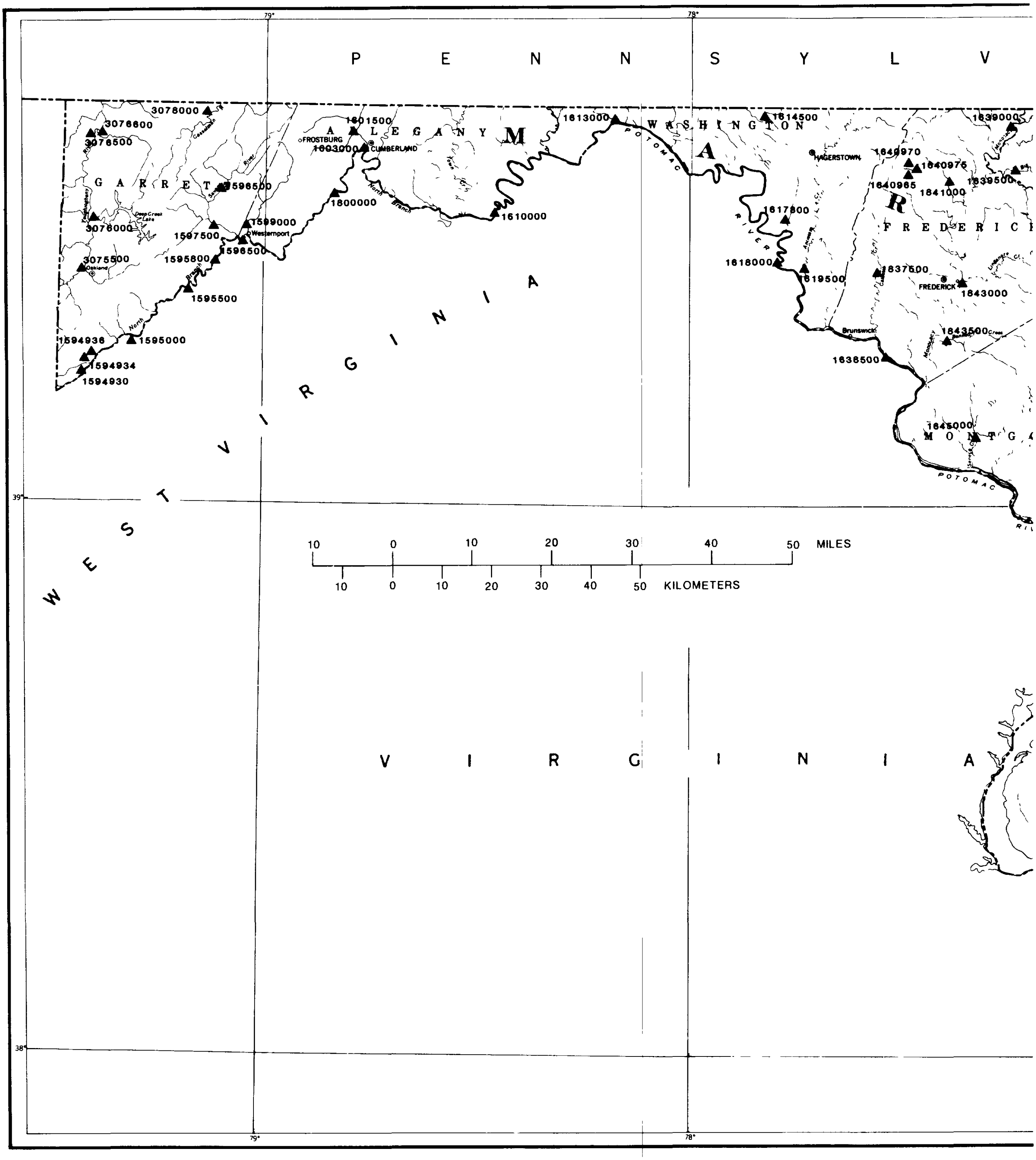


Figure 1.--Number of continuous-record stream gages in Maryland, Delaware, and D.C., 1892-1985.

Current Maryland, Delaware, and the District of Columbia Stream-Gaging Program

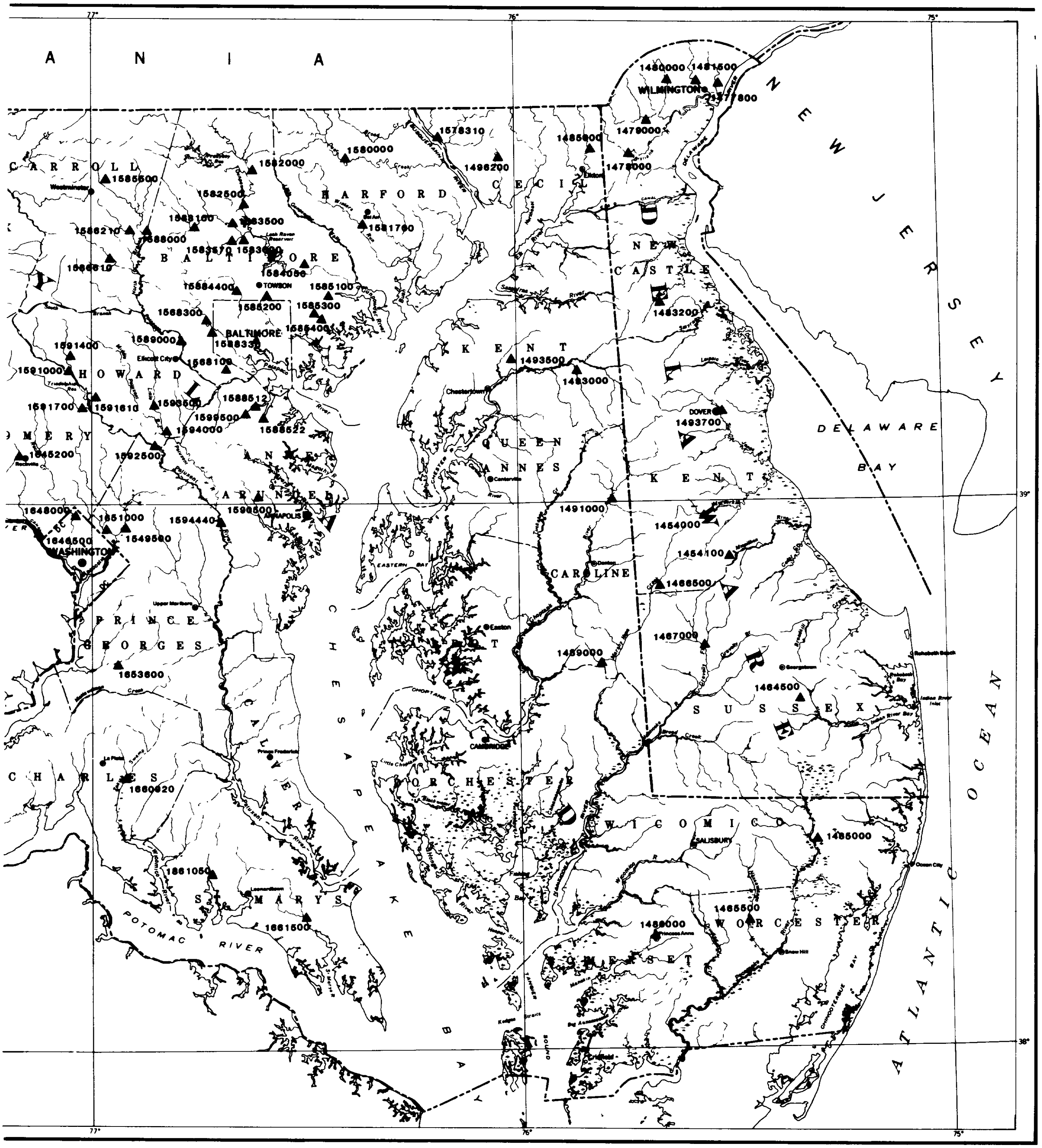
The areal distribution of the 99 stream gages in Maryland, Delaware, and the District of Columbia currently operated (1985) by the Mid-Atlantic District of the U.S. Geological Survey is shown in figure 2. The cost of operating the stream-gaging program in fiscal year 1985 was $465,260.

Selected hydrologic data, including drainage area, period of record, and mean annual flow, for the 99 stations are given in table 1. Station identification numbers used throughout this report are the last seven digits of the Survey's eight-digit downstream-order station numbers; the first digit of the standard Survey station numbers for all stations used in this report is zero.



Base from U.S. Geological Survey, 1: 500,000

Figure 2.--Location of stream gages.



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1660920
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1661500

Table 1.--Selected hydrologic data for stations in the Maryland, Delaware, and D.C. surface-water program

Station number	Station name	Drainage area (mi^2)	Period of record	Mean annual flow (ft^3/s)
1477800	Shellpot Creek at Wilmington, DE	7.46	December 1945-	9.73
1478000	Christina River at Coochs Bridge, DE	20.5	April 1943-	28.8
1479000	White Clay Creek near Newark, DE	89.1	October 1931-September 1936[1] June 1943-September 1957[1] October 1959- [1]	115
1480000	Red Clay Creek at Wooddale, DE	47.0	April 1943-	64.9
1481500	Brandywine Creek at Wilmington, DE	314	October 1946- [2]	488
1483200	Blackbird Creek at Blackbird, DE	3.85	October 1951-September 1956[3] October 1951-September 1953[4] October 1954-September 1956[4] October 1956-	4.82
1483700	St. Jones River at Dover, DE	31.9	January 1958-	37.9
1484000	Murderkill River near Felton, DE	13.6	July 1931-October 1933[5] October 1951-September 1960[3] October 1951-September 1953[4] October 1954-September 1957[4] October 1958-September 1960[4] June 1960-	18.7
1484100	Beaverdam Branch at Houston, DE	2.83	May 1958-	3.77
1484500	Stockley Branch at Stockley, DE	5.24	April 1943-	7.04
1485000	Pocomoke River near Willards, MD	60.5	December 1949-	72.6
1485500	Nassawango Creek near Snow Hill, MD	44.9	December 1949-	55.1
1486000	Manokin Branch near Princess Anne, MD	4.80	April 1951-September 1971 October 1974-	4.67
1487000	Nanticoke River near Bridgeville, DE	75.4	April 1943- [6]	92.8
1488500	Marshyhope Creek near Adamsville, DE	43.9	April 1943-March 1969 October 1971-	55.5
1489000	Faulkner Branch at Federalsburg, MD	7.10	July 1950-	9.23
1491000	Choptank River near Greensboro, MD	113	January 1948-	134
1493000	Unicorn Branch near Millington, MD	22.3	January 1948-	25.2

See footnotes at end of table.

Table 1.--Selected hydrologic data for stations in the Maryland, Delaware, and D.C. surface-water program--Continued

Station number	Station name	Drainage area (mi^2)	Period of record	Mean annual flow (ft^3/s)
1493500	Morgan Creek near Kennedyville, MD	12.7	May 1951-	10.8
1495000	Big Elk Creek at Elk Mills, MD	52.6	April 1932- 1/	69.8
1496200	Principio Creek near Principio Furnace, MD	9.03	June 1967-	13.2
1578310	Susquehanna River at Conowingo, MD	27,100	October 1967-	42,800
1580000	Deer Creek at Rocks, MD	94.4	October 1926- 7/	125
1581700	Winters Run near Benson, MD	34.8	August 1967-	54.1
1582000	Little Falls at Blue Mount, MD	52.9	June 1944-	69.2
1582500	Gunpowder Falls at Glencoe, MD	160	December 1982-	8/
1583100	Piney Run at Dover, MD	12.3	May 1982-	8/
1583500	Western Run at Western Run, MD	59.8	September 1944-	69.8
1583570	Pond Branch at Oregon Ridge, MD	0.16	January 1983-	8/
1583600	Beaverdam Run at Cockeysville, MD	20.9	October 1982-	8/
1584050	Long Green Creek at Glen Arm, MD	9.40	October 1975-	12.4
1585100	Whitemarsh Run at White Marsh, MD	7.61	February 1959-	11.6
1585200	West Branch Herring Run at Idlewylde, MD	2.13	July 1957-May 1965 January 1966-	2.66
1585300	Stemmers Run at Rossville, MD	4.46	December 1958- September 1972 October 1973-	6.80
1585400	Brien Run at Stemmers Run, MD	1.97	May 1958-	2.61
1585500	Cranberry Branch near Westminster, MD	3.29	September 1949-	3.54
1586000	North Branch Patapsco River at Cedarhurst, MD	56.6	September 1945-	64.9
1586210	Beaver Run near Finksburg, MD	14.0	October 1982-	8/

See footnotes at end of table.

Table 1.--Selected hydrologic data for stations in the Maryland, Delaware, and D.C. surface-water program--Continued

Station number	Station name	Drainage area (mi^2)	Period of record	Mean annual flow (ft^3/s)
1586610	Morgan Run near Louisville, MD	28.0	October 1982-	8/
1589000	Patapsco River at Hollofield, MD	285	May 1944-	9/
1589100	East Branch Herbert Run at Arbutus, MD	2.47	August 1957-	3.35
1589300	Gwynns Falls at Villa Nova, MD	32.5	February 1957-	39.7
1589330	Dead Run at Franklintown, MD	5.52	October 1959-	8.07
1589440	Jones Falls at Sorrento, MD	25.2	October 1957-September 1966 3/ April 1966-	34.3
1589500	Sawmill Creek at Glen Burnie, MD	4.97	May 1944-September 1952 October 1964-September 1970 3/ October 1983-	7.68
1589512	Sawmill Creek at Crain Highway at Glen Burnie, MD	8.24	October 1983-	8/
1589522	Marley Creek at Harundale, MD	4.79	October 1983-	8/
1590500	Bacon Ridge Branch at Chesterfield, MD	6.92	October 1942-September 1952 10/ October 1964-September 1974 3/ October 1974-	9.55
1591000	Patuxent River near Unity, MD	34.8	July 1944-	39.9
1591400	Cattail Creek near Glenwood, MD	22.9	June 1978- 11/	28.6
1591610	Patuxent River below Brighton Dam near Brighton, MD	78.6	October 1980-	9/
1591700	Hawlings River near Sandy Spring, MD	27.0	June 1978-	34.2
1592500	Patuxent River near Laurel, MD	132	October 1944-	9/
1593500	Little Patuxent River at Guilford, MD	38.0	April 1932- 12/	43.1
1594000	Little Patuxent River at Savage, MD	98.4	October 1939-September 1958 13/ Water years 1959-66, 68, 72, 75 14/ October 1975-September 1980 June 1985-	109
1594440	Patuxent River near Bowie, MD	348	April 1955-June 1977 15/ August 1977-	421

See footnotes at end of table.

Table 1.--Selected hydrologic data for stations in the Maryland, Delaware, and D.C. surface-water program--Continued

Station number	Station name	Drainage area (mi^2)	Period of record	Mean annual flow (ft^3/s)
1594930	Laurel Run at Dobbin Road near Wilson, MD	8.23	May 1980-	___8/
1594934	South Fork Sand Run near Wilson, MD	1.55	February-August 1980 October 1980-September 1981 16/ October 1981-	___8/
1594936	North Fork Sand Run near Wilson, MD	1.91	May 1980-	___8/
1595000	North Branch Potomac River at Steyer, MD	73.0	July 1956-	173
1595500	North Branch Potomac River at Kitzmiller, MD	225	October 1949-	452
1595800	North Branch Potomac River at Barnum, WV	266	July 1966-	538
1596500	Savage River near Barton, MD	49.1	September 1948-	75.3
1597500	Savage River, below Savage River Dam, near Bloomington, MD	106	October 1948-	165
1598500	North Branch Potomac River at Luke, MD	404	June 1899-July 1906 17/ October 1949-	717
1599000	Georges Creek at Franklin, MD	72.4	May 1905-July 1906 18/ October 1929-	82
1600000	North Branch Potomac River at Pinto, MD	596	October 1938-	897
1601500	Wills Creek near Cumberland, MD	247	May 1905-July 1906 19/ October 1929-	329
1603000	North Branch Potomac River near Cumberland, MD	875	May 1929-	1,270
1610000	Potomac River at Paw Paw, WV	3,109	October 1938-	3,300
1613000	Potomac River at Hancock, MD	4,073	October 1932	4,160
1614500	Conococheague Creek at Fairview, MD	494	June 1928-	596
1617800	Marsh Run at Grimes, MD	18.9	October 1963-	13.1
1618000	Potomac River at Shepherdstown, WV	5,936	August 1928-September 1953 October 1953-September 1964 14/ July 1964-	6,160

See footnotes at end of table.

