COST EFFECTIVENESS OF THE U.S. GEOLOGICAL SURVEY'S STREAM-GAGING PROGRAM IN WISCONSIN

By J. F. Walker, L. L. Osen, and P. E. Hughes

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CONTENTS

Page

Abstract ... 1
Introduction ... 1
  History of the stream-gaging program in Wisconsin ... 2
  Current Wisconsin stream-gaging program ... 2
  Acknowledgments ... 3
Uses, funding, and availability of continuous streamflow data ... 3
  Data-use classes ... 7
    Regional hydrology ... 7
    Hydrologic systems ... 9
    Legal obligations ... 9
    Planning and design ... 9
    Project operation ... 9
    Hydrologic forecasts ... 9
    Water-quality monitoring ... 10
    Research ... 10
  Funding ... 10
  Data availability ... 10
  Presentation and summary of data use ... 10
  Conclusions pertaining to data use ... 13
Alternative methods of developing streamflow information ... 13
  Description of flow-routing model ... 14
  Description of statistical model ... 14
  Identification of gaging stations suitable for evaluating alternative methods ... 15
  Results of flow-routing modeling ... 15
  Results of statistical modeling ... 19
  Conclusions pertaining to alternative methods of data generation ... 19
Cost-effective resource allocation ... 20
  Introduction to Kalman-filtering for cost-effective resource allocation (K-CERA) ... 20
  Description of mathematical program ... 22
  Description of uncertainty functions ... 23
  Application of K-CERA ... 26
    Missing record ... 26
    Cross-correlation coefficients and coefficients of variation ... 26
    Kalman-filter definition of variance ... 28
    Stream-gaging routes and costs ... 29
    Results of K-CERA ... 36
  Conclusions pertaining to the K-CERA analysis ... 42
Summary ... 42
Literature cited ... 43

ILLUSTRATIONS

Page

Figure 1. Graph showing the number of continuous-record streamflow stations operated in Wisconsin, 1888-1984 3
2. Index map showing location of continuous-record streamflow stations operated in Wisconsin during 1984 7
3. Index map showing location of continuous-record streamflow stations that provide information about regional hydrology 8
4. Map showing the Rock River basin flow-routing model study area 16
5. Graph showing comparison of observed and simulated daily mean streamflow for the Rock River at Afton, 1983 water year 17
6. Map showing the Menominee River basin flow-routing model study area 18
7. Graph showing comparison of observed and simulated daily mean streamflow for the Menominee River at McAllister, 1981 water year 20
8. Map showing the Pecatonica River basin statistical model study area 21
9. Mathematical formulation for the optimization of the routing of hydrographers 23
10. Schematic showing the mathematical formulation for the optimization of the routing of hydrographers 24
11. Graph showing uncertainty functions for three gaging stations in Wisconsin 31
12. Graph showing temporal-average standard error per gaging station 36

TABLES

Page

Table 1. Selected hydrologic data for gaging stations in the 1984 Wisconsin surface-water program 4
2. Data use, station funding, and data availability for gaging stations operated in the 1984 Wisconsin surface-water program 11
3. Selected reach characteristics used in the Rock River flow-routing model 17
4. Results of the Rock River flow-routing model analysis 19
5. Selected reach characteristics used in the Menominee River flow-routing model 19
6. Results of the Menominee River flow-routing model analysis 19
7. Summary of parameters for the MOVE.1 statistical analysis of daily mean streamflows for the Pecatonica River at Freeport, Ill. 22
8. Results of the MOVE.1 statistical analysis of daily mean streamflows for the Pecatonica River at Freeport, Ill.: 0-day lag 22
9. Results of the MOVE.1 statistical analysis of daily mean streamflows for the Pecatonica River at Freeport, Ill.: 1-day lag 22
10. Summary of parameters used for record reconstruction at gaging stations in Wisconsin 27
11. Uncertainty function autocovariance parameters for gaging stations in Wisconsin 30
12. Summary of routes used to visit stations in Wisconsin 32
13. Additional stations considered in evaluation of routes for Wisconsin's gaging station network operation 34
14. Criteria for assigning a minimum number of visits 37
15. Selected results of K-CERA analysis 38

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

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

COST EFFECTIVENESS OF THE U.S. GEOLOGICAL SURVEY'S STREAM-GAGING PROGRAM IN WISCONSIN

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ABSTRACT

This report presents the results of a three-step evaluation of the stream-gaging program in Wisconsin. First, data uses and funding sources were identified for the 89 continuous-record gaging stations operated during the 1984 water year. Next, alternative methods of streamflow estimation were examined for three stations. A flow-routing model was used for two of the stations and a statistical model was used for the third. The modeled discharges did not compare well enough with observed discharges to warrant elimination of any of the stations. Finally, an optimization model was used to assess the cost effectiveness of the stream-gaging program.

The annual budget, in 1984 dollars, for operating the 89 continuous-record gaging stations and 65 additional stations is $557,300. Based on a Kalman-filter analysis, the theoretical average standard error of instantaneous discharge associated with the current practice of visiting the stations is 13.8 percent. This overall level of accuracy could be maintained with a budget of $518,600 if stream-gaging activities were redistributed in an optimal fashion among the gaging stations. For the current budget, the theoretical average standard error would be reduced to 10.1 percent if the network is operated in an optimal fashion. Furthermore, the average standard error would be reduced to 7.3 percent if all missing record is eliminated and the network is operated optimally.

A minimum budget of $510,000 is required to operate the program; a budget less than this does not permit proper service and maintenance of the gaging stations. At this minimum budget, the theoretical average standard error of instantaneous discharge is 14.4 percent. The maximum budget analyzed was $650,000 and resulted in an average standard error of instantaneous discharge of 7.2 percent.

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 data are collected in cooperation with State and local governments and other Federal agencies. In 1984, the U.S. Geological Survey operated approximately 8,000 continuous-record streamflow stations throughout the Nation. A few of these records extend back before the turn of the century. Any activity of long standing, such as the collection of surface-water data, should be re-examined at intervals, if not continuously, because of changes in objectives, technology, or external constraints.

The last systematic nationwide evaluation of the streamflow information program was completed in 1970 and is documented by Benson and Carter (1973). A study by Campbell and Dreher (1975) described the development of Wisconsin's surface-water program and proposed a program to meet the future needs of water-data users.

The U.S. Geological Survey is presently (1984) undertaking a nationwide evaluation of the stream-gaging program that will be completed over a 5-year period with 20 percent of the program being analyzed each year. Stream gaging is the process of measuring the depths, areas, velocities, and rates of flow in natural or artificial channels (Langbein and Iseri, 1960, p. 19). The objective of this evaluation is to define and document the most cost-effective means of furnishing streamflow information.

This report documents the results of a three-step evaluation of the 1984 Wisconsin stream-gaging program. This first step of the evaluation identifies the principal uses of streamflow data and funding sources for every continuous-record streamflow station (hereafter referred to as "gaging station"). Gaging stations for which data are no longer needed are identified. In addition, gaging stations are categorized as to whether the data are available to users in a real-time sense, on a provisional basis, or at the end of the water year.

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

The final step of the evaluation involves the use of Kalman-filtering and mathematical-programing techniques to define strategies for operating the gaging stations that minimize the uncertainty in the streamflow records for given operating budgets. Kalman-filtering techniques are used to compute an uncertainty function for each gaging station in the stream-gaging network. The uncertainty function relates the standard errors of computed or estimated streamflow records to the frequency of visits to a gaging station. A steepest descent optimization program uses these uncertainty functions, information on practical routes to the gaging stations, the various costs associated with stream gaging, and the total operating budget to calculate the frequency of visits to each gaging station that minimizes the overall uncertainty in the streamflow records. The stream-gaging program that results from this final step of the evaluation will meet the expressed water-data needs in the most cost-effective manner.

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

History of the Stream-Gaging Program in Wisconsin

The first known streamflow measurements in Wisconsin were made shortly after the Civil War by General Gouverneur Warren on the Wisconsin River and its major tributaries. Several years later, the U.S. Geological Survey began collecting streamflow records at four sites: Chippewa River at Chippewa Falls (1888), Fox River at Rapide Croche (1896), Wolf River at New London (1896), and the Fox River at Berlin (1898). In 1913 the cooperative surface-water data program was started with the Wisconsin Railroad Commission and included the following stations: Oconto River near Gillet (04071000), Fox River at Berlin (04073500), Wolf River at Keshena Falls near Keshena (04077000), Wolf River at New London (04079000), St. Croix River at St. Croix Falls (05340500), Chippewa River at Bishops Bridge near Winter (05356000), Chippewa River at Chippewa Falls (05365500), Red Cedar River at Menomonie (05369000), Black River at Neillsville (05381000), Wisconsin River at Whirlpool Rapids (05392000), and Wisconsin River at Merrill (05395000). The number of gaging stations increased steadily to 58 in 1938, and reached a maximum of 135 in 1979, before decreasing to the present (1984) level of 89. The number of gaging stations operated by the U.S. Geological Survey is depicted in figure 1.

A network of crest-stage partial-record stations was established across the State in 1957 to define flood-frequency characteristics in Wisconsin. The program reached a maximum with 135 stations in 1981 and has since been reduced to 105 in 1984. Data obtained from the crest-stage stations as well as the continuous-record stations have been used to establish regression equations for estimating the magnitude and frequency of floods on rural streams in Wisconsin (Ericson, 1961; Conger, 1976 and 1981). A study has recently been completed to determine flood-frequency relationships for urban streams in Wisconsin (Conger, 1986).

A network of nearly 300 low-flow partial-record stations was established across Wisconsin in 1962. Beginning in 1971 low-flow data were collected at approximately 500 additional sites. The data obtained from the network of low-flow stations were used to establish relationships for estimation of low-flow characteristics of Wisconsin streams (Gebert, 1978, 1979a, 1979b, 1980 and 1982; Holmstrom 1978, 1979, 1980a, 1980b, and 1982; and Stedfast, 1979). The low-flow characteristics have been defined for these sites, hence data collection has been discontinued.

Current Wisconsin Stream-Gaging Program

The current (1984) stream-gaging program in Wisconsin consists of 89 gaging stations located throughout the State on streams draining watersheds with different physiographies (fig. 2). Physiography of Wisconsin is classified into five major divisions: The Western Upland, the Lake Superior Lowland, the Northern Highland, the Central Plain, and the Eastern Ridges and Lowland (Martin, 1932, and Thwaites, 1956). All of Wisconsin except portions of the Western Upland have been glaciated.

Thirty-six gaging stations are located in the Eastern Ridges and Lowlands section with 27 of the gaging stations located in the southern portion of the section. Nineteen gaging stations are located in the Northern Highland

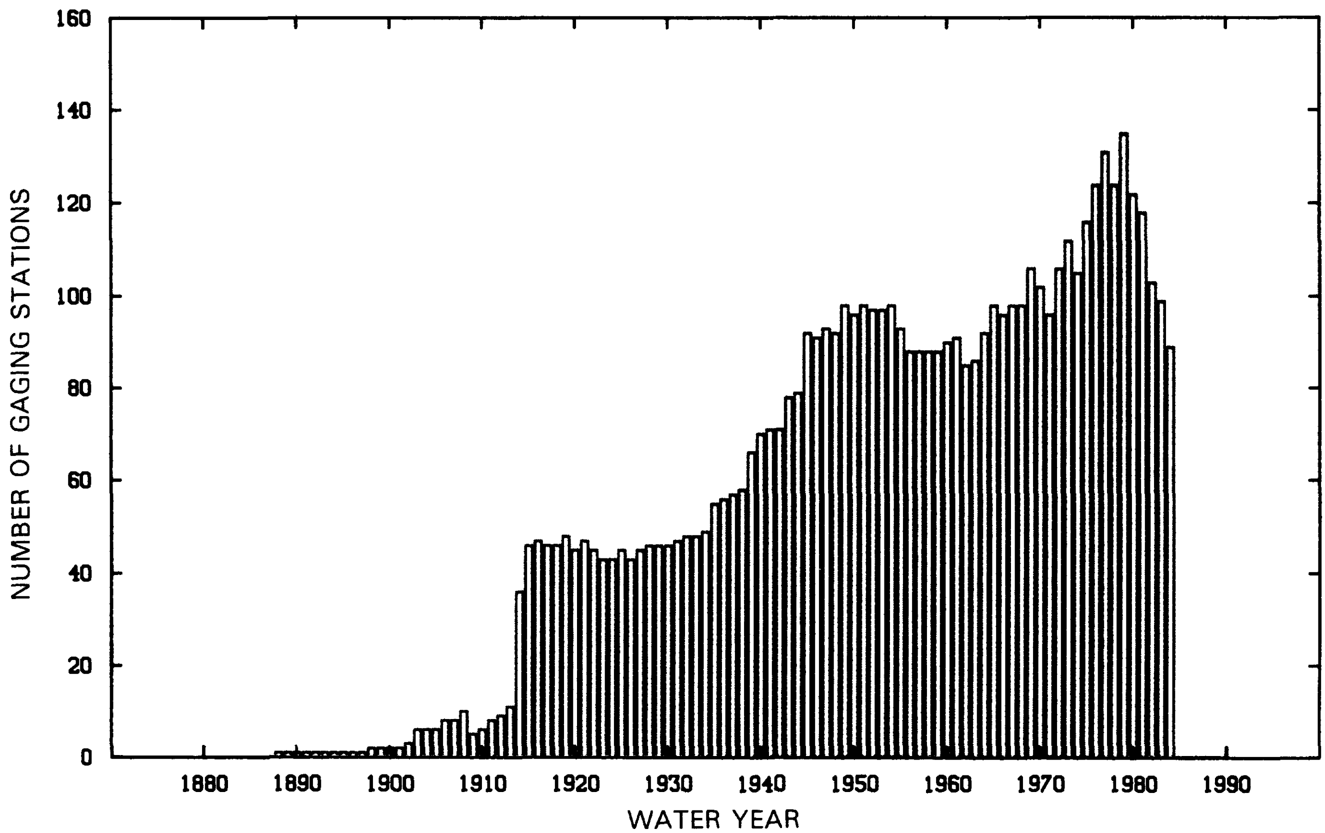

Figure 1. Number of continuous-record streamflow stations operated in Wisconsin, 1888–1984.

section and 16 gaging stations are located in the Western Upland. Fifteen gaging stations are located in the Central Plains section and 3 gaging stations are located in the Lake Superior Lowland section.

Map index numbers in figure 2 are referenced to U.S. Geological Survey eight-digit downstream-order station-identification numbers given in table 1.

Table 1 also shows the name and selected hydrologic data, including drainage area, period of record, and average discharge for each gaging station.

Acknowledgments

The authors wish to acknowledge the following agencies for their cooperation in identifying the uses of data collected at the gaging stations in the Wisconsin stream-gaging program:

U.S. Army, Corps of Engineers, Detroit district,
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Dane County Department of Public Works,
Dane County Regional Planning Commission,
Federal Energy Regulatory Commission,
Green Bay Metropolitan Sewerage District,
Illinois Department of Transportation,
Milwaukee Metropolitan Sewerage District,
National Weather Service,
Northern States Power Company,
Southeastern Wisconsin Regional Planning Commission,
Village of Slinger,
Wisconsin Department of Natural Resources,
Wisconsin Electric Power Company,
Wisconsin Power and Light, and
Wisconsin Valley Improvement Company.

