COST-EFFECTIVENESS OF THE STREAMFLOW-GAGING PROGRAM IN MINNESOTA

By Thomas A. Winterstein and Allan D. Arntson

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 88-4129

St. Paul, Minnesota

1989

DEPARTMENT OF THE INTERIOR

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U.S. GEOLOGICAL SURVEY

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CONVERSION FACTORS

Readers who prefer to use metric (International System) units rather than the inch-pound units in this report can make conversions using the following factors:

Multiply inch-pound unit	By	To obtain metric unit
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.590	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

A three-step analysis of the cost-effectiveness of the streamflow-gaging program in Minnesota is documented in this report.

In the first step of the analysis, the data uses and funding sources were identified for the 96 continuous-record streamflow-gaging stations operated in 1985. Nineteen sources of funding and 42 uses were identified for the data collected in this program. Two stations were identified as producing data no longer sufficiently needed to warrant continuing their operation. Three other stations were identified as having uses specific to short-term studies. One station was destroyed in 1985. It is recommended that the remaining 90 station be maintained in the program for the foreseeable future.

In the second step, multiple-linear-regression analysis was investigated as a possible method for providing the data collected at 23 stations. The multiple-linear-regression method was not sufficiently accurate to provide the needed data, and it is recommended that the 23 stations remain in the program. It also is recommended that flow-routing methods be investigated to see if they could provide the needed data for stations on the Red Lake River, the upper Minnesota River, and on the Mississippi River in the Minneapolis-St Paul metropolitan area.

In the third step, the cost-effectiveness of collecting data from 77 of the remaining 90 stations was determined for the open-water period, April 1 through October 30. Data for 13 stations are provided to the U.S. Geological Survey or are collected at fixed intervals and were, therefore, not used in the analysis. The average standard error per station for estimation of the streamflow records is about 24 percent for the statewide network, about 11 percent for the stations operated by the St. Paul field office, about 22 percent for the stations operated by the Grand Rapids field office, and about 37 percent for the stations operated by the Montevideo field office.

The current policy for collecting data from the 77 stations during the open-water period cost $198,000 in 1985. The estimated average standard error per station for the statewide network could be reduced from 24.4 percent to 20.6 percent at the $198,000 budget, if the minimum number of discharge measurements at each station were reduced from five to three during the open-water period and the remaining budget were used to make additional discharge measurements at stations with large standard errors.

It is recommended that, before this data-collection plan is implemented, the effects of the plan on the cost of collecting data be evaluated for (1) possible increased lost record because of the data collection plan, and (2) the possible need for additional trips to visit noncontinuous-record stations. It also is recommended that the data-accuracy needs of the funding agencies be considered before the plan is implemented.

INTRODUCTION

The U.S. Geological 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 U.S. Geological Survey (the Survey). These data are collected in cooperation with State and local governments and other Federal agencies. In 1984, the Survey operated 7,152 continuous-record streamflow gaging stations throughout the Nation (U.S. Geological Survey, 1985) with some records extending back to before the turn of the century. Any activity of long standing, such as the collection of surface-water data, should be reexamined at regular intervals, if not continuously, because objectives may change, technology changes, or external constraints also may change. The last systematic nationwide evaluation of the streamflow information program was completed in 1970 and is documented by Benson and Carter (1973). The Survey is presently (1985) making a 5-year nationwide analysis of the streamflow-gaging program that will be completed in 1986 with 20 percent of the program being analyzed each year. The objective of this analysis is to define and document the most cost-effective means of furnishing streamflow information.

There are three steps in the analysis. The first step is to identify principal uses of the data provided by every continuous-record gaging station and to relate these uses to funding sources. Gaged sites for which data is no longer needed are identified, as are deficient or unmet data demands. In addition, gaging stations are categorized as to whether the data are available to users in a real-time sense, on a monthly basis, or at the end of the water year.

The second step of the analysis is to identify less costly alternative methods of furnishing the needed information; among these are flow-routing models and statistical methods. The streamflow-gaging activity no longer is considered a network of observation points, but rather an information system in which data are provided both by observation and synthesis.

The final step 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 streamflow gages) for all stations in the analysis. A steepest-descent optimization program utilizes these uncertainty functions, information on practical streamflow-gaging routes, the various costs associated with streamflow gaging, and the total operating budget to identify the visit frequency for each station that minimizes the over-all uncertainty in the streamflow. The streamflow-gaging program that results from this analysis will meet the expressed water-data needs in the most cost-effective manner.

This report is organized into six sections; the first is an introduction to the streamflow-gaging activities in Minnesota and to the study itself. The second section presents selected hydrologic data for each of the gaging stations. The next three sections contain discussions of one of the steps in the analysis. Recommendations are made at the end of each step. The study, including all recommendations, is summarized in the final section.

History of Streamflow-Gaging in Minnesota

Streamflow gaging in Minnesota started in 1866 when the U.S. Army Corps of Engineers began measuring the Mississippi River at St. Paul for navigation purposes. In the 1880's the program was expanded with several more stations in the upper Mississippi River, Red River of the North, and the St. Louis River basins (Follansbee, 1939).

The Minnesota office of the Survey began collecting surface-water data in 1903 with the establishment of gaging stations on the Crow Wing, Rum, Minnesota, and Mississippi Rivers.

The program of surface-water investigations by the Survey has grown rather steadily through the years as Federal and State interest in water resources has grown. In 1909 the State of Minnesota became actively involved in the conservation of natural resources and the State legislature appropriated $12,500 to investigate water problems in the State. The Federal government added $2,750 through the Survey and created the first Federal-State cooperative program in Minnesota. The number of streamflow-gaging stations operated by the Survey, the U.S. Army Corps of Engineers, mining companies, and other private interests grew from 11 in 1909 to 67 in 1912 (State Drainage Commission, 1912). In the years following, the Federal-State cooperative program was gradually reduced and was suspended in 1917 when the state of Minnesota withdrew its funding. In 1919 the cooperative program was reinstated when the State legislature abolished the State Drainage Commission and transferred its duties to the newly formed Department of Drainage and Waters (Follansbee, 1939). The Federal-State cooperative program has continued since that time.

When the State withdrew its funding in 1917, the St. Paul office of the Survey was closed and the operation of the remaining stations was transferred to Survey field offices in Madison, Wisconsin, and Chicago. In 1930 the operation of the Survey's streamflow-gaging stations in Minnesota was transferred to the new Minnesota District office in St. Paul.

In 1928 the U.S. Department of State financed six stations to investigate Roseau River flooding along the international boundary to Canada (Follansbee, 1953). The drought years of the 1930's saw an increase in water conservation and an increase in the cooperative program; the network continued to grow to a peak of 157 stations in 1945. After 1945 the network fluctuated slightly as stations were added and discontinued. In the past several years the network has decreased considerably as cooperative funding has decreased and as basins have become hydrologically defined. In 1985 there were 96 stations in the Minnesota streamflow gaging network. Currently, the Minnesota Department of Natural Resources, the U.S. Department of State, the U.S. Army Corps of Engineers, the Minnesota Department of Transportation, and other local municipalities and commissions cooperate with the Survey in its streamflow gaging program.

Figure 1 shows the number of Minnesota gaging stations for which streamflow records were published, from 1900 through 1985.

In 1958 a network of crest-stage partial-record stations was established in cooperation with the Minnesota Department of Highways (now called Minnesota Department of Transportation) to collect high-flow data for basins smaller than 200 square miles but with an emphasis on basins less than 10 square miles and to provide information for detailed hydrologic studies. The network grew from 36 stations to a peak of 159 stations in 1965. Since then the network has been reduced as stations have become hydrologically defined; 100 stations were operated in 1984. Annual peak discharges from these stations and from the continuous-record stations were used for the analysis of flood frequency in Minnesota and to develop regional equations for predicting flood magnitudes at ungaged sites (Guetzkow, 1977).

In 1969 a low-flow cooperative program was established with the Minnesota Department of Natural Resources to provide data on low-flow characteristics of streams in order to evaluate, coordinate, and manage water-resource programs. The program was established with 400 low-flow stations, of which about 200 were active in 1985. The low-flow data collected from the program was compiled and analyzed with low-flow data from the continuous record stations in two reports, Lindskov (1977) and Warne (1978).

Conservation and efficient use of funds have always been concerns of Survey personnel and programs. In 1970 the available data on streamflow was evaluated and a data-collection program was designed that most efficiently produced the information needed. The results were published in "A proposed Streamflow Data Program for Minnesota" (Mann and Collier, 1970). The report recommended that 20 of the 125 operating stations be discontinued and that an additional 53 stations be established to fill specific needs. Survey offices were instructed again in 1982 to evaluate current streamflow networks. The results of that investigation are presented in this report.

Current Minnesota Stream Gaging Program

The State of Minnesota is divided into two major physiographic regions as noted by Fenneman (1946); the Superior Upland and the Central Lowland. The Central Lowland is further divided into three sections; the Western Lake section, the Wisconsin Driftless section, and the Dissected Till Plains. The locations of these regions and the location of the 96 streamflow-gaging stations currently operated by the Minnesota District of the Survey are in figure 2. Seventeen stations are located in the Superior uplands, sixty-nine in the Western Lakes section, seven in the Wisconsin Driftless section, and three in the Dissected Till Plains. The cost of operating these 96 stations in fiscal year 1985 was $558,000.

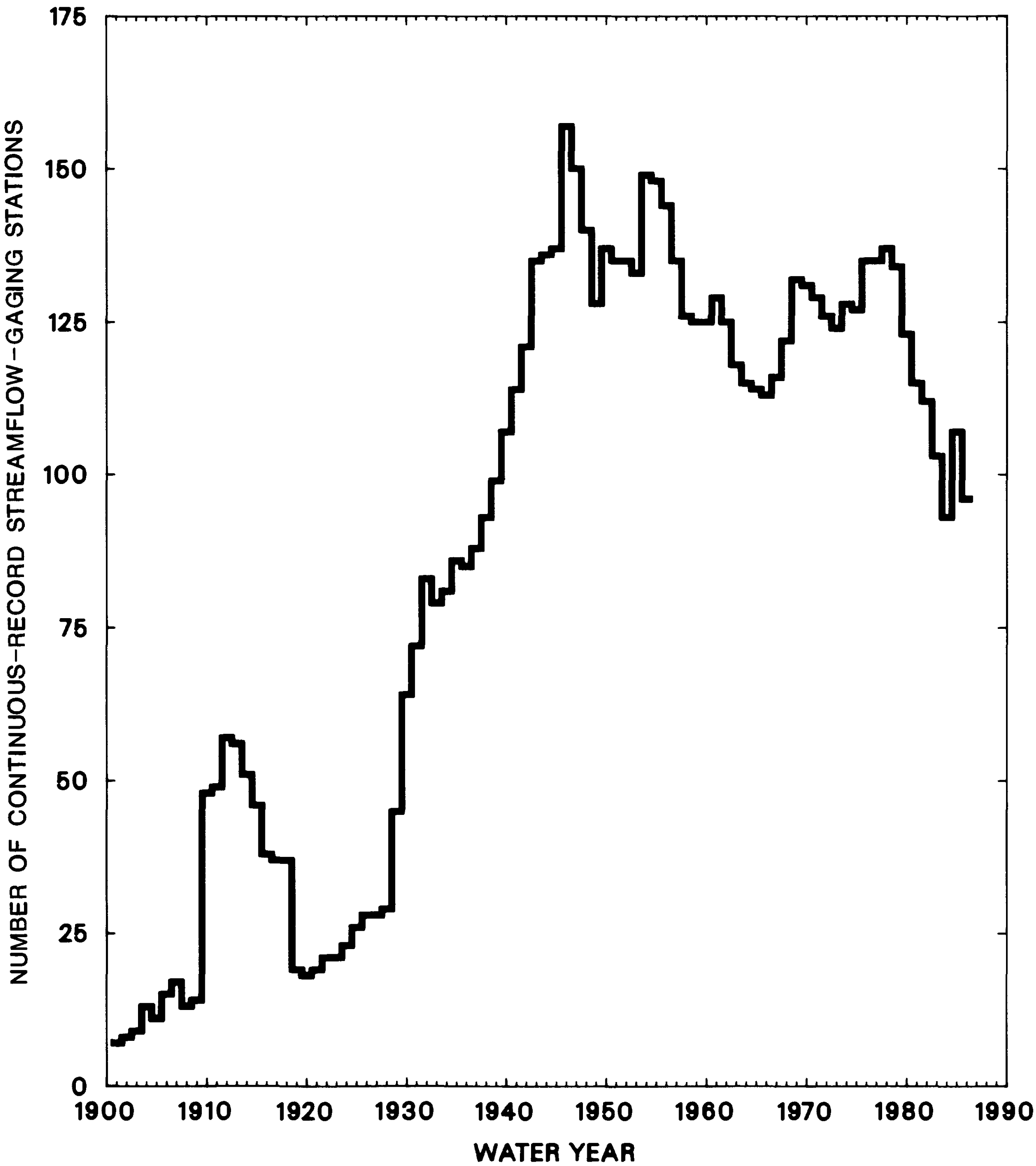


Figure 1.--Number of continuous-record streamflow gaging stations in Minnesota for which streamflow records were published, 1900-85

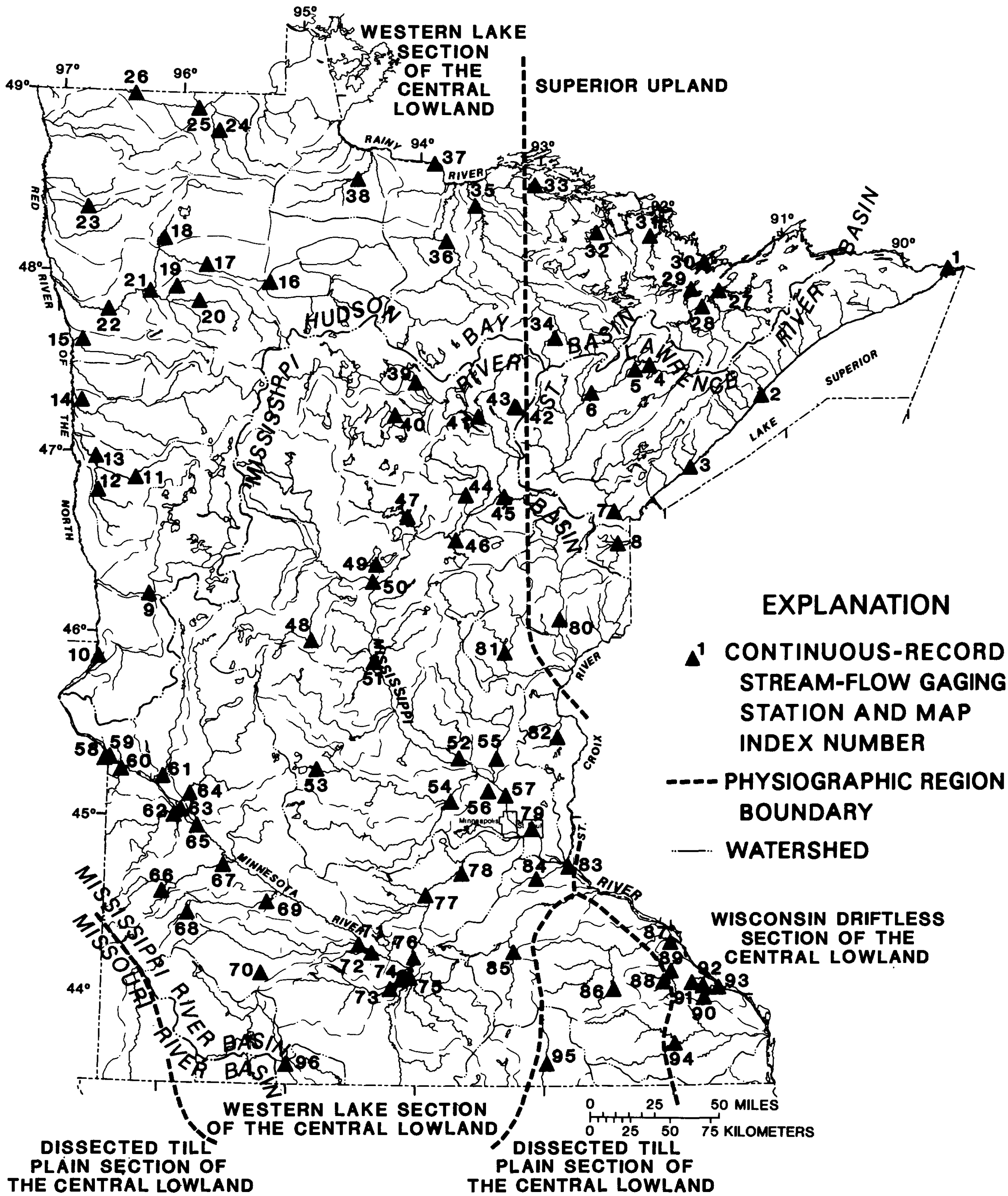


Figure 2.--Location of continuous-record streamflow-gaging stations in Minnesota (boundries of physiographic region from Fenneman, 1946)

The State contains two continental divides. One separates the rivers flowing north to Hudson Bay from those flowing south into the Mississippi River and eventually to the Gulf of Mexico. The second separates the rivers flowing eastward into Lake Superior and eventually to the St. Lawrence River from the rivers flowing into Hudson Bay or the Gulf of Mexico. A small part of the southwestern corner of the State is in the Missouri River drainage basin.

SELECTED HYDROLOGIC DATA

Selected hydrologic data, including drainage area, period of record, and mean annual flow for the 96 stations are given in table 1. Table 1 also provides the official name of each station. In some cases in this report the station name is abbreviated to the river or stream name on which the station is located.

Table 1. -- **Selected hydrologic data for continuous-record streamflow-gaging stations in the Minnesota surface-water program**

[---, not determined]

Map index no.	Station no.	Station name	Drainage area (mi^2)	Period of record	Mean annual flow (ft^3/s)
1	04010500	Pigeon River at Middle Falls nr Grand Portage, MN	600.00	1921,1922,1923- 1/	503
2	04014500	Baptism River near Beaver Bay, MN	140.00	1927- 1/	168
3	04015330	Knife River near Two Harbors, MN	85.60	1970-71 2/, 1974-	86
4	04015475	Partridge River abv Colby Lake at Hoyt Lakes, MN	106.00	1978-	---
5	04016500	St. Louis River near Aurora, MN	290.00	1942-	246
6	04018750	St. Louis River at Forbes, MN	713.00	1964-	546
7	04024000	St. Louis River at Scanlon, MN	3,430.00	1908- 1/	2,300
8	04024098	Deer Creek near Holyoke, MN	7.77	1976-	6.07
9	05046000	Otter Tail River bl Orwell D nr Fergus Falls, MN	1,830.00	1930- 4/	303
10	05050000	Bois De Sioux River near White Rock, SD	1,160.00	1941-	76.8
11	05061000	Buffalo River near Hawley, MN	322.00	1945-80,1981 5/, 1982- 6/	72.7 7/
12	05061500	South Branch Buffalo River at Sabin, MN	522.00	1945-80,1981 5/, 1982- 6/	56.0 7/
13	05062000	Buffalo River near Dilworth, MN	1,040.00	1931- 4/	128
14	05064000	Wild Rice River at Hendrum, MN	1,600.00	1944-	258
15	05069000	Sand Hill River at Climax, MN	426.00	1943- 8/ 9/	69.5 10/
16	05074500	Red Lake River near Red Lake, MN	1,950.00	1933- 11/	489
17	05075000	Red Lake River at High Landing nr Goodridge, MN	2,300.00	1929-	543
18	05076000	Thief River near Thief River Falls, MN	959.00	1909-17,1920-21, 1922-24,1928- 4/ 12/	158
19	05078000	Clearwater River at Plummer, MN	512.00	1939-79,1979-82 5/, 1982-	179 13/
20	05078230	Lost River at Oklee, MN	266.00	1960- 14/	75.9 15/

1. Monthly discharge only for some periods, published in Water Supply Paper 1307.
2. Operated as a low-flow partial record station.
4. Monthly discharge only for some periods, published in Water Supply Paper 1308.
5. Operated as a high-flow partial record station.
6. Daily discharge from March-August.
7. Mean annual flow based on water years 1945-80.
8. Winter records incomplete in some years.
9. Monthly discharge only for some periods, published in Water Supply Paper 1308 and 1728.
10. Mean annual flow based on period 1947-1982.
11. Monthly discharge only for May 1933, published in Water Supply Paper 1308.
12. Annual maximums for water years 1919, 1922, 1925, 1926, published in Water Supply Paper 1308.
13. Mean annual flow based on water years 1940-79.
14. Monthly and daily figures for April 1 to June 30, 1960, published in Water Supply Paper 2113.
15. Mean annual flow based on water years 1961-81.

Table 1. -- Selected hydrologic data for continuous-record streamflow-gaging stations in the Minnesota surface-water program--Continued

Map index no.	Station no.	Station name	Drainage area (mi^2)	Period of record	Mean annual flow (ft^3/s)
21	05078500	Clearwater River at Red Lake Falls, MN	1,370.00	1909-17,1934-81 16/, 1982 17/, 1982-	315 18/
22	05079000	Red Lake River at Crookston, MN	5,280.00	1901- 4/	1,122
23	05087500	Middle River at Argyle, MN	265.00	1945,1950-81 19/, 1982 20/, 1982-	41.2 21/
24	05104500	Roseau River below South Fork near Malung, MN	573.00	1946-	144
25	05107500	Roseau River at Ross, MN	1,220.00	1922-	262
26	05112000	Roseau River below State Ditch 51 nr Caribou, MN	1,570.00	1917,1920- 4/ 9/	280 23/
27	05124480	Kawishiwi River near Ely, MN	253.00	1966-	217
28	05124990	Filson Creek near Ely, MN	9.66	1974-	7.48
29	05127000	Kawishiwi River near Winton, MN	1,229.00	1905-07,1912-19 24/, 1923- 4/ 64/	1,028 25/
30	05127500	Basswood River near Winton, MN	1,740.00	1924,1925-28, 1930- 4/	1,389 26/
31	05128000	Namakan R at Outlet of Lac La Croix, Ontario Can	5,170.00	1921-22,1922- 4/ 27/	3,805 28/
32	05129115	Vermilion River nr Crane Lake, MN	---	1979-	---
33	05129290	Gold Portage Outlet from Kabetogama Lake nr Ray, MN	---	1982-	---
34	05130500	Sturgeon River near Chisholm, MN	187.00	1942-	124
35	05131500	Little Fork River at Littlefork, MN	1,730.00	1909,1910,1911-17 1917,1917-19 29/, 1928-	1,051 30/

4. Monthly discharge only for some periods, published in Water Supply Paper 1308.
9. Winter records incomplete in some years.
16. Monthly discharge only for October, November 1934, published in Water Supply Paper 1308.
17. Operated as a high-flow partial record station October 1981-February 1982.
18. Mean annual flow based on water years 1910-17,1935-81.
19. Monthly discharge only for some periods, published in Water Supply Paper 1728.
20. Operated as a high-flow partial record station October 1981-January 1982.
21. Mean annual flow based on water years 1951-81.
23. Mean annual flow based on water years 1921-30,1933,1937,1941-43,1973-82.
24. Fragmentary.
25. Mean annual flow based on water years 1906,1916-17,1919,1924-1982.
26. Mean annual flow based on water years 1926,1927,1931-82.
27. Station is maintained by Canada, Survey makes some measurements.
28. Mean annual flow based on water years 1923-1982.
29. Gage heights only.
30. Mean annual flow based on water years 1912-16, 1929-82.
64. Record furnished by Minnesota Power Co. Survey makes discharge measurements and reviews furnished record.

