COST EFFECTIVENESS OF THE STREAM-GAGING PROGRAM IN PENNSYLVANIA

By H. N. Flippo, Jr. and T. E. Behrendt

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DONALD PAUL HODEL, Secretary

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Dallas L. Peck, Director

For additional information write to:

District Chief
U.S. Geological Survey
4th Floor, Federal Building
P.O. Box 1107
Harrisburg, Pennsylvania 17108-1107

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FACTORS FOR CONVERTING INCH-POUND TO METRIC (SI) UNITS

Multiply inch-pound units	by	To obtain SI units
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
cubic foot (ft^3)	0.02832	cubic meter (m^3)
	Flow	
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 study of the cost-effectiveness of the stream-gaging program in Pennsylvania. Data uses and funding were identified for the 223 continuous-record stream gages operated in 1983. Four of these gages are planned for discontinuance in September 1985, at the end of the water year. Two gages are suggested for conversion, in October 1986, for the collection of only continuous stage records. Two of 11 special-purpose short-term gages are recommended for continuation when the supporting project ends; eight of these gages are to be discontinued and the other will be converted to a partial-record type.

Operation costs for the 212 stations recommended for continued operation is $1,199,000 per year in 1983. The average standard error of estimation for instantaneous streamflow is 15.2 percent. This error is distributed for the three subdistricts' operations as follows: Malvern, 14.3 percent; Harrisburg, 14.2 percent; Pittsburgh, 17.1 percent. An overall average standard error of 13.7 percent could be achieved with a minimal budget of $1,090,000 by adopting specified gaging strategies and redistributing gaging resources. For example, additional stage observers and auxiliary recorders could be used more cost effectively to reduce record losses at 54 identified stations. The program could not be properly administered on a smaller budget because of the level of fixed costs and limitations inherent in the level of gaging activity needed to produce records suitable for present uses.

The adoption of cost-effective stream gaging operations would result in a significant improvement in the overall standard error for a budget equal to or greater than the 1983 budget of $1,199,000. For example, a standard error of 11.0 percent could be attained on the same budget; alternatively, a standard error of 9.8 percent could be attained on a budget of $1,271,000.

INTRODUCTION

The U.S. Geological Survey is the principal Federal agency that collects surface-water data in the Nation. The collection of these data, in cooperation with State and local governments and other Federal agencies, is a major activity of the Water Resources Division (WRD) of the Survey. The Survey is presently (1983) operating approximately 8,000 continuous-record gaging stations throughout the Nation. Some of these records extend back to before the turn of the century. Any activity of longstanding, 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 (1983) undertaking another nationwide analysis of the stream-gaging program that will be completed over a 5-year period, beginning in 1983; 20 percent of the program will be analyzed each year. The objective of this analysis is to define and document the most cost-effective means of furnishing streamflow information in each State. This report summarizes the findings of a study of the cost-effectiveness of Pennsylvania's stream-gaging program.

The first phase of the analysis identifies the principal uses of the data and relates these uses to funding sources for each continuous-record gaging station. Gaged sites for which data are no longer needed are identified, as are deficient or unmet data demands. In addition, gaging stations are categorized as to whether the data are available to users in a real-time sense, on a provisional basis, or after the end of each water year1/.

The second phase of the analysis identifies less costly alternative methods of furnishing the needed information; among these are flow-routing models and statistical methods. 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 phase of the analysis involves the use of Kalman-filtering and mathematical-programing techniques to define strategies for operating the necessary stations so that the uncertainties in streamflow records for given operating budgets are minimized. 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 Pennsylvania and to the study itself. The middle three sections each contain discussions of an individual phase of the analysis. Because of the sequential nature of the three phases and the dependence of subsequent steps on the previous results, summaries of conclusions are made at the end of each of the middle three sections. The study is summarized in the final section.

The discussions of statistical procedures are taken wholely, or in part, from a report by Fontaine and others (1984) for a similar study of the stream-gaging program in Maine.

1/ A water year is from October 1 to September 30.

History of the Stream-gaging Program in Pennsylvania

Systematic stream-gaging activities by the Survey in Pennsylvania began in the 1890's when streamflow records were collected on a few mainstem streams. Figure 1 shows the number of continuous-record stream gages operated in Pennsylvania in each year since 1900. Short-term gages that were operated for other than surface-water projects, as well as those operated by WRD districts and agencies other than the Pennsylvania District and the Commonwealth of Pennsylvania, are not included in figure 1. The stream-gaging program expanded at a fairly constant rate between 1907 and 1969, except for periods of stagnation during the depression and war years. A dramatic increase in gaging activity occurred in the mid-1970's following the devastating flood caused by tropical storm Agnes in June of 1972. However, a sharp decline in the number of gages in operation began in 1979. This decline is mostly due to increasing costs of operation and limited funds and manpower.

Early streamflow investigations were conducted primarily to provide information required for water supply, assessment of hydropower potential, and flood control. Because of increased utilization of surface waters and a heightened interest in the control and protection of this water resource, streamflow data are now collected and published for a broader spectrum of needs. Most current (1983) data collection is for flood forecasting, flood control, flood-plain management, water-supply monitoring, hydropower generation, and water-resource assessment. Virtually all data are collected under cooperative agreements between the Survey and State and other Federal agencies.

The objective of the Pennsylvania streamflow-data program is to provide information on flow at any point on any stream. This objective is approached through strategic location of stations, anticipation of data needs, and continual revaluation of the program.

Page (1970) made the first statistically-oriented program review. That study investigated the utility of 101 continuous-record stations that were operated primarily to improve information-transfer models. Twenty of these stations were identified as candidates for further data-usage review to determine if their continuance was justifiable. Three other stations on regulated-flow streams were suggested for a similar review.

Flippo (1982), using a more rigorous statistical analysis than that used by Page (1970), evaluated the need to operate gaging stations for improving data-transfer models that relate flow characteristics to basin characteristics. That study found little improvement in existing models could be obtained by operating stations other than those maintained for managerial purposes. Consequently, 11 continuous-record and 25 partial-record gages were discontinued in Pennsylvania in 1981. Several other gages, which were suggested for discontinuance before October 1986, also had been discontinued by the close of the 1983 water year.

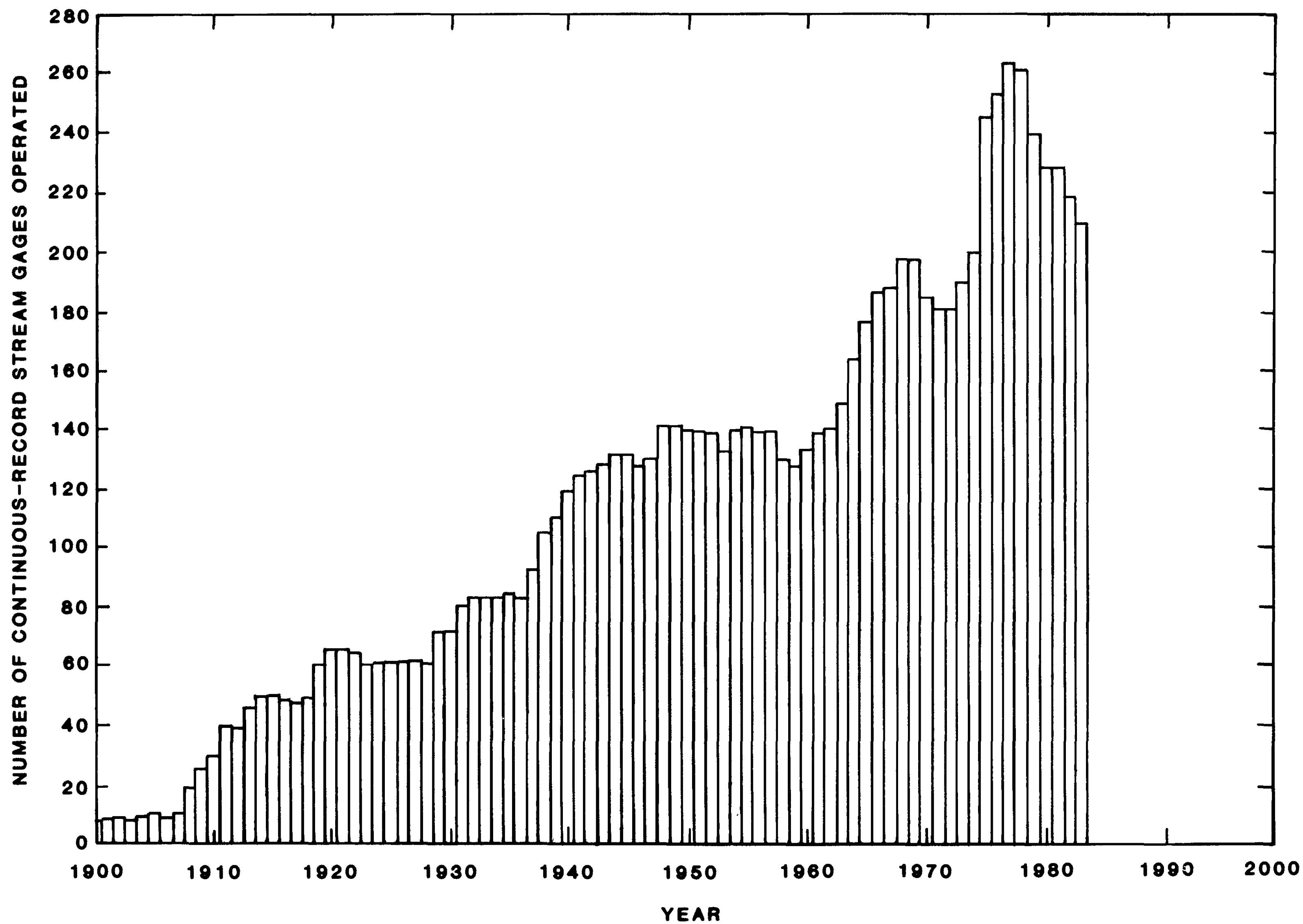


Figure 1.--Number of continuous-record gages in Pennsylvania, 1900-1983

Current Stream-Gaging Program

The Pennsylvania District operated 223 continous-record, 50 peak-recorder and wire-weight partial-record, and 18 pool gages--lake and reservoir--in the 1983 water year. Stage records for several other pool gages were furnished by the U.S. Army Corps of Engineers. Additionally, 188 low-flow sites were visited during the year. The locations of the continuous-record stations are shown in figure 2. The first two digits of the 8-digit downstream order numbers have been omitted from this figure. The two omitted digits are indexed to drainage regions as follows:

01 - North Atlantic Slope Basins--Delaware, Susquehanna, and Potomac Rivers
03 - Ohio River Basin--Allegheny, Monongahela, and Beaver Rivers
04 - St. Lawrence River Basin--Lake Erie and Lake Ontario tributaries

Stations will be referenced with their full 8-digit numbers elsewhere in this report.

Selected hydrologic data, including drainage area, period of record, and mean annual flow for the 212 continuous-record stations serviced on regular 6-week stream-gaging trips are given in table 1. The gages are serviced from three subdistrict offices--Malvern; Harrisburg; with a field office in Williamsport; and Pittsburgh. The area of each subdistrict's responsibility, the numbers of gages serviced at 6-week intervals, and the operational costs for these gages in water year 1983 for each subdistrict office are given in table 2.

USES, FUNDING, AND AVAILABILITY OF CONTINOUS STREAMFLOW DATA

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

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

Data-Use Classes

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

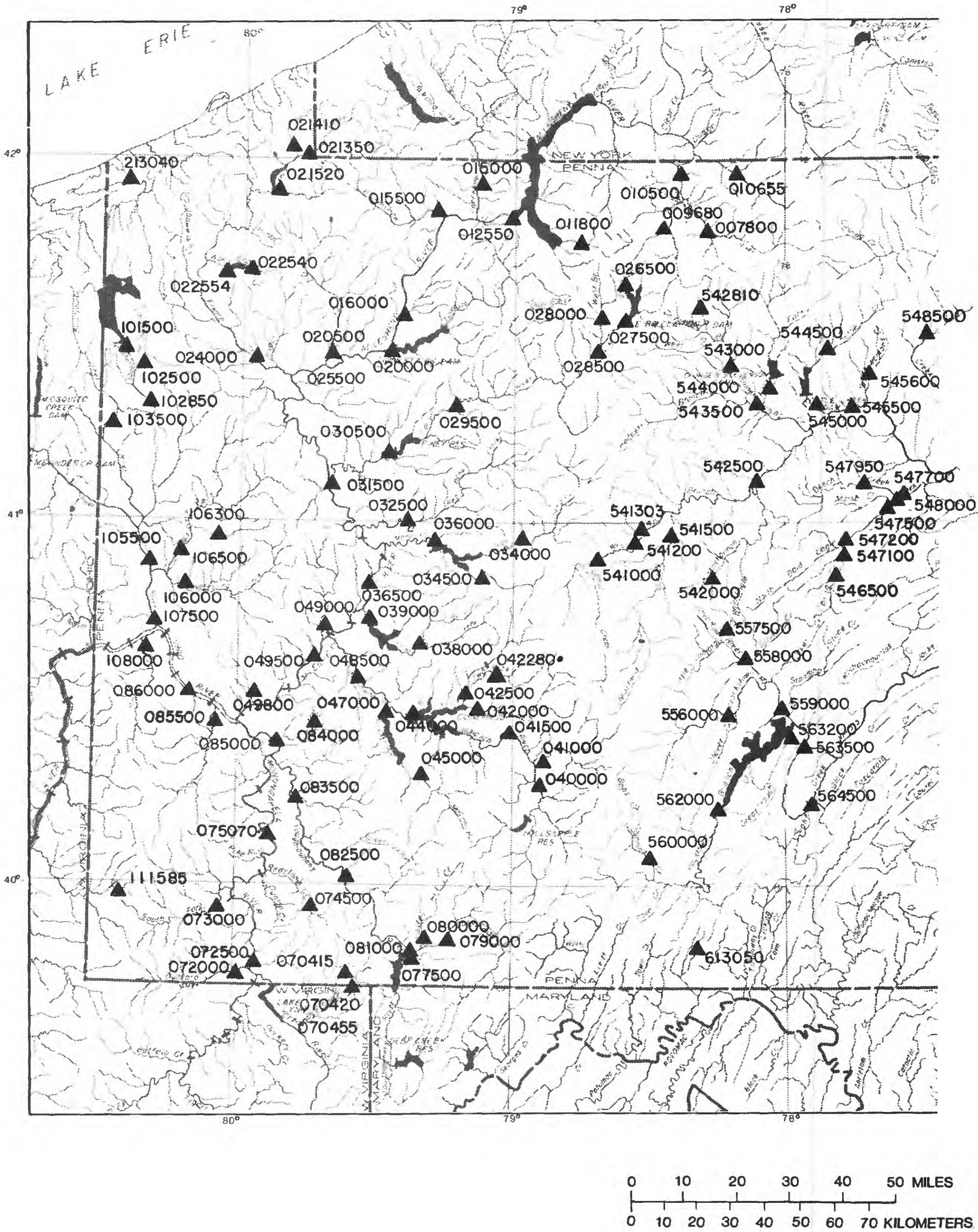
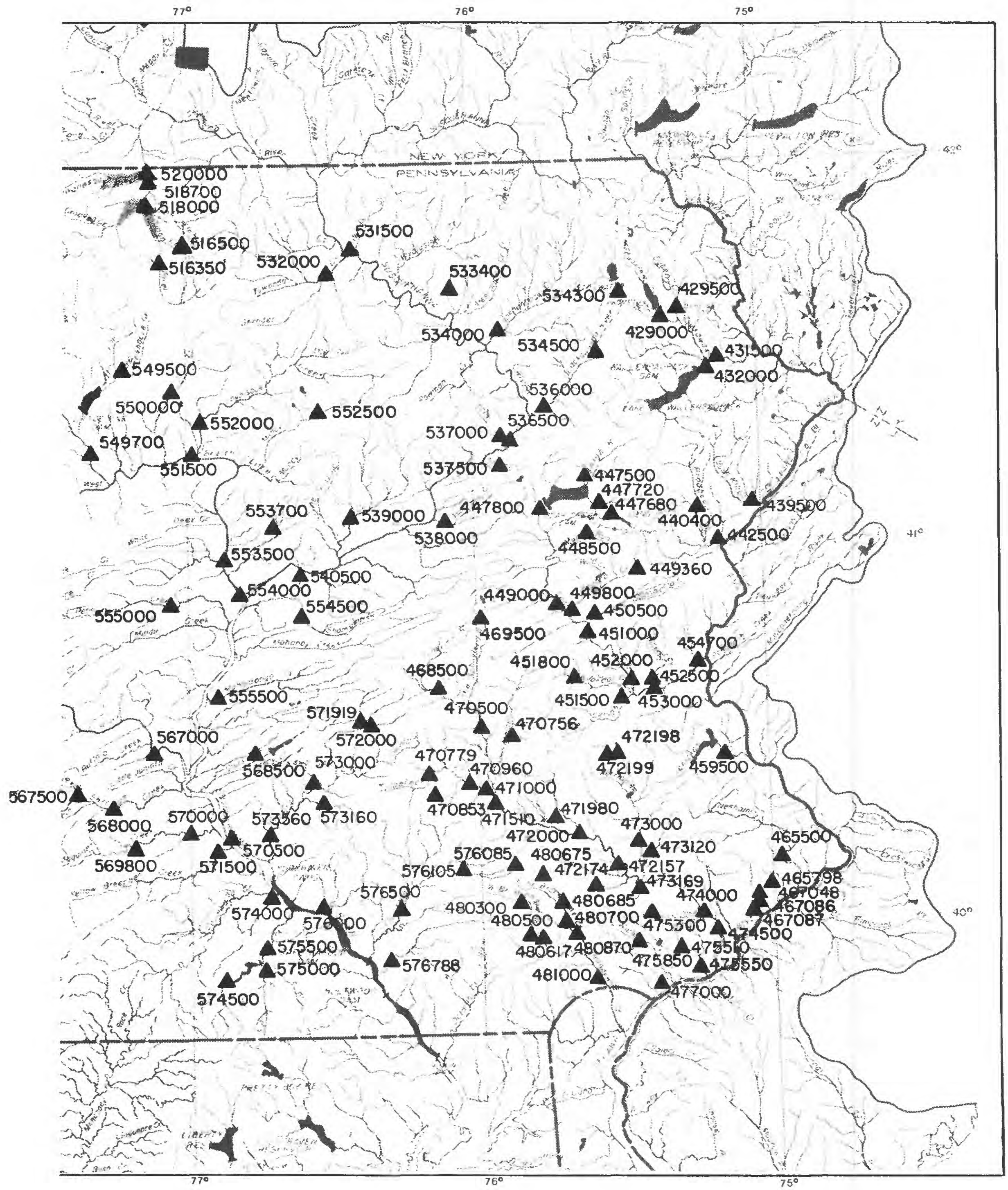


Figure 2.--Locations of continuous-record stream gages operated in 1983.



EXPLANATION

Major drainage basin boundary

▲471000 Gaging station and downstream order number

Table 1.--Selected hydrologic data for stations in the Pennsylvania surface-water program
[All stations are located in Pennsylvania, except as noted.]

Station no.	Station name	Drainage area (mi^2)	Period of record	Mean annual flow 1/ (ft^3/s)
01429000	West Branch Lackawaxen River at Prompton	59.7	August 1944-	110
01429500	Dyberry Creek near Honesdale	64.6	October 1943-	113
01431500	Lackawaxen River at Hawley	290	July 1908-September 1917; August 1938-2/	481
01432000	Wallenpaupack Creek at Wilsonville	228	October 1909-2/	362
01439500	Bush Kill at Shoemakers	117	October 1908-2/	235
01440400	Brodhead Creek near Analomink	65.9	October 1957-	136
01442500	Brodhead Creek at Minisink Hills	259	November 1950-	557
01447500	Lehigh River at Stoddartsville	91.7	October 1943-	186
01447680	Tunkhannock Creek near Long Pond	18.0	March 1965-	46.0
01447720	Tobyhanna Creek near Blakeslee	118	October 1961-	258
01447800	Lehigh River below F E Walter lake near White Haven	290	October 1957-	610
01448500	Dilldown Creek near Long Pond	2.39	October 1948-	4.88
01449000	Lehigh River at Lehighton	591	October 1945-September 1948; December 1982-3/	
01449360	Pohopoco Creek at Kresgeville	49.9	October 1966-	106
01449800	Pohopoco Creek below Beltzville Dam near Parryville	96.4	October 1967-	208
01450500	Aquashicola Creek at Palmerton	76.7	October 1939-	152
01451000	Lehigh River at Walnutport	889	October 1946-	1,850
01451500	Little Lehigh Creek near Allentown	80.8	October 1945-	96.9
01451800	Jordan Creek near Schnecksville	53.0	February 1966-	92.3
01452000	Jordan Creek near Allentown	75.8	October 1944-	112
01452500	Monocacy Creek at Bethlehem	44.5	October 1948-	51.9
01453000	Lehigh River at Bethlehem	1,279 4/	September 1902-February 1905; April 1909-2/	2,332
01454700	Lehigh River at Glendon	1,359	October 1966-	2,902
01459500	Tohickon Creek near Pipersville	97.4	July 1935-	144
01465500	Neshaminy Creek near Langhorne	210	October 1934-	288
01465798	Poquessing Creek at Grant Avenue, Philadelphia	21.4	July 1965-	33.7
01467048	Pennypack Creek at Lower Rhawn Street Bridge, Philadelphia	49.8	June 1965-	85.6
01467086	Tacony Creek above Adams Ave, Philadelphia	16.7	October 1965-	27.2
01467087	Frankford Creek at Castor Ave, Philadelphia	30.4	June 1982-3/	
01468500	Schuylkill River at Landingville	133	August 1947-April 1953; October 1963- September 1965; August 1973-	292
01469500	Little Schuylkill River at Tamaqua	42.9	October 1919-3/	92.7
01470500	Schuylkill River at Berne	355	August 1947-3	710
01470756	Maiden Creek at Virginville	159	January 1973-	270
01470779	Tulpehocken Creek near Bernville	66.5	November 1974-	111
01470853	Furnace Creek at Robesonia	4.18	November 1982-3/	

See footnotes at end of table.

Table 1.--Selected hydrologic data for stations in the Pennsylvania surface-water program-(continued)
[All stations are located in Pennsylvania, except as noted.]

Station no.	Station name	Drainage area (mi^2)	Period of record	Mean annual flow 1/ (ft^3/s)
01470960	Tulpehocken Creek at Blue Marsh Damsite near Reading	175	May 1965-	272
01471000	Tulpehocken Creek near Reading	211	October 1950-5/	307
01471510	Schuylkill River at Reading	880	May 1914-September 1915; October 1919 - September 1930; July 1977-2/	1,528
01471980	Manatawny Creek near Pottstown	85.5	August 1974-	134
01472000	Schuylkill River at Pottstown	1,147	October 1926-2/	1,888
01472157	French Creek near Phoenixville	59.1	October 1968-	90.8
01472174	Pickering Creek near Chester Springs	5.98	January 1967-	10.3
01472198	Perkiomen Creek near East Greenville	38.0	October 1981-3/	
01472199	North West Branch Perkiomen Creek at Hillegass	23.0	October 1981-3/	
01473000	Perkiomen Creek at Graterford	279	June 1914-2/	387
01473120	Skippack Creek near Collegeville	53.7	April 1966-	78.6
01473169	Valley Creek at turnpike bridge near Valley Forge	20.8	October 1982-3/	
01474000	Wissahickon Creek at Mouth, Philadelphia	64.0	June 1897-September 1903; January 1905-July 1906; October 1965-	102
01474500	Schuylkill River at Philadelphia	1,893	September 1931-	2,933
01475300	Darby Creek at Waterloo Mills near Devon	5.15	May 1972-	9.83
01475510	Darby Creek near Darby	37.4	February 1964-	67.5
01475550	Cobbs Creek at Darby	22.0	February 1964-	30.4
01475850	Crum Creek near Newton Square	15.8	October 1981-3/	
01477000	Chester Creek near Chester	61.1	August 1931-2/	87.1
01480300	West Branch Brandywine Creek near Honey Brook	18.7	June 1960-	25.5
01480500	West Branch Brandywine Creek at Coatesville	45.8	October 1943-December 1951; January 1970-	72.0
01480617	West Branch Brandywine Creek at Modena	55.0	January 1970-	96.2
01480675	Marsh Creek near Glenmoore	8.57	July 1966-	12.7
01480685	Marsh Creek near Downingtown	20.3	June 1973-	31.8
01480700	East Branch Brandywine Creek near Downingtown	60.6	October 1965-	91.1
01480870	East Branch Brandywine Creek below Downingtown	89.9	February 1972-	152
01481000	Brandywine Creek at Chadds Ford	287	August 1911-December 1953; October 1962-2/	396
01516350	Tioga River near Mansfield	153	July 1976-	217
01516500	Corey Crek near Mainesberg	12.2	May 1954-	12.4
01518000	Tioga River at Tioga	282	June 1938-	331
01518700	Tioga River at Tioga Junction	446	July 1976-	553
01520000	Cowanesque River near Lawrenceville	298	June 1951-	294
01531500	Susquehanna River at Towanda	7,797	October 1913-2/	10,600
01532000	Towanda Creek near Monroeton	214	February 1914-2/	288

See footnotes at end of table.

Table 1.--Selected hydrologic data for stations in the Pennsylvania surface-water program-(continued)
[All stations are located in Pennsylvania, except as noted.]