USES, FUNDING, AND AVAILABILITY OF CONTINUOUS STREAMFLOW DATA

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

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

Table 1. Selected hydrologic data for gaging stations in the 1984 Wisconsin surface-water program
[Information from Holmstrom and others (1984)]

Map index no.	Station number	Station name	Drainage area (mi^2)	Period of record	Mean flow (ft^3/s)
1	04024430	Nemadji River near South Superior	420	December 1973-	357
2	04027000	Bad River near Odanah	597	July 1914 to December 1922[1], May 1948-	612
3	04027500	White River near Ashland	301	May 1948-	280
4	04063700	Popple River near Fence	139	October 1963-	124
	04066000	Menominee River near Pembine	3,110	October 1949 to July 1982[2]	2,986
5	04066003	Menominee River below Pemene Creek near Pembine	3,140	October 1949-[3]	2,986
6	04067500	Menominee River near McAllister	3,930	March 1945 to September 1961, October 1961 to September 1979[4] October 1979-	3,437
7	04069500	Peshtigo River at Peshtigo	1,080	June 1953-	927
8	04071000	Oconto River near Gillett	705	June 1906 to March 1909, October 1913-[5]	580
9	04071858	Pensaukee River near Pensaukee	134	October 1972-	88.1
10	04073462	White Creek at Forest Glen Beach near Green Lake	3.05	December 1981-	—[6]
11	04073500	Fox River at Berlin	1,340	January 1898-	1,101
12	04074538	Swamp Creek above Rice Lake at Mole Lake	46.3	August 1977-	30.5
13	04074548	Swamp Creek below Rice Lake at Mole Lake	56.8	August 1977 to September 1979, April to September 1982	—[6]
14	04074950	Wolf River at Langlade	463	March 1966 to September 1979, October 1980-	458
15	04077000	Wolf River at Keshena Falls near Keshena	788	May 1907 to March 1909, October 1910-[7]	759
16	04078500	Embarrass River near Embarrass	384	June 1919-	292
17	04079000	Wolf River at New London	2,260	March 1896-[8]	1,738
18	04080000	Little Wolf River at Royalton	507	January 1914 to September 1970 October 1982-	399
19	04081000	Waupaca River near Waupaca	265	June 1916 to September 1966 October 1982-	237
20	04084500	Fox River at Rapide Croche Dam near Wrightstown	6,010	March 1896 to September 1917[9] October 1917-	4,175
21	04085200	Kewaunee River near Kewaunee	127	September 1964-[10]	80.2
22	04085281	East Twin River at Mishicot	110	July 1972-	70.9
23	04085427	Manitowoc River at Manitowoc	526	July 1972-	309
24	04086000	Sheboygan River at Sheboygan	418	June 1916 to September 1924[11], October 1950-	243
25	04087000	Milwaukee River at Milwaukee	696	April 1914-[12]	408
26	04087030	Menomonee River at Menomonee Falls	34.7	November 1974 to September 1977, July 1979-	—[6]
27	04087088	Underwood Creek at Wauwatosa	18.2	December 1974 to November 1979, July 1980-	11.1

Table 1. Selected hydrologic data for gaging stations in the 1984 Wisconsin surface-water program—Continued
[Information from Holmstrom and others (1984)]

Map index no.	Station number	Station name	Drainage area (mi²)	Period of record	Mean flow (ft³/s)
28	04087120	Menomonee River at Wauwatosa	123	October 1961-	90.3
29	04087159	Kinnickinnic River at South 11th Street at Milwaukee	20.4	September 1976-	24.9
30	04087204	Oak Creek at South Milwaukee	25.0	October 1963-	21.2
31	04087220	Root River near Franklin	49.2	October 1963-	43.8
32	04087233	Root River Canal near Franklin	57.0	October 1963-	45.1
33	04087240	Root River at Racine	190	August 1963-	148
34	04087257	Pike River near Racine	38.5	October 1971-	35.7
35	05340500	St. Croix River at St. Croix Falls	6,240	January 1902-[13]	4,206
36	05356000	Chippewa River at Bishops Bridge near near Winter	790	February 1912-[14]	713
37	05356500	Chippewa River near Bruce	1,650	December 1913-	1,460
38	05360500	Flambeau River near Bruce	1,860	August 1951-	1,831
39	05362000	Jump River at Sheldon	576	July 1915-	515
40	05365500	Chippewa River at Chippewa Falls	5,650	June 1888-[15]	5,110
41	05368000	Hay River at Wheeler	418	October 1950-	301
42	05369000	Red Cedar River at Menomonie	1,770	June 1907 to September 1908, May 1913[15]	1,256
43	05369500	Chippewa River at Durand	9,010	July 1928-	7,566
44	05370000	Eau Galle River at Spring Valley	64.1	March 1944-	33.1
45	05379500	Trempealeau River at Dodge	643	December 1913 to September 1919, April 1934-	415
46	05381000	Black River at Neillsville	749	April 1905 to March 1909, October 1913-[15]	588
47	05382000	Black River near Galesville	2,080	December 1931-	1,711
48	05391000	Wisconsin River at Rainbow Lake near Lake Tomahawk	758	July 1936-[16]	699
49	05393500	Spirit River at Spirit Falls	81.6	April 1942-	85.3
50	05394500	Prairie River near Merrill	184	January 1914 to September 1931, August 1939-[15]	180
51	05395000	Wisconsin River at Merrill	2,760	November 1902-	2,673
52	05397500	Eau Claire River at Kelly	375	January 1914 to November 1926, August 1939-	249
53	05398000	Wisconsin River at Rothschild	4,020	October 1944-	3,476
54	05399500	Big Eau Pleine River near Stratford	224	July 1914 to December 1925, April 1937-[15]	174
55	05400650	Little Plover River at Plover	[17]19.0	July 1959-	10.1
56	05400760	Wisconsin River at Wisconsin Rapids	5,420	May 1914 to March 1950[18] October 1957-	4,948
57	05402000	Yellow River at Babcock	215	March 1944-	151
58	05403500	Lemonweir River at New Lisbon	507	March 1944-	369
59	05404000	Wisconsin River near Wisconsin Dells	8,090	October 1934-	6,761
60	05405000	Baraboo River near Baraboo	609	December 1913 to March 1922, September 1942-	370
61	05406500	Black Earth Creek at Black Earth	45.6	February 1954-	31.7
62	05407000	Wisconsin River at Muscoda	10,400	December 1902 to December 1903, October 1913-[19]	8,626

This table is continued on the following page

Table 1. Selected hydrologic data for gaging stations in the 1984 Wisconsin surface-water program—Continued
[Information from Holmstrom and others (1984)]

Map index no.	Station number	Station name	Drainage area (mi^2)	Period of record	Mean flow (ft^3/s)
63	05408000	Kickapoo River at LaFarge	266	October 1938-	173
64	05410500	Kickapoo River at Steuben	687	May 1933-	472
65	05413500	Grant River at Burton	269	October 193[20]	166
66	05414000	Platte River near Rockville	142	October 1934-[21]	98.4
67	05415000	Galena River at Buncombe	125	September 1939-	76.9
68	05424082	Rock River at Hustisford	511	May 1978-	—[6]
69	05425500	Rock River at Watertown	969	June 1931 to September 1970, October 1976-	437
70	05426000	Crawfish River at Milford	762	June 1931-	369
71	05426031	Rock River at Jefferson	1,850	April 1978-	—[6]
72	05426250	Bark River near Rome	122	November 1979-	—[6]
73	05427570	Rock River at Indianford	2,630	May 1975-	1,611
74	05427948	Pheasant Branch at Middleton	[22]18.3	July 1974-	4.16
75	05427965	Spring Harbor Storm Sewer at Madison	3.29	February 1976-	1.46
76	05427970	Willow Creek at Madison	3.15	October 1973-	2.38
77	05429500	Yahara River near McFarland	327	September 1939-	152
78	05430150	Badfish Creek near Cooksville	82.6	July 1977-	96.4
79	05430175	Yahara River near Fulton	517	July 1977-	341
80	05430500	Rock River at Afton	3,340	January 1914-[23]	1,790
81	05431486	Turtle Creek at Carvers Rock Road near Clinton	199	September 1939-	119
82	05432500	Pecatonica River at Darlington	273	September 1939-	184
83	05433000	East Branch Pecatonica River near Blanchardville	221	September 1939-	141
84	05434500	Pecatonica River at Martintown	1,034	October 1939-	708
85	05436500	Sugar River near Brodhead	523	January 1914-[24]	344
86	05543830	Fox River at Waukesha	126	January 1963-	92
87	05544200	Mukwonago River at Mukwonago	74.1	July 1973-	59
88	5545300	White River near Burlington	110	April 1973-[25]	89.5
89	05546500	Fox River at Wilmot	868	October 1939-	519

[1] Monthly discharge only for some periods published in Water-Supply Paper 1307.
[2] Discontinued at this location. Monthly discharge only for some periods published in Water-Supply Paper 1307.
[3] Published as "near Pembine" prior to August 1982. Monthly discharge only for some periods published in Water-Supply Paper 1307.
[4] Miscellaneous measurements and peaks only.
[5] Monthly discharge only for some periods published in Water-Supply Paper 1307.
[6] No mean annual flow published, less than 5 years of streamflow record.
[7] Monthly discharge only for some periods published in Water-Supply Paper 1307. Published as "at Keshena" prior to April 1928. Published as "at Keshena Falls" April 1928 to September 1981.
[8] Prior to October 1913, monthly discharge only published in Water-Supply Paper 1307.
[9] Monthly discharge only.
[10] Annual maximum, water years 1958-65, and occasional low-flow measurements, water years 1963-64. No winter records for years 1965 and 1966.
[11] Published as "near Sheboygan". Monthly discharge only for some periods published in Water-Supply Paper 1307 and 1727.
[12] Published as "near Milwaukee" prior to 1936.
[13] Prior to January 1910, monthly discharge only published in Water-Supply Paper 1308. Prior to October 1939, published as "near St. Croix Falls".
[14] December to April 1913, monthly discharge only published in Water-Supply Paper 1308.
[15] Monthly discharge only for some periods published in Water-Supply Paper 1308.
[16] Prior to October 1955, published as "at Rainbow Reservoir, near Lake Tomahawk".
[17] 7.33 mi^2 probably is noncontributing.
[18] Published as "near Nekoosa".
[19] Monthly discharge only for October and November 1913 published in Water-Supply Paper 1308. Gageheight records collected at same site November 1908 to December 1912 are contained in reports of U.S. Weather Bureau.
[20] Published as "near Burton" October 1934 to September 1947. Records published for both sites March to September 1947. October 1934, monthly discharge only published in Water-Supply Paper 1308.
[21] Monthly discharge only for October and November 1934, published in Water-Supply Paper 1308.
[22] 1.22 mi^2 is noncontributing.
[23] Monthly discharge only for January 1914, published in Water-Supply Paper 1308.
[24] Monthly discharge only for January and February 1914, published in Water-Supply Paper 1308.
[25] Annual maximum, water years 1958-64, 1967-73; August 1964 to September 1966, no winter records.
[26] No winter records for 1964 and 1965 water years; operated as a crest-stage gage October 1966 to September 1970 and a flow-flow partial-record station October 1966 to September 1977.

Data-Use Classes

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

Regional Hydrology

For data to be useful in defining regional hydrology, the streamflow at a gaging station must be largely unaffected by manmade storage or diversion. In this class of

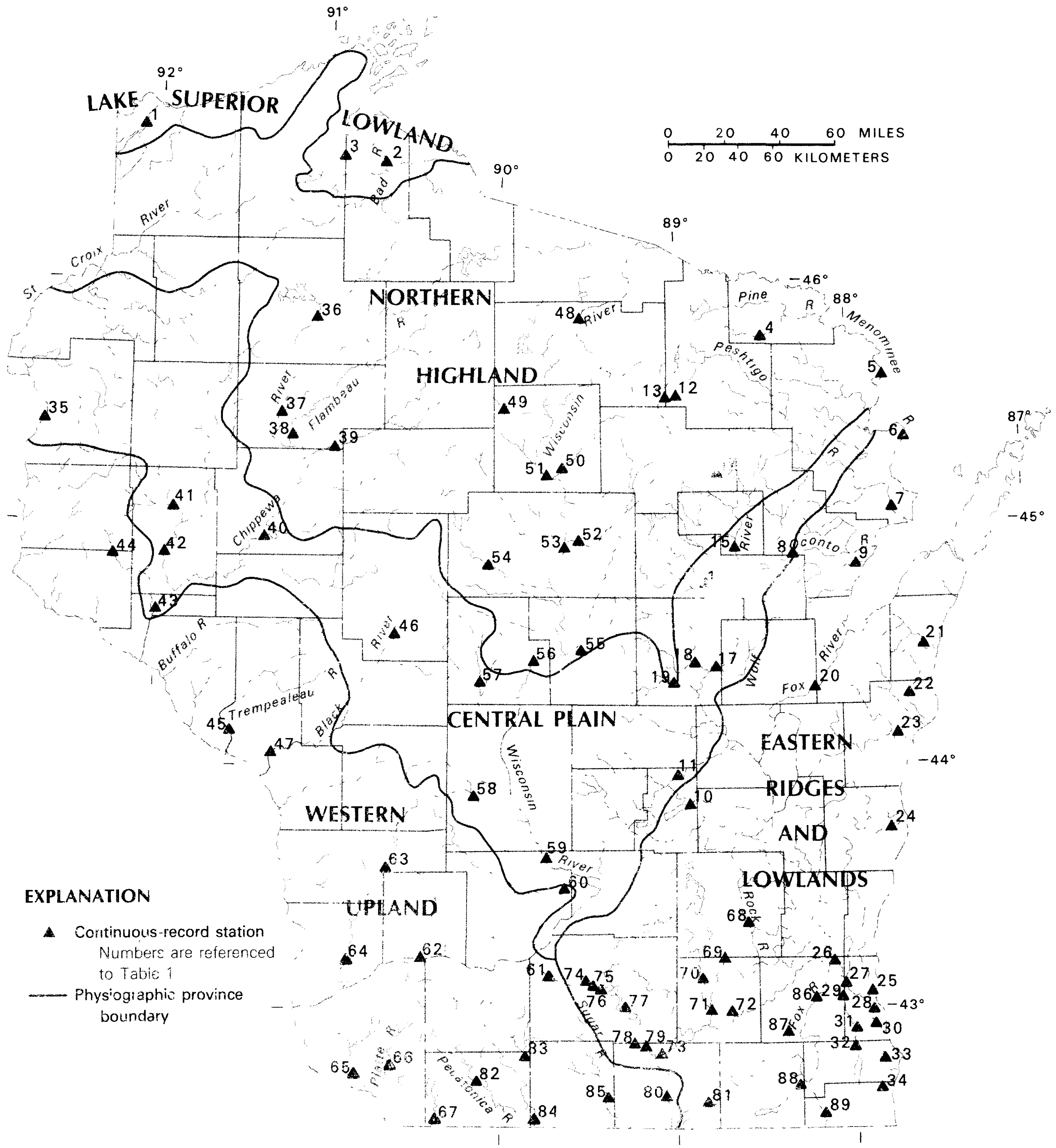

Figure 2. Location of continuous-record streamflow stations operated in Wisconsin during 1984.

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 providing the outflow is uncontrolled. These gaging stations are useful in developing regionally transferable information about the relation between basin characteristics and streamflow.

Sixty-three gaging stations (fig. 3) in the Wisconsin stream-gaging program are classified in the regional hydrology data-use category. Two of the gaging stations are index stations. The index stations, Oconto River near Gillett (04071000) and Jump River at Sheldon (05362000), are used to indicate current hydrologic conditions.

