COST-EFFECTIVENESS OF THE STREAM-GAGING PROGRAM IN KENTUCKY

By Kevin J. Ruhl

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CONVERSION FACTORS AND ABBREVIATIONS

Values in this report are given in inch-pound or English units. For those who may wish to use metric or International System units, the conversion factors are as follows:

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

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ABSTRACT

This report documents the results of a study of the cost-effectiveness of the stream-gaging program in Kentucky. The total surface-water program includes 97 daily-discharge stations, 12 stage-only stations, and 35 crest-stage stations, and is operated on a budget of $950,700. Most stations in the network are operated for multiple uses. Fifty-two stations are operated for defining hydrologic systems, 50 are operated for defining regional hydrology, 47 are operated for forecasting purposes, 31 are operated in support of water quality monitoring activities, and 29 are operated for project purposes. One station is operated for planning and design and one for research. The station used for research lacks an adequate source of funding and will be discontinued when the research is completed.

The average standard error of estimation of streamflow records was determined only for stations in the Louisville Subdistrict. Current operating policy and a budget of $223,500 produce an average standard error of streamflow estimation of 28.5 percent. By altering the present travel routes and station-visit frequency, the standard error can be reduced to 26.9 percent for the same $223,500 budget. The results indicate that the collection of streamflow records in the Louisville Subdistrict is cost effective in its present mode of operation.

In the Louisville Subdistrict, the minimum budget that will permit proper service and maintenance of the related equipment is about $214,200. The resulting average standard error is 32.7 percent. Alternately, the average standard error can be reduced to 16.9 percent by increasing the budget to $268,200.

INTRODUCTION

The U.S. Geological Survey (Survey) is the principal Federal agency collecting surface-water data in the Nation. The collection of these data is a major activity of the Water Resources Division of the Geological Survey. These data are collected in cooperation with State and local governments and other Federal agencies. The Survey presently (1988) is operating approximately 7,000 continuous-record gaging stations throughout the Nation. Some of these records extend back to the turn of the century. Any activity of long standing, such as the collection of surface-water data, should be re-examined periodically, because of changes of objectives, technology, and 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 began another nationwide analysis of the stream-gaging program in 1983. The objective of this analysis is to define and document the most cost-effective means of furnishing streamflow information and this report describes that analysis for the stream-gaging program in Kentucky.

The first phase of the analysis identifies the principal uses of the data for every continuous-record gaging station, and relates these uses to sources of funding. In addition, gaging stations are categorized as to whether the data are available to users in a real-time sense, on a periodic basis, or at the end of the water year.

The second phase of the analysis is to identify less costly alternative methods of furnishing the needed information; among these are flow-routing models and statistical models. The stream-gaging activity no longer is considered a network of observation points, but rather an integrated information system in which data are provided both by measurement and synthesis. Although no new analyses were undertaken as part of this study, the results of several previous studies, where streamflows were simulated by routing techniques, are presented and the methods of analysis identified.

The final part of the analysis involves the use of Kalman-filtering and mathematical-programming techniques to define strategies for operation of the necessary stations that minimize the uncertainty in the streamflow records for given operating budgets. Kalman-filtering techniques are used to compute uncertainty functions (relating the standard errors of computation or estimation of streamflow records to the frequencies of visits to the stream gages) for all stations in the analysis. A steepest-descent optimization program (the "Traveling Hydrographer") utilizes 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 stream-gaging network. Complex streamflow stations where water-surface slope or control structures affect flow were withheld from uncertainty function analysis. However, they were included in the gaging routes. The stream-gaging program that results from this analysis will meet the expressed water-data needs in the most cost-effective manner. Only the stream-gaging routes for one subdistrict office were included in the "Traveling Hydrographer" analysis, even though uncertainty functions are given for all of the stations in the network that are within the scope of the study.

This report is patterned after a prototype study for the State of Maine (Fontaine and others, 1984), and the descriptions of methods of analysis are taken from that report. This report is organized into five sections; the first being an introduction to the stream-gaging activities in Kentucky 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 phases and the dependence of subsequent phases on the previous results, conclusions are drawn at the end of each section. The entire study is summarized in the final section.

History of Stream-Gaging Program in Kentucky

The program of surface-water investigations by the Survey in Kentucky has grown rather steadily throughout the years as Federal, State, and local needs for surface-water data have increased. Most of the information which follows was taken from an open-file report by Beaber (1970). Surface-water data collection in Kentucky started with the establishment of two gages in 1907 by the Survey which were operated by the Tennessee District. The Kentucky Geological Survey was created in 1912 by the State Legislature which authorized it to cooperate with Federal agencies. In 1915, a cooperative agreement was established between the Kentucky Geological Survey and the Survey to collect streamflow data at about 3 sites. About 12 gages also were established by the Survey through a cooperative agreement with the U.S. Army Corps of Engineers as a result of the Rivers and Harbors Bill of 1915. From 1915 to 1927, about 15 stations were operated in Kentucky as a result of these cooperative efforts. By 1931, the number of gages had increased to about 30, but the reduction in funds resulting from the Depression reduced this number to only 12 gages by 1937.

In 1938, the Survey entered into a cooperative agreement with the Kentucky Department of Highways. This support, as well as support from the U.S. Army Corps of Engineers and the Works Progress Administration, warranted the establishment of a Survey District office in Louisville in 1938. By the end of that year, 32 gaging stations were in operation. A year later the number was 50. Twelve stations, located in Kentucky but operated by adjoining states, were transferred to the Louisville office during 1938-39. Over the next 10 years the number of gaging stations increased to about 90. From 1949 to 1954, some stations were also added as a result of cooperative agreements with the Soil Conservation Service and the Kentucky Department of Highways. A total of 35 gaging stations were added to the program from 1955 through 1969. Most of these gages were established in cooperation with the U.S. Army Corps of Engineers for information related to flood-control projects. By the end of the 1970 Water Year, 139 continuous-record gaging stations were in operation in Kentucky at which point Beaber (1970) completed a study of the development of the surface-water program in Kentucky and proposed a streamflow data program to meet Kentucky's future needs. Since October 1, 1985, there have been 97 daily-discharge stations and 12 stage-only stations in Kentucky.

One hundred low-flow sites were selected to provide coverage of the State during the drought of 1953. Sixty-six of these sites were eventually incorporated into a low-flow network in 1968. Some of these were subsequently dropped and 49 partial-record sites were correlated with 85 continuous-record stations, and a low-flow characteristics report was published in 1974 by the Survey (Swisshelm, 1974). Subsequently, reports by Sullavan (1980 and 1984) were published incorporating 127 and 203 partial-record sites, respectively.

In 1957 a crest-stage gage partial-record program was initiated and 36 stations were being operated by 1970. The program expanded to 119 stations in 1975. Thirty-five continuous-record stations were converted to crest-stage partial-record stations during 1965-75. The program was reduced in scope in October 1985 and now includes only 35 crest-stage partial-record stations.

Current Kentucky Steam-Gaging Program

Currently, there are 97 daily-discharge stations in Kentucky that are operated as part of the budget of $950,700. These stations are located in several physiographic regions including the Bluegrass, Eastern and Western Coal Fields, Mississippian Plateau, and the Jackson Purchase region of Kentucky (fig. 1). The distribution of stations is fairly uniform in the State, but the greatest density is in the Eastern Coal Region.

Selected hydrologic data including drainage area, period of record, and mean annual flow, for the 97 stations are listed in table 1. The stations are listed by downstream order number. Mean annual flow for stations with less than 5 years of continuous record are not shown.

USES, FUNDING, AND AVAILABILITY OF CONTINUOUS STREAMFLOW DATA

The first step of the analysis of the Kentucky stream-gaging program is to document the uses, funding, and availability of stream-flow data. The relevance of a stream gage is defined by the uses that are made of the data that are produced from the gage. The uses of the data from each gage in the Kentucky program were identified by a survey of the known data users. The results of the survey document the importance of each gage and identify gaging stations that may be considered for discontinuance.

Data uses for the daily-discharge stations are delineated using eight categories which are defined below. The source of funding and the frequency of data availability at each gage are also compiled.

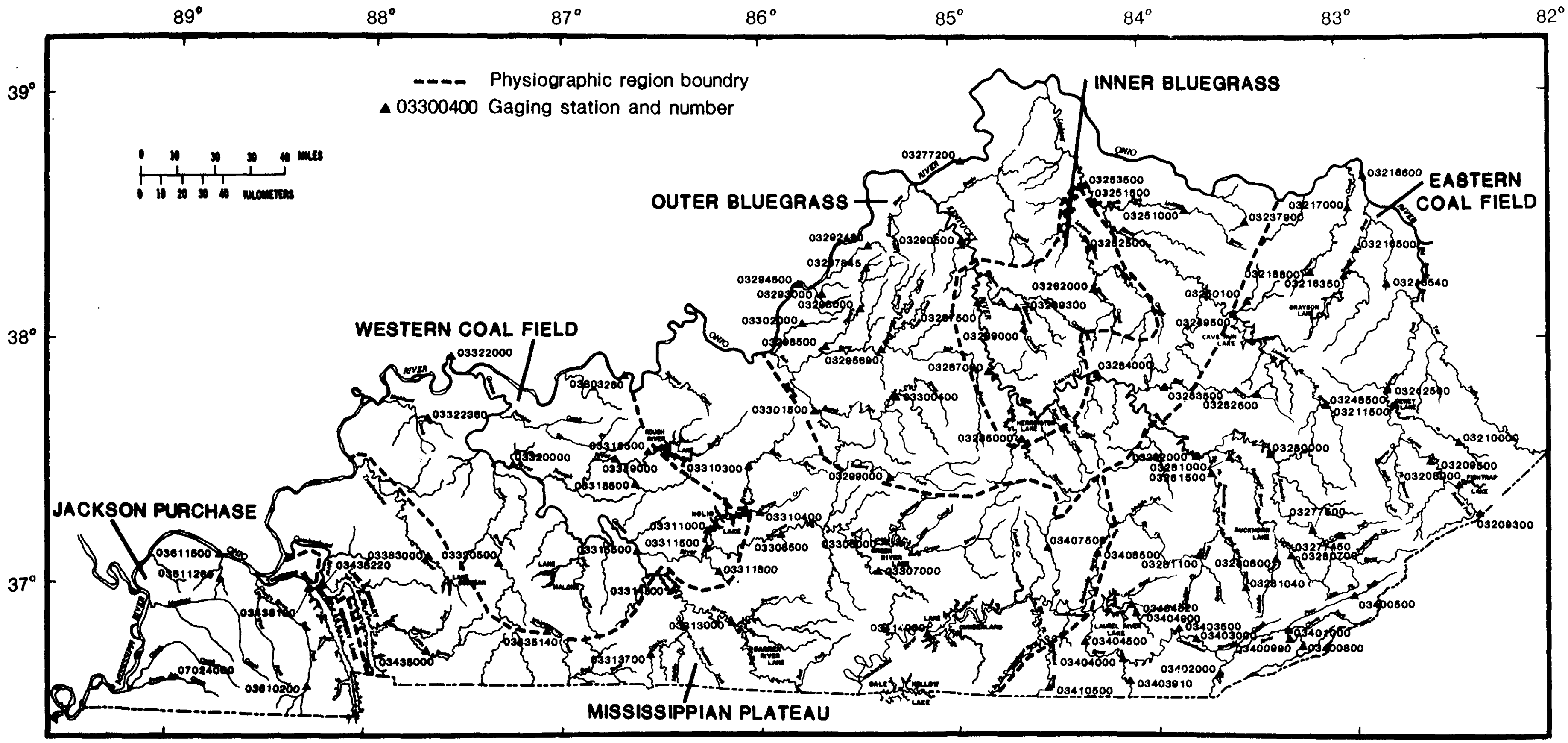

Figure 1.—Location of daily-discharge stations in Kentucky.