Table 1. -- Selected hydrologic data for continuous-record streamflow-gaging stations in the Minnesota surface-water program--Continued

Map index no.	Station no.	Station name	Drainage area (mi^2)	Period of record	Mean annual flow (ft^3/s)
36	05132000	Big Fork River at Big Falls, MN	1,460.00	1909,1910,1911-12, 1928-79,1980-83 5/, 1984-	713 31/
37	05133500	Rainy River at Manitou Rapids, MN	1,9400.00	1928- 4/	12,790
38	05134200	Rapid River near Baudette, MN	543.00	1956-	311
39	05201500	Mississippi River at Winnibigoshish Dam near Deer River, MN	1,442.00	1884- 4/ 65/	515
40	05206500	Leech Lake River at Federal Dam, MN	1,163.00	1884- 4/ 65/	362
41	05211000	Mississippi River at Grand Rapids, MN	3,370.00	1883- 4/	1,172
42	05216820	Initial Tailings Basin Outflow near Keewatin, MN	---	1983-	---
43	05216860	Swan River near Calumet, MN	114.00	1964-	65.7
44	05219000	Sandy River at Sandy Lake Dam, at Libby, MN	421.00	1893-1894,1894, 1894-1895,1895- 4/ 65/	216 32/
45	05220500	Mississippi River below Sandy River nr Libby, MN	5,060.00	1930-	2,038
46	05227500	Mississippi River at Aitkin, MN	6,140.00	1945-	2,901
47	05231000	Pine River at Cross Lake Dam, at Cross Lake, MN	562.00	1886- 4/ 65/	217
48	05245100	Long Prairie River at Long Prairie, MN	432.00	1971-	145
49	05247000	Gull River at Gull Lake Dam near Brainerd, MN	287.00	1911- 4/ 65/	107
50	05247500	Crow Wing River near Pillager, MN	3,300.00	1924-66,1967-68, 1969- 64/	1,244
51	05267000	Mississippi River near Royalton, MN	11,600.00	1924- 64/	4,477
52	05275000	Elk River near Big Lake, MN	615.00	1911-17,1931, 1932,1933,1934-	256 33/
53	05278000	Middle Fork Crow River near Spicer, MN	179.00	1949-	53.2
54	05280000	Crow River at Rockford, MN	2,520.00	1906,1909-17,1929, 1930-31,1932,1933,	643 34/
55	05286000	Rum River near St. Francis, MN	1,360.00	1929,1930-31,1932, 1933-	594 35/
56	05287890	Elm Creek nr Champlin, MN	84.90	1978-	---
57	05288500	Mississippi River near Anoka, MN	19,100.00	1931-	7,579

4. Monthly discharge only for some periods, published in Water Supply Paper 1308.
5. Operated as a high-flow partial record station.
31. Mean annual flow based on water years 1929-79.
32. Mean annual flow based on water years 1896-1982.
33. Mean annual flow based on water years 1912-17, 1935-82.
34. Mean annual flow based on water years 1910-17, 1931, 1935-82.
35. Mean annual flow based on water years 1931, 1934-82.
65. Gage operated by U.S. Army Corps of Engineers which computes daily discharge and furnishes it to Survey for publication. Survey makes several discharge measurements each year.

Table 1. -- Selected hydrologic data for continuous-record streamflow-gaging stations in the Minnesota surface-water program--Continued

Map index no.	Station no.	Station name	Drainage area (mi^2)	Period of record	Mean annual flow (ft^3/s)
58	05291000	Whetstone River near Big Stone City, SD	389.00	1910-12 3/, 1931- 4/	47.4 36/
59	05292000	Minnesota River at Ortonville, MN	1,160.00	1938-	106
60	05293000	Yellow Bank River near Odessa, MN	398.00	1939-	55.7
61	05294000	Pomme De Terre River at Appleton, MN	905.00	1931-35 3/, 1935-	104 37/
62	05300000	Lac Qui Parle River near Lac Qui Parle, MN	983.00	1910-14,1931- 38/	120 39/
63	05301000	Minnesota River near Lac Qui Parle, MN	4,050.00	1942-	618
64	05304500	Chippewa River near Milan, MN	1,870.00	1937-	267
65	05311000	Minnesota River at Montevideo, MN	6,180.00	1909-17,1917-29 3/, 1929- 4/	678 40/
66	05311400	South Branch Yellow Medicine R at Minneota, MN	111.00	1960-1981,1982 5/, 1983-	20.5
67	05313500	Yellow Medicine River near Granite Falls, MN	653.00	1931-35 3/, 1935-38,1939- 4/	103 41/
68	05315000	Redwood River near Marshall, MN	303.00	1940- 4/	45.3
69	05316500	Redwood River near Redwood Falls, MN	697.00	1909-14 42/, 1930-35 3/, 1935-	104 43/
70	05316900	Dry Creek near Jeffers, MN	3.13	1961-81 5/, 1982 -	---
71	05317000	Cottonwood River near New Ulm, MN	1,280.00	1909-13, 1931-38 44/, 1938-	271 45/
72	05317200	Little Cottonwood River near Courtland, MN	230.00	1969-73 2/, 1973-	38.2
73	05319500	Watonwan River near Garden City, MN	812.00	1940-45,(1953,1960, 1961,1969) 46/, 1976-	279 47/
74	05320000	Blue Earth River near Rapidan, MN	2,430.00	1909-10 3/, 1939-45 1949-	844 48/
75	05320500	Le Sueur River near Rapidan, MN	1,100.00	1939-45,1949-	434 48/

2. Operated as a low-flow record station.
3. No winter records.
4. Monthly discharge only for some periods, published in Water Supply Paper 1308.
5. Operated as a high-flow partial record station.
36. Mean annual flow based on water years 1932-82.
37. Mean annual flow based on water years 1936-82.
38. Winter records incomplete prior to 1934.
39. Mean annual flow based on water years 1913, 1932, 1934-82.
40. Mean annual flow based on water years 1910-17, 1930-82.
41. Mean annual flow based on water years 1936-38, 1940-82.
42. No winter records except 1911-12.
43. Mean annual flow based on water years 1912, 1930-82.
44. Winter records incomplete prior to 1936.
45. Mean annual flow based on water years 1912-13, 1936-37, 1939-82.
46. One or more miscellaneous discharge measurements each year.
47. Mean annual flow based on water years 1941-45, 1977-82.
48. Mean annual flow based on water years 1940-45, 1950-82.

Table 1. -- Selected hydrologic data for continuous-record streamflow-gaging stations in the Minnesota surface-water program--Continued

Map index no.	Station no.	Station name	Drainage area (mi^2)	Period of record	Mean annual flow (ft^3/s)
76	05325000	Minnesota River at Mankato, MN	14,900.00	1903- 4/ 49/	2,712 50/
77	05327000	High Island Creek near Henderson, MN	237.00	1970-73 2/, 1973-	60.5
78	05330000	Minnesota River near Jordan, MN	16,200.00	1934-	3,400
79	05331000	Mississippi River at St. Paul, MN	36,800.00	(1867-69,1872-1892) 51/ 1892- 52/	10,640 53/
80	05336700	Kettle River below Sandstone, MN	863.00	1967-	692
81	05337400	Knife River near Mora, MN	102.00	1969-74 2/, 1974-	55.4
82	05340050	Sunrise River near Lindstrom, MN	231.00	1965-	95.1
83	05344500	Mississippi River at Prescott, WI	44,800.00	1928-	16,370
84	05345000	Vermillion River near Empire, MN	110.00	1942-45 54/, 1969-73 55/, 1973-	43.6 56/
85	05353800	Straight River near Faribault, MN	442.00	1965-	237
86	05372995	South Fork Zumbro River at Rochester, MN	303.00	1981-	---
87	05374900	Zumbro River at Kellogg, MN	1,400.00	1975-	700
88	05376000	North Fork Whitewater River near Elba, MN	101.00	1939-41,1967-	44.6 57/
89	05376800	Whitewater River near Beaver, MN	271.00	1975-	152 58/
90	05378230	Stockton Valley Creek at Stockton, MN	---	1982- 3/	---
91	05378235	Garvin Brook near Minnesota City, MN	---	1982-	---
92	05378300	Straight Valley Creek near Rollingstone, MN	5.16	1959-66 5/, 1967-70 59/, 1970-	2.36 60/
93	05378500	Mississippi River at Winona, MN	59,200.00	1928-	26,520
94	05384000	Root River near Lanesboro, MN	615.00	1910,1911-14, 1915-17,1940-	341 61/

2. Operated as a low-flow partial record station.
3. No winter records.
4. Monthly discharge only for some periods, published in Water Supply Paper 1308.
5. Operated as a high-flow partial record station.
49. No winter records 1904,1906-1910,1918-1929.
50. Mean annual flow based on water years 1905, 1911-17, 1930-82.
51 Annual maximums.
52. Prior to 1901, fragmentary during some winters.
53. Mean annual flow based on water years 1895, 1897, 1901-82.
54. No record during July, August, and September 1944.
55. Miscellaneous discharge measurements only.
56. Mean annual flow based on water years 1943, 1974-82.
57. Mean annual flow based on water years 1940-41, 1968-82.
58. Mean annual flow based on water years 1976-82.
59. Peaks above base.
60. Mean annual flow based on water years 1971-82.
61. Mean annual flow based on water years 1912-14, 1916-17, 1941-82.

Table 1.--Selected hydrologic data for continuous-record streamflow-gaging stations in the Minnesota surface-water program--Continued

Map index no.	Station no.	Station name	Drainage area (mi^2)	Period of record	Mean annual flow (ft^3/s)
95	05457000	Cedar River near Austin, MN	425.00	1909-14,1944-	194 62/
96	05476000	Des Moines River at Jackson, MN	1,220.00	1909-13,1930- 44/	277 63/

44. Winter records incomplete prior to 1936.
62. Mean annual flow based on water years 1910-14, 1945-82.
63. Mean annual flow based on water years 1936-82.

STEP ONE: ANALYSIS OF THE USES OF CONTINUOUS STREAMFLOW DATA

The relevance of a streamflow-gaging station is defined by the uses of the data that are produced from the station. The uses of the data from each station in the Minnesota program were identified by a survey of known data users. This survey documents the importance of each station and identifies particular gaging stations of lesser importance that may be considered for discontinuation.

The data uses resulting from this survey were categorized into nine classes, defined below. The sources of funding for each station and the frequency at which data are provided to the users were also compiled.

Data-Use Classes

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

Regional Hydrology

For data to be useful in defining regional hydrology, a streamflow-gaging station 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 that the outflow is uncontrolled. These stations are useful in developing regionally transferable information about the relationship between basin characteristics and streamflow.

Sixty-five stations in the Minnesota network are classified in this data-use category. The two hydrologic benchmark stations are part of a nationwide network of gaging stations in watersheds that have been and probably will continue to be free of manmade influences. Data collected at a benchmark station may be used to separate effects of natural from manmade changes in other basins which have been developed and in which the physiography, climate, and geology are similar to those in the undeveloped benchmark basin. Five regional index stations are used to indicate current hydrologic conditions in the State.

Hydrologic Systems

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

Four stations are operated to monitor the diversion of water from and to streams by the iron-ore mining and processing industry in northern Minnesota.

One station is used to account for inflow to Lake Superior and another station is used to monitor the high-flow diversion to Marsh Lake.

Legal Obligations

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

There are four stations in the Minnesota gaging program that exist to fulfill a legal responsibility of the Survey. These stations are operated for the International Joint Commission in accordance with the Boundary Waters Treaty of 1909 between the United States and Canada. One additional station on the Namakan River at the outlet of Lac La Croix, Ontario, Canada, is operated by Canada; the Survey makes discharge measurements twice a year and reviews the station records computed by the Canadians.

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. This category is limited to stations that were instituted for such purposes and where this purpose is still valid.

Currently, 26 stations in the Minnesota program are being operated for planning or design purposes. Twenty-three of these stations are used to obtain discharge data used in developing alternative methods of flood control for the Red River of the North, the Roseau River, Upper Minnesota River basin, South Fork Zumbro River, and the Root River.

One station is operated for planning regional park facilities and designing flood control measures and two stations are used in the planning and design of hydropower plants.

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 operation, or diversions. This use generally implies that the data are routinely available to the operators on a rapid-reporting basis.

There are 52 stations in the Minnesota program that are used in this manner. Minnesota reservoirs are operated to control stage and/or discharge for purposes of hydropower production, iron-ore mining and processing, flood control, sediment control, and to maintain minimum flow conditions for navigational channels. Many of these stations are operated for more than one of these reasons.

Five stations are operated to regulate diversions for wild rice irrigation and eight stations are operated to help maintain lake levels. Information from five stations are used for purposes of making operational decisions for waste-water treatment plants.

Five stations are operated at hydroelectric generating stations by electric power companies to fulfill a licensing requirement of the Federal Energy Regulatory Commission. The data from these stations are used to determine if the power companies are making responsible use of the resource and if they are maintaining required minimum flows downstream of their hydroelectric dams as determined by the Federal Energy Regulatory Commission.

Hydrologic Forecasts

Gaging stations in this category are regularly used to provide information for hydrologic forecasting. These might be flood forecasts for a specific river reach, or periodic (daily, weekly, monthly, or seasonal) flow-volume forecasts for a specific site or for a region. This 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.

The 44 stations in the Minnesota program that are included in this category are those used for flood forecasting or stations equipped for remote stage data retrieval (Telemark or data collection platform). Data are used by the NWS (U.S. National Weather Service) to predict floodflows at downstream sites. Additionally, NWS uses the data at some stations as input to models that predict the probability of snowmelt floods.

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 18 stations in this category.

Two stations are designated benchmark stations and nine are NASQAN (National Stream Quality Accounting Network) stations. Water-quality samples from benchmark stations are used to indicate water-quality characteristics of streams that have been and probably will continue to be relatively free of manmade influence. NASQAN stations are part of a countrywide network designed to assess water-quality trends of significant streams.

Five stations in the Minnesota program are used for sediment-transport monitoring and are operated for the U.S. Army Corps of Engineers to help determine sediment loads into reservoirs.

There are two stations used to monitor water-quality in connection with the operation of waste-treatment plants.

Research

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

Four stations in the Minnesota program are used in the support of research activities. One station is used in a study of the hydrology of abandoned taconite tailings basins in northern Minnesota, one is used in a study of the determination of hydrologic budgets of small watersheds by remote sensing, and two stations are used to study agricultural runoff in southeastern Minnesota.

Other

Stations which do not fall into any of the categories listed above are included in this category.

There are no stations in the Minnesota program that fall into this category.

Funding

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

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

2. OFA program.--Funds that have been transferred to the Survey by other Federal agencies.

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 and are not matched by Survey cooperative funds.

The 96 stations are funded by 3 Federal agencies, 3 State agencies, 5 local districts or commissions, 3 power companies, and several mining companies who fund 3 stations through the Minnesota Department of Natural Resources. Seventeen stations are funded by more than one government body or agency. This occurs because the data collection needs of the funding agencies differ and each funding agency funds only that part of the station's operation needed to collect the data it needs. For instance, the Minnesota Department of Transportation funds two stations to collect information on high flows. The additional costs for determining mean-daily discharges at the stations are paid for by the Minnesota Department of Natural Resources at one station and the U.S. Army Corps of Engineers at the other.

Frequency of Data Availability

Frequency of data availability refers to the times at which the streamflow data may be furnished to the user. In this category, three distinct possibilities exist. Data can be furnished by direct-access telemetry equipment for immediate use, by periodic release of provisional data, or in publication format through the annual data report published by the Survey for Minnesota (Survey, 1984). These three categories are designated T, P, and A, respectively, in table 2. In the 1985 Minnesota program, data for all 96 stations are made available through the annual report, data from 28 stations are available in a real-time basis, and data are released on a provisional basis at one station regularly.

Data-Use Presentation

Data-use and other information is presented for each continuous gaging station in table 2.

Table 2.--Data use, station funding, and data availability for continuous-record streamflow-gaging stations in Minnesota

		Data Uses									Station Funding				
Map index no.	Station no.	Regional hydrology	Hydrologic systems	Legal obligations	Planning and design	Project operation	Hydrologic forecasts	Water-quality monitoring	Research	Other	Federal program	OFA program	Coop program	Other non-Federal	Data availability
1	04010500	1		2			9					F3			A T
2	04014500	1						5			F4		F1		A
3	04015330	1											F1		A
4	04015475		4			4		3						F5	A
5	04016500		4			4							F1		A
6	04018750		4			4								F5	A
7	04024000		6			7		5			F4	F2			A
8	04024098	1											F1		A
9	05046000					8	9,21					F2			A T
10	05050000					8	21					F2			A
11	05061000	1			14		21					F2			A
12	05061500	1			14		21					F2			A
13	05062000	1,11			14		21						F1		A P
14	05064000	1	13		14		21					F2			A
15	05069000	1			14							F2			A
16	05074500				14	8	9					F2			A
17	05075000				14	42	9,21					F2			A T

1 Natural regional hydrology
2 International gaging station operated under agreement with Canada (Department of State, Boundary Waters Treaty)
3 Water quality Minimonitor installed
4 Hydrologic systems involving reservoirs, diversions, and availability for iron-ore mining and processing
5 National Stream Quality Accounting Network (NASQAN) station
6 Accounting for inflow to Lake Superior at Duluth, Minnesota
7 Discharge data used to make operational decisions in the production of hydropower
8 Discharge data used to make operational decisions for reservoir control
9 Station contains instrumentation for remote stage data retrieval (Telemark or data collection platform)
11 Index station used in preparing report on current National Water Conditions
13 Discharge data used to monitor high flow diversion to Marsh River
14 Discharge data used in developing alternative methods of flood control for the Red River of the North
21 Discharge and stage data used to forecast floods by National Weather Service
42 Stage data used to make operational decisions about Red Lake Reservoir by Corps of Engineers
F1 Minnesota Department of Natural Resources
F2 U.S. Army Corps of Engineers
F3 Department of State, Boundary Waters Treaty
F4 Reimbursement from U.S. Geological Survey for NASQAN data collection costs
F5 Funded wholly by Mining Companies through Minnesota Department of Natural Resources
A Data published on an annual basis
T Data transmitted by telemetry such as satellite, radio, or phone line
P Provisional data provided to cooperator at specified intervals

Table 2.--Data use, station funding, and data availability for continuous-record streamflow-gaging stations in Minnesota --Continued

		Data Uses									Station Funding				
Map index no.	Station no.	Regional hydrology	Hydrologic systems	Legal obligations	Planning and design	Project operation	Hydrologic forecasts	Water-quality monitoring	Research	Other	Federal program	OFA program	Coop program	Other non-Federal	Data availability
18	05076000	1			14	15						F2		F7	A
19	05078000				14	15	9					F2	F1		A T
20	05078230	1			14	15						F2	F7		A
21	05078500				14	15							F7		A
22	05079000	1			14		9,21	5			F4	F2			A T
23	05087500	1				15							F8		A
24	05104500	1											F1		A
25	05107500	1			18							F3			A
26	05112000	1		2	18		9	5			F4	F3			A T
27	05124480	1,16						16			F9				A
28	05124990	1											F1		A
29	05127000					17								F10	A
30	05127500	1		2		20	9					F3			A T
31	05128000			19		20						F3			A
32	05129115	1				20	9					F3			A T
33	05129290					20	9					F3			A T

1 Natural regional hydrology
2 International gaging station operated under agreement with Canada (Department of State, Boundary Waters Treaty)
5 National Stream Quality Accounting Network (NASQAN) station
9 Station contains instrumentation for remote stage data retrieval (Telemark or data collection platform)
14 Discharge data used in developing alternative methods of flood control for the Red River of the North
15 Discharge data used in regulating diversions for wild rice irrigation
16 Benchmark station; hydrologic regime of its watershed is controlled by natural conditions
17 Federal Power Commission project
18 Discharge data used in developing alternative methods of flood control for the Roseau River
19 Station is operated by Canada; WRD required to visit station periodically and review the discharge records
20 Discharge data used in regulating the water level of Rainy Lake
21 Discharge and stage data used to forecast floods by National Weather Service
F1 Minnesota Department of Natural Resources
F2 U.S. Army Corps of Engineers
F3 Department of State, Boundary Waters Treaty
F4 Reimbursement from U.S. Geological Survey for NASQAN data collection costs
F7 Red Lake Watershed District
F8 Middle River-Snake River Watershed District
F9 U.S. Geological Survey
F10 Minnesota Power Co.
A Data published on an annual basis
T Data transmitted by telemetry such as satellite, radio, or phone line

Table 2.--Data use, station funding, and data availability for continuous-record streamflow-gaging stations in Minnesota --Continued

		Data Uses									Station Funding				
Map index no.	Station no.	Regional hydrology	Hydrologic systems	Legal obligations	Planning and design	Project operation	Hydrologic forecasts	Water-quality monitoring	Re-search search	Other	Federal program	OFA program	Coop program	Other non-Federal	Data availability
34	05130500	1											F1		A
35	05131500	1				23	9	5			F4	F3			A T
36	05132000	1				23	9					F2			A T
37	05133500			2		23	9	5			F4	F3,F2			A T
38	05134200	1				23							F1		A
39	05201500					24						F19			A
40	05206500					24						F19			A
41	05211000					24,17								F12	A
42	05216820								22				F11		A
43	05216860		4			4								F5	A
44	05219000					24						F19			A
45	05220500					24	21					F2			A
46	05227500					24,26	21,9					F2			A T
47	05231000					24						F19			A
48	05245100	1											F1		A
49	05247000					24						F19			A
50	05247500					17						F10			A
51	05267000					17						F10			A

1 Natural regional hydrology
2 International gaging station operated under agreement with Canada (Department of State, Boundary Waters Treaty)
4 Hydrologic systems involving reservoirs, diversions, and availability for iron-ore mining and processing
5 National Stream Quality Accounting Network (NASQAN) station
9 Station contains instrumentation for remote stage data retrieval (Telemark or data collection platform)
17 Federal Power Commission project
21 Discharge and stage data used to forecast floods by National Weather Service
22 Study of hydrology of abandoned taconite tailings basins
23 Discharge data used in regulating the water level of Lake of the Woods
24 Discharge data used for flood control, maintaining water levels on the Mississippi headwater reservoirs for recreation
26 Discharge data used to monitor Aitkin flood control diversion project
F1 Minnesota Department of Natural Resources
F2 U.S. Army Corps of Engineers
F3 Department of State, Boundary Waters Treaty
F4 Reimbursement from U.S. Geological Survey for NASQAN data collection costs
F5 Funded wholly by Mining Companies through Minnesota Department of Natural Resources
F10 Minnesota Power Co.
F11 Iron Range Resources and Rehabilitation Board
F12 Blandin Paper Co.
F19 Gage funded and operated by U.S. Army Corps of Engineers
A Data published on an annual basis
T Data transmitted by telemetry such as satellite, radio, or phone line

Table 2.--Data use, station funding, and data availability for continuous-record streamflow-gaging stations in Minnesota --Continued

		Data Uses									Station Funding				
Map index no.	Station no.	Re-gional hydrol-ogy	Hydro-logic sys-tems	Legal obli-ga-tions	Plan-ning and design	Pro-ject oper-ation	Hydro-logic fore-casts	Water-quality moni-toring	Re-search	Other	Fed-eral pro-gram	OFA pro-gram	Coop pro-gram	Other non-Fed-eral	Data avail-abil-ity
52	05275000	1											F1		A
53	05278000	1											F1		A
54	05280000	1,11					21								A
55	05286000	1					21						F1		A
56	05287890	1			25								F13		A
57	05288500	11				31,17	9	12				F2		F15	A T
58	05291000	1				29,30		12				F2	F1		A
59	05292000					29,30						F2	F1		A
60	05293000	1			34	30,33	9	12				F2			A T
61	05294000	1				30	9					F2			A T
62	05300000	1			34	30	9					F2			A T
63	05301000					30						F2			A
64	05304500	1				30	9					F2			A T
65	05311000					30	9,21					F2			A T
66	05311400	1			34							F2			A
67	05313500	1			34		21						F1		A
68	05315000	1			34,35		21					F2			A