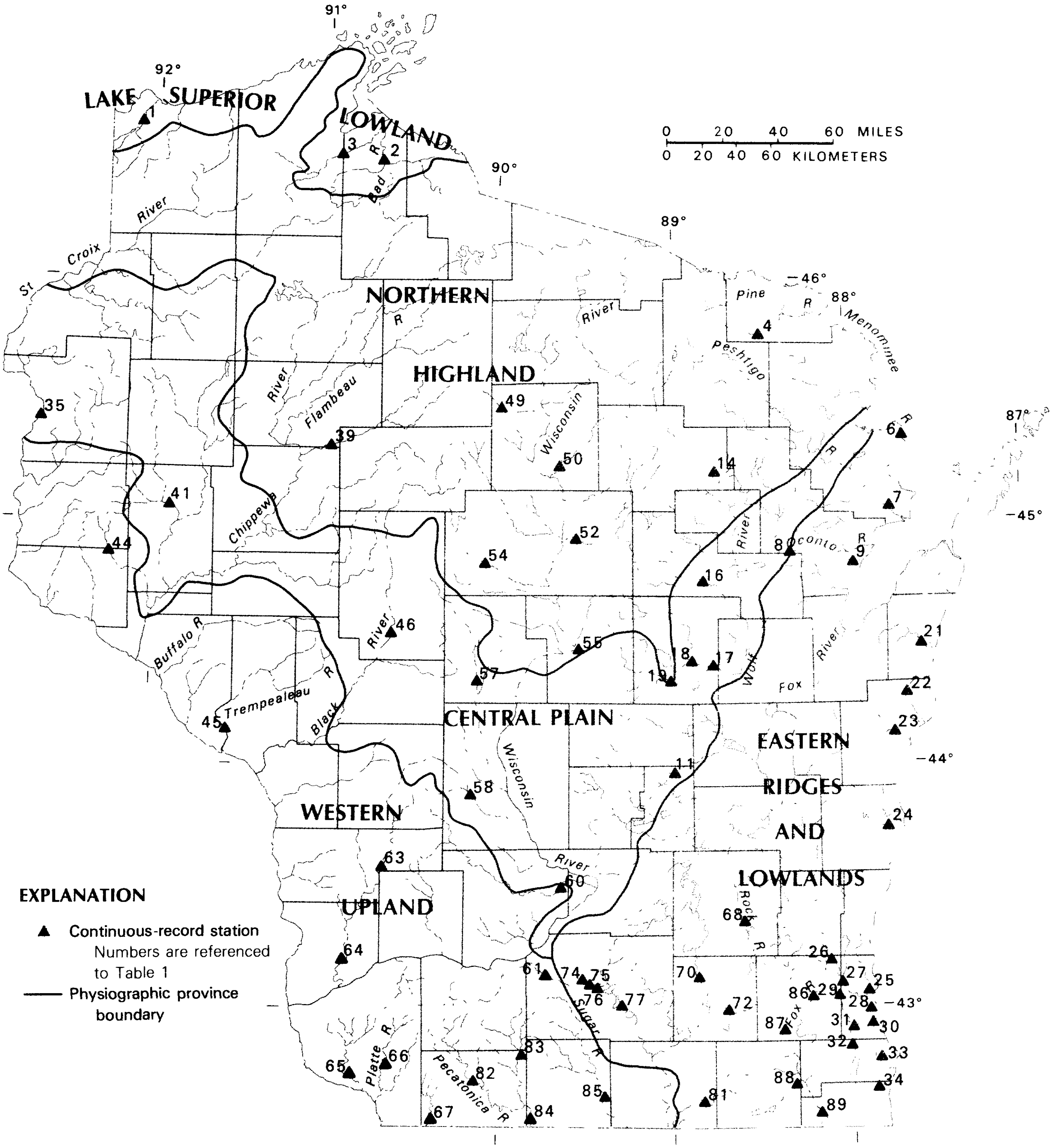

Figure 3. Location of continuous-record streamflow stations that provide information about regional hydrology.

Hydrologic Systems

Gaging stations that can be used for accounting—that is, to define current hydrologic conditions and the sources, sinks, and fluxes of water through hydrologic systems, including regulated systems—are designated as hydrologic-systems stations. Hydrologic-systems stations are useful for defining the interaction of water systems and measuring diversions and return flows. Index stations are included in the hydrologic-systems category because they account for current conditions of the hydrologic systems that they gage.

Wisconsin presently maintains 22 gaging stations where streamflow data are used for accounting purposes.

Legal Obligations

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

There are no gaging stations operated in the Wisconsin stream-gaging program to fulfill a legal responsibility.

Planning and Design

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

Seven gaging stations are maintained to provide data for the planning and design of projects. The U.S. Geological Survey is using data from the Swamp Creek gaging stations above and below Rice Lake (04074538 and 04074548) in a modeling effort to evaluate the potential effects of Exxon's proposed underground zinc, copper, and lead mine near Crandon, Wis., on the surface-water system. The Milwaukee River at Milwaukee (04087000), Menomonee River at Menomonee Falls (04087030), Menomonee River at Wauwatosa (04087120), and Kinnickinnic River at Milwaukee (04087160) gaging station data are used to evaluate the quantity and quality of the water discharged into the Milwaukee Harbor. Efforts are underway to decrease the pollutant load discharged to the harbor (Southeastern Wisconsin Regional Planning Commission, 1981). The Rock River at Indianford (05427570) gaging station data is used by the Wisconsin Department of Natural Resources to evaluate the quantity and baseline quality of the water at this site.

Project Operation

Gaging stations in this category are used to assist water managers in making operational decisions such as reservoir releases, hydropower operations, or diversions. "Project operation" generally implies that the data are routinely available to the operators on a rapid-reporting basis. For projects on large streams having less variable streamflow, data may be reported at less frequent intervals. Streamflow data are transmitted via telemetry or reported by observers who periodically visit the gaging stations.

Twenty-eight gaging stations are maintained to provide data for project operation. The Army Corps of Engineers uses data from 11 gaging stations to dictate the release of water from dams it maintains on the Mississippi and Fox Rivers. The Corps uses the data for several purposes: providing adequate depths for navigation, maintaining water levels for power generation, and aiding in flood mitigation.

The Federal Energy Regulatory Commission uses data from 11 gaging stations to make operational decisions regarding hydropower facilities located throughout the State.

Low-flow data from several gaging stations is used to determine and evaluate sewage-treatment plant operation.

Hydrologic Forecasts

Gaging stations in this category are regularly used to provide information for hydrologic forecasting. Forecasts of floods are carried out for a specific river reach, or periodic (daily, weekly, monthly, or seasonal) flow-volume forecasts are made for a specific site or region. The hydrologic-forecast use generally implies that the data are routinely available to the forecasters on a rapid-reporting basis. On large streams having less variable streamflow, data may be reported at less frequent intervals. Streamflow data may be transmitted via telemetry or reported by observers who periodically visit the gaging station.

The 31 gaging stations in the Wisconsin program included in the hydrologic forecast data-use category are used for flood forecasting. Streamflow data are used by the U.S. National Weather Service (NWS) and the U.S. Army Corps of Engineers to predict floodflows at downstream sites. Additionally, the streamflow data from some gaging stations are used to make long-range predictions of floods caused by snowmelt.

Water-Quality Monitoring

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

Nine gaging stations in Wisconsin are designated NASQAN (National Stream Quality Accounting Network) stations. NASQAN stations are part of a nation-wide network used to assess water-quality trends of significant streams. One gaging station, Popple River near Fence (04063700), is designated as a benchmark station, set up to collect baseline water-quality data from an undisturbed watershed. Several other gaging stations are national and State ambient water-quality sites. Four gaging stations are a part of the Milwaukee Harbor Project, set up to aid in the determination and evaluation of pollutant loading to the Milwaukee Harbor.

Research

Streamflow data from gaging stations in this category are used in particular research and water-investigations studies. Gaging stations operated solely for research needs usually are operated for a few years.

Currently, no streamflow data are being used by the Wisconsin District for research-type activities.

Funding

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

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

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

There are 18 sources of funding for the Wisconsin stream-gaging program. Four gaging stations are maintained solely or in part by Army Engineers Replacement (AER) funds directly allocated to the U.S. Geological Survey (Pecatonica River at Martintown, Pecatonica River at Darlington, Turtle Creek at Clinton, and the White River at Ashland). Nine gaging stations are maintained in part by funds allocated directly to the Wisconsin district from the U.S. Geological Survey headquarters. The OFA program consists of 3 Corps of Engineers Districts which fund 25 gaging stations, and the U.S. Bureau of Indian Affairs which funds 2 gaging stations. Forty-eight gaging stations are funded through the Coop program, which includes the following cooperators: Wisconsin Department of Natural Resources, Southeastern Wisconsin Regional Planning Commission, Milwaukee Metropolitan Sewerage District, Dane County Regional Planning Commission, Green Bay Metropolitan Sewerage District, Dane County Department of Public Works, Illinois Department of Transportation, and four other local entities. Other non-Federal funds are provided by three power companies in the Wisconsin stream-gaging program to operate six gaging stations.

Data Availability

Data availability refers to the method used to furnish streamflow data to the users. There are three distinct possibilities in this category. Data are furnished by direct-access telemetry for immediate use, by periodic release of provisional data, and by publication in the annual data report for Wisconsin (Holmstrom and others, 1984). Streamflow data for all 89 stations are published in the annual report; data from 15 stations are available by telemetry on a real-time basis, and data from 9 stations are released on a provisional basis.

Presentation and Summary of Data Use

Information regarding data use, funding source, and data availability is shown in table 2 and in the accompanying footnotes. An asterisk (*) or footnote in a particular data-use column indicates the streamflow data for that gaging station is used for the given data use category. Similarly, an asterisk (*) or footnote in a particular funding-source column indicates the source of funding for the appropriate gaging station.

Streamflow data collected at many gaging stations are used by several agencies for different purposes. An example is the Peshtigo River at Peshtigo, Wis. (04069500), which is funded through the Federal program. Streamflow data collected at this gaging station is used for sewage-treatment plant operation, monitoring peak flows, assessing water quality, and flood forecasting.

Table 2. Data use, station funding, and data availability for gaging stations operated in the 1984 Wisconsin surface-water program

[Asterisk (*) indicates explanation of data use or funding is given in text; footnotes are at end of table]

			Data use								Funding source					
Map index no.	Station no.	Station name	Regional hydrology	Hydrologic systems	Legal obligations	Planning and design	Project operation	Hydrologic forecasts	Water-quality monitoring	Research	Other	Federal program	OFA program	Co-op program	Other non-Federal	Frequency of data availability
1	04024430	Nemadji River near South Superior	*						1,12			*				A
2	04027000	Bad River near Odanah	*						1,7					*		A
3	04027500	White River near Ashland	*					8	1,7			16	8			A
4	04063700	Popple River near Fence	2						2			*				A
5	04066003	Menominee River below Pemene Creek near Pembine					3							*		A
6	04067500	Menominee River near McAllister		*					1			*				A
7	04069500	Peshtigo River at Peshtigo	*				*	4	5,12			*				A
8	04071000	Oconto River near Gillett	*	7					6			*		*		A,P,T
9	04071858	Pensaukee River near Pensaukee	*						6					*		A
10	04073462	White Creek near Green Lake					*		*					*		A
11	04073500	Fox River at Berlin	*				8	4	12				8			A,T
12	04074538	Swamp Creek above Rice Lake at Mole Lake				*							9			A
13	04074548	Swamp Creek below Rice Lake at Mole Lake				*								*		A
14	04074950	Wolf River at Langlade	*								10		9			A
15	04077000	Wolf River at Keshena Falls					3	4							11	A
16	04078500	Embarrass River near Embarrass	*				8	4					8			A
17	04079000	Wolf River at New London	*				8	4	12				8			A,T
18	04080000	Little Wolf River at Royalton	*				8	4					8			A,T
19	04081000	Waupaca River near Waupaca	*				8	4					8			A,T
20	04084500	Fox River near Wrightstown		*			*		1,12					*		A,P
21	04085200	Kewaunee River near Kewaunee	*						6					*		A
22	04085281	East Twin River at Mishicot	*											*		A
23	04085427	Manitowoc River at Manitowoc	*						1					*		A
24	04086000	Sheboygan River at Sheboygan	*						6,12					*		A
25	04087000	Milwaukee River at Milwaukee	*			13			1,13,19					*		A,P
26	04087030	Menomonee River at Menomonee Falls	*			13			13					*		A,P
27	04087088	Underwood Creek at Wauwatosa	*											*		A
28	04087120	Menomonee River at Wauwatosa	*	*		13			13					*		A,P
29	04087159	Kinnickinnic River at South 11th Street at Milwaukee	*	*		13			12,13					*		A,P
30	04087204	Oak Creek at South Milwaukee	*											*		A
31	04087220	Root River near Franklin	*											*		A
32	04087233	Root River Canal near Franklin	*											*		A
33	04087240	Root River at Racine	*					4	12			*				A
34	04087257	Pike River near Racine	*											*		A
35	05340500	St. Croix River at St. Croix Falls	*				*		1			*				A
36	05356000	Chippewa River at Bishops Bridge near Winter		*			3								14	A
37	05356500	Chippewa River near Bruce		*			3								14	A
38	05360500	Flambeau River near Bruce		*			3								14	A
39	05362000	Jump River at Sheldon	*	7										*		A,P
40	05365500	Chippewa River at Chippewa Falls		*			*						8			A,P
41	05368000	Hay River at Wheeler	*									*				A
42	05369000	Red Cedar River at Menomonie		*			3								14	A
43	05369500	Chippewa River at Durand		*			8	4					8			A,T

This table is continued on the following page →

Table 2. Data use, station funding, and data availability for gaging stations operated in the 1984 Wisconsin surface-water program—Continued

[Asterisk (*) indicates explanation of data use or funding is given in text; footnotes are at end of table]

			Data use								Funding source					
Map index no.	Station no.	Station name	Regional hydrology	Hydrologic systems	Legal obligations	Planning and design	Project operation	Hydrologic forecasts	Water-quality monitoring	Research	Other	Federal program	OFA program	Co-op program	Other non-Federal	Frequency of data availability
44	05370000	Eau Galle River at Spring Valley	*				8						8			A
45	05379500	Trempealeau River at Dodge	*				8	4,8					8			A,T
46	05381000	Black River at Neillsville	*					4	6					*		A
47	05382000	Black River near Galesville		*			8	8,4	1,12				8			A,T
48	05391000	Wisconsin River at Rainbow Lake near Lake Tomahawk		*			3							*		A
49	05393500	Spirit River at Spirit Falls	*				*							*		A
50	05394500	Prairie River near Merrill	*											*		A
51	05395000	Wisconsin River at Merrill		*			3	4						*		A,T
52	05397500	Eau Claire River at Kelly	*											*		A
53	05398000	Wisconsin River at Rothschild		*			3							*		A,T
54	05399500	Big Eau Pleine River near Stratford	*				3							*		A
55	05400650	Little Plover River at Plover	*											*		A
56	05400800	Wisconsin River at Wisconsin Rapids		*			3	4	12						15	A
57	05402000	Yellow River at Babcock	*											*		A
58	05403500	Lemonweir River at New Lisbon	*											*		A
59	05404000	Wisconsin River near Wisconsin Dells		*					12					*		A
60	05405000	Baraboo River near Baraboo	*					4				*				A
61	05406500	Black Earth Creek at Black Earth	*											*		A
62	05407000	Wisconsin River at Muscoda					8	4,8	1				8			A,P,T
63	05408000	Kickapoo River at LaFarge	*					4						*		A,T
64	05410500	Kickapoo River at Steuben	*				8	4,8	12				8			A,T
65	05413500	Grant River at Burton	*					8					8			A
66	05414000	Platte River near Rockville	*					8					8			A
67	05415000	Galena River at Buncombe	*					8					8			A,T
68	05424082	Rock River at Hustisford		*				8					8			A
69	05425500	Rock River at Watertown	*	*				8					8			A
70	05426000	Crawfish River at Milford	*					8					8			A
71	05426031	Rock River at Jefferson		*				8					8			A
72	05426250	Bark River near Rome	*										8			A
73	05427570	Rock River at Indianford		*		*			12					*		A
74	05427948	Pheasant Branch at Middleton	*						*					*		A
75	05427965	Spring Harbor Storm Sewer at Madison	*											*		A
76	05427970	Willow Creek at Madison	*						*					*		A
77	05429500	Yahara River near McFarland	*						6					*		A
78	05430150	Badfish Creek near Cooksville							6					*		A
79	05430175	Yahara River near Fulton							6					*		A
80	05430500	Rock River at Afton						4,8	12					*		A
81	05431486	Turtle Creek near Clinton	*									16	8			A
82	05432500	Pecatonica River at Darlington	*					4				16	8			A
83	05433000	East Branch Pecatonica River near Blanchardville	*					4					8			A
84	05434500	Pecatonica River at Martintown	*					4				16	8			A
85	05436500	Sugar River near Brodhead	*											*		A
86	05543830	Fox River at Waukesha	*						12					*		A
87	05544200	Mukwonago River at Mukwonago	*											*		A