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

Station number	Station name	Drainage Area (square miles)	Period of record	Mean annual (cubic feet per second)
03208000	Levisa Fork below Fishtrap Dam, near Millard	392	February 1938-	476
03209300	Russell Fork at Elkhorn City	554	October 1960-	724
03209500	Levisa Fork at Pikeville	1,232	October 1937-	1,464
03210000	Johns Creek near Meta	56.3	May 1941-	69.7
03211500	Johns Creek near Van Lear	206	October 1939-	232
03212500	Levisa Fork at Paintsville	2,144	June 1915-November 1920/ 1/ October 1928-	2,472
03216350	Little Sandy River below Grayson Dam, near Leon	196	October 1966-	242
03216500	Little Sandy River at Grayson	400	April 1938- 2/	472
03216540	East Fork Little Sandy River near Fallsburg	12.2	October 1972-	15.2
03216600	Ohio River at Greenup Dam	62,000	October 1968-	91,280
03216800	Tygarts Creek at Olive Hill	59.6	January 1957-	85.9
03217000	Tygarts Creek near Greenup	242	August 1940-	304
03237900	Cabin Creek near Tollesboro	22.4	April 1972-	30.1
03248500	Licking River near Salyersville	140	October 1938-	173

See footnotes at end of table.

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

Station number	Station name	Drainage Area (square miles)	Period of record	Mean annual (cubic feet per second)
03249500	Licking River at Farmers	82.7	July 1915 - June 1920/ May 1928- September 1931/ 1/ April 1938-	1,051
03250100	North Fork Triplett Creek near Morehead	84.7	August 1967-	129
03251000	North Fork Licking River near Lewisburg	119	August 1946-	149
03251500	Licking River at McKinneysburg	2,326	July 1924- August 1926/ October 1938-	3,014
03252000	Stoner Creek at Paris	239	April 1953-	288
03252500	South Fork Licking River at Cynthiana	621	April 1938-	762
03253500	Licking River at Catawba	3,300	Jan. 1914- July 1915/ Oct. 1917- July 1920/ 1/ Aug. 1915 - Sep. 1917/ July 1928	4,126
03277200	Ohio River at Markland Dam	83,170	May 1970-	120,000
03277450	Carr Fork near Sassafras	60.6	October 1963-	76.5
03277500	North Fork Kentucky River at Hazard	466	January 1940-	577
03280000	North Fork Kentucky River at Jackson	1,101	1904-1907/ 1921- 1931/ Feb.1934- Dec. 1934/ 1/ June 1928 - Sep. 1931/ Dec. 1936- Feb.1937/ Apr.1938-	1,353
03280600	Middle Fork Kentucky River near Hyden	202	October 1957-	297

See footnotes at end of table.

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

Station number	Station name	Drainage Area (square miles)	Period of record	Mean annual (cubic feet per second)
03280700	Cutshin Creek at Wooton	61.3	October 1957-	95.4
03281000	Middle Fork Kentucky River at Tallega	537	October 1930- March 1932/ October 1939-	726
03281040	Red Bird River near Big Creek	155	August 1972-	281
03281100	Goose Creek at Manchester	163	October 1964-	266
03281500	South Fork Kentucky River at Booneville	772	March 1925- September 1931/ October 1939-	1,054
03282000	Kentucky River at Lock 14, at Heidelberg	2,657	Oct. 1925 - Sep. 1931/ Dec. 1936- Feb 1937/ July 1938-	3,623
03282500	Red River near Hazel Green	65.8	April 1954-	88.2
03283500	Red River at Clay City	362	October 1930- March 1932/ April 1938-	480
03284000	Kentucky River at Lock 10, near Winchester	3,955	October 1907-	5,249
03285000	Dix River near Danville	318	May 1905- August 1905/ 1/ October 1942-	467
03287000	Kentucky River at Lock 6, near Salvisa	5,102	October 1925- 3/	6,713
03287500	Kentucky River at Lock 4, at Frankfort	5,411	March 1905- July 1906/ 1/ October 1925-	7,075
03289000	South Elkhorn Creek at Fort Spring	24.0	March 1950-	32.6

See footnotes at end of table.

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

Station number	Station name	Drainage Area (square miles)	Period of record	Mean annual (cubic feet per second)
03289300	South Elkhorn Creek near Midway	105	September 1982-	4/
03290500	Kentucky River at Lock 2, at Lockport	6,180	October 1925-	8,279
03292460	Harrods Creek near LaGrange	24.1	December 1969-	39.3
03293000	Middle Fork Beargrass Creek at Cannons Lane, at Louisville	18.9	August 1944-	25.9
03294500	Ohio River at Louisville	91,170	January 1928-	115,800
03295890	Brashears Creek at Taylorsville	259	July 1981-	4/
03297845	Floyds Fork near Crestwood	46.7	October 1979-	54.7
03298000	Floyds Fork at Fisherville	138	August 1944-	177
03298500	Salt River at Shepherdsville	1,197	May 1938-	1,563
03299000	Rolling Fork near Lebanon	239	May 1938-	342
03300400	Beech Fork at Maud	436	August 1972-	638
03301500	Rolling Fork near Boston	1,299	May 1938-	1,798
03302000	Pond Creek near Louisville	64.0	August 1944-	90.0
03303280	Ohio River at Cannelton Dam	97,000	October 1975-	129,610

See footnotes at end of table.

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

Station number	Station name	Drainage Area (square miles)	Period of record	Mean annual (cubic feet per second)
03306000	Green River near Campbellsville	682	October 1930-March 1932/ October 1963-	1,124
03307000	Russell Creek near Columbia	188 15 5/	October 1939-	295
03308500	Green River at Munfordsville	1,673 180 5/	Feb. 1915 - Dec. 1922/ Oct. 1927-Sep. 1931/ Dec. 1936 - Feb. 1937/ Oct. 1937-	2,730
03310300	Nolin River at White Mills	357 120 5/	October 1959-	495
03310400	Bacon Creek near Priceville	85.4 31 5/	October 1959-	59.7
03311000	Nolin River at Kyrock	703 223 5/	Oct. 1930 - March 1932/ July 1939-Sep. 1950/ Oct. 1960-	938
03311500	Green River at Lock 6, at Brownsville	2,762 690 5/	Oct. 1924 - Sep. 1931/ Dec. 1936-Feb. 1937/ July 1938-	4,389
03311600	Beaverdam Creek at Rhoda	10.9	October 1972-	19.4
03313000	Barren River near Finney	942 77 5/	October 1941-September 1950/ October 1960- 6/	1,518
03313700	West Fork Drakes near Franklin	110 19 5/	June 1968-	206

See footnotes at end of table.

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

Station number	Station name	Drainage Area (square miles)	Period of record	Mean annual (cubic feet per second)
03314500	Barren River at Bowling Green	1,849 490 5/	June 1938-	2,619
03315500	Green River at Lock 4, at Woodbury	5,404 1,360 5/	December 1936- February 1937/ October 1937-	8,469
03318500	Rough River at Falls of Rough	504 110 5/	October 1939-	778
03318800	Caney Creek near Horse Branch	124	October 1956-	191
03319000	Rough River near Dundee	757 120 5/	October 1939-	1,072
03320000	Green River at Lock 2, at Calhoun	7,566 1,540 5/	March 1930- 7/	11,260
03320500	Pond River near Apex	194	August 1940- 8/	275
03322000	Ohio River at Evansville, Indiana	107,000	December 1936- 9/	133,300
03322360	Beaverdam Creek near Corydon	14.3	July 1972- September 1982/ October 1983-	15.8
03383000	Tradewater River at Olney	255 9 5/	August 1940- May 1984/ March 1985-	334
03400500	Poor Fork at Cumberland	82.3	March 1940-	142
03400800	Martins Fork near Smith	55.8	Aprli 1971-	125

See footnotes at end of table.

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

Station number	Station name	Drainage Area (square miles)	Period of record	Mean annual (cubic feet per second)
03400990	Clover Fork at Harlan	222	October 1977-	407
03401000	Cumberland River near Harlan	374	March 1940-	686
03402000	Yellow Creek near Middlesboro	60.6	August 1940-	117
03403000	Cumberland River near Pineville	809	August 1938- September 1975/ October 1979-	1,394
03403500	Cumberland River at Barbourville	960	October 1922- September 1931/ April 1948-	1,766
03403910	Clear Fork at Saxton	331	July 1968-	577
03404000	Cumberland River at Williamsburg	1,607	October 1950-	2,719
03404500	Cumberland River at Cumberland Falls	1,977	August 1907- December 1911/ October 1914-	3,181
03404820	Laurel River at Municipal Dam near Corbin	140	October 1973-	245
03404900	Lynn Camp Creek at Corbin	53.8	1957-1973/ 10/ October 1973-	89.4
03406500	Rockcastle River at Billows	604	July 1936-	935
03407500	Buck Creek near Shopville	165	October 1952-	278
03410500	South Fork Cumberland River near Sterns	954	September 1942-	1,781
03414000	Cumberland River near Rowena	5,790	October 1939-	9,113

See footnotes at end of table.

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

Station number	Station name	Drainage Area (square miles)	Period of record	Mean annual (cubic feet per second)
03435140	Whipporwill Creek near Claymour	20.8	May 1973-	36.2
03438000	Little River near Cadiz	244 94 5/	February 1940- 1/	354
03438190	Barkley-Kentucky Canal near Grand Rivers	11/	June 1966-	7,408 12/
03438220	Cumberland River near Grand Rivers	17,598	February 1939-	27,510 13/ 38,270 14/
03610200	Clarks River at Almo	134	October 1982-	4/
03611260	Massac Creek near Paducah	14.6	October 1971-	20.2
03611500	Ohio River at Metropolis, Illinois	203,000	January 1928-	272,000
07024000	Bayou De Chien near Clinton	68.7	Oct. 1939 - Sep. 1950/ Oct. 1950 - Sep. 1978/ Sep. 1984-	107

1. Gage-heights only
2. Prior to October 1964, published as "near Grayson"
3. Prior to October 1953, published as "at Lock 6, at Warwick"
4. No mean annual flow published, less than 5 years of streamflow record
5. Area that does not contribute directly to surface runoff
6. Prior to October 1950, published as "at Port Oliver Ford"
7. Prior to October 1958, published as "at Livermore"
8. October 1953 to September 1971, published as "East Fork Pond River near Apex"
9. Flows above 100,000 cfs only
10. Annual maximums only
11. Drainage area not listed
12. Deflection - meter gage
13. Prior to opening of Barkley Canal (1940-65)
14. Since opening of Barkley Canal (1965-85)

Data-Use Classes

Definitions of each of the data-use classes are defined below. These classes are: regional hydrology, hydrologic systems, legal obligations, planning and design, project operation, hydrologic forecasts, water-quality monitoring, and research. These class distinctions are not mutually exclusive and most stations are multiple-use.

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 relation between basin characteristics and streamflow.

Fifty stations in the Kentucky network are classified under regional hydrology. One station is designated as a hydrologic benchmark station, and 14 others are designated as long-term index or trend gaging stations. The bench-mark station serves as an indicator of hydrologic conditions in a watershed relatively free of man's influence. The long-term index stations provide spatial coverage of the State and indicate trends in streamflow from changing hydrologic or climatic 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 systems stations. They include diversions and return flows and stations that are useful for defining the interaction of water systems.

Fifty-two stations in the Kentucky network are classified under the hydrologic systems data-use category. Hydrologic bench-mark and index stations are included in this category because they account for current and long-term conditions of the hydrologic systems they gage. Three Federal Energy Regulatory Commission stations, which monitor the compliance of control structures to downstream flow requirements, are also included in this category. Most of the stations in this category (37) are operated for the U.S. Army Corps of Engineers to monitor regulated stream systems and may also be used for flood forecasting. One station is a National Stream Quality Accounting Network site on the Ohio River operated by the Survey. One other station is also operated to monitor a regulated stream system.

Legal Obligations

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

There are no stations in the Kentucky program that exist to fulfill a legal responsibility of the Survey.