Station no.	Station name	Drainage area (mi^2)	Period of record	Mean annual flow 1/ (ft^3/s)
01533400	Susquehanna River at Meshoppen	8,720	October 1976-	12,590
01534000	Tunkhannock Creek near Tunkhannock	383	February 1914-2/	540
01534300	Lackwanna River near Forest City	38.8	October 1958-	71.9
01534500	Lackwanna River at Archbald	108	October 1939-2/	202
01536000	Lackawanna River at Old Forge	332	October 1938-	494
01536500	Susquehanna River at Wilkes-Barre	9,960	April 1899-2/	13,380
01537000	Toby Creek at Luzerne	32.4	August 1941-	45.3
01537500	Solomon Creek at Wilkes-Barre	15.7	March 1940-2/	19.3
01538000	Wapwallopen Creek near Wapwallopen	43.8	October 1919-2/	64.4
01539000	Fishing Creek near Bloomsberg	274	June 1938-	479
01540500	Susquehanna River at Danville	11,220	March 1899-2/	15,330
01541000	West Branch Susquehanna River at Bower	315	October 1913-2/	558
01541200	West Branch Susquehanna River at Curwensville	367	October 1955-	656
01541303	West Branch Susquehanna River at Hyde	474	October 1978-3/	
01541500	Clearfield Creek at Dimeling	371	October 1913-2/	580
01542000	Moshannon Creek at Osceola Mills	68.8	October 1940-	112
01542500	West Branch Susquehanna River at Karthus	1,462 6/	February 1940-	2,505
01542810	Waldy Run near Emporium	5.24	August 1964-	8.77
01543000	Driftwood Branch Sinnemahoning Creek at Sterling Run	272	October 1913-2/	449
01543500	Sinnemahoning Creek at Sinnemahoning	685	July 1938-	1,134
01544000	First Fork Sinnemahoning Creek near Sinnemahoning	245	October 1953-	391
01544500	Kettle Creek at Cross Fork	136	October 1940-2/	226
01545000	Kettle Creek near Westport	233	October 1954-	373
01545500	West Branch Susquehanna River at Renovo	2,975	October 1907-2/	4,975
01545600	Young Womans Creek near Renovo	46.2	December 1964-	76.5
01546500	Spring Creek near Axemann	87.2	October 1940-	90.8
01547100	Spring Creek at Milesburg	142	May 1967-	235
01547200	Bald Eagle Creek below Spring Creek at Milesburg	265	October 1955-7/	403
01547500	Bald Eagle Creek at Blanchard	339	May 1954-	458
01547700	Marsh Creek at Blanchard	44.1	October 1955-8/	58.5
01547950	Beech Creek at Monument	152	August 1968-	285
01548000	Bald Eagle Creek at Beech Creek Station	559	July 1910-2/	811
01548500	Pine Creek at Cedar Run	604	July 1918-2/	836
01549500	Blockhouse Creek near English Center	37.7	October 1940-2/	58.0
01549700	Pine Creek below Little Pine Creek near Waterville	944	October 1957-	1,422
01550000	Lycoming Creek near Trout Run	173	December 1913-2/	284
01551500	West Branch Susquehanna River at Williamsport	5,682	March 1895-2/	8,943
01552000	Loyalsock Creek at Loyalsockville	443	August 1925-September 1974; October 1975-2/	747
01552500	Muncy Creek near Sonestown	23.8	October 1940-	48.3

See footnotes at end of table.

Table 1.--Selected hydrologic data for stations in the Pennsylvania surface-water program-(continued)
[All stations are located in Pennsylvania, except as noted.]

Station no.	Station name	Drainage area (mi^2)	Period of record	Mean annual flow 1/ (ft^3/s)
01553500	West Branch Susquehanna River at Lewisburg	6,847	October 1939-2/	10,830
01553700	Chillisquaque Creek at Washingtonville	134	May 1979-3/	
01554000	Susquehanna River at Sunbury	18,300	October 1937-	26,570
01554500	Shamokin Creek near Shamokin	54.2	November 1939-	85.7
01555000	Penns Creek at Penns Creek	301	October 1929-2/	436
01555500	East Mahantango Creek near Dalmatia	162	October 1929-2/	224
01556000	Frankstown Branch Juniata River at Williamsburg	291	October 1916-2/	395
01557500	Bald Eagle Creek at Tyrone	44.1	October 1944-	76.9
01558000	Little Juniata River at Spruce Creek	220	June 1938-	375
01559000	Juniata River at Huntingdon	816	September 1941-2/	1,091
01560000	Dunning Creek at Belden	172	May 1939-	229
01562000	Raystown Branch Juniata River at Saxton	756	September 1911-2/	916
01563200	Raystown Br. Juniata River below Dam near Huntingdon	960	January 1946-2/	1,142
01563500	Juniata River at Mapleton Depot	2,030	October 1937-2/	2,503
01564500	Aughwich Creek near Three Springs	205 9/	May 1938-	246
01567000	Juniata River at Newport	3,354	March 1899-2/	4,300
01567500	Bixler Run near Loysville	15.0	January 1954-	18.6
01568000	Sherman Creek at Shermans Dale	200	October 1929-2/	287
01568500	Clark Creek near Carsonville	22.5	September 1937-	40.0
01569800	Letort Spring Run near Carlisle	21.6	June 1976-	46.7
01570000	Conodoguinet Creek near Hogestown	470	October 1911-September 1917; October 1929-September 1958; June 1967-2/	591
01570500	Susquehanna River at Harrisburg	24,100	October 1890-	34,390
01571500	Yellow Breeches Creek near Camp Hill	216	April 1909-December 1919; June 1954-2/	291
01571919	Swatara Creek above highway 895 at Pine Grove	72.6	October 1981-3/	
01572000	Lower Little Swatara Creek at Pine Grove	34.3	November 1919-September 1932; July 1981-	55.1
01573000	Swatara Creek at Harper Tavern	337	January 1919-2/	571
01573160	Quittaphilla Creek near Bellegrove	74.2	October 1975-	109
01573560	Swatara Creek near Hershey	483	September 1975-	815
01574000	West Conewago Creek near Manchester	510	October 1928-2/	585
01574500	Codorus Creek at Spring Grove	75.5	May 1929-September 1964; November 1965-2/	78.8
01575000	South Branch Codorus Creek near York	117	October 1927-2/	135
01575500	Codorus Creek near York	222	August 1940-3/	246
01576000	Susquehanna River at Marietta	25,990	October 1931-	36,900
01576085	Little Conestoga Creek near Churchtown	5.82	June 1982-3/	
01576105	Conestoga River near Terre Hill	49.2	November 1981-3/	

See footnotes at end of table.

Table 1.--Selected hydrologic data for stations in the Pennsylvania surface-water program-(continued)
[All stations are located in Pennsylvania, except as noted.]

Station no.	Station name	Drainage area (mi^2)	Period of record	Mean annual flow 1/ (ft^3/s)
01576500	Conestoga River at Lancaster	324	September 1928-March 1932; August, September 1932; April 1933-2/	398
01576788	Pequea Creek tributary near Mt. Nebo	.20	May 1979-May 1981; October 1981-3/	
01613050	Tonoloway Creek near Needmore	10.7	October 1965-	12.6
03007800	Allegheny River at Port Allegany	248	October 1974-	495
03009680	Potato Creek at Smethport	160	October 1974-	313
03010500	Allegheny River at Eldred	550	July 1939-	953
03010655	Oswayo Creek at Shinglehouse	98.7	October 1974-	166
03011800	Kinzua Creek near Guffey	46.4	October 1965-	78.1
03012550	Allegheny River at Kinzua Dam	2,180	October 1935-10/	3,824
03015000	Conewango Creek at Russell	816	October 1939-11/	1,513
03015500	Brokenstraw Creek at Youngsville	321 12/	October 1909-11/	583
03016000	Allegheny River at West Hickory	3,660	October 1941-	6,619
03020000	Tionesta Creek at Tionesta Dam	479	June 1940-	880
03020500	Oil Creek at Rouseville	300 13/	June 1932	535
03021350	French Creek at Wattsburg	92.0	October 1974-	233
03021410	West Branch French Creek near Lowville	52.3	October 1974-	133
03021520	French Creek near Union City	221	October 1909-11/ 14/	431
03022540	Woodcock Creek at Blooming Valley	31.1	October 1974-	58.8
03022554	Woodcock Creek at Woodcock Creek Dam	45.6	October 1974-	88.1
03024000	French Creek at Utica	1,028	August 1932-	1,812
03025500	Allegheny River at Franklin	5,982	October 1914-11/	10,480
03026500	Sevenmile Run near Rasselas	7.84	October 1951-	14.3
03027500	East Br. Clarion River at E Br. Clarion River Dam	73.2	October 1948-	136
03028000	West Branch Clarion River at Wilcox	63.0	October 1953-	124
03028500	Clarion River at Johnsonburg	204	October 1945-	382
03029500	Clarion River at Cooksburg	807	October 1938-11/	1,452
03030500	Clarion River near Piney	951	October 1944-15/	1,765
03031500	Allegheny River at Parker	7,671	October 1932-	13,400
03032500	Redbank Creek at St. Charles	528	October 1918-11/	864
03034000	Mahoning Creek at Punxsutawney	158	October 1938-	276
03034500	Little Mahoning Creek at McCormick	87.4	October 1939-	153
03036000	Mahoning Creek at Mahoning Creek Dam	344	August 1938- 11/	597
03036500	Allegheny River at Kittanning	8,973	August 1904-September 1928; October 1934-11/	15,720
03038000	Crooked Creek at Idaho	191	October 1937-11/	293
03039000	Crooked Creek at Crooked Creek Dam	278	October 1909-11/ 16/	423
03040000	Stonycreek River at Ferndale	451	October 1913-March 1936; October 1938-11/ 17/	777
03041000	Little Conemaugh River at East Conemaugh	183	April 1939-	332

See footnotes at end of table.

Table 1.--Selected hydrologic data for stations in the Pennsylvania surface-water program-(continued)
[All stations are located in Pennsylvania, except as noted.]

Station no.	Station name	Drainage area (mi²)	Period of record	Mean annual flow 1/ (ft³/s)
03041500	Conemaugh River at Seward	715	May 1938-	1,287
03042000	Blacklick Creek at Josephine	192	January 1952-	371
03042280	Yellow Creek near Homer City	57.4 18/	October 1967-	109
03042500	Two Lick Creek at Graceton	171	September 1951-	284
03044000	Conemaugh River at Tunnelton	1,358	October 1939-	2,392
03045000	Loyalhanna River at Kingston	172	October 1939-	302
03047000	Loyalhanna Creek at Loyalhanna Dam	292	October 1939-11/	484
03048500	Kiskiminetas River at Vandergrift	1,825	August 1937-11/	3,104
03049000	Buffalo Creek near Freeport	137	October 1940-11/	192
03049500	Allegheny River at Natrona	11,410	October 1938-	19,530
03049800	Little Pine Creek near Etna	5.78	October 1962-	6.15
03070415	Stony Fork near Farmington	2.50	March 1977-3/	
03070420	Stony Fork tributary near Gibbon Glade	.93	May 1977-	1.76
03070455	Stony Fork near Elliottsville	7.44	May 1977-	14.0
03072000	Dunkard Creek at Shannopin	229	October 1940-11/	279
03072500	Monongahela River at Greensboro	4,407	October 1938-11/	8,230
03073000	South Fork Tenmile Creek at Jefferson	180	October 1931-11/	203
03074500	Redstone Creek at Waltersburg	73.7	October 1942-11/	99.6
03075070	Monongahela River at Elizabeth	5,340	October 1933-11/ 19/	9,122
03077500	Youghiogheny River at Youghiogheny River Dam	436	October 1939-11/	875
03079000	Casselman River at Markleton	382	October 1920-11/	660
03080000	Laurelhill Creek at Ursina	121	October 1918-11/	266
03081000	Youghiogheny River below Confluence	1,029	June 1940-11/	1,997
03082500	Youghiogheny River at Connellsville	1,326	July 1908-11/	2,570
03083500	Youghiogheny River at Sutersville	1,715	October 1920-11/	3,024
03084000	Abers Creek near Murrysville	4.39	October 1948-	5.31
03085000	Monongahela River at Braddock	7,337	October 1938-11/	12,500
03085500	Chartiers Creek at Carnegie	257	October 1919-September 1933; October 1940-11/	292
03086000	Ohio River at Sewickley	19,500	October 1933-	32,830
03101500	Shenango River at Pymatuning Dam	167	June 1934-	203
03102500	Little Shenango River at Greenville	104	October 1913-11/	142
03102850	Shenango River near Transfer	337	October 1965-	470
03103500	Shenango River at Sharpsville	584	March 1938-11/	744
03105500	Beaver River at Wampum	2,235	July 1914-September 1918; August 1932-11/	2,451
03106000	Connoquenessing Creek near Zelienople	356	October 1919-11/	465
03106300	Muddy Creek near Portersville	51.2	March 1963-	74.2
03106500	Slippery Rock Creek at Wurtemburg	398	October 1911-11/	566

See footnotes at end of table.

Table 1.--Selected hydrologic data for stations in the Pennsylvania surface-water program-(continued)
[All stations are located in Pennsylvania, except as noted.]

Station no.	Station name	Drainage area (mi^2)	Period of record	Mean annual flow 1/ (ft^3/s)
03107500	Beaver River at Beaver Falls	3,106	October 1935-	3,659
03108000	Raccoon Creek at Moffatts Mill	178	September 1941-	193
03111585	Enlow Fork near West Finley	38.1	October 1979-3/	
04213040	Raccoon Creek near West Springfield	2.53	October 1968-	3.61

1/ Computed from discharge records collected through the 1982 water year.
2/ Monthly discharge only for some periods, published in Water-Supply Paper 1302.
3/ No mean annual flow published; less than 5 years of streamflow record, as of September 1982.
4/ Includes drainage area of Monocacy Creek.
5/ Monthly discharge only for October and November 1950, published in Water-Supply Paper 1722.
6/ Includes drainage area of Mosquito Creek.
7/ Monthly discharge only October and November 1955, published in Water-Supply Paper 1722.
8/ Monthly discharge only for October 1955, published in Water-Supply Paper 1722.
9/ Includes drainage area of Three Springs Creek.
10/ Published as "near Kinzua (station 03012500) prior to October 1968 and as "at Warren" (station 03012600) October 1968 to September 1972.
11/ Monthly discharge only for some periods, published in Water-Supply paper 1305.
12/ Includes drainage area of Matthews Run.
13/ Includes drainage area of Cherrytree Run.
14/ Published as North Branch French Creek at Kimmeytown May 1910-September 1914, as "at Kimmeytown" October 1915 - September 1932, and as "at Carters Corner" October 1932 - September 1971.
15/ Monthly discharge only October 1944 - September 1947.
16/ Published as "at Hileman's Farm" 1910-29 and as "near Ford City" 1930-39.
17/ Published as "at Johnstown", 1914-36, and as "Stony Creek at Ferndale", 1938-79.
18/ Excludes drainage area of Ferrier Run.
19/ Published as "at Charleroi" (station 03075000) October 1933 - September 1976.

Table 2.--Service areas, numbers of gages, and operational costs, by subdistrict, for water year 1983

Subdistrict office	Service area	Numbers of gages operated, by type: Continuous record 1/	Numbers of gages operated, by type: Peak recorder and wire-weight	Numbers of gages operated, by type: Pool	Operating cost
Malvern	Delaware River basins	62	32	4	$377,700
Harrisburg	Susquehanna and Potomac River basins	79	12	11	$455,000
Pittsburgh	Ohio and St. Lawrence River basins	71	6	3	$366,300

1/ Excludes 5 gages operated by the Harrisburg office and 4 gages operated by the Pittsburgh office, which were funded under several investigatory projects.

Regional Hydrology

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

One hundred forty-five stations in the Pennsylvania network are classified in the regional hydrology data-use category. Nine of the stations are special cases in that they are designated bench-mark or index stations. One hydrologic bench-mark station in Pennsylvania serves as an indicator of hydrologic conditions in a watershed relatively free of manmade alteration. Eight index stations, located in different regions of the State, are used to indicate current hydrologic conditions.

Hydrologic Systems

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

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

Twenty-seven stations are included in this category. The data collected at the six FERC stations are used to monitor the compliance of control structures to downstream flow requirements determined by FERC. One other FERC site is at a partial-record site, which is not listed in table 1.

Legal Obligations

Some stations provide records of flows for the verification or enforcement of existing treaties, compacts, or decrees. The legal obligation category contains only those stations that the Survey is required to operate to satisfy a legal responsibility. Three stations in the Pennsylvania program exist, in part, to fulfill a legal responsibility.

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 four stations that were instituted for such purposes and where this purpose is still valid.

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 the data are routinely available to the operators on a rapid-reporting basis. For projects on large streams, data may only be needed every few days. Sixty-seven stations in the Pennsylvania program are used in this manner.

Hydrologic Forecasts

Gaging stations in this category are regularly used to provide information for hydrologic forecasting, including 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.

Stations in the Pennsylvania program that are included in the hydrologic-forecast category are those used for flood forecasting by the National Weather Service (NWS) and for forecasting inflows to reservoirs. Additionally, NWS uses the data at some stations as input to long-range prediction models of the probability of snowmelt floods. Sixty-five gages are used for forecasting.

Water-Quality Monitoring

Gaging stations where regular water-quality or sediment-transport monitoring is being 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.

This category includes 142 stations. Eight stations in the program are National Stream Quality Accounting Network (NASQAN) stations and one is a designated bench-mark station. NASQAN stations are part of a nationwide network designed to assess water-quality trends of significant streams. Water-quality samples from bench-mark stations are used to indicate water-quality characteristics of streams that have been and probably will continue to be relatively free of manmade influence.

Research

Gaging stations in this category are operated for a particular research or water-investigations study. Typically, these are only operated for a few years. Three stations in the Pennsylvania program are used in the support of research activities. The State of Pennsylvania, Department of Environmental Resources, uses the data from a number of sites for research activities that involve nutrient loading and waste-load allocation.

Other

Three stations are operated primarily as public-supply monitors. Six others are used for hydrologic assessment of coal-mining areas in southwestern Pennsylvania. Three are used to research environmental changes.

Data-Use Presentation

Data-use and ancillary information are presented for each continuous gaging station in table 3, which includes footnotes to expand the information conveyed. The entry of an asterisk in the table indicates that no footnote is required.

Funding

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

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. Cooperative program.--Funds that come jointly from 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 Survey cooperative funds.

In all four categories, the identified sources of funding pertain only to the collection of streamflow data; sources of funding for other activities, particularly collection of water-quality samples, that might be carried out at the site may not necessarily be the same as those identified herein.

Twelve entities currently are contributing funds to the Pennsylvania stream-gaging program.

Table 3. Data use, funding, and data availability for continuous-record stations operated in water year 1983

STATION NUMBER	DATA USE									FUNDING				
	REGIONAL HYDROLOGY	HYDROLOGIC FORECASTS	LEGAL OBLIGATIONS	PLANNING & DESIGN	PROJECT OPERATION	HYDROLOGIC SYSTEMS	WATER-QUALITY MONITORING	RESEARCH	OTHER	FEDERAL PROGRAM	OFA PROGRAM	CO-OP PROGRAM	OTHER NON-FEDERAL	FREQUENCY OF DATA AVAILABILITY
01429000					2						9	10		AT
01429500					2						9	10		AT
01431500		2				4	3				9	10		AT
01432000		5			2 6							10	29	AO
01439500	*	1					3					10		A
01440400	*						3					10		A
01442500	*	1										10		A
01447500	*				7	4	3			*	9			AT
01447680	*								8			11		A
01447720	*				7	4	3			*	9			AT
01447800					2						9	10		AO
01448500	*										9	10		A
01449000					2						9			AO
01449360	*				7						9	10		AT
01449800					2		3				9	10		AO

1. Long-term index gaging station.
2. Reservoir release monitor.
3. Biological-chemical sample site of Pennsylvania Dept. of Environmental Resources.
4. Flood forecasting - U.S. National Weather Service.
5. Federal Energy Regulatory Commission hydropower licensing requirements.
6. Pennsylvania Power & Light Co. hydropower system operation.
7. Reservoir inflow monitor.
8. Public supply monitor.
9. U.S. Army Corps of Engineers.
10. Pennsylvania Department of Environmental Resources.
11. City of Bethlehem.
29. Pennsylvania Power and Light Company.
A. Annually, in serial data reports.
O. As required, by means of user observations of stage.
T. Immediately, by means of direct-access telemetry equipment.

Table 3. Data use, funding, and data availability for continuous-record stations operated in water year 1983 - (Continued)

STATION NUMBER	DATA USE: REGIONAL HYDROLOGY	HYDROLOGIC FORECASTS	LEGAL OBLIGATIONS	PLANNING & DESIGN	PROJECT OPERATION	HYDROLOGIC SYSTEMS	WATER-QUALITY MONITORING	RESEARCH	OTHER	FUNDING: FEDERAL PROGRAM	OFA PROGRAM	CO-OP PROGRAM	OTHER NON-FEDERAL	FREQUENCY OF DATA AVAILABILITY
01450500							3				9	10		A
01451000					2	4	3				9			AT
01451500	*						3				9	10		A
01451800	*			12							9	10		A
01452000	*						3				9	10		A
01452500	*						3				9	10		A
01453000							3			*				A
01454700		1					3					10		A
01459500					2		3					10		AO
01465500	*					4	3				9	10		AT
01465798	*						3 13					13		A
01467048	*						3 13					13		A
01467086	*						3 13					13		A
01467087	*						3 13					13		A
01468500	*										9	10		A

1. Long-term index gaging station.
2. Reservoir release monitor.
3. Biological-chemical sample site of Pa. Dept. of Environmental Resources.
4. Flood forecasting - U.S. National Weather Service.
9. U.S. Army Corps of Engineers
10. Pennsylvania Department of Environmental Resources.
12. Proposed dam site.
13. City of Philadelphia stream-quality sample site.
A. Annually, in serial data reports.
O. As required, by means of user observations of stage.
T. Immediately, by means of direct-access telemetry equipment.

Table 3. Data use, funding, and data availability for continuous-record stations operated in water year 1983 - (Continued)

STATION NUMBER	DATA USE									FUNDING				FREQUENCY OF DATA AVAILABILITY
	REGIONAL HYDROLOGY	HYDROLOGIC FORECASTS	LEGAL OBLIGATIONS	PLANNING & DESIGN	PROJECT OPERATION	HYDROLOGIC SYSTEMS	WATER-QUALITY MONITORING	RESEARCH	OTHER	FEDERAL PROGRAM	OFA PROGRAM	CO-OP PROGRAM	OTHER NON-FEDERAL	
01469500	*						3				9	10		A
01470500	*						3 14					10		A
01470756	*			12							9	10		A
01470779	*				7						9	10		AT
01470853	*											15		A
01470960					2		3				9	10		AO
01471000						4					9			AT
01471510	*					4					9			AT
01471980	*										9	10		A
01472000	1	1								*				A P
01472157	*						3					10		A
01472174	*						3					16		A
01472198	*												17	A
01472199	*												17	A
01473000	*						3					10		A

1. Long-term index gaging station.
2. Reservoir release monitor.
3. Biological-chemical sample site of Pa. Dept. of Environmental Resources.
4. Flood forecasting - U.S. National Weather Service.
7. Reservoir inflow monitor.
9. U.S. Army Corps of Engineers.
10. Pennsylvania Department of Environmental Resources.
12. Proposed dam site.
14. Sediment transport inventory site.
15. Mill Creek Township.
16. Chester County Water Resources Authority.
17. Delaware River Basin Commission.
A. Annually, in serial data reports.
O. As required, by means of user observations of stage.
P. Periodically, by both systematic and special-request releases of provisional data.
T. Immediately, by means of direct-access telemetry equipment.

Table 3. Data use, funding, and data availability for continuous-record stations operated in water year 1983 - (Continued)

STATION NUMBER	DATA USE									FUNDING				
	REGIONAL HYDROLOGY	HYDROLOGIC FORECASTS	LEGAL OBLIGATIONS	PLANNING & DESIGN	PROJECT OPERATION	HYDROLOGIC SYSTEMS	WATER-QUALITY MONITORING	RESEARCH	OTHER	FEDERAL PROGRAM	OFA PROGRAM	CO-OP PROGRAM	OTHER NON-FEDERAL	FREQUENCY OF DATA AVAILABILITY
01473120	*						3					10		A
01473169	*											16		A
01474000	*						3					13		A
01474500	*					13	3 18					13		AT
01475300	*											16		A
01475510	*										9	10		A
01475550	*										9	10		A
01475850	*												17	A
01477000	*					4	3				9	10		AT
01480300	*											10		A
01480500	*					19						16		AT
01480617	*					19	3					16		AT
01480675	*				7	19						10		AT
01480685					2	19						10		AT
01480700	*					19	3		8			10		AT
01480870					2	4	3 13					16		AT
01481000	*					4	3 13					10		AT

2. Reservoir release monitor.
3. Biological-chemical sample site of Pa. Dept. of Environmental Resources.
4. Flood forecasting - U.S. National Weather Service.
7. Reservoir inflow monitor.
9. U.S. Army Corps of Engineers.
10. Pennsylvania Department of Environmental Resources.
13. City of Philadelphia stream-quality sample site.
16. Chester County Water Resources Authority.
17. Delaware River Basin Commission.
18. National Stream Quality Accounting Network (NASQAN) site at or near station.
19. Flood-warning gage for local interests.
A. Annually, in serial data reports.
T. Immediately, by means of direct-access telemetry equipment.

Table 3. Data use, funding, and data availability for continuous-record stations operated in water year 1983 - (Continued)

STATION NUMBER	DATA USE									FUNDING				FREQUENCY OF DATA AVAILABILITY
	REGIONAL HYDROLOGY	HYDROLOGIC FORECASTS	LEGAL OBLIGATIONS	PLANNING & DESIGN	PROJECT OPERATION	HYDROLOGIC SYSTEMS	WATER-QUALITY MONITORING	RESEARCH	OTHER	FEDERAL PROGRAM	OFA PROGRAM	CO-OP PROGRAM	OTHER NON-FEDERAL	
01516350	*					4	3				9			AT
01516500	*											10		A
01518000					2		3				9			AO
01518700					2	4	3				9	10		AT
01520000					2	4	3				9			AT
01531500	*					4	3				9	10		AT
01532000	*					4	3					10		AO
01533400	*					4						10		AO
01534000	1	1				4	3					10		AO
01534300					2		3				9			AO
01534500					2		3				9			AT
01536000							3							AP
01536500	*					4	3					10		AOP
01537000	*											10		A
01537500	*										9			A
01538000	*						3					10		A
01539000	*						3					10		A
01540500	*	1					3 18					10		AP
01541000	*				7		3					10		AO
01541200					2		3				9			AO

1. Long-term index gaging station.
2. Reservoir release monitor.
3. Biological-chemical sample site of Pa. Dept. of Environmental Resources.
4. Flood forecasting - U.S. National Weather Service.
7. Resevoir inflow monitor.
9. U.S. Army Corps of Engineers.
10. Pennsylvania Department of Environmental Resources.
18. National Stream Quality Accounting Network (NASQAN) site at or near station.
A. Annually, in serial data reports.
O. As required, by means of user observations of stage.
P. Periodically, by both systematic and special-request releases of provisional data.
T. Immediately, by means of direct-access telemetry equipment.

Table 3. Data use, funding, and data availability for continuous-record stations operated in water year 1983 - (Continued)

STATION NUMBER	DATA USE									FUNDING				FREQUENCY OF DATA AVAILABILITY
	REGIONAL HYDROLOGY	HYDROLOGIC FORECASTS	LEGAL OBLIGATIONS	PLANNING & DESIGN	PROJECT OPERATION	HYDROLOGIC SYSTEMS	WATER-QUALITY MONITORING	RESEARCH	OTHER	FEDERAL PROGRAM	OFA PROGRAM	CO-OP PROGRAM	OTHER NON-FEDERAL	
01541303						4					9			AT
01541500	*						3				9	10		A
01542000	*						3					10		A
01542500						4	3				9	10		AT
01542810	*											10		A
01543000	*						3					10		A
01543500	*						3					10		A
01544000					2		3				9	10		AO
01544500	*				7						9			AO
01545000					2	4	3				9			AO
01545500						4	3				9	10		ATP
01545600	20	20					3 20			*				A
01546500	*						3					10		A
01547100	*											10		A
01547200	*				7						9			AO
01547500					2						9			AO
01547700	*									*	9			A
01547950	*						3					10		A
01548000						4					9			AT
01548500	*						3					10		A

2. Reservoir release monitor.
3. Biological-chemical sample site of Pa. Dept. of Environmental Resources.
4. Flood Forecasting - U.S. National Weather Service.
7. Reservoir inflow monitor.
9. U.S. Army Corps of Engineers.
10. Pennsylvania Department of Environmental Resources.
20. Hydrologic bench-mark gage.
A. Annually, in serial data reports.
O. As required, by means of user observations of stage.
P. Periodically, by both systematic and special-request releases of provisional data.
T. Immediately, by means of direct-access telemetry equipment.