Table 1.--Selected hydrologic data for stations in the Maryland, Delaware, and D.C. surface-water program--Continued

Station number	Station name	Drainage area (mi²)	Period of record	Mean annual flow (ft³/s)
1619500	Antietam Creek near Sharpsburg, MD	281	June 1897-September 1905 1/ August 1928- 1/	278
1637500	Catoctin Creek near Middletown, MD	66.9	August 1947-	76.9
1638500	Potomac River at Point of Rocks, MD	9,651	February 1895-	9,420
1639000	Monocacy River at Bridgeport, MD	173	May 1942-	206
1639500	Big Pipe Creek at Bruceville, MD	102	October 1947- 20/	112
1640965	Hunting Creek near Foxville, MD	2.14	October 1981-	8/
1640970	Hunting Creek Tributary near Foxville, MD	4.01	October 1981-	8/
1640975	Hunting Creek near Thurmont, MD	7.08	December 1981-	8/
1641000	Hunting Creek at Jimtown, MD	18.4	October 1949-	27.3
1643000	Monocacy River at Jug Bridge near Frederick, MD	817	October 1929- 21/	939
1643500	Bennett Creek at Park Mills, MD	62.8	July 1948-September 1958 October 1959-September 1966 3/ August 1966-	71.0
1645000	Seneca Creek at Dawsonville, MD	101	September 1930-	104
1645200	Watts Branch at Rockville, MD	3.70	June 1957-	4.20
1646500	Potomac River near Washington, DC	11,560	March 1930-	11,600
1648000	Rock Creek at Sherrill Drive, Washington, DC	62.2	October 1929-	62.7
1649500	Northeast Branch Anacostia River at Riverdale, MD	72.8	August 1938-	85.5
1651000	Northwest Branch Anacostia River near Hyattsville, MD	49.4	July 1938- 22/	47.0
1653600	Piscataway Creek at Piscataway, MD	39.5	October 1965-	48.1
1660920	Zekiah Swamp Run near Newtown, MD	79.9	June 1983-	8/
1661050	St. Clement Creek near Clements, MD	18.5	October 1968-	21.2
1661500	St. Marys River at Great Mills, MD	24.0	June 1946-	24.2
3075500	Youghiogheny River near Oakland, MD	134	August 1941-	298
3076500	Youghiogheny River at Friendsville, MD	295	August 1898-December 1904 October 1940- 23/	644

See footnotes at end of table.

Table 1.--Selected hydrologic data for stations in the Maryland, Delaware, and D.C. surface-water program--Continued

Station number	Station name	Drainage area (mi^2)	Period of record	Mean annual flow (ft^3/s)
3076600	Bear Creek at Friendsville, MD	48.9	October 1964-	88.7
3078000	Casselman River at Grantsville, MD	62.5	July 1947-	119

1. Monthly discharge only, for some periods.
2. Monthly discharge only, prior to December 1946.
3. Operated as a crest-stage gage.
4. Operated as a low-flow partial-record station.
5. Monthly discharge only, July to September 1931.
6. Prior to October 1955, published as "Gravelly Fork near Bridgeville."
7. Monthly discharge only, November and December 1926.
8. No mean-annual flow published, less than 5 years of streamflow record.
9. No mean-annual flow published, affected by major diversions for water supply.
10. Monthly discharge only, prior to December 1942.
11. Prior to January 1984, published as "Cattail Creek at Roxbury Mills Road at Roxbury Mills, MD."
12. Monthly discharge only, April 1932.
13. Monthly discharge only, October and November 1939.
14. Annual maximum discharges determined.
15. Gage heights and discharge measurements only.
16. Fragmentary.
17. Published as "at Piedmont, W. Va."
18. Published as "at Westernport."
19. Published as "at Cumberland."
20. Monthly discharge only, October and November 1947.
21. Monthly discharge only, October and November 1929.
22. Monthly discharge only, July 1938.
23. Monthly discharge only, October and November 1940.

USES, FUNDING, AND AVAILABILITY OF CONTINUOUS STREAMFLOW DATA

The relevance of a stream gage is determined by the uses that are made of data produced from the gage. The uses of the data from each gage in the Md.-Del.-D.C. program were identified by a survey of approximately 370 recipients of the annual water-data reports. The survey documented the relative importance of each gage and identified gaging stations that may be considered for discontinuation.

Data uses identified by the survey were categorized into nine classes, defined below, and were tabulated in table 2 by station number. The users and uses within most of the categories cover a broad spectrum of the community involved in water-resources activities. The individual users and uses are described in the footnotes to table 2. The sources of funding for each gage and the frequency at which data are provided to the users are included in table 2.

Data-Use Classes

The following definitions were used in categorizing the uses of streamflow for each continuous stream 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 case of uses, man's effects on streamflow are not necessarily small, but the effects considered are limited to those of land-use and climate changes. Large amounts of manmade storage may exist in the basin provided the outflow is uncontrolled. These stations are useful in developing regionally transferable information about the relationship between basin characteristics and streamflow.

Seventy-five stations in the Md.-Del.-D.C. network are classified in the regional hydrology data-use category.

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 hydrologic systems stations. They include diversions and return flows and stations that are useful for defining the interaction of water systems.

Seventy-eight of the 99 gaging stations in the Md.-Del.-D.C. program have one or more uses in this category. The long-term index stations are included in the hydrologic systems category because they account for the current and long-term conditions of the hydrologic system that they gage.

Legal Obligations

Some stations provide records of flows for the verification or enforcement of treaties, compacts, and decrees. The legal obligation category contains only those stations the Survey must operate to satisfy legal responsibilities of the Federal Government.

No stations in the Md.-Del.-D.C. program are operated to fulfill legal responsibilities of the Survey.

Planning and Design

Gaging stations in this category of data use 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 is limited to those stations that were instituted for such purposes and for which this purpose is still valid.

Currently, there are no stations in the Md.-Del.-D.C. program being operated for planning and design purposes.

Project Operation

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

There are 26 stations in the Md.-Del.-D.C. program that are used in this manner. Twenty-three of these are used to aid operators in the management of reservoir 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.

There are 24 stations in the Md.-Del.-D.C. program used for hydrologic forecasts. Stations in the program that are included in the hydrologic forecast category are used primarily for flood forecasting. Data are used mainly by the U.S. National Weather Service, but also by some local agencies for flood forecasting.

Water-Quality Monitoring

Gaging stations where regular water-quality or sediment-transport monitoring is conducted, and where the availability of streamflow data contributes to the utility or is essential to the interpretation of the water-quality or sediment data, are designated as water-quality-monitoring sites.

Four stations in the program are designated National Stream Quality Accounting Network (NASQAN) stations. NASQAN stations are part of a nationwide network designed to assess water-quality trends of significant streams. In addition to the NASQAN utilization, a wide variety of other uses within the water-quality monitoring category are made of stations in the Md.-Del.-D.C. program. Water-quality monitoring activities of one type or another are conducted at 80 of the stations.

Research

Gaging stations in this category are operated for specific research or water-investigations studies. Typically, these are operated for only a few years.

Nineteen stations in the Md.-Del.-D.C. program are being operated primarily in support of research activities. Eight of the stations are being operated in connection with county water-resources assessments. Four other stations were established for acid rain investigations. Another three of these stations are being operated in conjunction with a ground-water system analysis including evaluation of recharge.

Other

In addition to the eight data-use classes described above, the gaging stations in the Md.-Del.-D.C. program are used to provide streamflow information for a wide variety of other purposes. One important use is periodic, in connection with fishkill investigations and nutrient loading calculations.

Funding

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

1. Federal program.—Funds that have been directly allocated to the Survey.
2. Other Federal Agency (OFA) program.--Funds that have been transferred to the Survey by OFA's.
3. Coop program.--Funds that come jointly from the Survey cooperative-designated funding and from a non-Federal cooperating agency. Cooperating agency funds may be in the form of direct services or cash.
4. Other non-Federal.--Funds that are provided entirely by a non-Federal agency or a private concern under the auspices of a Federal agency. Funds in this category are not matched by the Survey cooperative funds.

In all four categories, 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 organizations, other than the Survey, currently contribute funds to the Md.-Del.-D.C. stream-gaging program.

Data Availability

Data availability refers to the times at which 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 annual data reports published by the Survey for Md.-Del.-D.C. (U.S. Geological Survey, 1984). These three categories are designated T, P, and A, respectively, in table 2. In the current Md.-Del.-D.C. program, data for all 99 stations are made available through annual reports, data from 17 stations are available on a real-time basis, and data are released on a provisional basis at 55 stations.

Data-Use Presentation

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

Conclusions Pertaining to Data Uses

A review of the data-use and funding information presented in table 2 indicates that, in general, the data from the gaging stations in this program are needed by significant numbers of organizations involved in water-resources related activities. Nearly all of the data have multiple uses.

Based on known data uses, six stations should be considered for discontinuation. Data from three of the stations, 1485500, 1493500, and 1590500, have only minimal known applications, with only one acknowledged use, each, for regional hydrology. Three other stations, 1589500, 1589512, and 1589522, are operated primarily in conjunction with a research investigation that should be completed in 1986. However, other uses may preclude discontinuing these stations after their primary research usage has been completed.

Based on the discussion above and the information presented in table 2, up to six stations could be discontinued. Regardless, in the interests of completeness and continuity, all 99 gaging stations will be included in the analysis in the following sections of this report.

Table 2.--Data-use table

[Asterisk indicates that station is used for regional hydrology purposes, and(or) is operated from Federal funds appropriated directly to the Geological Survey]

STATION NUMBER	DATA USE									FUNDING				AVAILABILITY OF DATA
	REGIONAL HYDROLOGY	HYDROLOGIC SYSTEMS	LEGAL OBLIGATIONS	PLANNING & DESIGN	PROJECT OPERATION	HYDROLOGIC FORECASTS	WATER-QUALITY MONITORING	RESEARCH	OTHER	FEDERAL PROGRAM	OFA PROGRAM	CO-OP PROGRAM	OTHER NON-FEDERAL	
1477800	*	1 2				3	2 4		5 6			7		A P
1478000	*	1 2				3	2 4		6 8			7 9		A P T
1479000	*	1 2				3	2		6 8			7 9		A P T
1480000	*	1 2				3	2 4 10		6 8			7		A P
1481500	*	1 2 11			12	3	2 4 10		6	*		9		A P
1483200	*	1 2					2		6			7		A P
1483700	*	1 2 11					2 4		6			7		A P
1484000	*	1 13 14					2 4		6			15		A P
1484100	*	1							6			7		A P
1484500	*	2					2		6			7		A P
1485000	*	2										16		A P
1485500	*											16		A
1486000	*	14 17										18		A
1487000	*	11 14 19					2 4		6	*		7		A P
1488500	*	14					2		6			7		A P
1489000	*	14										16		A
1491000	*	14 19					2 4 20 21			*				A P
1493000	*	14										16		A P
1493500	*											16		A P
1495000	*	22						23				16		A
1496200	*						24	23				16 25		A
1578310		18 26 27 28			27 29 30		4 20 21 29 30 31		31 32			18		A P T
1580000	*	18 27 28			30		24 30		31 33			16 18		A P
1581700	*	18 28			30		30		31 34			18		A P T
1582000	*	28					21 24 35 36		33 34 37			38		A P

See footnotes at end of table.

Table 2.--Data-use table--Continued

STATION NUMBER	DATA USE: REGIONAL HYDROLOGY	HYDROLOGIC SYSTEMS	LEGAL OBLIGATIONS	PLANNING & DESIGN	PROJECT OPERATION	HYDROLOGIC FORECASTS	WATER-QUALITY MONITORING	RESEARCH	OTHER	FUNDING: FEDERAL PROGRAM	OFA PROGRAM	CO-OP PROGRAM	OTHER NON-FEDERAL	AVAILABILITY OF DATA
1582500							39					40		A
1583100	*						41					21		A
1583500	*						21 24 35 36		33 37			38		A P
1583570	*							42		*				A
1583600							39					40		A
1584050	*						24		37			38		A
1585100	*								37			38		A
1585200	*								37			38		A
1585300	*								37			38		A
1585400	*								37			38		A
1585500	*	18					24					18		A
1586000	*	18			43		4 21 35 36		33			16		A P
1586210	*						44					40		A
1586610	*						44					40		A
1589000		18			43		4 21 31		31 45			16 18		A P
1589100	*								37			38		A
1589300	*						4 21 24 35		37 46			38		A P
1589330	*						45		37			38		A
1589440	*						4 21 24 35		33 37 46			38		A P
1589500		47						47				16 48		A
1589512		47						47				16 48		A
1589522		47						47				16 48		A
1590500	*											16		A
1591000	*	18 49 50 51 52			53	54	4 21 24 31 51 52		31 55			49		A P T
1591400	*	49 51 52			53	54	24 51 52		55			49		A P

See footnotes at end of table.

Table 2.--Data-use table--Continued

STATION NUMBER	DATA USE									FUNDING				AVAILABILITY OF DATA
	REGIONAL HYDROLOGY	HYDROLOGIC SYSTEMS	LEGAL OBLIGATIONS	PLANNING & DESIGN	PROJECT OPERATION	HYDROLOGIC FORECASTS	WATER-QUALITY MONITORING	RESEARCH	OTHER	FEDERAL PROGRAM	OFA PROGRAM	CO-OP PROGRAM	OTHER NON-FEDERAL	
1591610		18 49 51 52			53	54	24 31 51 52 56		31 55			49		A P
1591700	*	49 51 52			53	54	51 56		55			49		A P
1592500		18 49 51 52			53	3 54	4 21 51 52 56		55			49		A P
1593500	*						21 51 52 56		55			16		A
1594000		57					57	57				21		A P
1594440		18					4 20 21 51 52 56		55			18		A P
1594930	*	16 58					58	59				16		A P
1594934	*	16 58					58	59				16		A P
1594936	*	16 58					58	59				16		A P
1595000	*	26 58					21 24 31 50 58		31		26			A P
1595500	*	18 50 58 60			61 62	3	4 21 24 31 50 58 61 63		31		26	64		A P T
1595800	*	58 61			61	3	21 24 31 50 58 61 63		31		26			A P T
1596500	*	26 50 58 65					24 31 50 58 65		31		26	16		A P
1597500		18 58 66			61 62	3	21 24 31 50 58 63 66		31		26	64		A P T
1598500		60 61 66			60 61 62	3	21 24 31 50 58 60 63 66		31		26	64		A P T

See footnotes at end of table.

Table 2.--Data-use table--Continued

STATION NUMBER	DATA USE: REGIONAL HYDROLOGY	HYDROLOGIC SYSTEMS	LEGAL OBLIGATIONS	PLANNING & DESIGN	PROJECT OPERATION	HYDROLOGIC FORECASTS	WATER-QUALITY MONITORING	RESEARCH	OTHER	FUNDING: FEDERAL PROGRAM	OFA PROGRAM	CO-OP PROGRAM	OTHER NON-FEDERAL	AVAILABILITY OF DATA
1599000	*	50 58 60					4 21 24 50 58 63 67 68		67		26	16		A P
1600000		58 60 61 66			61		4 21 24 31 50 58 61 63 66		31		26			A P T
1601500	*	50 58 66			69	3	21 24 50 58 63 66 69				26	16		A P
1603000	*	58 61 66			61 62 69	3	21 24 50 58 63 66 69				26	16		A P T
1610000		58 61 66			61 62	3	21 24 31 50 58 63 66		31		26	16		A P T
1613000		58 61			61 62	3	4 21 24 31 50 58		31		26	16		A P T
1614500	*	50 58					21 31 50 58		31	*				A
1617800	*	50 58					24 50 58					16		A
1618000		50 58 61			61 62	3	4 20 21 24 31 50 58		31		26	16		A P T
1619500	*	50 58					4 21 24 31 50 58		31 70 71			16		A P

See footnotes at end of table.

Table 2.--Data-use table--Continued

STATION NUMBER	DATA USE: REGIONAL HYDROLOGY	DATA USE: HYDROLOGIC SYSTEMS	DATA USE: LEGAL OBLIGATIONS	DATA USE: PLANNING & 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: CO-OP PROGRAM	FUNDING: OTHER NON-FEDERAL	AVAILABILITY OF DATA
1637500	*	50 58 72					21 24 50 58 72	73				16		A
1638500		49 50 58 61 74 75			53 61 62	3	4 21 24 50 58 72			*		49		A P T
1639000	*	50 58 76					4 21 24 50 58 72	73				16		A
1639500	*	50 58 76					21 50 58 72	73	33			16		A
1640965		42					42	42		*				A
1640970		42					42	42		*				A
1640975		42					42	42		*				A
1641000	*	50 58 72					21 24 50 58 72	73				16		A
1643000	*	50 58 72 75			61 62	3	4 21 24 50 58 72	73	77		26	16		A P T
1643500	*	18 50 58 72					50 58 72	73				18		A
1645000	*	14 18 50 58 75			53		21 24 49 50 52 56 58 75		78			49		A P
1645200	*	50 58 75					50 52 56 58 75		79			16		A
1646500		18 50 52 58 61 80 81			53 61 62	3	4 21 24 50 52 58 75		32			16 81		A P T
1648000		52 75 82				3	4 50 52 56 58 75		5		82			A P
1649500	*	49 52 58 75 81					24 50 52 56 58 75					16 49 81		A

See footnotes at end of table.