Planning and Design

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

One station in the Kentucky program is operated for planning and design purposes.

Project Operation

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

There are currently 29 stations used in project operation. These stations are operated in support of navigation and flood-control structures. Data from 13 stations are used for maintaining a minimum pool elevation for navigation purposes, and the rest are for monitoring inflow or outflow values from flood-control structures.

Hydrologic Forecasts

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

Forty-seven stations are in this category and are used for flood forecasting by the National Weather Service.

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.

There are currently 31 stations which support water-quality monitoring activities. One station is a designated bench-mark station at which daily suspended sediment discharge, water temperature, and specific conductance are determined. Thirteen stations are part of the ambient surface water monitoring network of the Kentucky Natural Resources and Environmental Protection Cabinet. At seven other stations in the Eastern Coal Field Region daily suspended sediment discharge is also determined. Seven stations are also part of the National Stream Quality Accounting Network (NASQAN) program. Daily water temperature is determined at three stations, including the bench-mark station. A 4-parameter water-quality monitor is operated at one station and a 5-parameter water-quality monitor is operated at two stations.

Research

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

Only one station falls into this category and is funded by the Kentucky District. This site will be discontinued when project data collection is completed.

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 other agencies of the federal government.

3. Coop 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. In this study, funding from private concerns was limited to licensing and permitting requirements for hydropower development by the Federal Energy Regulatory Commission. Funds in this category are not matched by 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. Eight organizations currently are contributing funds to the Kentucky stream-gaging program.

Frequency of Data Availability

Frequency of data availability refers to the times at which the streamflow data may be furnished to the users. In this category, three possibilities exist. Data can be furnished by direct-access telemetry equipment for immediate use, by periodic release of provisional data, or in publication format through the annual data report published by the Survey for Kentucky (U.S. Geological Survey, 1985). These three categories are designated T, P, and A, respectively, in table 2. In the current Kentucky program, data for all 97 stations are made available through the annual report, data from 55 stations are available on a real-time basis, and data for 35 stations are released on a provisional basis.

Data-Use Presentation

Data-use and ancillary information are presented for each continuous gaging station in table 2. The entry of an asterisk in the table indicates that the data are used for regional hydrology.

Data-Use Conclusions

A review of the data-use and funding information presented in table 2 indicates that most stations in the Kentucky network have multiple data uses and all stations are currently funded. Many of the stations are used on an

Table 2.--Data use, station funding, and data availability

1. Multi-purpose Fishtrap Lake, Fishtrap Dam
2. Flood forecasting - National Weather Service
3. Corps of Engineers - Huntington District
4. Kentucky Geological Survey
5. Regulated Levisa Fork River system
6. Long-term index gaging station
7. Multi-purpose Dewey Lake, Dewey Dam
8. U.S. Geological Survey
9. Multi-purpose Grayson Lake, Grayson Dam
10. Regulated Little Sandy River system
11. Greenup Lock and Dam - Ohio River
12. National Stream Quality Accounting Network Station
13. Regulated Licking River system
14. Corps of Engineers - Louisville District
15. Multi-purpose Cave Run Lake, Cave Run Dam
16. Daily water temperature record
17. Ambient surface water monitoring network site
18. Kentucky Natural Resources and Environmental Protection Cabinet
19. Federal Energy Regulatory Commission, Hydropower License Requirement
20. Markland Lock and Dam - Ohio River
21. Public Service Indiana, Hydropower System Operation
22. Multi-purpose Carr Fork Lake, Carr Fork Dam
23. Regulated Kentucky River system

* No additional information
A Data published in Geological Survey Annual Data Report for Kentucky
P Periodic release of provisional data
T Data furnished by direct-access telemetry

	Data use								Funding				
Station number	Regional hydrology	Hydrologic systems	Legal oblig-ations	Planning and design	Project operation	Hydrologic forecasts	Water quality monitoring	Research	Federal program	Other Federal Agency program	Cooper-ative program	Other non Federal	Data avail-ability
03208000					1	2				3	4		AT
03209300		5				2				3	4		AT
03209500		5				2				3	4		ATP
03210000	6	5 6				2				3	4		AT
03211500					7					3	4		AT
03212500		5				2			8	3			ATP
03216350					9	2				3	4		AT
03216500		10				2				3	4		ATP
03216540	*										4		A
03216600					11	2	12		8	3			AT
03216800	6	6							8		4		AT
03217000	*								8	3	4		AP
03237900	*										4		A
03248500	*	13				2				14	4		ATP
03249500					15		16			14	4		AT
03250100	*										4		A
03251000	6	6					17				18		A
03251500		13				2				14	4		AP
03252000	6	6				2					4		A
03252500	*					2	17			14	18		AP
03253500		13				2			8	14			ATP
03277200		19			20	2	12		8	14		21	AT
03277450					22	2				14	4		AT
03277500		23				2				14	4		AT
03280000		23				2	17			14	18		AT

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

2. Flood forecasting - National Weather Service
4. Kentucky Geological Survey
6. Long-term index gaging station
8. U.S. Geological Survey
12. National Stream Quality Accounting Network Station
14. Corps of Engineers - Louisville District
17. Ambient surface water monitoring network site
18. Kentucky Natural Resources and Environmental Protection Cabinet
19. Federal Energy Regulatory Commission, Hydropower License Requirement
23. Regulated Kentucky River system
24. Lock and Dam 14 - Kentucky River
25. Lock and Dam 10 - Kentucky River
26. Inflow to Herrington Lake, Dix River Dam
27. Kentucky Utilities Company, Hydropower License Requirement
28. Lock and Dam 6 - Kentucky River
29. Lock and Dam 4 - Kentucky River
30. Regulated South Elkhorn Creek system
31. Lock and Dam 2 - Kentucky
32. McAlpine Lock and Dam - Ohio River
33. Regulated Salt River system

* No additional information
A Data published in Geological Survey Annual Data Report for Kentucky
P Periodic release of provisional data
T Data furnished by direct-access telemetry

	Data use								Funding				
Station number	Regional hydrology	Hydrologic systems	Legal oblig-ations	Planning and design	Project operation	Hydrologic forecasts	Water quality monitoring	Research	Federal program	Other Federal Agency program	Cooper-ative program	Other non Federal	Data avail-ability
03280600	*	23				2				14	4		AT
03280700	*	23								14	4		A
03281000		23					17			14	18		A
03281040	*										4		A
03281100	*	23								14	4		A
03281500	*	23				2	17			14	18		A
03282000		23			24	2				14	4		ATP
03282500	6	6									18		AP
03283500	*	23				2				14	4		AP
03284000		23			25	2			8	14			ATP
03285000	*	19			26						4	27	ATP
03287000		19 23			28	2				14	4	27	ATP
03287500		23			29	2				14	4		AP
03289000	*										4		A
03289300		30					17				18		AP
03290500		23			31		12		8	14			AT
03292460	6	6									4		A
03293000	*							8	8				A
03294500					32	2				14	4		ATP
03295890	*	33								14	4		A

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

2. Flood forecasting - National Weather Service
4. Kentucky Geological Survey
6. Long-term index gaging station
8. U.S. Geological Survey
12. National Stream Quality Accounting Network Station
14. Corps of Engineers - Louisville District
16. Daily water temperature record
17. Ambient surface water monitoring network site
18. Kentucky Natural Resources and Environmental Protection Cabinet
33. Regulated Salt River system
34. Proposed multi-purpose dam
35. Cannelton Lock and Dam - Ohio River
36. Multi-purpose Green River Lake, Green River Dam
37. Regulated Green River system
38. Hydrologic benchmark station
39. Daily specific conductance record
40. Daily suspended sediment record
41. Multi-purpose Nolin Lake, Nolin River Dam
42. Lock and Dam 6 - Green River
43. Multi-purpose Barren River Lake, Barren River Dam
44. Lock and Dam 4 - Green River
45. Multi-purpose Rough River Lake, Rough River Dam
46. Lock and Dam 2 - Green River

* No additional information
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P Periodic release of provisional data
T Data furnished by direct-access telemetry

	Data use								Funding				
Station number	Regional hydrology	Hydrologic systems	Legal oblig-ations	Planning and design	Project operation	Hydrologic forecasts	Water quality monitoring	Research	Federal program	Other Federal Agency program	Cooper-ative program	Other non Federal	Data avail-ability
03297845	*										18		A
03298000	6	6									4		A
03298500		33				2	12		8	14			ATP
03299000	6	6									4		A
03300400	*			34						14	18		AP
03301500	*					2			8	14			A
03302000	*						17				18		AP
03303280					35	2	12		8	14			AT
03306000					36		16			14	4		AT
03307000	6	6 37				2				14	4		AT
03308500	38	37 38				2	16 39 40			14	4		ATP
03310300	*						17				18		AP
03310400	*						17				18		AP
03311000					41					14	4		AT
03311500					42	2				14	4		AT
03311600	*										4		A
03313000					43	2				14	4		AT
03313700	6	6									4		A
03314500		37				2				14	4		ATP
03315500					44	2				14	4		AP
03318500					45	2				14	4		AT
03318800	6	6									4		A
03319000		37				2				14	4		ATP
03320000					46	2			8	14			AT
03320500	*						17				18		AP

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

2. Flood forecasting - National Weather Service
4. Kentucky Geological Survey
6. Long-term index gaging station
8. U.S. Geological Survey
12. National Stream Quality Accounting Network Station
14. Corps of Engineers - Louisville District
17. Ambient surface water monitoring network site
18. Kentucky Natural Resources and Environmental Protection Cabinet
40. Daily suspended sediment record
47. Newburgh Lock and Dam - Ohio River
48. Corps of Engineers - Nashville District
49. Multi-purpose Martins Fork Lake, Martins Fork Dam
50. Four parameter water-quality monitor
51. Regulated Cumberland River system
52. Five parameter water-quality monitor
53. Inflow to Laurel River Lake, Laurel River Dam
54. Multi-purpose Lake Cumberland, Wolf Creek Dam
55. Lake Barkley - Kentucky Lake Canal
56. Multi-purpose Lake Barkley, Barkley Dam

- * No additional information
- A Data published in Geological Survey Annual Data Report for Kentucky
- P Periodic release of provisional data
- T Data furnished by direct-access telemetry

	Data use								Funding				
Station number	Regional hydrology	Hydrologic systems	Legal oblig-ations	Planning and design	Project operation	Hydrologic forecasts	Water quality monitoring	Research	Federal program	Other Federal Agency program	Cooper-ative program	Other non Federal	Data avail-ability
03322000					47	2			8	14			AT
03322360	*										4		A
03383000	6	6					17			14	18		AP
03400500	*					2			8		4		AT
03400800					49		50			48	4		AT
03400990		51				2	40			48	4		AT
03401000		51				2				48	4		AT
03402000		51				2	40			48	4		AT
03403000		51				2	40			48			AT
03403500		51				2	40			48	4		AT
03403910	*								8		4		AT
03404000		51				2	40			48	4		AT
03404500	6	6 51					40 52		8	48	4		ATP
03404820					53					48	4		AT
03404900	*				53	2				48	4		AT
03406500	*	51								48	4		ATP
03407500	6	6									4		A
03410500	*	51					40 52			48			ATP
03414000					54						4		ATP
03435140	*										4		A
03438000	*	51								48	4		AT
03438190					55					48			AP
03438220					56		12			48	4		AT
03610200	*						17				18		ATP
03611260	*										4		A
03611500		8				2	12		8				A
07024000	*						17				18		AP

ongoing basis for project operation. Middle Fork Beargrass Creek at Cannons Lane at Louisville (03293000) is currently being operated for research purposes and may be discontinued if no source of funding becomes available. However, this station does provide information on urban streamflow, and long records of this type are not available at many sites in Kentucky. Other sources of funding for this station should be sought.