Table 3. Data use, funding, and data availability for continuous-record stations operated in water year 1983 - (Continued)

STATION NUMBER	DATA USE									FUNDING				
	REGIONAL HYDROLOGY	HYDROLOGIC FORECASTS	LEGAL OBLIGATIONS	PLANNING & DESIGN	PROJECT OPERATION	HYDROLOGIC SYSTEMS	WATER-QUALITY MONITORING	REARCH	OTHER	FEDERAL PROGRAM	OFA PROGRAM	CO-OP PROGRAM	OTHER NON-FEDERAL	FREQUENCY OF DATA AVAILABILITY
01549500	*											10		A
01549700	*	1					3					10		A
01550000	*						3					10		A
01551500	1	1				4					9	10		AO
01552000	*						3					10		A
01552500	*											10		A
01553500						4	3 18				9	10		AO
01553700	*		30										10	A
01554000						4	3					10		AT
01554500	*						3					10		A
01555000	*											10		A
01555500	*						3					10		A
01556000	*						3					10		A
01557500	*											10		A
01558000	*						3				9	10		A
01559000	*	5			2	4	3				9		25	AO
01560000	*						3					10		A
01562000	1	1			7	4	3				9			ATP
01563200					2	4					9			AO
01563500	*					4					9	10		AT

1. Long-term index gaging station.
2. Reservoir release monitor.
3. Biological-chemical sample site of Pa. Dept. of Environmental Resources.
4. Flood forecasting - U.S. National Weather Service.
5. Federal Energy Regulatory Commission hydropower licensing requirements.
7. Reservoir inflow monitor.
9. U.S. Army Corps of Engineers.
10. Pennsylvania Department of Environmental Resources.
18. National Stream Quality Accounting Network (NASQAN) site at or near station.
25. Pennsylvania Electric Company.
30. State water-allocation permit.
A. Annually, in serial data reports.
O. As required, by means of user observations of stage.
P. Periodically, by both systematic and special-request releases of provisional data.
T. Immediately, by means of direct-access telemetry equipment.

Table 3. Data use, funding, and data availability for continuous-record stations operated in water year 1983 - (Continued)

STATION NUMBER	DATA USE									FUNDING				FREQUENCY OF DATA AVAILABILITY
	REGIONAL HYDROLOGY	HYDROLOGIC FORECASTS	LEGAL OBLIGATIONS	PLANNING & DESIGN	PROJECT OPERATION	HYDROLOGIC SYSTEMS	WATER-QUALITY MONITORING	RESEARCH	OTHER	FEDERAL PROGRAM	OFA PROGRAM	CO-OP PROGRAM	OTHER NON-FEDERAL	
01564500	*											10		A
01567000		1				4	3 14 18			*				AP
01567500	*											10		A
01568000	*											10		A
01568500			30		7							10 21		AO
01569800	*											22		A
01570000	*					4	3					10		APO
01570500	1	1 5	30			4	3 14 18				9	10	26	ATP
01571500	*					4	3					10		APO
01571919				12			3					10		AP
01572000				12			3					10		AP
01573000	*					4 19	3 14					10		ATPO
01573160	*					19	3					10		AO
01573560	*					19						10		ATPO
01574000	*						3					10		A

1. Long-term index gaging station.
3. Biological-chemical sample site of Pa. Dept. of Environmental Resources.
4. Flood Forecasting - U.S. National Weather Service.
5. Federal Energy Regulatory Commission hydropower licensing requirement.
7. Reservoir inflow monitor.
9. U.S. Army Corps of Engineers.
10. Pennsylvania Department of Environmental Resources.
12. Proposed dam site.
14. Sediment transport inventory site.
18. National Stream Quality Accounting Network (NASQAN) site at or near station.
19. Flood-warning gage for local interests.
21. City of Harrisburg.
22. Letort Regional Authority.
26. Susquehanna Electric Company.
30. State water-allocation permit.

A. Annually, in serial data reports.
O. As required, by means of user observations of stage.
P. Periodically, by both systematic and special-request releases of provisional data.
T. Immediately, by means of direct-access telemetry equipment.

Table 3. Data use, funding, and data availability for continuous-record stations operated in water year 1983 - (Continued)

STATION NUMBER	DATA USE									FUNDING				FREQUENCY OF DATA AVAILABILITY
	REGIONAL HYDROLOGY	HYDROLOGIC FORECASTS	LEGAL OBLIGATIONS	PLANNING & DESIGN	PROJECT OPERATION	HYDROLOGIC SYSTEMS	WATER-QUALITY MONITORING	RESEARCH	OTHER	FEDERAL PROGRAM	OFA PROGRAM	CO-OP PROGRAM	OTHER NON-FEDERAL	
01574500	*						3				9			A
01575000							3		8			10		A
01575500						4					9			AT
01576000	*	5			7		3					10	27	AO
01576085								31					*	AP
01576105								31					*	AP
01576500	*	5				4	3					10	28	APO
01576788								31					*	AP
01613050	*											10		A
03007800	*					4				*		23		AT
03009680	*					4				*		23		AT
03010500	*						3				9			A
03010655	*					4				*		23		AT
03011800	*				7		3				9			AT

3. Biological-chemical sample site of Pa. Dept. of Environmental Resources.
4. Flood forecasting - U.S. National Weather Service.
5. Federal Energy Regulatory Commission hydropower licensing requirements.
7. Reservoir inflow monitor.
8. Public supply monitor.
9. U.S. Army Corps of Engineers.
10. Pennsylvania Department of Environmental Resources.
23. New York Department of Environmental Conservation.
27. Safe Harbor Water Company.
28. Philadelphia Electric Company.
31. Non-point sources of pollution.
A. Annually, in serial data reports.
O. As required, by means of user observations of stage.
P. Periodically, by both systematic and special-request releases of provisional data.
T. Immediately, by means of direct-access telemetry equipment.

Table 3. Data use, funding, and data availability for continuous-record stations operated in water year 1983 - (Continued)

STATION NUMBER	DATA USE									FUNDING				FREQUENCY OF DATA AVAILABILITY
	REGIONAL HYDROLOGY	HYDROLOGIC FORECASTS	LEGAL OBLIGATIONS	PLANNING & DESIGN	PROJECT OPERATION	HYDROLOGIC SYSTEMS	WATER-QUALITY MONITORING	RESEARCH	OTHER	FEDERAL PROGRAM	OFA PROGRAM	CO-OP PROGRAM	OTHER NON-FEDERAL	
03012550					2						9	10		AT
03015000	*					4	3				9			AT
03015500	*						3			*	9	10		A
03016000						4	3				9	10		AO
03020000					2		3				9	10		AT
03020500	1	1				4	3			*		10		AT
03021350	*				7					*		10		AT
03021410	*				7						9	10		AT
03021520					2		3				9	10		AT
03022540	*				7						9	10		AT
03022554					2						9	10		AT
03024000							3				9	10		A
03025500						4	3				9	10		AO
03026500	*				7						9	10		AT
03027500					2		3				9	10		AT

1. Long-term index gaging station.
2. Reservoir release monitor.
3. Biological-chemical sample site of Pa. Dept. of Environmental Resources.
4. Flood forecasting - U.S. National Weather Service.
7. Reservoir inflow monitor.
9. U.S. Army Corps of Engineers.
10. Pennsylvania Department of Environmental Resources.
A. Annually, in serial data reports.
O. As required, by means of user observations of stage.
T. Immediately, by means of direct-access telemetry equipment.

Table 3. Data use, funding, and data availability for continuous-record stations operated in water year 1983 - (Continued)

STATION NUMBER	DATA USE									FUNDING				
	REGIONAL HYDROLOGY	HYDROLOGIC FORECASTS	LEGAL OBLIGATIONS	PLANNING & DESIGN	PROJECT OPERATION	HYDROLOGIC SYSTEMS	WATER-QUALITY MONITORING	RESEARCH	OTHER	FEDERAL PROGRAM	OFA PROGRAM	CO-OP PROGRAM	OTHER NON-FEDERAL	FREQUENCY OF DATA AVAILABILITY
03028000	*				7		3				9	10		AT
03028500						4					9	10		AO
03029500						4	3			*	9			AO
03030500		5			2		3					10	25	AO
03031500						4	3			*	9			AO
03032500	*						3 14			*		10		A
03034000	*					4					9	10		AT
03034500	*				7							10		AO
03036000					2		3				9	10		AT
03036500		1								*		10		A
03038000	*				7						9	10		AT
03039000					2		3				9	10		AT
03040000	*						3 14				9	10		AT
03041000	*						3				9	10		A
03041500	*				7		3				9	10		AT

1. Long-term index gaging station.
2. Reservoir release monitor.
3. Biological-chemical sample site of Pa. Dept. of Environmental Resources.
4. Flood forecasting - U.S. National Weather Service.
5. Federal Energy Regulatory Commission hydropower licensing requirements.
7. Reservoir inflow monitor.
9. U.S. Army Corps of Engineers.
10. Pennsylvania Department of Environmental Resources.
14. Sediment transport inventory site.
25. Pennsylvania Electric Company.
A. Annually, in serial data reports.
O. As required, by means of user observations of stage.
T. Immediately, by means of direct-access telemetry equipment.

Table 3. Data use, funding, and data availability for continuous-record stations operated in water year 1983 - (Continued)

STATION NUMBER	DATA USE									FUNDING				FREQUENCY OF DATA AVAILABILITY
	REGIONAL HYDROLOGY	HYDROLOGIC FORECASTS	LEGAL OBLIGATIONS	PLANNING & DESIGN	PROJECT OPERATION	HYDROLOGIC SYSTEMS	WATER-QUALITY MONITORING	RESEACH	OTHER	FEDERAL PROGRAM	OFA PROGRAM	CO-OP PROGRAM	OTHER NON-FEDERAL	
03042000	*				7		3				9	10		AT
03042280					2				8			10		AO
03042500					7		3				9	10		AT
03044000		1			2		3				9			AT
03045000	*				7		14				9	10		AO
03047000					2		3				9	10		AO
03048500		1			2	4	3			*		10		AO
03049000	*											10		A
03049500		1				4	3 18			*		10		APO
03049800	*											10		A
03070415	*						3 14		24				*	A
03070420	*						3 14		24				*	A
03070455	*						3 14		24				*	A
03072000	*						3				9	10		A
03072500						4	3			*	9	10		AO

1. Long-term index gaging station.
2. Reservoir release monitor.
3. Biological-chemical sample site of Pa. Dept. of Environmental Resources.
4. Flood forecasting - U.S. National Weather Service.
7. Reservoir inflow monitor.
8. Public supply monitor.
9. U.S. Army Corps of Engineers.
10. Pennsylvania Department of Environmental Resources.
14. Sediment transport inventory site.
18. National Stream Quality Accounting Network (NASQAN) at or near station.
24. Coal Hydrology study.

A. Annually, in serial data reports.
O. As required, by means of user observations of stage.
P. Periodically, by both systematic and special-request releases of provisional data.
T. Immediately, by means of direct-access telemetry equipment.

Table 3. Data use, funding, and data availability for continuous-record stations operated in water year 1983 - (Continued)

STATION NUMBER	DATA USE									FUNDING				FREQUENCY OF DATA AVAILABILITY
	REGIONAL HYDROLOGY	HYDROLOGIC FORECASTS	LEGAL OBLIGATIONS	PLANNING & DESIGN	PROJECT OPERATION	HYDROLOGIC SYSTEMS	WATER-QUALITY MONITORING	RESEARCH	OTHER	FEDERAL PROGRAM	OFA PROGRAM	CO-OP PROGRAM	OTHER NON-FEDERAL	
03073000	*						3					10		A
03074500	*						3				9	10		A
03075070						4	3				9	10		AO
03077500					2						9	10		AT
03079000	1	1					3				9	10		A
03080000	*				7		3					10		AO
03081000							3					10		A
03082500						4	3				9	10		AO
03083500						4	3				9	10		AO
03084000	*						3					10		A
03085000		1				4	3 14 18				9	10		APO
03085500							3				9	10		A
03086000						4	3				9			AO

1. Long-term index gaging station.
2. Reservoir release monitor.
3. Biological-chemical sample site of Pa. Dept. of Environmental Resources.
4. Flood forecasting - U.S. National Weather Service.
7. Reservoir inflow monitor.
9. U.S. Army Corps of Engineers
10. Pennsylvania Department of Environmental Resources
14. Sediment transport inventory site.
18. National Stream Quality Accounting Network (NASQAN) site at or near station.
A. Annually, in serial data reports.
O. As required, by means of user observations of stage.
P. Periodically, by both systematic and special-request releases of provisional data.
T. Immediately, by means of direct-access telemetry equipment.

Table 3. Data use, funding, and data availability for continuous-record stations operated in water year 1983 - (Continued)

STATION NUMBER	DATA USE									FUNDING				FREQUENCY OF DATA AVAILABILITY
	REGIONAL HYDROLOGY	HYDROLOGIC FORECASTS	LEGAL OBLIGATIONS	PLANNING & DESIGN	PROJECT OPERATION	HYDROLOGIC SYSTEMS	WATER-QUALITY MONITORING	RESEARCH	OTHER	FEDERAL PROGRAM	OFA PROGRAM	CO-OP PROGRAM	OTHER NON-FEDERAL	
03101500					2		3					10		AO
03102500	*				7		3				9	10		AO
03102850					7						9	10		AT
03103500					2		3				9			AT
03105500							3				9	10		A
03106000	1	1					3				9	10		A
03106300					2							10		AO
03106500	*						3				9	10		A
03107500		1				4	3 18				9	10		AT
03108000	*						3				9	10		A
03111585	*						3 14		24				*	A
04213040	*											10		A

1. Long-term index gaging station.
2. Reservoir release monitor.
3. Biological-chemical sample site of Pa. Dept. of Environmental Resources.
4. Flood forecasting - U.S. National Weather Service.
7. Reservoir inflow monitor.
9. U.S. Army Corps of Engineers.
10. Pennsylvania Department of Environmental Resources.
14. Sediment transport inventory site.
18. National Stream Quality Accounting Network (NASQAN) site at or near station.
24. Coal hydrology study.
A. Annually, in serial data reports.
O. As required, by means of user observations of stage.
T. Immediately, by means of direct-access telemetry equipment.

Frequency of Data Provision

Frequency of data provision refers to the periodicity and manner in which streamflow data are funished to users. Four frequency categories are used. Data can be furnished by direct-access telemetry equipment for immediate use, through the user's observations of stage, by periodic release of provisional data, or in publication format through the annual data reports published by the U.S.Geological Survey for Pennsylvania (U.S. Geological Survey, 1982). These four categories are designated T, O, P, and A, respectively, in table 3. In the Pennsylvania program for 1983, data for all 223 stations are made available through the annual report, data from 39 stations are available on a real-time basis, and data are released on a provisional basis for 20 stations.

Conclusions Pertaining to Data Use

The compiled information on current (1983) usage of data collected at continuous-record stations showed sufficient interest in records to warrant further operation of all gages except four continuous-record stations that Flippo (1982, table 8) suggested for discontinuance at the close of the 1985 water year and that are still in operation. These stations are:

01542810	Waldy Run near Emporium,
01567500	Bixler Run near Loysville,
01613050	Tonoloway Creek near Needmore, and
04213040	Raccoon Creek near West Springfield.

The plan for their discontinuance remains in effect, as it does for the remaining 26 partial-record stations that Flippo (1982, table 8) suggested for discontinuance by October 1985.

Two stations operated for a short-term hydrology study in the Delaware River basin are planned for continued operation after the project ends. These two stations, which are included in the third phase of this cost-effectiveness study, are:

01470853	Furnace Creek at Robesonia, and
01473169	Valley Creek at Turnpike bridge near Valley Forge.

Nine other stations are operated for short-term hydrology projects:

01571919, 01572000, 01576085, 01576105, 01576788, 03070415, 03070420, 03070455, and 03111585.

Only one of the stations, Conestoga River at Terre Hill (01576105), is planned for continuance (as a crest-stage partial-record station) at the end of the supporting project. None of these stations are considered further in this report.

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 place of operating continuous-record gaging stations. The objective of the analysis is to identify gaging stations where alternative technology, such as flow-routing or statistical methods, will provide information about daily mean streamflow in a more cost-effective manner than continuous operation of a stream gage. No guidelines exist for determining suitable accuracies for particular uses of the data; therefore, judgement is required in deciding whether the accuracy of the estimated daily flows is suitable for the intended purpose of the records. The uses of a flow record provide a means of evaluating the potential for the application of alternate methods to synthesize future records for the station. For example, those stations for which flood hydrographs are required in a real-time sense, such as for hydrologic forecasts or project operation, are not candidates for the alternative methods. Likewise, a legal obligation to operate a continuous-record gaging station would preclude use of alternative methods. The primary candidates for alternative methods are stations that are operated upstream or downstream of other stations on the same stream. The accuracy of the estimated streamflow at these sites is likely to be suitable because of the high redundancy of flow information between sites. Similar watersheds, located in the same physiographic and climatic area, also could have potential for use of alternative methods. Each station in the Pennsylvania stream-gaging program (table 3) was reviewed to assess its potential for the use of alternative methods. Selected methods were applied at eight stations. This section briefly describes the two alternative methods that were used in the Pennsylvania analysis and documents why these specific methods were chosen.

Because of the short time frame of this analysis, only two methods were considered. Desirable attributes of a proposed alternative method are as follows: (1) the proposed method should be computer oriented and easy to apply, for obvious reasons; (2) the proposed method should have an available interface with the Survey's WATSTORE Daily Values File (Hutchinson, 1975), which will permit the proposed alternate method to be easily calibrated; (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 adequacy and accuracy of the sumulated streamflow records. These selection criteria were used to select two methods--multiple regression analysis and a flow-routing model.

Description of Regression Analysis

Simple- and multiple-regression techniques can be used to simulate daily flow records for a station. 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 to stations where an upstream station is located on the same stream. The explanatory variables in the regression analysis can be daily mean discharges for stations in tributary or other 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 of 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). A brief description of regression analysis is provided below.

A linear-regression model of the following form was developed for estimating daily mean discharges in Pennsylvania:

$$y_i = B_o + \sum_{j=1}^{p} B_j x_j + e_i \qquad (1)$$

where

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

The above equation is calibrated (B_o and B_j are estimated) using 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 subsequent 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 if they are significantly different from zero. A given station j should only be retained in the regression equation if its regression coefficient (B_j) is significantly different from zero. The regression equation should be calibrated using one period of time and then verified or tested on a different period of time to obtain a measure of the true predictive accuracy. Both the calibration and verification period should be representative of the range of flows that could occur at station i.

The equation should be verified by (1) plotting the residuals e_i (difference between simulated and observed discharges) against the dependent and all explanatory variables in the equation, and (2) plotting the simulated and observed discharges versus time. These tests are intended to identify if (1) the linear model is appropriate or whether some transformation of the variables is needed, and (2) if there is any bias in the equation, such as a tendency to overestimate low flows. These tests might indicate, for example, that a logarithmic transformation is desirable, that a nonlinear-regression equation is appropriate, that the regression equation is biased in some way, or that the regression equation is appropriate. In this study, these tests indicated that a linear model with y_i and x_j in cubic feet per second was appropriate. The application of this model to eight stations in Pennsylvania is described in the next 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 stream flow 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.

Results of Regression Analysis

Linear-regression techniques were applied to all eight of the selected sites. The streamflow record for each station considered for simulation (the dependent variable) was regressed against streamflow records at other stations (explanatory variables) during a given period of record (the calibration period). "Best fit" linear regression models were developed and used to provide a daily streamflow record that was compared to the observed streamflow record. The percent difference between the simulated and actual record for each day was calculated. The results of the regression analysis for each site are summarized in table 4.

Records for one (03086000) of the eight stations could possibly be synthesized by regression methods with sufficient accuracy to satisfy present (1983) uses of the data. Uses of the daily flow records for quality of water monitoring at this station requires that values of daily discharge be within 10 percent of actual discharge for no less than 90 percent of the time.

Stations 01454700 is also used as a quality of water monitor. Daily flows for this station could be simulated with $\pm$ 10 percent accuracy 33.2 percent of the time, which does not meet the 90 percent objective. Daily flow data for station 01563500 have been used to route flows on the Junita River (Armbruster, 1977); however, no regular uses of daily flow data, other than for flow modeling, are known. It is assumed the accuracy of regression-simulated flow (table 4) is suitable for such purposes. A stage recorder, telemetry equipment, and a discharge rating must be maintained at stations 01563500 and 03086000 for flood forecasting and low-flow monitoring.

The accuracy of simulated daily flows for the other five stations were much lower than those needed for current uses of the record.

Table 4.--Summary of calibration for regression modeling of mean daily streamflow at selected gaging stations in Pennsylvania

Station no.	Model1/	Percentage of simulated flow within 5 percent of actual	Percentage of simulated flow within 10 percent of actual	Calibration period (water years)
01454700	$Q_{01454700} = 160 + 1.0012\ (Q_{01453000})$	58.9	83.2	1968-70
01467086	$Q_{01467086} = 8.5 + 0.324\ (Q_{01467089})$ 2/	12.9	24.6	1976-79
01480500	$Q_{01480500} = -2.6 + 0.760\ (Q_{01480617})$	35.5	59.2	1976-79
01563500	$Q_{01563500} = 70.0 + 1.295\ (Q_{01559000}) + 0.992\ (Q_{01563200})$	54.2	82.7	1976-79
01573560	$Q_{01573560} = 77.8 + 1.222\ (Q_{01573000})$	31.1	55.6	1976-79
03084000	$Q_{03084000} = 0.6 + 0.025\ (Q_{03049000})$	31.1	55.6	1976-79
03086000	$Q_{03086000} = -130 + 1.016\ (Q_{03049500}) + 1.021\ (Q_{03085000})$	63.2	90.7	1976-79
03102850	$Q_{03102850} = 9.3 + 1.018\ (Q_{03101500}) + 1.575\ (Q_{03102500})$	24.6	50.2	1976-79

1/ Discharge (Q) in ft^3/s.
2/ Used in lieu of $Q_{01467087}$, which has too little record for meaningful correlation.

Description of Flow-Routing Model

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

The unit-response method was selected because it fulfilled the criteria noted in the introduction to this section. Computer programs for the unit-response method can be used to route stream-flow from one or more upstream locations to a downstream location. Downstream hydrographs are produced by the convolution of upstream hydrographs with their appropriate unit-response functions. This method can only be applied at a downstream station where an upstream station exists on the same stream. An advantage of this model is that it can be used for regulated-stream systems. Reservior 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. Routing can be accomplished using hourly data, but only daily data are used in this analysis.

The objective in either the storage-continuity or diffusion analogy flow-routing method is to calibrate two parameters that describe the storage-discharge relationship in a given reach and the 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 (Keefer and McQuivey, 1974) is routed through reservoir-type storage and then transformed by a summation curve technique to a unit response of desired duration. The two parameters that describe the routing reach are K_s, a storage coefficient which is the slope of the storage-discharge relation, and W_s, the translation hydrograph time base. These two parameters determine the shape of the resulting unit-response function.

In the diffusion-analogy theory, the two parameters requiring calibration in this method are K_o, a wave dispersion or damping coefficient, and C_o, the flood-wave 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 C_o value are used. In the multiple linearization method, C_o and K_o are varied with discharge. The relationships are input to the routing program by matricies of wave celerity (C_o), dispersion coefficient (K_o), and discharge (Q) values.

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

The modeler can use single or multiple unit-(system-)response functions. The choice depends primarily upon the variability of wave celerity (traveltime) and dispersion (channel storage) throughout the range of discharges to be routed. Adequate routing of daily flows can usually be accomplished using a single unit response function (linearization about a single discharge) to represent the system response. However, if the routing coefficients vary drastically with discharge, linearization about a low-range discharge results in overestimated high flows that arrive late at the downstream site; conversely, 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. Thus, the option of multiple linearization (Keefer and McQuivey, 1974), which uses a family of unit-response functions to represent the system response, is the logical choice.

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. If such flows are totally unknown, they can be estimated from some combination of gaged and ungaged flows. An estimating technique that proves satisfactory in many instances is the multiplication of known flows at an index gaging station by a factor--usually a drainage-area ratio.

Results of Flow-Routing Analyses

Unit-response routing models were developed to route measured daily flows from the nearest upstream station to three stations:

01454700 Lehigh River at Glendon,
01563500 Juniata River at Mapleton Depot, and
03086000 Ohio River at Sewickley.

Model parameters C_o, floodwave celerity, and K_o, wave dispersion coefficient, were initially computed from the following equations (Doyle and others, 1979):

$$C_o = \frac{1}{W_o} \frac{dQ_o}{dY_o} \qquad (2)$$

$$K_o = \frac{Q_o}{2\ S_o W_o} \qquad (3)$$

The functions are:

W_o = channel width, in feet;

S_o = channel slope, in feet per foot (ft/ft);

$\frac{dQ_o}{dY_o}$ = slope of the stage-discharge relation, in square feet per second (ft^2/s); and

Q_o = the discharge, in cubic feet per second (ft^3/s), for the reach being modeled.

The discharge, Q_o, was singularly linearized with initial values of C_o and K_o in the routing models for daily flows of the Lehigh River and Ohio River. Multiple linearization of discharge with C_o and K_o, as developed by Armbruster (1977, table 4), was used in the Juniata River model.

Flow-Routing Model for Lehigh River at Glendon (01454700)

The routing model developed for simulation of daily flows at station 01454700 is based on flow records for the long-term stations on the Lehigh River at Bethlehem (01453000) and on Little Lehigh Creek near Allentown (01451500), as noted in table 5. Daily-flow data for water years 1968-70 were used to calibrate the model in which

$$\underbrace{Q_{01454700}}_{\text{simulated}} = \underbrace{Q_{01453000} + 1.6 \times Q_{01451500}}_{\text{routed}} \qquad (4)$$

Table 5.--Gaging stations used in the Lehigh River at Glendon (01454700) flow-routing study

Station no.	Station name	Drainage area (mi^2)	Period of record
01451500	Little Lehigh Creek near Allentown	80.8	October 1945-
01453000	Lehigh River at Bethlehem	1,279	September 1902-February 1905; April 1909-
01454700	Lehigh River at Glendon	1,357	October 1966-

Flows at station 01451500 serve to simulate ungaged inflow in the 9.5 mile reach between stations 01453000 and 01454700. The summation hydrograph, represented by the right side of the equation, is routed through this reach using the values of C_o and K_o shown in table 6. These values of C_o and K_o are those found by trial-and-error adjustment of the initial C_o and K_o values to minimize errors in the simulated daily flows for station 01454700. The absolute mean error in simulated daily flows for the calibration period was 6.24 percent. The corresponding net error in flow volume was -2.48 percent.