1 Natural regional hydrology
9 Station contains instrumentation for remote stage data retrieval (Telemark or data collection platform)
11 Index station used in preparing report on current National Water Conditions
12 Sediment data collected for Corps of Engineers
17 Federal Power Commission project
21 Discharge and stage data used to forecast floods by National Weather Service
25 Discharge data used in planning regional park facilities and designing flood control measures
29 Sediment and flood control project for Big Stone Lake and Ortonville, Minnesota
30 Discharge data used in regulating the headwater reservoirs of the Minnesota River
33 Discharge data used for sediment control for Highway 75 reservoir on the Minnesota River
34 Discharge data used in developing alternative methods of flood control
35 Discharge data used to monitor the Redwood River diversion at Marshall, Minnesota
F1 Minnesota Department of Natural Resources
F2 U.S. Army Corps of Engineers
F13 Elm Creek Conservation Management and Protection Commission
F15 Ford Motor Co.
A Data published on an annual basis
T Data transmitted by telemetry such as satellite, radio, or phone line

Table 2.--Data use, station funding, and data availability for continuous-record streamflow-gaging stations in Minnesota --Continued

Map index no.	Station no.	Data Uses: Regional hydrology	Hydrologic systems	Legal obligations	Planning and design	Project operation	Hydrologic forecasts	Water-quality monitoring	Research	Other	Station Funding: Federal program	OFA program	Coop program	Other non-Federal	Data availability
69	05316500	1			34		21					F2			A
70	05316900	1							32			F2		F16	A
71	05317000	1			34		21						F1		A
72	05317200	1											F1		A
73	05319500	1											F1		A
74	05320000	1			38		21						F1		A
75	05320500	1					9,21						F1		A T
76	05325000	1				31	9,21	12				F2			A T
77	05327000	1											F1		A
78	05330000	11				31,37	9,21	5,36			F4	F2			A T
79	05331000	11				31,37	9,21	41				F2			A T
80	05336700	1			38								F1		A
81	05337400	1											F1		A
82	05340050	1											F1		A
83	05344500					31	9				F9				A T

1 Natural regional hydrology
5 National Stream Quality Accounting Network (NASQAN) station
9 Station contains instrumentation for remote stage data retrieval (Telemark or data collection platform)
11 Index station used in preparing report on current National Water Conditions
12 Sediment data collected for Corps of Engineers
21 Discharge and stage data used to forecast floods by National Weather Service
31 Discharge data used for regulating pool levels of the Mississippi River 9-foot navigation channel
32 U.S. Army Cold Regions Research and Engineering Laboratory project to calibrate the remote sensing of watersheds to determine their hydrologic budget
34 Discharge data used in developing alternative methods of flood control
36 Metropolitan Waste Control Commission monitors water quality at this site (automatic monitor)
37 Daily discharge used in making operational decisions for wastewater treatment plant
38 Discharge data used in planning and designing hydropower plant
41 Recording thermograph installed
F1 Minnesota Department of Natural Resources
F2 U.S. Army Corps of Engineers
F4 Reimbursement from U.S. Geological Survey for NASQAN data collection costs
F9 U.S. Geological Suvery
F16 Minnesota Department of Transportation (High flow site)
A Data published on an annual basis
T Data transmitted by telemetry such as satellite, radio, or phone line

Table 2.--Data use, station funding, and data availability for continuous-record streamflow-gaging stations in Minnesota --Continued

Map index no.	Station no.	Data Uses: Regional hydrology	Data Uses: Hydrologic systems	Data Uses: Legal obligations	Data Uses: Planning and design	Data Uses: Project operation	Data Uses: Hydrologic forecasts	Data Uses: Water-quality monitoring	Data Uses: Research	Data Uses: Other	Station Funding: Federal program	Station Funding: OFA program	Station Funding: Coop program	Station Funding: Other non-Federal	Data availability
84	05345000	1				37		36					F17		A
85	05353800	1											F1		A
86	05372995	1			34	37	9,21					F2			A T
87	05374900	1				31	9					F2			A T
88	05376000	1,16						16			F9				A
89	05376800	1				31						F2			A
90	05378230	1							39				F18		A
91	05378235	1							39				F18		A
92	05378300	1											F1	F16	A
93	05378500					31	9,21	5,12			F4	F2			A T
94	05384000	1			34		9					F2			A T
95	05457000	1				37	21						F1		A
96	05476000	1					21						F1		A

1 Natural regional hydrology
5 National Stream Quality Accounting Network (NASQAN) station
9 Station contains instrumentation for remote stage data retrieval (Telemark or data collection platform)
12 Sediment data collected for Corps of Engineers
16 Benchmark station; hydrologic regime of its watershed is controlled by natural conditions
21 Discharge and stage data used to forecast floods by National Weather Service
31 Discharge data used for regulating pool levels of the Mississippi River 9-foot navigation channel
34 Discharge data used in developing alternative methods of flood control
36 Metropolitan Waste Control Commission monitors water quality at this site (automatic monitor).
37 Daily discharge used in making operational decisions for wastewater treatment plant
39 Study of agricultural runoff
F1 Minnesota Department of Natural Resources
F2 U.S. Army Corps of Engineers
F4 Reimbursement from U.S. Geological Survey for NASQAN data collection costs
F9 U.S. Geological Survey
F16 Minnesota Department of Transportation (High flow site)
F17 Metropolitan Waste Control Commission
F18 Minnesota Pollution Control Agency
A Data published on an annual basis
T Data transmitted by telemetry such as satellite, radio, or phone line

Conclusions Pertaining to Data-Use Analysis

An analysis was made of the distribution of 205 continuous-record gaging stations that have been or currently are operated by the U.S. Geological Survey in Minnesota. The analysis was restricted to those gaging stations whose drainage basins lie completely within a hydrologic cataloging unit as defined by the Water Resources Council and the U.S. Geological Survey (U.S. Geological Survey, 1976). This restriction was used for two reasons, (1) the cataloging units are the watersheds of the major rivers in Minnesota and, therefore, the distribution of gages by watershed can be analyzed and (2) the hydrologic unit codes corresponding to each gaging stations are on computer retrievable lists. As a result, the hydrologic cataloging unit is a convenient way to analyze the areal distribution of gaging stations. Restricting the gaging stations to those within a cataloging unit excluded the few stations on the Red River, the Minnesota River, the St. Croix River, the Red Lake River, and the Mississippi River whose watersheds include more than one cataloging unit.

An analysis of the worth of peak flow information in developing regional flood frequency equations showed that at least 20-years of peak flows were needed to develop good flood statistics, but that in Minnesota the marginal increase in information for flood statistics becomes small for each additional year after 25-years (Oral commun., James E. Jacques, U.S. Geological Survey). In addition at least 20 years of record are needed to define a 20-year recurrence-interval annual minimum flow adequately (Riggs, 1972, p. 6). As a result, the gaging stations were divided into those with 25 or more years of record and those with less than 25 years of record.

The results of the analysis are shown in figures 3 through 5. Figure 3 shows the distribution of all 205 stations; these include stations with less than a year of record to those with over 80 years of record. Figure 4 shows the distribution of the 137 stations with less than 25 years of continuous record. Figure 5 shows the distribution of the 68 stations with 25 and more years of record.

Because of research projects or because of an ongoing need to monitor river flows for maintenance of navigation channels, for flood control, and for other projects, more than 10 continuous-record gaging stations have been operated in some cataloging units while only one or two gaging stations have been operated in many of them, and some units have not had any gaging stations. This disparity in distribution becomes more evident when the gaging stations are divided into those that have more than 25-years of record (fig. 5) and those that have less than 25-years of record (fig. 4).

Most of the gaging stations in Minnesota are established to provide data for a particular purpose and as a result cannot be moved elsewhere. However, thirteen stations have no other purpose than to provide information on regional hydrology and can be moved when enough data is collected to adequately define the hydrology of the watershed being gaged. These stations are listed in table 3.

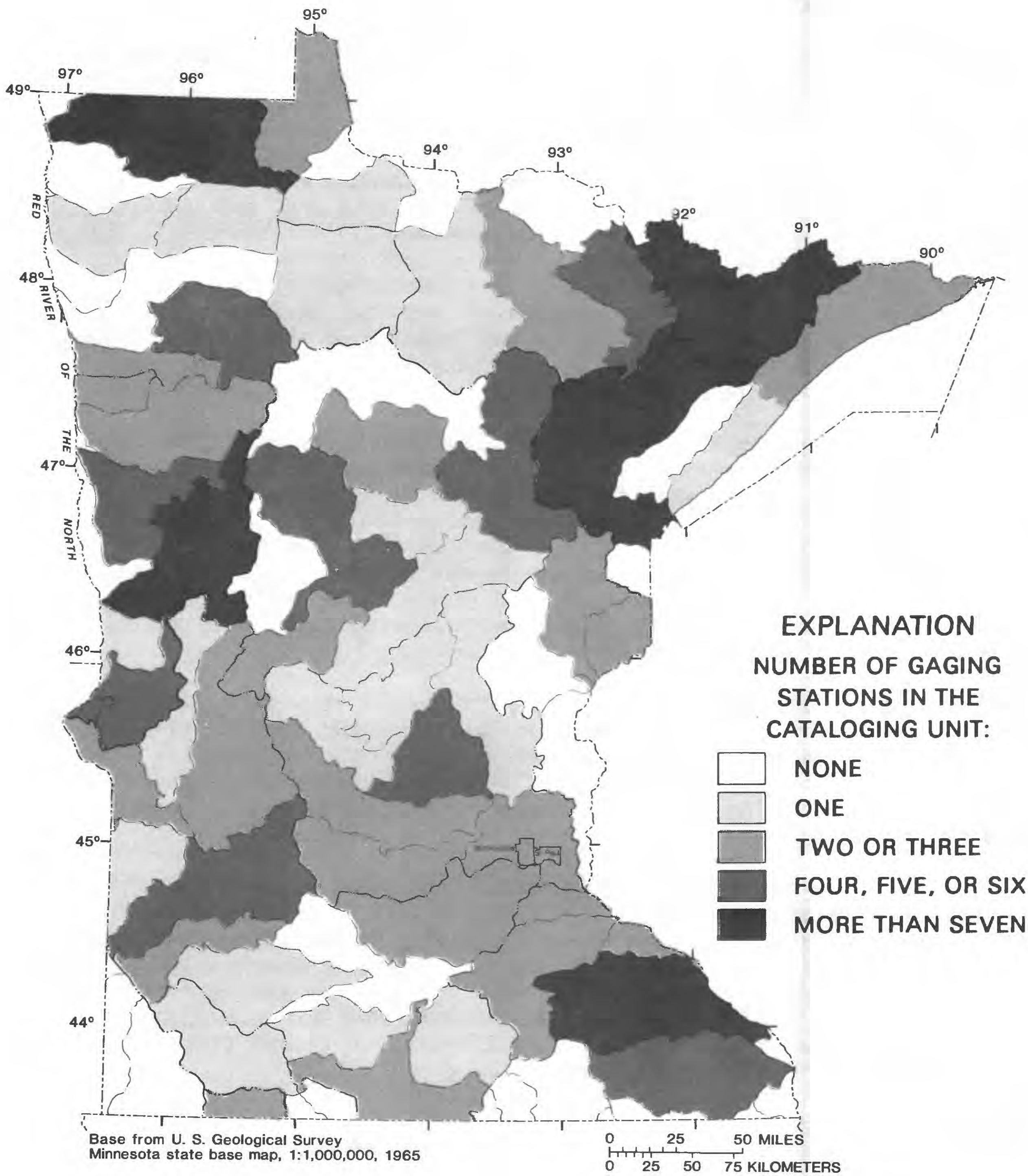


Figure 3.--Distribution by hydrological cataloging unit of all continuous-record streamflow-gaging stations in Minnesota whose watershed lies within one hydrologic cataloging unit

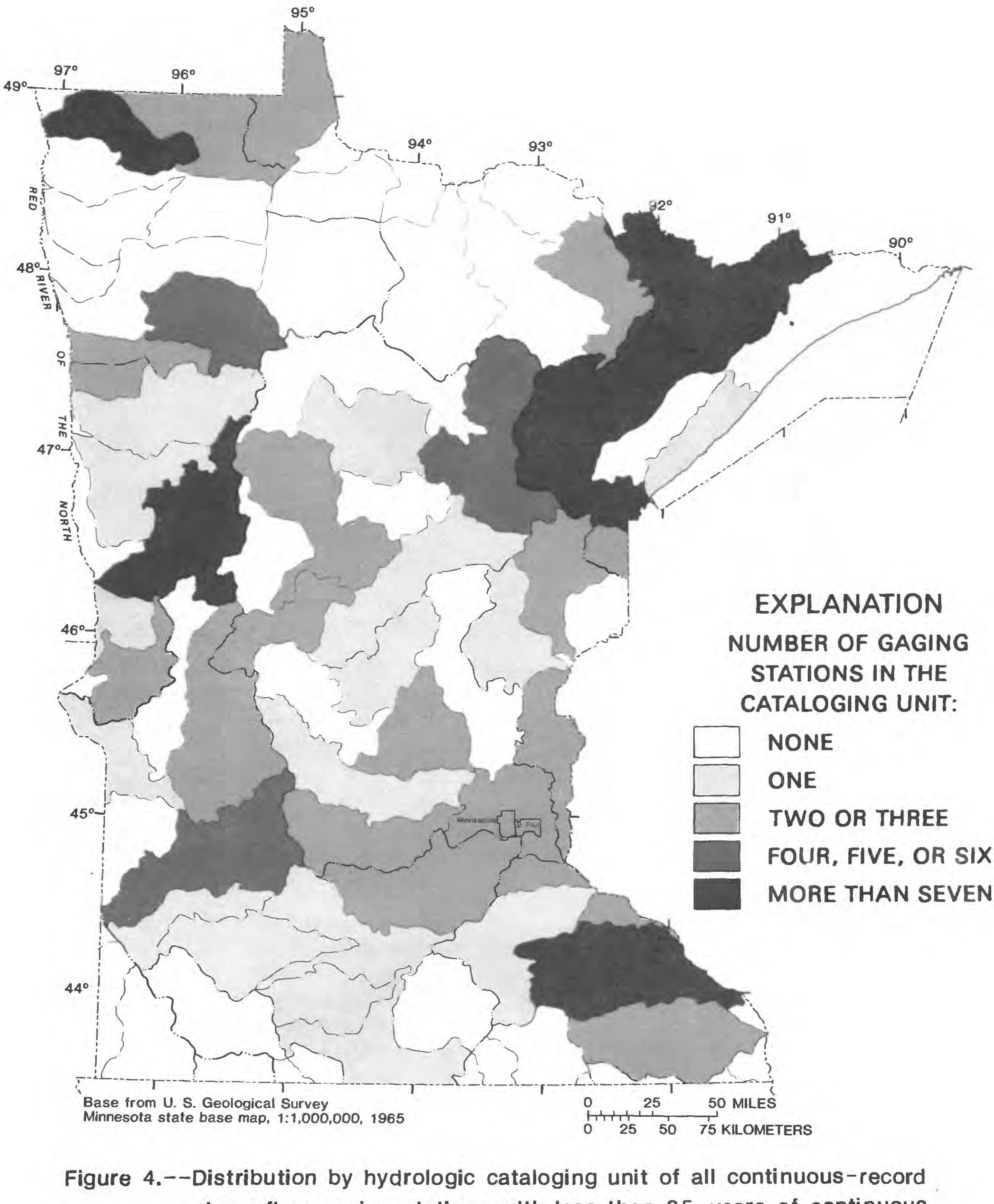


Figure 4.--Distribution by hydrologic cataloging unit of all continuous-record streamflow-gaging stations with less than 25-years of continuous record whose watershed lies within one hydrologic cataloging unit

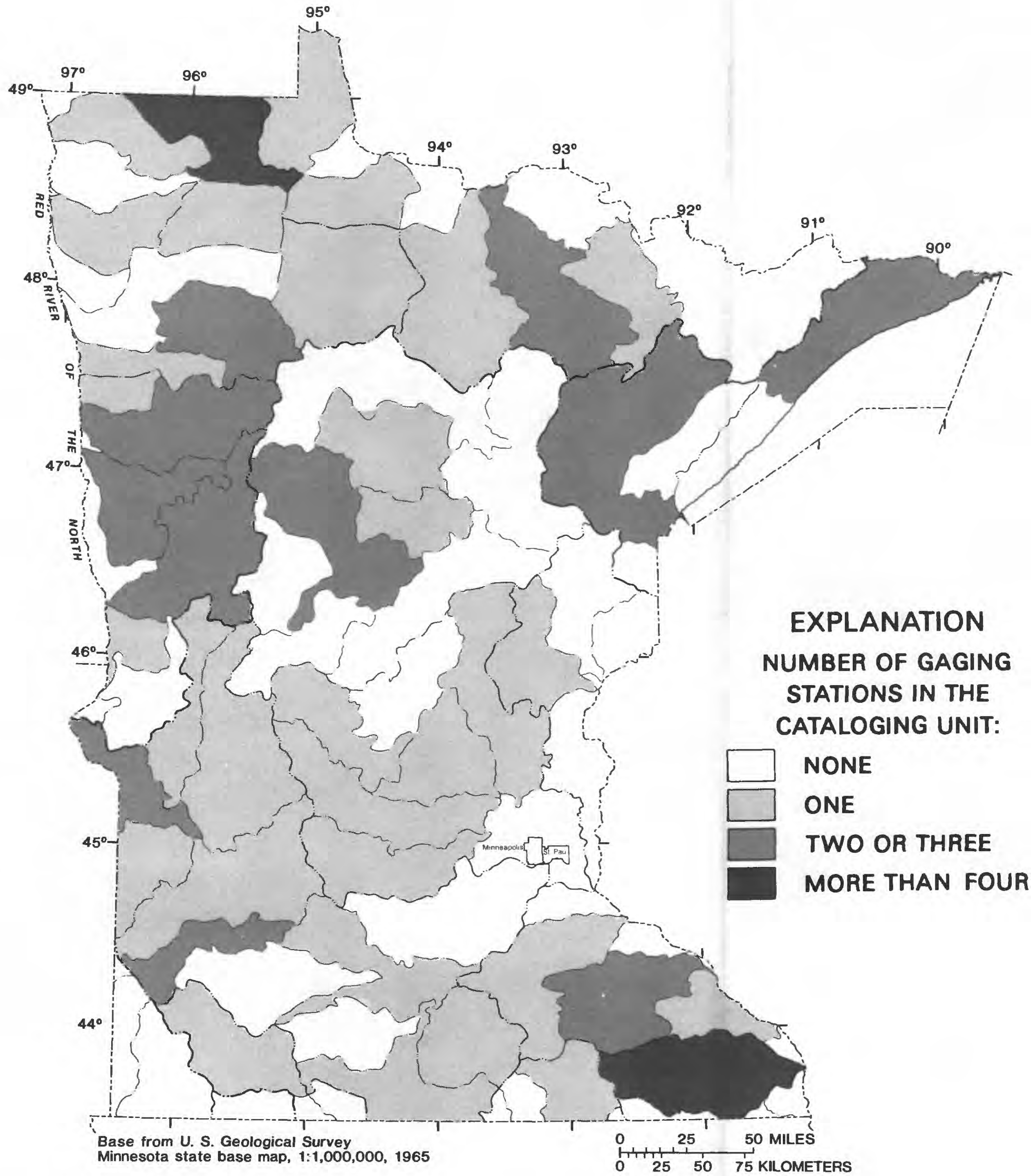


Figure 5.--Distribution by hydrologic cataloging unit of all continuous-record streamflow-gaging stations with 25-years of continuous record whose watershed lies within one hydrologic cataloging unit

Table 3.--Continuous-record streamflow-gaging stations operated to provide information on regional hydrology

Station number	Station name	Years of Record	Drainage Area (mi^2)	Mean Annual Flow (ft^3/s)
04024098	Deer Creek near Holyoke	10	7.77	6.07
05124990	Filson Creek near Ely	12	9.66	7.48
05130500	Sturgeon River near Chisholm	44	187	124
05245100	Long Prairie River at Long Prairie	15	432	145
05275000	Elk River near Big Lake	57	615	256
05278000	Middle Fork Crow River at Spicer	37	179	53.2
05317200	Little Cottonwood River near Courtland	18[1/] 13	230	38.2
05319500	Watonwan River near Garden City	16	812	279
08327000	High Island Creek near Henderson	17[1/] 13	237	60.5
05337400	Knife River near Mora	18[1/] 12	102	692
05340050	Sunrise River near Lindstrom	21	231	95.1
05353800	Straight River near Faribault	21	442	237
05378300	Straight Valley Creek near Rollingstone	28[2/] 16	5.16	2.36

[1/] Years of record including the years the station was operated as a low-flow partial record station.

[2/] Years of record including the years the station was operated as a high-flow partial record station.

It is recommended that the gaging stations on the Elk River near Big Lake, Minnesota, and on the Middle Fork of the Crow River near Spicer, Minnesota, be discontinued immediately, because they have long records greater than 25 years. It is also recommended that the remaining stations, with the exception of the station on the Sturgeon River near Chisholm, Minnesota, be discontinued after they have 25-years of continuous record. The gaging station on the Sturgeon River at Chisholm is not recommended for deactivation at this time because it is the only station left in the area that is unaffected by regulation or diversion. It is used as a natural hydrology index station in the computation of discharge for nearby stations. It is recommended that the funds that had been used to operate the discontinued stations be used to start new gaging stations or to reactivate old gaging stations in hydrologic cataloging units that have not been sufficiently gaged.

Four stations are used to provide data for research projects: Initial tailings basin outflow near Keewatin, Minnesota; Dry Creek near Jeffers, Minnesota; Stockton Valley Creek at Stockton, Minnesota; and Garvin Brook near Minnesota City, Minnesota. The station on Garvin Brook is a station in a karst region with a stable base flow and a good stage-discharge rating over a wide range of flows. The stream is also a designated trout stream. Because of this, the Minnesota Department of Natural Resources has included this station in its cooperative program with the Minnesota District of the Survey. It is recommended that the remaining three stations be discontinued when the research projects end.

The station on Straight Valley Creek near Rollingstone, Minnesota, was destroyed in June, 1985, when the bridge it was near was removed prior to reconstruction. The station was not reconstructed; instead the funds used to operate this station were transferred to the operation of the station on Garvin Brook near Minnesota City, Minnesota.

Based on the recommendations made above, the following six stations will not be considered further in this report: Elk River near Big Lake, Minnesota; Middle Fork of the Crow River near Spicer, Minnesota; Initial tailings basin outflow near Keewatin, Minnesota; Dry Creek near Jeffers, Minnesota; Stockton Valley Creek at Stockton, Minnesota; and Straight Valley Creek near Rollingstone, Minnesota.

STEP TWO: ANALYSIS OF ALTERNATIVE METHODS OF DEVELOPING STREAMFLOW INFORMATION

The second step of the analysis of the streamflow-gaging program is to investigate alternative methods of providing daily streamflow information in lieu of operating continuous-record gaging stations. The objective of the analysis is to identify gaging stations where alternative technology, such as flow-routing or statistical methods, will provide information about daily mean streamflow in a more cost-effective manner than operating a continuous-record 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 discharges is suitable for the intended purpose. The data uses at a station will influence whether a site has potential for alternative methods. For example, those stations for which real-time flood hydrographs are required, such as hydrologic forecasts and project operation, are not candidates for the alternative methods. Likewise a legal obligation to operate a gaging station would preclude utilizing alternative methods. The primary candidates for alternative methods are stations that are operated upstream or downstream of other stations on the same stream. The accuracy of the estimated streamflow at these sites may be suitable because of the high redundancy of flow information between sites. Similar drainage basins, located in the same physiographic and climatic area, also may have potential for alternative methods.

Because of the short timeframe of this analysis, only certain alternative methods were considered. Desirable attributes of a proposed method are: (1) it should be computer oriented and easy to apply, (2) it should have an available interface with the Survey WATSTORE Daily Values File (Hutchinson, 1975), and (3) the proposed method should be technically sound and generally acceptable to the hydrologic community. The interface with the WATSTORE Daily Values File is needed to easily calibrate the proposed alternative method. The alternative method selected for analysis must be technically sound or it will not be able to provide data of suitable accuracy. The above selection criteria were used to select multiple regression techniques as the method of analysis.