Table 2. **Data use, station funding, and data availability for gaging stations operated in the 1984 Wisconsin surface-water program—Continued**

[Asterisk (*) indicates explanation of data use or funding is given in text; footnotes are at end of table]

			Data use								Funding source					
Map index no.	Station no.	Station name	Regional hydrology	Hydrologic systems	Legal obligations	Planning and design	Project operation	Hydrologic forecasts	Water-quality monitoring	Research	Other	Federal program	OFA program	Co-op program	Other non-Federal	Frequency of data availability
88	05545300	White River near Burlington	*											*		A
89	05546500	Fox River at Wilmot	*					4						*		A,T

[1] = NASQAN station
[2] = Benchmark station
[3] = FERC (Federal Energy Regulatory Commission)
[4] = Flood forecasting by National Weather Service
[5] = City of Peshtigo for sewage-treatment plant loading
[6] = Wisconsin Department of Natural Resources ambient water-quality site
[7] = Index station for Water Resources Review
[8] = U.S. Army Corps of Engineers
[9] = U.S. Bureau of Indian Affairs
[10] = Streamflow data provided for canoeing
[11] = Wisconsin Power and Light
[12] = National ambient monitoring station
[13] = Water-quality station for Milwaukee Harbor project for Southeastern Wisconsin Regional Planning Commission and Milwaukee Metropolitan Sewerage District
[14] = Northern States Power
[15] = Wisconsin Valley Improvement Company
[16] = Maintained solely or in part by AER funds
[17] = Record is used to determine disc^harge for Bad River at Odana (04027595), a NASQAN station
T = Direct-access telemetry for immediate use
P = Periodic release of provisional data
A = Publication in the annual data report

Conclusions Pertaining to Data Use

1. Surveys of gaging-station data use should be conducted at regular intervals of about 5 years. The following sections of this report provide information for assessing if the accuracy of instantaneous discharge at existing gaging stations is sufficient for the intended use of the data. Annual meetings between the U.S. Geological Survey and cooperators in the stream-gaging program and other activities, such as collection of water-quality samples, serve to identify the immediate stream-gaging needs of a cooperator. Information from the present evaluation, coupled with the periodic documentation of the multiple uses of streamflow data collected at a gaging station, will ensure that funds from Federal and other sources are effectively distributed. This is particularly important if the availaiblity of funds, reflected in the number of gaging stations maintained, continues to decline with time.

2. All gaging stations in the current stream-gaging program had at least one data use, thus all stations will be included for analysis in the following sections of this report.

ALTERNATIVE METHODS OF DEVELOPING STREAMFLOW INFORMATION

The objective of the second step of the stream-gaging program evaluation is to identify gaging stations where alternative techniques, such as flow-routing or statistical methods, can be used to accurately estimate daily mean streamflow in a more cost-effective manner than operating a gaging station. Those gaging stations for which flood hydrographs are required at time intervals less than a day, such as for hydrologic forecasts, water-quality monioring, and project operation, generally are not candidates for the alternative methods. However, gaging stations on the same stream, separated by a small percentage of intervening drainage and gaging stations on similar watersheds having the same physiographic and climatic characteristics may have potential for alternative methods. The accuracy of estimated streamflow at those gaging stations may be suitable because of the high correlation of streamflow at the gaging stations.

Desirable attributes of an alternative method are: (1) The method should be computer oriented and easy to apply, (2) the method should have an available interface with the U.S. Geological Survey National Water Data Storage and Retrieval System (WATSTORE) Daily Values File (Hutchinson, 1975), (3) the method should be technically sound and generally acceptable to the hydrologic community, and (4) the method should permit easy evaluation of the accuracy of the estimated streamflow. Because of time limitations, only two methods were considered—a flow-routing model and a statistical model.

Description of Flow-Routing Model

There are two classes of flow-routing models available to the hydrologist—hydrologic and hydraulic models. Hydrologic flow-routing models use the law of conservation of mass and the relation between the storage in a stream reach and the outflow from the reach. Examples of hydrologic flow-routing techniques include the Modified Puls, Muskingum, and storage-continuity methods. Hydraulic flow-routing models use the laws of conservation of mass and momentum. Examples of hydraulic flow-routing techniques are the kinematic wave and diffusion-analogy methods.

The CONROUT model (Doyle and others, 1983) was selected for the analysis because several members of the district staff were familiar with the model. CONROUT uses a unit-response convolution flow-routing technique. The convolution procedure treats a stream reach as a linear, one-dimensional system in which the downstream hydrograph is computed by multiplying the ordinates of the upstream hydrograph by a unit-response function and lagging them appropriately. There are two methods available for determining the unit-response function: storage continuity or diffusion analogy. Calibration and verification of the model are achieved using observed upstream and downstream hydrographs and estimates of tributary inflows.

The objective in calibrating the storage-continuity and diffusion-analogy flow-routing models is to determine two parameters that describe the storage-discharge relation in a given reach and the traveltime of streamflow passing through the reach. In the storage-continuity model (Sauer, 1973), a response function is derived by modifying a translation-hydrograph technique developed by Mitchell (1962) to apply to open channels. A triangular pulse (Sauer, 1973) is routed through reservoir-type storage and then transformed by a summation curve technique to a unit response of desired duration. The two parameters that describe the routing reach are K_S, a storage coefficient which is the slope of the storage-discharge relation, and W_S, the translation hydrograph time base. These two parameters determine the shape of the resulting unit-response function.

In the diffusion-analogy model (Keefer, 1974), the two parameters are K_0, a wave dispersion or damping coefficient, and C_0, the flood-wave celerity. K_0 controls the spreading of the wave (analogous to K_S in the storage-continuity model) and C_0 controls the traveltime of the flood wave. Two options are available for determining the unit (system) response function: single linearization and multiple linearization. In the single linearization model only one K_0 and C_0 value are used. In the multiple linearization model C_0 and K_0 are varied with streamflow so that tables of wave celerity (C_0) versus streamflow (Q) and dispersion coefficient (K_0) versus streamflow (Q) are used.

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

In both the storage-continuity and diffusion-analogy models, the two parameters are determined by trial and error. The analyst must decide if suitable parameters have been derived by comparing the calculated streamflow to the observed streamflow.

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

The diffusion-analogy, single unit-response function model was applied to two watersheds in Wisconsin. The application is described in a subsequent section of the report.

Description of Statistical Model

Hirsch (1982) presented a method for developing time series of streamflow at a gaging station based on correlation with streamflow at a nearby long-term base gaging station. The method, termed MOVE.1, preserves the variance of the historic record at the gaging station which is being analyzed. The method is easy to apply and provides indices of accuracy.

The estimating equation used by the MOVE.1 method to estimate daily mean streamflow in this study has the following form:

$$\hat{y}_i = m(y_1) + \frac{S(y_1)}{S(x_1)} [x_i - m(x_1)] \qquad (1)$$

where

$\hat{y}_i$ = estimated daily mean streamflow at the gaging station for which records are being extended in time period *i*,

x_i = observed daily mean streamflow at a nearby gaging station in time period *i*,

$m(y_1)$ = mean of the historic daily mean streamflows (y_i) at the dependent gaging station,

$m(x_1)$ = mean of the historic daily mean streamflows at the independent gaging station for the same period of record as the dependent gaging station,

$S(y_1)$ = standard deviation of the historic daily mean streamflows at the dependent gaging station, and

$S(x_1)$ = standard deviation of the historic daily mean streamflows at the independent gaging station.

Observed daily mean streamflows (y_i and x_i) can be retrieved from the WATSTORE Daily Values File for a designated period of time. Then P-STAT (P-STAT, Inc., 1983)[1] may be used to calculate means and standard deviations for the observations of y_i and x_i. These statistics are used in equation 1 to calculate y_i for all x_i. Comparisons of the estimated streamflow, y_i, to the observed streamflow, y_i, are made to determine the adequacy of the estimating equation.

The adequacy of the estimating equation is tested by (1) plotting the differences between $\hat{y}_i$ and y_i (estimated and observed streamflow) against the dependent variable (y_i) and independent variable (x_i), and (2) plotting the estimated and observed streamflow versus time. These tests are intended to identify (1) if the linear model (equation 1) is appropriate or whether some transformation of the discharges is needed, and (2) if there is any bias in the equation such as overestimating low flows.

The MOVE.1 model was applied to one watershed in Wisconsin and Illinois. The application of the MOVE.1 model is described in a subsequent section of the report.

Identification of Gaging Stations Suitable for Evaluating Alternative Methods

Three gaging stations were identified for which alternative methods for determining daily mean streamflow could be applied. A flow-routing model was used to calculate daily mean streamflow for two of the stations: the Rock River at Afton (05430500) and the Menominee River at McAllister (04067500). The MOVE.1 model was used to calculate daily mean streamflows at the Pecatonica River at Freeport, Ill. (05435500). This gaging station is not in the Wisconsin stream-gaging network but the analysis was done because there is a high cross-correlation (0.95) between the daily mean flows at this station and the gaging station at Martintown (05434500).

Results of Flow-Routing Modeling

CONROUT was used to simulate daily mean streamflows for the Rock River at Afton (05430500) for the entire range of streamflows observed at the gaging station. A diagram of the Rock River study area is shown in figure 4. The daily mean streamflow data for the Rock River at Indianford and the Yahara River at McFarland were used in the simulation.

The gaging station at Afton (05430500) is located 19.5 mi downstream from the gaging station at Indianford and 40.0 mi downstream from the gaging station at McFarland (05429500). The Indianford station has a drainage area of 2,630 mi^2 while the McFarland station has a drainage area of 327 mi^2. The Afton station drains 3,340 mi^2 leaving an ungaged drainage area of 383 mi^2 if the Afton gaging station is not in operation.

Daily mean streamflow at McFarland was routed to the confluence of the Yahara River and the Rock River using the diffusion analogy, single unit-response model. The daily values were added to the daily mean streamflow at Indianford and the total flow was routed to the Afton gaging station. A limited amount of data were available for the routing calibration and verification. The gaging station at McFarland has 54 years (1930-present) of continuous record but the Indianford gaging station has only 9 years (1975-present) of continuous record. The gaging station at Afton currently has 70 years (1914-present) of continuous record.

The flow routing to the Afton station was done previously by Krug and House (1984). At the time, only 4 years of continuous record were available. The simulation was extended to incorporate the remaining 5 years of data. To route the streamflow, it was necessary to determine the model parameters C_0 (flood-wave celerity) and K_0 (wave-dispersion coefficient). The previous estimates were 1.15 and 3,440 ft^3/s, respectively, for the Yahara River reach and 2.6 and 8,000 ft^3/s for the Rock River reach.

[1] Use of SAS and P-STAT in this report is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey.

Krug and House (1984) also noted that it is necessary to add a ground-water component to accurately simulate the low flows at Afton. Their estimate of this component was approximately 100 ft^3/s. Another 54 ft^3/s was also added to account for the effluent discharged to Badfish Creek basin during the years the modeling was done.

Verification of the previously calibrated model using daily mean streamflow data for water years 1980-83 indicated that the celerity and dispersion coefficients previously chosen were reasonable for both reaches. A modified drainage area correction factor of 1.75 was used to adjust the flow from the McFarland station as it was routed down to Indianford. The usual drainage area correction factor was modified based on the observed average annual discharges at the two gaging stations. No correction factor was used for the Rock River reach because a constant ground-water component was added to the flow in this reach and a correction factor caused

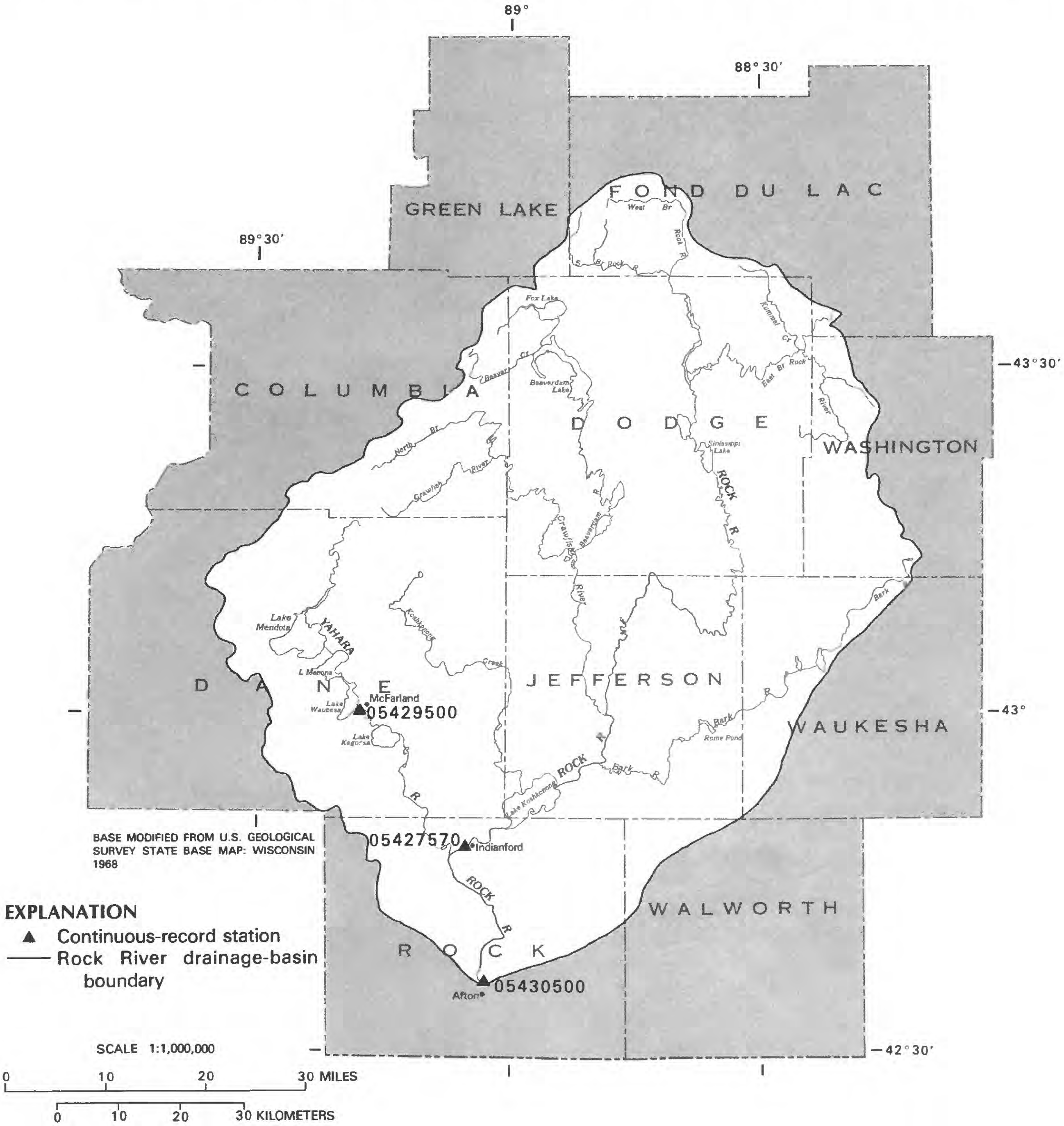

Figure 4. Rock River basin flow-routing model study area.

overestimation of the total volume of flow for the gaging station at Afton. The model parameters are summarized in table 3.