Table 6.--Selected reach characteristics used in the Lehigh River River at Glendon (01454700) flow-routing study

Site	1/ Q_o (ft^3/s)	2/ W_o (ft)	3/ S_o (ft/ft)	4/ $\frac{dQ_o}{dY_o}$ (ft^2/s)	5/ C_o (ft/s)	6/ K_o (ft^2/s)
Bethlehem	2,335	270	1.74×10^{-3}	1,750	6.1	2,800
Glendon	2,930			1,520		

1/ Mean discharge calculated over the period of record.
2/ Channel width.
3/ Channel slope.
4/ Slope of stage-discharge relation.
5/ Floodwave celerity.
6/ Wave dispersion coefficient

The utility of the model for simulating flows at station 01454700 was evaluated on the basis of simulation results for the period 1968-80, which are summarized in table 7.

Table 7.--Results of routing model for Lehigh River at Glendon (01454700)

Mean absolute error for 4,749 days = 7.19 percent
Mean negative error (2,810 days) = -7.48 percent
Mean positive error (1,939 days) = 6.76 percent
Net volume error = 0.62 percent

Errors in simulated daily flows, in percent	Percentage of total observations
$\leq$ 5	47.2
$\leq$ 10	73.8
$\leq$ 15	89.6
$\leq$ 20	95.5
$\leq$ 25	97.8
$\geq$ 25	2.2

Typical daily hydrographs of simulated and measured flows for the Lehigh River at Glendon (01454700) are plotted in figure 3 for a 2-month period. Simulated daily flows were within 10 percent of corresponding observed values 73.8 percent of the time, as compared to 83.2 percent of the time for the regression model (table 4). Neither the regression model or the flow-routing model can be used to simulate daily flows with sufficient accuracy for current (1983) needs.

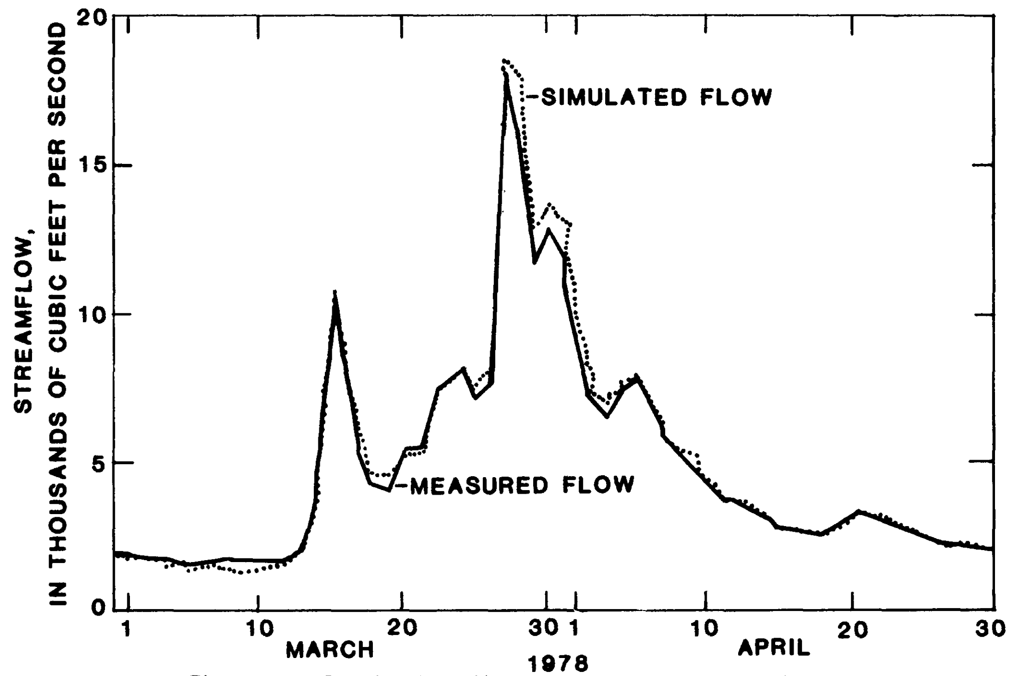


Figure 3. --Typical daily hydrograph, Lehigh River4 at Glendon (01454700).

Flow-Routing Model for Juniata River at Mapleton Depot (01563500)

The routing model developed for simulation of daily flows at station 01563500 is based on flow records for the long-term stations on the Juniata River at Huntingdon (01559000) and on Raystown Branch Juniata River below Raystown Dam near Huntingdon (01563200), as noted in table 8. Armbruster's (1977) model was revised so that the hydrograph for station 01559000 is routed to the confluence of the Juniata River with the Raystown Branch; the combined hydrograph, which consists of the routed hydrograph added to that for the Raystown Branch, is then routed to station 01563500. Ungaged inflow down-stream of stations 01559000 and 01563200 are accounted for by applying multiplication factors to the combined hydrograph prior to the second routing step. This revision to the model was necessary because flow data for the station that Armbruster (1977) used to estimate ungaged inflow are no longer collected.

Table 8.--Gaging stations used in the Juniata River at Mapleton Depot (01563500) flow-routing study

Station no.	Station name	Drainage area (mi^2)	Period of record
01559000	Juniata River at Huntingdon	816	September 1941-
01563200	Raystown Branch Juniata River below Raystown Dam near Huntingdon	960	January 1946-
01563500	Juniata River at Mapleton Depot	2,030	October 1937-

Thus, the revised model is of the form:

$$\underbrace{Q_{01563500}}_{\text{simulated}} = \underbrace{\underbrace{Q_{01559000}}_{\text{routed}} + 0.14 \times Q_{01559000} + 1.15 \times Q_{01563200}}_{\text{routed}} \qquad (5)$$

The distributions of C_0 and K_0 with discharge for both the upper 4.2-mile reach and the lower 5.0-mile reach are shown in table 9.

The absolute mean error of simulated daily flows at station 01563500 for the period 1973-82, was 6.18 percent. The corresponding net error in flow volume was -0.55 percent. The results of this simulation are summarized in table 10. Simulated daily flows were within 10 percent of corresponding observed values 81.1 percent of the time, as compared to 82.7 percent of the time for the regression model (table 4).

A comparison of hydrographs of measured and simulated daily flows during low-flow periods, as depicted by figure 4, suggests some improvement could be made to the routing model. Such an improvement would largely offset any loss in the accuracy of flows, for points downstream of station 01563500, that would be simulated by a routing model in which actual daily flows for station 01563500 are not used. Thus, flows could be successfully routed for the Juniata River without benefit of daily-flow observations for the station at Mapleton Depot (01563500).

Table 9.--Selected reach characteristics used in the Juniata River at Mapleton Depot (01563500) flow-routing study

Site	Q_o (ft^3/s)	W_o 2/ (ft)	S_o 3/ (ft/ft)	$\frac{dQ_o}{dY_o}$ 4/ (ft^2/s)	C_o 5/ (ft/s)	K_o 6/ (ft^2/s)
Huntingdon	1,089 1/					
	500	320	0.016	540	1.7	50
	2,000	500	.0020	1,120	2.3	1,000
	4,000	520	.0010	1,490	2.9	4,000
	8,000	530	.0005	2,130	4.2	14,000
	15,000	540	.0004	2,610	6.2	34,000
	25,000	570	.0004	3,330	8.6	54,000
	40,000	600	.0004	4,120	11.6	84,000
Mapleton Depot	2,498 1/					

1/ Mean discharge calculated over the period of record.
2/ Channel width.
3/ Channel slope.
4/ Slope of stage-discharge relation.
5/ Floodwave celerity (from Armbruster, 1977, Table 4).
6/ Wave dispersion coefficient.

Table 10.--Results of routing model for Juniata River at Mapleton Depot (01563500)

Mean absolute error for 3,652 days = 6.18 percent
Mean negative error (1,781 days) = -6.45 percent
Mean positive error (1,871 days) = 5.93 percent
Net volume error = -0.55 percent

Errors in simulated daily flows, in percent	Percentage of total observations
$\leq$ 5	49.3
$\leq$ 10	81.1
$\leq$ 15	94.3
$\leq$ 20	97.7
$\leq$ 25	99.1
$\geq$ 25	.9

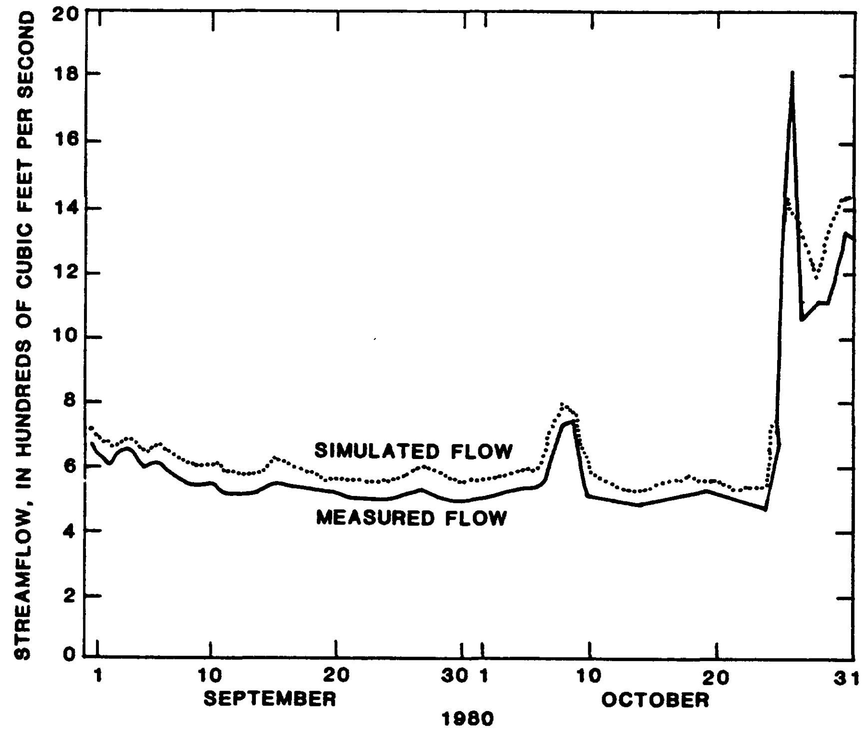


Figure 4.--Hydrograph of low daily flow, Juniata River at Mapleton Depot (01563500).

Flow-Routing Model for Ohio River at Sewickley (03086000)

The routing model developed to simulate of daily flows at station 03086000 is based on flow records for the long-term stations on the Allegheny River at Natrona (03049500) and on the Monongahela River at Braddock (03085000), as noted in table 11. The model routes daily flows for these two stations to the confluence of the two rivers. The hydrographs are combined and the resultant hydrograph is routed to station 03086000. This model contains three routing steps and is of the form:

$$\underbrace{Q_{03086000}}_{\text{simulated}} = \underbrace{\underbrace{1.035 \text{ X } Q_{0304950}}_{\text{routed}} + \underbrace{1.02 \text{ X } Q_{03085000}}_{\text{routed}}}_{\text{routed}} \qquad (6)$$

Table 11.--Gaging stations used in the Ohio River at Sewickley (03086000) flow-routing study

Station no.	Station name	Drainage area (mi^2)	Period of record
03049500	Allegheny River at Natrona	11,410	October 1938-
03085000	Monongahela River at Braddock	7,337	October 1938-
03086000	Ohio River at Sewickley	19,500	October 1933-

The optimized values of C_o and K_o for the three routing steps are given in table 12. These routings were made for 11.8 miles on the Allegheny River, 11.2 miles on the Monongahela River, and 12.0 miles on the Ohio River.

Table 12.--Selected reach characteristics used in the Ohio River at Sewickley (03086000) flow-routing study

Site	Q_o 1/ (ft^3/s)	W_o 2/ (ft)	S_o 3/ (ft/ft)	$\frac{dQ_o}{dY_o}$ 4/ (ft^2/s)	C_o 5/ (ft/s)	K_o 6/ (ft^2/s)
Natrona	19,510			9,480	11.8	29,200
		850	3.9×10^{-4}			
Mouth of	20,190					
Allegheny River	12,250			6,800	6.8	11,500
03085000		900	6.0×10^{-4}			
Mouth of	12,620					
Monongehela River		1,200	4.6×10^{-4}			
Sewickley	32,810			14,400	12.0	30,000

1/ Mean discharge calculated over the period of record.
2/ Channel width.
3/ Channel slope.
4/ Slope of stage-discharge relation.
5/ Floodwave celerity.
6/ Wave dispersion coefficient.

Results of the routing model for Ohio River at Sewickley (03086000) are given in table 13 for the period 1967-82. This model resulted in a net volume error of +0.29 percent and simulated daily flows with errors of 10 percent or less for 92.7 percent of the time. A typical hydrograph of measured and simulated flow for August and September 1982, is shown in figure 5.

Table 13.--Results of routing model for Ohio River at Sewickley (03086000)

Mean absolute error for 5,844 days = 4.16 percent
Mean negative error (2,667 days) = -4.29 percent
Mean positive error (3,177 days) = 4.04 percent
Net volume error = 0.29 percent

Errors in simulated daily flows, in percent	Percentage of total observations
$\leq$ 5	70.0
$\leq$ 10	92.7
$\leq$ 15	98.0
$\leq$ 20	99.3
$\leq$ 25	99.7
$\geq$ 25	.3

Either the regression model (table 4) or the routing model (equation 6) could be used to simulate daily flow data for Ohio River at Sewickley (03086000) that are of suitable accuracy for all known current (1983) uses.

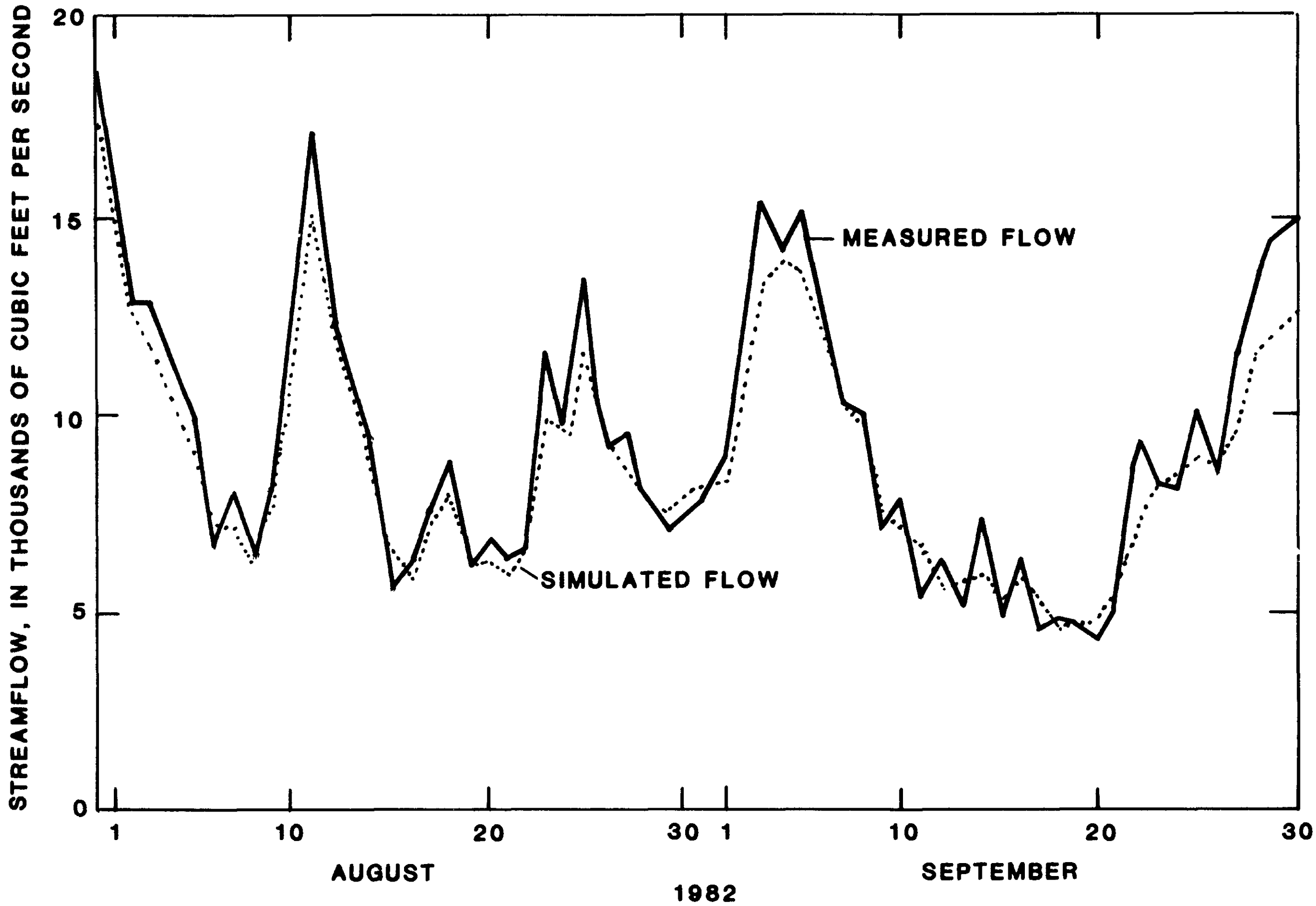


Figure 5.--Typical daily hydrograph, Ohio River at Sewickley (03086000).

Conclusions Regarding Alternative Methods

On the basis of the regression and flow-routing analyses described above, the gaging stations on the Juniata River at Mapleton Depot (01563500) and on the Ohio River at Sewickley (03086000) are suggested for operation as continuous-stage stations for which daily discharges are not computed and published. All existing recording equipment and a stage-discharge relationship are to be maintained primarily for real-time use by the cooperating agencies. Agreements have been signed for full continuous-record operation of these two gages in fiscal year 1986. Therefore, the suggested changes in gaging activity might best be implemented at the beginning of the 1987 water year.

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 were developed (Moss and Gilroy, 1980). Because of the water-balance nature of that study, the measure of effectiveness of the network was chosen to be the minimization of the sum of variances of errors of estimation of annual mean discharges at each site in the network. This measure of effectiveness tends to concentrate stream-gaging resources on the larger, less stable streams where potential errors are greatest. Although such a tendency is appropriate for a water-balance network, it is not desirable in the broader context of the multitude of uses of the the streamflow data collected in the Survey's Streamflow Information Program. An undue concentration of stream-gaging activity on larger streams will result in excessive errors in the flow records for some minor streams. Therefore, the original version of K-CERA was extended to include, as optional measures of effectiveness, the sums of the variances of errors of estimation of the following streamflow variables: annual mean discharge in cubic feet per second, annual mean discharge in percentage, average instantaneous discharge in cubic feet per second, and average instantaneous discharge in percentage. The use of percentage errors does not unduly weight activities at large streams to the detriment of records on small streams. In addition, the instantaneous discharge is the basic variable from which all other streamflow data are derived.

For these reasons, this study used the K-CERA techniques with the sum of the variances of the percentage errors of the instantaneous discharges at 212 continuously gaged sites as the measure of the effectiveness of the data-collection activity. No attempt has been made to estimate standard errors for other than instantaneous discharges or for discharges determined by methods other than those described in this report. Such errors could differ from the errors presented herein. The magnitude and direction of the differences would be primarily a function of methods used to acccount for shifting controls and for estimating discharges during periods of missing record.

The original version of K-CERA also did not account for error contributed by missing stage or other correlative data that are used to compute streamflow data. In general, the percentage of missing correlative data increases as the period between service visits to a stream gage increases. A procedure for dealing with the missing record has been developed and was incorporated into this study.

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

Description of Mathematical Program

The program called "The Traveling Hydrographer," attempts to allocate among stream gages a predefined budget for the collection of streamflow data in such a manner that the field operation is the most cost-effective possible. The measure of effectiveness is discussed above. The set of decisions available to the manager is the frequency of use (number of times per year) of each of a number of routes that may be used to service the stream gages and to make discharge measurements. The range of options within the program is from zero usage to daily usage for each route. A route is defined as a set of one or more stream gages and the associated least cost of travel that will take 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 included in the route. The first step in this part of the analysis is to define the set of practical routes. This set of routes commonly will contain routes that visit a single stream gage. Routes are devised in this manner so that the individual needs of selected stream gages can be considered apart from other gages.

Another step in this part of the analysis is the determination of any special requirements for visits to each of the gages for such things as necessary periodic maintenance, service 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 $i = 1, 2, \ldots, NR$, where NR is the number of practical routes, is used during a year such that (1) the budget for the network is not exceeded, (2) the minimum number of visits to each station is made, and (3) the total uncertainty in the network, expressed by the sum of variances of percentage errors in instantaneous discharge, is minimized. Figure 6 represents this step in the form of a mathematical program. Figure 7 presents a tabular layout of the problem. Each of the NR routes is represented by a row of the table and each of the stations is represented by a column. The zero-one matrix, (ω_{ij}), defines the routes in terms of the stations that comprise it. A value of one in row i and column j indicates that gaging station j will be visited on route i; a value of zero indicates that it will not. The unit travel costs, β_i, are the per-trip costs of the hydrographer's travel time and any related per diem and operation, maintenance, and rental costs of vehicles. The sum of the products of β_i and N_i for $i = 1, 2, \ldots, NR$ is the total travel cost associated with the set of decisions $\underline{N} = (N_1, N_2, \ldots, N_{NR})$.

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

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

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

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

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

V ≡ total uncertainty in the network

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

MG ≡ number of gages in the network

M_j ≡ annual number of visits to station j

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

Such that

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

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

F_c ≡ fixed cost

α_j ≡ unit cost of visit to station j

NR ≡ number of practical routes chosen

β_i ≡ travel cost for route i

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

and such that

$$M_j \geq \lambda_j$$

λ_j ≡ minimum number of annual visits to station j

Figure 6.-- Mathematical-programming form of the optimization of routing of hydrographers.

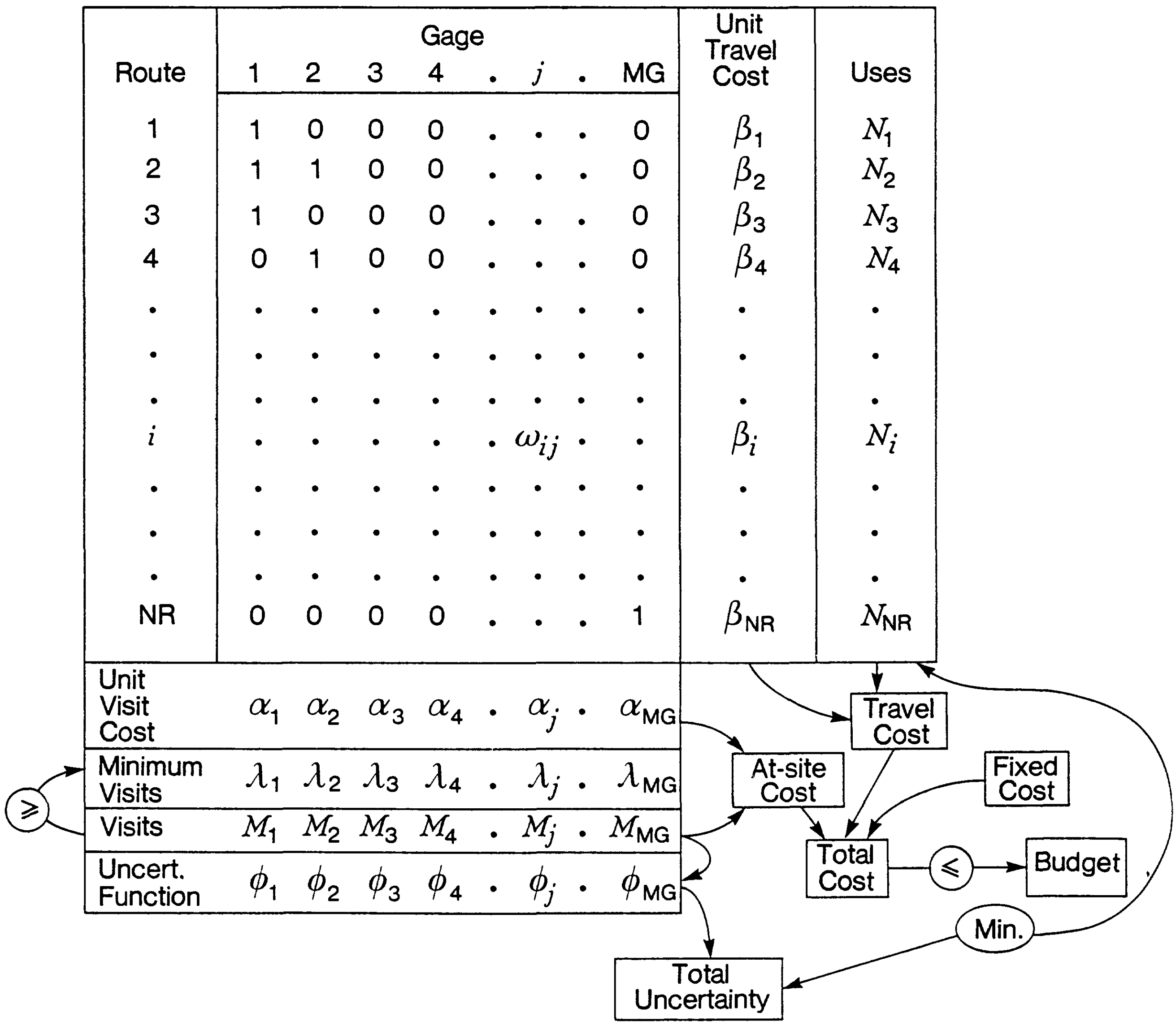


Figure 7.--Tabular form of the optimization of the routing of hydrographers.

Description of Uncertainty Functions

As noted earlier, uncertainty in streamflow records is measured in this study as the average relative variance of estimation of instantaneaous 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:

$$\overline{V} = \varepsilon_f V_f + \varepsilon_r V_r + \varepsilon_e V_e \tag{7}$$

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 stream 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

$$f(\tau) = ke^{-k\tau}/(1-e^{-ks}) \tag{8}$$

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,

$$\varepsilon_f = (1 - e^{-ks})/(ks) \tag{9}$$

(Fontaine and others, 1984, equation 21).