Description of Regression Analysis

Simple- and multiple-regression techniques can be used to estimate daily flow records. Regression equations can be computed that relate daily discharges (or their logarithms) at a single station to daily discharges at a combination of upstream, downstream, and/or tributary stations. This statistical method is not limited to downstream stations where an upstream station exits on the same stream. The independent variables in the regression analysis can be stations from different drainage basins, or downstream and tributary drainage basins. The regression method has the attributes that it is easy to apply, provides indices of accuracy, and is generally accepted as a good tool for estimation. The theory and assumptions of regression analysis are described in several textbooks such as Draper and Smith (1981) and Kleinbaum and Kupper (1978). The application of regression analysis to hydrologic problems is described and illustrated by Riggs (1973) and Thomas and Benson (1970). Only a brief description of regression analysis is provided in this report.

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

$$Y_i = B_o + \sum_{j=1}^{p} B_j X_j + e_i$$

where

Y_i = mean-daily discharge at station i or the log transformed mean-daily discharge at station i (dependent variable),

X_j = mean-daily discharges at nearby stations or the log transformed mean-daily discharges at nearby stations (independent variables),

B_o and B_j = regression constant and coefficients,

e_i = the random error term, and

p = the number of nearby stations used in the regression analysis.

The above equation was calibrated (B_o and B_j were estimated) using observed and log transformed mean-daily discharges as values for Y_i and X_j. These observed mean-daily discharges were retrieved from the WATSTORE Daily Values File. The values of X_j may have been discharges observed on the same day as the discharges at station i or may have been for previous or future days depending on whether station j is upstream or downstream of station i. Once the equation was calibrated and verified, future values of Y_i were estimated using observed values of X_j. The regression constant and coefficients (B_o and B_j) were tested to determine if they were significantly different from zero. A given station j was retained in the regression equation if its regression coefficient (B_j) was significantly different from zero. The regression equation was calibrated using one period of time and then tested on a different period of time to obtain a measure of the true predictive accuracy. Both the calibration and verification period are representative of the range of discharges that could occur at station i. The equation was verified by (1) comparing the variability (variance) of the simulated daily mean discharges to the observed values, (2) plotting the residuals (difference between simulated and observed discharges) against the dependent and all independent variables in the equation, and (3) plotting the simulated and observed discharges versus time. These tests were intended to identify if (1) the simulated discharges had the same range of variability as the observed values, (2) the linear model was appropriate or whether some transformation of the variables was needed, and (3) there was any bias in the equation such as over estimating low discharges. These tests might indicate, for example, that a nonlinear regression equation was appropriate, or that the regression equation was biased in some way.

Categorization of Continuous-Record Streamflow-Gaging Stations by Their Potential for Alternative Methods

All stations in the Minnesota streamflow-gaging program were categorized as to their potential for alternative methods. They were further categorized as to their suitability for the chosen alternative method, multiple-linear regression analysis. Twenty-three stations were identified at which multiple-linear regression analysis could be used to provide the needed streamflow information. These stations and the nearby stations used in the linear regressions are listed in table 4.

Table 4. Continuous-record streamflow-gaging stations selected for alternative methods analysis

Model number	Variable type	Station number	Station name	Drainage area ($mile^2$)
1	Dependent	05104500	Roseau River below South Fork near Malung, MN	573
	Independent	05107500	Roseau River at Ross, MN	1,220
2	Dependent	05061000	Buffalo River near Hawley, MN	322
	Independent	05062000	Buffalo River near Dilworth, MN	1,040
3	Dependent	05061500	South Branch Buffalo River at Sabin, MN	522
	Independent	05062000	Buffalo River near Dilworth, MN	1,040
4	Dependent	05124990	Filson Creek near Ely, MN	9.66
	Independent	05124480	Kawishiwi River near Ely, MN	253
5	Dependent	05132000	Big Fork River at Big Falls, MN	1,460
	Independent	05131500	Little Fork River at Littlefork, MN	1,730
6	Dependent	05227500	Mississippi River at Aitkin, MN	6,140
	Independent	05220500	Mississippi River nr Sandy River near Libby, MN	5,060
7	Dependent	05291000	Whetstone River near Big Stone City, SD	389
	Independent	05293000	Yellow Bank River near Odessa, MN	398
8	Dependent	05292000	Minnesota River at Ortonville, MN	1,160
	Independent	05293000	Yellow Bank River near Odessa, MN	398
9	Dependent	05293000	Yellow Bank River near Odessa, MN	398
	Independent	05291000	Whetstone River near Big Stone City, SD	389
	Independent	05292000	Minnesota River at Ortonville, MN	1,160
10	Dependent	05294000	Pomme de Terre River at Appleton, MN	905
	Independent	05304500	Chippewa River near Milan, MN	1,870
11	Dependent	05300000	Lac qui Parle River near Lac qui Parle, MN	983
	Independent	05293000	Yellow Bank River near Odessa, MN	398
12	Dependent	05301000	Minnesota River near Lac qui Parle, MN	4,050
	Independent	05300000	Lac qui Parle River near Lac qui Parle, MN	983
	Independent	05293000	Yellow Bank River near Odessa, MN	398
	Independent	05294000	Pomme de Terre River at Appleton, MN	905
	Independent	05304500	Chippewa River near Milan, MN	1,870
	Independent	05292000	Minnesota River at Ortonville, MN	1,160
13	Dependent	05304500	Chippewa River near Milan, MN	1,870
	Independent	05294000	Pomme de Terre River at Appleton, MN	905

Table 4. Continuous-record streamflow-gaging stations selected for alternative methods analysis--Continued

Model number	Variable type	Station number	Station name	Drainage area ($mile^2$)
14	Dependent	05311000	Minnesota River at Montevideo, MN	6,180
	Independent	05301000	Minnesota River near Lac qui Parle, MN	4,050
	Independent	05293000	Yellow Bank River near Odessa, MN	398
15	Dependent	05311400	South Branch Yellow Medicine River at Minneota, MN	111
	Independent	05315000	Redwood River at Marshall, MN	303
16	Dependent	05313500	Yellow Medicine River near Granite Falls, MN	653
	Independent	05300000	Lac qui Parle river near Lac qui Parle, MN	983
	Independent	05311400	South Branch Yellow Medicine River at Minneota, MN	111
	Independent	05316500	Redwood River near Redwood Falls, MN	697
17	Dependent	05315000	Redwood river near Marshall, MN	303
	Independent	05311400	South Branch Yellow Medicine River at Minneota, MN	111
18	Dependent	05317200	Little Cottonwood near Courtland, MN	230
	Independent	05317000	Cottonwood River near New Ulm, MN	1,280
	Independent	05320000	Blue Earth River near Rapidan, MN	2,430
	Independent	05320500	Le Sueur River near Rapidan, MN	1,100
19	Dependent	05319500	Watonwan River near Garden City, MN	812
	Independent	05317000	Cottonwood River near New Ulm, MN	1,280
	Independent	05320000	Blue Earth River near Rapidan, MN	2,430
	Independent	05320500	Le Sueur River near Rapidan, MN	1,100
20	Dependent	05330000	Minnesota River near Jordan, MN	16,200
	Independent	05325000	Minnesota River at Mankato, MN	14,900
21	Dependent	05331000	Mississippi River at St. Paul, MN	36,800
	Independent	05288500	Mississippi River near Anoka, MN	19,600
	Independent	05330000	Minnesota River near Jordan, MN	16,200
22	Dependent	05337400	Knife River near Mora, MN	102
	Independent	05336700	Kettle River below Sandstone, MN	863
23	Dependent	05376800	Whitewater River near Beaver, MN	271
	Independent	05376000	North Fork Whitewater River near Elba, MN	101

Regression Modeling

The streamflow record for each station considered for simulation (the dependent station) was regressed against streamflow records at other stations (independent station). Linear regression models were developed using mean-daily discharges in ft^3/s and using the logarithms of the mean-daily discharges. The model that provided the best estimates of mean-daily discharge at the dependent station was used. Linear regression analysis was done for two groups of stations. For the first group of stations half of the available data was used to calibrate the best fit linear model; estimates of the discharge at the dependent station were verified using the remaining data. The second group of stations were selected later for the alternative methods analysis. Because the results for the first group of stations had been so poor, only one year of data was used to calibrate the regression models for the second group in order to quickly determine which stations were good candidates for regression modeling. For both groups of stations the percent difference between the estimated discharges and the actual discharges was computed.

The linear model was considered to be an acceptable, alternative method if the estimates of mean-daily discharges were within 10% of the actual mean-daily discharges for 95% or more of the discharges estimated. None of the linear models developed for the 24 stations met this test.

The best linear models from the regression analysis are given in table 5.

Table 5. -- Results of alternative methods analysis

[Q_{1045}, mean daily discharge at station 05104500; Q_{x2205}, mean daily discharge for the previous day at station 05220500; Q_{xx3250}, mean daily discharge lagged two days at station 05325000]

Dependent Station	Model	Percent of simulated flow within 5 percent of actual flow	Percent of simulated flow within 10 percent of actual flow	Calibration period (Water Years)
Roseau River below South Fork near Malung, MN				
05104500	$Q_{1045}=0.406(Q_{1075})^{0.988}$	7	13	1946-64
Buffalo River near Hawley, MN				
05061000	$Q_{0610}=2.05(Q_{0620})^{0.742}$	19	37	1946-62
South Branch Buffalo River at Sabin, MN				
05061500	$Q_{0615}=0.0339(Q_{0620})^{1.35}$	5	11	1946-62
Filson Creek near Ely, MN				
05124990	$Q_{1249.9}=0.646(Q_{1244.8})^{0.795}$	3	6	1975-78
Big Fork River at Big Falls, MN				
05132000	$Q_{1320}=1.66(Q_{1315})^{0.869}$	9	19	1929-53
Mississippi River at Aitkin, MN				
05227500	$Q_{2275}=0.833(Q_{2205})^{0.201}(Q_{x2205})^{0.849}$	20	42	1946-64
Whetstone River near Big Stone City, SD				
05291000	$Q_{2910}=1.73(Q_{2930})^{0.874}$	8	16	1982
Minnesota River at Ortonville, MN				
05292000	$Q_{2920}=2.82(Q_{2930})^{0.857}$	2	4	1940-65
Yellow Bank River near Odessa, MN				
05293000	$Q_{2930}=10^{-0.216}(Q_{2910})^{0.859}(Q_{2920})^{0.179}$	5	15	1982

Table 5. -- Results of alternative methods analysis -- Continued

Dependent Station	Model	Percent of simulated flow within 5 percent of actual flow	Percent of simulated flow within 10 percent of actual flow	Calibration period (Water Years)
Pomme de Terre River at Appleton, MN				
05294000	$Q_{2940}=1.35(Q_{3045})^{0.789}$	9	18	1937-50
Lac qui Parle River near Lac qui Parle, MN				
05300000	$Q_{3000}=2.00(Q_{2930})^{1.03}$	8	15	1940-42
Minnesota River near Lac qui Parle, MN				
05301000	$Q_{3010}= -142 + 1.52(Q_{3000}) - 6.65(Q_{2930}) - 2.89(Q_{2940}) + 3.81(Q_{3045}) + 2.74(Q_{x2920})$	4	6	1969
Chippewa River near Milan, MN				
05304500	$Q_{3045}=1.42(Q_{2940})^{1.06}$	7	14	1937-50
Minnesota River at Montevideo, MN				
05311000	$Q_{3110}=4.80(Q_{3010})^{0.678}(Q_{2930})^{0.244}$	23	44	1969
South Branch Yellow Medicine at Minneota, MN				
05311400	$Q_{3114}=0.270(Q_{3150})^{1.03}$	6	12	1960-70
Yellow Medicine River near Granite Falls, MN				
05313500	$Q_{3135}= -10.5 - 0.206(Q_{3114}) + 0.451(Q_{3000}) + 0.606(Q_{3165})$	8	16	1960-71
Redwood River near Marshall, MN				
05315000	$Q_{3150}=4.90(Q_{3114})^{0.753}$	7	13	1960-70
Little Cottonwood River near Courtland, MN				
05317200	$Q_{3172}=0.0219(Q_{3170})^{0.723}(Q_{3200})^{0.628}(Q_{3205})^{-0.126}$	8	14	1974-April, 1979

Table 5. -- Results of alternative methods analysis -- Continued

Dependent Station	Model	Percent of simulated flow within 5 percent of actual flow	Percent of simulated flow within 10 percent of actual flow	Calibration period (Water Years)
Watonwan River near Garden City, MN				
05319500	$Q_{3195}=0.939(Q_{3172})^{0.323}(Q_{3170})^{0.206}(Q_{3200})^{0.497}(Q_{3205})^{-0.0268}$	12	26	Sept, 1976-
Minnesota River near Jordan, MN				
05330000	$Q_{3300}=109 + 1.13(Q_{xx3250})$	37	61	1974-75
Mississippi River at St. Paul, MN				
05331000	$Q_{3310}= -27.3 + 0.960(Q_{2885}) + 1.27(Q_{x3300})$	64	85	1940
Knife River near Mora, MN				
05337400	$Q_{3374}= -12.1 + 0.121(Q_{3367})$	7	13	July, 1974- June, 1978
Whitewater River near Beaver, MN				
05376800	$Q_{3768}=10(Q_{3760})^{0.704}$	45	72	1975-77 April, 1979

Conclusions Pertaining to Alternate-Methods Analysis

The regression equations were not sufficiently accurate at any of the twenty-three selected stations to recommend this method in lieu of operating a continuous-record streamflow gaging station.

It is recommended that flow routing be tried as an alternative method for providing discharge information at three groups of stations: (1) the stations on the Mississippi River at St. Paul, Minnesota, and at Prescott, Wisconsin, (2) the stations on the Minnesota River near Lac Qui Parle, and Montevideo, Minnesota, and (3) the stations on the Red Lake River at Highlanding, near Goodridge, and at Crookston, Minnesota.

The stations on the Mississippi Rivers at St. Paul and Prescott are particularly good candidates for flow routing. The stations are located on the navigation pools formed by the locks and dams operated by the U.S. Army Corps of Engineers to maintain the nine-foot navigation channel on the Mississippi River. At lower discharges the U.S. Army Corps of Engineers maintains the required stages in the pools by varying the discharge through the dams. As a result a stage-discharge relation cannot be established for discharges less than about 15,000 ft^3/s for the station at St. Paul. Below 15,000 ft^3/s the discharge for the station at St. Paul is determined by routing the discharges from the station on the Minnesota River at Jordan and the station on the Mississippi River near Anoka. The discharges from St. Paul and from the station on the St. Croix River at St. Croix Falls, Wisconsin, are then routed to determine the discharge at the station at Prescott.

It is recommended that the 23 stations remain part of the Minnesota streamflow-gaging program. They will be included in the next step of this study.

STEP THREE: COST-EFFECTIVE RESOURCE ALLOCATION

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

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

The original version of K-CERA was therefore altered to include as optional measures of effectiveness the sums of the variances of errors of estimation of the following streamflow variables; annual mean discharge, in cubic feet per second; annual mean discharge, in percent; average instantaneous discharge, in cubic feet per second; or average instantaneous discharge in percent (Fontaine and others, 1984). The use of percentage errors effectively gives equal weight to large and small streams. In addition, instantaneous discharge is the basic variable from which all other streamflow data are derived. For these reasons, this study used the K-CERA techniques with the sums of the variances of the percentage errors of the instantaneous discharges at continuous-record streamflow-gaging stations as the measure of the effectiveness of the data-collection activity.

The original version of K-CERA also did not account for error contributed by missing stage or other correlative data that are used to compute streamflow data. The probabilities of missing correlative data increase as the period between service visits to a streamflow-gaging station increases. A procedure for dealing with the missing record has been developed (Fontaine and others, 1984) and was incorporated into this study.

Brief descriptions of the mathematical program used to minimize the total error variance of the data-collection activity for given budgets and of the application of Kalman filtering (Gelb, 1974) to the determination of the accuracy of a streamflow-gaging record are presented by Fontaine and others (1984). For more detail on either the theory or the applications of the K-CERA model, see Moss and Gilroy (1980) and Gilroy and Moss (1981).

Description of Mathematical Program

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

Another step in this part of the analysis is the determination of any special requirements for visits to each of the stations for such things as necessary periodic maintenance, rejuvenation of recording equipment, or required periodic sampling of water-quality data. The minimum number of visits to each station usually are limited by these special requirements.

The final step is to use all of the above to determine the number of times that each route 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. This step in the form of a mathematical program is presented in figure 6. A tabular presentation of the problem is presented in figure 7. Each of the routes is represented by a row of the table and each of the stations is represented by a column. The zero-one matrix defines the routes in terms of the stations that comprise it. A value of one in the row indicates that a gaging station will be visited on the route; a value of zero indicates that it will not. The unit travel costs 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 the unit travel costs multiplied by the times the route was used is the total travel cost.

The unit-visit cost is comprised of the average service and maintenance costs incurred on a visit to the station plus the average cost of making a discharge measurement. The minimum visit constraints are set for each station. The product of the visits to each station per route and the times the route is used must equal or exceed the minimum visit constraints.

Minimize $V \equiv \sum_{j=1}^{MG} \phi_j(M_j)$

V ≡ total uncertainty in the network,

MG ≡ number of gages in the network,

M_j ≡ annual number of visits to station j,

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

Such that

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

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

F_c ≡ fixed cost,

α_j ≡ unit cost of visit to station j,

NR ≡ number of practical routes chosen,

β_i ≡ travel cost for route i,

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

and such that

$M_j \geq \lambda_j$

λ_j ≡ minimum number of annual visits to station j.

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

Route	Gage 1	2	3	4	•	j	•	MG	Unit Travel Cost	Uses
1	1	0	0	0	•	•	•	0	β_1	N_1
2	1	1	0	0	•	•	•	0	β_2	N_2
3	1	0	0	0	•	•	•	0	β_3	N_3
4	0	1	0	0	•	•	•	0	β_4	N_4
•	•	•	•	•	•	•	•	•	•	•
•	•	•	•	•	•	•	•	•	•	•
•	•	•	•	•	•	•	•	•	•	•
i	•	•	•	•	•	$(\omega)_{ij}$	•	•	β_i	N_i
•	•	•	•	•	•	•	•	•	•	•
•	•	•	•	•	•	•	•	•	•	•
•	•	•	•	•	•	•	•	•	•	•
NR	0	0	0	0	•	•	•	1	β_{NR}	N_{NR}
Unit Visit Cost	α_1	α_2	α_3	α_4	•	α_κ	•	α_{MG}		
Minimum Visits	λ_1	λ_2	λ_3	λ_4	•	λ_κ	•	α_{MG}		
Visits	M_1	M_2	M_3	M_4	•	M_j	•	M_{MG}		
Uncert. Function	ϕ_1	ϕ_2	ϕ_3	ϕ_4	•	ϕ_j	•	ϕ_{MG}		

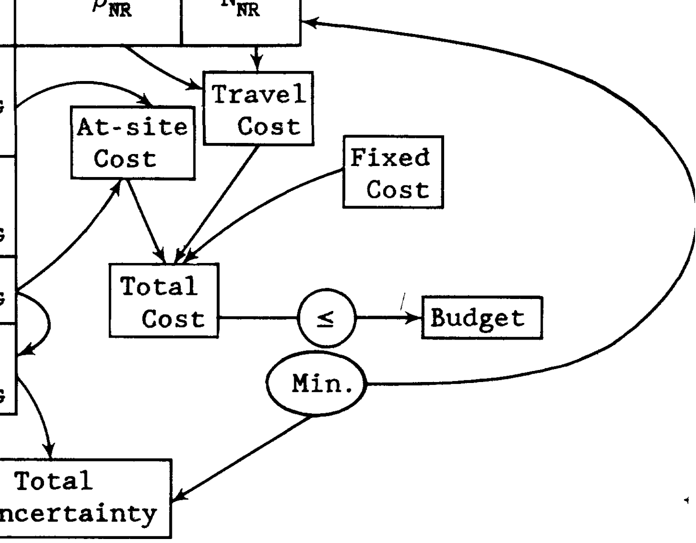


Figure 7.--Tabular form of the optimization of the routing of hydrographers

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

The total uncertainty in the estimates of discharges at all the stations in the network is determined by summing the uncertainty functions evaluated for the total visits to all stations.

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 obtained with this technique specify an efficient strategy for operating the network, which may be the true optimum strategy. The true optimum strategy cannot be guaranteed without testing all undominated, feasible strategies.

A detailed description of the uncertainty function (Fontaine and others, 1984) and a similar description of the method for deriving the relationship of visit frequency to lost record (Moss, 1984), as published in the report of the pilot study of cost effectiveness in Maine, are found in the Appendix of this report.

It is assumed in this study that the differences between the logarithms of the computed discharges and the true discharges at each instance are normally (Gaussian) distributed with a mean of zero and a variance of either V_f, V_r, or V_e depending on whether the at-site streamflow recorder was functioning (f), whether the record was reconstructed (r) from another primary source of data, or whether the record was estimated (e) without the aid of other concurrent data. Therefore, the resulting a priori distribution of errors is not normally distributed in terms of the logarithms of discharge data. This lack of normality causes difficulty in interpretation of the resulting errors of estimation, that is, the square root of the uncertainty contained in the streamflow record. If the logarithmic errors were normally distributed, approximately two-thirds of the time the true logarithmic error would be within the range defined by plus and minus one standard error from the mean. The lack of normality caused by the multiple sources of error increases the percentage of errors contained within this range above that of a Gaussian probability distribution of logarithmic errors with the same standard deviation.

The Application of K-CERA in Minnesota

As a result of the first two parts of this study it has been recommended that 91 of the 96 existing streamflow-gaging stations in the State of Minnesota be continued in operation. An additional station was discontinued in 1985. Of the remaining 90 stations the records for nine stations are supplied by the U.S. Army Corps of Engineers, the Minnesota Power Company, or Canada. The Survey reviews the records and makes discharge measurements at the stations to check the records. The U.S. Army Corps of Engineers computes the mean daily discharge for stations on the (1) Mississippi River at Winnibigoshish Dam near Deer River, Minnesota, (2) Leech Lake River at Federal Dam, Minnesota, (3) Sandy River at Sandy Lake Dam at Libby, Minnesota, (4) Pine river at Cross Lake Dam at Cross Lake, Minnesota, and (5) Gull River at Gull Lake Dam near Brainerd, Minnesota. The Minnesota Power Company computes the mean daily discharge for stations on the (1) Kawishiwi River near Winton, Minnesota, (2) Crow Wing River near Pillager, Minnesota, and (3) Mississippi River near Royalton, Minnesota. The Canadian government supplies the record for the station on the Namakan River at the outlet of Lac La Croix, Ontario, Canada. Because the records for these stations are not computed by the Survey, these stations will not be considered further in the report. The records of the 81 remaining streamflow-gaging stations were subjected to the K-CERA analysis with results that are described below.

The K-CERA analysis was applied only to a 214-day period of open-water, April 1 to October 31. In Minnesota the winter record is based upon several factors. First, the daily discharge is computed as in the open-water period. These values are plotted on a hydrograph with respect to day. Actual discharge measurements are made during the ice-affected period and the measured discharges are plotted on the graph. The measured discharge is always less than the discharge computed by the open-water rating if there is backwater from ice. The maximum and minimum daily temperatures for the regional area of the station, the abnormal fluctuations of stages, and the pen trace on the strip chart are used as indicators of the presence of ice effect. Extra visual observations by hydrographers, precipitation records, and observer reports verify the ice condition. Two or more nearby stations are examined together to add information to the entire evaluation of the magnitude of ice effect. On the basis of the above information for all of the stations assumed to be similarly affected, the open-water discharge is adjusted to a realistic actual discharge.