ALTERNATIVE METHODS OF DEVELOPING STREAMFLOW INFORMATION

The second step of the analysis of the stream-gaging program is to investigate alternative methods of providing daily streamflow information in lieu of operating continuous-flow gaging stations. The objective of the analysis is to identify gaging stations where alternative technology, such as flow-routing or statistical methods, will provide information about daily mean streamflow in a more cost-effective manner than operating a continuous stream gage. No guidelines exist concerning suitable accuracies for particular uses of the data; therefore, judgment is required in deciding whether the accuracy of the estimated daily flows is suitable for the intended purpose.

The data uses at a station will influence whether a site has potential for alternative flow estimation methods. For example, those stations for which flood hydrographs are required in a real-time sense, such as hydrologic forecasts and project operation, are not candidates for the alternative methods. Likewise, there might be a legal obligation to operate an actual gaging station that would preclude utilizing alternative methods.

The primary candidates for alternative methods are stations that are operated upstream or downstream of other stations on the same stream. The accuracy of the estimated streamflow at these sites may be suitable because of the high correlation between flows at the sites. Similar watersheds, located in the same physiographic and climatic area, also may have potential for alternative methods.

For this series of cost-effective stream-gaging strategy studies conducted by the Survey, usually only two alternative methods are considered. These are hydrologic flow-routing and regression analysis. These methods lend themselves to the limited time frame involved in the study and exhibit the desired attributes that include: (1) computer-oriented and ease of application, (2) an available interface with the Survey's WATSTORE Daily Values File (Hutchinson, 1975), (3) incorporation of technically sound methods acceptable to the hydrologic community, and (4) easy evaluation of the accuracy of the simulated streamflow records.

Most of Kentucky's streamflow stations are used for project operation or in support of those projects and alternative techniques are not feasible under any circumstance. Therefore, no alternative methods of developing streamflow information were independently investigated for this report. However, three previous related studies are cited. These studies utilized flow-routing techniques to simulate streamflow by routing observed flows downstream to selected points of interest. The theoretical background of the flow-routing techniques are briefly described in the following section.

Description of Flow-Routing Model

Hydrologic flow-routing methods use the law of conservation of mass and the relation between the storage in a reach and the outflow from the reach. The hydraulics of the system are not considered. The method usually requires only a few parameters and the reach is not subdivided. The input is usually a discharge hydrograph at the upstream end of the reach and the output, a discharge hydrograph at the downstream end. Several different types of hydrologic routing are available such as Muskingum, Modified Puls, Kinematic Wave, and the unit-response flow-routing method. The unit-response method is the method most commonly used in the cost-effective studies, and was the method used to model streamflow in two basins in Kentucky (Shearman and Swisshelm, 1973; Hale, 1979; and Sholar, 1986).

The unit-response method uses two techniques--storage continuity (Sauer, 1973) and diffusion analogy (Keefer, 1974; Keefer and McQuivey, 1974). The method can be used to route streamflow from one or more upstream locations to a downstream location. Downstream hydrographs are produced by the convolution of upstream hydrographs with their appropriate unit-response functions. This method can only be applied at a downstream site where an upstream station exists on the same stream. An advantage of this method is that it can be used for regulated stream systems. Reservoir routing techniques can be included in the model so flows can be routed through reservoirs if the reservoir operations are known. Calibration and verification of the flow-routing model is achieved using observed upstream and downstream hydrographs and estimates of tributary inflows. The convolution model treats a stream reach as a linear one-dimensional system in which the system output (downstream hydrograph) is computed by multiplying (convoluting) the ordinates of the upstream hydrograph by the unit-response function and lagging them appropriately. The model has the capability of combining hydrographs, multiplying a hydrograph by a ratio, and changing the timing of a hydrograph.

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

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

The objective in either the storage-continuity or diffusion analogy flow-routing method is to calibrate two parameters that describe the storage-discharge relation in a given reach and the traveltime of flow passing through the reach. In the storage-continuity method, a response function is derived by modifying a translation hydrograph technique developed by Mitchell (1962) to apply to open channels. A triangular pulse (Sauer, 1973) is routed through reservoir-type storage and then transformed by a summation curve technique to a unit response of desired duration. The two parameters that describe the routing reach are K_s, a storage coefficient 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 floodwave celerity. K_o controls the spreading of the wave (analogous to K_s in the storage-continuity method) and C_o controls the traveltime (analogous to W_s in the storage-continuity method). In the single linearization method, only one K_o and C_o value are used. In the multiple linearization method, C_o and K_o are varied with discharge so a table of wave celerity (C_o) versus discharge (Q) and a table of dispersion coefficient (K_o) versus discharge (Q) are used.

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

Categorization of Stream Gages by Their Potential for Alternative Methods

As mentioned previously and as indicated in table 2, a large number of stations in the Kentucky network are used for project operation or in support of those projects. Because these types of gages are not candidates for discontinuance, no stations or groups of stations were considered for alternative methods.

Studies Performed in Kentucky to Develop Streamflow Information

Three previous studies were conducted by the Kentucky District of the Survey to simulate streamflow records using flow-routing techniques. A digital model of the upper Kentucky River basin was developed to estimate the regulated low-flow characteristics of the Kentucky River at Lock 10 near Winchester, Kentucky (Shearman and Swisshelm, 1973). Increased knowledge of low-flow characteristics would aid water managers in decisions regarding municipal water supply and construction of additional reservoirs. Another study was made to simulate flows on streams in the Green River basin (Hale, 1979). The modeling effort was conducted to provide estimates of reservoir-altered low-flow characteristics for eight sites in the Green River basin. During the course of the study, 11 channel-routing submodels were calibrated and, where possible, verified. The third study was made to simulate flows on the main stem of the Kentucky River near Lexington and Frankfort, Kentucky (Sholar, 1986). The stream-flow routing model provides a tool to evaluate the stresses on the stream flow characteristics of that portion of the Kentucky River. Unlike the previous two studies, no attempt was made to route flow through a reservoir.

Upper Kentucky River Basin Study

To aid water managers in decisions regarding municipal water supply in the Kentucky River basin, increased knowledge of low-flow characteristics are needed. A study was made to investigate the application of river basin modeling in determining regulated low-flow characteristics for the Kentucky River at Lock 10 near Winchester, Kentucky.

The study was divided into four reaches and three submodels were used to route daily flows both in a downstream and upstream direction, and through a reservoir. Homogeneous streamflow data for 31 years were simulated for both natural and regulated conditions at four sites (Shearman and Swisshelm, 1973). Segments of the data were compared with observed data to evaluate the adequacy of the model. An adjustment was made to the computed values when it was discovered that the simulated values were not accounting for leakage and storage from the locks and dams in reaches 3 and 4. When the adjustment was made, the frequency curves from simulated and observed flows showed reasonably close agreement.

Kentucky River Basin Study

Because of expected population increases in the Kentucky River basin, especially with regard to the cities of Frankfort and Lexington, a streamflow-routing model was developed for the main stem of the Kentucky River. This model could be used to evaluate various stresses, such as water supply, placed on the streamflow of the Kentucky River and would be an aid in water-resources planning and management.

The stream was divided into four reaches, and the model was developed to simulate daily streamflows at the downstream end of each reach. The model was calibrated using 2 years of observed streamflow record for each reach (Sholar, 1986). Results of statistical analyses on observed and simulated flows from

1941 to 1981 indicated close agreement. For all four reaches for the periods analyzed, simulated values were within 15 percent of observed values 60 percent of the time. Simulated 7-day, 10-year low-flow frequency discharge values were 7 to 29 percent less than those determined from observed flow values. Flow duration curves generated from simulated flow values showed close agreement with those of observed values, except in the high exceedance range (generally, greater than 90 percent). The results of the statistical analyses indicate that the model yielded reasonable simulated flow values.

Green River Basin Study

The Green River is used for barge traffic, steam power generation, and water supply. Four major flood-control structures were built in the basin and significantly affect downstream flow characteristics. A digital-computer model of the reservoirs and the stream reaches from the reservoirs downstream to a particular site was developed to simulate mean daily streamflows. The purpose of the study was to provide estimates of reservoir-altered low-flow characteristics for eight stream sites downstream of the reservoirs.

The four reservoir submodels adhere to a particular regulation schedule, but each could be altered to simulate different release conditions. The basin model included eight channel-routing submodels. Three additional channel-routing submodels were developed for use in estimating reservoir inflows and index station flows. Using streamflow information from 13 sites as inputs to the model, simulations of 1941 to 1971 streamflows were made for both pre- and post-reservoir basin conditions. This supplied a homogeneous data set for the analysis of low-flow characteristics at eight selected stream sites (Hale, 1979).

Results from the model simulations indicated that for seven of eight stream sites the simulated pre-reservoir annual minimum 7-day average discharges are not significantly different from the observed flows. However, for the post-reservoir conditions, the simulated discharges are significantly different from the observed values but only 2 complete years of streamflow data were available for comparison. This indicates that the actual reservoir operation was not matched by the model and that there may be errors in the estimated reservoir inflows.

Conclusions of Alternative-Methods Analysis

As indicated by the results of the three reports mentioned, plots of annual minimum 7-day discharges computed from observed and simulated daily streamflow data showed good agreement. The majority of the information used for these flow-routing studies came from gage installations which are designated for project operations and/or hydrologic forecasts. These gages monitor either the outflow from regulated sytems or the stage required to facilitate barge operations. It is academic, therefore, whether streamflow could be adequately simulated to the extent that a gage could be eliminated. The results of these flow-routing studies are, however, useful for record reconstruction when a gage is inoperative. Flows can be simulated and a level of confidence associated with the estimates.

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 Kalman-filtering cost-effective resource allocation (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. While such a tendency is appropriate for a water-balance network, in the broader context of the multitude of uses of the streamflow data collected in the Survey's Streamflow Information Program, this tendency causes undue concentration on larger 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, or average instantaneous discharge in percentage.

The use of percentage errors does not unduly weight activities at large streams to the detriment of records on small streams. In addition, the instantaneous discharge is the basic variable from which all other streamflow data are derived. For these reasons, this study used the K-CERA techniques with the sums of the variances of the percentage errors of the instantaneous discharges at all continuously gaged sites as the measure of the effectiveness of the data-collection activity.

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

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

Description of Mathematical Program

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

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

The final step is to use all of the above to determine the number of times, N_i, that the i^{th} route for $i = 1, 2, \ldots, NR$, 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 is minimized. Figure 2 represents this step in the form of a mathematical program. Figure 3 presents a tabular layout of the problem. Referring to these figures, 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 traveltime 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 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.

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

$V \equiv$ total uncertainty in the network

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

$MG \equiv$ number of gages in the network

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

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

Such that

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

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

$F_c \equiv$ fixed cost

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

$NR \equiv$ number of practical routes chosen

$\beta_i \equiv$ travel cost for route i

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

and such that

$$M_j \geq \lambda_j$$

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

Figure 2.--Mathematical-programming form of the optimization of the routing of hydrographers.