Table 2.--Data-use table--Continued

STATION NUMBER	DATA USE									FUNDING				AVAILABILITY OF DATA
	REGIONAL HYDROLOGY	HYDROLOGIC SYSTEMS	LEGAL OBLIGATIONS	PLANNING & DESIGN	PROJECT OPERATION	HYDROLOGIC FORECASTS	WATER-QUALITY MONITORING	RESEARCH	OTHER	FEDERAL PROGRAM	OFA PROGRAM	CO-OP PROGRAM	OTHER NON-FEDERAL	
1651000	*	49 58 75 81					24 50 51 56 58 75					16 49 81		A
1653600	*	58 75					50 51 58 75					16		A
1660920	*	83										16		A
1661050	*	22 58 75					50 58					16		A
1661500	*	14 58 75					50 58					16		A
3075500	*	84					4 21 24 31		31		85	16		A
3076500		50			84	3	4 21 31		31		85			A P
3076600	*	66					24 66					16		A
3078000	*	50 66					21 24 66					16		A

1. Delaware River Basin Commission.
2. U.S. Soil Conservation Service.
3. U.S. National Weather Service - flood forecasting.
4. U.S. Environmental Protection Agency.
5. U.S. Environmental Protection Agency - effluent limitations development for wastewater treatment facilities.
6. Delaware Division of Fish and Wildlife - periodic use in fishkill investigations and nutrient loading calculations.
7. Delaware Geological Survey.
8. Wilmington Suburban Water Corporation - source projection studies, withdrawal planning, and treatment plant design.
9. Newcastle County, Delaware.
10. Brandywine Valley Association.
11. Delaware Division of Environmental Control, Water Resources Section - determining Delaware Water Shortage Index.
12. Wilmington, Delaware, Water Division, Department of Public Works - managing water supply.
13. Delaware Department of Natural Resources and Environmental Control, Water Pollution Branch - drought index station.
14. U.S. Soil Conservation Service - Public Law-566 project.
15. Delaware Department of Natural Resources and Environmental Control.
16. Maryland Geological Survey.
17. Maryland Water Resources Administration Resource Management Program - effects of channel modifications.
18. Maryland Water Resources Administration.
19. Long-term index gaging station.
20. NASQAN Station.
21. Maryland Department of Health and Mental Hygiene, Office of Environmental Programs.
22. U.S. Soil Conservation Service - resources conservation and development project.
23. Cecil County water resources assessment.
24. Maryland Wildlife Administration - cold water fisheries program.
25. Cecil County, Maryland.
26. U.S. Army Corps of Engineers, Baltimore District.
27. Susquehanna River Basin Commission.
28. Harford County Public Works Department - withdrawal availability studies.

29. Baltimore City, Water Quality Management Office - manage water supply.
30. Maryland Water Works Company, Bel Air, Maryland - manage water supply.
31. Maryland Power Plant Siting Program - impact evaluation; existing and potential hydropower plants.
32. University of Maryland, Chesapeake Biological Laboratory - research on fluctuations in commercial and nuisance estuarine organisms in Chesapeake Bay.
33. Century Engineering, Inc. - flood hydrology project.
34. Harford County Public Works Department - calibration of streamflow models.
35. Baltimore City, Water Quality Management Office - pollutant loading estimates.
36. Baltimore City, Bureau of Water and Wastewater.
37. Baltimore County Public Works Department - planning and design of storm water projects.
38. Baltimore County.
39. Quality evaluation, inflow (constituent loads) to Loch Raven Reservoir.
40. Baltimore City.
41. Quality evaluation, inflow (constituent loads) to Loch Raven Reservoir (part of "Clean Lakes" program).
42. Acid rain investigation.
43. Baltimore City Department of Public Works, Water Engineering Division.
44. Quality evaluation, inflow (constituent loads) to Liberty Reservoir.
45. Maryland Wildlife Administration, Inland Fisheries - predict flows for fisheries management.
46. Baltimore City Water Quality Management Office - predicting flow for water supply management.
47. Ground water system analysis; evaluation of recharge for water budget.
48. Anne Arundel County.
49. Washington Surburban Sanitary Commission.
50. Interstate Commission on the Potomac River Basin.
51. Prince Georges County, Department of Public Works.
52. Montgomery County Department of Environmental Protection.
53. Washington Suburban Sanitary Commission - manage water supply system and reservoir operation, including flow prediction.
54. Washington Suburban Sanitary Commission - flood forecasting.
55. Clark, Finefrock, and Sackett (consulting engineers) - compare data with watershed models.
56. Maryland-National Capital Park and Planning Commission.
57. Non-point source water-quality (nutrient) modeling study, including interaction of surface water, ground water, rainfall, and evaporation.
58. Potomac River Fisheries Commission.
59. Coal mine hydrology project.
60. Westvaco Corporation (paper manufacturer) - effluent discharge regulations and diversion management.
61. U.S. Army Corps of Engineers - flood control and Washington, D.C., water supply system management, including flow prediction.
62. Interstate Commission on the Potomac River Basin - planning and low-flow coordination.
63. Institute of Paper Chemistry.
64. Upper Potomac River Commission.
65. Allegany County - water supply management for Barton, Maryland.
66. Allegany County.
67. Allegany County - evaluate impact of impending sewage treatment facility.
68. Frostburg State College, Geography Department.
69. City of Cumberland - manage flood control facilities.
70. National Park Service - long-term natural resource monitoring program.
71. University of California, Berkeley - streamflow velocity analysis (exceptional record).
72. Frederick County Planning Department.
73. Frederick County water resources assessment.
74. Frederick County Planning Department - water supply and flood management planning.
75. Metropolitan Washington Council of Governments.
76. Frederick County Planning Department - water supply planning.
77. Frederick County Planning Department - planning and design, water-supply and storm-water structures.
78. Washington Suburban Sanitary Commission - preparation water-quality management plan.
79. More studies of urbanization here than any gage in the East.
80. Metropolitan Washington Council of Governments - sewage treatment plant planning and operation coordination.
81. District of Columbia, Department of Environmental Services.
82. U.S. National Park Service.
83. Monitor ongoing hydrologic conditions related to growth and development of Charles County.
84. U.S. Army Corps of Engineers, flood control.
85. U.S. Army Corps of Engineers, Pittsburgh District.

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-flow 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 continous stream gage. No guidelines concerning suitable accuracies exist 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, stations for which real-time flood hydrographs are required, for uses such as hydrologic forecasts and project operation, are not candidates for the alternative methods. Likewise, a legal obligation to operate a gaging station would preclude utilizing alternative methods. The primary candidates for alternative methods are stations 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, in the same physiographic and climatic area, also may have potential for alternative methods.

All stations in the Md.-Del.-D.C. stream-gaging program were evaluated regarding their potential for utilization of alternative methods. Selected methods were applied at eight of the stations. These applications are described later in this section of the report. This section also briefly describes the two alternative methods used in the Md.-Del.-D.C. analysis and documents why these methods were chosen.

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 Survey's WATSTORE Daily Values File (Hutchinson, 1975), (3) the proposed method should be technically sound and generally acceptable to the hydrologic community, and (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 relationship between storage in a reach and 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 a discharge hydrograph at the downstream end. Several different types of hydrologic routing, such as Muskingum, Modified Puls, Kinematic Wave, and the unit-response flow-routing method, are available. 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 be applied only 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.

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 usually can be accomplished using a single unit-response function (linearization about a single discharge) to represent the system response. However, if the routing coefficients vary 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.

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

The objective in both the storage-continuity and the diffusion analogy flow-routing methods is to calibrate two parameters that describe the storage-discharge relationship in a given reach and the traveltime 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 that is the slope of the storage-discharge relation, and W_s, the translation hydrograph time base. These two parameters determine the shape of the resulting unit-response function.

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

In both the storage-continuity and diffusion-analogy methods, the two parameters are calibrated by trial and error. The analyst must decide whether suitable parameters have been derived by comparing the simulated discharge with the observed discharge. The application of flow-routing techniques to six watersheds in Md.-Del.-D.C. is described in a subsequent section of this report.

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 those by Draper and Smith (1966) and Kleinbaum and Kupper (1978). The application of regression analysis to hydrologic problems is described and illustrated by Riggs (1973) and Thomas and Benson (1970). Only a brief description of regression analysis is provided in this report.

A linear regression model of the following form was used for estimating daily mean discharges in Md.-Del.-D.C.:

$$y_i = B_o + \sum_{j=1}^{\rho} B_j x_j + e_i$$

where

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

x_j is the daily mean discharges at nearby stations (explanatory variables),

B_o and B_j are the regression constant and coefficients, and

e_i is the random error term.

The above equation is calibrated (B_o 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_o and B_j) are tested to determine whether they are significantly different from zero. A given station j should be retained in the regression equation only 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 for 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 j. The equation should be verified by plotting the residuals e_i (difference between simulated and observed discharges) against the dependent and all explanatory variables in the equation, and by plotting the simulated and observed discharges versus time. These tests are intended to determine whether the linear model is appropriate or some transformation of the variables is needed and whether 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 was appropriate, with y_i and x_j, in cubic feet per second, logarithmically transformed. The application of linear-regression techniques to five watersheds in Md.-Del.-D.C. 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.

Potential for Use of Alternative Methods to Determine Streamflow

Analyses of the areal distribution (closeness) of the gaging stations in the program and of the data uses presented in table 2 identified eight possible stations at which to test alternative methods for obtaining the needed streamflow information. The eight stations were 1481500, 1488500, 1591000, 1610000, 1613000, 1618000, 1638500, and 1646500. Based on the capabilities and limitations of the methods and data availability, flow-routing techniques were applied at six of the stations and regression methods were used at five of the sites. Three of the stations (1481500, 1610000, and 1613000) were modeled with both techniques.

Brandywine Creek Flow-Routing Analysis

The purpose of this flow-routing analysis was to investigate the potential for use of the unit-response model for streamflow routing to simulate daily-mean discharges at station 1481500, Brandywine Creek at Wilmington, Del. This station was chosen for demonstration purposes, to illustrate the level of accuracy that reasonably can be expected from simulation of streamflow using currently available practical techniques. This station (and river system) was chosen primarily because of the minimal intervening ungaged drainage area and the lack of apparent regulation in that intervening area. In reality, this site would not be a suitable target for discontinuing because of the heavy and high-priority usage, including use for flood forecasting and as a Delaware water-shortage index station, as summarized in table 2.

This flow-routing analysis, of station 1481500, will be referred to hereafter as the Brandywine Creek flow-routing study. In this application, a best-fit model for the entire flow range is the desired product. A schematic diagram of the Brandywine Creek study area is presented in figure 3. Streamflow data available for this analysis are summarized in table 3.

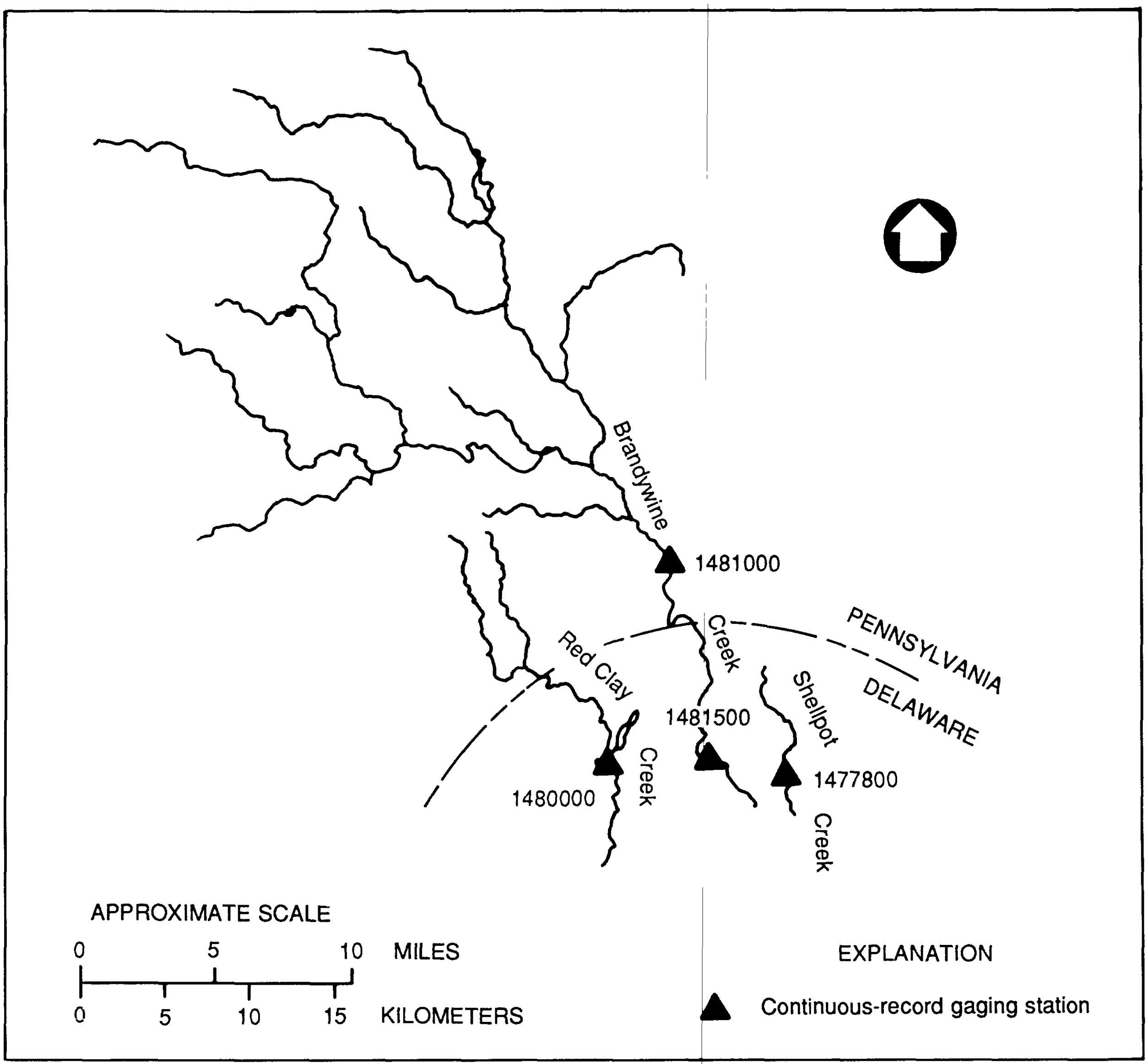


Figure 3.--The Brandywine Creek flow-routing study area.

Table 3.--Gaging stations used in the Brandywine Creek flow-routing study

Station No.	Station name	Drainage area (mi^2)	Period of record
1477800	Shellpot Creek at Wilmington, Del.	7.46	December 1945 - present
1480000	Red Clay Creek at Wooddale, Del.	47.0	April 1943 - present
1481000	Brandywine Creek at Chadds Ford, Pa.	287	August 1911 - December 1953, October 1962 - present
1481500	Brandywine Creek at Wilmington, Del.	314	October 1946 - present

The Brandywine Creek gage being modeled (1481500) is located 10.2 mi downstream from the next upstream gage (1481000), Brandywine Creek at Chadds Ford, Pa. In this reach there is some diurnal fluctuation at low flow caused by mills upstream. This fluctuation does not appear to have any significant effect on the daily discharge at 1481500. The intervening drainage area between stations 1481000 and 1481500 is 27 mi^2, or 8.6 percent of the total drainage area contributing to the downstream station. There are no gages located within the 27 mi^2 intervening area.

To simulate the daily-mean discharges, flows were routed from station 1481000 to station 1481500 using the diffusion analogy method with a single linearization. The intervening drainage area was accounted for by using data from the upstream station (1481000) adjusted by drainage area ratio. The total discharge at 1481500 was the summation of the routed discharge from 1481000 and adjusted discharge from 1481000. Daily streamflow data for water years 1981-83 were used to calibrate the model.

To route flow from station 1481000 to station 1481500, it was necessary to determine the model parameters C_o (floodwave celerity) and K_o (wave-dispersion coefficient). The coefficients C_o and K_o are functions of channel width (W_o) in feet, channel slope (S_o) in feet per foot (ft/ft), the slope of the stage-discharge relation (dQ_o/dY_o) in square feet per second (ft^2/s), and discharge (Q_o) in cubic feet per second (ft^3/s) representative of the reach in question and are determined as follows:

$$C_o = \frac{1}{W_o} \cdot \frac{dQ_o}{dY_o} \quad (1)$$

$$K_o = \frac{Q_o}{2S_oW_o} \quad (2)$$

The discharge, Q_o, for which initial values of C_o and K_o were linearized, was the mean daily discharge for the period of record for stations 1481000 and 1481500. The channel width, W_o, was the width at each station corresponding to the Q_o discharge and determined from field discharge measurement data. Channel slope, S_o, was determined by converting the corresponding gage heights of the initial discharges, Q_o, taken from the stage-discharge relationships at each gage to a common datum. The difference between these values was then divided by channel length to obtain a slope. The slope of the stage discharge relations, dQ_o/dY_o, was determined from the rating curves at each gage by using the 0.1-ft increment in stage that bracketed the mean discharge, Q_o. The difference in the discharge divided by the 0.1-ft increment therefore represents the slope of the function at that point. The model parameters as determined above are listed in table 4.

For the first routing trial, average values for the model parameters, $C_o = 5.66$ and $K_o = 1{,}350$ were used. To simulate the contribution of the intervening drainage area of 27 mi^2, the drainage basin above station 1481000 was assumed to be representative of the total intervening drainage area. Therefore, a drainage area ratio of 27 mi^2 divided by 287 mi^2 (0.094) was applied to the flow at station 1481000 and added in at the downstream end to simulate the input from the intervening drainage area. The two other stations in the vicinity (1477800 and 1480000) were tested as alternatives for simulating intervening flow, both separately and in combination, with increments of flow added in based on their drainage area ratios applied to the daily flow at those sites. Neither of these stations provided flow estimates as good as resulted from using 1481000 alone.

Using the 1981-83 water years as a calibration data set, several trials were made, adjusting the values of both C_o and K_o over a wide range (C_o over one order and K_o over two orders of magnitude). An adjustment was made to the intervening drainage area ratio factor in order to minimize the volume error associated with

Table 4.--Characteristics of selected reaches used in the Brandywine Creek flow-routing study

Station No.	Q_o (ft^3/s)	W_o (ft)	S_o (ft/ft)	$\frac{dQ_o}{dY_o}$ (ft^2/s)	C_o (ft/s)	K_o (ft^2/s)
1481000	396	109	1.503×10^{-3}	440	4.04	1,210
1481500	479	107		780	7.29	1,490

using the pure drainage area ratio (0.094). The adjusted ratio, 0.140, reduced the total volume error from -5.8 to -1.9 percent. The best-fit single linearization model was determined to be that which used the initially set values of $C_o = 5.66$ and $K_o = 1{,}350$ as no significant improvement could be made by varying these parameters.