The winter records for Minnesota gaging stations are generally rated fair, 95 percent of the computed discharges for the period are within 10 to 15 percent of the actual discharge. The magnitude of the ice affect may vary during the day. The ice affect is usually more consistent if the stream surface freezes completely at the beginning of winter and remains frozen until spring. A discharge measurement made soon after the freeze, one during the middle of winter and one just before melting, can give a fairly good trend for the whole period. However, temperatures can fluctuate enough to cause periods of ice cover followed by periods of open water.

Definition of Missing Record Probabilities

To estimate the percentage of missing record for a streamflow discharge station in Minnesota, the records for the streamflow-gaging stations operated by the St. Paul field office were examined for a ten-year period in which little change in technology occurred and in which the stations were visited on a consistent pattern of monthly frequency.

The water stage at the stations was determined by a gas manometer or by a float in a stilling well. The stage may have been recorded on a punched tape, a strip chart, or both. The common practice in the St. Paul field office is not to make expensive, special trips to repair equipment during the ice-affected periods of the year because the measured discharge, not the recorded stage, is used to compute the mean daily discharge during this period of the year. In addition, the equipment in the gaging stations fails more often during this period compared to the rest of the year because of extreme cold, storms and ice.

The percentage of missing record because of equipment failure was analyzed for the entire year, the open-water period, and the ice-affected period. For the purposes of this analysis the open-water period was defined to be from April 1 to October 31 each year; the ice-affected period was defined to be from November 1 to March 31 each year. The analysis was also broken down into station type, manometer or stilling well, and by recording equipment, punched tape recorder, strip chart recorder, or both. During this period the gaging stations were visited an average of 11 times per year, 6.2 times in the open-water period and 4.4 times in the ice-affected period. The results are presented in table 6.

The station type, type of equipment in the station, and the expected lost record for the open-water period are given in table 7. Several of the stations are equipped with a wire weight instead of a manometer or a stilling well. At these stations an observer lowers a weight at the end of a wire once or twice a day to the water surface and then reads the water-surface elevation from a dial turned by the wire. It was assumed that this system has as much reliability as a station with a stilling well and punched tape recorder.

Table 6.--Missing record frequency at continuous-record streamflow-gaging stations operated by the St. Paul field office

Equipment type	Ice-affected period Nov. 1 - March 31 (151 days)		Open-water period April 1 - Oct. 31 (214 days)		Yearly (365 days)	
	Days of missing record	Percent of period	Days of missing record	Percent of period	Days of missing record	Percent of period
	Stations equipped with stilling wells					
Punched tape recorder	16	10.6	9	4.2	25	6.8
Strip chart recorder	11	7.30	4	1.9	15	1.1
Punched tape and strip chart recorder	4	2.6	1	0.5	5	1.4
	Stations equipped with manometers					
Punched tape recorder	39	25.8	19	8.9	58	15.9
Strip chart recorder	35	23.2	14	6.5	49	13.4
Punched tape and strip chart recorder	25	16.6	7	3.3	32	8.8

Table 7.-- Expected lost record for the open-water period, April 1 through October 31, at continuous-record streamflow-gaging stations in Minnesota

Map index no.	Station no.	Station name	Station type	Equipment type	Expected lost record for open-water period, April 1 - Oct. 31 (in percent)
1	04010500	Pigeon River at Middle Falls nr Grand Portage, MN	Stilling well	Punched tape	4.2
2	04014500	Baptism River near Beaver Bay, MN	Manometer	Punched tape	8.9
3	04015330	Knife River near Two Harbors, MN	Manometer	Punched tape	8.9
4	04015475	Partridge River abv Colby Lake at Hoyt Lakes, MN	Manometer	Punched tape	8.9
5	04016500	St. Louis River near Aurora, MN	Stilling well	Punched tape	4.2
6	04018750	St. Louis River at Forbes, MN	Stilling well	Punched tape	4.2
7	04024000	St. Louis River at Scanlon, MN	Stilling well	Punched tape	4.2
8	04024098	Deer Creek near Holyoke, MN	Manometer	Punched tape and strip chart	3.3
9	05046000	Otter Tail River bl Orwell D nr Fergus Falls, MN	Stilling well	Punched tape	4.2
10	05050000	Bois De Sioux River near White Rock, SD	Stilling well	Punched tape and strip chart	0.5
11	05061000	Buffalo River near Hawley, MN	Stilling well	Punched tape	4.2
12	05061500	South Branch Buffalo River at Sabin, MN	Wire weight	------------	4.2
13	05062000	Buffalo River near Dilworth, MN	Stilling well	Punched tape and strip chart	.5
14	05064000	Wild Rice River at Hendrum, MN	Wire weight	------------	4.2
15	05069000	Sand Hill River at Climax, MN	Wire weight	------------	4.2
16	05074500	Red Lake River near Red Lake, MN	Stilling well	Punched tape	4.2
17	05075000	Red Lake River at High Landing nr Goodridge, MN	Stilling well	Punched tape	4.2
18	05076000	Thief River near Thief River Falls, MN	Stilling well	Punched tape	4.2

Table 7.--Expected lost record for the open-water period, April 1 through October 31, at continuous-record streamflow-gaging stations in Minnesota--Continued

Map index no.	Station no.	Station name	Station type	Equipment type	Expected lost record for open-water period, April 1 - Oct. 31 (in percent)
19	05078000	Clearwater River at Plummer, MN	Stilling well	Punched tape	4.2
20	05078230	Lost River at Oklee, MN	Wire weight	------------	4.2
21	05078500	Clearwater River at Red Lake Falls, MN	Stilling well	Punched tape	4.2
22	05079000	Red Lake River at Crookston, MN	Stilling well	Punched tape	4.2
23	05087500	Middle River at Argyle, MN	Manometer	Punched tape	8.9
24	05104500	Roseau River below South Fork near Malung, MN	Stilling well	Punched tape	4.2
25	05107500	Roseau River at Ross, MN	Stilling well	Punched tape	4.2
26	05112000	Roseau River below State Ditch 51 nr Caribou, MN	Stilling well	Punched tape	4.2
27	05124480	Kawishiwi River near Ely, MN	Manometer	Punched tape	8.9
28	05124990	Filson Creek near Ely, MN	Manometer	Punched tape	8.9
30	05127500	Basswood River near Winton, MN	Stilling well	Punched tape and strip chart	.5
32	05129115	Vermilion River nr Crane Lake, MN	Manometer	Punched tape	8.9
33	05129290	Gold Portage Outlet From Kabetogama Lake nr Ray, MN	Manometer	Punched tape	8.9
34	05130500	Sturgeon River near Chisholm, MN	Stilling well	Punched tape	4.2
35	05131500	Little Fork River at Littlefork, MN	Manometer	Punched tape	8.9

Table 7. Expected lost record for the open-water period, April 1 through October 31, at continuous-record streamflow-gaging stations in Minnesota--Continued

Map index no.	Station no.	Station name	Station type	Equipment type	Expected lost record for open-water period, April 1 - Oct. 31 (in percent)
36	05132000	Big Fork River at Big Falls, MN	Stilling well	Punched tape	4.2
37	05133500	Rainy River at Manitou Rapids, MN	Stilling well	Punched tape	4.2
38	05134200	Rapid River near Baudette, MN	Stilling well	Punched tape	4.2
41	05211000	Mississippi River at Grand Rapids, MN	Manometer	Punched tape	8.9
43	05216860	Swan River near Calumet, MN	Stilling well	Punched tape	4.2
45	05220500	Mississippi River below Sandy River nr Libby, MN	Stilling well	Punched tape	4.2
46	05227500	Mississippi River at Aitkin, MN	Manometer	Punched tape	8.9
48	05245100	Long Prairie River at Long Prairie, MN	Manometer	Punched tape and strip chart	3.3
54	05280000	Crow River at Rockford, MN	Stilling well	Strip chart	1.9
55	05286000	Rum River near St. Francis, MN	Stilling well	Punched tape and strip chart	.5
56	05287890	Elm Creek nr Champlin, MN	Manometer	Punched tape	8.9
57	05288500	Mississippi River near Anoka, MN	Stilling well	Punched tape and strip chart	.5
58	05291000	Whetstone River near Big Stone City, SD	Stilling well	Punched tape and strip chart	.5
59	05292000	Minnesota River at Ortonville, MN	Stilling well	Punched tape and strip chart	.5
60	05293000	Yellow Bank River near Odessa, MN	Stilling well	Punched tape and strip chart	.5
61	05294000	Pomme De Terre River at Appleton, MN	Stilling well	Punched tape	4.2
62	05300000	Lac Qui Parle River near Lac Qui Parle, MN	Stilling well	Punched tape	4.2
63	05301000	Minnesota River near Lac Qui Parle, MN	Stilling well	Punched tape	4.2

Table 7. Expected lost record for the open-water period, April 1 through October 31, at continuous-record streamflow-gaging stations in Minnesota--Continued

Map index no.	Station no.	Station name	Station type	Equipment type	Expected lost record for open-water period, April 1 - Oct. 31 (in percent)
64	05304500	Chippewa River near Milan, MN	Stilling well	Punched tape and strip chart	.5
65	05311000	Minnesota River at Montevideo, MN	Manometer	Punched tape	8.9
66	05311400	South Branch Yellow Medicine R at Minneota, MN	Wire weight	------------	4.2
67	05313500	Yellow Medicine River near Granite Falls, MN	Stilling well	Punched tape and strip chart	.5
68	05315000	Redwood River near Marshall, MN	Manometer	Punched tape	8.9
69	05316500	Redwood River near Redwood Falls, MN	Stilling well	Punched tape and strip chart	.5
71	05317000	Cottonwood River near New Ulm, MN	Stilling well	Punched tape and strip chart	.5
72	05317200	Little Cottonwood River near Courtland, MN	Manometer	Punched tape and strip chart	3.3
73	05319500	Watonwan River near Garden City, MN	Manometer	Punched tape and strip chart	3.3
74	05320000	Blue Earth River near Rapidan, MN	Stilling well	Punched tape and strip chart	.5
75	05320500	Le Sueur River near Rapidan, MN	Manometer	Punched tape and strip chart	3.3
76	05325000	Minnesota River at Mankato, MN	Manometer	Punched tape and strip chart	3.3
77	05327000	High Island Creek near Henderson, MN	Manometer	Punched tape and strip chart	3.3
78	05330000	Minnesota River near Jordan, MN	Manometer	Punched tape and strip chart	3.3
79	05331000	Mississippi River at St. Paul, MN	Stilling well	Punched tape and strip chart	.5
80	05336700	Kettle River below Sandstone, MN	Manometer	Punched tape and strip chart	3.3
81	05337400	Knife River near Mora, MN	Manometer	Punched tape and strip chart	3.3
82	05340050	Sunrise River near Lindstrom, MN	Stilling well	Punched tape and strip chart	.5

Table 7. Expected lost record for the open-water period, April 1 through October 31, at continuous-record streamflow-gaging stations in Minnesota--Continued

Map index no.	Station no.	Station name	Station type	Equipment type	Expected lost record for open-water period, April 1 - Oct. 31 (in percent)
83	05344500	Mississippi River at Prescott, WI	Stilling well	Punched tape	4.2
84	05345000	Vermillion River near Empire, MN	Manometer	Punched tape and strip chart	3.3
85	05353800	Straight River near Faribault, MN	Stilling well	Punched tape and strip chart	.5
86	05372995	South Fork Zumbro River at Rochester, MN	Stilling well	Punched tape and strip chart	.5
87	05374900	Zumbro River at Kellogg, MN	Manometer	Punched tape and strip chart	3.3
88	05376000	North Fork Whitewater River near Elba, MN	Manometer	Punched tape	8.9
89	05376800	Whitewater River near Beaver, MN	Manometer	Punched tape and strip chart	3.3
91	05378235	Garvin Brook near Minnesota City, MN	Stilling well	Punched tape and strip chart	.5
93	05378500	Mississippi River at Winona, MN	Stilling well	Punched tape and strip chart	.5
94	05384000	Root River near Lanesboro, MN	Stilling well	Punched tape and strip chart	.5
95	05457000	Cedar River near Austin, MN	Stilling well	Punched tape and strip chart	.5
96	05476000	Des Moines River at Jackson, MN	Manometer	Punched tape and strip chart	3.3

Definition of Cross-Correlation Coefficient and Coefficient of Variation

To compute the values of V_e and V_r of the needed uncertainty functions, daily streamflow records for each of the 80 stations for the last 30 years or part of the last 30 years for which daily streamflow values are stored in WATSTORE were retrieved. For each of the streamflow gaging stations that had 3 or more complete water years of data, the value of C_v was computed and various options, based on combinations of other streamflow gaging stations, were explored to determine the maximum rho_c (see the Appendix for definition of C_v and rho_c). The values of C_v and rho_c were calculated for the open-water period, April 1 to October 31. The values of C_v and rho_c were estimated for the stations that did not have nearby stations from which to reconstruct lost record.

The values of C_v and rho_c for each station and the sources of the reconstructed records that gave the highest cross correlation coefficient are listed in table 8.

Table 8.--Statistics of record reconstruction for continuous-record streamflow-gaging stations in Minnesota

[C_v, coefficient of variation; rho_c, correlation coefficient between the streamflows at the station of interest and at the source station(s); number in parenthesis shows the number of days mean daily discharge of the source station in lagged (-) or advanced (+)]

Map index no.	Station no.	Station name	C_v	rho_c	Source of reconstructed record
1	04010500	Pigeon River at Middle Falls nr Grand Portage,	0.6483	0.7030	04014500, 04015330
2	04014500	Baptism River near Beaver Bay, MN	.9910	.7952	04010500, 04015330
3	04015330	Knife River near Two Harbors, MN	1.1941	.7102	04014500, 04010500
4	04015475	Partridge River abv Colby Lake at Hoyt Lakes, MN	.8464	.7210	04016500, 05124990, 05130500
5	04016500	St. Louis River near Aurora, MN	.7077	.8858	04018750 (+1), 05130500
6	04018750	St. Louis River at Forbes, MN	.6714	.8982	04016500 (-1), 05130500, 04024000 (+1)
7	04024000	St. Louis River at Scanlon, MN	.6953	.7554	04016500 (-1)
8	04024098	Deer Creek near Holyoke, MN	.9755	----	04024110 (High-flow partial-record station, Rock Creek tributary near Blackhoof, MN)
9	05046000	Otter Tail River bl Orwell D nr Fergus Falls, MN		----	Records maintained by the U.S. Army Corps of Engineers at Orwell Reservoir
10	05050000	Bois De Sioux River near White Rock, SD	1.7689	----	Records maintained by the U.S. Army Corps of Engineers at Mud Lake Reservoir
11	05061000	Buffalo River near Hawley, MN	1.1112	.8261	05016500, 05062000 (-1)
12	05061500	South Branch Buffalo River at Sabin, MN	2.0399	.6803	05061000, 05062000 (-1)

Table 8.--Statistics of record reconstruction for continuous-record streamflow-gaging stations in Minnesota --Continued

Map index no.	Station no.	Station name	C_v	rho_c	Source of reconstructed record
13	05062000	Buffalo River near Dilworth, MN	1.4902	.8411	05061000 (+1), 05061500 (+1)
14	05064000	Wild Rice River at Hendrum, MN	1.1953	.8114	05069000, 05076000, 05078230
15	05069000	Sand Hill River at Climax, MN	1.2066	.7923	05064000, 05076000, 05078230
16	05074500	Red Lake River near Red Lake, MN	.7890	.8799	05075000 (+1), 05079000 (+2)
17	05075000	Red Lake River at High Landing nr Goodridge, MN	.7618	.9483	05074500 (-1), 05079000 (+1)
18	05076000	Thief River near Thief River Falls, MN	1.5760	.5923	05078230, 05078500
19	05078000	Clearwater River at Plummer, MN	1.0497	.9196	05078500 (+1), 05079000, 05078230
20	05078230	Lost River at Oklee, MN	1.4927	.8642	05069000, 05078500 (+1)
21	05078500	Clearwater River at Red Lake Falls, MN	1.2039	.9428	05078000 (-1), 05079000 (+1), 05078230
22	05079000	Red Lake River at Crookston, MN	.9017	.9272	05075000 (-1), 05078500 (-1)
23	05087500	Middle River at Argyle, MN	1.6869	.7238	05104500, 05134200
24	05104500	Roseau River below South Fork near Malung, MN	1.5505	.8511	05107500 (+2), 05112000 (+4), 05134200
25	05107500	Roseau River at Ross, MN	1.2671	.9509	05104500 (-2), 05112000 (+2), 05134200
26	05112000	Roseau River below State Ditch 51 nr Caribou, MN	1.0780	.9247	05107500 (-2), 05104500 (-4), 05134200
27	05124480	Kawishiwi River near Ely, MN	.5574	.9157	05127500 (+2)
28	05124990	Filson Creek near Ely, MN	1.0106	.6228	04015475, 05130500
30	05127500	Basswood River near Winton, MN	.5064	.8169	05127000
32	05129115	Vermilion River nr Crane Lake, MN	.5374	.4766	05127500, 05127000

Table 8.--Statistics of record reconstruction for continuous-record streamflow-gaging stations in Minnesota--Continued

Map index no.	Station no.	Station name	C_v	rho_c	Source of reconstructed record
33	05129290	Gold Portage Outlet from Kabetogama Lake nr Ray, MN	----	----	Lake stage for Kabetogama lake from 05128000, Namakan River at the outlet of Lac La Croix, Ontario
34	05130500	Sturgeon River near Chisholm, MN	.7223	.8841	05131500 (+1), 05132000 (+1), 04016500
35	05131500	Little Fork River at Littlefork, MN	.8837	.9240	05132000, 05130500 (-1), 05133500 (+1)
36	05132000	Big Fork River at Big Falls, MN	.8132	.8934	05131500, 05133500 (+1). 05135000 (-1)
37	05133500	Rainy River at Manitou Rapids, MN	.4646	.6754	05131500 (-1), 05132000 (-1)
38	05134200	Rapid River near Baudette, MN	1.2689	.8530	05104500, 05107500 (+2), 05131500
41	05211000	Mississippi River at Grand Rapids, MN	.6152	.4155	05219000 (+1)
43	05216860	Swan River near Calumet, MN	.7106	.6985	05130500, 04016500
45	05220500	Mississippi River below Sandy River nr Libby, MN	.5187	.9807	05211000 (-1), 05227500 (+1), 05219000
46	05227500	Mississippi River at Aitkin, MN	.5492	.9774	05220500 (-1), 05267000 (+1)
48	05245100	Long Prairie River at Long Prairie, MN	.9024	.7148	05220500 (-1), 05267000 (+1)
54	05280000	Crow River at Rockford, MN	1.1756	.7217	05275000, 05317000
55	05286000	Rum River near St. Francis, MN	.9626	.8436	05275000
56	05287890	Elm Creek nr Champlin, MN	.7075	.4056	05340050
57	05288500	Mississippi River near Anoka, MN	.6632	.9806	05331000, 05330000 (-1), Discharge from Ford Motor Company hydroelectric power plant at Lock and Dam 1

Table 8. Statistics of record reconstruction for continuous-record streamflow-gaging stations in Minnesota --Continued

Map index no.	Station no.	Station name	C_v	rho_c	Source of reconstructed record
58	05291000	Whetstone River near Big Stone City, SD	1.8985	.7782	05293000
59	05292000	Minnesota River at Ortonville, MN	1.6159	.6481	05291000, 05293000
60	05293000	Yellow Bank River near Odessa, MN	1.7057	.7876	05291000, 05292000
61	05294000	Pomme De Terre River at Appleton, MN	1.1007	.8546	05293000, 05304500
62	05300000	Lac Qui Parle River near Lac Qui Parle, MN	1.6490	.7277	05301000, 05304500
63	05301000	Minnesota River near Lac Qui Parle, MN	1.1250	.9648	05311000, 05304500
64	05304500	Chippewa River near Milan, MN	1.1958	.8732	05301000, 05294000
65	05311000	Minnesota River at Montevideo, MN	1.0547	.9758	05301000, 05304500 (+1)
66	05311400	South Branch Yellow Medicine R at Minneota, MN	1.8511	.8376	05313500, 05315000
67	05313500	Yellow Medicine River near Granite Falls, MN	1.7117	.8869	05311400, 05316500, 05315000
68	05315000	Redwood River near Marshall, MN	1.6369	.8602	05316500, 05311400
69	05316500	Redwood River near Redwood Falls, MN	1.6240	.8089	05315000
71	05317000	Cottonwood River near New Ulm, MN	1.4642	.5259	05280000
72	05317200	Little Cottonwood River near Courtland, MN	1.1956	.7496	05327000
73	05319500	Watonwan River near Garden City, MN	1.0150	.7654	05320500, 05320000, 05317000
74	05320000	Blue Earth River near Rapidan, MN	1.2197	.8611	05320500, 05319500, 05317000
75	05320500	Le Sueur River near Rapidan, MN	1.4347	.8450	05320000, 05319500, 05317000
76	05325000	Minnesota River at Mankato, MN	.9644	.9644	05330000 (+3)

Table 8. Statistics of record reconstruction for continuous-record streamflow-gaging stations in Minnesota --Continued

Map index no.	Station no.	Station name	C_v	rho_c	Source of reconstructed record
77	05327000	High Island Creek near Henderson, MN	1.2346	.7836	05317200, 05345000
78	05330000	Minnesota River near Jordan, MN	.9393	.9644	05325000 (-3)
79	05331000	Mississippi River at St. Paul, MN	.6565	.9904	05288500 05330000 (-1), Discharge from Ford Motor Company hydroelectric power plant at Lock and Dam 1
80	05336700	Kettle River below Sandstone, MN	1.0290	.8124	05338500
81	05337400	Knife River near Mora, MN	.9636	.6598	05275000, 05286000
82	05340050	Sunrise River near Lindstrom, MN	.7198	.4056	05287890
83	05344500	Mississippi River at Prescott, WI	.5905	.9831	05331000 05340500 (St. Croix River at St. Croix Falls, Wisconsin)
84	05345000	Vermillion River near Empire, MN	.6711	.5783	05327000
85	05353800	Straight River near Faribault, MN	1.1581	.7781	05457000
86	05372995	South Fork Zumbro River at Rochester, MN	1.4625	.7997	05457000
87	05374900	Zumbro River at Kellogg, MN	.7120	.6382	05372995
88	05376000	North Fork Whitewater River near Elba, MN	1.0415	.8263	05376800, 05372995, 05378300

Table 8. Statistics of record reconstruction for continuous-record streamflow-gaging stations in Minnesota --Continued

Map index no.	Station no.	Station name	C_v	rho_c	Source of reconstructed record
89	05376800	Whitewater River near Beaver, MN	.6137	.7559	05376000
91	05378235	Garvin Brook near Minnesota City, MN	----	----	None
93	05378500	Mississippi River at Winona, MN	.5096	----	Records maintained by Corps of Engineers at Lock and Dam 5a
94	05384000	Root River near Lanesboro, MN	1.3912	----	05385000 (High-flow partial-record station, Root River near Houston)
95	05457000	Cedar River near Austin, MN	1.4233	.7781	05353800
96	05476000	Des Moines River at Jackson, MN			05476500 (Des Moines River at Estherville, Iowa)

Determining the Auto-correlation Coefficient and the Process Variance

A rating analysis to define the time series of residuals was performed on the discharge measurements for the last ten years for the 80 stations. The rating function was of the form:

$$LQM = B_1 + (B_3)\ln(GHT - B_2)$$

where

LQM is the logarithm (base e) of the measured discharge,

GHT is the recorded gage height corresponding to the measured discharge,

B_1 is the logarithm of the discharge for a flow depth of 1 foot,

B_2 is the gage height of zero flow,

and

B_3 is the slope of the rating curve.

The rating function was fitted to the measured discharges using a non-linear regression technique of the statistical program SPSS (Nie and others, 1975).