The fraction of time, ε_e that no records are collected at either the primary or secondary sites also can be derived assuming that the time between failues 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, equations 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

$$\begin{aligned}\varepsilon_r &= 1 - \varepsilon f - \varepsilon_e. \\ &= [(1-e^{-ks}) - 0.5(1-e^{-2ks})]/(ks)\end{aligned} \qquad (10)$$

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 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

$$x(t) = \ln q_T(t) - \ln q_R(t) = \ln [q_T(t)/q_R(t)] \qquad (11)$$

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

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

$$\hat{x}(t) = \ln q_c(t) - \ln q_R(t) \qquad (12)$$

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

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

$$z(t) = x(t) + v(t) = \ln q_m(t) - \ln q_R(t) \qquad (13)$$

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, which is the reciprocal of the correlation time of the Markovian porcess 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

$$\mathrm{Var}[x(t)] = p = q/(2\beta) \tag{14}$$

The variance of the observed residuals z(t) is

$$\mathrm{Var}[z(t)] = p + r \tag{15}$$

where r is the variance of the measurement error v(t). The three parameters, p, β, and r, are computed by analyzing the statistical properites 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:

$$\overline{C}_v = \left(\frac{1}{365} \sum_{i=1}^{365} \left(\frac{\sigma i}{\mu i} \right)^2 \right)^{1/2} \tag{16}$$

where

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

μ_i is the expected value of discharge on the i^{th} day of the year, and

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

The variance V_r of the relative error during 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 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

$$V_r = (1-\rho_c^2)\ \overline{C}_v^2 \tag{17}$$

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 seconday data are unavailable, the relative error variance V_e may be very large. This could yield correspondingly large values of V in equation (7) even though the fraction of time that primary and secondary information are not available, ε_e is relatively 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 (7) are log-normally distributed, the value of EGS was determined by the probability statement that

$$\text{Probability } [e^{-EGS} \leq (q_c(t)\ /\ q_T(t)) \leq e^{+EGS}] = 0.683 \tag{18}$$

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 Pennsylvania

As a result of the first two parts of this program review, it has been recommended that 222 continuous-record stream gages in the 1983 program be continued in operation in 1984. In this group of gages there are 210 co-operatively operated and 2 special-project gages that will be considered in the K-CERA analysis. Responsibility for these 212 gages is distributed among the three subdistrict offices as follows:

Malvern	62
Harrisburg	79
Pittsburgh	71
Pennsylvania District	212

Definition of Missing-Record Probabilities

As was described earlier, the statistical characteristics of missing stage or other correlative data for computation of streamflow records can be defined by a single parameter, the value of k in the truncated negative exponential probability distribution of times to failure of the equipment. In the representation of $f(\tau)$ as given in equation 8, the average time to failure is 1/k. The value of 1/k will differ from site to site depending on 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 or by collection of supplemental continuous-stage record.

To determine 1/k, a 10-year history (1973-82) of missing stage record was compiled for each station. The most recent data on missing record within this 10-year period that was consistent with present (1983) data-collection practices was used as the estimate of future missing record. Stage record that had been reconstructed from supplemental sources and without loss in accuracy was not considered as missing.

The range in missing record for the 212 stations was from zero to 69 days per year, corresponding to a range in 1/k from near infinity to 119 days. Record loss averaged 12.5 days per year, or 3.4 percent. The average interval between visits was 41 days. The individual values 1/k were used to determine ε_f, ε_e and ε_r as a function of the visit frequency, during 1981 and 1982, for each of the 212 stations.

Definition of Cross-Correlation Coefficient and Coefficient of Variation

To compute the values of V_e and V_r of the needed uncertainty functions, daily streamflow records for each of the 212 stations for the last 30 years, or the part of the last 30 years for which daily streamflow values are stored in WATSTORE (Hutchinson, 1975), were retrieved. For each of the stream gages that had 3 or more complete water years of data, the value of C_v was computed and various options, based on combinations of other stream gages, were explored to determine the maximum ρ_c. For the seven stations that had less than 3 water years of data, values of C_v and ρ_c were estimated subjectively. The values of C_v and ρ_c were used to compute a set of 212 uncertainty functions for the current status of missing record.

In addition to the use of records from other nearby stream gages, some of the stations had other means by which streamflow data could be reconstructed when the primary recorder was malfunctioning. Some stations are equipped with telemetry systems that operate independently from the primary recorder and are routinely queried either once or twice per day. At other locations, a local resident is hired as an observer, to read and record stage at a station once or twice daily. Hydropower records at one site are used to compute the flow record for the nearby gaging station. At 33 gages, supplemental recorders are operated to provide 'backup' stage record. Several of these gages, as are many others, have supplemental satellite and/or land-based telemetry equipment.

Estimations of the cross correlations, ρ_c, between daily discharges at stations and the available sources of supplemental stage records were based on the histories of record loss for the several supplemental sources. The probability of complete record loss for any given day is less than 0.01 for stations with supplemental recorders. Consequently, a ρ_c of 0.99 was used for such stations, in lieu of that value obtained through correlation with flow records for other sites. Flow records of below-normal accuracies caused by missing stage data for gages equipped with land-based telemetry or at which an observer makes one or two daily stage readings when the primary gage is inoperative generally ranges from 2 to 3 percent. For such stations, a ρ_c of 0.98 or 0.97 was used, depending on the coefficient of variation, C_v, for the station record and the frequency of the supplemental stage readings. These estimates of ρ_c are consistent with those used by Fontaine and others (1984) for similarly operated stations in Maine.

Inspection of "original" uncertainty functions for the 212 stations disclosed that a substantial reduction in the variance of the instantaneous discharge could be attained for some stations lacking in supplemental stage records by using observers or auxiliary recorders. For each such station, the cost of adding an observer or a supplemental recorder was weighed against the cost of making visits to the station to produce a similar reduction in the uncertainty. This analysis showed that the addition of an observer or a supplemental recorder was cost effective for most stations when the missing stage record was equal to or greater than 4 percent. An observer or a supplemental stage recorder, depending on the remoteness and record-loss history for the gage, is proposed for each station where its addition would be cost effective. The numbers of these sources of supplemental stage record proposed for each subdistrict's operations are tabulated in table 14. Stage data telemetered to a satellite are routinely used to reconstruct missing record for several stations; however, recorders with satellite-telemetry capability are not cost competetive with observers and auxiliary analog recorders as a single-purpose "back-up" system.

Table 14.--Proposed additions of observers and auxiliary recorders, by subdistrict

Subdistrict	Number of proposed additions	
	Observers 1/	Auxiliary recorders 2/
Malvern	12	6
Harrisburg	22	2
Pittsburgh	11	1

1/ To read stage weekly when the recorder is operating satisfactorily and once daily when the recorder is malfunctioning.
2/ Continuous-analog type.

Table 15.--Statistics of record reconstruction

Station no.	C_v(%)	ρc	Source of reconstructed records		
			Delaware River Basin		
01429000	129	0.99	Supplemental recorder at site.[2]		
01429500	151	.931	431500		
01431500	141	.98	Observer; read daily.[2]		
01432000	126	.99	Upstream hydropower plant.		
01439500	120	.93	440400		
01440400	113	.95	439500	442500	
01442500	117	.98	Observer, read daily. [2]		
01447500	114	.99	Supplemental recorder at site. [2]		
01447680	85.2	.91	447720		
01447720	97.9	.91	447680		
01447800	101	.99	Supplemental recorder at site.		
01448500	118	.86	447720	447680	447500
01449000 [1]	100	.90	447800		
01449360	80.0	.84	449800	450500	
01449800	95.1	.71	449360	450500	451000
01450500	106	.98	Observer; read daily. [2]		
01451000	97.4	.96	449800	450500	447800
01451500	79.2	.87	451800	452500	
01451800	124	.88	470756		
01452000	144	.87	451500	451800	
01452500	74.0	.98	Observer; read daily. [2]		
01453000	90.5	.95	454700		
01454700	74.0	.95	453000		
01459500	214	.84	473000		
01465500	170	.99	Supplemental recorder at site. [2]		
01465798	166	.98	Observer; read daily. [2]		
01467048	127	.98	Observer; read daily. [2]		
01467086	117	.84	473000		
01467087 [1]	130	.90	467086		
01468500	83.1	.99	Supplemental recorder at site. [2]		
01469500	125	.99	Supplemental recorder at site. [2]		
01470500	112	.99	Supplemental recorder at site. [2]		
01470756	101	.88	451800		
01470779	65.6	.99	Supplemental recorder at site.		
01470853 [1]	100	.90			
01470960	101	.95	471000		
01471000	101	.98	Observer; read daily. [2]		
01471510	82.6	.78	471000	470500	
01471980	84.8	.79	470756		
01472000	101	.89	471000	471510	471980
01472157	101	.98	Observer; read daily. [2]		

See footnotes at end of table.

Table 15.--Statistics of record reconstruction--(continued)

Station no.	C_v(%)	ρc	Source of reconstructed records
			Delaware River Basin
01472174	106	0.98	Observer; read daily. [2/]
01472198 [1/]	100	.80	472199
01472199 [1/]	100	.70	472198
01473000	169	.82	473120
01473120	164	.82	473000
01473169 [1/]	100	.90	
01474000	121	.91	467048
01474500	125	.95	472000
01475300	90.9	.84	475510
01475510	102	.98	Observer; read daily. [2/]
01475550	160	.82	475510
01475850 [1/]	130	.80	475300
01477000	121	.82	481000
01480300	129	.98	Observer; read daily. [2/]
01480500	98.0	.98	480617
01480617	94.2	.95	480500
01480675	111	.86	480700
01480685	94.9	.73	480700
01480700	101	.98	Observer; read daily. [2/]
01480870	87.1	.87	480700
01481000	95.9	.92	480685
			Susquehanna River Basin
01516350	103	.92	518000
01516500	175	.98	Observer; read daily. [2/]
01518000	157	.98	Observer; read daily. [2/]
01518700	109	.92	516350
01520000	171	.92	520500
01531500	115	.97	Satellite telemetry at site.
01532000	162	.86	552000
01533400	93.9	.99	Supplemental recorder at site. [2/]
01534000	142	.98	Supplemental recorder at site.
01534300	118	.99	Supplemental recorder at site.
01534500	107	.92	536000
01536000	113	.98	Observer; read daily. [2/]
01536500	110	.99	Satellite telemetry and supplemental recorder at site.
01537000	131	.80	537500 538000
01537500	130	.98	Observer; read daily. [2/]
01538000	122	.87	537000 537500
01539000	125	.98	Observer; read daily. [2/]
01540500	107	.99	Satellite telemetry at site.
01541000	127	.99	Supplemental recorder at site.
01541200	118	.99	Satellite telemetry and supplemental recorder at site.

See footnotes at end of table.

Table 15.--Statistics of record reconstruction--(continued)

Station no.	C_V(%)	ρc	Source of reconstructed records
			Susquehanna River Basin
01541303	77.7	0.99	Satellite telemetry and supplemental telemetry at site.
01541500	121	.98	Observer; read daily. 2/
01542000	107	.99	Supplemental recorder at site. 2/
01542500	108	.99	Satellite telemetry at site.
01542810	150	.98	Observer; read daily. 2/
01543000	146	.90	543500
01543500	134	.99	Satellite telemetry at site.
01544000	136	.98	Observer; read daily. 2/
01544500	136	.98	Observer; read daily. 2/
01545000	139	.99	Supplemental recorder at site.
01545500	112	.99	Satellite telemetry at site.
01545600	115	.99	Supplemental recorder at site.
01546500	68.0	.94	547100
01547100	52.4	.98	Observer; read daily. 2/
01547200	96.5	.98	Observer; read daily. 2/
01547500	91.6	.99	Supplemental recorder at site.
01547700	149	.89	547500
01547950	97.5	.88	547700
01548000	106	.97	547700
01548500	133	.98	Observer; read daily. 2/
01549500	153	.99	Supplemental recorder at site.
01549700	134	.96	548500
01550000	133	.90	549500
01551500	110	.99	Satellite telemetry at site.
01552000	134	.92	550000 553700
01552500	143	.87	552000
01553500	108	.99	Satellite telemetry at site.
01553700	69.5	.98	Observer; read daily. 2/
01554000	103	.99	Satellite telemetry at site.
01554500	67.0	.74	555500
01555000	122	.98	Observer; read daily. 2/
01555500	147	.87	553500
01556000	150	.98	Observer; read daily. 2/
01557500	133	.93	558000
01558000	101	.99	Satellite telemetry at site.
01559000	99.3	.99	Satellite telemetry at site.
01560000	150	.98	Observer; read daily 2/
01562000	136	.99	Satellite telemetry and telemetry at site.
01563200	115	.99	Satellite telemetry and supplemental recorder at site.
01563500	112	.99	Satellite telemetry and supplemental recorder at site.

See footnotes at end of table.

Table 15.--Statistics of record reconstruction--(continued)

Station no.	C_v(%)	ρc	Source of reconstructed records
			Susquehanna River Basin
01564500	171	0.83	562000
01567000	117	.99	Satellite telemetry and supplemental recorder at site.
01567500	140	.88	568000
01568000	153	.98	Observer; read daily. 2/
01568500	156	.90	Upstream municipal reservoir.
01569800	40.0	.63	567500 568000 570000
01570000	117	.88	569800 571500
01570500	102	.99	Satellite telemetry and supplemental recorder at site.
01571500	80.9	.99	Observer; read daily. 2/
01573000	144	.87	555500
01573160	61.7	.69	576500
01573560	102	.83	573000
01574000	173	.98	Observer; read daily. 2/
01574500	117	.98	Observer; read daily. 2/
01575000	154	.96	575500
01575500	137	.98	Telemetry; read daily.
01576000	100	.98	Observer; read daily. 2/
01576500	118	.98	Observer; read daily. 2/
			Potomac River Basin
01613050	144	.79	560000
			Ohio River Basin
03007800	95.0	.97	Telemetry; read daily.
03009680	88.0	.88	007800
03010500	123	.99	Telemetry; read daily.
03010655	96.0	.97	Observer; read daily. 2/
03011800	101	.99	Telemetry; read daily.
03012550	77.1	.99	Supplemental recorder at site.
03015000	107	.99	Telemetry; read daily.
03015500	125	.97	Observer; read daily. 2/
03016000	95.0	.97	Telemetry; read daily.
03020000	121	.73	016000 025500
03020500	131	.97	Telemetry; read daily.
03021350	107	.89	021410
03021410	112	.97	Telemetry; read daily.
03021520	98.6	.97	Telemetry; read daily.

See footnotes at end of table.

Table 15.--Statistics of record reconstruction--(continued)

Station no.	C_V(%)	ρc	Source of reconstructed records
			Ohio River Basin
03022540	104	0.98	Telemetry; read daily.
03022554	99.1	.98	Telemetry; read daily.
03024000	112	.99	Supplemental recorder at site.
03025500	93.2	.98	031500
03026500	140	.98	Telemetry; read daily.
03027500	91.1	.99	Supplemental recorder at site.
03028000	119	.98	Telemetry; read daily.
03028500	84.4	.98	Telemetry; read daily.
03029500	101	.98	Telemetry; read daily.
03030500	105	.92	029500
03031500	89.8	.99	036500
03032500	120	.92	034000 036000
03034000	127	.97	Observer; read daily. 2/
03034500	149	.92	038000
03036000	124	.99	Supplemental recorder at site.
03036500	89.1	.98	Telemetry; read daily.
03038000	148	.98	Telemetry; read daily.
03039000	140	.99	Supplemental recorder at site.
03040000	140	.97	041500
03041000	129	.93	041500
03041500	104	.98	Telemetry; read daily.
03042000	122	.99	Supplemental recorder at site.
03042280	104	.99	Supplemental recorder at site.
03042500	120	.98	Telemetry; read daily.
03044000	103	.99	Supplemental recorder at site.
03045000	144	.97	Observer; read daily. 2/
03047000	127	.98	Observer; read daily. 2/
03048500	103	.98	Observer; read daily. 2/
03049000	145	.91	106000
03049500	86.5	.99	Supplemental recorder at site. 2/
03049800	140	.74	084000
03072000	184	.98	Observer; read daily.
03072500	112	.98	Observer; read daily. 2/
03073000	192	.98	Observer; read daily.
03074500	113	.98	Observer; read daily. 2/
03075070	91.2	.86	085000
03077500	79.6	.99	Supplemental recorder at site.
03079000	130	.92	080000
03080000	132	.92	082500
03081000	79.9	.99	Supplemental recorder at site.
03082500	84.4	.99	Supplemental recorder at site.
03083500	88.5	.98	Telemetry; read daily.

See footnotes at end of table.

Table 15.--Statistics of record reconstruction--(continued)

Station no.	C_V(%)	ρc	Source of reconstructed records
			Ohio River Basin
03084000	154	0.98	Observer; read daily. 2/
03085000	98.2	.95	072500
03085500	111	.98	Observer; read daily.
03086000	81.3	.99	Corps of Engineers.
03101500	86.8	.98	Observer; read daily.
03102500	152	.76	102850
03102850	88.0	.99	Supplemental recorder at site.
03103500	94.3	.99	Supplemental recorder at site.
03105500	86.9	.99	Supplemental recorder at site.
03106000	144	.99	Supplemental recorder at site.
03106300	131	.99	Supplemental recorder at site.
03106500	126	.90	107500
03107500	87.3	.99	Supplemental recorder at site.
03108000	130	.98	Observer; read daily. 2/
			St. Lawrence River Basin
04213040	161	.98	Observer; read daily. 2/

1/ Less than 3 years of data are available. Estimates of C_v and P_c are subjective.

2/ Noted sources of supplemental stage record is proposed to be added to data-collection operations. P_c was estimated on basis of history of record loss and type of proposed supplemental record for the station.

Table 16.--Summary of autocovariance analysis of streamflow measurements made by the Malvern subdistrict office

Station no.	Number of measurements used	Rho*	Process variance (log base e)[2]	Length of period (days)
01429000	53	0.985	0.0036	355
01429500	54	.966	.0313	329
01431500	56	.973	.0052	326
01432000	8	.990	.0040	365
01439500	54	.982	.0088	322
01440400	59	.989	.0041	333
01442500	53	.988	.0188	335
01447500	63	.965	.0065	330
01447680	56	.926	.0079	325
01447720	63	.972	.0030	334
01447800	57	.931	.0016	351
01448500	57	.987	.0186	343
01449000	21	.923	.0037	335
01449360	58	.972	.0031	350
01449800	59	.969	.0019	365
01450500	59	.989	.0596	355
01451000	58	.772	.0094	335
01451500	58	.976	.0028	362
01451800	55	.993	.0609	349
01452000	56	.961	.0130	355
01452500	53	.994	.0171	363
01453000	53	.992	.0101	359
01454700	63	.988	.0066	360
01459500	61	.963	.0092	346
01465500	62	.985	.0207	348
01465798	62	.981	.0449	335
01467048	55	.993	.0513	343
01467086	60	.954	.0161	358
01467087	12	.960	.0308	355
01468500	54	.993	.0273	344
01469500	54	.981	.0490	349
01470500	59	.974	.0018	351
01470756	61	.953	.0190	339
01470779	59	.985	.0061	341
01470853	--	.950[1/]	.0150[1/]	362
01470960	61	.988	.0631	349
01471000	57	.795	.0017	359
01471510	25	.864	.0010	351
01471980	52	.991	.0261	333
01472000	62	.947	.0058	356
01472157	60	.968	.0057	344

See footnotes at end of table.

Table 16.--Summary of the autocovariance analysis of streamflow measurements made by the Malvern subdistrict office--(continued)

Station no.	Number of measurements used	Rho*	Process variance (log base e)^2	Length of period (days)
01472174	32	0.987	0.2234	341
01472198	18	.975	.0221	345
01472199	18	.960	.0232	345
01473000	52	.921	.0013	352
01473120	48	.985	.0508	342
01473169	--	.950 1/	.0010 1/	361
01474000	50	.982	.0058	358
01474500	50	.989	.0116	363
01475300	60	.983	.0226	357
01475510	57	.981	.0030	355
01475550	51	.994	.0188	356
01475850	20	.989	.0297	355
01477000	19	.981	.0198	348
01480300	61	.979	.0096	355
01480500	57	.947	.0042	360
01480617	22	.975	.0283	357
01480675	53	.956	.0224	356
01480685	60	.970	.0139	363
01480700	40	.916	.0036	360
01480870	61	.984	.0110	356
01481000	55	.984	.0096	358

*One-day autocorrelation coefficient, denoted as ρ in the discussion of the application of Kalman-filter techniques.

1/ Estimated.

Table 17.--Summary of autocovariance analysis of streamflow measurements made by the Harrisburg subdistrict office

Station no.	Number of measurements used	Rho*	Process variance (log base e)^2	Length of period (days)
01516350	59	0.999	0.8592	295
01516500	55	.994	.9741	293
01518000	53	.989	.0611	314
01518700	46	.980	.0029	307
01520000	52	.977	.0505	308
01531500	51	.985	.0027	327
01532000	53	.986	.3025	310
01533400	46	.847	.0104	325
01534000	55	.959	.0180	320
01534300	55	.941	.0195	359
01534500	55	.976	.0055	364
01536000	50	.975	.0058	348
01536500	53	.967	.0061	336
01537000	55	.980	.0072	334
01537500	60	.967	.0061	332
01538000	49	.971	.0097	320
01539000	54	.981	.0144	340
01540500	50	.943	.0001	336
01541000	49	.776	.0026	307
01541200	53	.995	.2515	354
01541303	31	.877	.0012	319
01541500	53	.973	.0022	304
01542000	53	.986	.0235	321
01542500	60	.977	.0028	343
01542810	56	.958	.0369	317
01543000	54	.957	.0369	311
01543500	60	.985	.0196	316
01544000	58	.983	.0094	354
01544500	52	.992	.2435	314
01545000	50	.938	.0012	326
01545500	58	.983	.0012	333
01545600	52	.989	.0150	315
01546500	54	.961	.0064	363
01547100	54	.986	.0010	363
01547200	50	.988	.0038	363
01547500	51	.892	.0024	365
01547700	50	.983	.1313	327
01547950	54	.984	.0698	318
01548000	49	.995	.0087	360
01548500	52	.991	.0893	302

See footnotes at end of table.

Table 17.--Summary of autocovariance analysis of streamflow measurements made by the Harrisburg subdistrict office--(continued)

Station no.	Number of measurements used	Rho*	Process variance (log base e)^2	Length of period (days)
01549500	58	0.993	0.0724	298
01549700	57	.992	.0164	300
01550000	58	.991	.4210	313
01551500	52	.967	.0010	320
01552000	53	.998	.0607	302
01552500	50	.992	.0979	307
01553500	55	.951	.0017	332
01553700	35	.978	.0069	332
01554000	61	.982	.0022	348
01554500	55	.963	.0021	365
01555000	52	.977	.0046	332
01555500	55	.973	.0161	331
01556000	49	.963	.0011	363
01557500	59	.997	.1737	326
01558000	59	.968	.0036	363
01559000	55	.976	.0020	344
01560000	60	.992	.0609	340
01562000	54	.962	.0023	323
01563200	54	.987	.0015	365
01563500	53	.987	.0009	346
01564500	57	.984	.0130	333
01567000	53	.982	.0066	331
01567500	53	.994	.1373	356
01568000	52	.975	.0099	346
01568500	52	.969	.0067	363
01569800	59	.790	.0033	362
01570000	51	.981	.0030	342
01570500	41	.652	.0094	330
01571500	55	.991	.0069	356
01573000	51	.977	.0058	336
01573160	25	.982	.1605	365
01573560	53	.934	.0047	325
01574000	58	.985	.0436	349
01574500	53	.965	.0026	362
01575000	58	.957	.0105	351
01575500	62	.987	.0108	358
01576000	36	.927	.0017	348
01576500	56	.967	.0027	350
01613050	61	.973	.0873	331

*One-day autocorrelation coefficient, denoted as ρ in the discussion of the application of Kalman-filter techniques.

Table 18.--Summary of autocovariance analysis of streamflow measurements made by the Pittsburgh subdistrict office

Station no.	Number of measurements used	Rho*	Process variance (log base e)^2	Length of period (days)
03007800	51	0.893	0.0047	310
03009680	59	.936	.0032	306
03010500	59	.959	.0109	317
03010655	56	.866	.0127	318
03011800	29	.973	.0121	308
03012550	60	.947	.0089	365
03015000	53	.822	.0084	343
03015500	51	.986	.1012	327
03016000	52	.982	.0022	340
03020000	57	.932	.0142	365
03020500	57	.984	.0034	329
03021350	58	.976	.0547	320
03021410	49	.992	.0762	302
03021520	33	.992	.0138	333
03022540	49	.989	.0485	310
03022554	56	.983	.0143	354
03024000	54	.944	.0019	347
03025500	55	.960	.0002	357
03026500	49	.982	.0190	326
03027500	58	.899	.0071	365
03028000	56	.988	.0162	319
03028500	54	.971	.0053	343
03029500	51	.926	.0013	329
03030500	62	.975	.1317	365
03031500	56	.973	.0012	332
03032500	59	.988	.0736	336
03034000	56	.981	.0077	337
03034500	63	.992	.1433	321
03036000	67	.924	.0031	347
03036500	55	.902	.0001	365
03038000	62	.982	.0046	361

See footnotes at end of table.

Table 18.--Summary of autocovariance analysis of streamflow measurements made by the Pittsburgh subdistrict office--(continued)

Station no.	Number of measurements used	Rho*	Process variance (log base e)^2	Length of period (days)
03039000	60	.962	.0041	363
03040000	64	.990	.0201	336
03041000	62	.990	.3264	333
03041500	67	.945	.0106	342
03042000	54	.977	.2294	324
03042280	58	.985	.2833	341
03042500	65	.975	.0037	342
03044000	54	.980	.0010	349
03045000	58	.956	.0055	327
03047000	59	.934	.0031	354
03048500	60	.990	.0016	346
03049000	54	.997	.0546	319
03049500	56	.958	.0032	365
03049800	61	.972	.2659	323
03072000	63	.953	.0140	337
03072500	52	.979	.1077	365
03073000	56	.974	.0357	334
03074500	64	.987	.0152	348
03075070	50	.916	.0108	365
03077500	50	.969	.0106	365
03079000	55	.975	.0032	333
03080000	55	.986	.0184	324
03081000	53	.935	.3818	365
03082500	57	.968	.0019	341
03083500	56	.946	.0013	339
03084000	58	.993	.3902	318
03085000	58	.934	.0044	365
03085500	55	.987	.0097	341
03086000	53	.987	.0033	365
03101500	61	.948	.0080	365
03102500	53	.938	.0094	322
03102850	60	.983	.0162	333
03103500	59	.952	.0015	365
03105500	56	.955	.0015	364
03106000	60	.962	.0124	321
03106300	81	.991	1.3508 1/	365
03106500	58	.979	.0453	327
03106500	66	.950	.0095	365
03108000	57	.979	.0054	329
04213040	42	.976	.0740	320

*One-day autocorrelation coefficient, denoted as ρ in the discussion of the application of Kalman-filter techniques.

1/ High variance is caused by beaver dams.

C_v, ρ_c, and the sources auxiliary records that can be used to reconstruct missing record are given in table 15 for each station. Values for ρ_c for 54 stations were revised (table 15, footnote 2) to reflect the reduction in missing record that could be attained by adding the proposed (table 14) sources of supplmental stage record to the stream-gaging program. The values of C_v and ρc in table 15 were used, jointly with autocovariance parameters (summarized in tables 16-18), to compute uncertainty functions for a cost-optimized reduction of missing record. These uncertainty functions were used in the K-CERA analysis to define standard error-budget relationships for gaging operations that will result in "reduced missing record."

Kalman-Filter Definition of Variance

The determination of the variance V_f for each of 212 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 for the Kalman-filter analysis of streamflow records, and (3) computation of the process error variance, V_f, as a function of the time-series parameters, the discharge-measurement-error variance, and the frequency of discharge measurement.