A summary of the simulation of mean-daily discharge at station 1481500 on Brandywine Creek for water years 1981-83 is given in table 5.

Figure 4 is a comparison of the observed and simulated discharge for Brandywine Creek station 1481500 during an October, when base flow is generally low, and an April when base flow is generally high. The fit for October 1982 was reasonably good with an average daily absolute difference in flow of 8.2 percent. The maximum difference occurred on October 13 when the flow was overestimated by 14.5 percent. The fit for the following April (1983) was, in general, better with an average daily difference of 3.4 percent. The maximum difference for April was 16.8 percent, underestimated, on the 11th.

Flow-Routing Analysis Summary

The Brandywine Creek flow-routing analysis resulted in a fairly effective model for simulating daily streamflow at station 1481500 (see table 5). The other five flow-routing models, which were calibrated in a flow-routing study of the Potomac River (Trombley, 1982), met with similar success as summarized in table 6. Table 6 provides flow-routing modeling data for the six stations where this

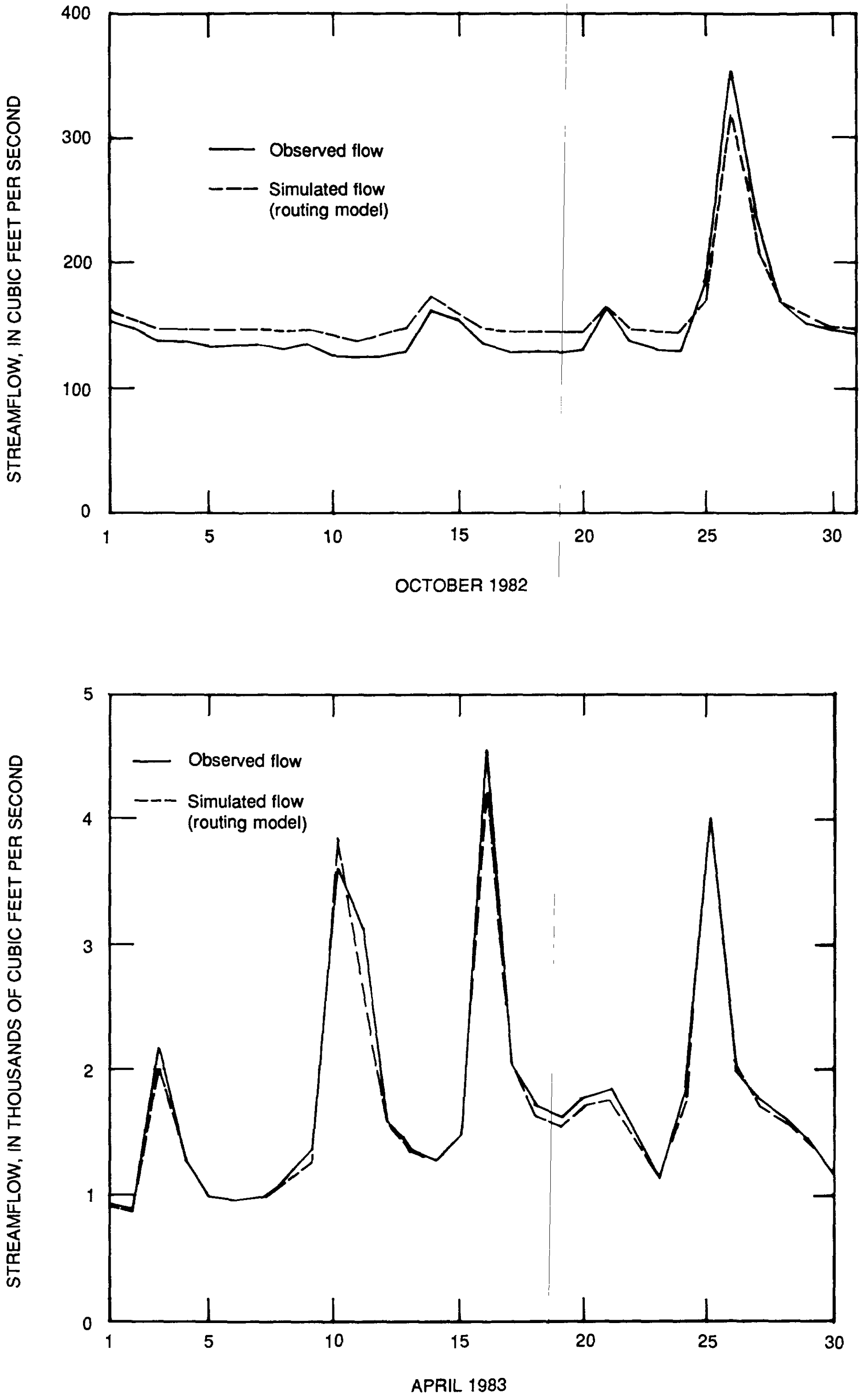


Figure 4.--Daily hydrograph,Brandywine Creek, October 1982 and April 1983.

Table 5.--Results of Brandywine Creek flow-routing model

Mean absolute error for 1,095 days	= 7.82 percent
Mean negative error (487 days)	= -6.90 percent
Mean positive error (608 days)	= 8.55 percent
Total volume error	= -1.89 percent

45 percent of the total observations had errors ≤ 5 percent
70 percent of the total observations had errors ≤ 10 percent
86 percent of the total observations had errors ≤ 15 percent
94 percent of the total observations had errors ≤ 20 percent
97 percent of the total observations had errors ≤ 25 percent
3 percent of the total observations had errors > 25 percent

technique was applied. Location, drainage area, and other information about the stations involved are available from table 1, figure 2, and Trombley (1982). None of the six models is considered accurate enough to justify discontinuing any of the gaging stations. In addition, the uses, summarized in table 2, in some cases would have precluded discontinuing their operation.

Regression Analysis Results

Linear regression techniques were applied to five of the eight selected modeling sites: stations 1481500, 1488500, 1591000, 1610000,and 1613000. 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), which was water years 1981-83 for the gaging stations (systems) analyzed. 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.

Station 1591000, Patuxent River near Unity, Md., provides a fairly representative example of the regression modeling technique. A schematic diagram of the study area related to station 1591000 is presented in figure 5, which shows the

Table 6.--Summary of daily streamflow flow-routing models

Station No.	Model	C_o (ft/s)	K_o (ft^2/s)	Percentage of simulated flow within stated percent of actual: 5	10	20
1481500	$Q_{1481500} = (Q_{1481000})_{Routed} + 0.140(Q_{1481000})$	5.66	1,350	45	70	94
1610000	$Q_{1610000} = [Q_{1603000} + 2.0(Q_{1604500}) + Q_{1608500}]_{Routed} + Q_{Intr}$	3.50	8,000	45	73	93
	$Q_{Intr} = 26.4(Q_{1604500})$ for $Q_{1604500} \leq 40\ ft^3/s$					
	$= 4.60(Q_{1604500})$ for $Q_{1604500} > 40\ ft^3/s$					
1613000	$Q_{1613000} = (Q_{1610000})_{Routed} + 1.3(Q_{1611500})$	3.75	15,000	60	84	96
1618000	$Q_{1618000} = [Q_{1613000} + Q_{1614500} + 1.5(Q_{1616500})]_{Routed\ 55\ mi}$	4.25	20,000	53	76	94
	$+ [0.90(Q_{1614500}) + Q_{1616500}]_{Routed\ 25\ mi}$					
1638500	$Q_{1638500} = [Q_{1618000} + 1.5(Q_{1619500}) + Q_{1636500}]_{Routed}$	4.25	15,000	53	84	96
	$+ (Q_{1637500})_{Lagged\ 6\ hours} + 2.60(Q_{1637500})$					
1646500	$Q_{1646500} = (Q_{1638500} + Q_{1643000} + Q_{1644000})_{Routed} + Q_{1645000}$	3.00	30,000	54	82	95
	$+ Q_{1646000} + Q_{Intr}$					
	$Q_{Intr} = 55.7(Q_{1644000})^{0.362}$ for $Q_{1644000} \leq 350\ ft^3/s$					
	$= 0.254(Q_{1644000})^{1.32}$ for $350\ ft^3/s < Q_{1644000} \leq 1,600\ ft^3/s$					
	$= 2.15(Q_{1644000})$ for $Q_{1644000} > 1,600\ ft^3/s$					

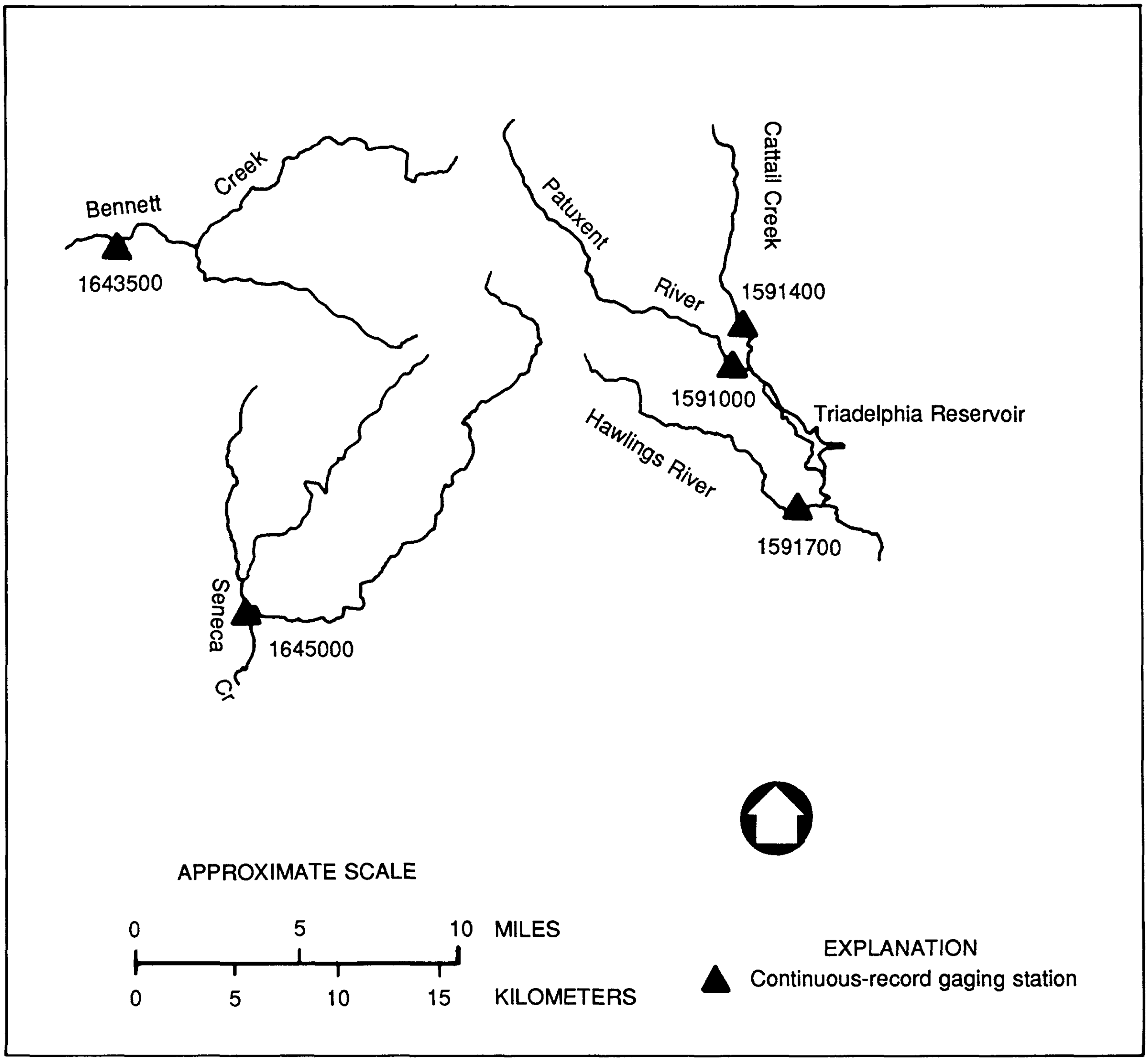


Figure 5.--The Patuxent River, station 1591000, study area.

stations included in the final model. All the streamflow data considered (some of which did not prove helpful) for this analysis are summarized in table 7. A daily mean-flow hydrograph is presented in figure 6 for October and April of water year 1983 for comparison of the observed discharge at the station with the discharge simulated by the regression model developed for this streamflow system. The model, $Q_{1591000} = 1.159(Q_{1591400})^{0.536}(Q_{1591700})^{0.122}(Q_{1643500})^{0.338}$, is included in table 8 which presents a summary of the regression models for the five sites which were analyzed thereby.

The somewhat more successful simulations of streamflow records at stations 1481500, 1610000, and 1613000 were produced from regressions with at least one explanatory variable (station) located on the same stream as the dependent variable (station). The streamflows at these stations experience varying degrees of regulation. The dependent streamflow records were regressed against upstream and downstream records on the main stems of the rivers, tributaries to the main stems, and stations in adjacent drainage basins. Special explanatory variables specified as LAG1 Q and LAG-1 Q were created by lagging the discharges by plus 1 day or minus 1 day. The interaction in a regression of the lagged and unlagged values for a given streamflow record acts to statistically route the flow from an upstream to a downstream site. The lagged discharge values account for the traveltime between the two sites.

Conclusions Pertaining to Alternative Methods of Data Generation

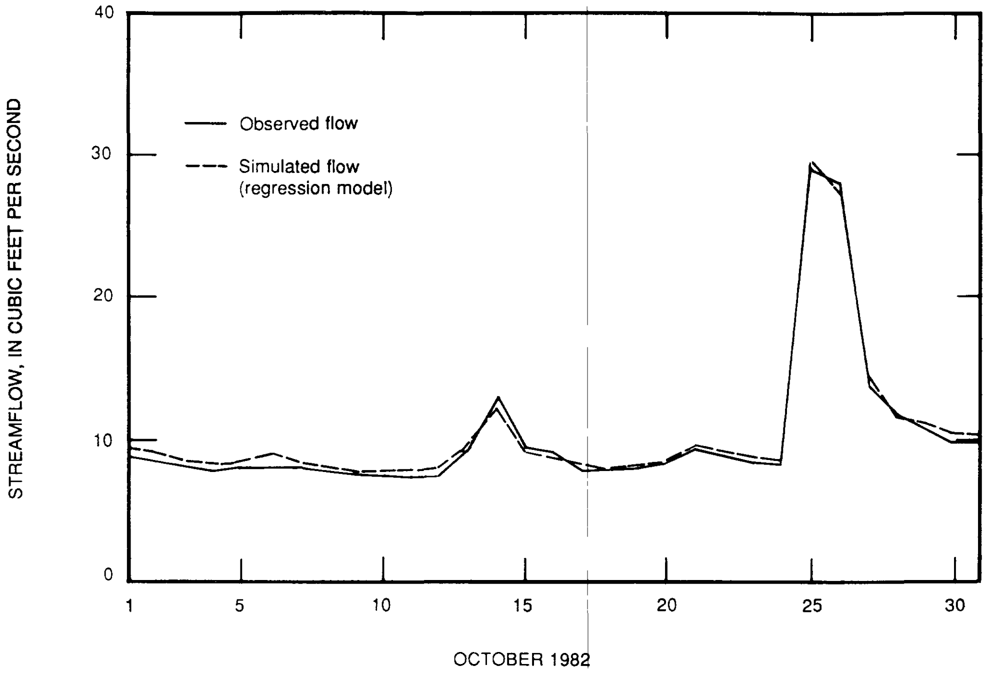
The simulated data from both the flow-routing and regression methods for the eight modeled stream systems were not considered sufficiently accurate to substitute for the operation of any continuous stream gages. In general, models based only on streamflow in adjacent drainage basins (which are necessarily regression models) are not very effective in simulating streamflow to reasonable levels of accuracy. The most successful simulation, overall, of streamflow was obtained from the flow-routing model of the Potomac River station 1613000 system, and even that model was able to produce flow records within 5 percent of the actual values only 60 percent of the time.

In summary, all eight stations considered in this section should remain in operation as part of the Md.-Del.-D.C. stream-gaging program and will be included in the next step of this analysis.

Table 7.--Gaging stations used in the Patuxent River, station 1591000, regression model study

Station No.	Station name	Drainage area (mi^2)	Period of record
1591000	Patuxent River near Unity, Md.	34.8	July 1944-present
1591400	Cattail Creek near Glenwood, Md.	22.9	June 1978-present
1591700	Hawlings River near Sandy Spring, Md.	27.0	June 1978-present
1643500	Bennett Creek at Park Mills, Md.	62.8	July 1948-September 1958, October 1959-September 1966* August 1966-present
1645000	Seneca Creek at Dawsonville, Md.	101	September 1930-present

* Operated as a crest-stage gage.