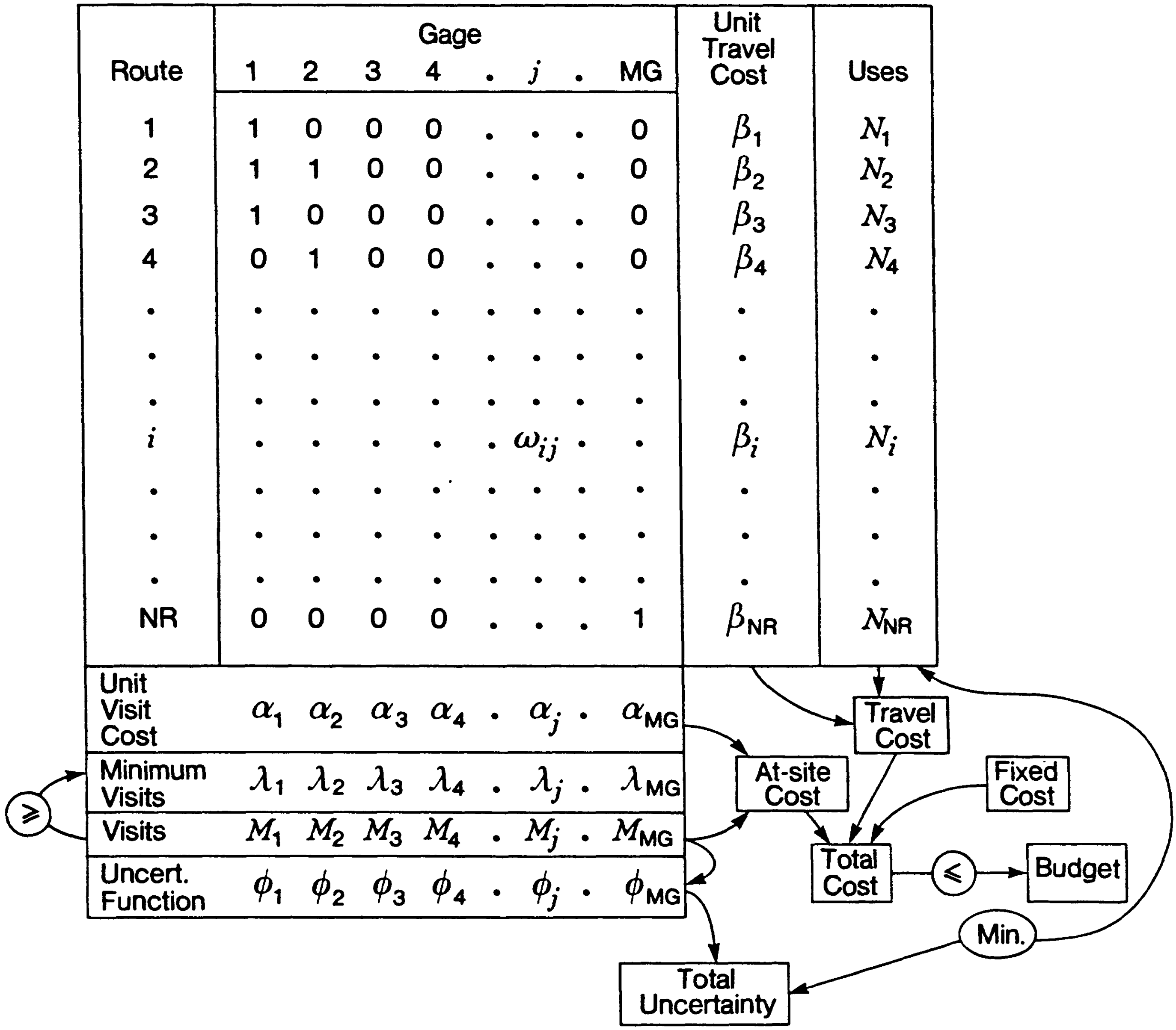

Figure 3.--Tabular form of the optimization of the routing of hydrographers.

M_j is the sum of the products of ω_{ij} and N_i for all i and must equal or exceed λ_j for all j if $\underline{N}$ is to be a feasible solution to the decision problem.

The total cost expended at the stations is equal to the sum of the products of α_j and M_j for all j. The cost of record computation, documentation, and publication is assumed to be influenced negligibly by the number of visits to the station and is included along with overhead, F_c, in the fixed cost of operating the network. The total cost of operating the network, T_c, 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, V, is determined by summing the uncertainty functions, ϕ_j, evaluated at the value of M_j from the row above it, for j = 1, 2, ..., MG.

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

Description of Uncertainty Functions

As noted earlier, uncertainty in streamflow records is measured in this study as the average relative variance of estimation of instantaneous discharges. The accuracy of a streamflow estimate depends on how that estimate was obtained. Three situations are considered in this study: (1) streamflow is estimated from measured discharge and correlative data using a stage-discharge relation (rating curve), (2) the streamflow record is reconstructed using secondary data at nearby stations because primary correlative data are missing, 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:

$$\bar{V} = \xi_f V_f + \xi_r V_r + \xi_e V_e \qquad (1)$$

with

$$1 = \xi_f + \xi_r + \xi_e \qquad (2)$$

where

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

ξ_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,

ξ_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,

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

V_e is the relative error variance of the third situation.

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

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

$$f(\tau) = ke^{-k\tau}/(1-e^{-ks}) \qquad (3)$$

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:

$$\xi_f = (1-e^{-ks})/(ks) \qquad (4)$$

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

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

$$\xi_e = 1 - [2(1-e^{-ks}) + 0.5(1-e^{-2ks})]/(ks) \qquad (5)$$

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

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

$$\xi_r = 1 - \xi_f - \xi_e = [(1-e^{-ks}) + 0.5(1-e^{-2ks})]/(ks). \qquad (6)$$

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

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

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

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

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

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

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

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

where

v(t)	is the measurement error, and
$\ln q_m(t)$	is the logarithm of the measured discharge equal to plus v(t).

In the Kalman-filter analysis, the z(t) time series was analyzed to determine three site-specific parameters. The Kalman filter used in this study assumes that the time residuals, x(t), arise from a continuous first-order Markovian process that has a Gaussian (normal) probability distribution with zero mean and variance (subsequently referred to as process variance) equal to p. A second important parameter is β, the reciprocal of the correlation time of the Markovian process giving rise to x(t); the correlation between $x(t_1)$ and $x(t_2)$ is exp $[-\beta|t_1-t_2|]$. Fontaine and others (1984) also define q, the constant value of the spectral density function of the white noise which drives the Markovian process. The parameters, p, q, and β are related by:

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

The variance of the observed residuals, z(t), is:

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

where r is the variance of the measurement error v(t).

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

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

$$\bar{C}_v = \left[\frac{1}{365} \sum_{i=1}^{365} \left(\frac{\sigma i}{\mu i}\right)^2 \right]^{\frac{1}{2}} \tag{12}$$

where

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

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

$\bar{C}_v^2$ is the 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^2 between the streamflows with seasonal trends removed at the site of interest and detrended streamflows at the other sites is a measure of the goodness of their linear relationship. The fraction of the variance of streamflow at the primary site that is explained by data from the other sites is equal to ρ_c^2. Thus, the relative error variance of flow estimates at the primary site obtained from secondary information will be:

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

Because errors in streamflow estimates arise from three different sources with widely varying precisions, the resultant distribution of those errors may differ significantly from a normal or log-normal distribution. This lack of normality causes difficulty in interpretation of the resulting average estimation variance. When primary and secondary data are unavailable, the relative error variance V_e may be very large. This could yield correspondingly large values of $\bar{V}$ in equation (1) even if the probability that primary and secondary information are not available, ξ_e, is quite small.

A new parameter, the equivalent Gaussian spread (EGS), is introduced here to assist in interpreting the results of the analyses. If it is assumed that the various errors arising from the three situations represented in equation (1) are normally distributed, the value of EGS was determined by the probability statement that:

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

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

The Application of K-CERA in Kentucky

The continuation of all of the currently existing daily-discharge stations operated by the Kentucky District was assumed as a result of the first two parts of this analysis, even though the funding at one site in the research category will be discontinued when the project data collection is completed. Therefore, all 97 daily discharge stations currently in operation were subject to the K-CERA analysis.

Uncertainty functions were computed for only 63 of the 97 daily discharge stations currently in operation in the Kentucky District. The majority of the 34 stations that were excluded, (1) experienced a rating change or channel changes where the number of consecutive measurements were not adequate to define uncertainty functions, or (2) were stations where stage-fall discharge ratings are applied. Uncertainty functions were not determined for stations in the second category because this type of gaging operation was considered outside the scope of this study. Excluded stations, and the reason they were excluded from the analysis are summarized in table 3. Uncertainty functions were also not defined for the crest-stage partial-record stations given in table 4 because continuous record is not collected at these sites.

Even though uncertainty functions were defined for 63 streamflow stations, only the stations in the Louisville Subdistrict operation were used as input for the "Traveling Hydrographer" analysis. It was decided that the analysis of one subdistrict operation would be adequate in evaluating the cost-effectiveness of the entire District stream-gaging operation. The other field offices are run in similar fashion with approximately the same number of sites for the available personnel.

Determination of Missing Record Probabilities

As described earlier, the statistical characteristics of missing stage or other correlative data for computation of streamflow records can be defined by a single parameter. This parameter is 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 3, the average

Table 3.--Stations with no defined uncertainty function

1. Slope station
2. Rating change
3. Lacks adequate number of consecutive measurements
4. Outflow from a control structure
5. Deflection gage

Station number	Station name	Reason uncertainty function not determined
03216600	Ohio River at Greenup Dam	1
03249500	Licking River at Farmers	1
03250100	North Fork Triplett Creek near Morehead	2
03277200	Ohio River at Markland Dam	1
03280700	Cutshin Creek at Wooton	2
03284000	Kentucky River Lock 10, near Winchester	1
03285000	Dix River near Danville	1
03287000	Kentucky River Lock 6, near Salvisa	1
03287500	Kentucky River Lock 4, at Frankfort	1
03289300	South Elkhorn Creek near Midway	3
03290500	Kentucky River Lock 2, at Lockport	1
03294500	Ohio River at Louisville	1
03295890	Brashears Creek at Taylorsville	1
03298500	Salt River at Shepherdsville	1
03301500	Rolling Fork near Boston	1
03303280	Ohio River at Cannelton Dam	1
03311000	Nolin River at Kyrock	1
03311500	Green River Lock 6, at Brownsville	1
03311600	Beaverdam Creek at Rhoda	2
03314500	Barren River at Bowling Green	1
03315500	Green River Lock 4, at Woodbury	1
03319000	Rough River near Dundee	1
03320000	Green River Lock 2, at Calhoun	1
03322000	Ohio River at Evansville	1
03401000	Cumberland River near Harlan	2
03403000	Cumberland River near Pineville	1
03403500	Cumberland River at Barbourville	1
03404820	Laurel River at Municipal Dam near Corbin	4
03414000	Cumberland River near Rowena	3
03438190	Barkley-Kentucky Canal near Grand Rivers	5
03438220	Cumberland River near Grand Rivers	1
03610200	Clarks River at Almo	3
03611500	Ohio River at Metropolis, Illinois	1
07024000	Bayou de Chien near Clinton	2

Table 4.--Crest-stage gages in Kentucky

Station number	Station name
03210160	Caney Fork near Gulnare
03212515	Rush Fork near Paintsville
03216563	Mile Branch near Rush
03250150	Indian Creek near Owingsville
03260012	Pleasant Run Creek Tributary at Fort Mitchell
03277070	Fowlers Fork at Union
03277290	Bottom Fork near Mayking
03280935	Stamper Fork at Canoe
03282198	Clear Creek Tributary near West Irvine
03287128	Tanners Creek at Mortonsville
03289190	Wolf Run at Cambridge Drive near Lexington
03290000	Flat Creek near Frankfort
03291500	Eagle Creek at Glencoe
03292472	South Fork Harrods Creek near Crestwood
03300065	North Prong near Willisburg
03305835	Gum Lick Creek Tributary at Clementsville
03310385	Bacon Creek Tributary at Upton
03313020	Solomon Creek Tributary near Scottsville
03314750	Barren River Tributary near Bowling Green
03318500	Pleasant Run Tributary near Falls of Rough
03400700	Clover Fork at Evarts
03401400	Little Yellow Creek at Middlesboro
03401500	Yellow Creek Bypass at Middlesboro
03406000	Wood Creek near London
03407100	Cane Branch near Parkers Lake
03407200	Westfork Cane Branch near Parkers Lake
03407300	Helton Branch near Greenwood
03413202	Elk Spring Creek near Spann
03414102	Bear Creek near Burksville
03437490	South Fork Little River Tributary near Hopkinsville
03438120	North Fork Dryden Creek Tributary near Confederate
03610470	York Creek near Benton
07022500	Perry Creek at Mayfield
07023040	Lick Creek Tributary near Kirbyton
07023935	South Fork Bayou de Chien Tributary near Water Valley

time to failure is 1/k. The value of 1/k varies from site to site depending upon the type of equipment at the site and upon its exposure to natural elements and vandalism. The value of 1/k can be changed by advances in the technology of data collection and recording.