The time series of residuals from the non-linear regression (in logarithmic units) was used to compute two of the three parameters required to compute V_f (see the Appendix), by determining a best fit autocovariance function to the time series of residuals. Measurement variance, the third parameter, was determined from an assumed constant percentage standard error. For the Minnesota program, all open-water measurements were assumed to have a measurement error of 3 percent. The autocovariance analysis is summarized in table 9.

Table 9.--Summary of the autocovariance analysis and uncertainty functions

[RHO is one-day autocorrelation coefficient. Measurement variance is 0.00090. Analysis is for open-water period only, April 1 through October 31.]

Map index no.	Station no.	Station name	RHO	Process variance (log base e)	Standard error, in percent, for 2, 5, 10, 20 visits during the open-water period: 2	5	10	20
1	04010500	Pigeon River at Middle Falls nr Grand Portage, MN	.66174	.0042	18.76	12.66	9.84	7.91
2	04014500	Baptism River near Beaver Bay, MN	.43408	.0282	40.35	27.56	22.25	19.03
3	04015330	Knife River near Two Harbors, MN	.82464	.0172	49.93	32.50	23.96	17.82
4	04015475	Partridge River abv Colby Lake at Hoyt Lakes, MN	.93074	.0135	35.50	23.14	16.76	12.03
5	04016500	St. Louis River near Aurora, MN	.41943	.0893	32.05	30.54	29.86	28.90
6	04018750	St. Louis River at Forbes, MN	.89102	.0061	15.42	10.37	8.07	6.17
7	04024000	St. Louis River at Scanlon, MN	.72593	.0042	18.97	12.63	9.73	7.73
8	04024098	Deer Creek near Holyoke, MN	.99569	.0497	9.24	5.87	4.22	3.06
9	05046000	Otter Tail River bl Orwell D nr Fergus Falls, MN	.97321	.0139	9.73	7.39	5.51	3.98
10	05050000	Bois De Sioux River near White Rock, SD	.97498	.3925	54.04	39.26	28.24	19.76
11	05061000	Buffalo River near Hawley, MN	.52199	.1756	48.26	44.61	42.88	40.74
12	05061500	South Branch Buffalo River at Sabin, MN	.52481	.4648	91.30	81.42	76.68	71.67
13	05062000	Buffalo River near Dilworth, MN	.94527	.0219	17.08	13.39	10.46	7.70
14	05064000	Wild Rice River at Hendrum, MN	.87075	.0351	33.39	24.09	19.46	15.27
15	05069000	Sand Hill River at Climax, MN	.97734	.5338	65.78	46.75	33.50	23.48
16	05074500	Red Lake River near Red Lake, MN	.98405	.1789	33.43	22.81	16.25	11.46
17	05075000	Red Lake River at High Landing nr Goodridge, MN	.95697	.0073	15.38	9.46	6.72	4.77
18	05076000	Thief River near Thief River Falls, MN	.95930	.1085	41.03	30.33	22.75	16.35
19	05078000	Clearwater River at Plummer, MN	-----	----[1]	--	--	--	--
20	05078230	Lost River at Oklee, MN	.98633	1.031	79.97	51.68	35.94	24.99
21	05078500	Clearwater River at Red Lake Falls, MN	.85889	.0066	23.12	13.77	10.14	7.64
22	05079000	Red Lake River at Crookston, MN	.89794	.0027	17.78	10.43	7.38	5.32
23	05087500	Middle River at Argyle, MN	.96111	3.949	390.3	241.4	147.5	92.00
24	05104500	Roseau River below South Fork near Malung, MN	..98633	.2773	81.88	52.33	36.68	25.78
25	05107500	Roseau River at Ross, MN	.90646	.2598	53.10	47.14	40.30	31.32
26	05112000	Roseau River below State Ditch 51 nr Caribou, MN	.91160	.1143	37.04	31.29	26.37	20.42
27	05124480	Kawishiwi River near Ely, MN	.62917	.0033	4.92	5.27	5.25	5.09

Table 9. **Summary of the autocovariance analysis and uncertainty functions**--Continued

Map index no.	Station no.	Station name	RHO	Process variance (log base e)	Standard error, in percent, for 2, 5, 10, 20 visits during the open-water period			
					2	5	10	20
28	05124990	Filson Creek near Ely, MN	.97128	.6651	79.19	59.45	43.51	30.73
30	05127500	Basswood River near Winton, MN	.89830	.0032	6.56	5.56	4.73	3.77
32	05129115	Vermilion River nr Crane Lake, MN	.80352	.0011	2.97	2.96	2.90	2.57
33	05129290	Gold Portage Outlet From Kabetogama Lake nr Ray, MN	-----	----[1]	--	--	--	--
34	05130500	Sturgeon River near Chisholm, MN	.55214	.0048	16.55	11.00	8.86	7.54
35	05131500	Little Fork River at Littlefork, MN	-----	----[1]	--	--	--	--
36	05132000	Big Fork River at Big Falls, MN	-----	----[1]	--	--	--	--
37	05133500	Rainy River at Manitou Rapids, MN	.95570	.0002	13.13	8.26	5.82	4.12
38	05134200	Rapid River near Baudette, MN	.97080	.0009	28.56	16.90	11.60	8.07
41	05211000	Mississippi River at Grand Rapids, MN	.85169	.0114	30.41	21.27	16.29	12.34
43	05216860	Swan River near Calumet, MN	.95930	.0476	26.69	19.70	14.82	10.67
45	05220500	Mississippi River below Sandy River nr Libby, MN	.91932	.0009	2.64	2.52	2.17	1.74
46	05227500	Mississippi River at Aitkin, MN	.94120	.0012	2.76	2.63	2.23	1.75
48	05245100	Long Prairie River at Long Prairie, MN	.99156	.0251	23.11	14.56	10.27	7.29
54	05280000	Crow River at Rockford, MN			21.72	14.29	10.50	7.62
55	05286000	Rum River near St. Francis, MN	.96425	.0013	47.41	34.90	23.56	2.56
56	05287890	Elm Creek nr Champlin, MN	.98798	.0293	34.88	23.19	16.65	11.89
57	05288500	Mississippi River near Anoka, MN	-----	----[2]	52.93	52.75	52.13	50.76
58	05291000	Whetstone River near Big Stone City, SD	.95285	.7217	89.61	71.72	54.02	38.20
59	05292000	Minnesota River at Ortonville, MN	.97054	.2012	41.64	31.09	22.83	16.16
60	05293000	Yellow Bank River near Odessa, MN	.98633	.7605	65.61	42.49	29.52	20.51
61	05294000	Pomme De Terre River at Appleton, MN	.71890	.0176	27.51	19.14	15.72	13.22
62	05300000	Lac Qui Parle River near Lac Qui Parle, MN	.97642	.7136	83.31	58.37	41.60	29.09
63	05301000	Minnesota River near Lac Qui Parle, MN	.97156	.0684	28.83	19.53	14.07	9.94
64	05304500	Chippewa River near Milan, MN	.95475	.0283	16.85	13.47	10.43	7.61
65	05311000	Minnesota River at Montevideo, MN	.83242	.0113	32.79	18.05	12.67	9.50
66	05311400	South Branch Yellow Medicine R at Minneota, MN	.95475	1.718	166.1	125.6	89.31	60.70
67	05313500	Yellow Medicine River near Granite Falls, MN	.80352	.0742	28.86	26.90	24.94	21.74
68	05315000	Redwood River near Marshall, MN	.97889	.3420	71.22	36.16	32.34	22.54
69	05316500	Redwood River near Redwood Falls, MN	.97490	.257	44.19	32.27	23.37	16.45

Table 9.--Summary of the autocovariance analysis and uncertainty functions--Continued

Map index no.	Station no.	Station name	RHO	Process variance (log base e)	Standard error, in percent, for 2, 5, 10, 20 visits during the open-water period			
					2	5	10	20
71	05317000	Cottonwood River near New Ulm, MN	.75682	.0004	15.98	10.22	7.32	5.28
72	05317200	Little Cottonwood River near Courtland, MN	-----	----[1]	--	--	--	--
73	05319500	Watonwan River near Garden City, MN	.97321	.0360	27.15	18.19	1309	9.29
74	05320000	Blue Earth River near Rapidan, MN	.49666	.0068	11.48	9.54	8.72	8.08
75	05320500	Le Sueur River near Rapidan, MN	.95803	.1019	39.33	28.62	21.44	15.39
76	05325000	Minnesota River at Mankato, MN	.64836	.0034	14.61	8.89	7.00	5.93
77	05327000	High Island Creek near Henderson, MN	.92450	.0586	34.67	26.09	20.65	15.48
78	05330000	Minnesota River near Jordan, MN	.94196	.0104	15.92	10.50	7.84	5.71
79	05331000	Mississippi River at St. Paul, MN	-----	----[2]	--	--	--	--
80	05336700	Kettle River below Sandstone, MN	.95475	.0022	21.85	13.48	9.47	6.68
81	05337400	Knife River near Mora, MN	.98684	.0261	26.37	16.88	11.96	8.48
82	05340050	Sunrise River near Lindstrom, MN	.97734	.1159	28.41	20.61	14.93	10.57
83	05344500	Mississippi River at Prescott, WI	-----	----[2]	--	--	--	--
84	05345000	Vermillion River near Empire, MN			21.12	15.94	13.49	11.54
85	05353800	Straight River near Faribault, MN	.95545	.0376	19.69	15.62	12.06	8.76
86	05372995	South Fork Zumbro River at Rochester, MN	-----	----[1]	--	--	--	--
87	05374900	Zumbro River at Kellogg, MN	.99283	.0136	19.19	12.17	8.62	6.11
88	05376000	North Fork Whitewater River near Elba, MN	.49818	.0026	38.60	23.16	16.11	11.59
89	05376800	Whitewater River near Beaver, MN	.99302	.0938	20.53	13.15	9.31	6.67
91	05378235	Garvin Brook near Minnesota City, MN	-----	----[1]	--	--	--	--
93	05378500	Mississippi River at Winona, MN	-----	----[2]	--	--	--	--
94	05384000	Root River near Lanesboro, MN	.94453	.0013	3.30	2.87	2.34	1.80
95	05457000	Cedar River near Austin, MN	.47931	.0009	11.89	7.81	5.87	4.56
96	05476000	Des Moines River at Jackson, MN	.98633	.2924	37.96	25.29	17.79	12.46

[1] Less than three years of record for current rating

[2] One-day autocorrelation coefficient and process variance not determined. Station is not used in Traveling Hydrographer analysis.

The autocovariance parameters and data from the definition of missing record probabilities, summarized in table 9, are used jointly to define uncertainty functions for each gaging station. The uncertainty functions give the relationship of total error variance to the number of visits and discharge measurements. The standard error, in percent, for 2, 5, 10, and 20 visits during the open-water period are given in table 9 for each station.

The feasible routes to service the 81 stations were determined after consultation with the Network Surveillance Section of the Minnesota District Office. In Minnesota routes are devised to service more than one network. As a result, on a typical route a hydrographer will visit and make discharge measurements at continuous-record gaging stations, visit and possibly make discharge measurements at high-flow partial record stations, will make water level measurements at ground-water network wells, and visit miscellaneous stations such as lake stage stations. As a result, the routes determined include the multi-purpose routes that are currently being used (1985), routes that visit only continuous-record gaging stations, routes that visit single gaging stations, and routes that visit a group of gaging stations in the same area.

Three field offices, St. Paul, Grand Rapids, and Montevideo, service the continuous-record gaging stations in Minnesota. Most of the stations in Minnesota are within a 150-mile radius of a field office. The stations serviced by each field office are shown in table 10. There are many possible routes to visit the stations operated by the St. Paul and Montevideo field offices because of the many roads and highways in southern and central Minnesota. However, in northern Minnesota there are few roads and highways and, as a result, only a few possible routes to visit the stations operated by the Grand Rapids field office. For instance, all routes to visit the stations on the north shore of Lake Superior must go through Duluth and up the single highway that runs along the north shore. This is a severe constraint on developing alternative routes to more cost-effectively collect the needed data.

The hydrographers kept records of several of their trips to service the continuous-record gaging stations. These records were analyzed to determine the average time to make a discharge measurement at a station, the average time to service the station, and the average mileage and time between stations. The average length of time to make a discharge measurement and service the station was multiplied by the average hourly salary of hydrographers in Minnesota offices to determine total visit costs. Route costs include the vehicle cost associated with the total mileage of the route, the cost of the hydrographer's time in transit, and any per diem. The costs for the route were divided equally between each of the stations visited on a route.

Table 10.--*Stations operated by the Grand Rapids, Montevideo, and St. Paul field offices*

Map no.	Station no.	Station name
		Grand Rapids field office
1	04010500	Pigeon River at Middle Falls nr Grand Portage, MN
2	04014500	Baptism River near Beaver Bay, MN
3	04015330	Knife River near Two Harbors, MN
4	04015475	Partridge River abv Colby Lake at Hoyt Lakes, MN
5	04016500	St. Louis River near Aurora, MN
6	04018750	St. Louis River at Forbes, MN
7	04024000	St. Louis River at Scanlon, MN
14	05064000	Wild Rice River at Hendrum, MN
15	05069000	Sand Hill River at Climax, MN
16	05074500	Red Lake River near Red Lake, MN
17	05075000	Red Lake River at High Landing nr Goodridge, MN
18	05076000	Thief River near Thief River Falls, MN
[1]19	05078000	Clearwater River at Plummer, MN
20	05078230	Lost River at Oklee, MN
21	05078500	Clearwater River at Red Lake Falls, MN
22	05079000	Red Lake River at Crookston, MN
23	05087500	Middle River at Argyle, MN
24	05104500	Roseau River below South Fork near Malung, MN
25	05107500	Roseau River at Ross, MN
26	05112000	Roseau River below State Ditch 51 nr Caribou, MN
27	05124480	Kawishiwi River near Ely, MN
28	05124990	Filson Creek near Ely, MN
30	05127500	Basswood River near Winton, MN
32	05129115	Vermilion River nr Crane Lake, MN
[1]33	05129290	Gold Portage Outlet From Kabetogama Lake nr Ray, MN
34	05130500	Sturgeon River near Chisholm, MN
[1]35	05131500	Little Fork River at Littlefork, MN
[1]36	05132000	Big Fork River at Big Falls, MN
37	05133500	Rainy River at Manitou Rapids, MN
38	05134200	Rapid River near Baudette, MN

Table 10.--*Stations operated by the Grand Rapids, Montevideo, and St. Paul field offices*--Continued

Map no.	Station no.	Station name
		Grand Rapids field office--Continued
41	05211000	Mississippi River at Grand Rapids, MN
43	05216860	Swan River near Calumet, MN
45	05220500	Mississippi River below Sandy River nr Libby, MN
46	05227500	Mississippi River at Aitkin, MN
		Montevideo field office
9	05046000	Otter Tail River bl Orwell D nr Fergus Falls, MN
10	05050000	Bois De Sioux River near White Rock, SD
11	05061000	Buffalo River near Hawley, MN
12	05061500	South Branch Buffalo River at Sabin, MN
13	05062000	Buffalo River near Dilworth, MN
48	05245100	Long Prairie River at Long Prairie, MN
58	05291000	Whetstone River near Big Stone City, SD
59	05292000	Minnesota River at Ortonville, MN
60	05293000	Yellow Bank River near Odessa, MN
61	05294000	Pomme De Terre River at Appleton, MN
62	05300000	Lac Qui Parle River near Lac Qui Parle, MN
63	05301000	Minnesota River near Lac Qui Parle, MN
64	05304500	Chippewa River near Milan, MN
65	05311000	Minnesota River at Montevideo, MN
66	05311400	South Branch Yellow Medicine R at Minneota, MN
67	05313500	Yellow Medicine River near Granite Falls, MN
68	05315000	Redwood River near Marshall, MN
69	05316500	Redwood River near Redwood Falls, MN
96	05476000	Des Moines River at Jackson, MN
		St. Paul field office
8	04024098	Deer Creek near Holyoke, MN
54	05280000	Crow River at Rockford, MN
55	05286000	Rum River near St. Francis, MN
56	05287890	Elm Creek nr Champlin, MN
[2]57	05288500	Mississippi River near Anoka, MN

Table 10.--*Stations operated by the Grand Rapids, Montevideo, and St. Paul field offices*--Continued

Map no.	Station no.	Station name
		St. Paul field office--Continued
71	05317000	Cottonwood River near New Ulm, MN
[1]72	05317200	Little Cottonwood River near Courtland, MN
73	05319500	Watonwan River near Garden City, MN
74	05320000	Blue Earth River near Rapidan, MN
75	05320500	Le Sueur River near Rapidan, MN
76	05325000	Minnesota River at Mankato, MN
77	05327000	High Island Creek near Henderson, MN
78	05330000	Minnesota River near Jordan, MN
[2]79	05331000	Mississippi River at St. Paul, MN
80	05336700	Kettle River below Sandstone, MN
81	05337400	Knife River near Mora, MN
82	05340050	Sunrise River near Lindstrom, MN
[2]83	05344500	Mississippi River at Prescott, WI
84	05345000	Vermillion River near Empire, MN
85	05353800	Straight River near Faribault, MN
[1]86	05372995	South Fork Zumbro River at Rochester, MN
87	05374900	Zumbro River at Kellogg, MN
88	05376000	North Fork Whitewater River near Elba, MN
89	05376800	Whitewater River near Beaver, MN
[1]91	05378235	Garvin Brook near Minnesota City, MN
[2]93	05378500	Mississippi River at Winona, MN
94	05384000	Root River near Lanesboro, MN
95	05457000	Cedar River near Austin, MN

[1] Less than three years for current rating. One-day autocorrelation coefficient not determined; uncertainty function set to zero in Traveling Hydrographer analysis.

[2] Station not used in Traveling Hydrographer analysis.

The fixed costs to operate a gage typically include equipment rental, batteries, electricity, data processing and storage, computer charges, maintenance, miscellaneous supplies, and analysis and supervisory charges. An average fixed cost per station was used for each of the stations. Some of the stations have telephones and electrically operated heaters and have utility bills of up to a thousand dollars a year. The utility costs were added to the fixed costs. The utility costs were prorated between the ice-affected and the open-water periods; 5/12 of the costs for the ice-affected period and 7/12 for the open-water period. The analysis and supervisory costs were apportioned differently. It is more difficult to interpret the data from the ice-affected period and determine the mean-daily discharge than it is during the open-water period; 60 percent of the analysis and supervision costs were allocated to the ice-affected period, November 1-March 31. The division was based upon past experience.

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 streamflow-gaging program. In this application, the first step was to simulate the current practice and determine the total uncertainty associated with it. To accomplish this, the number of visits made to each streamflow gage and the specific routes used to make these visits were fixed. In Minnesota, the current practice is to visit and make discharge measurements at each of the stations in the network four times during the ice-affected period and five times during the open-water period. For this analysis the minimum visit frequency to each station was set to at least two visits during the ice-affected period and at least three visits during the open-water period. These visit frequencies were based upon the limitations of the batteries used to drive recording equipment, capacities of the uptake spools on the digital recorders, and the need to install frost floors in late October or early November and remove frost floors before spring breakup in early March.

Currently (1985), the hydrographers collect data from more than one data network on their routes; data is collected from high-flow partial record, water-quality, ground-water, and lake- and reservoir-stage networks. The networks are operated together because the routes used to collect data from each of the networks are essentially duplicates of each other. The data from several of these networks must be collected more often than three times during the open-water period. As a result, an additional Traveling Hydrographer analysis was made using a minimum visit frequency of at least five visits to each station during the open-water period.

Four of the stations on the Mississippi River, the stations near Anoka, at St. Paul, at Prescott, and at Winona, were not used in the Traveling Hydrographer analysis. At these stations the discharge is measured at fixed intervals during the year because a boat and three hydrographers are required for the measurements. For seven of the remaining 77 stations (identified in table 10) the one-day autocorrelation coefficient could not be determined because there was less than three years of record for the current rating at the stations. These stations were included in the Traveling Hydrographer analysis but the uncertainty function was set to zero for these stations.

The results of the Traveling Hydrographer analysis are shown in figures 8 and 9 and summarized in table 11. Figure 8 shows the results for at least three visits per station during the open-water period and figure 9 the results for at least five visits per station. The figures show the estimated average standard error per station at various budgets, in 1985 dollars, of operating the 77 stations during the open-water period. The analysis assumes that after the fixed costs and the visit and travel costs at the minimum visit frequency are deducted from the budget, any monies left over will be used to make discharge measurements to reduce the discharge estimation errors at the stations with the largest errors subject to the restrictions discussed below.

There is a practical limit of the number of discharge measurements that can be made at a station. The number of hydrographers in each field office is limited not only by the budget but by employment restrictions imposed by the Federal government. Record analysis, gaging-station construction, equipment repair, and other duties also limit the number of discharge measurements each hydrographer can make. A limit of one discharge measurement every two weeks (15 during the open-water period) was selected as a reasonable restriction after consultation with the Network Surveillence Section.

Three scenarios are shown on figures 8 and 9. The bottom line is the estimated average standard error if (1) there is no lost record and (2) the only constraint on the number of discharge measurements made at each station is the budget. The other two lines show the estimated average standard error if record is lost because of equipment malfunction and either (1) the budget is the only constraint on the number of discharge measurements made at each station, or (2) the maximum number of visits to a station is 15.

The results for at least three visits per station and at least five visits per station are compared in figure 10. The minimum budget for operating the 77 stations with at least three discharge measurements per station during the open-water period is $172,000. The 1985 budget of $198,000 is just sufficient to cover the costs of operating the 77 stations if there are five discharge measurements per station during the open-water period. As shown in figure 10, by reducing the minimum number of discharge measurements at each station from five to three and using the remaining budget to make additional discharge measurements at stations with large errors, the estimated average standard error per station for the entire network could be reduced from 24.4 to 20.6 percent at the same budget or the budget could be reduced from $198,000 to $179,000 at the same average standard error for the network.