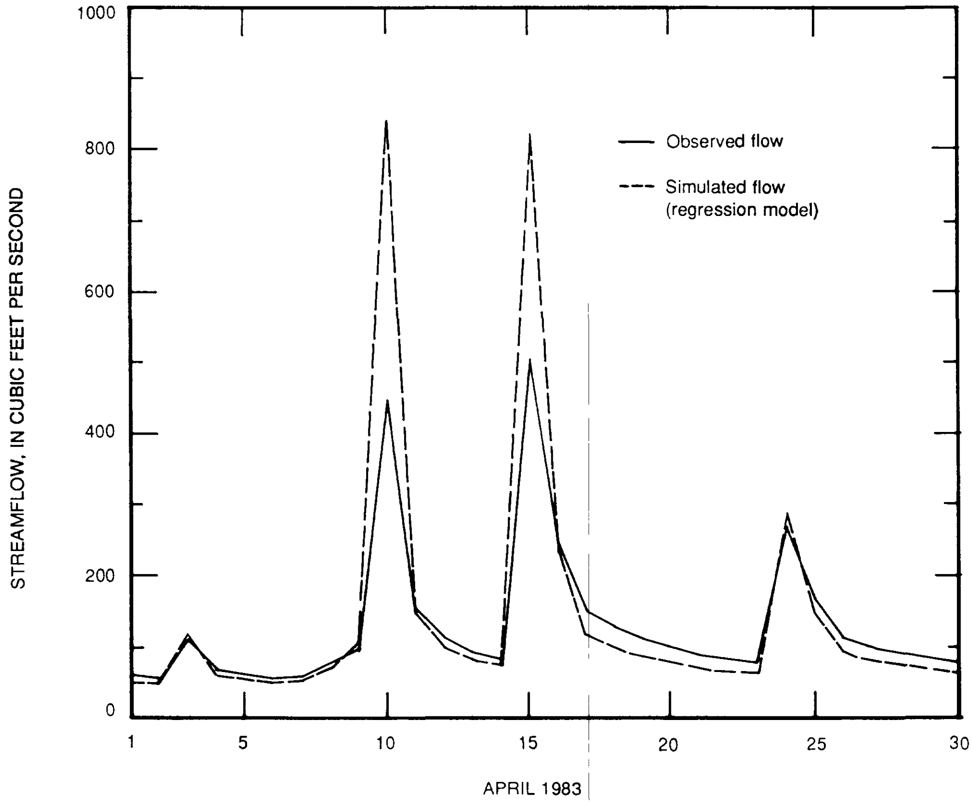


Figure 6.--Daily hydrograph, Patuxent River, station 1591000, October 1982 and April 1983.

Table 8.--Summary of daily streamflow regression models

Station No.	Model	Percentage of simulated flow within stated percent of actual		
		5 %	10 %	20 %
1481500	$Q_{1481500} = 1.10(Q_{1477800})^{0.0163}(Q_{1480000})^{0.161}(Q_{1481000})^{0.761}(\text{LAG1 } Q_{1481000})^{0.137}$	52	78	97
1488500	$Q_{1488500} = 3.73(Q_{1484000})^{0.309}(Q_{1484100})^{0.560}(Q_{1491000})^{0.215}$	20	41	72
1591000	$Q_{1591000} = 1.16(Q_{1591400})^{0.536}(Q_{1591700})^{0.122}(Q_{1643500})^{0.338}$	40	65	91
1610000	$Q_{1610000} = 1.53(Q_{1603000})^{0.275}(\text{LAG1 } Q_{1603000})^{0.0602}(Q_{1604500})^{0.0444}(Q_{1608500})^{0.214}(\text{LAG-1 } Q_{1611500})^{-0.0590}(Q_{1613000})^{0.222}(\text{LAG-1 } Q_{1613000})^{0.249}$	62	82	95
1613000	$Q_{1613000} = 1.07(Q_{1610000})^{0.360}(\text{LAG1 } Q_{1610000})^{0.363}(Q_{1611500})^{0.0988}(Q_{1614500})^{-0.0381}(Q_{1616500})^{-0.0570}(Q_{1618000})^{0.264}$	58	81	92

COST-EFFECTIVE RESOURCE ALLOCATION

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 that study concerned water balance, the network's effectiveness was measured in terms of the extent to which it minimized the sum of error variances in estimating annual mean discharges at each site in the network. This measure of effectiveness tends to concentrate stream-gaging resources on the larger streams where potential errors in total volume of flow 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 Streamflow Information 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 in estimating 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. Using 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 continuously gaged sites to measure the effectiveness of the data-collection activity.

The original version of K-CERA also failed to 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 collecting data and of the techniques of applying Kalman filtering (Gelb, 1974) to determine stream-gage record accuracy are presented below. For more detail on the theory or the applications of K-CERA, see Moss and Gilroy (1980), Gilroy and Moss (1981), and Fontaine and others (1984).

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. However, for this analysis, an upper limit was set at 72 trips per year. This constraint was considered a reasonable maximum and is discussed later under K-CERA results.

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 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 sole stop and return to the home base so that the individual needs of stream gages 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 purposes 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 the budget for the network is not exceeded, the minimum number of visits to each station is made, and the total uncertainty in the network is minimized. Figure 7 represents this step in the form of a mathematical program. Figure 8 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 compose 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

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

$V \equiv$ total uncertainty in the network

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

$MG \equiv$ number of gages in the network

$M_j \equiv$ annual number of visits to station j

$\phi_j \equiv$ function relating number of visits to uncertainty at station j

Such that

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

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

$F_c \equiv$ fixed cost

$\alpha_j \equiv$ unit cost of visit to station j

$NR \equiv$ number of practical routes chosen

$\beta_i \equiv$ travel cost for route i

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

and such that

$$M_j \geq \lambda_j$$

$\lambda_j \equiv$ minimum number of annual visits to station j

Figure 7.--Mathematical-programming form of the optimization of the routing of hydrographers.

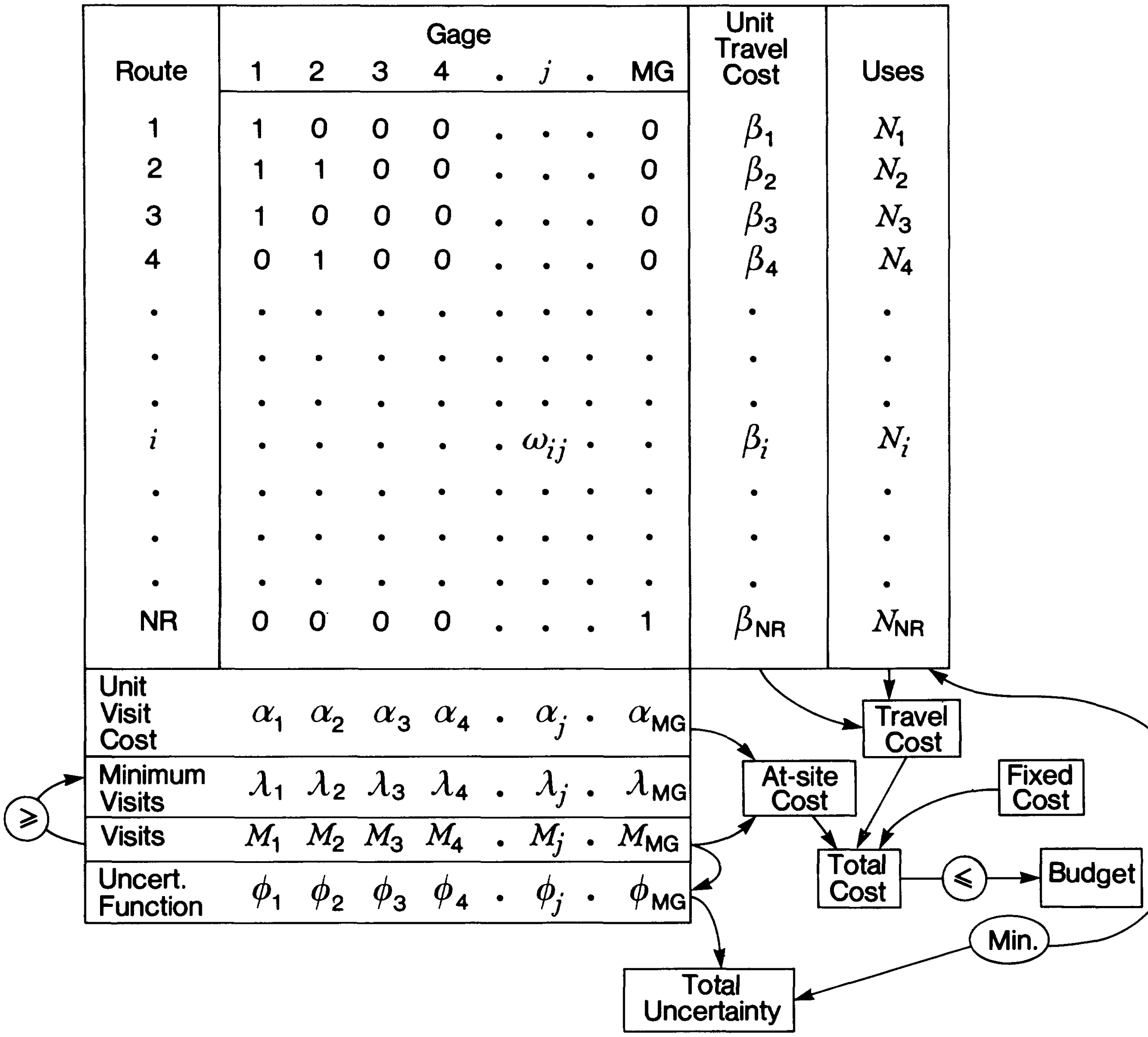


Figure 8.--Tabular form of the optimization of the routing of hydrographers.

not. The unit-travel costs, β_i, are the per-trip costs of the hydrographer's travel time, average servicing and maintenance costs at the gaging stations, and any related per diem. The sum of the products of β_i and N_i for i = 1, 2, ..., NR is the total travel and servicing costs associated with the set of decisions $\underline{N} = (N_1, N_2, ..., N_{NR})$.

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

The total cost expended for discharge measurements 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 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, and (3) primary and secondary data are unavailable for estimating streamflow. The variances of the errors of the estimates of flow that would be employed in each situation were weighted by the fraction of time each situation is expected to occur. Thus, the average relative variance would be

$$\overline{V} = \varepsilon_f V_f + \varepsilon_r V_r + \varepsilon_e V_e \tag{3}$$

with

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

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 estimates from primary recorders,

ε_r is the fraction of time that secondary data are available to reconstruct streamflow records given that the primary data are missing,

V_r is the relative variance of the errors of estimation of flows reconstructed from secondary data,

ε_e is the fraction of time that primary and secondary data are not available to compute streamflow records, and

V_e is the relative error variance of the third situation.

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

The time 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

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

where

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

e is the base of natural logarithms, and

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

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

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

(Fontaine and others, 1984, eq. 21).

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

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

(Fontaine and others, 1984, eqs. 23 and 25).

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

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

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

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 relationship between discharge and some correlative data, such as water-surface elevation at the gaging station. The measured discharge is the discharge determined by field observations of depths, widths, and velocities. Let $q_T(t)$ be the true instantaneous discharge at time t and let $q_R(t)$ be the value that would be estimated using the rating curve. Then

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

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

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

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

$$z(t) = x(t) + v(t) = \ln q_m(t) - \ln q_R(t) \tag{9}$$

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 (1984) 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

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

The variance of the observed residuals z(t) is

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

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 relationship. The Kalman filter utilizes these three parameters to determine the average relative variance of the errors of estimation of discharges as a function of the number of discharge measurements per year (Moss and Gilroy, 1980).

If the recorder at the primary site fails and there are no concurrent data at other sites that can be used to reconstruct the missing record at the primary site, there are at least two ways of estimating discharges at the primary site. A recession curve could be applied from the time of recorder stoppage until the 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 variation squared $(C_v)^2$ is an estimate of the required relative error variance V_e. Because C_v varies seasonally and the times of failures cannot be anticipated, a seasonally averaged value of C_v is used:

$$\bar{C}_v = \left(\frac{1}{365} \sum_{i=1}^{365} \left(\frac{\sigma_i}{\mu_i} \right)^2 \right)^{1/2} \tag{12}$$

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 gaged nearby 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 relationship. 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

$$V_r = (1 - \rho_c^2)\, \bar{C}_v^2 \tag{13}$$

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 $\overline{V}$ 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 is determined by the probability statement that

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

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

The Application of K-CERA in Maryland, Delaware, and the District of Columbia

As discussed in the first two parts of this analysis, data are currently being used from all 99 stream gages being operated in the Md.-Del.-D.C. program. Also, there is no effective way to generate from other sources of hydrologic data reasonably accurate records at these sites. Therefore, anticipating these gages will continue to be operated, at least for the time being, all were included in the K-CERA analysis. Acceptable uncertainty functions were determined for 90 of the 99 stations and results are described below. At the other nine sites, most of which were established very recently, there were too few discharge measurements available, at least under current rating conditions, to develop stable uncertainty functions. These nine stations were included as "dummy" stations (in the network, but not included in the accuracy optimization process which is described in a subsequent section).

Determination of Missing-Record Probabilities

As described earlier, the statistical characteristics of missing stage or other correlative data for computation of streamflow records can be defined by a single parameter, the value of k in the truncated negative exponential probability distribution of times to failure of the equipment. In the representation of $f(\tau)$, 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 Md.-Del.-D.C., the most recent records available, 1983 and 1984, were used to represent the most current technology and the most current general pattern in which the stream gages are serviced. During this period, the gages malfunctioned on the average 2.6 percent of the time.

The lost record data were analyzed for any discernible patterns in the data losses. The analysis indicated there were no appreciable variations in record losses related to the different physiographic regions in which the gages are located. However, the analysis did indicate that the type of gaging equipment used has a substantial effect on the losses experienced. The majority of gaging stations are equipped with recorders driven by floats (with stilling wells). These stations provide reasonably reliable records--those with dual recorders averaged 0.9 percent lost record and those with single recorders, 3.8 percent lost. Gaging stations equipped with bubble gages lose significantly more record--those with dual recorders (which were operated in tandem) averaged 3.2 percent record lost and those with single recorders were estimated to have 6.0 percent losses.

Therefore, gaging stations were grouped according to the equipment used. Average monthly visit frequencies and average record losses were used to determine 1/k values as follows:

Gaging station equipment	Average time to failure (1/k), in days [percent lost record]			
	Single recorders		Dual recorders	
Bubble gages	265	[6.0]	504	[3.2]
Float driven gages	338	[3.8]	1,390	[0.9]

The 1/K values given above were used to determine ε_f, ε_e, and ε_r for each of the 90 stream gages (for which stable uncertainty functions could be developed) as a function of the individual frequencies of visit.

Determination of Cross-Correlation Coefficients and Coefficients of Variation

To compute the values of V_e and V_r of the uncertainty functions, daily streamflow records for each of the 90 stations for the 1975-83 water years, or the part thereof for which daily streamflow values are stored in WATSTORE (Hutchinson, 1975), were retrieved. For stream gages that had 3 or more complete water years of data, the values of C_v were computed and various options, based on combinations of other stream gages, were explored to determine the maximum ρ_c values. For seven stations, that had less than 3 water years of data, values of C_v and ρ_c were estimated subjectively.

Single and multiple linear regression analyses were performed to determine the cross-correlation relationships between daily discharges at the gaging stations and various nearby stations. The nearby stations were considered to be the independent variables (auxiliary stations) in the relationships and were analyzed both singly and in combination, both coincident and, in some instances, lagged in time. The analyses were performed on the stations' records subsequent to 1974 to help insure the relationships reflected current field conditions.

The coefficient of variation and the highest cross-correlation coefficient for each station, and the auxiliary station(s) whose records gave the highest cross-correlation coefficient, are listed in table 9.

Kalman-Filter Definition of Variance

The determination of the variance V_f for each of the 90 stream gages required the execution of three distinct steps: (1) long-term rating analysis and computation of residuals of measured discharges from the long-term rating, (2) time-series analysis of the residuals to determine the input parameters of the Kalman-filter streamflow records, and (3) computation of the error variance, V_f, as a function of the time-series parameters, the discharge-measurement-error variance, and the frequency of discharge measurement.

In the Md.-Del.-D.C. program analysis, definition of long-term rating functions was accomplished by a trial and error curve-fitting process generally using the most recent stage-discharge rating curve for a given station as a starting point. The curve and discharge measurements are plotted (for visual verification) and the residuals of the measurements are computed in logarithm (base 10) space.

Table 9.--Statistics of record reconstruction

Station number	C_v (percent)	ρ_c	Source of reconstructed records		
1477800	151.7	0.796	1478000	1479000	
1478000	136.9	.845	1479000	1480000	1481500
1479000	95.5	.954	1478000	1480000	1481500
1480000	88.0	.951	1478000	1479000	1481500
1481500	85.1	.987	1480000	1481000	
1483200	109.7	.876	1478000	1483700	1493500
1483700	109.4	.836	1483200	1484000	
1484000	97.1	.936	1483700	1487000	1488500
1484100	82.6	.881	1484000	1484500	
1484500	79.3	.814	1484000	1484100	
1485000	112.9	.907	1485500	1486000	1487000
1485500	132.9	.894	1485000	1486000	1487000
1486000	133.6	.876	1485000	1485500	1487000
1487000	69.9	.888	1484000	1484500	1488500
1488500	99.4	.890	1489000	1491000	
1489000	104.7	.835	1488500	1491000	
1491000	105.0	.912	1483700	1488500	1493500
1493000	79.7	.803	1483200	1493500	
1493500	96.8	.820	1483200	1493000	
1495000	88.3	.941	1480000	1481500	1496200
1496200	104.0	.882	1478000	1481500	1495000
1580000	79.9	.965	1581700	1582000	
1581700	88.3	.945	1580000	1584050	
1582000	74.4	.976	1580000	1583500	
1582500	[1]76.	[1].97			
1583100	[1]80.	[1].95			
1583500	77.6	.969	1582000	1589440	
1583600	[1]96.	[1].90			
1584050	84.5	.900	1580000	1581700	
1585100	141.6	.952	1585300	1585400	
1585200	133.9	.863	1585300	1585400	
1585300	156.5	.965	1585100	1585200	1585400
1585400	142.4	.922	1585100	1585200	1585300
1585500	95.1	.835	1586000		
1586000	87.7	.905	1583500		
1586210	[1]89.	[1].90			
1586610	[1]89.	[1].90			
1589000	102.2	.877	1586000		
1589300	104.8	.887	1589440		

[1] Less than 3 years of data are available. C_v and ρ_c are estimated from nearby (generally in same river basin) stations' values.