Because only the stations in one subdistrict office were used in the actual cost-effective gaging analysis, missing record was determined for the stations serviced by that office only. This included 21 stations, and missing record was determined for each station for the period 1978-84. The period coincides with the time period from which the measurements were made to define the uncertainty functions. The lost record averaged 4.6 percent, and no distinction was made for sites having back-up recorders. Using this value of missing record and a frequency of eight visits per year, a value of 1/k of 443 days was obtained and was used to determine ξ_f, ξ_e, and ξ_r for each of the 63 stream gages as a function of the individual frequencies of visit.

Determination of Cross-Correlation Coefficient and Coefficient of Variation

To compute the values of V_e and V_r of the needed uncertainty function, daily streamflow records for each of the 63 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 correlations were explored to determine the maximum ρ_c. All stations had more than 3 water years of record.

The set of parameters for each station and the auxiliary records that gave the highest cross correlation coefficient are listed in table 5.

Kalman-Filter Determination of Variance

The determination of the variance V_f for each of 63 stream gages required the execution of three distinct steps: (1) the development of a long-term rating and the computation of residuals of the logarithms of the measured discharges from the logarithms of the long-term rating, (2) time series analysis of the residuals to determine the input parameters of the Kalman-filter streamflow records, and (3) computation of the error variance, V_f, as a function of the time-series parameters, the discharge-measurement error variance, and the frequency of discharge measurement.

Table 5.--Statistics of record reconstruction

Station number	Coefficient of variation	Coefficient of cross correlation	Source of reconstructed records (lag, in days)
03208000	1.45	0.873	03209500 (0)
03209300	1.23	.901	03209500 (0)
03209500	1.35	.910	03212500 (1)
03210000	1.81	.812	03212500 (1)
03211500	1.76	.761	03212500 (0)
03212500	1.29	.910	03209500 (-1)
03216350	1.43	.827	03216500 (0)
03216500	1.63	.827	03216350 (0)
03216540	1.64	.682	03216800 (0)
03216800	2.07	.823	03217000 (1)
03217000	1.94	.826	03216800 (-1)
03237900	1.86	.724	03251000 (0)
03248500	1.74	.822	03282500 (0)
03251000	2.25	.743	03253500 (1)
03251500	1.53	.980	03253500 (0)
03252000	2.16	.744	03283500 (0)
03252500	2.06	.863	03253500 (0)
03253500	1.62	.980	03215000 (0)
03277450	1.64	.764	03277500 (0)
03277500	1.61	.845	03280000 (0)
03280000	1.51	.917	03282000 (0)
03280600	1.67	.874	03280700 (0)
03281000	1.31	.833	03282000 (0)
03281040	1.50	.806	03281100 (0)
03281100	1.78	.806	03281040 (0)
03281500	1.74	.890	03282000 (0)
03282000	1.41	.921	03284000 (0)
03282500	1.87	.854	03283500 (0)
03283500	1.67	.854	03282500 (0)
03289000	1.72	.740	03284550 (0)
03292460	2.07	.753	03298000 (0)
03293000	1.66	.807	03298000 (0)
03297845	1.27	.560	03298000 (0)
03298000	2.32	.753	03292460 (0)
03299000	2.13	.778	03307000 (0)

Table 5.--Statistics of record reconstruction--Continued

Station number	Coefficient of variation	Coefficient of cross correlation	Source of reconstructed records (lag, in days)
03300400	1.67	0.730	03299000 (0)
03302000	1.88	.610	03299000 (0)
03306000	1.51	.685	03308500 (0)
03307000	1.89	.788	03308500 (0)
03308500	1.37	.788	03307000 (-1)
03310300	1.35	.868	03310400 (0)
03310400	1.29	.735	03308500 (1)
03313000	1.05	.387	03308500 (-1)
03313700	1.46	.633	03311600 (0)
03318500	1.17	.797	03319000 (0)
03318800	2.22	.671	03319000 (0)
03320500	2.16	.697	03383000 (0)
03322360	1.81	.345	03320500 (0)
03383000	2.13	.736	03320500 (-1)
03400500	1.22	.893	03401000 (0)
03400800	1.16	.720	03401000 (0)
03400990	.98	.756	03401000 (0)
03402000	1.65	.777	03403000 (0)
03403910	1.33	.773	03402000 (0)
03404000	1.36	.979	03404500 (0)
03404500	1.32	.979	03404000 (0)
03404900	1.44	.807	03404820 (0)
03406500	1.84	.825	03407500 (0)
03407500	2.10	.825	03406500 (0)
03410500	1.63	.802	03403910 (0)
03435140	1.72	.612	03313700 (0)
03438000	1.39	.600	03435140 (-1)
03611260	1.89	.512	07024000 (0)

Even though all 63 stations were not used in the "Traveling Hydrographer", the results of this analysis are useful in identifying which stations outside the Louisville Subdistrict have a high associated uncertainty. These sites could be visited more frequently, when possible, to reduce the uncertainty.

A long-term rating was defined for each of the 63 continuous recording gaging stations in Kentucky using procedures outlined by Fontaine and others, (1984). Most of the ratings were determined using 50 to 75 discharge measurements made during the period 1977-84. The measurements were plotted against the corresponding stream stage on logarithmic paper, and a best fit curve drawn through all the points. These long-term ratings were used to compute the time series of residuals (logarithm of measured discharge minus logarithm of rated discharge) for determining the input parameters of the Kalman-filter streamflow records.

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 measurement error. For the Kentucky program, measurement error ranges from 2 to 10 percent, with most stations being 5 to 8 percent. Therefore, all open-water measurements were assumed to have a measurement error of 5 percent. The total error variance for Cumberland River at Stearns (03415000) was set at 2 percent because the process variance was less than the measurement variance when a 5 percent measurement error was assumed.

As discussed earlier, q and β can be expressed as the process variance of the shifts from the rating curve and the 1-day autocorrelation coefficient of these shifts. A summary of the autocovariance analysis expressed in terms of process variance and 1-day autocorrelation is presented in table 6.

Several stations had streamflow record lengths shorter than that needed to determine uncertainty functions. In most cases, the channel had undergone a severe change which altered the shape of the existing rating. These stations are listed in table 3. An uncertainty function was not assigned for those sites, and they were treated as dummy stations in the route schematizations.

The autocovariance parameters, summarized in table 6, and data from the definition of missing record probabilities, summarized in table 5, were used to define uncertainty functions for each gaging station. The uncertainty functions relate total error variance to the number of visits and discharge measurements. Typical examples of the uncertainty function are indicated by the two stations shown in figure 4. These functions are based on the assumption that a measurement was made during each visit to the station.

Table 6.--Summary of autocovariance analysis

Station number	Station name	RHO	Process variance (log base 10)^2
03208000	Levisa Fork below Fishtrap Dam, near Millard	0.886	0.0019
03209300	Russell Fork at Elkhorn City	.990	.0042
03209500	Levisa Fork ar Pikeville	.928	.0105
03210000	Johns Creek near Meta	.975	.0212
03211500	Johns Creek near Van Lear	.945	.0013
03212500	Levisa Fork at Paintsville	.928	.0006
03216350	Little Sandy River below Grayson, Dam, near Leon	.933	.0032
03216500	Little Sandy River at Grayson	.898	.0021
03216540	East Fork Little Sandy River near Fallsburg	.936	.0218
03216800	Tygarts Creek at Olive Hill	.957	.0482
03217000	Tygarts Creek near Greenup	.975	.0382
03237900	Cabin Creek near Tollesboro	.975	.0169
03248500	Licking River near Salyersville	.968	.0296
03251000	North Fork Licking River near Lewisburg	.951	.0131
03251500	Licking River at McKinneysburg	.962	.0033
03252000	Stoner Creek at Paris	.972	.0111
03252500	South Fork Licking River at Cynthiana	.920	.0024
03253500	Licking River at Catawba	.967	.0016
03277450	Carr Fork near Sassafras	.987	.0138
03277500	North Fork Licking River at Hazard	.934	.0850
03280000	North Fork Kentucky River at Jackson	.618	.0009
03280600	Middle Fork Kentucky River near Hyden	.955	.0118
03281000	Middle Fork Kentucky River at Tallega	.909	.0083
03281040	Red Bird River near Big Creek	.979	.0790
03281100	Goose Creek at Manchester	.988	.0265
03281500	South Fork Kentucky RIver at Booneville	.969	.0084
03282000	Kentucky River at Lock 14, at Heidelberg	.638	.0010
03282500	Red River near Hazel Green	.994	.0140
03283500	Red River at Clay City	.970	.0054
03289000	South Elkhorn Creek at Fort Spring	.973	.0212
03292460	Harrods Creek near LaGrange	.906	.0127
03293000	Middle Fork Beargrass Creek at Cannons Lane, at Louisville	.982	.0070

Table 6.--Summary of autocovariance analysis--Continued

Station number	Station name	RHO	Process variance (log base 10)^2
03297845	Floyds Fork near Crestwood	0.973	0.0048
03298000	Floyds Fork at Fisherville	.980	.0171
03299000	Rolling Fork near Lebanon	.980	.0164
03300400	Beech Fork at Maud	.975	.0044
03302000	Pond Creek near Louisville	.998	.0529
03306000	Green River near Campbellsville	.940	.0013
03307000	Russell Creek near Columbia	.988	.0275
03308500	Green River at Munfordsville	.966	.0004
03310300	Nolin River at White Mills	.967	.0005
03310400	Bacon River near Priceville	.994	.0075
03313000	Barren River near Finney	.948	.0071
03313700	West Fork Drakes Creek near Franklin	.965	.0048
03318500	Rough River at Falls of Rough	.971	.0012
03318800	Caney Creek near Horse Branch	.943	.0787
03320500	Pond River near Apex	.946	.0219
03322360	Beaverdam Creek near Corydon	.980	.0563
03383000	Tradewater River at Olney	.943	.0872
03400500	Poor Fork at Cumberland	.987	.0035
03400800	Martins Fork near Smith	.967	.0142
03400900	Clover Fork at Harlan	.988	.0410
03402000	Yellow Creek near Middlesboro	.967	.0071
03403910	Clear Fork at Saxton	.922	.0004
03404000	Cumberland River at Williamsburg	.947	.0011
03404500	Cumberland River at Cumberland Falls	.972	.0007
03404900	Lynn Camp Creek at Corbin	.972	.0026
03406500	Rockcastle River at Billows	.973	.0010
03407500	Buck Creek near Shopville	.957	.0083
03410500	South Fork Cumberland River near Sterns	.973	.0002
03435140	Whipporwill Creek near Claymour	.661	.0200
03438000	Little River near Cadiz	.957	.0024
03611260	Massac Creek near Paducah	.641	.0142