The results of the Traveling Hydrographer program are shown for each of the field offices in figure 11 and 12. Figure 11 shows the results if there are at least three discharge measurements made during the open-water season at each station and figure 12 shows the results if there are at least five discharge measurements at each station. The estimated average standard error for the stations operated by the St. Paul field office is similar to the error for gaging stations in Iowa (Burmeister and Lara, 1984) probably because the drainage basins in southeastern Minnesota are similar to those in Iowa. The continuous-record gaging station networks operated by the Montevideo and Grand Rapids field offices have large estimated average standard errors that are a result of generally more difficult gaging conditions than exist for the network operated by the St. Paul field office. The stations located on tributaries of the Red River of the North are affected by backwater from the Red

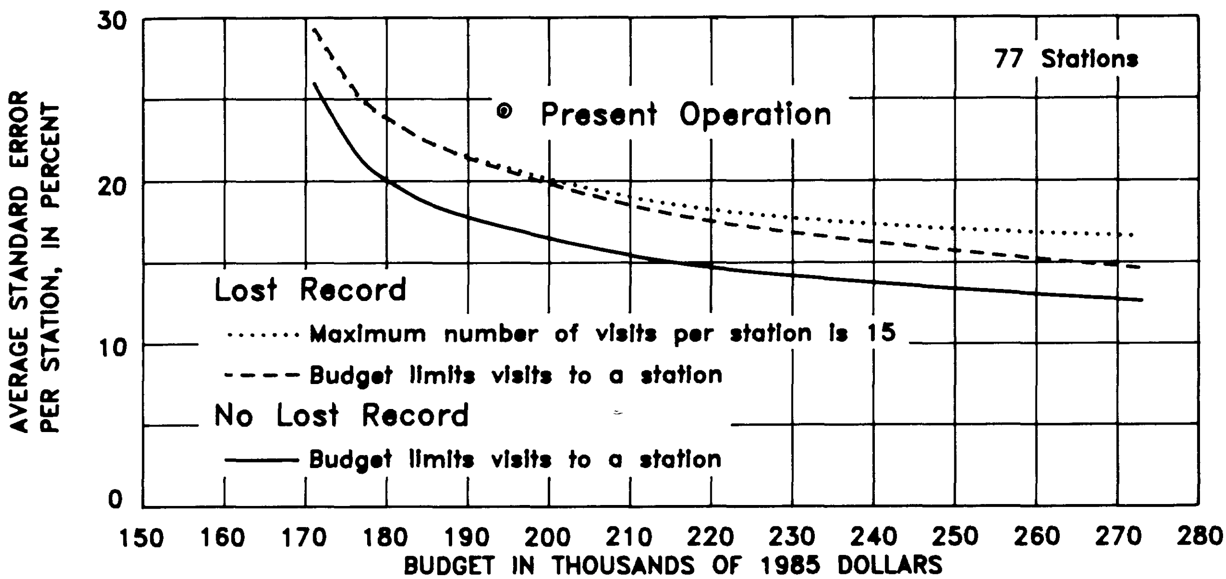


Figure 8. – – Temporal average standard error per station for the open–water period only, at least three visits per station

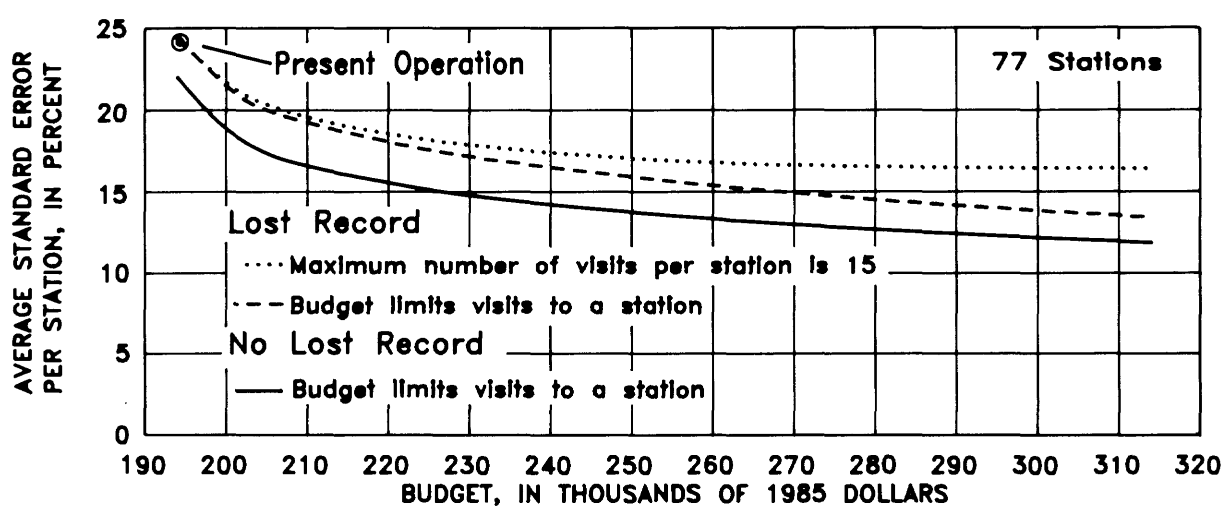
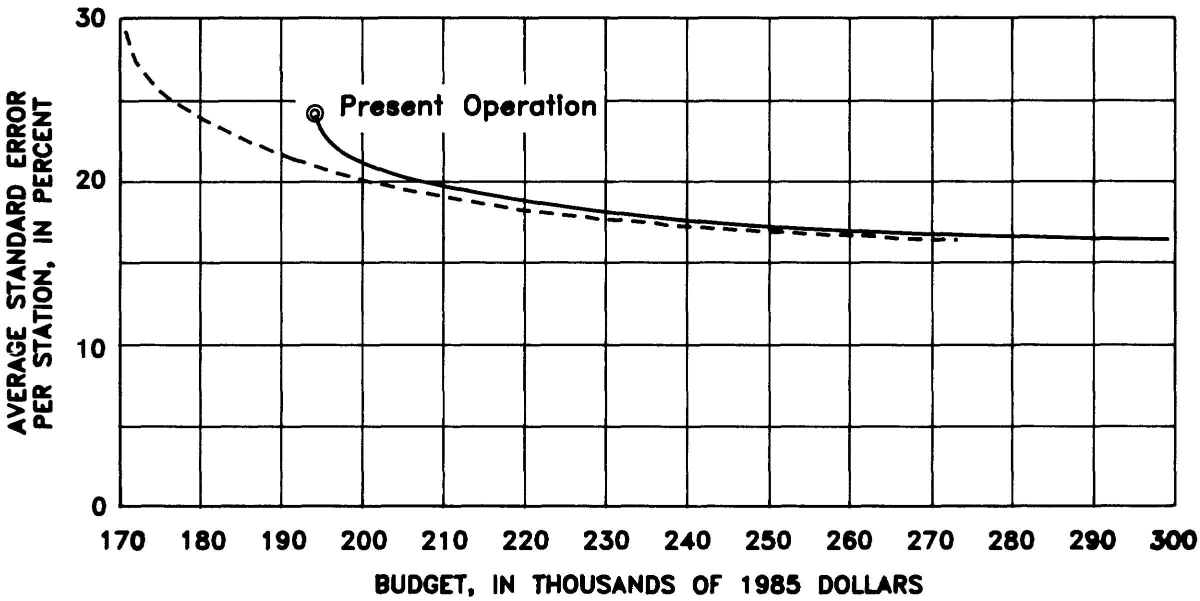


Figure 9. – – Temporal average standard error per station for the open–water period only, at least five visits per station



EXPLANATION

——— Minimum of 5 visits per station

- - - - Minimum of 3 visits per station

Assumptions:
1. There is missing record
2. There is a maximum of 15 visits per station

Figure 10. – – Comparison of the temporal average standard error per station for at least three visits per station and at least five visits per station, open-water period only

River. Backwater also occurs from debris, plant growth in the channel, marshes and lakes, and beaver dams. Several stations, identified in table 9, have extremely large standard errors. These stations raise the average standard error for the entire network.

Before the results of the Traveling Hydrographer analysis can be imple mented the following need to be considered: (1) the effects of lost record and visit frequency upon record computation costs, (2) how accurately the funding agencies need the data collected at each station, and (3) the effect changing the operation of the continuous-record network has on the other networks operated by the District.

A major assumption in this analysis is that the cost of record computa tion for a station is negligibly affected by the amount of lost record at the station and by the number of visits to the station. However, in the Minnesota District the cost of record computation may be significantly affected by lost record and by the number of visits to the station. The mean-daily discharge record is computed for four periods; they are, from least difficult to compute to most difficult, (1) open-water period with stage record available, (2) ice-affected period with stage record available, (3) ice-in and ice-out periods with stage record available, and (4) when there is no stage record available. The last is by far the most difficult and time-consuming to compute. This study assumes that as the number of visits to a station decline the amount of lost record increases (see the Appendix for the description of the method for deriving the relationship between visit frequency and lost record). The visit frequency did not vary enough during the 10-year period selected for the lost-record analysis (table 7) to determine empirically the relationship between visit frequency to a station and lost record at that station. The relationship between the amount of lost stage record and the increased costs computing the discharge record is unknown. Any lost stage record greatly increases the time needed to compute the discharge record for a station, perhaps by several weeks.

Before any adjustment is made to the operation of the continuous-record gaging-station network, the increased cost in computing discharge record because of possible increases in the amount of lost record needs to be determined. In addition, the use of new technology, such as satelite telemetry, needs to be investigated to reduce the amount of lost record.

The Traveling Hydrographer analysis assumes that all stations have equal importance and therefore all should have about the same error. However, the agencies funding the network may accept a very large error in the computed discharge at one station but require that another have a very small error. Before the results of this analysis can be applied to the continuous-gaging station network operated by the Minnesota District, the level of error acceptable at each of the gaging stations in the network must be determined. This will help determine where additional discharge measurements need to be made.

The analysis was applied as if the continuous-record gaging station net work was the only network that was operated by the Minnesota District. Several other networks are operated by the District including water-quality, ground-water, and high-flow partial record networks. Stations in these networks are currently visited on the same routes used to visit the continuous-record gaging stations and at the same frequency. The stations in the water-

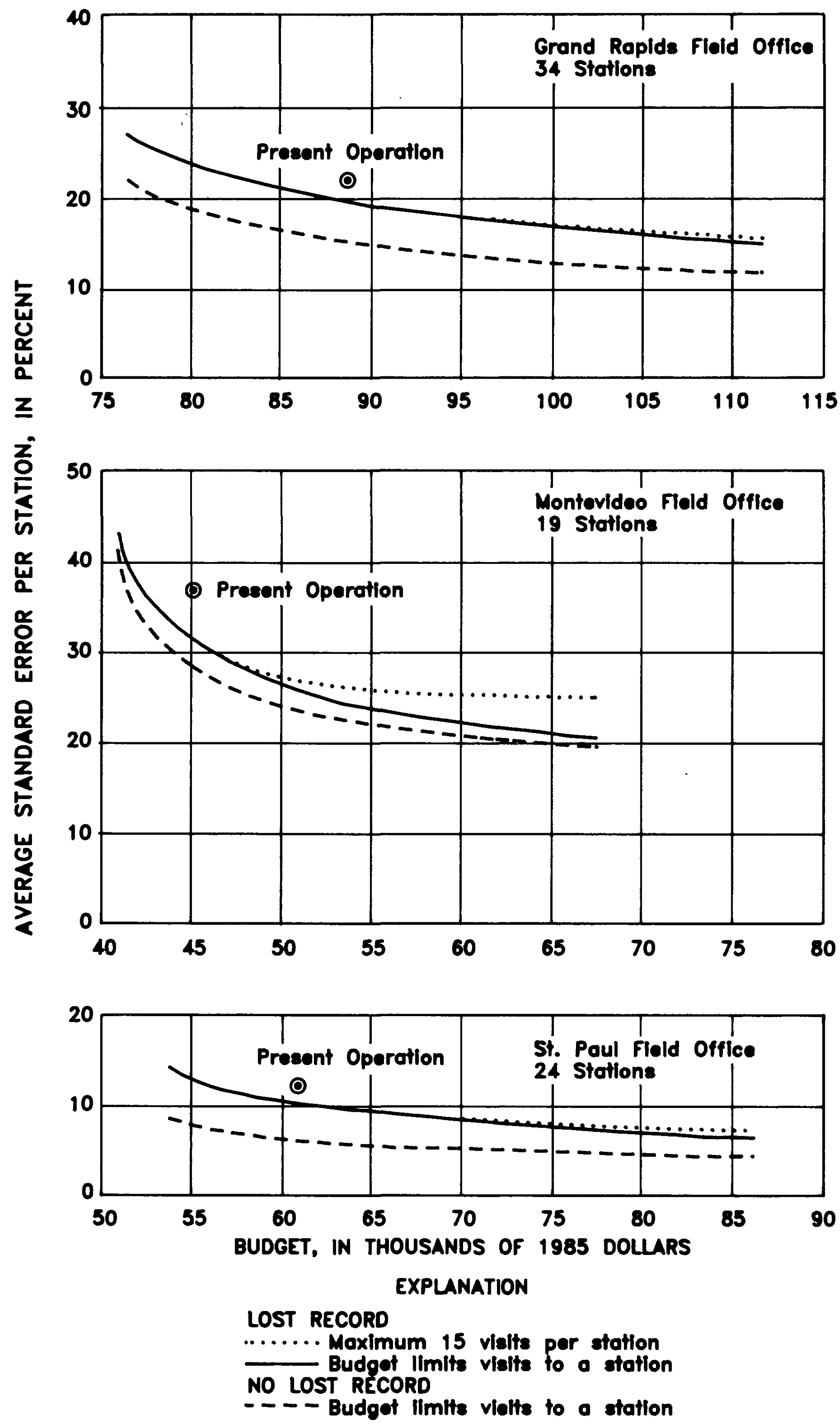


Figure 11.--Temporal average standard error per station for the networks operated by the three field offices, open-water period only, at least three visits per station

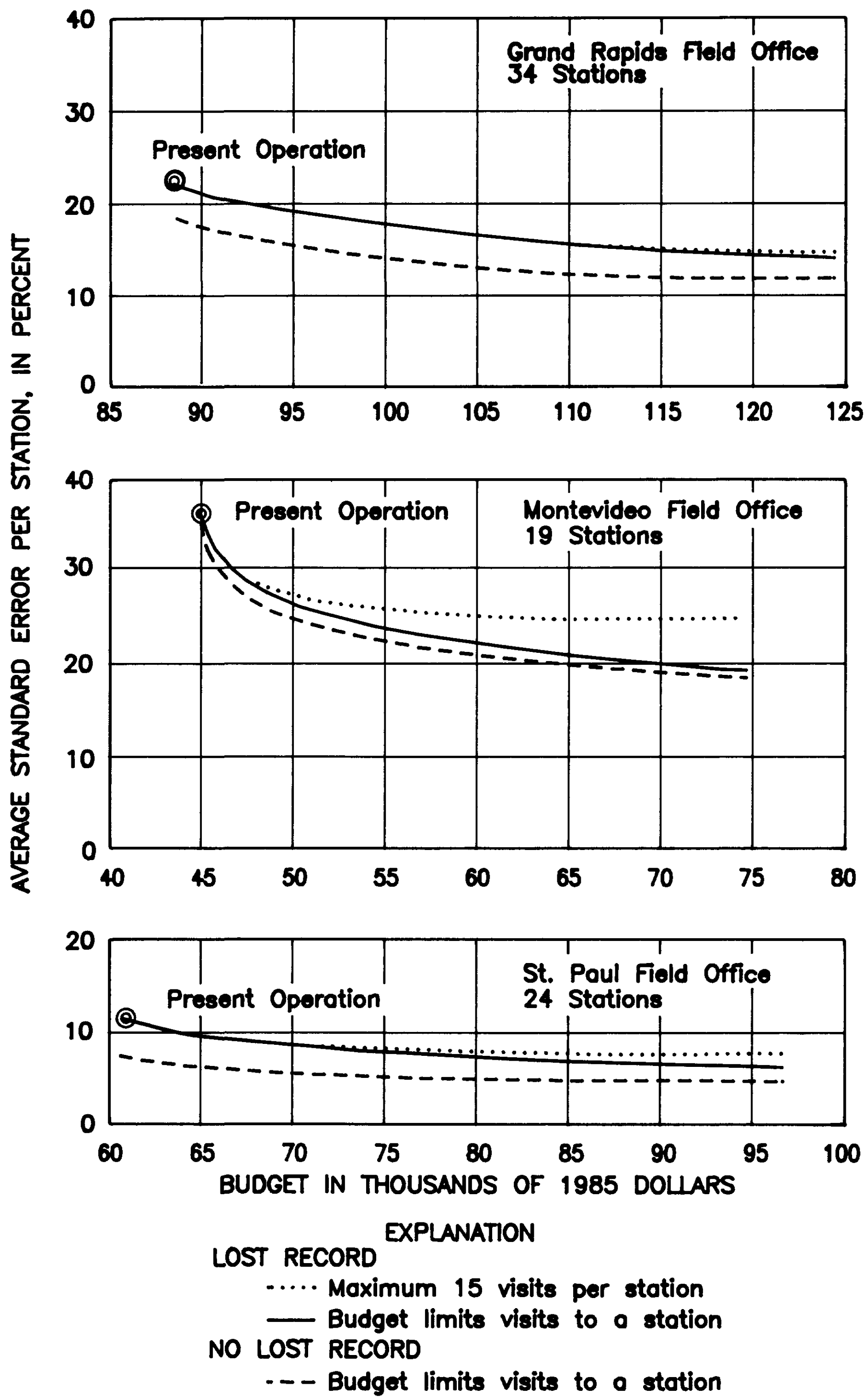


Figure 12.—– Temporal average standard error per station for the networks operated by the three field offices, open–water period only, at least five visits per station

quality, ground-water, and high-flow partial record networks must be visited more often than three times a summer. As a result, if the number of visits to the continuous-record stations is reduced from five to three, additional trips will have to be made to visit the stations in these networks. This may raise the District's overall cost for collecting data and offset any savings made in operating the continuous-record network. The effect of reducing the number of visits to the continuous-record network on the operation of the other networks needs to be determined before the number of visits are reduced from five to three.

Conclusions pertaining to K-CERA Analysis

1. The policy for operation of the network should be altered to reduce the average standard error per station as much as possible while maintaining the efficiency of the District's entire data collection program.

2. Before any changes in the present operation of the network are made the following need to be determined:

    A. The effect of changing the operation of the network on the cost of computing the discharge record because of increased lost record,

    B. The cost of making additional trips to visit stations in the other networks operated by the District,

    C. The data accuracy required by the data users at each of the stations in the network.

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

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

5. Methods 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.

Table 11.--Selected results of K-CERA Analysis for the open-water period

[Minimum number of visits to a station is 3; maximum number of visits is 14. Standard error is the standard error of instantaneous discharge, in percent; EGS is the equivalent Gaussian spread.]

Map no.	Station number / Station name		Budget, 1985 dollars: Current operation 198,000	Optimized values 172,000	204,000	218,000	239,000	256,000
	Average standard error per station for the statewide network		24.4	29.2	19.6	18.2	17.3	16.8
	Grand Rapids field office							
		Average standard error per station	22.0	26.9	19.7	17.8	16.4	15.5
		EGS for the Grand Rapids field office	14.7	17.3	14.1	13.0	12.1	11.4
1	04010500 Pigeon River at Middle Falls nr Grand Portage, MN	Standard error	12.7	15.6	15.6	15.6	13.9	12.7
		EGS	6.7	7.1	7.1	7.1	6.9	6.7
		Number of visits	5	3	3	3	4	5
2	04014500 Baptism River near Beaver Bay, MN	Standard error	27.6	33.7	33.7	30.0	25.9	24.6
		EGS	18.8	20.5	20.5	19.4	18.4	18.1
		Number of visits	5	3	3	4	6	7
3	04015330 Knife River near Two Harbors, MN	Standard error	32.5	41.2	29.9	28.0	24.0	21.4
		EGS	14.3	16.3	13.8	13.3	12.4	11.7
		Number of visits	5	3	6	7	10	13
4	04015475 Partridge River abv Colby Lake at Hoyt Lakes, MN	Standard error	23.1	29.4	23.1	21.3	18.6	16.0
		EGS	11.2	13.3	11.2	10.5	9.5	8.4
		Number of visits	5	3	5	6	8	11
5	04016500 St. Louis River near Aurora, MN	Standard error	30.5	31.2	31.2	31.2	31.2	30.8
		EGS	30.4	30.7	30.7	30.7	30.7	30.5
		Number of visits	5	3	3	3	3	4
6	04018750 St. Louis River at Forbes, MN	Standard error	10.4	12.7	12.7	12.7	12.7	11.3
		EGS	7.4	8.1	8.1	8.1	8.1	7.7
		Number of visits	5	3	3	3	3	4
7	04024000 St. Louis River at Scanlon, MN	Standard error	12.6	15.7	15.7	15.7	13.9	12.6
		EGS	6.7	7.1	7.1	7.1	6.97	6.7
		Number of visits	5	3	3	4	45	5
14	05064000 Wild Rice River at Hendrum, MN	Standard error	24.1	28.6	25.9	24.1	22.8	22.8
		EGS	18.2	19.7	18.9	18.2	17.7	17.7
		Number of visits	5	3	4	5	6	6
15	05069000 Sand Hill River at Climax, MN	Standard error	46.8	57.6	40.0	35.3	31.2	29.3
		EGS	45.5	56.6	38.6	34.0	30.6	28.0
		Number of visits	5	3	7	9	11	13
16	05074500 Red Lake River near Red Lake, MN	Standard error	22.8	28.6	20.9	18.2	15.5	14.8
		EGS	21.9	27.6	20.0	17.3	14.6	14.0
		Number of visits	5	3	6	8	11	12
17	05075000 Red Lake River at High Landing nr Goodridge, MN	Standard error	9.5	12.3	8.6	7.5	6.4	6.2
		EGS	6.7	7.8	6.3	5.6	4.9	4.7
		Number of visits	5	3	6	8	11	12
18	05076000 Thief River near Thief River Falls, MN	Standard error	30.3	36.2	28.3	225.1	21.8	20.9
		EGS	25.4	29.9	23.8	21.1	18.2	17.5
		Number of visits	5	3	6	8	11	12

Table 11.--Selected results of K-CERA Analysis for the open-water period--Continued

Map no.	Station number / Station name		Budget, 1985 dollars: Current operation 198,000	Optimized values 172,000	204,000	218,000	239,000	256,000
19	05078000	Standard error	See footnote 1 at the end of the table.					
	Clearwater River at Plummer,	EGS						
	MN	Number of visits						
20	05078230	Standard error	51.7	66.6	38.0	37.7	30.1	30.1
	Lost River at Oklee, MN	EGS	50.5	65.6	36.7	31.3	28.8	28.8
		Number of visits	5	3	9	12	14	14
21	05078500	Standard error	13.8	18.1	15.4	13.8	12.6	12.6
	Clearwater River at Red Lake	EGS	8.0	8.6	8.2	8.0	7.7	7.8
	Falls, MN	Number of visits	5	3	4	5	6	6
22	05079000	Standard error	10.4	13.9	11.8	10.4	9.5	9.5
	Red Lake River at Crookston,	EGS	5.0	5.4	5.1	5.0	4.8	4.8
	MN	Number of visits	5	3	4	5	6	6
23	05087500	Standard error	52.2	67.4	41.1	36.7	33.4	30.9
	Middle River at Argyle, MN	EGS	28.2	38.7	21.3	18.6	16.8	15.4
		Number of visits	5	3	8	10	12	14
24	05104500	Standard error	45.1	58.9	37.8	33.1	29.8	27.3
	Roseau River below South Fork	EGS	44.8	58.6	37.4	32.6	29.2	26.7
	near Malung, MN	Number of visits	5	3	7	9	11	13
25	05107500	Standard error	47.1	50.6	45.6	42.8	39.2	36.1
	Roseau River at Ross, MN	EGS	46.7	49.5	45.3	42.6	39.0	36.0
		Number of visits	5	3	6	8	11	14
26	05112000	Standard error	31.3	34.3	30.1	28.1	25.6	24.9
	Roseau River below State	EGS	30.6	32.9	29.5	27.6	25.2	24.5
	Ditch 51 nr Caribou, MN	Number of visits	5	3	6	8	11	12
27	05124480	Standard error	5.3	5.1	5.1	5.1	5.1	5.1
	Kawishiwi River near Ely, MN	EGS	5.2	4.9	4.9	4.9	4.9	4.69
		Number of visits	5	3	3	3	3	3
28	05124990	Standard error	59.5	71.3	43.5	36.8	36.8	36.8
	Filson Creek near Ely, MN	EGS	58.2	70.5	41.5	34.7	34.7	34.7
		Number of visits	5	3	10	14	14	14
30	05127500	Standard error	See footnote 2 at the end of the table.					
	Basswood River near Winton,	EGS						
	MN	Number of visits						
32	05129115	Standard error	3.0	2.9	2.9	2.9	2.9	2.9
	Vermilion River nr Crane	EGS	2.9	2.8	2.8	2.8	2.8	2.8
	Lake, MN	Number of visits	5	3	3	3	3	3
33	05129290	Standard error	See footnote 1 at the end of the table.					
	Gold Portage Outlet From	EGS						
	Kabetogama Lake nr Ray, MN	Number of visits						
34	05130500	Standard error	11.0	13.6	13.6	13.6	12.0	11.0
	Sturgeon River near Chisholm,	EGS	7.2	7.6	7.6	7.6	7.4	7.2
	MN	Number of visits	5	3	3	3	4	5
35	05131500	Standard error	See footnote 1 at the end of the table.					
	Little Fork River at	EGS						
	Littlefork, MN	Number of visits						
36	05132000	Standard error	See footnote 1 at the end of the table.					
	Big Fork River at Big Falls,	EGS						
	MN	Number of visits						

Table 11.--Selected results of K-CERA Analysis for the open-water period--Continued