The results of the verification indicate that there is a problem in estimating the low-flow values for Afton (fig. 5). Krug and House (1984) also noted this problem in their study but they were primarily concerned with high flows. Part of the problem in calibrating for low flow undoubtedly lies in the modeling of the ground-water component. The physical layout of the study site may also be causing problems in the low-flow calibration. Two lakes, Mud Lake and Lake Kegonsa, lie along the reach between the Yahara River at McFarland gaging station and the confluence of the Rock and Yahara Rivers. There is no reason to believe the inflow and the outflow from these two lakes are equal throughout the year.

The model was verified using daily mean streamflow for the 1980-83 water years. A summary of the modeling errors is given in table 4. Only 74 percent of the simulated daily mean flows had less than 10 percent error, which is not within the range of accuracy desired for daily mean streamflow data.

As more data become available for the calibration of the model, a reduction in the error in the simulated values may be possible. It may also be worthwhile in the future to try a different flow-routing model for these reaches or attempt to better quantify the ground-water component of the flow on a seasonal basis.

CONROUT was also used to simulate daily mean streamflows for the Menominee River at McAllister (04067500). A diagram of the Menominee River study

Table 3. Selected reach characteristics used in the Rock River flow-routing model

Reach 1:

Location: Yahara River near McFarland to Yahara River at mouth

Reach length (mi): 20.5

C_o (ft/s): 1.15

K_o (ft²/s): 3,440

Reach 2:

Location: Rock River at mouth of Yahara River to Afton gaging station

Reach length (mi): 19.5

C_o (ft/s): 2.6

K_o (ft²/s): 8,000

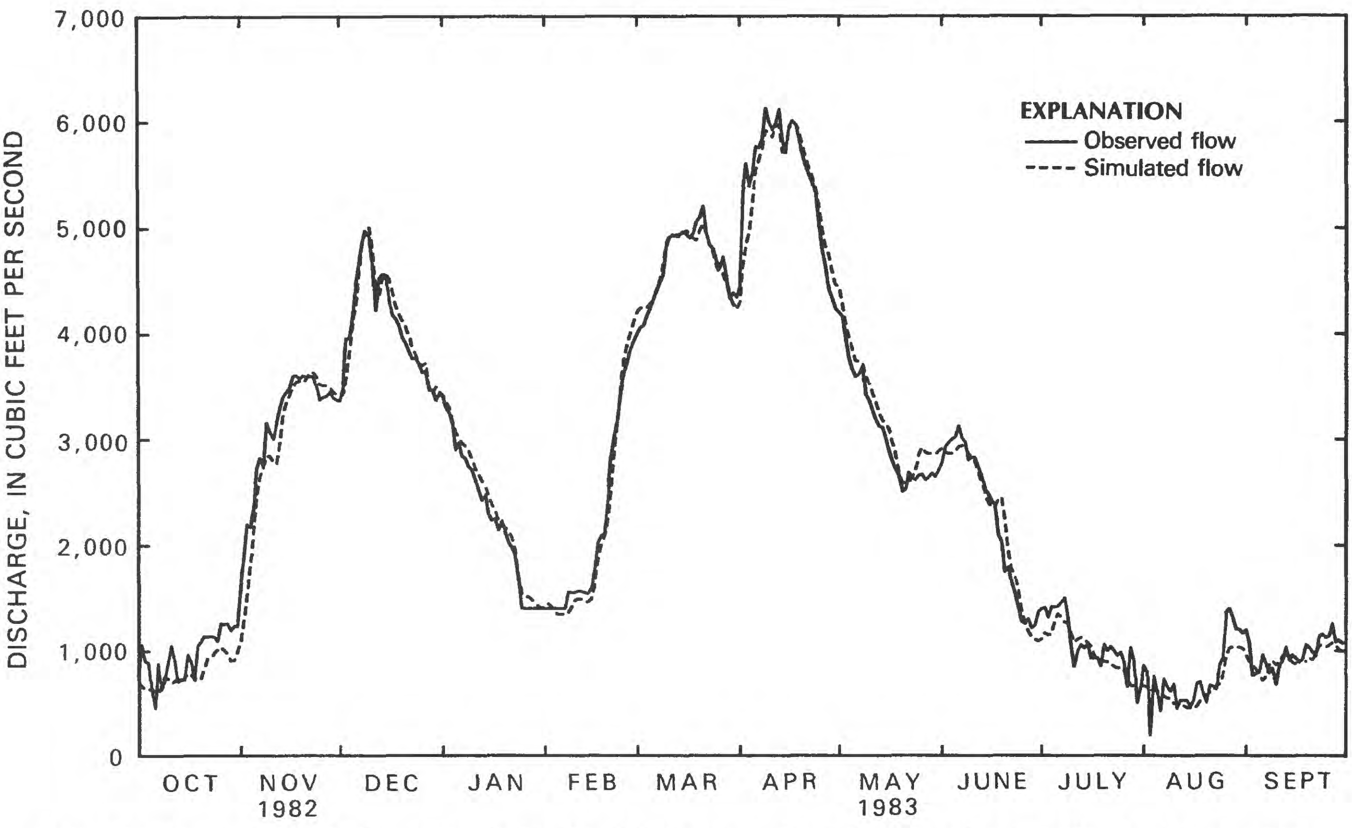

Figure 5. Comparison of observed and simulated daily mean streamflow for the Rock River at Afton, 1983 water year.

area is presented in figure 6. The daily mean streamflow data for the Menominee River at Pembine (04066003) were used in the simulation.

The gaging station at McAllister (04067500) is located 43.3 mi downstream from the Pembine station (04066003). The McAllister station currently has a drainage area of 3,930 mi². The Pembine station has a drainage area of 3,140 mi².

To route the streamflow from Pembine to McAllister, it was necessary to determine the model parameters C_0 (flood-wave celerity) and K_0 (wave-dispersion coefficient). The coefficients C_0 and K_0 are functions of channel width (W_0), in feet; channel slope (S_0), in feet per foot (ft/ft); the slope of the stage-discharge relation (dQ_0/dY_0), in square feet per second (ft²/s); and the discharge (Q_0), in cubic feet per second. The parameters are determined as follows:

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

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

The streamflow, Q_o, for which initial values of C_o and K_o were linearized was the average discharges for the Pembine and McAllister gaging stations. The channel width, W_o, is the average width in the 43.3 mi reach between Pembine and McAllister and was determined from topographic maps and discharge measurements. Channel slope, S_o, was determined by converting the gage heights corresponding to the initial streamflows, Q_o, at both gaging stations to a common datum. The difference between the values was then divided by the channel length between the gaging stations to obtain a

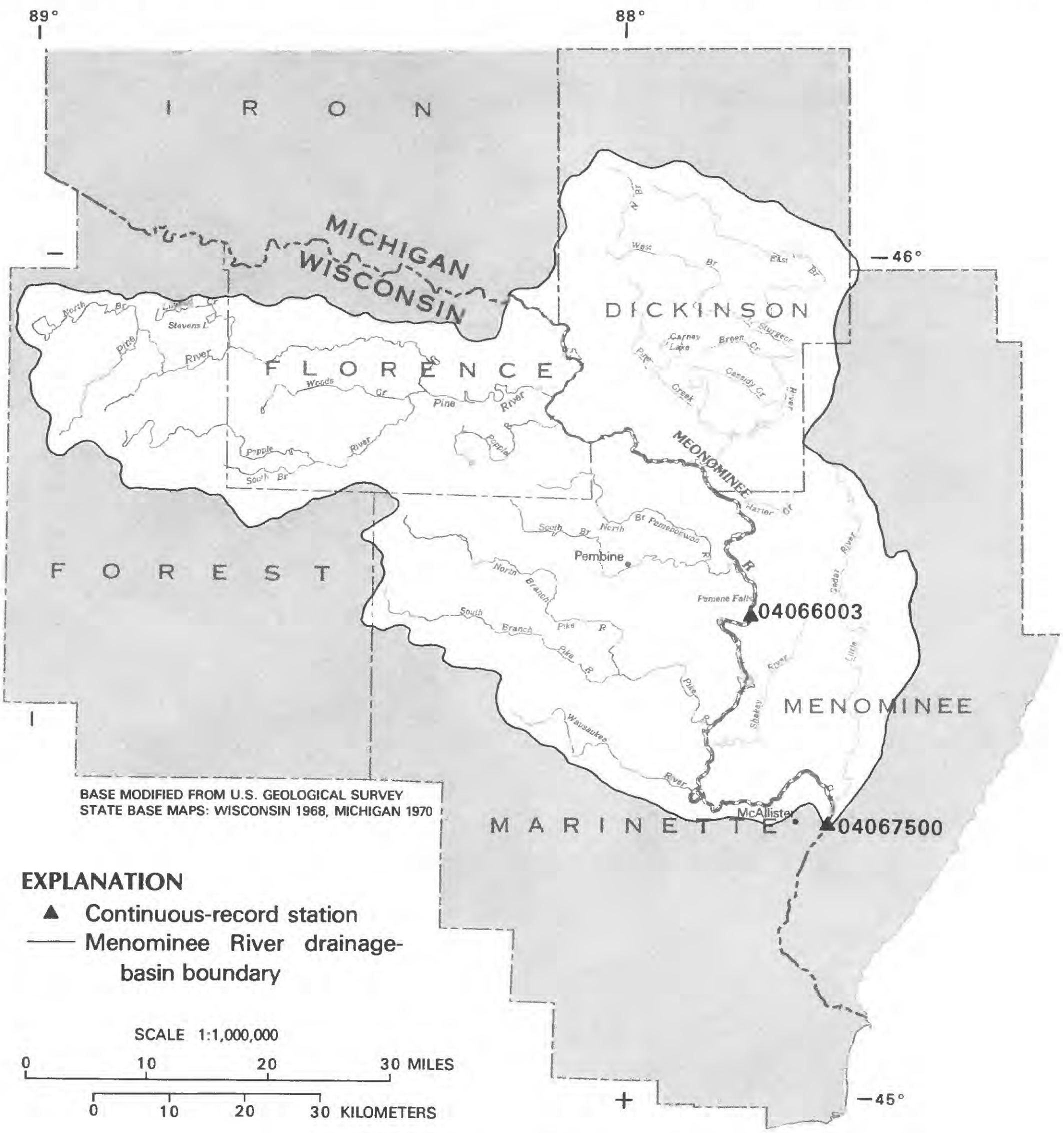

Figure 6. Menominee River basin flow-routing model study area.

slope. The slope of the stage-discharge relations, dQ_0/dY_0, was determined from the rating curves at Menominee and McAllister gaging stations and represents the mean change in discharge for a 1 ft change in gage height that brackets the initial streamflow, Q_0. The resulting estimates for C_0 and K_0 were 4.4 and 9,140 ft^3/s, respectively, as summarized in table 5.

Water years 1950 to 1961 were used to calibrate the model. The flow was routed from Pembine to McAllister with an applied correction factor of 1.18 (slightly less than the computed drainage-area ratio).

The model was verified using daily mean streamflow for the period October 1980 through July 1982. A plot of a portion of the simulated versus observed values is depicted in figure 7 and a summary of the modeling errors is given in table 6. With the exception of February and March, the model appears to reproduce the conditions at McAllister quite well. The significant underestimation in February and March may be due to inaccurate discharge records due to ice condition. Nonetheless, the resulting errors are still unacceptable. Only 65 percent of the observations had errors less than 10 percent.

Results of Statistical Modeling

The MOVE.1 method was used to simulate daily mean streamflow for the Pecatonica River at Freeport, Ill. (05435500). A diagram of the Pecatonica River study area is presented in figure 8. The mean and standard deviation of the daily mean streamflows for the calibration period (1960-74) were calculated for the dependent gaging station (Q_d) where streamflow is to be estimated and the base gaging station (Q_b) where streamflow would be used to extend the record at the dependent gaging station. The statistical parameters are shown in table 7. Discharges (Q_d) for the dependent gaging station were estimated for another period of analysis, the verification period (1974-80), using the statistical parameters and the observed streamflows at the base gaging station. Comparisons of the estimated and observed daily mean streamflow at the dependent gaging station were made using a relative traveltime between stations of 0 days and 1 day. The results are shown in tables 8 and 9.

The streamflow records for the Pecatonica River at Freeport, Ill., were not satisfactorily simulated with an acceptable degree of accuracy using the MOVE.1 method. A dam at Freeport controls the low flows and high flows at the station are affected by backwater.

Conclusions Pertaining to Alternative Methods of Data Generation

1. The Rock River at Afton gaging station (05430500) should remain in operation. The flow-routing model did

Table 4. Results of the Rock River flow-routing model analysis

Mean absolute error[1] for 1,461 days	= 8.41 percent
Mean negative error (832 days)	= -6.18 percent
Mean positive error (629 days)	= 11.36 percent
Total volume error	= -0.23 percent
45 percent of the total observations had errors	≤ 5 percent
74 percent of the total observations had errors	≤ 10 percent
86 percent of the total observations had errors	≤ 15 percent
91 percent of the total observations had errors	≤ 20 percent
93 percent of the total observations had errors	≤ 25 percent
7 percent of the total observations had errors	≥ 25 percent

[1] The error is defined as follows:

$$\text{error} = \left(\frac{Q_s - Q_o}{Q_o}\right) \times 100$$

where: Q_s is simulated daily discharge, and Q_o is observed daily discharge.

Table 5. Selected reach characteristics used in the Menominee River flow-routing model

Reach 1

Location: Pembine to McAllister gaging stations

Reach length (mi): 43.3

C_o (ft/s): 4.4

K_o (ft^2/s): 9,140

Table 6. Results of the Menominee River flow-routing model

Mean absolute error[1] for 669 days	= 9.15 percent
Mean negative error (391 days)	= -7.10 percent
Mean positive error (278 days)	= 12.02 percent
Total volume error	= -0.17 percent
39 percent of the total observations had errors	≤ 5 percent
68 percent of the total observations had errors	≤ 10 percent
84 percent of the total observations had errors	≤ 15 percent
90 percent of the total observations had errors	≤ 20 percent
94 percent of the total observations had errors	≤ 25 percent
6 percent of the total observations had errors	≥ 25 percent

[1] The error is defined as follows:

$$\text{error} = \left(\frac{Q_s - Q_o}{Q_o}\right) \times 100$$

where: Q_s is simulated daily discharge, and Q_o is observed daily discharge.

not simulate the streamflow records accurately enough to justify deactivating the gaging station. This station currently has several uses, including hydrologic forecasting and water-quality monitoring.

2. The gaging station for the Menominee River near McAllister (04067500) should remain in operation. The flow-routing model did not simulate the flows within the desired degree of accuracy. The Menominee River gaging station is currently a part of NASQAN and is used for hydrologic systems analyses.

3. The Pecatonica River gaging station at Freeport, Ill., (05435500) should remain in operation. The MOVE.1 model cannot simulate streamflow records accurately enough to justify deactivating the gaging station. Currently the gaging station has a number of uses. The station is used for regional hydrology, hydrologic forecasts, water-quality monitoring, and research (Mades and Oberg, 1984). The alternative to deactivating this gaging station would be to remove the gaging station at Martintown (05434500). This gaging station is currently used for regional hydrology and hydrologic forecasts.

At present, there is no basis for deactivating any gaging stations in lieu of an alternative method for determining daily mean streamflow. However, the U.S. Geological Survey and the agencies that cooperate in the stream-gaging program should periodically review the streamflow records of the network gaging stations to ensure that highly redundant (correlated) streamflow records are not being determined by stream gaging unless absolutely necessary. The time constraints of this project precluded application of the flow-routing and MOVE.1 models to all of the "best candidate" gaging stations based solely on hydrologic factors and data use.