Table 9.--Statistics of record reconstruction--Continued

Station number	C_v (percent)	ρ_c	Source of reconstructed records
1589330	155.0	0.878	1589100
1589440	87.7	.887	1589300
1590500	81.1	.860	1593500 1649500
1591000	91.8	.893	1591400 1591700
1591400	83.1	.947	1591000 1591700
1591610	85.2	[2].99	Upstream reservoir.
1591700	89.3	.932	1591000 1591400
1592500	138.6	[2].99	Upstream reservoir.
1593500	106.6	.856	1591000 1591400 1591700
1594440	95.3	.838	1592500 1593500
1594930	[3]77.	[3].73	
1594934	76.4	.791	1594930 1594936 1595000
1594936	78.3	.669	1594930 1595000
1595000	96.1	.944	1594930 1595500
1595500	99.4	.949	1595000
1595800	95.7	[2].99	Upstream reservoir.
1596500	111.3	.920	1599000 3076600 3078000
1597500	98.4	[2].99	Upstream reservoir.
1598500	91.5	.969	1595800 1600000
1599000	101.5	.885	1596500 3078000
1600000	90.9	.974	1598500 1603000
1601500	104.2	.909	1599000 1603000
1603000	93.5	.976	1600000 1610000
1610000	96.8	.971	1603000 1613000
1613000	99.4	.979	1610000 1618000
1614500	94.4	.815	1617800 1619500
1617800	72.8	.907	1614500 1619500
1618000	98.1	.974	1613000 1638500
1619500	68.5	.942	1614500 1617800
1637500	109.1	.763	1643500
1638500	93.9	.984	1618000 1636500 1646500
1639000	143.8	.908	1639500 1643000
1639500	97.2	.880	1639000 1643000
1640965	[1]104.	[1].82	
1640975	[1]104.	[1].82	

[1] Less than 3 years of data are available. C_v and ρ_c are estimated from nearby (generally in same river basin) stations' values.

[2] ρ_c estimated as was done with upstream hydropower plants in Maine (see Fontaine and others, 1984).

[3] C_v and ρ_c estimated from nearby stations' values.

Table 9.--Statistics of record reconstruction--Continued

Station number	C_v (percent)	ρ_c	Source of reconstructed records	
1641000	99.5	0.875	1637500	
1643000	112.1	.905	1639000	
1643500	98.4	.924	1645000	
1645000	97.9	.924	1643500	
1645200	129.4	.837	1649500	1651000
1646500	97.2	.986	1638500	1643000
1648000	107.0	.909	1649500	1651000
1649500	120.5	.929	1648000	1651000
1651000	121.0	.942	1648000	1649500
1653600	126.7	.801	1661050	
1661050	124.7	.882	1653600	1661500
1661500	125.7	.840	1661050	
3075500	100.7	.941	3076500	3076600
3076500	82.8	.947	3075500	3076600
3076600	98.6	.934	3075500	3078000
3078000	97.7	.908	1596500	3075500

The mean and variance of the residuals are computed and a plot is made of residuals against gage height. The curve is refit manually until the mean squared of the residuals is less than 10 percent of the variance, and the variance of the residuals appears essentially minimized. For example, for the rating function at station 1591700, the mean of the residuals is 0.00516 and the variance is 0.00377. The residuals of the discharge measurements about that rating function are presented in table 10.

The time series of residuals (in logarithmic units) of the discharge measurements is used to compute sample estimates of q and β, two of the three parameters required to compute V_f, by means of an autocovariance analysis. Measurement variance, the third parameter, is determined from an assumed constant-percentage standard error. For the Md.-Del.-D.C. program, all open-water measurements were assumed to have a measurement error of 2 percent. Ice measurements do not constitute a significant part of the rating effort in the study area and therefore were not included in the analysis.

The parameters q and β can be expressed as functions of p (process variance) and Rho (1-day autocorrelation coefficient). The process variance (p) is the total variance, minus the measurement variance, of the residuals about the rating curve. As discussed earlier, $p = q/2\beta$ (eq. 10). Rho is the 1-day autocorrelation coefficient of the residuals about the rating curve:

$$\text{Rho} = e^{-\beta|t_1-t_2|} . \qquad (16)$$

Table 11 presents a summary of the autocovariance analysis expressed in terms of process variance and 1-day autocorrelation coefficients (Rho). Autocorrelation coefficients were not determined at 9 of the 99 (total) stations included in the analysis. At these sites (1578310, 1583570, 1589100, 1589500, 1589512, 1589522, 1594000, 1640970, and 1660920), there either were too few measurements available in general, or too few relative to the residual scatter encountered, to enable definition of stable coefficients. Therefore, only the remaining 90 stations were included in table 11 and used in the optimizing process of the Traveling Hydrographer program. The other nine stations were used (as dummy stations) in the determination of costs, but not in the accuracy-optimization procedure for the overall network operation.

Table 10.--Residual data for station 1591700

Observation number	Date	Measured discharge (ft^3/s)	Measured discharge (log base 10)	Residuals (log base 10)
1	June 12, 1978	21.0	1.3222	-0.0069
2	July 3, 1978	498	2.6972	.0526
3	July 21, 1978	15.4	1.1875	.0049
4	Sept. 8, 1978	10.5	1.0212	-.0459
5	Dec. 12, 1978	25.9	1.4133	-.0033
6	Jan. 2, 1979	593	2.7730	.0377
7	Jan. 23, 1979	48.3	1.6839	.0138
8	Feb. 26, 1979	480	2.6812	.0245
9	Mar. 2, 1979	107	2.0294	.0640
10	Apr. 24, 1979	31.4	1.4969	.0526
11	July 10, 1979	16.3	1.2122	.1060
12	Aug. 24, 1979	25.3	1.4031	.1280
13	Sept. 6, 1979	4,300	3.6335	-.0005
14	Oct. 1, 1979	1,240	3.0934	-.0066
15	Nov. 20, 1979	34.8	1.5416	-.0616
16	Dec. 13, 1979	35.3	1.5478	-.0330
17	Jan. 30, 1980	28.8	1.4594	-.0391
18	Mar. 12, 1980	23.2	1.3655	-.0788
19	Apr. 24, 1980	29.7	1.4728	-.0739
20	July 15, 1980	14.5	1.1614	-.0023
21	Aug. 28, 1980	7.40	0.8692	-.0976
22	Oct. 2, 1980	5.34	0.7275	-.1513
23	Nov. 20, 1980	12.1	1.0828	-.0234
24	Dec. 12, 1980	11.7	1.0682	-.0380
25	Jan. 22, 1981	11.6	1.0645	-.0223
26	Mar. 10, 1981	19.1	1.2810	.0059
27	Apr. 20, 1981	18.3	1.2624	-.0127
28	June 8, 1981	22.3	1.3483	.0551
29	July 13, 1981	8.28	0.9180	-.0282
30	Aug. 24, 1981	4.66	0.6684	.0081
31	Oct. 16, 1981	4.13	0.6159	-.1293
32	Nov. 13, 1981	6.74	0.8287	-.0501
33	Dec. 16, 1981	21.0	1.3222	.0290
34	Jan. 29, 1982	10.9	1.0374	-.0297
35	Mar. 5, 1982	18.9	1.2765	.0565
36	Apr. 15, 1982	20.0	1.3010	.0259
37	May 14, 1982	16.1	1.2068	.0813
38	July 9, 1982	11.3	1.0531	.1068
39	Aug. 26, 1982	4.97	0.6964	.1465
40	Oct. 1, 1982	5.52	0.7419	.0531
41	Nov. 18, 1982	8.71	0.9400	.0144
42	Jan. 17, 1983	15.0	1.1761	.0894
43	Feb. 17, 1983	24.3	1.3856	.0565
44	Mar. 28, 1983	76.1	1.8814	-.0175
45	Apr. 5, 1983	32.7	1.5145	.0160
46	May 7, 1983	74.8	1.8739	.0075
47	June 24, 1983	29.8	1.4742	.0162
48	Aug. 16, 1983	7.36	0.8669	.0142
49	Oct. 12, 1983	67.4	1.8287	-.0622

Table 11.--Summary of the autocovariance analysis

Station number	Rho[1/]	Process variance (log base 10)^2
1477800	0.978	0.00582
1478000	.978	.02645
1479000	.990	.00593
1480000	.982	.00087
1481500	.972	.00146
1483200	.982	.00191
1483700	.980	.00096
1484000	.985	.00769
1484100	.909	.00028
1484500	.938	.00195
1485000	.985	.00293
1485500	.977	.00117
1486000	.961	.00265
1487000	.977	.00633
1488500	.984	.00151
1489000	.947	.00095
1491000	.547	.00061
1493000	.975	.00182
1493500	.981	.00216
1495000	.982	.00345
1496200	.982	.00422
1580000	.952	.00060
1581700	.994	.01298
1582000	.987	.00118
1582500	.995	.00158
1583100	.998	.00791
1583500	.974	.00055
1583600	.971	.00153
1584050	.979	.00054
1585100	.998	.01463

[1/] One-day autocorrelation coefficient.

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

Station number	Rho[1/]	Process variance (log base 10)[2]
1585200	0.941	0.00114
1585300	.976	.00220
1585400	.964	.00444
1585500	.967	.00388
1586000	.991	.00189
1586210	.991	.00634
1586610	.996	.01357
1589000	.996	.00954
1589300	.988	.00324
1589330	.981	.00893
1589440	.997	.01379
1590500	.982	.00312
1591000	.987	.00124
1591400	.986	.00120
1591610	.953	.00057
1591700	.984	.00362
1592500	.982	.05380
1593500	.977	.00249
1594440	.933	.00208
1594930	.937	.00619
1594934	.968	.00186
1594936	.553	.00058
1595000	.969	.00203
1595500	.973	.00222
1595800	.980	.03303
1596500	.959	.00173
1597500	.983	.00297
1598500	.611	.00045
1599000	.986	.00464
1600000	.981	.00042

[1/]One-day autocorrelation coefficient.

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

Station number	Rho[1]	Process variance (log base 10)[2]
1601500	0.976	0.00039
1603000	.963	.00104
1610000	.979	.00085
1613000	.979	.00056
1614500	.978	.00051
1617800	.986	.00115
1618000	.974	.00029
1619500	.975	.00043
1637500	.989	.00104
1638500	.000	.00102
1639000	.928	.00066
1639500	.989	.00218
1640965	.970	.02116
1640975	.980	.00259
1641000	.953	.00287
1643000	.993	.00099
1643500	.993	.00337
1645000	.973	.00071
1645200	.974	.00383
1646500	.982	.00073
1648000	.981	.00184
1649500	.965	.01462
1651000	.985	.00827
1653600	.980	.00335
1661050	.952	.00144
1661500	.650	.00123
3075500	.967	.00056
3076500	.967	.00067
3076600	.966	.00100
3078000	.985	.00166

[1]One-day autocorrelation coefficient.

The autocovariance parameters, summarized in table 11, and data from the determination of missing record probabilities, summarized in table 9, are used jointly to define uncertainty functions for each gaging station. The uncertainty functions give the relationship of total error variance to the number of visits and discharge measurements.

Station 1591700 provides a typical example of an uncertainty function, shown in figure 9. These uncertainty functions are based on the assumption that measurements are made during each visit to the stations.

Network Operation--Routes and Cost Determination

In Maryland, Delaware, and the District of Columbia, feasible routes to service the 99 stream gages were determined in consultation with the Chief of the Hydrologic Data Section of the Md.-Del.-D.C. office after review of the uncertainty functions. In summary, 129 routes were selected to service the stream gages in the study area. 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 proximate gages where the levels of uncertainty indicated more frequent visits might be useful. These routes and the stations visited on each are summarized in table 12. Visits to sites (such as ground-water wells) other than the primary network stations were included in the route determinations, but are not listed in table 12 to save space and avoid confusion. Also, routes which would be repetitive or would not exist, if not for the inclusion of such secondary sites, are not listed in the table.

The costs associated with the practical routes must be determined. Fixed costs to operate a gage typically include equipment rental, batteries, electricity, data processing and storage, computer charges, maintenance, miscellaneous supplies, and analysis and supervisory charges. For Md.-Del.-D.C., average values were applied to each station in the program for all the above categories except analysis and supervisory costs. Costs of analysis and supervision form a large percentage of the cost at each gaging station and can vary widely. These costs were determined on a station-by-station basis from past experience.

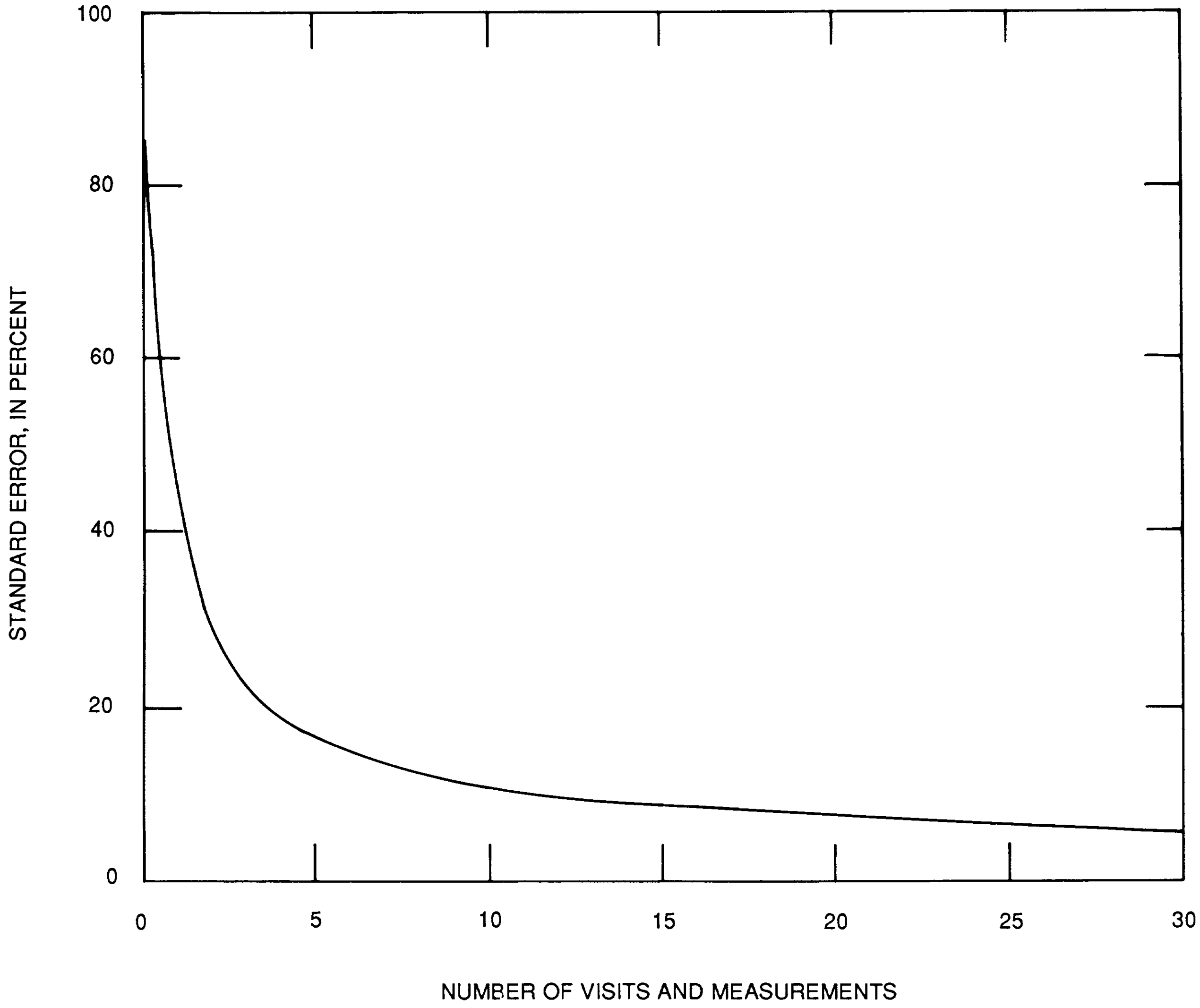


Figure 9.--Uncertainty function for instantaneous discharge at station 1591700.

Table 12.--Summary of the routes that may be used to visit stations in Maryland, Delaware, and D.C.