Map no.	Station number / Station name		Budget, 1985 dollars: Current operation 198,000	Optimized values 172,000	204,000	218,000	239,000	256,000
37	05133500	Standard error	8.3	10.7	10.7	10.7	10.7	10.7
	Rainy River at Manitou	EGS	1.1	1.4	1.4	1.4	1.4	1.4
	Rapids, MN	Number of visits	5	3	3	3	3	3
38	05134200	Standard error	16.9	22.6	22.6	19.1	16.9	15.3
	Rapid River near Baudette, MN	EGS	2.2	2.7	2.6	2.3	2.1	2.0
		Number of visits	5	3	3	4	5	6
41	05211000	Standard error	21.3	26.0	19.8	17.0	17.0	14.7
	Mississippi River at Grand	EGS	11.4	12.9	10.9	10.0	10.0	9.1
	Rapids, MN	Number of visits	5	3	6	9	9	12
43	05216860	Standard error	19.7	23.5	18.4	16.3	16.3	13.7
	Swan River near Calumet, MN	EGS	16.7	19.6	15.6	13.9	13.9	11.6
		Number of visits	5	3	6	8	8	12
45	05220500	Standard error	2.5	2.6	2.6	2.6	2.6	2.6
	Mississippi River below Sandy	EGS	2.5	2.6	2.6	2.6	2.6	2.6
	River nr Libby, MN	Number of visits	5	3	3	3	3	3
46	05227500	Standard error	2.6	2.8	2.8	2.8	2.8	2.8
	Mississippi River at Aitkin,	EGS	2.6	2.7	2.7	2.7	2.7	2.7
	MN	Number of visits	5	3	3	3	3	3
		Montevideo field office						
		Average standard error per station	36.7	43.4	27.3	26.4	25.4	25.1
		EGS for the Montevideo field office	29.8	33.8	23.9	21.9	20.7	19.8
9	05046000	Standard error	7.4	8.8	6.9	5.5	5.1	5.1
	Otter Tail River bl Orwell D	EGS	7.4	8.8	6.9	5.5	5.1	5.1
	nr Fergus Falls, MN	Number of visits	5			6	12	12
10	05050000	Standard error	39.3	47.9	31.6	25.7	23.8	23.8
	Bois De Sioux River near	EGS	39.3	47.9	31.6	25.9	23.8	23.8
	White Rock, SD	Number of visits	5	3	8	12	14	14
11	05061000	Standard error	44.6	46.3	44.1	42.9	42.4	42.4
	Buffalo River near Hawley, MN	EGS	43.9	44.9	43.6	42.6	42.1	42.1
		Number of visits	5	3	6	10	12	12
12	05061500	Standard error	81.4	86.1	80.1	76.7	74.0	74.0
	South Branch Buffalo River at	EGS	77.8	80.3	77.0	74.8	73.0	73.0
	Sabin, MN	Number of visits	5	3	6	10	14	14
13	05062000	Standard error	13.4	15.4	12.6	10.5	9.7	9.7
	Buffalo River near Dilworth,	EGS	11.8	13.1	11.2	9.4	8.8	8.8
	MN	Number of visits	5	3	6	10	12	12
48	05245100	Standard error	14.6	18.9	18.9	16.3	13.3	9.8
	Long Prairie River at Long	EGS	6.2	8.2	8.2	7.0	5.6	4.1
	Prairie, MN	Number of visits	5	3	3	4	6	11
58	05291000	Standard error	71.7	82.9	45.9	45.9	45.9	45.9
	Whetstone River near Big	EGS	71.5	82.8	45.7	45.7	45.7	45.7
	Stone City, SD	Number of visits	5	3	14	14	14	14

Table 11.--Selected results of K-CERA Analysis for the open-water period--Continued

Map no.	Station number Station name		Current operation 198,000	Optimized values 172,000	204,000	218,000	239,000	256,000
59	05292000 Minnesota River at Ortonville, MN	Standard error EGS Number of visits	31.1 29.8 5	37.3 35.5 3	22.8 21.8 10	20.9 20.0 12	19.4 18.5 14	19.4 18.5 14
60	05293000 Yellow Bank River near Odessa, MN	Standard error EGS Number of visits	42.5 42.0 5	54.8 54.3 3	28.1 27.6 11	24.7 24.3 14	24.7 24.3 14	24.7 24.3 14
61	05294000 Pomme De Terre River at Appleton, MN	Standard error EGS Number of visits	19.1 13.6 5	23.1 14.4 3	15.7 12.7 10	15.0 12.5 12	15.0 12.5 12	14.5 12.2 14
62	05300000 Lac Qui Parle River near Lac Qui Parle, MN	Standard error EGS Number of visits	58.4 55.1 5	72.4 69.2 3	35.0 32.0 14	35.0 32.0 14	35.0 32.0 14	35.0 32.0 14
63	05301000 Minnesota River near Lac Qui Parle, MN	Standard error EGS Number of visits	19.5 17.5 5	24.3 21.1 3	18.0 16.1 6	15.7 14.2 8	14.1 12.8 10	11.9 10.8 14
64	05304500 Chippewa River near Milan, MN	Standard error EGS Number of visits	13.5 12.7 5	15.5 14.4 3	15.5 14.4 3	15.5 14.4 3	12.7 12.0 6	9.0 8.6 14
65	05311000 Minnesota River at Montevideo, MN	Standard error EGS Number of visits	18.0 11.0 5	24.9 12.1 3	16.3 10.6 6	13.3 9.9 9	12.7 9.7 10	11.0 9.0 14
66	05311400 South Branch Yellow Medicine R at Minneota, MN	Standard error EGS Number of visits	125.6 125.6 5	150.9 149.6 3	74.2 73.9 14	74.2 73.9 14	74.2 73.9 14	74.2 73.9 14
67	05313500 Yellow Medicine River near Granite Falls, MN	Standard error EGS Number of visits	26.9 26.3 5	28.0 27.1 3	28.0 27.1 3	27.4 26.7 4	25.3 25.0 9	23.6 23.3 14
68	05315000 Redwood River near Marshall, MN	Standard error EGS Number of visits	46.2 37.1 5	59.2 47.8 3	29.4 23.1 12	27.1 21.2 14	27.1 21.2 14	27.1 21.2 14
69	05316500 Redwood River near Redwood Falls, MN	Standard error EGS Number of visits	32.3 31.6 5	39.2 38.4 3	24.6 24.1 9	20.5 20.0 13	19.7 19.3 14	19.7 19.3 14
96	05476000 Des Moines River at Jackson, MN	Standard error EGS Number of visits	25.3 25.3 5	32.2 32.2 3	25.3 25.3 5	21.4 21.4 7	17.8 17.8 10	15.0 15.0 14
	St. Paul field office							
		Average standard error per station	11.4	14.1	9.4	8.43	7.81	7.54
		EGS for the St. Paul field office	0.0	0.0	0.0	0.0	0.0	0.0
8	04024098 Deer Creek near Holyoke, MN	Standard error EGS Number of visits	5.9 5.9 5	7.6 7.6 3	7.6 7.6 3	7.6 7.6 3	6.6 6.6 4	5.4 5.4 6

Budget, 1985 dollars (columns 198,000 through 256,000).

Table 11.--Selected results of K-CERA Analysis for the open-water period--Continued

Map no.	Station number Station name		Current operation 198,000	Optimized values 172,000	Optimized values 204,000	Optimized values 218,000	Optimized values 239,000	Optimized values 256,000
			Budget, 1985 dollars					
54	05280000	Standard error	14.3	18.0	13.2	11.6	10.0	9.0
	Crow River at Rockford, MN	EGS	6.3	6.8	6.1	5.6	5.1	4.7
		Number of visits	5	3	6	8	11	14
55	05286000	Standard error	4.9	6.2	6.2	6.2	4.9	4.5
	Rum River near St. Francis,	EGS	2.6	2.9	2.9	2.9	2.6	2.4
	MN	Number of visits	5	3	3	3	5	6
56	05287890	Standard error	23.2	29.3	15.9	14.1	14.1	14.1
	Elm Creek nr Champlin, MN	EGS	8.8	12.2	5.5	4.8	4.8	4.8
		Number of visits	5	3	11	14	14	14
57	05288500	Standard error	See footnote 2 at the end of the table.					
	Mississippi River near Anoka,	EGS						
	MN	Number of visits						
71	05317000	Standard error	10.2	13.1	11.4	9.4	8.7	7.0
	Cottonwood River near New	EGS	1.9	2.0	2.0	1.9	1.9	1.8
	Ulm, MN	Number of visits	5	3	4	6	7	11
72	05317200	Standard error	See footnote 1 at the end of the table.					
	Little Cottonwood River near	EGS						
	Courtland, MN	Number of visits						
73	05319500	Standard error	18.2	22.8	14.6	13.1	11.1	11.1
	Watonwan River near Garden	EGS	12.5	15.3	10.1	9.0	7.6	7.6
	City, MN	Number of visits	5	3	8	10	14	14
74	05320000	Standard error	9.5	10.5	9.9	9.5	9.5	9.3
	Blue Earth River near	EGS	8.2	8.3	8.2	8.2	8.2	8.1
	Rapidan, MN	Number of visits	5	3	4	5	5	6
75	05320500	Standard error	28.6	34.3	20.5	18.3	18.3	18.3
	Le Sueur River near Rapidan,	EGS	24.6	28.7	17.8	15.9	15.9	15.9
	MN	Number of visits	5	3	11	14	14	14
76	05325000	Standard error	8.9	11.4	9.8	8.9	8.3	7.2
	Minnesota River at Mankato,	EGS	5.9	6.2	6.1	5.9	5.9	5.7
	MN	Number of visits	5	3	4	5	6	9
77	05327000	Standard error	26.1	30.5	18.6	18.1	18.1	18.1
	High Island Creek near	EGS	21.6	23.8	16.1	15.6	15.6	15.6
	Henderson, MN	Number of visits	5	3	13	14	14	14
78	05330000	Standard error	10.5	13.1	10.5	9.7	8.2	6.7
	Minnesota River near Jordan,	EGS	8.5	9.6	8.5	8.1	7.1	5.9
	MN	Number of visits	5	3	5	6	9	14
79	05331000	Standard error	See footnote 2 at the end of the table.					
	Mississippi River at St.	EGS						
	Paul, MN	Number of visits						
80	05336700	Standard error	13.5	17.6	12.3	10.6	9.5	8.0
	Kettle River below Sandstone,	EGS	3.8	4.4	3.5	3.2	2.9	2.5
	MN	Number of visits	5	3	6	8	10	14
81	05337400	Standard error	16.9	21.7	13.4	11.4	10.1	10.1
	Knife River near Mora, MN	EGS	7.8	10.2	6.1	5.2	4.6	4.6
		Number of visits	5	3	8	11	14	14
82	05340050	Standard error	20.6	25.1	14.9	12.7	12.5	12.6
	Sunrise River near Lindstrom,	EGS	20.1	24.5	14.5	12.5	12.3	12.3
	MN	Number of visits	5	3	10	14	14	14

Table 11.--Selected results of K-CERA Analysis for the open-water period--Continued

Map no.	Station number Station name		Current operation 198,000	Optimized values 172,000	204,000	218,000	239,000	256,000
			Budget, 1985 dollars					
83	05344500 Mississippi River at Prescott, WI	Standard error EGS Number of visits	See footnote 2 at the end of the table.					
84	05345000 Vermillion River near Empire, MN	Standard error	16.0	18.5	14.7	13.5	12.5	12.5
		EGS	11.9	12.4	11.6	11.2	10.8	10.8
		Number of visits	5	3	7	10	14	14
85	05353800 Straight River near Faribault, MN	Standard error	15.6	18.0	13.9	12.1	10.4	10.4
		EGS	14.6	16.6	13.1	11.4	9.8	9.8
		Number of visits	5	3	7	10	14	14
86	05372995 South Fork Zumbro River at Rochester, MN	Standard error EGS Number of visits	See footnote 1 at the end of the table.					
87	05374900 Zumbro River at Kellogg, MN	Standard error	12.2	15.7	12.2	10.3	8.6	7.3
		EGS	4.3	5.7	4.3	3.6	3.0	3.0
		Number of visits	5	3	5	7	10	14
88	05376000 North Fork Whitewater River near Elba, MN	Standard error	23.2	30.8	16.1	14.7	13.7	13.7
		EGS	5.9	6.7	5.4	5.3	5.1	5.1
		Number of visits	5	3	10	12	14	14
89	05376800 Whitewater River near Beaver, MN	Standard error	13.2	16.9	13.2	11.1	9.3	8.2
		EGS	10.6	14.0	10.6	8.9	7.4	6.5
		Number of visits	5	3	5	7	10	13
91	05378235 Garvin Brook near Minnesota City, MN	Standard error EGS Number of visits	See footnote 1 at the end of the table.					
93	05378500 Mississippi River at Winona, MN	Standard error EGS Number of visits	See footnote 2 at the end of the table.					
94	05384000 Root River near Lanesboro, MN	Standard error	2.9	3.2	3.2	3.2	3.2	3.2
		EGS	2.9	3.2	3.2	3.2	3.2	3.2
		Number of visits	5	3	3	3	3	3
95	05457000 Cedar River near Austin, MN	Standard error	7.8	9.8	8.63	7.8	7.8	6.4
		EGS	3.0	3.0	3.0	2.9	2.9	2.9
		Number of visits	5	3	4	5	5	8

[1] Less than three years for current rating. One-day autocorrelation function not determined; uncertainty function set to zero in Traveling Hydrographer analysis.

[2] Station not used in Traveling Hydrographer analysis.

SUMMARY

Currently (1985), there are 96 continuous-record streamflow-gaging stations operated by the Minnesota District at a cost of $558,000. Nineteen sources of funding contribute to this program and 42 uses were identified for the data collected in this program.

In an anlysis of the uses made of the data thirteen stations were identified that only provide information on regional hydrology. Two of the stations were recommended to be discontinued immediately because they have more than 25 years of record. Ten of the remaining eleven were recommended to be discontinued when they have 25 years of record. The thirteenth station was recommended to be continued because it is used as a natural hydrology index station in the computation of nearby records. It is recommended that the funds used to operate the stations that are discontinued be used to reactivate or start stations in hydrologic cataloging units in Minnesota that have not been sufficiently gaged. Three other stations were identified as having uses specific to short-term studies. These stations should also be deactivated at the end of the data-collection phases of the studies. One station was destroyed and its funds transferred to the operation of a nearby station. The remaining 90 stations should be maintained in the program for the foreseeable future.

Multiple-linear-regression techniques were applied to the records of 23 stations to see if the mean daily streamflow could be supplied by a method other than operating the stations. None of regression equations developed were accurate enough to recommend discontinuing any of the stations. It was recommended that flow routing be tried as an alternative method for providing discharge information at three groups of stations: (1) the stations on the Mississippi River at St. Paul, Minnesota, and Prescott, Wisconsin, (2) the stations on the Minnesota River near Lac Qui Parle and Montevideo, Minnesota, and (3) the stations on the Red Lake River at Highlanding, near Goodridge, and at Crookston, Minnesota.

The Traveling Hydrographer analysis was applied to 77 of the remaining 90 stations. Data for 13 stations are provided to the U.S. Geological Survey or are collected at fixed intervals and were, therefore, not used in the analysis. Current (1985) policy for the operation of the 77 stations costs $198,000 for the open-water period of the year, April 1 to October 31. It was shown that the estimated standard error per station for the statewide network could be reduced from 24.4 percent to 20.6 percent for the same budget if the minimum number of discharge measurements at each station were reduced from five to three for the open-water period and the remaining budget used to make discharge measurements at stations with large errors.

It was recommended that before this data collection plan is implemented that the effects on the cost of collecting data be evaluated for (1) possible increased lost record because of the data collection plan, and (2) the possible need for additional trips to visit noncontinuous-record stations. It was also recommended that the data accuracy needs of the funding agencies be considered before the plan is implemented.

It was recommended that the overall error of the network be reduced as much as possible while not significantly raising the costs of computing the discharge record and the costs of the other networks.

Cost-effective studies of the streamflow-gaging program need to be continued as the continuous-record streamflow-gaging network changes in response to changing data needs of the funding agencies. Methods of decreasing the amount of lost record, such as satellite data-collection platforms, need to be investigated.

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APPENDICES

A: 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

$$\bar{V} = \varepsilon_f V_f + \varepsilon_r V_r + \varepsilon_e V_e$$

with (3)

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

where

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

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

V_f is the relative variance of the errors of flow estimates from primary recorders,

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

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

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

V_e is the relative error variance of the third situation.

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

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

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

where

k is the failure rate in units of day^{-1};

e is the base of natural logarithms; and

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

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

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

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

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

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

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

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

$$\begin{aligned} \varepsilon_r &= 1 - \varepsilon_f - \varepsilon_e \\ &= [(1-e^{-ks}) + 0.5(1-e^{-2ks})]/(ks) \end{aligned} \tag{6}$$

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

$$x(t) = \ln q_T(t) - \ln q_R(t) = \ln [q_T(t)/q_R(t)] \tag{7}$$

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

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

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

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

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

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

where

v(t) is the measurement error, and

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

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

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

The variance of the observed residuals z(t) is

$$Var[z(t)] = p + r, \qquad (11)$$

where r is the variance of the measurement error v(t). The three parameters, p, β, and r, are computed by analyzing the statistical properties of the z(t) time series. These three site-specific parameters are needed to define this component of the uncertainty 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 date 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 seasonally varying parameter, is an estimate of the error variance that results from using the expected value as an estimate. Thus the coefficient of variation squared $(C_v)^2$ is an estimate of the required relative error variance V_e. Because C_v varies seasonally and the times of failures cannot be anticipated, a seasonally averaged value of C_v is used:

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

where

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

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

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

The variance V_r of the relative error during period of reconstructed streamflow records is estimated on the basis of correlation between records at the primary site and records from other gaged nearby sites. The correlation coefficient ρ_c between the streamflows with seasonal trends removed at the site of interest and detrended streamflows at the other sites is a measure of the goodness of their linear relationship. The fraction of the variance of streamflow at the primary site that is explained by data from the other sites is equal to $\rho_c{}^2$. 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 (3) even if the probability that primary and secondary information are not available, ε_e, is quite small.

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

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

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.

B: RELATION OF VISIT FREQUENCY TO LOST RECORD

by M. E. Moss

It is assumed that, if the sensing or recording equipment at a stream gage fails between service visits to the gage, the time, τ, from the last service visit until the failure has a conditional probability distribution that is defined by the truncated negative exponential family

$$f_\tau=ke^{-k\tau}/(1-e^{-ks}), \tag{16}$$

where s is the interval between visits and k is a parameter of the family of probability distributions (1/k is the average time to failure). It also is assumed that the recorder continues to malfunction from the instant of failure until the next service visit. Thus, the fraction of time, ε_f, during which the gage can be expected to function properly is

$$\varepsilon_f=1-E[d]/s, \tag{17}$$

where E[·] is the expected value of the random variable contained in the brackets and d is the downtime of the recorder between visits. Down time is defined as:

$$d=\begin{cases} s-\tau & \text{if a failure occurs,} \\ 0 & \text{if no failure occurs} \end{cases} \tag{18}$$

as shown in figure 13.

The expected value of down time is

$$E[d]=\int_0^s (s-\tau)f_\tau d\tau, \tag{19}$$

which, when evaluated, results in

$$E[d]=(ks+e^{-ks}-1)/k. \tag{20}$$

Substituting equation 20 into equation 17 and simplifying result in

$$\varepsilon_f=(1-e^{-ks})/ks. \tag{21}$$

The fraction of time, ε_e, for which no record is available at the station of interest and no record is available from an auxiliary site to reconstruct at the station of interest (both caused by equipment failures) is obtainable from a bivariate application of equation 16. If it is assumed that the probability distributions of failure times are identical and independent at the primary and auxiliary sites and that the primary and auxiliary sites are serviced at about the same times, ε_e can be evaluated as follows.

The concurrent downtime, d_2, of both stations is defined as:

$$d_2 = \begin{cases} \min(s-\tau_a,\ s-\tau) \text{ if both stations fail,} \\ 0 \text{ otherwise, if one or no station fails,} \end{cases} \tag{22}$$

where τ_a is the time to failure at the auxiliary site. The case in which $s-\tau_a$ is the minimum and equals d_2 is shown in figure 14. The value of ε_e can be defined in terms of d_2 as

$$\varepsilon_e = E[d_2]/s. \tag{23}$$

The expected value of concurrent downtime is

$$E[d_2] = \int_o^s (s-\tau)P[\tau_a \leq \tau] f_\tau d\tau + \int_o^s (s-\tau_a)P[\tau \leq \tau_a] f_{\tau_a} d\tau_a, \tag{24}$$

where P[·]is the probability of the event contained within the brackets occurring. Evaluation of equation 24 under the given assumptions results in

$$E[d_2] = s - \frac{2}{k}(1-e^{-ks}) - \frac{1}{2k}(1-e^{-2ks}), \tag{25}$$

which can be substituted into equation 23 to obtain ε_e.

Because ε_f, ε_e, and ε_r are mutually exclusive and all encompassing

$$\varepsilon_f + \varepsilon_e + \varepsilon_r = 1. \tag{26}$$

From equation 26, ε_τ can be defined as:

$$\varepsilon_r = 1 - \varepsilon_f - \varepsilon_e. \tag{27}$$

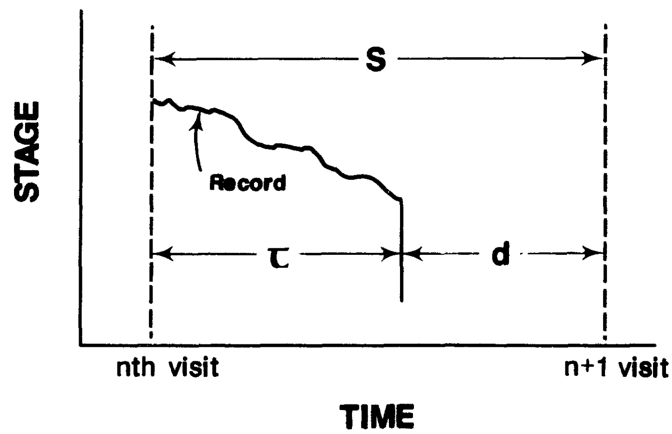

Figure 13.--Definition of downtime for a single station.

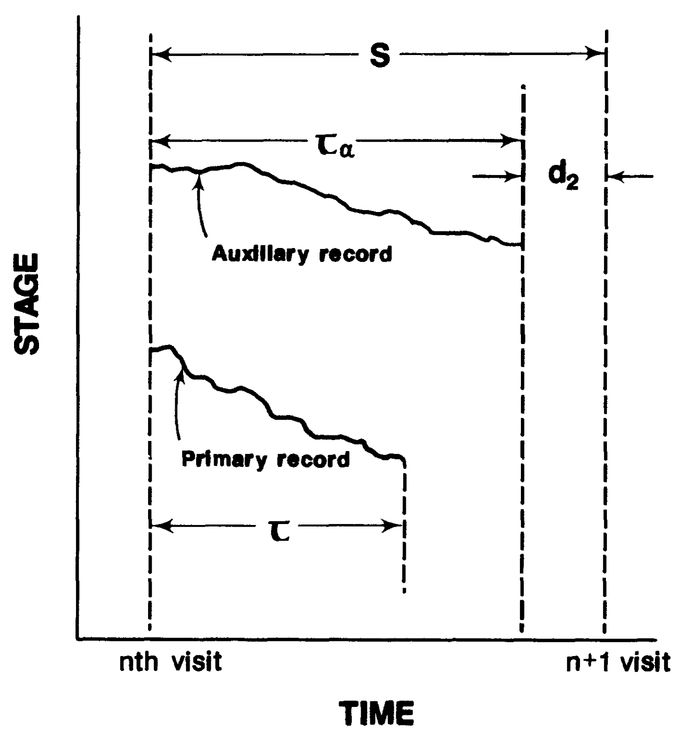

Figure 14.--Definition of joint downtime for a pair of stations.