COST-EFFECTIVE RESOURCE ALLOCATION

The final step of the evaluation is to determine the cost effectiveness of the current schedule for visiting gaging stations (operating strategies) in the Wisconsin stream-gaging program. Current operating strategies are compared to optimal strategies determined by a steepest-descent optimization procedure. Optimal strategies minimize the average uncertainty of instantaneous streamflow records for all of the gaging stations while satisfying various operational constraints, including budgetary considerations.

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

In a study of the cost effectiveness of a network of gaging stations operated to determine water consumption in the Lower Colorado River basin, a set of techniques called K-CERA (Kalman-Filtering for Cost-Effective Resource Allocation) was developed (Moss and Gilroy,

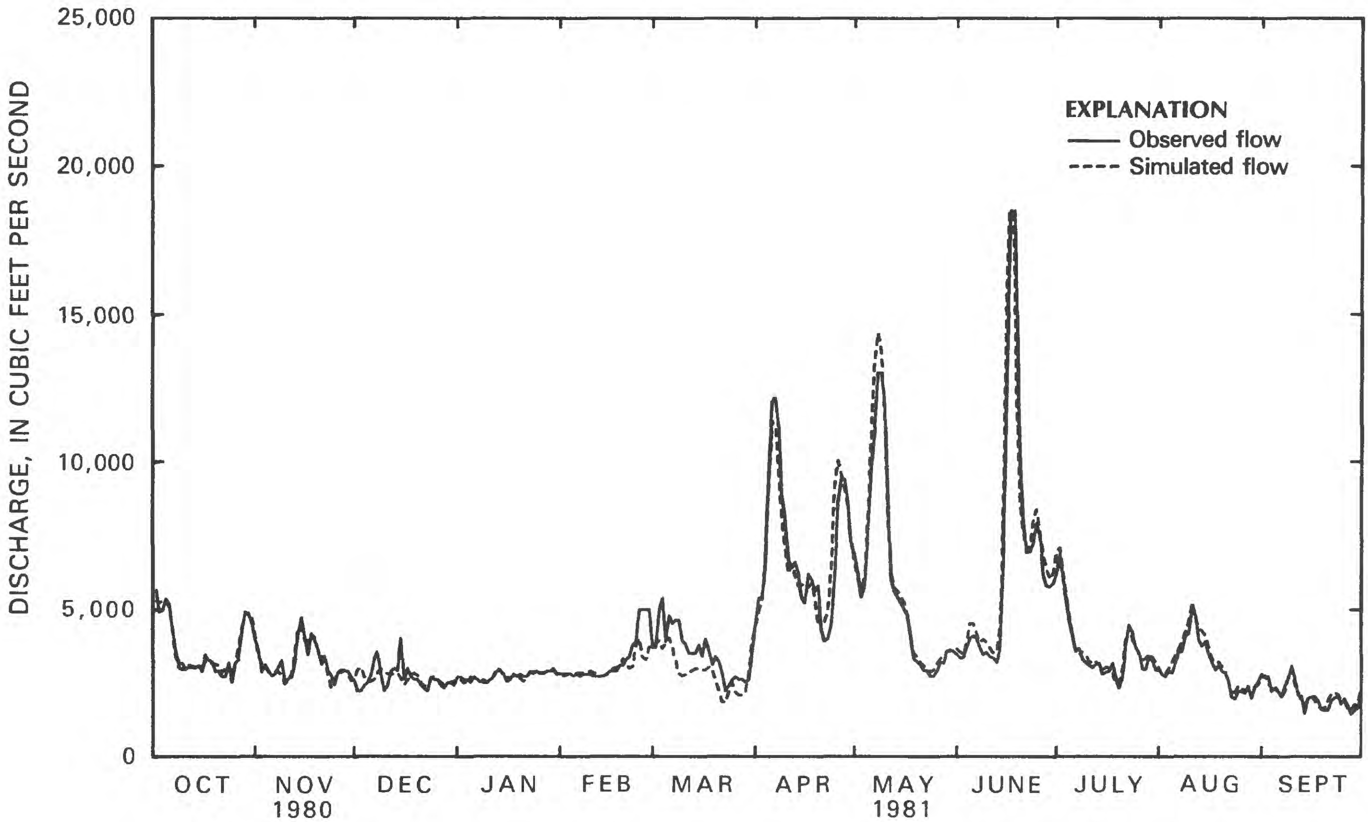

Figure 7. Comparison of observed and simulated daily mean streamflow for the Menominee River at McAllister, 1981 water year.

1980). Because of the water-balance nature of that study, the measure of effectiveness of the network was chosen to be the minimization of the sum of variances of errors for estimating annual mean discharges at each gaging station in the network. This measure of effectiveness tends to concentrate stream-gaging resources on the larger, less stable streams where potential errors are greatest. Although such a tendency is appropriate for a water-balance network, in the broader context of the multitude of uses of the streamflow data collected in the U.S. Geological Survey's streamflow-information program, this tendency causes undue concentration on larger streams.

The original version of K-CERA was extended to include, as optional measures of effectiveness, the sums of the variances of errors (uncertainties) for estimating the following streamflow variables: average discharge (mean annual flow), in cubic feet per second; average discharge, in percent; average instantaneous discharge, in cubic feet per second; or average instantaneous discharge, in percent. The use of percentage errors does not unduly weight activities at large streams to the detriment of records on small streams. In addition, instantaneous discharge is the basic variable from which all other streamflow data are derived. For these reasons, the measure of effectiveness used in this study is the sum of the variances of the percentage errors for instantaneous discharges at all gaging stations.

The original version of K-CERA did not account for errors caused by missing stage record or other correlative data used to compute streamflow records. The probabilities of missing correlative data increase as the period between service visits to a gaging station increases. A procedure for dealing with the missing stage record was developed and has been incorporated into this study.

Brief descriptions of the optimization procedure used to determine optimal strategies and of the application of Kalman filtering (Gelb, 1974) for determining the accuracy of instantaneous streamflow records are presented below. Details concerning the theory and the applications of K-CERA are discussed by Moss and Gilroy (1980), Gilroy and Moss (1981), and Fontaine and others (1984).

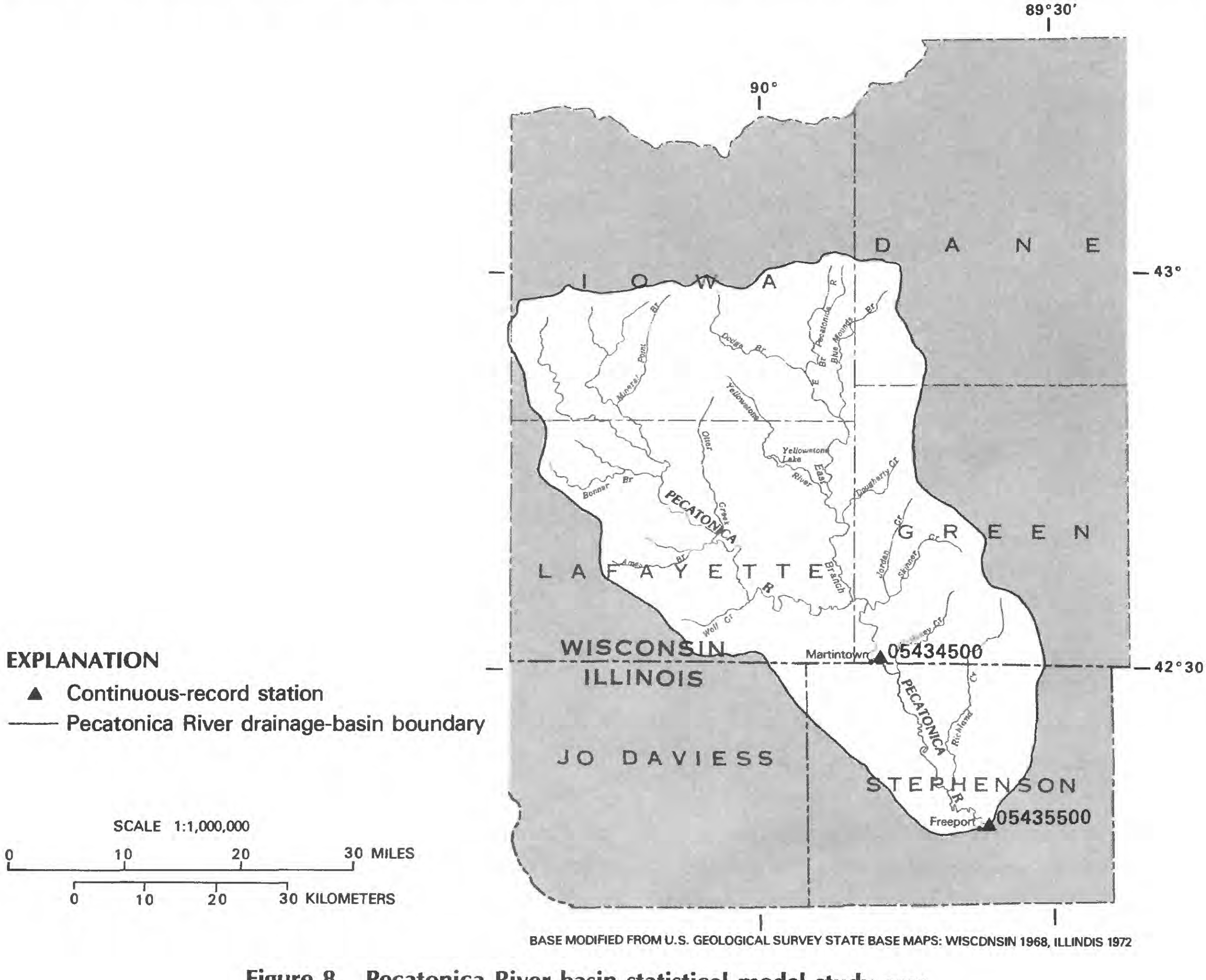

Figure 8. Pecatonica River basin statistical model study area.

Description of Mathematical Program

The optimization procedure, called the "Traveling Hydrographer Program", allocates a predefined budget for collecting streamflow among gaging stations in the most cost-effective manner. The measure of effectiveness is discussed above. The set of decision variables available to the manager is comprised of the frequency (visits/year) that each of a number of routes is used to service the gaging stations and make discharge measurements. Frequencies ranging from zero to daily usage are considered for each route. A route is defined as a set of one or more gaging stations and the least-cost travel that takes the hydrographer from the base of operations to each of the gaging stations and back to the base. Associated with a route is an average cost of travel and an average cost of servicing each gaging station along the way.

The K-CERA techniques require definition of the set of practical routes. This set of routes frequently will contain single-station routes, so that the individual needs of a station can be considered separately from other gaging stations. Mandatory activities, such as necessary periodic maintenance and rejuvenation of recording equipment, are considered by specifying a minimum number of visits for each gaging station.

A computer model is used to determine the visitation frequency for each route which minimizes total network uncertainty such that (1) the budget for the network is not exceeded, and (2) the minimum number of visits to each gaging station is made. Figure 9 shows the mathematical form of the problem to be solved.

Figure 10 shows a tabular layout of the problem. Each of the NR routes is represented by a row of the table and each of the gaging stations is represented by a column. The matrix, ω_{ij}, defines the routes in terms of the

Table 7. Summary of parameters for the MOVE.1 statistical analysis of daily mean streamflows for the Pecatonica River at Freeport, Ill.

Station number[1] and name		Model[2] $\hat{Q}_d = m(Q_d) + \frac{S(Q_d)}{S(Q_b)}(Q_b - m(Q_b))$		Calibration period	Verification period
05435500	Pecatonica River at Freeport, Ill.	$m(Q_d)=931.8$	$S(Q_d)=931.3$		
(05434500)	Pecatonica River at Martintown, Wis.	$m(Q_b)=732.8$	$S(Q_b)=859.5$	1960-74	1974-80

[1] Upper most station is dependent gaging station. Station number enclosed by parentheses is base gaging station, used to extend record at dependent gaging station.

[2] Q_d is daily mean streamflow at dependent gaging station. Caret ( ) indicates an estimated value.
Q_b is daily mean streamflow observed at base gaging station.
m ( ) denotes mean of observed streamflows.
S ( ) denotes standard deviation of observed streamflows.

Table 8. Results of the MOVE.1 statistical analysis of daily mean streamflows for the Pecatonica River at Freeport, Ill.: 0-day lag

Mean absolute error for 2,192 days	=	-12.59 percent
Mean negative error (1,541 days)	=	-21.95 percent
Mean positive error (651 days)	=	9.57 percent
Total volume error	=	-3.14 percent

24 percent of the total observations had errors ≤ 5 percent
42 percent of the total observations had errors ≤10 percent
55 percent of the total observations had errors ≤15 percent
66 percent of the total observations had errors ≤20 percent
74 percent of the total observations had errors ≤25 percent
26 percent of the total observations had errors ≥25 percent

Table 9. Results of the MOVE.1 statistical analysis of daily mean streamflows for the Pecatonica River at Freeport, Ill.: 1-day lag

Mean absolute error for 2,191 days	=	-12.53 percent
Mean negative error (1,623 days)	=	-20.51 percent
Mean positive error (568 days)	=	10.27 percent
Total volume error	=	-3.14 percent

24 percent of the total observations had errors ≤ 5 percent
44 percent of the total observations had errors ≤ 10 percent
56 percent of the total observations had errors ≤ 15 percent
66 percent of the total observations had errors ≤ 20 percent
75 percent of the total observations had errors ≤ 25 percent
25 percent of the total observations had errors ≥ 25 percent

gaging stations that comprise it. A value of one in row i and column j indicates gaging station j will be visited on route i; a value of zero indicates that it will not. The unit-travel costs, β_i, are the per-trip costs of the hydrographer's traveltime and any related per diem costs. The sum of the products of β_i and N_i (the number of times the ith route is visited) for i = 1, 2, ..., NR is the total travel cost associated with the set of decisions $\underline{N} = (N_1, N_2, \ldots, N_{NR})$.

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

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

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

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

Description of Uncertainty Functions

As noted earlier, uncertainty in streamflow records is measured in this study as the variance of the percentage error of estimation of instantaneous discharge. The accuracy of a streamflow estimate depends on how that

Figure 9. Mathematical formulation for the optimization of the routing of hydrographers.

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

V = total uncertainty in the network
$\underline{N}$ = vector of annual number times each route was used
MG = number of gages in the network
M_j = annual number of visits to station j
Φ_j = function relating number of visits to uncertainty at station j

Such that

$$F_C + \sum_{j=1}^{MG} \alpha_j M_j + \sum_{i=1}^{NR} \beta_i N_i \leq \text{Budget}$$

$$M_j \geq \lambda_j$$

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 $\underline{N}$)
λ_j = minimum number of annual visits to station j

estimate was obtained. Three situations are considered in this study: (1) Streamflow is estimated from a stage-discharge relation (rating curve) developed from measured discharge and primary correlative data such as stage, (2) the streamflow record is reconstructed using secondary data at nearby gaging stations because primary correlative data are missing, and (3) primary and secondary data are unavailable for estimating streamflow. The variances of the errors associated with these situations are weighted by the fraction of time each situation is expected to occur and combined to estimate the expected total error variance. Thus, the expected total error variance would be

$$V_T = \epsilon_f V_f + \epsilon_r V_r + \epsilon_e V_e \qquad (4)$$

with

$$\epsilon_f + \epsilon_r + \epsilon_e = 1 \qquad (5)$$

where

- V_T is the expected total error variance of the percentage errors of estimation of streamflow estimates,
- ϵ_f is the fraction of time that the primary recorders are functioning,
- V_f is the variance of the errors of streamflow records estimated from primary recorders and rating curves,
- 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 variance of the errors of streamflow records 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 variance of errors during periods of no concurrent data at nearby gaging stations.