Route number	Stations serviced on the route				
1	1477800				
2	1477800	1478000			
3	1477800	1480000	1479000	1478000	1495000
	1496200	1493500	1483200		
4	1478000				
5	1479000				
6	1480000	1479000			
7	1481500				
8	1483200				
9	1483700				
10	1484000	1488500	1489000		
11	1484000	1488500	1489000	1486000	1485500
	1484500				
12	1484000	1484100	1487000	1484500	1485000
	1485500	1486000	1489000	1488500	
13	1484100				
14	1485000				
15	1485000	1484500			
16	1485500	1487000			
17	1486000				
18	1486000	1485500	1484500		
19	1486000	1485500	1485000	1484500	1487000
20	1487000				
21	1488500				
22	1489000	1488500	1484100	1484000	
23	1491000				
24	1493000	1483200	1483700		
25	1493500				
26	1493500	1493000			
27	1495000				
28	1495000	1496200			
29	1578310	1580000	1581700		
30	1581700				
31	1582000	1584050	1585200		
32	1582500	1583600	1589440		
33	1583100	1582500	1583600		
34	1583100	1583500	1582000		
35	1583570	1589500	1589512	1589522	
36	1583600				
37	1584050	1585200			
38	1585100				
39	1585300	1585400	1585100	1578310	1580000
	1581700	1584050			
40	1585400				
41	1585400	1585300	1585100		

Table 12.--Summary of the routes that may be used to visit stations in Maryland, Delaware, and D.C.--Continued

Route number	Stations serviced on the route				
42	1586000	1586210	1586610	1585500	1639500
	1639000	1641000			
43	1586000	1586210	1586610	1585500	1639500
	1639000	1641000	1640975	1640965	1640970
44	1586000	1586210	1586610	1585500	1639500
	1639000	1641000	1640975	1640965	1640970
	1637500	1643000	1643500		
45	1586210				
46	1586210	1586610	1585500	1586000	
47	1589100	1589000	1589330		
48	1589300				
49	1589300	1589440	1583500		
50	1589330				
51	1589330	1589000	1591610	1593500	1594000
	1592500	1649500	1651000	1648000	1653600
	1594440	1590500	1589522	1589512	1589500
	1589100				
52	1589440				
53	1589500	1589512	1589522	1590500	1594440
	1649500	1651000	1648000	1645200	1592500
	1594000	1593500	1591610	1591700	1591000
	1591400				
54	1590500	1594440			
55	1590500	1594440	1653600		
56	1590500	1594440	1661500	1661050	1653600
57	1590500	1594440	1661500	1661050	1660920
	1653600				
58	1590500	1594440	1661500	1661050	1660920
	1653600	1589500	1589512	1589522	
59	1591400	1591000	1591700	1591610	
60	1591400	1591000	1591700	1591610	1593500
	1594000	1592500	1649500	1651000	1648000
61	1591400	1591000	1591700	1591610	1593500
	1594000	1592500	1649500	1651000	1648000
	1645200	1645000			
62	1592500				
63	1592500	1594000	1593500	1591700	1591610
	1591000	1591400			
64	1593500	1594000	1592500		
65	1593500	1594000	1592500	1653600	1660920
	1661050	1661500	1594440	1590500	1589500
	1589512	1589522			
66	1594440				
67	1594930				
68	1594930	1594934	1594936		

Table 12.--Summary of the routes that may be used to visit stations in Maryland, Delaware, and D.C.--Continued

Route number	Stations serviced on the route				
69	1594930	1594934	1594936	1595000	
70	1594934				
71	1594936				
72	1595500				
73	1595500	1595800			
74	1595500	1595800	1597500	1598500	1599000
	1600000	1603000			
75	1597500	1596500	3078000		
76	1598500	1599000	1600000		
77	1600000	1603000	1601500		
78	1601500	1603000			
79	1603000				
80	1610000				
81	1613000				
82	1614500				
83	1617800	1619500	1614500		
84	1617800	1619500	1618000	1614500	1613000
85	1618000	1613000			
86	1638500				
87	1640965				
88	1643000	1643500	1638500	1637500	1640975
	1640965	1640970	1641000	1639000	1639500
	1585500	1586000	1586210	1586610	
89	1643500				
90	1643500	1643000	1637500	1640965	1640970
	1640975				
91	1645000	1646500			
92	1645000	1645200	1646500		
93	1645000	1645200	1648000	1651000	1649500
	1592000				
94	1645000	1645200	1648000	1651000	1649500
	1592500	1594000	1593500	1591610	1591700
	1591000	1591400	1589500	1589512	1589522
95	1649500				
96	1649500	1651000	1648000		
97	1653600				
98	1660920				
99	1660920	1653600			
100	1661500	1661050	1660920		
101	3076600				
102	3076600	3076500	3075500		
103	3078000				

Visit costs are those associated with paying the hydrographer for the time actually spent at a station making discharge measurements. These costs vary from station to station as a function of the difficulty encountered in servicing the equipment and the time required to make the discharge measurement. Average visit times were calculated for each station based on an analysis of discharge measurement data available, equipment at the site, and accessibility of the site. This time was then multiplied by the average hourly salary of hydrographers in the Md.-Del.-D.C. offices to determine total visit costs.

Route costs include the cost of the hydrographer's time while in transit and while servicing equipment at the gaging stations. Route costs also include any per diem associated with the time it takes to complete the trip. Because of the accounting system used in the District, vehicle costs are included in overhead.

K-CERA Results

The Traveling Hydrographer program utilizes the uncertainty functions along with the appropriate cost data and route definitions to compute the most cost-effective way of operating the stream-gaging program. In this application, the first step was to simulate the current practice and determine the associated total uncertainty. To accomplish this, the number of visits made to each stream gage and the specific routes used to make these visits were fixed. The resulting average error of estimation for the current practice in Md.-Del.-D.C. is plotted as a point in figure 10 and is 11.8 percent.

The curve labeled "with missing record" in figure 10 represents the minimum average standard error 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 primarily to the physical limitations of the method used to record data. The effect of visitation frequency on the accuracy of the data and amount of lost record is taken into account in the uncertainty analysis. In Md.-Del.-D.C., a minimum of four visits per year was applied to most gaging stations. This value was based on limitations of the batteries used to drive recording equipment, capabilities of the uptake spools on the digital recorders, problems related to humidity, and the need to protect gages from freezing winter conditions and

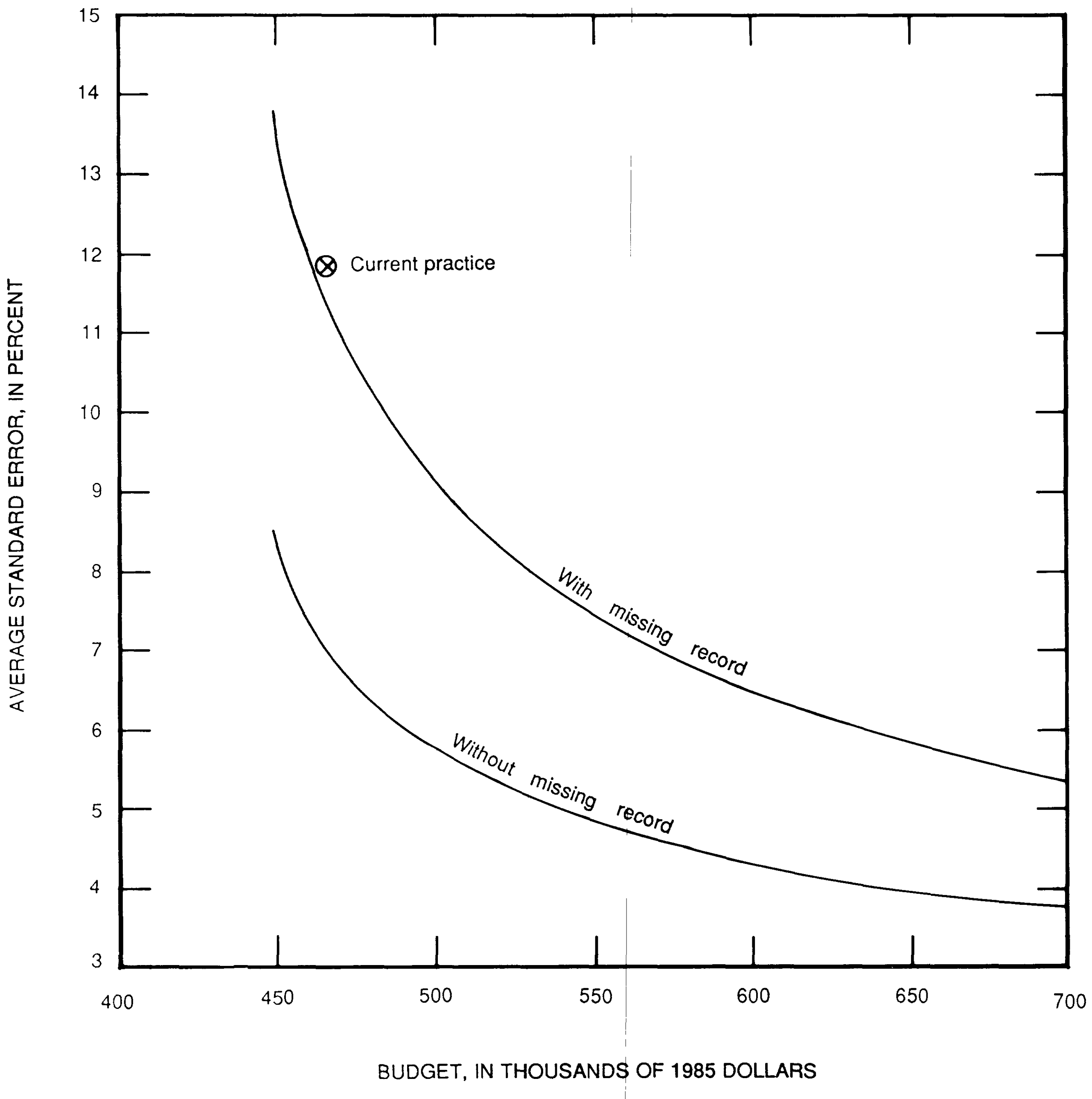


Figure 10.--Temporal average standard error per stream gage.

their intakes from sediment plugging and debris obstructions. At some stations, the four-visit minimum was increased to reflect additional requirements such as water-quality sampling.

A constraint also was placed on the maximum number of visits at each site. A limit of 72 visits per year was put in effect (as being a reasonable maximum) at all stations by flattening the uncertainty function beyond 72 visits.

At 13 of the gaging stations, measurements are not made with every visit. A probability of making measurements was assigned to those stations and was reflected in the visit costs and subsequently in the budget costs of the Traveling Hydrographer program.

The results of the K-CERA analysis are summarized in figure 10 and table 13. It can be seen that the current policy results in an average standard error of estimate of streamflow of 11.8 percent. This policy requires a budget of $465,260 to operate the 99-station stream-gaging program. The range in standard errors is from a low of 3.8 percent for station 1600000 to a high of 28.1 percent at station 1592500. It is possible to obtain the same average standard error with a reduced budget of $461,000 with a change of policy in the field activities of the stream-gaging program. This policy and budget change would result in an increase in standard error from 3.8 to 4.7 percent at station 1600000, while the standard error at station 1592500 would decrease from 28.1 percent to 21.8 percent. These two stations would still have the greatest extremes of standard error.

It also would be possible to reduce the average standard error by a policy change while maintaining the $465,260 budget. In this case, the average standard error would decrease from 11.8 to 11.4 percent. Extremes of standard errors for individual sites would be 4.4 and 20.6 percent for stations 1600000 and 1640965, respectively.

A minimum budget of $448,500 is required to operate the 99-station program; a smaller budget would not permit effective 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 13.7 percent. The minimum standard error of 4.5 percent would occur at station 1610000, while the maximum of 24.9 percent would occur at station 1640965.

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

Station number	Standard error of instantaneous discharge (SE), in percent [Equivalent Gaussian spread (EGS)] (Number of visits per year to site)					
	Current operation	Budget, in thousands of 1985 dollars				
		448.5	461	465.3	540	700
Average per station	[1] 11.8 [6.0]	[1] 13.7 [7.0]	[1] 11.8 [6.3]	[1] 11.4 [6.1]	[1] 7.7 [4.4]	[1] 5.3 [3.1]
1477800	14.9 [10.0] (9)	15.7 [10.6] (8)	12.5 [8.5] (13)	12.5 [8.5] (13)	8.1 [5.5] (31)	6.1 [4.2] (54)
1478000	22.8 [21.4] (9)	21.8 [20.4] (10)	18.6 [17.4] (14)	16.9 [15.8] (17)	11.1 [10.3] (39)	8.2 [7.6] (71)
1479000	7.8 [7.0] (9)	11.6 [10.3] (4)	10.4 [9.3] (5)	9.5 [8.5] (6)	6.4 [5.8] (13)	4.5 [4.1] (26)
1480000	5.0 [3.6] (9)	7.5 [5.0] (4)	6.7 [4.6] (5)	7.5 [5.0] (4)	4.5 [3.3] (11)	3.2 [2.4] (22)
1481500	5.2 [4.9] (12)	5.2 [4.9] (12)	5.2 [4.9] (12)	5.2 [4.9] (12)	5.2 [4.9] (12)	4.1 [3.9] (20)
1483200	15.1 [5.6] (9)	15.1 [5.6] (9)	12.9 [4.8] (12)	12.3 [4.6] (13)	7.9 [3.0] (30)	5.4 [2.1] (63)
1483700	8.3 [4.0] (9)	12.3 [5.5] (4)	9.4 [4.4] (7)	3.8 [4.2] (8)	6.0 [3.0] (17)	4.0 [2.0] (40)
1484000	13.7 [10.1] (9)	19.1 [13.5] (5)	13.7 [10.1] (9)	13.7 [10.1] (9)	8.9 [6.6] (20)	5.7 [4.2] (47)
1484100	11.0 [3.7] (9)	15.3 [4.1] (5)	11.0 [3.7] (9)	10.4 [3.6] (10)	6.9 [2.8] (22)	4.9 [2.1] (45)
1484500	9.9 [8.3] (9)	11.7 [9.3] (5)	9.9 [8.3] (9)	9.9 [8.3] (9)	6.8 [6.0] (24)	4.3 [3.8] (63)
1485000	8.4 [6.0] (9)	12.4 [8.6] (4)	12.4 [8.6] (4)	11.1 [7.9] (5)	7.6 [5.4] (11)	4.9 [3.5] (26)

[1] Square root of seasonally averaged station variance.

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

Station number	Standard error of instantaneous discharge (SE), in percent [Equivalent Gaussian spread (EGS)] (Number of visits per year to site)					
	Current operation	Budget, in thousands of 1985 dollars				
		448.5	461	465.3	540	700
1485500	8.7 [4.6] (9)	13.0 [6.3] (4)	10.6 [5.4] (6)	9.8 [5.1] (7)	6.5 [3.6] (16)	4.3 [2.4] (37)
1486000	11.5 [8.5] (9)	15.9 [10.6] (4)	13.6 [9.6] (6)	12.8 [9.2] (7)	8.9 [6.8] (16)	6.0 [4.6] (37)
1487000	11.2 [10.6] (9)	15.1 [14.3] (4)	12.4 [11.8] (7)	11.7 [11.2] (8)	7.7 [7.3] (20)	5.4 [5.1] (40)
1488500	7.1 [4.5] (9)	9.5 [5.8] (5)	7.1 [4.5] (9)	7.1 [4.5] (9)	4.8 [3.0] (20)	3.1 [2.0] (47)
1489000	8.9 [5.6] (9)	11.4 [6.4] (5)	8.9 [5.6] (9)	8.9 [5.6] (9)	6.3 [4.2] (20)	4.2 [2.9] (47)
1491000	7.2 [5.6] (12)	7.2 [5.6] (12)	7.2 [5.6] (12)	7.2 [5.6] (12)	7.2 [5.6] (12)	6.3 [5.4] (23)
1493000	8.2 [6.0] (9)	10.6 [7.4] (5)	9.2 [6.6] (7)	9.2 [6.6] (7)	6.3 [4.6] (16)	4.1 [3.0] (37)
1493500	8.8 [5.8] (9)	10.7 [6.9] (6)	10.7 [6.9] (6)	10.7 [6.9] (6)	6.6 [4.4] (16)	4.6 [3.0] (34)
1495000	7.9 [7.1] (9)	11.3 [9.9] (4)	9.5 [8.4] (6)	9.5 [8.4] (6)	6.0 [5.3] (16)	4.1 [3.7] (34)
1496200	9.8 [7.8] (9)	14.0 [11.0] (4)	11.8 [9.4] (6)	11.8 [9.4] (6)	7.4 [5.9] (16)	5.1 [4.1] (34)
1580000	8.3 [4.5] (9)	10.6 [5.1] (6)	10.6 [5.1] (6)	10.6 [5.1] (6)	7.3 [4.2] (11)	4.9 [3.2] (22)
1581700	10.3 [8.1] (9)	12.9 [10.1] (6)	12.9 [10.1] (6)	11.8 [9.3] (7)	7.8 [6.2] (15)	5.3 [4.2] (32)