Long-term rating analysis was based upon discharge measurements that were not materially affected by backwater due to ice. Thus, the K-CERA procedures were applied for 'open-water' conditions on the gaged streams. A review of rating analyses for years 1973-82 showed the annual open-water period to average 339 days, and range from 293 to 365 days, for the stations considered in this analysis. Fewer than 10 ice-affected discharge measurements were made at most of the stations during the period 1975-82. Therefore, too little correlative data were available to define currently-valid "winter" discharge ratings.

Open-water rating functions for most of the stations were satisfactorily defined by equations of the form:

$$LQM = B1 + B3 * LOG(GHT - B2), \qquad (19)$$

in which:

LQM is the logarithmic (base e) value of the measured discharge,
GHT is the recorded gage height corresponding to the measured discharge,
B1 is the logarithm of discharge for a flow depth of 1 foot,
B2 is the gage height of zero flow, and
B3 is the slope of the rating curve.

Two-segment rating functions for several stations were defined by computing two equations, of the form of equation 19, which would solve for a common LQM when GHT was that of the 'break-point' in a nonlinear stage-discharge relationship. Discharge measurements for several stations did not conform to a convenient mathematical function; residuals for these measurements were made from least-squares-fitted stage-discharge relationships for the respective stations.

The open-water measurements used to define the rating function and for computation of the time series of measurement residuals were primarily those made in the period 1975-82. However, some measurements made prior to 1975 and in 1983 were used for those stations with fewer than 50 open-water measurements in the 1975-82 period. The numbers of measurements used for the analysis are tabulated in tables 16, 17, and 18 for the three subdistrict offices.

The time series of residuals is used to compute sample estimates of q and β, two of the three parameters required to compute V_f, by determining a best fit autocovariance function to the time series of residuals. Measurement variance, the third parameter, is determined from an assumed constant-percentage standard error. For the Pennsylvania program, all open-water measurements were assumed to have a measurement error of 3 percent. This error was based on measurement variablities for several stations that have very stable hydraulic controls.

As discussed earlier, q and β can be expressed as the process variance of the residuals from the rating curve and the 1-day autocorrelation coefficient of these residuals. Tables 16-18 present summaries of the autocovariance analysis, expressed in terms of process variance and 1-day autocorrelation, for each subdistrict. Measurement variance r, in squared natural base log units, is 0.0009 for the measurements made at each station.

An "original" set of uncertainty functions was defined through use of original ρc values obtained by correlation of daily-flow data for each station, as priviously discussed. Because the computations of missing stage record ignored primary record losses that were reconstructed from secondary sources without loss in the accuracies of computed discharges, and because most of the discharge records for the compiled periods of lost record were based on hydrographic comparisons, the "original" set of uncertainty functions more correctly defines the uncertainties associated with current (1983) losses of primary stage record. This "original" set of uncertainty functions are used to determine standard errors for the current (1983) operations and to define standard error-budget relationships for cost-optimized operations with "current missing record." A third set of uncertainty functions was prepared using ρc = 1.00 for all stations, for the hypothetical condition of no losses in primary stage records. The three sets of uncertainty functions were computed for current (1981-82) measurement frequencies in the average annual open-water periods shown, in days, in tables 16 - 18.

Feasible and practical routes to service the 212 stream gages were determined for the three subdistrict operations through review of current (1983) routes, consideration of minimum visitation requirements for the various types of data collections, and a comparison of uncertainty functions for proximate stations. Most of the divised route constructions consisted of proximate stations that exhibit similar uncertainties for approximately the same numbers of measurements. Many stations were included in more than one route. More than 50 possible routes were constructed, and tested for cost-effectiveness, for both the Malvern and Harrisburg subdistricts. About 30 routes were tested for gaging operations in the Pittsburgh subdistrict. Routes shown, by application of the 'traveling-hydrographer' program, as not cost effective at budgets as great as 110 percent of the respective subdistrict operating budgets for 1983 were deleted from the respective group of feasible routes. The stations to be visited on the identified practical routes are listed in tables 19, 20, and 21 for the Malvern, Harrisburg, and Pittsburgh subdistricts, respectively. Routes flagged with an asterisk will permit attainment of the lowest practical average standard error for the minimum budgets (see footnotes to tables 19-21) when the proposed sources of supplemental stage record (table 14) become part of stream-gaging operations. Other route combinations could provide less error at higher cost. Partial-record stations, including crest-stage, annual-peak, and pool types, are not identified in tables 19-21. Individual routes for the Harrisburg subdistrict are to be used by the office--Harrisburg or Williamsport--that can travel the route with the least mileage.

Operational costs for each station were partitioned into fixed, visit, travel, and overhead costs. All cost estimates were based on actual costs incurred for various operations in 1983, and were annualized by combining visit and travel costs for winter operations with normal fixed costs.

Normal fixed costs to operate a station typically include those for equipment rental, batteries, processing and storage of data, computer charges, maintenance, observer's pay, miscellaneous supplies, analysis of data, publication of data, and supervisory costs. Costs for auxiliary equipment that is often used for reconstruction of lost record, but which is not necessary for normal stream-gaging operations, were excluded from fixed costs. Such equipment includes that associated with experimental satellite telemetry and quality-of-water activities.

Visit costs are those associated with paying the hydrographer for the time actually spent at a station servicing the equipment and making a discharge measurement. These costs vary from station to station and are largely a function of the time required to make the discharge measurement. Average visit times were calculated for each station through review of the time hydrographers have spent making various measurements and servicing the equipment. This time was then multiplied by the average hourly salary and benefits of hydrographers, for the respective subdistrict, to determine typical visit costs.

Travel costs include the vehicle cost associated with driving the number of miles it takes to cover the route, the cost of the hydrographer's time while in transit, and any per diem associated with the time it takes to complete the trip. Initially, travel costs were computed for the routes used to service the gages in 1983. These costs were subsequently recomputed to determine the travel costs for the individual routes shown in tables 19-21.

Overhead costs for all stations were at the average rate for the District in 1983 -- 42 percent of the total budget for stream-gaging operations.

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

Table 19.--Summary of routes that may be used to visit stations serviced by the Malvern subdistrict

Route number	Stations serviced on the route							
1*	468500	469500	470500	470756	470779	470853	470960	471000	471510
2*	474000	474500	475300	475510	475550	475850	477000		
3*	432000	439500	440400	447680	447720	447800	448500		
4*	451000	451500	452500	453000	454700	459500	465500		
5*	473169	480500	480700	480870	481000				
6*	472157	472174	472198	472199	473120				
7*	429000	429500	431500	442500	447500				
8*	480300	480617	480675	480685					
9*	449000	449360	449800						
10*	450500	451800	452000						
11*	472198	472199	473120						
12	470756	470853	470960						
13*	475550	475850	477000						
14*	471980	472000	473000						
15*	448500	450500	451800						
16	472000	473000							
17	467086	467087							
18*	465798	467048							
19*	474000	474500							
20*	452000								
21	469500								
22	459500								
23	465500								
24*	465798								
25*	472174								
26	472157								
27*	467087								
28	429500								
29*	467048								
30*	467086								

*Routes to use for minimum practicable budget of $345,000.

Table 20.--Summary of routes that may be used to visit stations serviced by the Harrisburg subdistrict

Route number	Stations serviced on the route							
1*	546500	547100	547200	547500	547950	548000	549500	549700
2*	540500	553500	554000	559000	563200	563500	567000	
3*	541000	542500	543500	545000	545500	545600		
4*	516350	518700	531500	551500	552000			
5*	534000	534300	536000	538000	539000			
6*	541200	541303	541500	542000	547700			
7*	555000	555500	560000	562000	564500			
8*	571500	574500	575000	575500				
9*	542810	543000	544000	544500				
10*	534500	536500	554500					
11*	556000	557500	558000					
12*	571500	575000	575500					
13	574000	574500	613050					
14*	573000	573160	576500					
15*	567500	568000	568500					
16*	548500	552500	553700					
17*	541200	542000	542810					
18*	533400	537500	537000					
19*	573560	576000						
20	574000	613050						
21	574500	613050						
22	516350	520000						
23*	569800	570000						
24*	550000	552500						
25	560000	613050						
26*	518000	532000						
27*	547700							
28*	574000							
29*	516500							
30*	613050							
31*	550000							
32*	532000							
33*	570500							
34*	520000							
35*	1/							

*Routes to use for minimum practicable budget of $410,000.

1/Route consists of four partial-record stations.

Table 21.-Summary of routes that may be used to visit stations serviced by the Pittsburgh subdistrict

Route number	Stations serviced on the route								
1*	007800	009680	010500	011800	027500	028000	028500	036000	036500
2*	021520	022540	022554	101500	102850	103500	105500	106000	
3*	012550	015000	016000	020500	024000	025500	029500	031500	
4*	075070	077500	079000	080000	082500	083500	085500		
5*	041000	042000	042280	045000	047000	084000			
6*	010655	020000	026500	032500	034000	034500			
7*	038000	041500	044000	048500	049000				
8*	072000	072500	073000	074500	108000				
9*	049500	085000	086000	107500					
10	007800	027500	101500	106000					
11*	041000	042000	042280	084000					
12*	021350	102500	106500						
13*	015500	021410	030500						
14	020000	032500	034500						
15*	032500	034000	034500						
16*	039000	040000	042500						
17	075070	077500	085500						
18	022540	022554							
19	021410	030500							
20*	072500	073000							
21*	010655	034000							
22*	106300	213040							
23*	049800								
24*	081000								
25	072500								

*Routes to use for suggested minimum practicable budget of $335,000.

total uncertainty associated with it. To accomplish this the number of visits being made to each stream gage and the routes that are being used to make these visits were specified according to actual operations in 1983. The probability for making a discharge measurement on each visit was fixed equal to the fraction of visits on which measurements were made at the individual gages in water years 1981-82. The uncertainty functions were weighted by the average percentage of the years represented by open-water conditions. These percentages were computed by dividing the lengths of open-water periods, in days, (See tables 16-18.) by 365.

Figures 8-10 summarize the cost-effectiveness analyses for the three subdistricts. The resulting average errors of estimation (uncertainties), in percent, of instantaneous discharge, for current (1983) operations are:

Malvern subdistrict,	14.3 percent;
Harrisburg subdistrict,	14.2 percent; and
Pittsburgh subdistrict,	17.1 percent.

These values are plotted as points on figures 8-10 for the respective subdistricts' operating costs (table 2).

The upper curves on figures 8-10 define the 'open-water' relationships between minimum average uncertainty and operating costs, for the three subdistricts, for the devised routes (tables 19-21) and existing equipment. Minimum-visit constraints, as described below, and approximately optimized measurement probabilities were included in the analysis from which these curves, denoted as "current missing record" in figures 8-10, were derived.

To determine the minimum number of times each station must be visited, consideration was given only to the physical limitations of the method used to record data. The effect of visitation frequency on the accuracy of the data and amount of lost record is taken into account in the uncertainty analysis. A minimum requirement of five visits per annual open-water period was applied to all stations. This value was based on limitations of batteries used to power recording equipment and the record-storage capacities of uptake spools on digital equipment that record gage height every 15 minutes. Minimum visit requirements should also reflect the need to visit stations for special reasons such as water-quality sampling. Virtually all water-quality work is being done on separate trips not integrated with the surface-water field work and, therefore, did not influence minimum visit requirements.

Each subdistrict can attain a more efficient operation than that indicated by the respective "current missing record" curves in figures 8-10. These improved efficiencies can be attained by the use of gage observers and supplemental recorders at some stations (See table 15.), as discussed previously. Adoption of these proposed sources of supplemental stage record would reduce the amount of missing record, as well as the errors in estimated discharges, for these stations. The relationships between average standard error and operational budgets for this cost effective reduction in missing record are shown by the middle curves in figures 8-10.

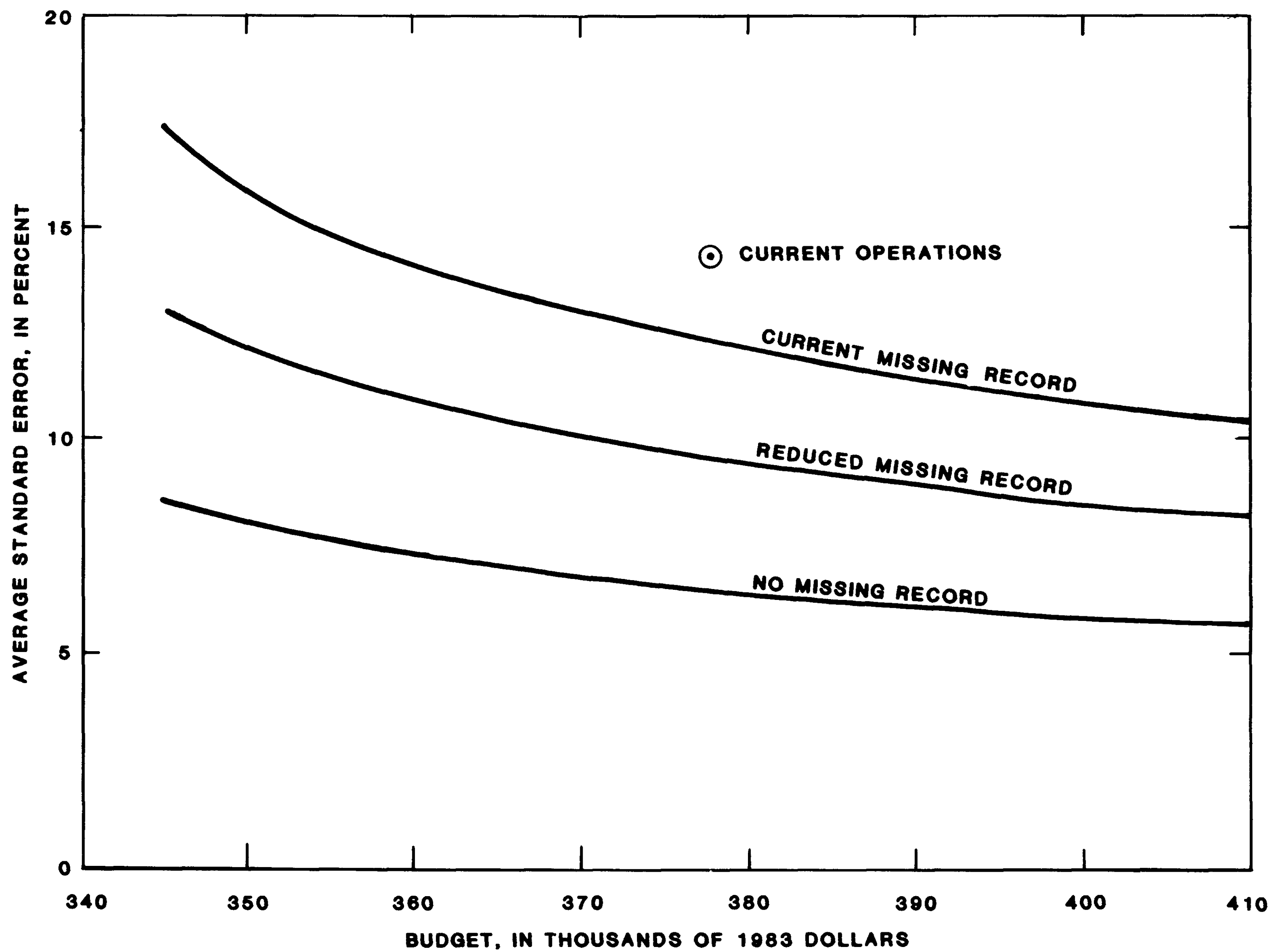


Figure 8.--Temporal average standard error of 62 gaged flows as a function of operating budget for the Malvern subdistrict office.

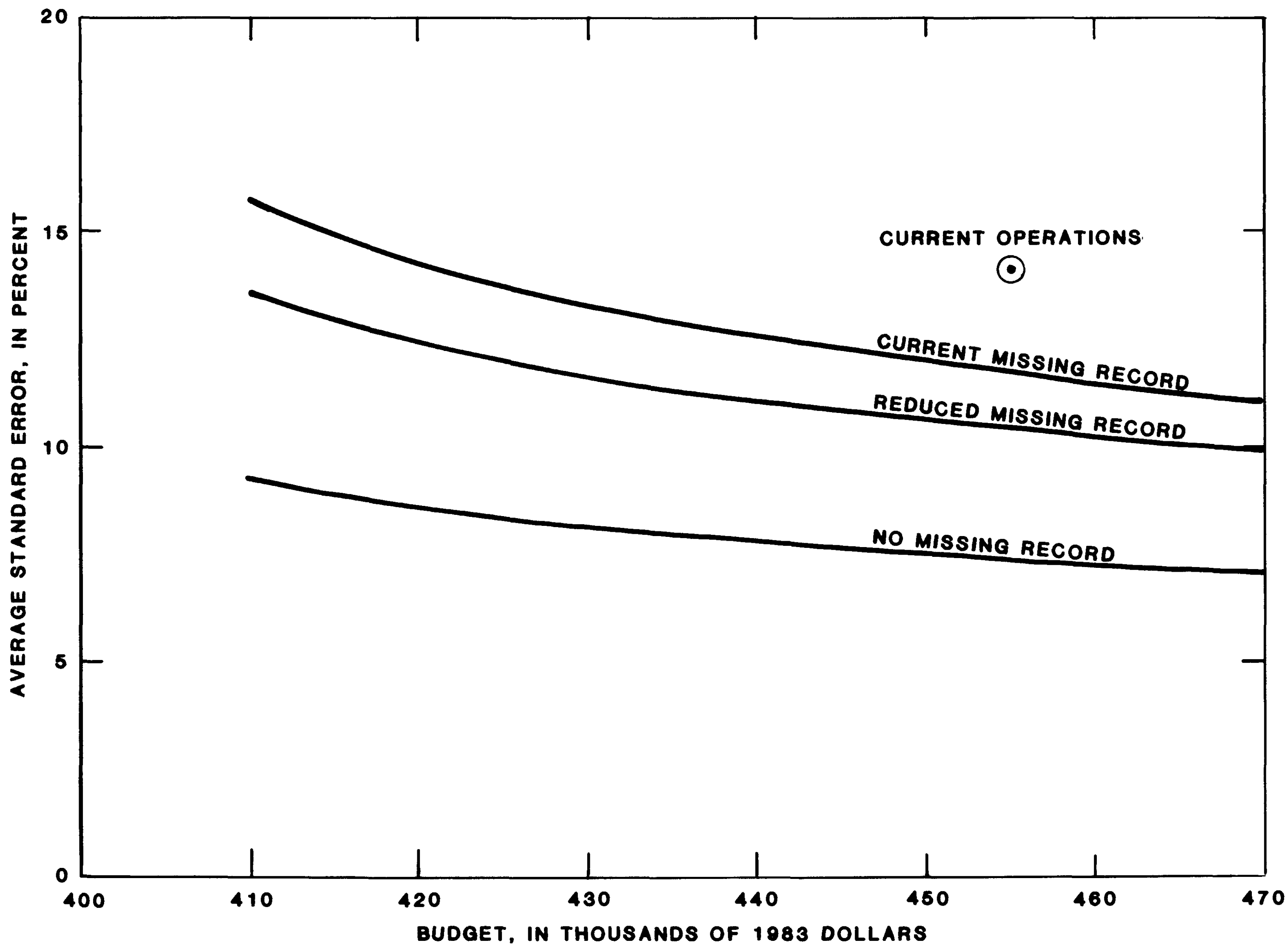


Figure 9.--Temporal average standard error of 79 gaged flows as a function of operating budget for the Harrisburg subdistrict office.

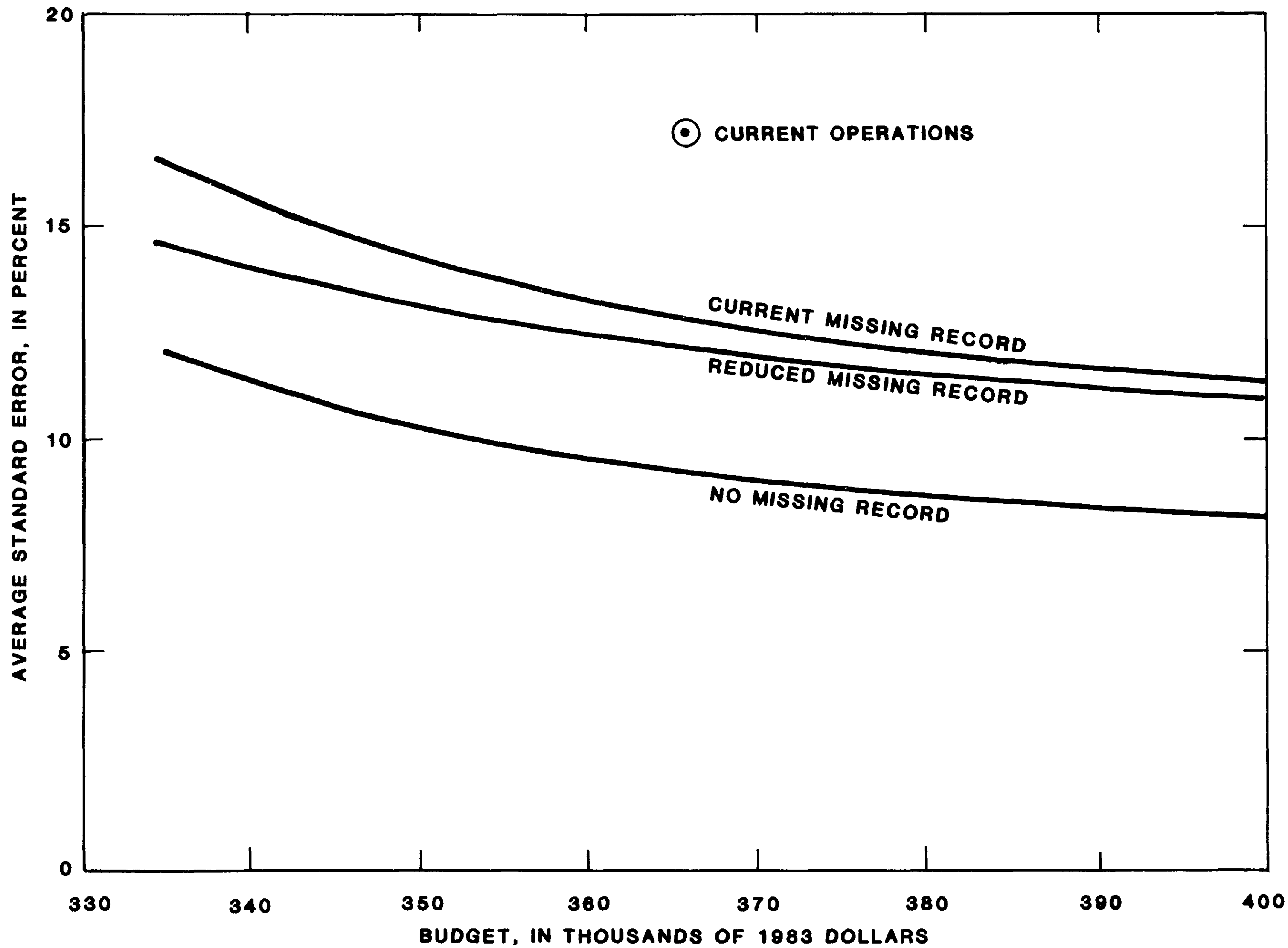


Figure 10. --Temporal average standard error of 71 gaged flows as a function of operating budget for the Pittsburgh subdistrict office.

Tables 22, 23, and 24 summarize; for the Malvern, Harrisburg and Pittsburgh subdistricts' operations, respectively; standard errors, equivalent Gaussian spread, and the number of 'open-water' visits, for both current (1983) operations and operations for reduced missing record at selected budgets. The smallest budgets in these tables, which are for $345,000, $410,000 and $335,000 for the Malvern, Harrisburg, and Pittsburgh operations, respectively, would be sufficient for each subdistrict to adequately service its gages and also reduce the average standard error from its current level. The indicated route (tables 19-21) and visitation strategies (tables 22-24) for these minimum budgets substantially reduce the standard errors for most high-error stations and increase such errors slightly for some low-error stations, as compared to corresponding errors for current operations. An overall operational savings of $109,000, or 9.1 percent of the 1983 streamgaging budget of the Pennsylvania District, could be achieved by operating the stations to reduce record losses and within the visit and measurement-probability constraints used in the K-CERA analysis at these minimum budgets. None of the three subdistricts could properly service and maintain its complement of stations if as little as $5,000 were cut from the minimum budgets indicated in figures 8-10 and tables 22-24.

Budgets greater than the practicable minimums discussed above would permit a reduction in standard errors, particularly for high-error stations. The number of visits was restricted for some high-error stations that exhibited little reduction in uncertainty with increased measurement frequency, as indicated by the footnotes in tables 23 and 24. A 6 percent increase in the current (1983) budgets could be used to reduce average standard errors by 33 to 40 percent below those of the subdistricts' current operations, which can be computed from the reduced missing record curves of figures 8-10.

It is emphasized that figures 8-10 and tables 22-24 are based on various assumptions (stated previously) concerning both the time series of residuals and the existing and proposed methods of record reconstruction. Where a choice of assumptions was available, the assumption that would not underestimate the magnitude of the error variances was chosen. Although the standard errors in these figures and tables were determined solely for open-water periods (table 16-18), the budgets include the costs for winter operations, which would entail one more discharge measurement annually for most stations.

The analysis also was performed with the uncertainty functions that were based on the assumption that no correlative data at any stream gage was lost. The curves labeled "no missing record" on figures 8-10 show 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 operational budgets the impacts of less than perfect equipment are greatest. The minimum errors indicated by these curves are not obtainable with current equipment. However, the errors are markedly lower than those for the two upper curves, which indicates that improved recording equipment could have a pronounced and beneficial impact on uncertainties in streamflow records.

Table 22.--Selected results of K-CERA analysis of stream-gaging operations in Delaware River basin

Station no.	Standard error of instantaneous discharge, in percent 1/ [Equivalent Gaussian spread] (Number of visits per year to site)2/					
	Current operation	Budget, in thousands of 1983 dollars				
	377,700	345,000	350,000	360,000	380,000	400,000
Average per station	14.3	12.9	12.0	10.8	9.4	8.5
01429000	19.2 [3.2] (9)	8.6 [4.0] (5)	8.6 [4.0] (5)	8.6 [4.0] (5)	7.3 [3.6] (7)	6.5 [3.2] (9)
01429500	15.7 [12.3] (9)	20.0 [14.6] (5)	17.2 [13.0] (7)	14.6 [11.3] (10)	12.4 [9.8] (14)	11.0 [8.7] (18)
01431500	13.1 [4.6] (9)	11.2 [5.5] (5)	11.2 [5.5] (5)	11.2 [5.5] (5)	9.3 [4.9] (7)	8.2 [4.4] (9)
01432000	5.6 [5.6] (9)	5.9 [5.9] (5)	5.9 [5.9] (5)	5.9 [5.9] (5)	5.9 [5.9] (5)	5.9 [5.9] (5)
01439500	8.7 [5.5] (9)	11.3 [6.2] (5)	11.3 [6.2] (5)	11.3 [6.2] (5)	11.3 [6.2] (5)	11.3 [6.2] (5)
01440400	4.2 [2.9] (9)	5.7 [3.8] (5)	5.7 [3.8] (5)	5.7 [3.8] (5)	5.7 [3.8] (5)	5.7 [3.8] (5)
01442500	12.0 [6.4] (9)	9.9 [7.6] (5)	9.9 [7.6] (5)	9.9 [7.6] (5)	8.3 [6.5] (7)	7.4 [5.8] (9)
01447500	13.1 [5.9] (9)	8.6 [6.4] (5)	8.6 [6.4] (5)	8.6 [6.4] (5)	7.6 [5.8] (7)	6.8 [5.4] (9)
01447680	9.6 [7.8] (9)	11.5 [8.6] (5)	11.5 [8.6] (5)	11.5 [8.6] (5)	11.5 [8.6] (5)	11.5 [8.6] (5)

See footnotes at end of table.