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

$$f(\tau) = ke^{-k\tau}/(1-e^{-ks}) \qquad (6)$$

where

- k is the failure rate in units of $(\text{day})^{-1}$,
- e is the base of natural logarithms, and
- s is the interval between visits to the gaging station in days.

It is assumed that, if a recorder fails, it continues to malfunction until the next service visit. As a result, it can be shown (Fontaine and others, 1984) that

$$\epsilon_f = (1-e^{-ks})/(ks) \qquad (7)$$

The fraction of time that no records exist at either the primary or secondary gaging stations, ϵ_e, can also be derived by assuming that the times between failures at both sites are independent and have negative exponential distributions with the same failure rate. It then follows (Fontaine and others, 1984) that

$$\epsilon_e = 1 - [2(1-e^{-ks}) - 0.5(1-e^{-2ks})]/(ks) \qquad (8)$$

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

$$\epsilon_r = 1 - \epsilon_f - \epsilon_e \qquad (9)$$
$$= [(1-e^{-ks}) - 0.5(1-e^{-2ks})]/(ks).$$

The 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 natural logarithms of measured discharge and the rating curve discharge. The rating curve discharge is determined from a relation between discharge and some correlative data, such as water-surface elevation (stage) at the gaging station. The measured discharge, $q_m(t)$, is the

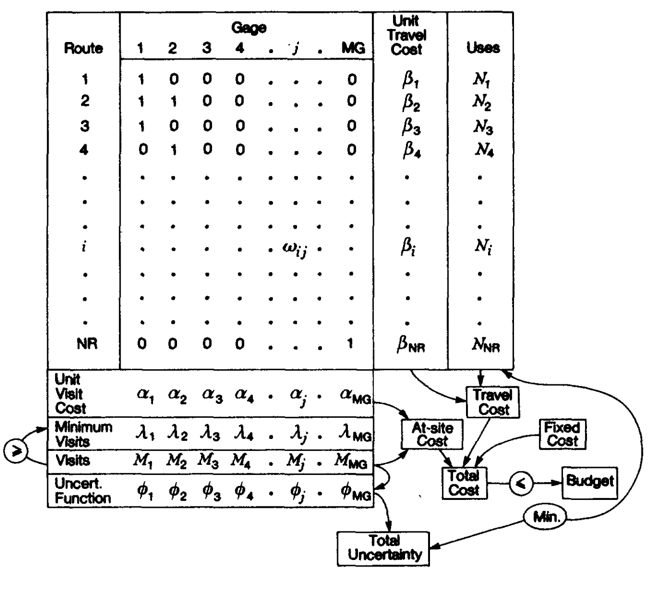

Figure 10. Mathematical formulation for the optimization of the routing of hydrographers.

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 discharge estimated using the rating curve. Then

$$x(t) = \log_e q_T(t) - \log_e q_R(t) = \log_e[q_T(t)/q_R(t)] \qquad (10)$$

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

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

$$\hat{x}(t) = \log_e q_c(t) - \log_e q_R(t), \qquad (11)$$

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

$$z(t) = x(t) + v(t) = \log_e q_m(t) - \log_e q_R(t) \qquad (12)$$

where

$v(t)$ is the measurement error, and

$\log_e q_m(t)$ is the natural logarithm of the measured discharge, equal to $\log_e q_T(t) + v(t)$.

The time series of residuals, $z(t)$, was analyzed using a Kalman filter to determine three site-specific parameters.

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

$$\mathrm{Var}[x(t)] = p = q/2\beta. \qquad (13)$$

The variance of the observed residuals $z(t)$ is

$$\mathrm{Var}[z(t)] = p + r \qquad (14)$$

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 variance of the errors of streamflow records estimated from a rating curve and primary recorder, V_f, as a function of the number of discharge measurements made at a gaging station each year (Moss and Gilroy, 1980).

If the recorder at the gaging station (primary station) fails and there are no concurrent data at other gaging stations that can be used to reconstruct the missing record at the primary station, there are at least two ways of estimating discharges at the primary station. The stage hydrograph could be extended as a recession curve from the time of recorder stoppage until the recorder 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 variance of errors during periods of no concurrent data at nearby gaging stations. The expected value used should be the expected value of discharge at the time of year when the missing record occurred because of the seasonality of streamflow. The variance of streamflow also varies seasonally and is an estimate of the error variance that results from using the expected value as an estimate of discharge. Thus, the coefficient of variation (C_v) squared is an estimate of the error variance V_e. Because C_v varies seasonally and the times of failures cannot be anticipated, a seasonally averaged C_v is used:

$$\bar{C}_v = 100 \left[\frac{1}{365} \sum_{i=1}^{365} \left(\frac{\sigma_i}{\mu_i} \right)^2 \right]^{1/2} \qquad (15)$$

where

$\bar{C}_v$ is the seasonally averaged coefficient of variation (in percent),

σ_i is the standard deviation of daily discharges for the i^{th} day of the year, μ_i is the expected value of discharge on the i^{th} day of the year, and

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

The variance of the error during periods of reconstructed streamflow records, V_r, is estimated on the basis of correlation between records at the primary station and records from other nearby gaging stations. The cross-correlation coefficient, ϱ_c, between the streamflows with seasonal trends removed (detrended) at the primary stations and detrended streamflows at the other gaging stations is a measure of the goodness of their linear relation. The fraction of the variance of streamflow at the primary station that is explained by data from the other gaging stations is equal to ϱ_c^2. The fraction of unexplained variance, attributable to the error in reconstructed records at the primary station, is $(1 - \varrho_c^2)$. The relative variance of the errors of streamflow records reconstructed from secondary data is

$$V_r = (1 - \varrho_c^2)\overline{C}_v^2. \qquad (16)$$

Sometimes the record for a gaging station can be reconstructed by correlation with more than one nearby gaging station. For the fraction of time when no secondary data are available from the gaging station typically used (secondary station) for record reconstruction (ϵ_e), data from another (tertiary) gaging station can be used. The correlation of data from the tertiary station with data from the station of interest is denoted R_2. the value of R_2 is always less than or equal to ϱ_c. The error variance of records estimated from a tertiary source of information is

$$(1 - R_2^2)\ (\overline{C}_v)^2 = (1 - R_2^2)\ V_e. \qquad (17)$$

Because errors in streamflow estimates arise from three different sources with widely varying precisions, the resultant distributions of those errors may differ significantly from a normal or log-normal distribution. This lack of normality causes difficulty in interpreting the expected total error variance. When data are unavailable, the error variance V_e may be very large. This could yield correspondingly large values of V_T in equation 4 even if the probability that auxiliary correlative data are not available, ϵ_e, is quite small.

A new statistic, the equivalent Gaussian spread (EGS), is introduced here to asssist in interpreting the results of the analyses. If it is assumed that the various errors arising from the three situations represented in equation 4 are log-normally disturbed, the value of EGS is determined by the probability statement that

$$\text{Probability}\ [10^{-EGS} \leq q_c(t)/q_T(t) \leq 10^{+EGS}] = 0.683 \qquad (18)$$

Thus, if the residuals, $\log q_c(t) - \log q_T(t)$, were normally distributed, $(EGS)^2$ would be their variance. The 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.

Application of K-CEREA

As a result of the first two steps of the stream-gaging program evaluation, it was determined that all of the gaging stations in the Wisconsin stream-gaging program should continue to be operated. These gaging stations were studied using the K-CERA techniques, with results that are described below.

Missing Record

As was described earlier, the statistical characteristics of missing stage records or other correlative data for computing streamflow records can be defined by a single parameter, the value of k in the truncated, negative-exponential probability distribution of times to failure for the equipment at a gaging station. In the representation of $f(\tau)$ as given in equation 6, the average time to failure is 1/k. The value of 1/k varies from station to station depending upon the type of equipment at the station and upon its exposure to natural elements and vandalism. The value of 1/k can be changed by advances in the technology of data collection and recording.

A 5- to 15-year period of data collection during which little change in technology occurred was used to estimate values of 1/k in Wisconsin. During the 5- to 15-year period, the equipment at gaging stations malfunctioned between 1 and 30 percent of the time, with a median of 5 percent. The stations were visited at frequencies ranging from 4 to 14 times per year, with a median frequency of 8 visits per year. The resulting values of 1/k ranged from 60 to 4,500 days, with a median value of 390 days.

The most common causes of missing stage record were malfunctioning timing devices and dead batteries, accounting for 39 percent of the missing record. Manometer and float problems, malfunctioning recorders, and frozen or clogged orifice lines resulted in 12, 10, and 5 percent of the missing record, respectively. Unspecified problems accounted for 34 percent of the missing record.

Cross-Correlation Coefficients and Coefficients of Variation

Daily streamflow records for 73 stations having 5 or more years of data were analyzed to compute the values of V_e and V_r. As many as 20 years of daily streamflow records for each gaging station, back to water year 1962, were retrieved from WATSTORE (Hutchinson, 1975) and used to compute the seasonally averaged coefficient of variation $(\overline{C}_v)$ for each station. Various options, based on combinations of other gaging stations, were explored to determine the maximum ϱ_c.

Parameters for each gaging station and the auxiliary sources of hydrographic records that gave the highest cross-correlation coefficients are listed in table 10. The seasonally averaged coefficient of variation ranged from 32 percent for Badfish Creek near Cooksville (05430150) to 229 percent for the Big Eau Pleine River near Stratford (05399500). Approximately 25 percent of the gaging

Table 10. Statistics of record reconstruction at gaging stations in Wisconsin

Station no.	Station name	Missing record (percent)	Visits per year	C_V[1]	ϱ[2]	Source for reconstructing record	Ice-free period (days)
04024430	Nemadji River near South Superior	17	7	1.02	.61	04024000	220
04027000	Bad River near Odanah	5	6	1.08	.72	04027500	220
04027500	White River near Ashland	5	8	.58	.72	04027000	220
04063700	Popple River near Fence	6	8	.70	.74	04061000	220
04066003	Menominee River below Pemene Creek near Pembine	22	5	.47	.61	04065397	220
04069500	Peshtigo River at Peshtigo	11	5	.59	.62	04071858	220
04071000	Oconto River near Gillett	5	7	.49	.84	04077000	220
04071858	Pensaukee River near Pensaukee	11	8	1.29	.62	04069500	220
04073500	Fox River at Berlin	8	7	.53	.76	04079000	250
04074950	Wolf River at Langlade	3	7	.46	.77	04077000	220
04077000	Wolf River at Keshena Falls near Keshena	15	8	.39	.84	04079000	220
04078500	Embarrass River near Embarrass	3	8	.84	.80	04079000	250
04079000	Wolf River at New London	4	7	.55	.81	04077000	250
04085200	Kewaunee River near Kewaunee	13	8	1.30	.83	04085281	250
04085281	East Twin River at Mishicot	12	8	1.08	.83	04085200	250
04085427	Manitowoc River at Manitowoc	4	7	.97	.74	04085281	250
25086000	Sheboygan River at Sheboygan	5	8	1.20	.52	04085845	250
04087000	Milwaukee River at Milwaukee	4	8	1.10	.74	04087120	280
04087030	Menomonee River at Menomonee Falls	4	10	.98	.70	04087120	280
04087088	Underwood Creek at Wauwatosa	7	8	.99	.70	04087220	280
04087120	Menomonee River at Wauwatosa	5	12	1.52	.79	04087220	280
04087204	Oak Creek at South Milwaukee	9	12	1.69	.88	04087220	280
04087220	Root River near Franklin	8	10	1.57	.88	04087233	280
04087233	Root River Canal near Franklin	3	10	1.69	.91	04087240	280
04087240	Root River at Racine	4	10	1.52	.79	04087220	280
04087257	Pike River near Racine	10	9	1.28	.79	04087240	280
05340500	St. Croix River at St. Croix Falls	13	4	.70	.81	05344500	220
05356000	Chippewa River at Bishops Bridge near Winter	1	4	.86	.71	05356500	220
05356500	Chippewa River near Bruce	3	6	.74	.88	05360500	220
05360500	Flambeau River near Bruce	5	6	.61	.88	05362000	220
05362000	Jump River at Sheldon	7	8	1.40	.88	05360500	220
05365500	Chippewa River at Chippewa Falls	7	4	.77	.94	05356500	250
05368000	Hay River at Wheeler	5	10	.75	.82	05369000	250
05369000	Red Cedar River at Menomonie	7	5	.58	.82	05369500	250
05369500	Chippewa River at Durand	8	10	.63	.94	05365500	250
05370000	Eau Galle River at Spring Valley	7	4	1.64	.64	05368000	250
05379500	Trempealeau River at Dodge	8	8	.75	.75	05385000	250
05381000	Black River at Neillsville	8	7	1.73	.87	05382000	250
05382000	Black River near Galesville	6	9	1.07	.87	05385000	250
05393500	Spirit River at Spirit Falls	1	8	1.42	.72	05395000	220
05394500	Prairie River near Merrill	5	8	.73	.75	05395000	220
05397500	Eau Claire River at Kelly	6	9	1.06	.82	05398000	250
05398000	Wisconsin River at Rothschild	3	4	.68	.82	05397500	250
05399500	Big Eau Pleine River near Stratford	4	8	2.29	.72	05397500	250
05400650	Little Plover River at Plover	9	8	.36	.52	05400760	250
05402000	Yellow River at Babcock	10	8	1.98	.77	05381000	250
05403500	Lemonweir River at New Lisbon	0	8	1.03	.76	05404000	250
05404000	Wisconsin River near Wisconsin Dells	12	7	.61	.76	05405000	250
05405000	Baraboo River near Baraboo	30	8	.97	.75	05407000	250

This table is continued on the following page →

Table 10. Statistics of record reconstruction at gaging stations in Wisconsin—Continued

Station no.	Station name	Missing record (percent)	Visits per year	C_V[1]	ϱ[2]	Source for reconstructing record	Ice-free period (days)
05406500	Black Earth Creek at Black Earth	2	8	.64	.75	05436500	280
05407000	Wisconsin River at Muscoda	3	8	.53	.63	05410500	280
05408000	Kickapoo River at LaFarge	1	8	.92	.81	05410500	250
05410500	Kickapoo River at Steuben	2	9	.62	.81	05389500	280
05413500	Grant River at Burton	8	12	1.13	.88	05414000	280
05414000	Platte River near Rockville	4	14	1.08	.88	05413500	280
05415000	Galena River at Buncombe	4	10	1.29	.77	05418200	280
05424082	Rock River at Hustisford	6	8	.88	.73	05426031	280
05425500	Rock River at Watertown	3	12	1.18	.87	05427570	280
05426000	Crawfish River at Milford	5	12	1.20	.84	05427570	280
05426031	Rock River at Jefferson	12	8	.67	.89	05427570	280
05426250	Bark River near Rome	7	9	.47	.73	05426031	280
05427570	Rock River at Indianford	3	6	.73	.92	05430500	280
05427948	Pheasant Branch at Middleton	3	12	1.12	.47	05427965	280
05429500	Yahara River near McFarland	4	12	.68	.35	05430150	280
05430150	Badfish Creek near Cooksville	5	10	.32	.91	05430175	280
05430175	Yahara River near Fulton	3	7	.49	.64	05430500	280
05430500	Rock River at Afton	5	7	.74	.92	05437500	280
05432500	Pecatonica River at Darlington	2	11	1.19	.92	05433000	280
05433000	East Branch Pecatonica River near Blanchardville	5	9	.94	.92	05434500	280
05434500	Pecatonica River at Martintown	2	8	.94	.95	05435500	280
05436500	Sugar River near Brodhead	2	8	.80	.78	05437500	280
05543830	Fox River at Waukesha	5	8	1.07	.60	05544200	280
05544200	Mukwonago River at Mukwonago	15	10	.57	.66	05545300	280

[1] Seasonally-averaged coefficient of variation, expressed as a fraction.