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

Station number	Standard error of instantaneous discharge (SE), in percent [Equivalent Gaussian spread (EGS)] (Number of visits per year to site)					
	Current operation	Budget, in thousands of 1985 dollars				
		448.5	461	465.3	540	700
1582000	7.1 [3.8] (9)	12.6 [5.7] (4)	9.4 [4.6] (6)	9.4 [4.6] (6)	5.5 [3.1] (13)	3.8 [2.3] (24)
1582500	7.1 [2.8] (9)	10.8 [3.9] (5)	8.4 [3.2] (7)	7.7 [3.0] (8)	5.0 [2.1] (15)	3.3 [1.5] (29)
1583100	8.6 [3.9] (9)	10.1 [4.4] (7)	8.0 [3.6] (10)	8.0 [3.6] (10)	5.3 [2.5] (20)	3.8 [2.0] (36)
1583500	7.5 [3.5] (9)	9.9 [4.2] (6)	7.5 [3.5] (9)	7.5 [3.5] (9)	4.7 [2.5] (19)	3.2 [1.8] (36)
1583600	12.8 [6.1] (9)	14.7 [6.8] (7)	11.5 [5.6] (11)	11.5 [5.6] (11)	7.2 [3.7] (26)	5.0 [2.5] (54)
1584050	8.7 [3.5] (9)	12.0 [4.4] (5)	10.0 [3.8] (7)	9.3 [3.6] (8)	5.7 [2.4] (20)	3.8 [1.6] (44)
1585100	7.4 [4.9] (9)	7.9 [5.2] (8)	6.7 [4.4] (11)	6.4 [4.2] (12)	4.4 [3.0] (25)	3.2 [2.3] (49)
1585200	10.5 [6.6] (9)	13.3 [7.3] (5)	11.6 [6.9] (7)	11.0 [6.8] (8)	7.6 [5.2] (20)	5.3 [3.8] (44)
1585300	15.3 [6.8] (9)	16.6 [7.2] (8)	13.4 [6.1] (11)	12.6 [5.9] (12)	8.0 [4.1] (25)	5.5 [2.9] (49)
1585400	12.5 [10.7] (9)	13.1 [11.1] (8)	11.5 [9.9] (11)	11.1 [9.5] (12)	7.9 [6.8] (25)	5.3 [4.6] (55)
1585500	11.4 [9.6] (9)	12.6 [10.6] (7)	10.9 [9.3] (10)	10.9 [9.3] (10)	7.3 [6.2] (24)	5.1 [4.4] (49)
1586000	6.0 [3.8] (9)	6.8 [4.3] (7)	5.7 [3.6] (10)	5.7 [3.6] (10)	3.6 [2.4] (24)	2.6 [1.7] (49)

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

Station number	Standard error of instantaneous discharge (SE), in percent [Equivalent Gaussian spread (EGS)] (Number of visits per year to site)					
	Current operation	Budget, in thousands of 1985 dollars				
		448.5	461	465.3	540	700
1586210	12.6 [7.2] (9)	14.5 [8.3] (7)	11.8 [6.8] (10)	11.2 [6.4] (11)	7.4 [4.3] (24)	5.1 [3.0] (49)
1586610	12.4 [7.0] (9)	14.4 [8.1] (7)	11.7 [6.6] (10)	11.7 [6.6] (10)	7.3 [4.2] (24)	5.1 [3.0] (49)
1589000	11.8 [5.8] (9)	11.8 [5.8] (9)	11.8 [5.8] (9)	11.8 [5.8] (9)	8.2 [4.0] (18)	5.7 [2.9] (36)
1589300	8.2 [5.7] (9)	12.2 [8.3] (4)	11.0 [7.5] (5)	10.0 [6.9] (6)	6.5 [4.5] (14)	4.5 [3.1] (30)
1589330	14.6 [11.6] (9)	14.6 [11.6] (9)	14.6 [11.6] (9)	13.9 [11.1] (10)	8.8 [7.0] (25)	6.2 [4.9] (50)
1589440	7.6 [5.8] (9)	11.5 [8.8] (4)	9.3 [7.1] (6)	8.6 [6.6] (7)	6.1 [4.6] (14)	4.2 [3.2] (29)
1590500	12.7 [7.1] (9)	17.3 [9.5] (5)	13.5 [7.5] (8)	12.0 [6.7] (10)	8.4 [4.7] (20)	5.6 [3.1] (44)
1591000	11.8 [3.9] (9)	15.0 [4.9] (6)	11.8 [3.9] (9)	11.8 [3.9] (9)	7.8 [2.7] (19)	5.2 [1.8] (41)
1591400	9.0 [4.0] (9)	11.7 [4.9] (6)	9.0 [4.0] (9)	9.0 [4.0] (9)	5.7 [2.7] (19)	3.7 [1.9] (41)
1591610	6.4 [4.8] (9)	7.9 [5.1] (6)	6.4 [4.8] (9)	6.4 [4.8] (9)	4.5 [3.9] (19)	3.2 [2.9] (41)
1591700	11.6 [7.2] (9)	14.6 [8.9] (6)	11.6 [7.2] (9)	11.6 [7.2] (9)	7.6 [4.9] (19)	5.1 [3.3] (41)
1592500	28.1 [27.4] (9)	25.5 [25.0] (11)	21.8 [21.5] (15)	20.5 [20.2] (17)	13.5 [13.4] (38)	9.8 [9.7] (71)

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

Station number	Standard error of instantaneous discharge (SE), in percent [Equivalent Gaussian spread (EGS)] (Number of visits per year to site)					
	Current operation	Budget, in thousands of 1985 dollars				
		448.5	461	465.3	540	700
1593500	16.0 [7.1] (9)	15.9 [7.1] (9)	14.3 [6.4] (11)	15.1 [6.7] (10)	9.9 [4.5] (22)	7.1 [3.2] (42)
1594440	11.4 [3.6] (9)	14.2 [4.5] (6)	12.2 [3.9] (8)	10.8 [3.4] (10)	7.5 [2.4] (20)	5.0 [1.7] (44)
1594930	14.6 [13.7] (12)	14.6 [13.7] (12)	14.6 [13.7] (12)	14.6 [13.7] (12)	10.7 [10.1] (27)	7.1 [7.0] (64)
1594934	7.6 [5.9] (12)	7.6 [5.9] (12)	7.6 [5.9] (12)	7.6 [5.9] (12)	5.2 [4.1] (27)	3.4 [2.7] (64)
1594936	13.5 [5.7] (12)	13.5 [5.7] (12)	13.5 [5.7] (12)	13.5 [5.7] (12)	9.7 [5.3] (27)	7.1 [4.7] (64)
1595000	13.1 [7.3] (9)	18.8 [9.3] (5)	15.3 [8.1] (7)	14.1 [7.7] (8)	8.0 [4.9] (21)	4.9 [3.1] (52)
1595500	11.7 [7.1] (9)	13.6 [7.9] (7)	9.9 [6.2] (12)	9.1 [5.8] (14)	6.1 [4.0] (29)	4.0 [2.7] (64)
1595800	23.1 [22.2] (9)	25.9 [24.6] (7)	20.1 [19.6] (12)	18.6 [18.2] (14)	12.8 [12.7] (29)	8.6 [8.5] (64)
1596500	8.7 [7.0] (9)	10.2 [7.8] (6)	10.2 [7.8] (6)	10.2 [7.8] (6)	7.3 [5.9] (14)	4.9 [4.1] (32)
1597500	6.7 [6.4] (9)	8.1 [7.6] (6)	8.1 [7.6] (6)	8.1 [7.6] (6)	5.4 [5.1] (14)	3.6 [3.4] (32)
1598500	5.6 [4.8] (9)	7.0 [5.0] (4)	7.0 [5.0] (4)	6.5 [5.0] (5)	5.5 [4.8] (10)	4.9 [4.6] (23)
1599000	9.2 [7.3] (9)	13.5 [10.5] (4)	13.5 [10.5] (4)	12.2 [9.6] (5)	8.7 [6.9] (10)	5.8 [4.5] (23)

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

Station number	Standard error of instantaneous discharge (SE), in percent [Equivalent Gaussian spread (EGS)] (Number of visits per year to site)					
	Current operation	Budget, in thousands of 1985 dollars				
		448.5	461	465.3	540	700
1600000	3.8 [2.6] (9)	4.7 [3.0] (6)	4.7 [3.0] (6)	4.4 [2.9] (7)	3.3 [2.3] (12)	2.3 [1.7] (24)
1601500	12.4 [2.9] (9)	15.9 [3.5] (6)	13.3 [3.1] (8)	12.4 [2.9] (9)	8.3 [2.1] (18)	5.6 [1.5] (38)
1603000	5.8 [5.2] (9)	6.9 [5.9] (6)	6.1 [5.4] (8)	5.8 [5.2] (9)	4.3 [3.9] (18)	3.0 [2.8] (38)
1610000	4.5 [3.7] (12)	4.5 [3.7] (12)	4.5 [3.7] (12)	4.5 [3.7] (12)	4.5 [3.7] (12)	3.6 [3.0] (19)
1613000	5.2 [4.5] (9)	6.0 [4.8] (6)	6.0 [4.8] (6)	6.0 [4.8] (6)	4.7 [4.1] (12)	3.6 [3.2] (24)
1614500	7.3 [3.0] (9)	10.9 [4.1] (4)	9.8 [3.8] (5)	8.9 [3.6] (6)	6.1 [2.6] (13)	4.3 [1.9] (26)
1617800	9.3 [3.9] (9)	15.0 [6.0] (4)	13.1 [5.3] (5)	11.7 [4.8] (6)	7.5 [3.2] (13)	5.1 [2.3] (26)
1618000	8.7 [2.8] (9)	11.7 [3.3] (6)	11.7 [3.3] (6)	11.7 [3.3] (6)	7.1 [2.5] (12)	4.5 [1.8] (24)
1619500	4.3 [3.2] (9)	6.1 [4.1] (4)	5.5 [3.8] (5)	5.1 [3.6] (6)	3.6 [2.7] (13)	2.6 [2.0] (26)
1637500	18.1 [3.7] (9)	18.1 [3.7] (9)	17.1 [3.5] (10)	16.3 [3.3] (11)	11.7 [2.4] (21)	8.0 [1.7] (44)
1638500	7.7 [7.4] (9)	8.6 [7.5] (4)	8.5 [7.5] (4)	8.5 [7.5] (4)	8.2 [7.5] (5)	7.7 [7.4] (9)
1639000	17.5 [5.3] (9)	20.3 [5.7] (7)	17.5 [5.3] (9)	16.5 [5.2] (10)	11.6 [4.2] (19)	7.4 [2.9] (45)

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

Station number	Standard error of instantaneous discharge (SE), in percent [Equivalent Gaussian spread (EGS)] (Number of visits per year to site)					
	Current operation	Budget, in thousands of 1985 dollars				
		448.5	461	465.3	540	700
1639500	13.3 [5.3] (9)	15.4 [6.1] (7)	13.3 [5.3] (9)	12.6 [5.0] (10)	8.8 [3.5] (19)	5.6 [2.3] (45)
1640965	25.9 [22.6] (9)	25.9 [22.6] (9)	21.3 [18.5] (14)	20.6 [17.9] (15)	13.2 [11.2] (37)	9.5 [8.0] (71)
1640975	18.6 [7.0] (9)	18.6 [7.0] (9)	16.7 [6.3] (11)	15.9 [6.0] (12)	10.4 [3.9] (27)	6.8 [2.6] (62)
1641000	10.9 [9.3] (9)	11.9 [10.0] (7)	10.9 [9.3] (9)	10.5 [9.0] (10)	8.1 [7.1] (19)	5.4 [4.7] (45)
1643000	6.6 [2.9] (9)	10.2 [4.3] (4)	9.0 [3.9] (5)	9.0 [3.9] (5)	6.6 [2.9] (9)	4.3 [2.0] (21)
1643500	11.7 [4.7] (9)	11.7 [4.7] (9)	10.9 [4.4] (10)	10.3 [4.2] (11)	7.1 [3.0] (21)	4.8 [2.1] (44)
1645000	5.6 [3.9] (12)	5.4 [3.8] (13)	5.6 [3.9] (12)	5.6 [3.9] (12)	4.2 [3.1] (22)	3.1 [2.3] (42)
1645200	10.6 [7.7] (12)	13.6 [9.7] (7)	13.6 [9.7] (7)	14.6 [10.3] (6)	9.0 [6.6] (17)	6.1 [4.5] (37)
1646500	8.4 [4.7] (12)	8.4 [4.7] (12)	8.4 [4.7] (12)	8.4 [4.7] (12)	5.6 [3.7] (22)	3.9 [2.8] (41)
1648000	7.6 [5.3] (9)	9.3 [6.3] (6)	7.6 [5.3] (9)	7.2 [5.1] (10)	5.0 [3.5] (21)	3.6 [2.6] (41)
1649500	23.7 [20.0] (9)	25.0 [21.0] (8)	19.2 [16.5] (14)	18.6 [16.0] (15)	12.5 [10.8] (33)	8.7 [7.5] (67)
1651000	13.6 [10.3] (9)	16.9 [12.6] (6)	13.6 [10.3] (9)	12.8 [9.7] (10)	8.6 [6.6] (21)	6.1 [4.7] (41)

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

Station number	Standard error of instantaneous discharge (SE), in percent [Equivalent Gaussian spread (EGS)] (Number of visits per year to site)					
	Current operation	Budget, in thousands of 1985 dollars				
		448.5	461	465.3	540	700
1653600	20.7 [7.8] (9)	22.0 [8.2] (8)	18.6 [7.0] (11)	17.8 [6.7] (12)	11.7 [4.4] (27)	7.8 [2.9] (60)
1661050	14.2 [6.9] (9)	17.4 [7.8] (6)	17.4 [7.8] (6)	17.4 [7.8] (6)	11.8 [6.0] (13)	7.7 [4.1] (31)
1661500	11.5 [8.0] (9)	13.0 [8.1] (6)	13.0 [8.1] (6)	13.0 [8.1] (6)	10.4 [7.8] (13)	8.5 [7.3] (31)
3075500	10.9 [3.9] (9)	14.1 [4.6] (6)	12.8 [4.3] (7)	12.8 [4.3] (7)	8.0 [3.1] (15)	5.2 [2.2] (32)
3076500	5.2 [4.0] (9)	6.3 [4.6] (6)	5.9 [4.4] (7)	5.8 [4.4] (7)	4.2 [3.3] (15)	2.9 [2.3] (32)
3076600	9.4 [5.1] (9)	11.8 [5.9] (6)	10.8 [5.6] (7)	10.8 [5.6] (7)	7.2 [4.1] (15)	4.8 [2.9] (32)
3078000	6.8 [4.5] (9)	8.3 [5.5] (6)	8.3 [5.5] (6)	8.3 [5.5] (6)	5.4 [3.7] (14)	3.6 [2.5] (32)

The maximum budget analyzed was $700,000, which resulted in an average standard error of estimate of 5.3 percent. Thus, increasing the budget about 50 percent in conjunction with a policy change would more than halve the average standard error that results from the current policy and current budget. For the $700,000 budget, the extremes of standard error are 2.3 percent for station 1600000 and 9.8 percent at station 1592500. Thus, it is apparent that significant improvements in accuracy of streamflow records can be obtained if larger budgets become available.

In order to estimate the amount of uncertainty in the stream-gaging records as a result of less than perfect instrumentation, the analysis also was performed under the assumption that no correlative data at a stream gage were lost. The curve, labeled "Without missing record" on figure 10, shows 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.

For the minimal operating budget of $448,500, the effect of having completely reliable equipment would be the greatest, reducing the average standard error from 13.7 to 8.5 percent. At the other budgetary extreme of $700,000, under which stations are visited more frequently and less record should be lost, the standard error would be reduced from 5.3 percent, with the current system for sensing and recording hydrologic data, to 3.7 percent with reliable equipment. For the current operation and budget ($465,260), the use of completely reliable equipment would reduce the standard error from 11.8 to 8.0 percent. Thus, it is apparent that improved equipment can have a very positive impact on uncertainties in streamflow data throughout the range of operating budgets that might be anticipated for the stream-gaging program in Md.-Del.-D.C..

Conclusions from the K-CERA Analysis

As a result of the K-CERA analysis, the following conclusions were drawn:

1. The policy for conducting field operations in the stream-gaging program could be altered to maintain the current average standard error of estimate of streamflow records of 11.8 percent with a budget of $461,000. This shift would result in some increases and some decreases in accuracy of records at individual sites.

2. The funding for stations with unacceptable accuracies for the data uses should be renegotiated with the data users.

3. The K-CERA analysis should be repeated 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, such as increased use of dual recorders, local gage observers, and satellite relay of data, should be studied with respect to their cost-effectiveness in providing streamflow information.

SUMMARY

Currently (1985), 99 continuous stream gages are operated in Maryland, Delaware, and the District of Columbia by the U.S. Geological Survey at a cost of $465,260. Fifteen separate sources of funding contribute to this program and as many as 19 separate uses were identified for data from a single gage.

In an analysis of the uses made of the data, data from three stations were identified possibly to be of insufficient importance to warrant continuing the stations' operation. Data from three other stations were identified as having uses primarily related to a short-term study. All six of these stations should be considered for discontinuing in the near future. Data from the remaining 93 stations in the program probably will continue to have multiple significant uses for the foreseeable future.

The current (1985) policy for operation of the 99-station program requires a budget of $465,260 per year. It was shown that the overall level of accuracy of the records at these 99 sites could be maintained with a budget of $461,000, if the allocation of gaging resources among the gages were altered.

The study indicates that a major component of error in the streamflow records results from lost or missing data. If perfect equipment were available and no data were lost, the standard error for the current program and budget could be reduced from 11.8 to 8.0 percent. This also can be interpreted to mean that the current streamflow data have a standard error of 8.0 percent during times when the equipment is operating properly. Upgrading equipment and developing strategies to minimize lost record appear to be key actions available to improve the reliability and accuracy of the streamflow data generated in the Md.-Del.-D.C. water-data program.

Studies of the cost-effectiveness of the stream-gaging program should be continued in relation to increases in data available from gaging-station operations and streamflow measurements, and especially in relation to ongoing changes in stage-recording and discharge-measuring equipment. Future studies also should be made to reflect subsequent addition and deletion of stream gages in relation to changing demand for streamflow information. Such changes will affect the operation of other stations in the program both because of the interdependence (among stations) of the information that is generated (data redundancy) and because of the interdependence of the costs of collecting the data from which the information is derived.

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