Table 22.--Selected results of K-CERA analysis of stream-gaging operations in Delaware River basin--(continued)

Station no.	Standard error of instantaneous discharge, in percent 1/ [Equivalent Gaussian spread] (Number of visits per year to site) 2/					
	Current operation	Budget, in thousands of 1983 dollars				
	377,700	345,000	350,000	360,000	380,000	400,000
01447720	6.4 [3.5] (9)	8.7 [4.5] (5)	8.7 [4.5] (5)	8.7 [4.5] (5)	8.7 [4.5] (5)	8.7 [4.5] (5)
01447800	3.4 [3.4] (9)	3.8 [3.8] (5)	3.8 [3.8] (5)	3.8 [3.8] (5)	3.8 [3.8] (5)	3.8 [3.8] (5)
01448500	11.3 [6.6] (9)	11.7 [6.4] (8)	11.0 [6.1] (9)	11.7 [6.4] (8)	9.9 [5.5] (11)	9.1 [5.1] (13)
01449000	6.6 [5.1] (9)	8.0 [5.6] (5)	8.0 [5.6] (5)	8.0 [5.6] (5)	8.0 [5.6] (5)	7.6 [5.5] (6)
01449360	7.6 [3.7] (9)	10.1 [4.4] (5)	10.1 [4.4] (5)	10.1 [4.4] (5)	10.1 [4.4] (5)	9.2 [4.1] (6)
01449800	6.6 [3.0] (9)	8.8 [3.7] (5)	8.8 [3.7] (5)	8.8 [3.7] (5)	8.8 [3.7] (5)	8.1 [3.5] (6)
01450500	15.0 [10.3] (9)	15.8 [13.4] (5)	15.8 [13.4] (5)	13.4 [11.4] (7)	10.7 [9.0] (11)	9.5 [8.0] (14)
01451000	9.3 [9.3] (9)	9.4 [9.4] (5)	9.4 [9.4] (5)	9.4 [9.4] (5)	9.4 [9.4] (5)	9.3 [9.3] (7)
01451500	6.3 [3.4] (9)	8.4 [4.3] (5)	8.4 [4.3] (5)	8.4 [4.3] (5)	8.4 [4.3] (5)	7.2 [3.9] (7)

See footnotes at end of table.

Table 22.--Selected results of K-CERA analysis of stream-gaging operations in Delaware River basin--(continued)

Station no.	Standard error of instantaneous discharge, in percent 1/ [Equivalent Gaussian spread] (Number of visits per year to site)2/					
	Current operation	Budget, in thousands of 1983 dollars				
	377,700	345,000	350,000	360,000	380,000	400,000
01451800	11.5 [8.5] (9)	15.0 [10.9] (5)	15.0 [10.9] (5)	12.6 [9.1] (7)	10.0 [7.2] (11)	8.9 [6.4] (14)
01452000	14.6 [8.5] (9)	17.4 [9.4] (6)	16.2 [8.9] (7)	14.4 [8.2] (9)	11.6 [6.9] (14)	10.6 [6.3] (17)
01452500	13.9 [4.6] (9)	8.8 [5.6] (5)	8.8 [5.6] (5)	8.8 [5.6] (5)	8.8 [5.6] (5)	7.4 [4.7] (7)
01453000	7.7 [4.0] (9)	11.0 [5.1] (5)	11.0 [5.1] (5)	11.0 [5.1] (5)	11.0 [5.1] (5)	8.9 [4.3] (7)
01454700	6.1 [4.6] (9)	8.3 [5.8] (5)	8.3 [5.8] (5)	8.3 [5.8] (5)	8.3 [5.8] (5)	7.0 [5.1] (7)
01459500	43.2 [8.1] (9)	16.5 [7.9] (5)	15.2 [7.5] (6)	13.3 [6.9] (8)	11.5 [6.1] (11)	10.2 [5.6] (14)
01465500	34.7 [8.4] (9)	15.2 [8.8] (5)	13.9 [8.2] (6)	11.4 [6.8] (9)	9.5 [5.7] (13)	8.9 [5.3] (15)
01465798	26.0 [12.1] (9)	17.2 [12.4] (7)	14.4 [10.4] (10)	12.7 [9.2] (13)	10.8 [7.8] (18)	9.3 [6.7] (24)
01467048	19.8 [8.2] (9)	14.8 [9.9] (5)	13.5 [9.0] (6)	11.6 [7.7] (8)	9.5 [6.3] (12)	8.5 [5.6] (15)

See footnotes at end of table.

Table 22.--Selected results of K-CERA analysis of stream-gaging operations in Delaware River basin--(continued)

Station no.	Standard error of instantaneous discharge, in percent 1/ [Equivalent Gaussian spread] (Number of visits per year to site) 2/					
	Current operation	Budget, in thousands of 1983 dollars				
	377,700	345,000	350,000	360,000	380,000	400,000
01467086	12.9 [9.7] (9)	16.5 [11.4] (5)	14.4 [10.5] (7)	12.9 [9.7] (9)	10.7 [8.2] (14)	9.8 [7.6] (17)
01467087	18.0 [14.4] (10)	20.0 [14.7] (6)	17.8 [13.9] (8)	14.3 [11.1] (13)	12.3 [9.6] (18)	10.9 [8.6] (23)
01468500	14.3 [6.4] (9)	8.5 [7.1] (5)	8.5 [7.1] (5)	8.5 [7.1] (5)	8.5 [7.1] (5)	7.7 [6.5] (6)
01469500	17.5 [13.3] (9)	16.5 [14.8] (5)	15.3 [13.8] (6)	13.5 [12.2] (8)	11.2 [10.1] (12)	10.0 [9.0] (15)
01470500	8.9 [3.1] (9)	6.2 [3.2] (5)	6.2 [3.2] (5)	6.2 [3.2] (5)	6.2 [3.2] (5)	5.7 [3.0] (6)
01470756	14.2 [11.2] (9)	17.3 [12.4] (5)	15.1 [11.3] (7)	13.6 [10.4] (9)	11.7 [9.1] (13)	10.6 [8.4] (16)
01470779	5.2 [3.8] (9)	7.4 [5.7] (5)	7.4 [5.7] (5)	7.4 [5.7] (5)	7.4 [5.7] (5)	6.9 [5.4] (6)
01470853	10.3 [9.4] (8)	12.1 [10.8] (5)	11.1 [10.0] (7)	10.3 [9.4] (9)	9.0 [8.3] (13)	8.3 [7.7] (16)
01470960	13.6 [10.9] (9)	18.8 [14.7] (5)	15.6 [12.5] (7)	13.6 [10.9] (9)	11.1 [9.0] (13)	10.0 [8.1] (16)

See footnotes at end of table.

Table 22.--Selected results of K-CERA analysis of stream-gaging operations in Delaware River basin--(continued)

Station no.	Standard error of instantaneous discharge, in percent 1/ [Equivalent Gaussian spread] (Number of visits per year to site)2/					
	Current operation	Budget, in thousands of 1983 dollars				
	377,700	345,000	350,000	360,000	380,000	400,000
01471000	11.0 [4.2] (9)	7.7 [4.2] (5)	7.7 [4.2] (5)	7.7 [4.2] (5)	7.7 [4.2] (5)	7.1 [4.1] (6)
01471510	8.6 [3.0] (9)	11.4 [3.3] (5)	11.4 [3.3] (5)	11.4 [3.3] (5)	11.4 [3.3] (5)	10.5 [3.2] (6)
01471980	7.5 [6.1] (9)	10.3 [8.5] (5)	10.3 [8.5] (5)	8.8 [7.3] (7)	7.8 [6.5] (9)	6.7 [5.6] (12)
01472000	10.3 [6.2] (9)	13.4 [7.0] (5)	13.4 [7.0] (5)	10.8 [6.3] (8)	9.3 [5.7] (11)	8.3 [5.2] (14)
01472157	17.7 [5.8] (9)	12.3 [6.1] (5)	12.3 [6.1] (5)	9.9 [5.2] (8)	8.5 [4.6] (11)	7.6 [4.2] (14)
01472174	25.9 [23.0] (9)	19.8 [18.5] (11)	17.5 [16.3] (14)	15.4 [14.3] (18)	12.6 [11.6] (27)	11.3 [10.5] (33)
01472198	13.9 [9.0] (10)	16.8 [10.7] (6)	14.8 [9.5] (8)	12.1 [7.9] (12)	10.6 [6.9] (16)	9.2 [6.0] (21)
01472199	16.6 [11.0] (9)	19.7 [12.6] (6)	17.5 [11.5] (8)	14.6 [9.9] (12)	12.8 [8.7] (16)	11.3 [7.7] (21)
01473000	9.0 [3.1] (9)	11.9 [3.3] (5)	11.9 [3.3] (5)	9.5 [3.1] (8)	8.2 [2.9] (11)	7.3 [2.8] (14)

See footnotes at end of table.

Table 22.--Selected results of K-CERA analysis of stream-gaging operations in Delaware River basin--(continued)

Station no.	Standard error of instantaneous discharge, in percent [1/] [Equivalent Gaussian spread] (Number of visits per year to site)[2/]					
	Current operation	Budget, in thousands of 1983 dollars				
	377,700	345,000	350,000	360,000	380,000	400,000
01473120	13.1 [10.4] (9)	15.9 [12.6] (6)	13.9 [11.1] (8)	11.4 [9.0] (12)	9.9 [7.8] (16)	8.6 [6.9] (21)
01473169	5.7 [2.4] (12)	7.6 [2.8] (5)	7.6 [2.8] (5)	7.6 [2.8] (5)	6.0 [2.5] (8)	5.4 [2.4] (10)
01474000	9.7 [4.4] (9)	12.0 [4.9] (6)	12.0 [4.9] (6)	10.2 [4.3] (8)	8.6 [3.7] (11)	7.6 [3.3] (14)
01474500	9.3 [6.0] (9)	10.9 [5.6] (6)	10.9 [5.6] (6)	9.2 [4.9] (8)	7.7 [4.2] (11)	6.7 [3.7] (14)
01475300	9.1 [7.6] (9)	11.9 [9.8] (5)	11.9 [9.8] (5)	11.9 [9.8] (5)	10.2 [8.5] (7)	9.6 [8.0] (8)
01475510	16.4 [3.3] (9)	10.9 [4.1] (5)	10.9 [4.1] (5)	10.9 [4.1] (5)	9.2 [3.6] (7)	8.6 [3.4] (8)
01475550	13.2 [4.7] (9)	13.8 [4.5] (8)	12.4 [4.1] (10)	10.4 [3.5] (14)	8.7 [2.9] (20)	7.9 [2.7] (24)
01475850	16.8 [7.3] (11)	17.8 [7.8] (8)	15.9 [6.9] (10)	13.4 [5.8] (14)	11.2 [4.8] (20)	10.2 [4.4] (24)
01477000	13.7 [7.9] (9)	14.3 [8.0] (8)	12.8 [7.2] (10)	10.8 [6.1] (14)	9.1 [5.1] (20)	8.3 [4.7] (24)

See footnotes at end of table.

Table 22.--Selected results of K-CERA analysis of stream-gaging operations in Delaware River basin--(continued)

Station no.	Standard error of instantaneous discharge, in percent 1/ [Equivalent Gaussian spread] (Number of visits per year to site)2/					
	Current operation	Budget, in thousands of 1983 dollars				
	377,700	345,000	350,000	360,000	380,000	400,000
01480300	19.1 [6.1] (9)	12.7 [6.6] (6)	11.0 [5.8] (8)	9.4 [5.1] (11)	7.8 [4.2] (16)	7.1 [3.9] (19)
01480500	7.8 [5.4] (9)	10.6 [6.0] (5)	10.6 [6.0] (5)	10.6 [6.0] (5)	8.2 [5.4] (8)	7.3 [5.0] (10)
01480617	12.9 [10.4] (9)	16.0 [12.3] (6)	13.7 [11.0] (8)	11.6 [9.5] (11)	9.4 [7.9] (16)	8.6 [7.3] (19)
01480675	12.3 [11.2] (9)	13.7 [12.3] (6)	12.6 [11.4] (8)	11.2 [10.2] (11)	9.7 [8.9] (16)	9.0 [8.2] (19)
01480685	12.1 [8.1] (9)	14.2 [9.0] (6)	12.6 [8.1] (8)	10.9 [7.1] (11)	9.1 [6.0] (16)	8.4 [5.6] (19)
01480700	13.7 [5.6] (9)	9.9 [5.7] (5)	9.9 [5.7] (5)	9.9 [5.7] (5)	8.2 [5.4] (8)	7.5 [5.1] (10)
01480870	7.4 [5.3] (9)	9.9 [6.8] (5)	9.9 [6.8] (5)	9.9 [6.8] (5)	7.9 [5.6] (8)	7.0 [5.0] (10)
01481000	6.2 [5.1] (9)	8.1 [6.6] (5)	8.1 [6.6] (5)	8.1 [6.6] (5)	6.6 [5.4] (8)	5.9 [4.9] (10)

1/ Square root of variance for average annual period without backwater from ice.
2/ Minimum visits limited to five.

Table 23.--Selected results of K-CERA analysis of stream-gaging operations in Susquehanna and Potomac River basins

Station no.	Standard error of instantaneous discharge, in percent [1/] [Equivalent Gaussian spread] (Number of visits per year to site)[2/]					
	Current operation	Budget, in thousands of 1983 dollars				
	455,000	410,000	415,000	430,000	450,000	470,000
Average per station	14.2	13.5	12.9	11.6	10.5	9.8
01516350	10.0 [10.0] (9)	13.3 [13.3] (5)	13.3 [13.3] (5)	11.3 [11.3] (7)	10.0 [10.0] (9)	9.0 [9.0] (11)
01516500	32.8 [27.3] (9)	26.9 [23.1] (12)	25.8 [22.2] (13)[3/]	25.8 [22.2] (13)[3/]	25.8 [22.2] (13)[3/]	25.8 [22.2] (13)[3/]
01518000	23.4 [11.2] (9)	18.2 [10.2] (8)	17.1 [9.6] (9)	16.2 [9.1] (10)	14.8 [8.3] (12)	14.2 [7.9] (13)
01518700	6.4 [3.3] (9)	8.4 [3.6] (5)	8.4 [3.6] (5)	8.4 [3.6] (5)	8.4 [3.6] (5)	7.6 [3.4] (6)
01520000	14.7 [12.2] (9)	17.8 [14.6] (6)	16.6 [13.7] (7)	14.0 [11.6] (10)	12.3 [10.2] (13)	11.5 [9.5] (15)
01531500	5.3 [3.1] (9)	7.3 [3.5] (5)	7.3 [3.5] (5)	7.3 [3.5] (5)	7.3 [3.5] (5)	6.5 [3.3] (6)
01532000	27.8 [26.0] (9)	23.2 [21.4] (11)	22.2 [20.4] (12)[4/]	22.2 [20.4] (12)[4/]	22.2 [20.4] (12)[4/]	22.2 [20.6] (13)[4/]
01533400	14.6 [10.0] (9)	11.3 [9.9] (5)	11.3 [9.8] (5)	11.3 [9.9] (5)	11.3 [9.9] (5)	11.3 [9.9] (5)
01534000	13.4 [10.1] (9)	16.4 [11.2] (5)	16.4 [11.2] (5)	14.3 [10.2] (7)	12.9 [9.4] (9)	11.4 [8.4] (12)

See footnotes at end of table.

Table 23.--Selected results of K-CERA analysis of stream-gaging operations in Susquehanna and Potomac River basins--(continued)

Station no.	Standard error of instantaneous discharge, in percent 1/ [Equivalent Gaussian spread] (Number of visits per year to site)2/					
	Current operation	Budget, in thousands of 1983 dollars				
	455,000	410,000	415,000	430,000	450,000	470,000
01534300	12.5 [11.4] (9)	14.2 [12.5] (5)	14.2 [12.5] (5)	13.1 [11.8] (7)	12.2 [11.2] (9)	11.2 [10.3] (12)
01534500	7.5 [4.7] (9)	9.8 [5.6] (5)	9.8 [5.6] (5)	9.8 [5.6] (5)	9.8 [5.6] (5)	9.8 [5.6] (5)
01536000	10.4 [4.9] (9)	12.4 [5.9] (5)	12.4 [5.9] (5)	10.3 [5.2] (7)	9.0 [4.7] (9)	7.7 [4.1] (12)
01536500	6.7 [6.1] (9)	12.4 [6.5] (5)	12.4 [6.5] (5)	10.3 [6.5] (5)	9.0 [6.5] (5)	7.7 [6.5] (5)
01537000	23.7 [5.5] (9)	26.7 [6.5] (5)	26.7 [6.5] (5)	26.1 [6.2] (7)	23.7 [5.5] (9)	20.3 [5.1] (12)
01537500	14.8 [5.3] (9)	13.4 [6.4] (5)	13.4 [6.4] (5)	11.5 [6.4] (5)	10.2 [6.4] (5)	8.8 [6.4] (5)
01538000	10.5 [6.7] (9)	13.4 [7.6] (5)	13.4 [7.6] (5)	11.5 [6.7] (7)	10.2 [6.1] (9)	8.8 [5.4] (12)
01539000	13.5 [6.7] (9)	16.0 [8.3] (5)	16.0 [8.3] (5)	13.5 [7.2] (7)	11.9 [6.4] (9)	10.3 [5.6] (12)
01540500	4.1 [0.8] (9)	5.7 [0.8] (5)	5.7 [0.8] (5)	5.7 [0.8] (5)	5.7 [0.8] (5)	5.7 [0.8] (5)
01541000	7.6 [5.0] (9)	9.3 [5.1] (5)	9.3 [5.1] (5)	9.3 [5.1] (5)	9.3 [5.1] (5)	9.3 [5.1] (5)

See footnotes at end of table.

Table 23.--Selected results of K-CERA analysis of stream-gaging operations in Susquehanna and Potomac River basins--(continued)

Station no.	Standard error of instantaneous discharge, in percent 1/ [Equivalent Gaussian spread] (Number of visits per year to site)2/					
	Current operation	Budget, in thousands of 1983 dollars				
	455,000	410,000	415,000	430,000	450,000	470,000
01541200	20.3 [17.0] (9)	20.8 [17.1] (6)	20.8 [17.1] (6)	17.9 [14.6] (8)	15.3 [12.4] (11)	14.0 [11.3] (13)
01541303	11.4 [3.3] (9)	3.3 [3.3] (5)	3.3 [3.3] (5)	3.3 [3.3] (5)	3.2 [3.2] (7)	3.1 [3.1] (8)
01541500	9.3 [3.2] (9)	10.9 [3.5] (5)	10.9 [3.5] (5)	10.9 [3.5] (5)	9.1 [3.1] (7)	8.4 [3.0] (8)
01542000	16.8 [7.3] (9)	10.0 [8.1] (6)	10.0 [8.1] (6)	8.7 [7.1] (8)	7.4 [6.1] (11)	6.9 [5.6] (13)
01542500	5.3 [3.5] (9)	7.0 [4.1] (5)	7.0 [4.1] (5)	7.0 [4.1] (5)	7.0 [4.1] (5)	7.0 [4.1] (5)
01542810	21.5 [15.2] (9)	21.0 [14.8] (7)	19.9 [14.2] (8)	16.7 [12.1] (12)	14.6 [10.7] (16)	3.2 [9.7] (20)
01543000	14.4 [13.4] (9)	16.5 [15.2] (6)	15.7 [14.5] (7)	14.4 [13.4] (9)	12.9 [12.0] (12)	11.7 [10.9] (15)
01543500	8.5 [7.0] (9)	10.4 [8.2] (5)	10.4 [8.2] (5)	10.4 [8.2] (5)	10.4 [8.2] (5)	10.4 [8.2] (5)
01544000	16.0 [5.6] (9)	14.0 [6.0] (6)	12.9 [5.6] (7)	11.3 [5.0] (9)	9.7 [4.4] (12)	8.7 [3.9] (15)

See footnotes at end of table.

Table 23.--Selected results of K-CERA analysis of stream-gaging operations in Susquehanna and Potomac River basins--(continued)

Station no.	Standard error of instantaneous discharge, in percent 1/ [Equivalent Gaussian spread] (Number of visits per year to site)2/					
	Current operation	Budget, in thousands of 1983 dollars				
	455,000	410,000	415,000	430,000	450,000	470,000
01544500	21.4 [17.4] (9)	22.3 [20.0] (6)	20.6 [18.4] (7)	18.2 [16.1] (9)	15.7 [13.8] (12)	14.0 [12.3] (15)
01545000	3.0 [3.0] (9)	3.2 [3.2] (5)	3.2 [3.2] (5)	3.2 [3.2] (5)	3.2 [3.2] (5)	3.2 [3.2] (5)
01545500	5.7 [2.2] (9)	7.8 [2.4] (5)	7.8 [2.4] (5)	7.8 [2.4] (5)	7.8 [2.4] (5)	7.8 [2.4] (5)
01545600	5.3 [5.3] (9)	6.8 [6.8] (5)	6.8 [6.8] (5)	6.8 [6.8] (5)	6.8 [6.8] (5)	6.8 [6.8] (5)
01546500	6.6 [5.8] (9)	8.2 [7.1] (5)	8.2 [7.1] (5)	8.2 [7.1] (5)	7.8 [6.8] (6)	7.4 [6.6] (7)
01547100	5.9 [1.9] (9)	5.1 [2.2] (5)	5.1 [2.2] (5)	5.1 [2.2] (5)	4.6 [2.1] (6)	4.2 [2.0] (7)
01547200	5.1 [3.6] (9)	6.6 [3.9] (5)	6.6 [3.9] (5)	6.6 [3.9] (5)	6.0 [3.6] (6)	5.6 [3.4] (7)
01547500	4.5 [4.5] (9)	4.7 [4.7] (5)	4.7 [4.7] (5)	4.7 [4.7] (5)	4.7 [4.7] (6)	4.6 [4.6] (7)
01547700	19.6 [17.6] (9)	18.6 [16.7] (10)	17.7 [15.9] (11)	14.7 [13.1] (16)	12.8 [11.4] (21)	12.0 [10.7] (24)

See footnotes at end of table.

Table 23.--Selected results of K-CERA analysis of stream-gaging operations in Susquehanna and Potomac River basins--(continued)

Station no.	Standard error of instantaneous discharge, in percent 1/ [Equivalent Gaussian spread] (Number of visits per year to site)2/					
	Current operation	Budget, in thousands of 1983 dollars				
	455,000	410,000	415,000	430,000	450,000	470,000
01547950	17.7 [17.4] (9)	16.6 [15.9] (5)	16.6 [15.9] (5)	16.6 [15.9] (5)	15.3 [14.7] (6)	14.3 [13.7] (7)
01548000	6.9 [3.4] (9)	10.0 [3.8] (5)	10.0 [3.8] (5)	10.0 [3.8] (5)	8.8 [3.4] (6)	7.9 [3.2] (7)
01548500	14.0 [11.0] (9)	14.2 [12.5] (6)	14.2 [12.5] (6)	11.6 [10.2] (9)	9.9 [8.9] (12)	8.8 [7.8] (15)
01549500	8.1 [8.1] (9)	10.6 [10.6] (5)	10.6 [10.6] (5)	10.6 [10.6] (5)	9.6 [9.6] (6)	8.9 [8.9] (7)
01549700	4.8 [4.8] (9)	6.1 [6.1] (5)	6.1 [6.1] (5)	6.1 [6.1] (5)	5.6 [5.6] (6)	5.2 [5.2] (7)
01550000	23.4 [22.4] (9)	20.2 [19.2] (12)	18.0 [17.1] (15)	16.0 [15.1] (19)	13.6 [12.8] (26)	12.6 [11.9] (30)
01551500	2.6 [2.6] (9)	2.8 [2.8] (5)	2.8 [2.8] (5)	2.8 [2.8] (5)	2.8 [2.8] (5)	2.7 [2.7] (6)
01552000	9.4 [4.4] (9)	12.9 [5.5] (5)	12.9 [5.5] (5)	12.9 [5.5] (5)	12.9 [5.5] (5)	11.6 [5.0] (6)
01552500	14.6 [10.8] (9)	15.1 [10.8] (8)	15.1 [10.8] (8)	12.8 [9.1] (11)	11.0 [7.8] (15)	9.7 [6.9] (19)

See footnotes at end of table.

Table 23.--Selected results of K-CERA analysis of stream-gaging operations in Susquehanna and Potomac River basins--(continued)

Station no.	Standard error of instantaneous discharge, in percent 1/ [Equivalent Gaussian spread] (Number of visits per year to site)2/					
	Current operation	Budget, in thousands of 1983 dollars				
	455,000	410,000	415,000	430,000	450,000	470,000
01553500	4.1 [3.6] (9)	4.8 [3.8] (5)	4.8 [3.8] (5)	4.8 [3.8] (5)	4.8 [3.8] (5)	4.8 [3.8] (5)
01553700	13.4 [5.0] (9)	13.0 [5.7] (6)	13.0 [5.7] (6)	10.7 [4.7] (9)	9.3 [4.1] (12)	8.3 [3.7] (15)
01554000	7.1 [3.9] (9)	5.9 [3.4] (5)	5.9 [3.4] (5)	5.9 [3.4] (5)	5.9 [3.4] (5)	5.9 [3.4] (5)
01554500	6.9 [3.2] (9)	9.0 [3.9] (5)	9.0 [3.9] (5)	9.0 [3.9] (5)	9.0 [3.9] (5)	9.0 [3.9] (5)
01555000	12.8 [4.9] (9)	14.7 [5.0] (5)	13.4 [4.7] (6)	11.6 [4.1] (8)	10.4 [3.8] (10)	9.4 [3.5] (12)
01555500	12.3 [8.0] (9)	15.9 [9.6] (5)	14.6 [9.0] (6)	12.8 [8.0] (8)	11.5 [7.3] (10)	10.5 [6.8] (12)
01556000	9.4 [2.5] (9)	9.8 [2.8] (5)	9.8 [2.8] (5)	8.8 [2.7] (6)	8.0 [2.6] (7)	6.9 [2.4] (9)
01557500	10.6 [9.8] (9)	12.4 [11.3] (5)	12.4 [11.3] (5)	11.3 [10.2] (5)	10.5 [9.5] (5)	9.3 [8.4] (6)
01558000	6.1 [4.1] (9)	8.2 [5.1] (5)	8.2 [5.1] (7)	7.5 [4.9] (9)	7.0 [4.7] (11)	6.3 [4.3] (13)

See footnotes at end of table.