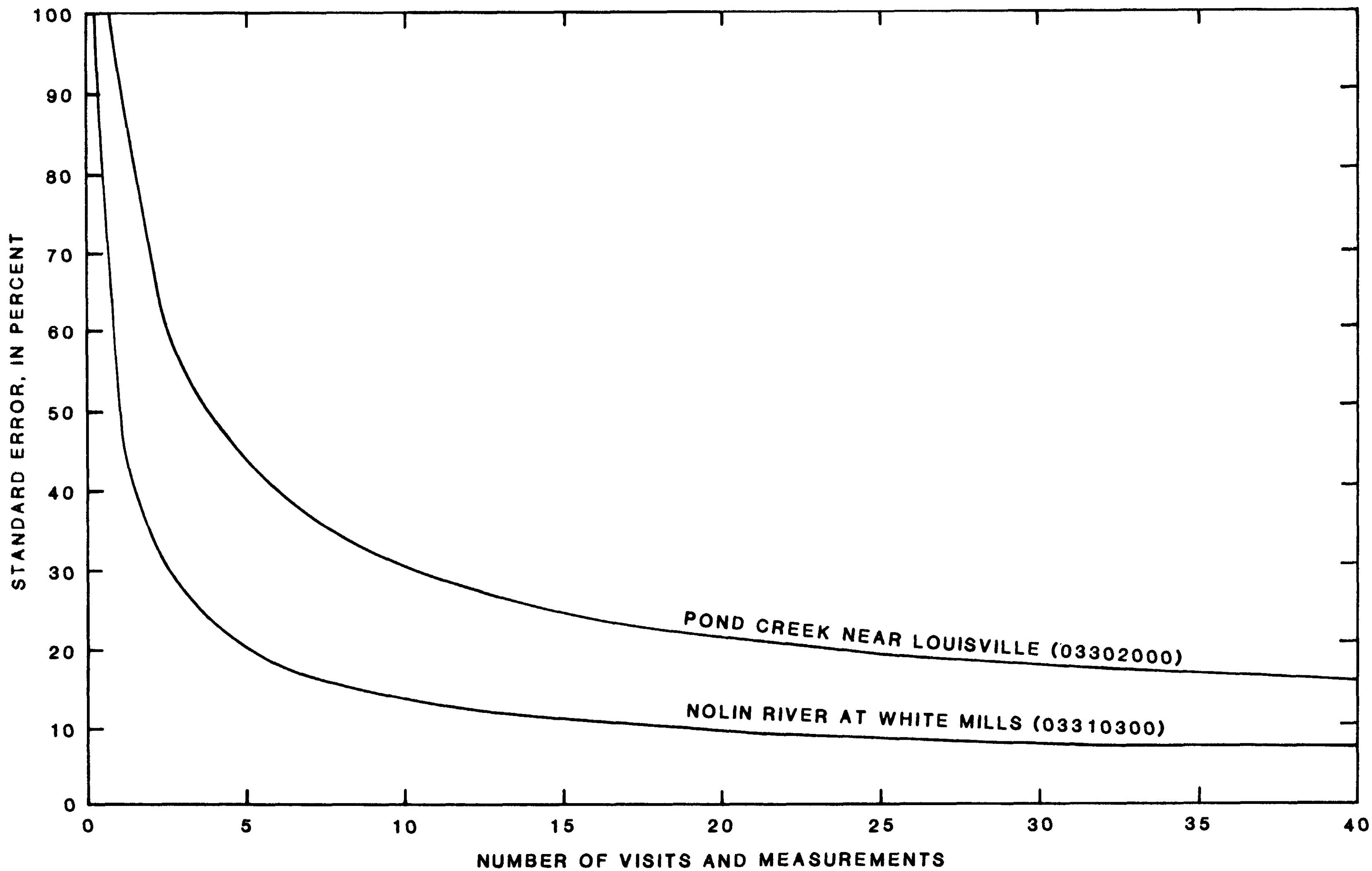

Figure 4.--Typical uncertainty functions for instantaneous discharge.

Determination of Routes

Feasible routes to service the 21 stations operated out of the Louisville Subdistrict and for 27 dummy sites, were determined after consultation with personnel in the Hydrologic Data Section of that office and after review of the uncertainty functions. The dummy sites included continuous streamflow gages where the uncertainty function was not determined, crest-stage partial record stations, stage-only stations and an acid rain monitoring station. NASQAN stations are run on a station by station basis, and are therefore not included in the analysis. The only ground-water stations in the network are those which are measured on a bi-yearly basis, and 11 stations where continuous water-level data are recorded. The bi-yearly sites were not included in the routes, and the other 11 sites were also excluded from the analysis because they are run as a single trip and are in the immediate proximity of the Louisville office.

In summary, 24 routes were selected to service 48 stations, of which 21 stations were used to evaluate the most effective scheme. These routes included current operating practice. Alternate routes which include key individual stations and combinations that grouped proximate stations where more visits might decrease the uncertainty were also determined. These routes and the stations visited on each route are given in table 7. The dummy stations (i.e. stations not used in the optimization scheme) are indicated by a negative sign (-) before the station number. The acid rain site was given the station number, 00000001.

The costs associated with operating the station must be determined. This cost was broken into three categories: (1) the fixed cost, (2) the visit cost, and (3) the route cost. The fixed costs to operate a gage typically include equipment rental, batteries, electricity, data processing and storage, computer charges, maintenance and miscellaneous supplies, and analysis and supervisory charges. An average fixed cost was applied to all of the gaging stations. Visit costs are those costs associated with making a discharge measurement. These costs vary from station to station and are a function of the difficulty and time required to make the discharge measurement. Average visit times were calculated for each station based on an analysis of discharge measurement data available. This time was then multiplied by the average hourly salary of hydrographers to determine average visit costs. Route costs include the vehicle cost associated with driving the route, the cost of the hydrographer's time spent while in transit and servicing the recording equipment, and any per diem associated with the time it takes to complete the trip.

K-CERA Results

The "Traveling Hydrographer Program" utilizes the uncertainty functions along with the appropriate cost data and route definitions to compute the most cost-effective way of operating the stream-gaging program. The first step in the analysis is to simulate current operating practice and determine the total uncertainty for it. This simulation assumes a regular field schedule

Table 7.--Summary of the routes that may be used to visit stations out of the Louisville Subdistrict

Route number	Stations serviced on the route (the negative sign before the station number denotes a dummy station)			
1	03302000	03293000	03300400	-03300065
	-03295890	03292460	03297845	-03292472
	-03301500	-03301630	03298000	
2	-03310385	03308500	-03311600	03307000
	-03306500	03306000	-03305835	03299000
	03310300	03310400		
3	-03250150	-03249500	-03250000	-00000001
	03250100	03251000	03237900	-03238000
	03255000	-03260012	-03277070	03253500
	03251500	03252500	03252000	
4	-03287500	03289300	-03289190	-03284000
	-03283500	-03282500	-03282198	03289000
	-03285000	-03287250	-03287000	-03287128
5	03302000	03293000		
6	03300400	-03300065	-03295890	
7	03292460	03297845	-03292472	
8	-03301500	-03301630		
9	03298000			
10	-03310385	03308500		
11	-03311600	03307000	-03306500	
12	03306000	-03305835	03299000	
13	03310300	03310400		
14	-03250150	-03249500	-03250000	
15	-00000001	03250100	03251000	
16	03237900	-03238000	-03255000	-03260012

Table 7.--Summary of the routes that may be used to visit stations out of the Louisville Subdistrict--Continued

Route number	Stations serviced on the route (the negative sign before the station number denotes a dummy station)		
17	-03277070	03253500	03251500
18	03252500	03252000	
19	-03287500	-03289300	
20	-03289190	-03284000	
21	03283500	03282500	-03282198
22	03289000	-0328500	
23	-03287750		
24	-03287000	-03287128	

performed at a fixed interval. It cannot account for additional measurments made at selected stations because of extreme events, such as floods or droughts. This additional information, plus the use of adjustments or shifts to the stage-discharge rating resulting from the measurements, should produce a standard error less than that determined using the autocovariance analysis. The relative magnitude of the standard error, however, can be used for comparative purposes to determine a more cost-effective operation of the stream-gaging program. The standard errors of estimate given in the report are those that would occur if daily discharges were computed through the use of methods described in this study. No attempt has been made to estimate standard errors for discharges that are computed by other means. Such errors could differ from the errors computed in this report. The magnitude and direction of the differences would be a function of methods used to account for shifting controls and for estimating discharges during periods of missing record. Additionally, because of the non-normality associated with the distribution of errors, the value of Equivalent Gaussion Spread (EGS), as defined previously, is also determined. The EGS can be interpreted as the percent (plus or minus) of the reported value that two-thirds of the errors in instantaneous streamflow data will be within.

The primary constraint on the program is the minimum number of visits to maintain the equipment in working order. 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. This number was set at four visits per year for the daily discharge stations. This value was based on limitations of the batteries used to drive recording equipment, and the capacity of uptake spools on the digital recorders.

Minimum visit requirements should also reflect the need to visit stations for special reasons such as water-quality sampling. In the Louisville Subdistrict, water-quality field work is being done on separate field trips and, therefore, did not influence minimum visit requirements.

The results of the K-CERA analyses for the Louisville Subdistrict are summarized in figure 5 and table 8. These results were determined assuming a measurement was taken during every visit. It should be emphasized that the results shown in figure 5 and in table 8 are based on various assumptions concerning both the time series of shifts to the stage-discharge relation and the methods of record reconstruction. Where a choice of assumptions are available, the assumption that would not underestimate the magnitude of the error variances was chosen.

The current stream-gaging procedure for the Louisville Subdistrict results in an average standard error of estimate of instantaneous streamflow of 28.5 percent. This policy requires a budget of $223,50 to operate the 48-station network. The range in standard errors is from a low of 12.5 percent for Licking River at Catawba (03253500), to a high of 39.1 percent for North Fork Licking River near Lewisburg (03251000). It is possible to obtain the same average budget standard error with a reduced budget of about $220,000, provided that changes of policy in the field activities of the stream-gaging program are implemented. This policy and budget change would result in an increase in standard error from 12.5 percent to 15.2 percent at Catawba, and from 39.1 to 44.4 percent at Lewisburg. The annual savings resulting from these changes is less than 2 percent.

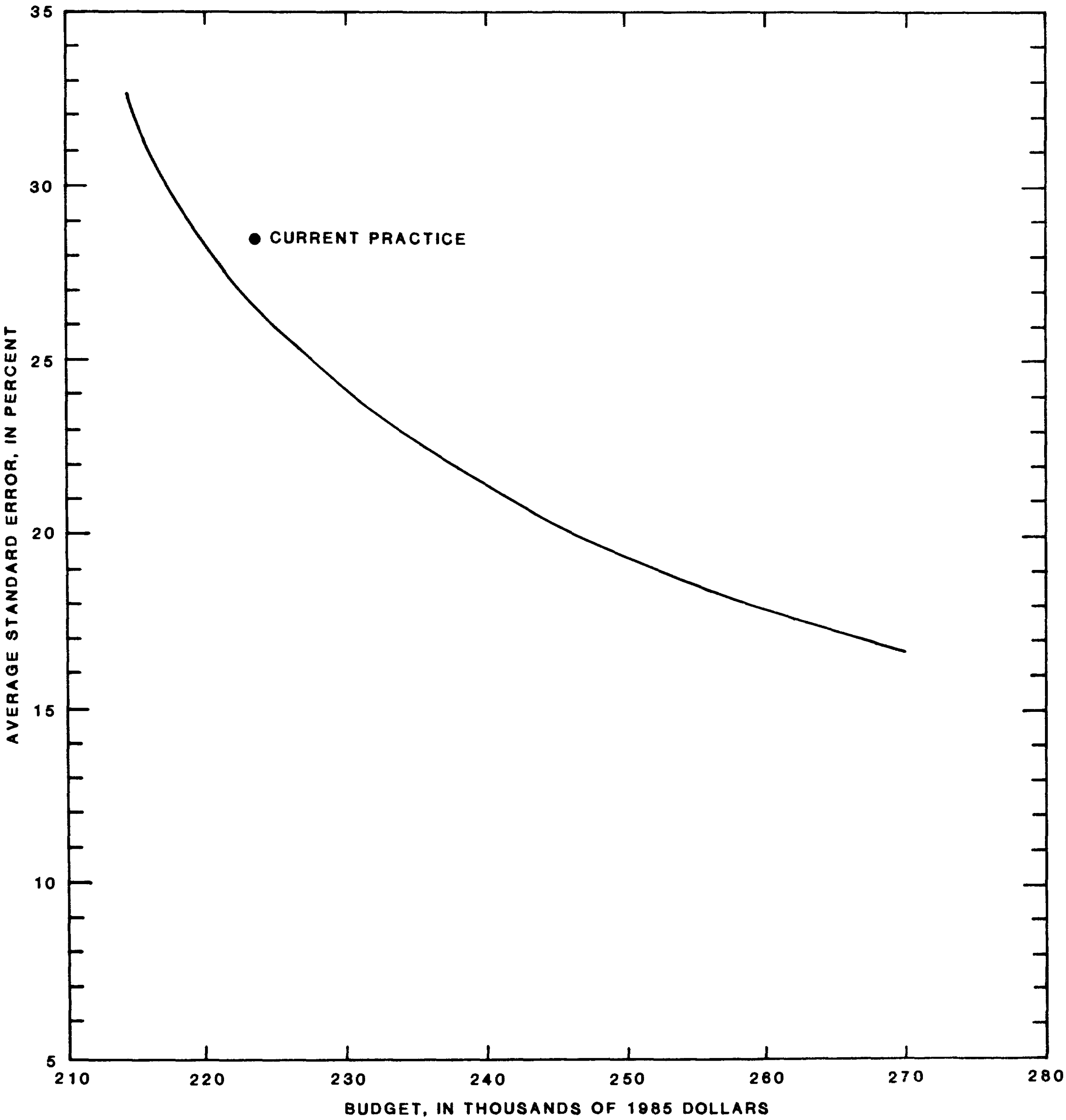

Figure 5.--Relation between average standard error per station and budget.