Table 23.--Selected results of K-CERA analysis of stream-gaging operations in Susquehanna and Potomac River basins--(continued)

Station no.	Standard error of instantaneous discharge, in percent [1/] [Equivalent Gaussian spread] (Number of visits per year to site)[2/]					
	Current operation	Budget, in thousands of 1983 dollars				
	455,000	410,000	415,000	430,000	450,000	470,000
01559000	5.0 [3.0] (9)	6.7 [3.5] (5)	6.7 [3.5] (5)	6.7 [3.5] (5)	6.7 [3.5] (5)	6.7 [3.5] (5)
01560000	15.9 [9.8] (9)	18.8 [11.7] (5)	15.7 [9.7] (7)	13.7 [8.6] (9)	12.3 [7.7] (11)	11.3 [7.0] (13)
01562000	13.1 [3.9] (9)	18.0 [4.2] (5)	16.2 [3.9] (6)	13.8 [3.6] (8)	12.2 [3.3] (10)	11.1 [3.0] (12)
01563200	4.6 [2.1] (9)	6.1 [2.5] (5)	6.1 [2.5] (5)	6.1 [2.5] (5)	6.1 [2.5] (5)	6.1 [2.5] (5)
01563500	1.7 [1.7] (9)	2.1 [2.1] (5)	2.1 [2.1] (5)	2.1 [2.1] (5)	2.1 [2.1] (5)	2.1 [2.1] (5)
01564500	13.6 [5.7] (9)	18.2 [7.2] (5)	16.6 [6.6] (6)	14.4 [5.8] (8)	12.8 [5.2] (10)	11.7 [4.8] (12)
01567000	4.4 [4.4] (9)	5.6 [5.6] (5)	5.6 [5.6] (5)	5.6 [5.6] (5)	5.6 [5.6] (5)	5.6 [5.6] (5)
01567500	15.0 [11.8] (9)	16.5 [12.8] (7)	15.4 [11.9] (8)	13.8 [10.6] (10)	11.6 [8.9] (14)	10.5 [8.i] (17)
01568000	17.9 [6.6] (9)	14.5 [6.6] (7)	13.5 [6.3] (8)	12.1 [5.7] (10)	10.2 [4.9] (14)	9.2 [4.5] (17)

See footnotes at end of table.

Table 23.--Selected results of K-CERA analysis of stream-gaging operations in Susquehanna and Potomac River basins--(continued)

Station no.	Standard error of instantaneous discharge, in percent 1/ [Equivalent Gaussian spread] (Number of visits per year to site)2/					
	Current operation	Budget, in thousands of 1983 dollars				
	455,000	410,000	415,000	430,000	450,000	470,000
01568500	16.8 [5.5] (9)	19.0 [6.0] (7)	17.8 [5.7] (8)	15.9 [5.3] (10)	13.5 [4.6] (14)	12.3 [4.2] (17)
01569800	9.1 [5.8] (9)	9.4 [6.0] (5)	9.4 [6.0] (5)	8.4 [5.8] (7)	7.8 [5.6] (9)	7.6 [5.6] (10)
01570000	12.0 [3.1] (9)	11.5 [3.8] (5)	11.5 [3.8] (5)	9.6 [3.3] (7)	8.4 [3.0] (9)	8.0 [2.8] (10)
01570500	9.6 [9.6] (9)	9.6 [9.6] (5)	9.6 [9.6] (5)	9.6 [9.6] (5)	9.6 [9.6] (5)	9.6 [9.6] (5)
01571500	15.1 [3.6] (9)	9.1 [4.0] (6)	8.4 [3.7] (7)	7.0 [3.1] (10)	6.3 [2.8] (12)	5.9 [2.6] (14)
01573000	17.2 [4.6] (9)	9.2 [4.8] (7)	8.6 [4.6] (8)	7.4 [4.0] (11)	6.4 [3.5] (15)	5.8 [3.2] (18)
01573160	22.6 [21.4] (9)	25.2 [24.1] (7)	23.8 [22.6] (8)	20.6 [19.4] (11)	17.7 [16.6] (15)	16.2 [15.1] (18)
01573560	7.5 [5.6] (9)	9.2 [6.2] (5)	9.2 [6.2] (5)	9.2 [6.2] (5)	9.2 [6.2] (5)	9.2 [6.2] (5)
01574000	32.9 [10.9] (9)	17.7 [9.5] (10)	16.1 [8.6] (12)	13.9 [7.4] (16)	12.1 [6.5] (21)	11.1 [5.9] (25)

See footnotes at end of table.

Table 23.--Selected results of K-CERA analysis of stream-gaging operations in Susquehanna and Potomac River basins--(continued)

Station no.	Standard error of instantaneous discharge, in percent 1/ [Equivalent Gaussian spread] (Number of visits per year to site)2/					
	Current operation	Budget, in thousands of 1983 dollars				
	455,000	410,000	415,000	430,000	450,000	470,000
01574500	20.5 [4.1] (9)	13.0 [4.4] (5)	11.7 [4.2] (6)	10.0 [3.8] (8)	8.9 [3.5] (10)	7.7 [3.2] (13)
01575000	11.9 [7.6] (9)	14.8 [8.7] (6)	13.6 [8.3] (7)	11.3 [7.4] (10)	10.2 [6.9] (12)	9.5 [6.5] (14)
01575500	14.6 [5.1] (9)	10.1 [5.8] (6)	9.2 [5.4] (7)	7.5 [4.5] (10)	6.8 [4.1] (12)	6.3 [3.8] (14)
01576000	4.2 [4.0] (9)	4.1 [4.0] (5)	4.1 [4.0] (5)	4.1 [4.0] (5)	4.1 [4.0] (5)	4.1 [4.0] (5)
01576500	20.5 [3.9] (9)	13.0 [3.9] (7)	12.2 [3.7] (8)	10.3 [3.3] (11)	8.8 [2.9] (15)	8.1 [2.7] (18)
01613050	28.0 [18.6] (9)	26.6 [17.7] (10)	24.3 [16.2] (12)	21.8 [14.4] (15)	18.4 [12.1] (21)	16.5 [10.8] (26)

1/ Square root of variance for average annual period without backwater from ice.
2/ Minimum visits limited to five.
3/ Maximum visits restricted to 13. (See 01516500)
4/ Maximum visits restricted to 12. (See 01532000)

Table 24.--Selected results of K-CERA analysis of stream-gaging operations in Ohio and St. Lawrence River basins

Station no.	Standard error of instantaneous discharge, in percent [1/] [Equivalent Gaussian spread] (Number of visits per year to site)[2/]					
	Current operation	Budget, in thousands of 1983 dollars				
	366,300	335,000	340,000	350,000	360,000	380,000
Average per station	17.1	14.7	14.0	13.1	12.5	11.7
03007800	8.4 [6.1] (9)	10.3 [6.6] (5)	10.3 [6.6] (5)	10.3 [6.6] (5)	9.6 [6.5] (6)	8.7 [6.2] (8)
03009680	6.6 [4.5] (9)	8.4 [5.2] (5)	8.4 [5.2] (5)	8.4 [5.2] (5)	8.4 [5.2] (5)	8.4 [5.2] (5)
03010500	8.1 [8.1] (9)	8.5 [8.5] (5)	8.5 [8.5] (5)	8.5 [8.5] (5)	8.5 [8.5] (5)	8.5 [8.5] (5)
03010655	18.0 [11.3] (9)	12.9 [10.9] (6)	12.9 [10.9] (6)	11.5 [10.2] (10)	11.5 [10.2] (10)	11.0 [9.9] (12)
03011800	6.6 [6.6] (9)	8.4 [8.4] (5)	8.4 [8.4] (5)	8.4 [8.4] (5)	8.4 [8.4] (5)	8.4 [8.4] (5)
030125500	7.5 [7.5] (9)	8.2 [8.2] (5)	8.2 [8.2] (5)	8.2 [8.2] (5)	8.2 [8.2] (5)	8.2 [8.2] (5)
03015000	8.6 [8.6] (9)	8.8 [8.8] (5)	8.8 [8.8] (5)	8.8 [8.8] (5)	8.8 [8.8] (5)	8.8 [8.8] (5)
03015500	22.6 [15.0] (9)	19.5 [17.2] (6)	18.1 [16.0] (7)	14.5 [12.7] (11)	13.8 [12.2] (12)	11.6 [10.2] (17)
03016000	3.5 [2.7] (9)	4.7 [3.6] (5)	4.7 [3.6] (5)	4.7 [3.6] (5)	4.7 [3.6] (5)	4.7 [3.6] (5)

See footnotes at end of table.

Table 24.-Selected results of K-CERA analysis of stream-gaging operations in Ohio and St. Lawrence River basins--(continued)

Station no.	Standard error of instantaneous discharge, in percent 1/ [Equivalent Gaussian spread] (Number of visits per year to site) 2/					
	Current operation	Budget, in thousands of 1983 dollars				
	366,300	335,000	340,000	350,000	360,000	380,000
03020000	12.8 [9.9] (9)	15.5 [11.0] (5)	15.5 [11.0] (5)	13.9 [10.4] (7)	12.8 [9.9] (9)	12.0 [9.5] (11)
03020500	5.6 [2.9] (9)	7.7 [3.9] (5)	7.7 [3.9] (5)	7.7 [3.9] (5)	7.7 [3.9] (5)	7.7 [3.9] (5)
03021350	14.4 [14.4] (9)	15.3 [15.3] (6)	15.3 [15.3] (6)	12.9 [12.9] (9)	11.8 [11.8] (11)	9.9 [9.9] (16)
03021410	24.0 [23.8] (9)	25.2 [25.0] (6)	23.5 [23.3] (9)	21.9 [21.7] (12)	20.1 [20.0] (16)	17.4 [17.2] (24)
03021520	6.8 [4.6] (9)	9.1 [5.9] (5)	9.1 [5.9] (5)	9.1 [5.9] (5)	8.3 [5.5] (6)	9.1 [5.9] (8)
03022540	10.2 [8.4] (9)	13.6 [11.1] (5)	13.6 [11.1] (5)	11.6 [9.5] (7)	10.8 [8.8] (8)	9.3 [7.6] (11)
03022554	10.5 [6.4] (9)	13.6 [7.8] (5)	13.6 [7.8] (5)	11.6 [6.8] (7)	10.9 [6.4] (8)	9.3 [5.5] (11)
03024000	3.5 [3.5] (9)	4.1 [4.1] (5)	4.1 [4.1] (5)	4.1 [4.1] (5)	4.1 [4.1] (5)	4.1 [4.1] (5)
03025500	4.2 [1.0] (9)	6.4 [1.1] (5)	6.4 [1.1] (5)	6.4 [1.1] (5)	6.4 [1.1] (5)	6.4 [1.1] (5)

See footnotes at end of table.

Table 24.-Selected results of K-CERA analysis of stream-gaging operations in Ohio and St. Lawrence River basins--(continued)

Station no.	Standard error of instantaneous discharge, in percent 1/ [Equivalent Gaussian spread] (Number of visits per year to site)2/					
	Current operation	Budget, in thousands of 1983 dollars				
	366,300	335,000	340,000	350,000	360,000	380,000
03026500	13.7 [13.7] (9)	13.8 [13.8] (5)	13.8 [13.8] (5)	13.8 [13.8] (5)	13.8 [13.8] (5)	13.8 [13.8] (6)
03027500	9.9 [8.0] (9)	11.5 [8.3] (5)	11.5 [8.3] (5)	11.5 [8.3] (5)	11.0 [8.2] (6)	10.2 [8.1] (8)
03028000	6.0 [5.2] (9)	8.6 [7.5] (5)	8.6 [7.5] (5)	8.6 [7.5] (5)	8.6 [7.5] (5)	8.6 [7.5] (5)
03028500	5.6 [4.8] (9)	6.8 [5.9] (5)	6.8 [5.9] (5)	6.8 [5.9] (5)	6.8 [5.9] (5)	6.8 [5.9] (5)
03029500	5.8 [3.2] (9)	7.5 [3.4] (5)	7.5 [3.4] (5)	7.5 [3.4] (5)	7.5 [3.4] (5)	7.5 [3.4] (5)
03030500	22.9 [22.8] (9)	25.6 [25.5] (6)	21.9 [21.8] (9)	19.3 [19.2] (12)	16.8 [16.7] (16)	13.8 [13.7] (24)
03031500	2.6 [2.3] (9)	3.4 [3.0] (5)	3.4 [3.0] (5)	3.4 [3.0] (5)	3.4 [3.0] (5)	3.4 [3.0] (5)
03032500	13.0 [11.9] (9)	14.1 [12.7] (7)	14.1 [12.7] (7)	13.2 [11.9] (8)	11.3 [10.1] (11)	9.3 [8.4] (16)
03034000	16.8 [5.1] (9)	18.4 [5.4] (8)	18.4 [5.4] (8)	14.5 [4.6] (11)	13.6 [4.4] (12)	10.6 [3.6] (17)

See footnotes at end of table.

Table 24.-Selected results of K-CERA analysis of stream-gaging operations in Ohio and St. Lawrence River basins--(continued)

Station no.	Standard error of instantaneous discharge, in percent 1/ [Equivalent Gaussian spread] (Number of visits per year to site)2/					
	Current operation	Budget, in thousands of 1983 dollars				
	366,300	335,000	340,000	350,000	360,000	380,000
03034500	13.5 [12.4] (9)	15.4 [14.1] (7)	15.4 [14.1] (7)	14.3 [13.1] (8)	12.2 [11.2] (11)	10.1 [9.2] (16)
03036000	4.6 [4.6] (9)	5.1 [5.1] (5)	5.1 [5.1] (5)	5.1 [5.1] (5)	5.1 [5.1] (5)	5.1 [5.1] (5)
03036500	2.2 [1.0] (9)	3.3 [1.1] (5)	3.3 [1.1] (5)	3.3 [1.1] (5)	3.3 [1.1] (5)	3.3 [1.1] (5)
03038000	3.7 [3.7] (9)	5.2 [5.2] (5)	5.2 [5.2] (5)	5.2 [5.2] (5)	5.2 [5.2] (5)	5.2 [5.2] (5)
03039000	8.8 [4.5] (9)	11.5 [5.3] (5)	11.5 [5.3] (5)	9.9 [4.9] (7)	9.3 [4.7] (8)	8.0 [4.2] (11)
03040000	8.4 [5.5] (9)	12.0 [7.4] (5)	12.0 [7.4] (5)	9.8 [6.3] (7)	9.0 [5.8] (8)	7.5 [5.0] (11)
03041000	23.5 [21.8] (9)	20.2 [18.7] (12)	18.7 [17.2] (14)	16.4 [15.1] (18)	14.8 [13.6] (22)	12.8 [11.8] (29)
03041500	8.1 [8.1] (9)	9.2 [9.2] (5)	9.2 [9.2] (5)	9.2 [9.2] (5)	9.2 [9.2] (5)	9.2 [9.2] (5)
03042000	26.3 [26.3] (9)	23.0 [23.0] (12)	21.3 [21.3] (14)	18.8 [18.8] (18)	17.0 [17.0] (22)	14.7 [14.7] (29)

See footnotes at end of table.

Table 24.-Selected results of K-CERA analysis of stream-gaging operations in Ohio and St. Lawrence River basins--(continued)

Station no.	Standard error of instantaneous discharge, in percent 1/ [Equivalent Gaussian spread] (Number of visits per year to site)2/					
	Current operation	Budget, in thousands of 1983 dollars				
	366,300	335,000	340,000	350,000	360,000	380,000
03042280	26.9 [26.2] (9)	22.1 [21.4] (7)	20.5 [19.8] (7)	18.0 [17.3] (8)	16.2 [15.6] (22)	14.1 [13.5] (29)
03042500	9.2 [3.8] (9)	12.2 [4.6] (5)	12.2 [4.6] (5)	10.3 [4.0] (7)	9.7 [3.8] (8)	8.3 [3.4] (11)
03044000	2.8 [2.0] (9)	3.8 [2.6] (5)	3.8 [2.6] (5)	3.8 [2.6] (5)	3.8 [2.6] (5)	3.8 [2.6] (5)
03045000	19.7 [5.7] (9)	14.5 [6.6] (5)	12.5 [6.2] (7)	11.8 [5.9] (8)	10.6 [5.6] (10)	9.4 [5.1] (13)
03047000	25.6 [5.3] (9)	14.8 [5.2] (5)	12.6 [4.9] (7)	11.8 [4.8] (8)	10.6 [4.5] (10)	9.3 [4.2] (13)
03048500	6.3 [1.7] (9)	5.9 [2.4] (5)	5.9 [2.4] (5)	5.9 [2.4] (5)	5.9 [2.4] (5)	5.9 [2.4] (5)
03049000	4.7 [4.7] (9)	8.0 [8.0] (5)	8.0 [8.0] (5)	8.0 [8.0] (5)	8.0 [8.0] (5)	8.0 [8.0] (5)
03049500	9.2 [4.9] (9)	5.2 [4.8] (5)	5.2 [4.8] (5)	5.2 [4.8] (5)	5.2 [4.8] (5)	5.2 [4.8] (5)
03049800	33.3 [31.5] (9)	27.2 [25.6] (14)	24.7 [23.2] (17)3/	24.7 [23.3] (17)3/	24.7 [23.2] (17)3/	24.7 [23.2] (17)3/

See footnotes at end of table.

Table 24.-Selected results of K-CERA analysis of stream-gaging operations in Ohio and St. Lawrence River basins--(continued)

Station no.	Standard error of instantaneous discharge, in percent 1/ [Equivalent Gaussian spread] (Number of visits per year to site)2/					
	Current operation	Budget, in thousands of 1983 dollars				
	366,300	335,000	340,000	350,000	360,000	380,000
03072000	15.1 [8.8] (9)	18.1 [9.9] (6)	16.9 [9.5] (7)	15.1 [8.8] (9)	14.4 [8.5] (10)	12.3 [7.5] (14)
03072500	26.0 [23.8] (9)	20.7 [20.4] (7)	18.6 [18.3] (9)	16.3 [16.0] (12)	14.2 [13.9] (16)	11.8 [11.6] (23)
03073000	16.9 [11.2] (9)	19.0 [12.5] (7)	16.9 [11.2] (9)	14.7 [9.9] (12)	13.6 [9.2] (14)	11.4 [7.7] (20)
03074500	18.4 [5.8] (9)	15.2 [6.8] (6)	14.0 [6.3] (7)	12.4 [5.6] (9)	11.7 [5.3] (10)	9.9 [4.5] (14)
03075070	10.0 [9.3] (9)	10.8 [9.7] (5)	10.8 [9.7] (5)	10.8 [9.7] (5)	10.8 [9.7] (5)	9.9 [9.1] (8)
03077500	8.5 [6.8] (9)	10.7 [8.2] (5)	10.7 [8.2] (5)	10.7 [8.2] (5)	10.7 [8.2] (5)	8.9 [7.1] (8)
03079000	7.4 [3.7] (9)	9.8 [4.2] (5)	9.8 [4.2] (5)	9.8 [4.2] (5)	9.8 [4.2] (5)	9.8 [4.2] (5)
03080000	7.6 [6.3] (9)	9.7 [7.8] (5)	9.7 [7.8] (5)	9.7 [7.8] (5)	9.7 [7.8] (5)	9.7 [7.8] (5)
03081000	59.4 [59.3] (9)	43.3 [43.3] (17)3/	43.3 [43.3] (17)3/	43.3 [43.3] (17)3/	43.3 [43.3] (17)3/	43.3 [43.3] (17)3/

See footnotes at end of table.

Table 24.-Selected results of K-CERA analysis of stream-gaging operations in Ohio and St. Lawrence River basins--(continued)

Station no.	Standard error of instantaneous discharge, in percent [1/] [Equivalent Gaussian spread] (Number of visits per year to site)[2/]					
	Current operation	Budget, in thousands of 1983 dollars				
	366,300	335,000	340,000	350,000	360,000	380,000
03082500	2.8 [2.8] (9)	3.8 [3.8] (5)	3.8 [3.8] (5)	3.8 [3.8] (5)	3.8 [3.8] (5)	3.8 [3.8] (5)
03083500	3.3 [2.9] (9)	4.0 [3.3] (5)	4.0 [3.3] (5)	4.0 [3.3] (5)	4.0 [3.3] (5)	4.0 [3.3] (5)
03084000	29.6 [19.8] (9)	21.2 [16.5] (12)	19.6 [15.2] (14)	17.3 [13.3] (18)	15.6 [12.0] (22)	13.6 [10.4] (29)
03085000	7.4 [5.8] (9)	9.2 [6.3] (5)	9.2 [6.3] (5)	9.2 [6.3] (5)	9.2 [6.3] (5)	9.2 [6.3] (5)
03085500	7.4 [4.4] (9)	9.8 [5.7] (5)	9.8 [5.7] (5)	9.8 [5.7] (5)	9.8 [5.7] (5)	7.8 [4.6] (8)
03086000	3.3 [3.2] (9)	4.3 [4.1] (5)	4.3 [4.1] (5)	4.3 [4.1] (5)	4.3 [4.1] (5)	4.3 [4.1] (5)
03101500	9.3 [7.0] (9)	11.4 [7.9] (5)	11.4 [7.9] (5)	11.4 [7.9] (5)	10.2 [7.4] (7)	9.7 [7.2] (8)
03102500	14.6 [7.7] (9)	17.5 [8.5] (6)	17.5 [8.5] (6)	14.6 [7.7] (9)	13.4 [7.3] (11)	11.3 [6.4] (16)
03102850	6.2 [6.2] (9)	8.6 [8.6] (5)	8.6 [8.6] (5)	8.6 [8.6] (5)	8.1 [8.1] (6)	8.6 [8.6] (5)

See footnotes at end of table.

Table 24.-Selected results of K-CERA analysis of stream-gaging operations in Ohio and St. Lawrence River basins--(continued)

Station no.	Standard error of instantaneous discharge, in percent 1/ [Equivalent Gaussian spread] (Number of visits per year to site)2/					
	Current operation 366,300	Budget, in thousands of 1983 dollars 335,000	340,000	350,000	360,000	380,000
03103500	6.1 [3.0] (9)	8.0 [3.5] (5)	8.0 [3.5] (5)	8.0 [3.5] (5)	7.3 [3.4] (6)	8.0 [3.5] (5)
03105500	5.3 [3.1] (9)	7.2 [3.6] (5)	7.2 [3.6] (5)	7.2 [3.6] (5)	6.5 [3.4] (6)	7.2 [3.6] (5)
03106000	9.5 [7.8] (9)	11.6 [9.0] (5)	11.6 [9.0] (5)	11.6 [9.0] (5)	10.2 [8.2] (7)	9.7 [7.8] (8)
03106300	44.9 [44.4] (9)	35.4 [34.8] (14)	31.9 [31.3] (17)3/	31.9 [31.3] (17)3/	31.9 [31.3] (17)3/	31.9 [31.3] (17)3/
03106500	14.9 [11.6] (9)	18.1 [13.9] (6)	18.1 [13.9] (6)	14.9 [11.6] (9)	13.5 [10.5] (11)	11.2 [8.7] (16)
03107500	8.5 [8.2] (9)	9.2 [8.8] (5)	9.2 [8.8] (5)	9.2 [8.8] (5)	9.2 [8.8] (5)	9.2 [8.8] (5)
03108000	15.5 [4.1] (9)	12.2 [4.8] (6)	11.3 [4.5] (7)	10.0 [4.0] (9)	9.5 [3.9] (10)	8.0 [3.3] (14)
04213040	51.9 [18.2] (9)	19.4 [12.5] (14)	17.6 [11.3] (17)3/	17.6 [11.3] (17)3/	17.6 [11.3] (17)3/	17.6 [11.3] (17)3/

1/ Square root of variance for average annual period without backwater from ice.
2/ Minimum visits limited to five.
3/ Maximum visits restricted to 17. (See 03049800, 03081000, 03106300, 04213040)

Conclusions From the K-CERA Analysis

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

1. Field operations in the stream-gaging program should be altered to reduce costs and average standard errors of discharge records by utilizing optimized routes, visitation frequencies, and measurement frequencies indicated in this report. Loss of stage record can be cost-effectivey reduced by selective use of additional gage observers and auxiliary recorders (table 15). Upon adoption of the indicated cost-effective improvements to stream-gaging operations, the three subdistricts can attain the following average standard errors in instantaneous discharge data while operating on minimum practicable budgets.

Subdistrict	Minimum practicable annual budget	Potential average standard error, in percent
Malvern	$ 345,000	12.9
Harrisburg	$ 410,000	13.5
Pittsburgh	$ 335,000	14.7

   These gaging operations would cause minor changes in the accuracies of records for most stations. On balance, average standard errors in discharge records would improve modestly while operational costs, in 1983 dollars, would be reduced by 9.1 percent for the District if the minimum budgets were adopted.

2. The amount of funding for stations with accuracies that are not acceptable for the data uses should be renegotiated with the data users. The budgets of the above conclusion would be revised accordingly.

3. The K-CERA analysis should be repeated with new stations included whenever sufficient information about the characteristics of the new stations has been obtained. New stations are those that may be added to the program at a cooperator's request.

4. Comparative cost and reliability information should be compiled annually on the use of local observers, various types of recorders, and satellite telemetry for providing both primary and "back-up" streamflow data.

Summary

Currently (1983), 223 continuous stream gages are operated in Pennsylvania. Twelve sources of funding contribute to the stream-gaging programs. Nine classes of use were identified for the data that are collected.

An analyses of the uses of data disclosed that continued operation of all stations is justified by the current (1983) usage of their data. Thirteen stations were identified or have special-purpose uses for short-term studies. Ten of these should be discontinued at the end of the data-collection phases of the supporting projects. Two of them should be continued at such times. The other short-term gage should be converted to a crest-stage partial-record gage. The remaining 210 gages and the 2 short-term gages noted above for continuance are currently operated at a cost of $1,199,000. Two stations in this group are suggested, for conversion, at the end of the 1985 water year, to continuous-stage gages for which flow records will not be computed.

The K-CERA analyses showed the overall level of accuracy for the 212 stations could be improved upon while reducing operating costs by 9.1 percent. These improvements would be approximately the same magnitude for each of the three subdistricts. The changes in stream-gaging operations necessary to achieve these improvements have been documented; their adoption will result in a more cost-effective stream-gaging program.

A major component of the error in streamflow records is caused by loss of primary stage records at the stream gages, which is caused mostly by malfunctions of sensing and recording equipment. The provision of supplemental recorders and the hiring of stage observers are the principal cost-effective actions that will improve the reliability and accuracy of streamflow data.

Future studies of the cost-effectiveness of the stream-gaging program should include a detailed analysis for the optimization of the ratio of the number of annual discharge measurements to the number of annual visits. Additional investigations into cost-effective ways of reducing lost records also are needed. Changes in cooperator interests and in demands for streamflow information will impact the size and relevancy of the program. The recent history of such changes suggest that another cost-effectiveness study will be desirable within 5 years.

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