Table 8.--Selected results from K-CERA analysis

Station number	Standard error of instantaneous discharge, in percent [Equivalent Gaussian spread] (Number of visits per year to site)						
		Budget, in thousands of 1985 dollars					
	Current operation	214.2	223.5	234.7	245.8	257.0	268.2
Average per station	28.5 [12.2]	32.7 [13.4]	26.9 [11.4]	22.8 [9.8]	20.2 [8.7]	18.0 [8.0]	16.9 [7.4]
03237900	33.9 [19.9] (8)	46.6 [26.3] (4)	33.9 [19.9] (8)	30.4 [17.9] (10)	26.8 [15.8] (13)	24.2 [14.2] (16)	22.2 [13.0] (19)
03251000	39.1 [21.9] (8)	53.1 [26.4] (4)	39.1 [21.9] (8)	35.4 [20.3] (10)	31.4 [18.4] (13)	28.5 [16.9] (16)	26.3 [15.7] (19)
03251500	13.9 [10.0] (8)	20.9 [12.3] (4)	13.9 [10.0] (8)	12.3 [9.2] (10)	10.7 [8.3] (13)	9.6 [7.7] (16)	8.8 [7.1] (19)
03252000	35.6 [16.8] (8)	31.9 [15.2] (10)	29.2 [14.0] (12)	23.2 [11.2] (19)	21.6 [10.4] (22)	19.5 [9.4] (27)	17.9 [8.6] (32)
03252500	26.0 [10.4] (8)	23.2 [9.8] (10)	21.3 [9.4] (12)	17.0 [8.1] (19)	15.9 [7.7] (22)	14.4 [7.1] (27)	13.2 [6.1] (32)
03253500	12.5 [6.7] (8)	20.2 [8.4] (4)	12.5 [6.7] (8)	10.9 [6.2] (10)	9.2 [5.5] (13)	8.2 [5.1] (16)	7.4 [4.7] (19)
03282500	23.9 [9.0] (8)	35.1 [13.3] (4)	31.0 [11.7] (5)	28.0 [10.5] (6)	23.9 [9.0] (8)	21.2 [8.0] (10)	20.2 [7.6] (11)
03283500	23.0 [12.1] (8)	32.6 [15.6] (4)	29.1 [14.4] (5)	26.5 [13.5] (6)	23.0 [12.1] (8)	20.5 [11.0] (10)	19.6 [10.5] (11)
03289000	33.3 [22.8] (8)	31.5 [21.6] (9)	22.6 [19.0] (12)	23.3 [16.0] (17)	21.5 [14.8] (20)	19.6 [13.4] (24)	18.9 [12.9] (26)

Table 8.--Selected results from K-CERA analysis--Continued

Station number	Standard error of instantaneous discharge, in percent [Equivalent Gaussian spread] (Number of visits per year to site)						
		Budget, in thousands of 1985 dollars					
	Current operation	214.2	223.5	234.7	245.8	257.0	268.2
03292460	38.0	32.6	28.6	24.0	21.1	19.4	17.9
	[24.6]	[22.6]	[20.6]	[17.8]	[15.8]	[14.6]	[13.5]
	(8)	(12)	(17)	(26)	(35)	(42)	(50)
03293000	24.4	20.7	16.6	14.3	12.3	11.2	10.4
	[11.1]	[9.5]	[7.6]	[6.6]	[5.7]	[5.2]	[4.8]
	(8)	(11)	(17)	(23)	(31)	(37)	(43)
03297845	25.0	20.6	17.4	14.1	12.2	11.2	10.2
	[11.0]	[9.2]	[7.8]	[6.3]	[5.5]	[5.1]	[4.7]
	(8)	(12)	(17)	(26)	(35)	(42)	(50)
03298000	38.0	47.9	40.6	34.0	29.8	26.8	25.3
	[18.2]	[22.2]	[19.5]	[16.4]	[14.3]	[12.9]	[12.2]
	(8)	(5)	(7)	(10)	(13)	(16)	(18)
03299000	34.3	43.2	36.6	29.2	25.9	23.5	20.6
	[17.9]	[22.2]	[19.1]	[15.3]	[13.5]	[12.3]	[10.7]
	(8)	(5)	(7)	(11)	(14)	(17)	(22)
03300400	27.0	28.9	24.2	20.4	18.0	17.1	16.0
	[10.21	[10.8]	[9.2]	[7.9]	[7.0]	[6.6]	[6.2]
	(8)	(7)	(10)	(14)	(18)	(20)	(23)
03302000	34.3	29.2	23.6	20.3	17.5	16.1	14.9
	[11.6]	[9.8]	[7.9]	[6.8]	[6.0]	[5.5]	[5.1]
	(8)	(11)	(17)	(23)	(31)	(37)	(43)
03306000	25.1	31.6	26.8	21.5	19.1	17.4	15.4
	[7.3]	[8.2]	[7.5]	[6.6]	[6.1]	[5.7]	[5.2]
	(8)	(5)	(7)	(11)	(14)	(17)	(22)
03307000	31.2	39.5	33.4	26.5	23.4	21.3	18.6
	[18.2]	[23.4]	[19.6]	[15.4]	[13.5]	[12.2]	[10.6]
	(8)	(5)	(7)	(11)	(14)	(17)	(22)
03308500	19.3	24.7	19.3	16.4	14.4	13.1	11.5
	[3.6]	[4.2]	[3.6]	[3.2]	[2.9]	[2.6]	[2.4]
	(8)	(5)	(8)	(11)	(14)	(17)	(22)

Table 8.--Selected results from K-CERA analysis--Continued

Station number	Standard error of instantaneous discharge, in percent [Equivalent Gaussian spread] (Number of visits per year to site)						
		Budget, in thousands of 1985 dollars					
	Current operation	214.2	223.5	234.7	245.8	257.0	268.2
03310300	16.0	17.2	14.2	12.3	11.0	10.1	9.3
	[3.8]	[4.0]	[3.5]	[3.1]	[2.9]	[2.7]	[2.5]
	(8)	(7)	(10)	(13)	(16)	(19)	(22)
03310400	20.3	21.7	18.1	15.9	14.3	13.1	12.2
	[6.7]	[7.2]	[6.0]	[5.2]	[4.7]	[4.3]	[4.1]
	(8)	(7)	(10)	(13)	(16)	(19)	(22)

It also would be possible to reduce the average standard error by a policy change while maintaining the current budget of $223,500. The average standard error would decrease from 28.5 percent to 26.9 percent. Extremes of standard error for individual sites would be 12.5 percent at Licking River at Catawba (03253500), and 40.6 percent at Floyds Fork at Fisherville (03298000).

A minimum budget of about $214,200 is required to operate the 48-station network. A budget less than $214,200 will not permit proper service and maintenance of the gages and recorders, thereby violating the minimum visit constraints. Stations would have to be eliminated from the program if the budget fell below this minimum. At the minimum budget, the average standard error is 32.7 percent. The minimum standard error is 17.2 percent at Nolin River at White Mills (03310300) and the maximum standard error is 53.1 percent at North Fork Licking River at Lewisburg (03251000).

The maximum budget analyzed was $268,200, which resulted in an average standard error of estimate of 16.9 percent, indicating that when the budget is increased by 20 percent, the percent standard error is reduced by 40 percent. The minimum standard error of this budget is 7.4 percent at Licking River at Catawba (03253500) and the maximum is 26.3 percent at North Fork Licking River at Lewisburg (03251000). As indicated by the results, significant improvements in accuracy of streamflow records can be obtained if larger budgets become available.

Conclusions from the K-CERA Analysis

The results obtained from the analysis using only the Louisville Subdistrict stations are representative of those that would be obtained if an analysis of the total stream-gaging program in Kentucky were conducted. Even though these results are based on a limited sample size, it is believed that they are indicative of the entire surface-water network in Kentucky.

The Traveling Hydrographer program minimizes the uncertainty of the network by optimizing the visitation frequency to gaging stations for a given budget. For the current budget this optimization procedure would decrease the standard error of estimate to 26.9 percent from 28.5 percent obtained from the current procedure. This 1.6 percent reduction in standard error is not considered significant. However, the frequency of visits for daily-discharge stations with relatively large uncertainty should be increased from current operations in order to reduce the uncertainty for the program. The amount of funding for stations with accuracies that are not acceptable for the data uses should be renegotiated with the data users.

In addition to the above, it is recommended that the K-CERA analysis be rerun when uncertainty functions can be determined for all or almost all of the stations. Schemes for reducing the probabilities of missing record, for example, increased use of local gage observers and satellite relay of data, should be explored and evaluated as to their cost-effectiveness in providing streamflow information. The K-CERA analysis might also be helpful in evaluating alternate field office locations in the State or in a redistribution of gages to the existing offices.

SUMMARY

In the Kentucky stream-gaging program, there are currently 97 continuous-record stream gages, 12 stage-only stations, and 35 crest-stage stations, which are operated with a budget of $950,700. Most of the 97 stations in the network are multiple use with nearly half operated for project purposes. One station, which is used for research, lacks an adequate source of funding and is suggested for discontinuance when the research ends, if additional funding cannot be found. All other stations should remain in the program.

No alternative methods of developing streamflow information were studied. However, the results of the previous studies indicate that annual minimum 7-day discharge computed from observed and simulated daily streamflow data showed good agreement. Because of the large number of gaging stations in Kentucky operated to monitor project operations, the utility of using alternative methods to eliminate streamflow stations is quite limited. The results of the studies are, however, useful for record reconstruction when a gage fails to operate.

The cost-effective analyses performed on stations operated by the Louisville Subdistrict are believed to be indicative of the entire stream-gaging network in Kentucky. Each of the subdistrict and field offices in the Kentucky program are operated in similar fashion.

The current policy for the operation of the 48 stations in the Louisville Subdistrict requires a budget of $223,500 per year. The overall level of accuracy of the records at those stations could be maintained with a budget of about $220,000, if the gaging operation were altered. A savings of 2 percent would be realized, which would be offset by the additional money spent to implement a revised measurement scheme. It would be more feasible to keep the existing network and supplement it with measurements at sites with high uncertainty. It is suggested that no change be made to the current stream-gaging operation in Kentucky, except to measure stations with high uncertainty more frequently when possible.

Some component of the error in streamflow records is caused by loss of primary record (stage or other correlative data) at the stream gages because of malfunctions of sensing and recording equipment. Upgrading of equipment and development of strategies to minimize lost record would improve the reliability and accuracy of the streamflow data generated in the State. Loss of record also increases the fixed costs at the station because more time is needed to attempt to reconstruct record or to estimate daily values.

Studies of the cost-effectiveness of the stream-gaging program should be continued and should include investigation of the optimum ratio of discharge measurements to total site visits for each station. Future studies also will be required because of changes in demands for stream-flow information with subsequent addition and deletion of stream gages.

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