[2] ϱ is the correlation between hydrographic records, with seasonal trends removed, at the station of interest and a secondary source used for record reconstruction.

stations have a $\overline{C}_V$ greater than 118 percent, and roughly 25 percent of the gaging stations have a $\overline{C}_V$ less than 63 percent. The median seasonally averaged coefficient of variation is 92 percent.

Missing streamflow records at the 73 gaging stations are reconstructed from hydrographic records at nearby gaging stations. The cross-correlation coefficient for daily mean streamflows at those stations ranges from 0.35 at the Yahara River near McFarland to 0.95 at the Pecatonica River at Martintown. Roughly 25 percent of the gaging stations have a value of ϱ_c greater than 0.84, and approximately 25 percent of the ϱ_c values are less than 0.73. The median ϱ_c is 0.79.

Kalman-Filter Definition of Variance

The error variance V_f for each gaging station was determined from a 3-step procedure: (1) Long-term rating analysis and computation of residuals of measured discharges from the long-term rating, (2) time-series analysis of the residuals to determine the input parameters of the Kalman-filter streamflow records, and (3) computation of the relative variance V_f as a function of the time-series parameters, the discharge-measurement error variance, and the frequency of measuring discharge.

The standard errors of estimate given in the report are those that would occur if daily discharges were computed through the use of methods described in this study. Because this is not the procedure used to compute daily discharge the standard error as stated in this report is different than the error associated with daily discharges that have been published. The magnitude and direction of the differences would be a function of methods used to account for shifting controls and for estimating discharges during periods of missing record. In Wisconsin the normal practice is to make periodic shift adjustments, thus it is likely that the standard error of published discharge records is lower than the standard errors stated in this report.

The rating functions determined for the gaging stations have the form

$$LQM = B1 + B3 \times LOG(GHT - B2) \quad (19)$$

where

LQM is the natural logarithm of measured discharge,
GHT is the gage height observed during the discharge measurement,
*B*1 is the natural logarithm of discharge for an effective flow depth of 1 foot (when $GHT - B2 = 1.0$),
*B*2 is the effective gage height of zero flow,
*B*3 is the slope of the discharge versus gage-height relation plotted on logarithmic paper, and
LOG is the natural logarithm function.

Between 28 and 171 pairs of discharge and corresponding gage height from recent discharge measurements at the 73 gaging stations were analyzed using a nonlinear optimization algorithm (PROC NLIN) available with SAS (Statistical Analysis System, SAS Institute, 1982). The measurements are representative of present (1983) stream-channel conditions. Measurements significantly affected by ice cover were omitted from analysis. PROC NLIN computes values for *B*1, *B*2, and *B*3 that minimize the sum of the squared difference between the estimated LQM's and natural logarithms of observed discharges.

At many gaging stations, the stage-discharge rating function is segmented; it can be plotted as a number of straight-line segments on logarithmic paper for different values of *B*2. All rating functions were segmented to remove any interdependency between residuals and gage height. Many of the rating functions consist of two or three sets of *B*1, *B*2, and *B*3 that are appropriate within prescribed ranges of gage height.

The relation for the residual calculated for each measurement as a function of time, in days, is referred to as a time series of residuals. This time series was used to compute sample estimates of q and β(equation 13), two of the three parameters required to compute V_f. This was accomplished by determining a best-fit autocovariance function to the time series of residuals. Measurement error variance, the third parameter, is assumed to be a constant 3 percent standard error.

The process variance of the residuals is a function of q and β, and the 1-day autocorrelation coefficient (RHO) is a function of β. Table 11 presents a summary of the autocorrelation analyses expressed in terms of process variance and 1-day autocorrelation.

The autocovariance parameters, summarized in table 11, and statistics for reconstructing missing record, summarized in table 10, are used jointly to define an uncertainty function for each gaging station. The uncertainty function gives the relation of expected total error variance to the number of visits and discharge measurements. Three uncertainty functions are shown in figure 11. The functions are based on the assumption that a measurement was made during each visit to the gaging station.

Stream-Gaging Routes and Costs

In Wisconsin, feasible routes to service the 89 gaging stations were determined after consulting with U.S. Geological Survey personnel located in field offices in Madison, Merrill, Rice Lake, and the old field office in Wales, and after reviewing the uncertainty functions. A total of 94 routes were selected to service all of the gaging stations in Wisconsin. These routes included all possible combinations that describe the current operating practice, alternatives that were under consideration as future possibilities, routes that visited certain individual gaging stations, and combinations that grouped proximate stations where the levels of uncertainty indicated more frequent visits might be useful. These routes and the stations visited on each route are summarized in table 12. A negative station number identifies a "dummy" station. Dummy stations, such as crest-stage partial-record stations and stations where ratings are maintained for water-quality sampling, are routinely visited but do not have uncertainty functions. In addition, there were 16 dummy stations in situations where there was not enough information to generate uncertainty functions. Station names and numbers, and principal types of data collected for the 81 dummy stations included in this study are listed in table 13.

The costs, in 1984 dollars, associated with stream gaging were then determined. The costs are categorized as annual fixed, visit, and route costs. Annual fixed costs to operate a gage typically include equipment rental, batteries, electricity, data processing and storage, computer charges, maintenance and miscellaneous supplies, and analysis and supervisory charges. Costs of analysis and supervision are a large percentage of the fixed cost of a gaging station. These costs were determined by estimating, on a station-by-station basis from past experience, the time spent performing such activities. That time was then multiplied by the average hourly salary of hydrographers in each field office and added to all other fixed station costs.

Visit costs are associated with the salary of the hydrographer for the time actually spent at a gaging station making a discharge measurement during a visit. These costs differ from station to station and are a function of the difficulty and time required to make the discharge measurement. Average visit times were estimated for each station based on the field-office personnel's past experience. This time was then multiplied by the average hourly salary of hydrographers in each field office to determine total visit costs.

Table 11. Uncertainty function autocovariance parameters for gaging stations in Wisconsin

Station no.	Station name	Number of measurements analyzed	RHO	Process variance (log base e)²
04024430	Nemadji River near South Superior	50	0.988	0.02748
04027000	Bad River near Odanah	110	.975	.00860
04027500	White River near Ashland	140	.959	.01546
04063700	Popple River near Fence	128	.973	.00505
04066003	Menominee River below Pemene Creek near Pembine	45	.968	.00041
04069500	Peshtigo River at Peshtigo	167	.978	.01485
04071000	Oconto River near Gillett	80	.629	.00014
04071858	Pensaukee River near Pensaukee	65	.980	.05624
04073500	Fox River at Berlin	117	.936	.00520
04074950	Wolf River at Langlade	73	.996	.02271
04077000	Wolf River at Keshena Falls near Keshena	104	.980	.00216
04078500	Embarrass River near Embarrass	129	.978	.00289
04079000	Wolf River at New London	117	.963	.00240
04085200	Kewaunee River near Kewaunee	73	.986	.05182
04085281	East Twin River at Mishicot	76	.984	.02648
04085427	Manitowoc River at Manitowoc	66	.967	.00768
04086000	Sheboygan River at Sheboygan	84	.990	.00803
04087000	Milwaukee River at Milwaukee	97	.974	.02730
04087030	Menomonee River at Menomonee Falls	66	.975	.03947
04087088	Underwood Creek at Wauwatosa	40	.952	.08560
04087120	Menomonee River at Wauwatosa	70	.991	.05066
04087204	Oak Creek at South Milwaukee	122	.981	.10460
04087220	Root River near Franklin	114	.934	.03020
04087233	Root River Canal near Franklin	124	.995	.25150
04087240	Root River at Racine	106	.980	.02884
04087257	Pike River near Racine	92	.983	.05308
05340500	St. Croix River at St. Croix Falls	74	.706	.00654
05356000	Chippewa River at Bishops Bridge near Winter	103	.986	.00474
05356500	Chippewa River near Bruce	130	.969	.00852
05360500	Flambeau River near Bruce	68	.961	.00545
05362000	Jump River at Sheldon	131	.989	.05277
05365500	Chippewa River at Chippewa Falls	147	.979	.00875
05368000	Hay River at Wheeler	133	.995	.02478
05369000	Red Cedar River at Menomonie	123	.985	.00871
05369500	Chippewa River at Durand	171	.993	.00677
05370000	Eau Galle River at Spring Valley	64	.985	.01570
05379500	Trempealeau River at Dodge	120	.992	.02577
05381000	Black River at Neillsville	107	.638	.02795
05382000	Black River near Galesville	115	.985	.05666
05393500	Spirit River at Spirit Falls	115	.856	.00826
05394500	Prairie River near Merrill	97	.956	.03260
05397500	Eau Claire River at Kelly	116	.996	.01373
05398000	Wisconsin River at Rothschild	130	.968	.00440
05399500	Big Eau Pleine River near Stratford	129	.950	.02582
05400650	Little Plover River at Plover	137	.950	.00245
05402000	Yellow River at Babcock	143	.988	.17520
05403500	Lemonweir River at New Lisbon	100	.641	.00694
05404000	Wisconsin River near Wisconsin Dells	141	.996	.00182
05405000	Baraboo River near Baraboo	102	.979	.00397

Table 11. Uncertainty function autocovariance parameters for gaging stations in Wisconsin—Continued

Station no.	Station name	Number of measurements analyzed	RHO	Process variance (log base e)²
05406500	Black Earth Creek at Black Earth	137	.989	.04426
05407000	Wisconsin River at Muscoda	94	.992	.00576
05408000	Kickapoo River at LaFarge	94	.994	.01817
05410500	Kickapoo River at Steuben	106	.991	.01430
05413500	Grant River at Burton	128	.992	.01445
05414000	Platte River near Rockville	126	.996	.06012
05415000	Galena River at Buncombe	80	.996	.03261
05424082	Rock River at Hustisford	39	.754	.01344
05425500	Rock River at Watertown	69	.972	.08139
05426000	Crawfish River at Milford	98	.946	.00270
05426031	Rock River at Jefferson	60	.797	.01486
05426250	Bark River near Rome	33	.990	.01529
05427570	Rock River at Indianford	65	.982	.24360
05427948	Pheasant Branch at Middleton	28	.954	.08411
05429500	Yahara River near McFarland	134	.992	.26510
05430150	Badfish Creek near Cooksville	129	.975	.01901
05430175	Yahara River near Fulton	34	.972	.00165
05430500	Rock River at Afton	127	.937	.00398
05432500	Pecatonica River at Darlington	109	.979	.00798
05433000	East Branch Pecatonica River near Blanchardville	122	.984	.01901
05434500	Pecatonica River at Martintown	131	.979	.01318
05436500	Sugar River near Brodhead	129	.975	.01055
05543830	Fox River at Waukesha	105	.972	.02526
05544200	Mukwonago River at Mukwonago	60	.986	.01031

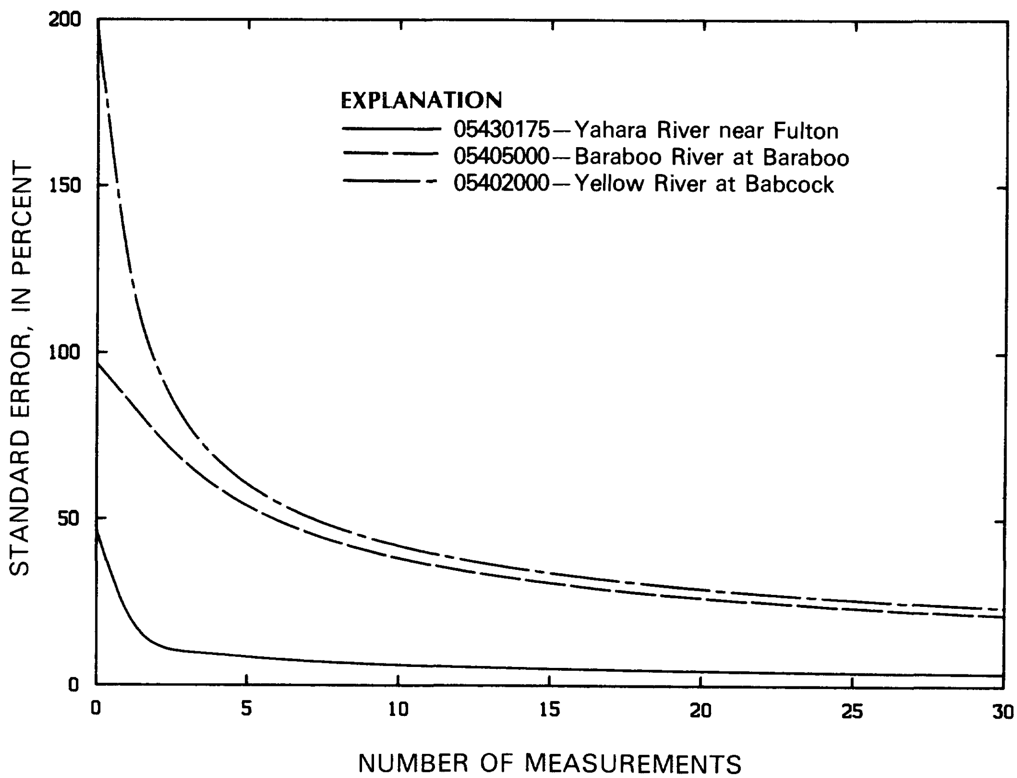

Figure 11. Uncertainty functions for three gaging stations in Wisconsin.

Table 12. Summary of routes used to visit stations in Wisconsin

[Negative station numbers correspond to dummy stations described in table 13]

Route no.	Stations serviced on the route							
1	-77770010	05410500	05413500	05414000	-88880010	05415000		
2	-88880010							
3	05410500	05413500	05414000	05415000				
4	-77770020	05436500	-05434510	05434500	-88880020			
5	-05434510							
6	-88880020							
7	05436500	05434500						
8	05433000	-77770030	05432500	-88880030				
9	-88880030							
10	05433000	05432500						
11	05429500	-99990010	-05431486	-99990030	05430500	05427570	05430175	05430150
	-77770040							
12	-99990010							
13	05429500	05430500	05427570	05430175	05430150			
14	-99990010	05429500	-99990020	05427570	05430150			
15	05429500	05427570	05430150					
16	-99990020							
17	-05431486	-77770270	05430500					
18	05430500							
19	05427570	05430175	05430150					
20	-99990010	05429500						
21	05429500							
22	-77770050	-05406464	-05406470	-05406460	-05406491			
23	-05406464	-05406470	-05406460	-05406491				
24	-05406490	-77770060	05406500					
25	-05406490							
26	05406500							
27	-77770070	-04072490	05405000	-88880040				
28	-04027490							
29	-88880040							
30	05405000							
31	05404000	-77770080	05403500					
32	05404000	05403500						
33	05408000	-77770090	-88880050					
34	-88880050							
35	05408000							
36	05407000							
37	-77770100	-05425912	-04084038	-43471908				
38	-05425912	-04084038	-04347191					
39	04073500	-04073462						
40	04073500							
41	-99990040	-05427965	05427948					
42	05427948							
43	-77770110	05426031	05426000					
44	05426031	05426000						
45	05424082	05425500						
46	05426250	05544200	-77770120	-05546500	-88880060	04087257	04087240	04087233
	04087220	04087204	-04087159	04087120	04087088	04087030	05543830	
47	-05546500	-88880060	-04087159					
48	05426250	05544200	04087257	04087240	04087233	04087220	04087204	04087120
	04087088	04087030	05543830					

Table 12. Summary of routes used to visit stations in Wisconsin—Continued

[Negative station numbers correspond to dummy stations described in table 13]

Route no.	Stations serviced on the route							
49	04087257	04087220	04087204	04087088				
50	04087000	-04086600	-04086500	-77770130	04086000	-88880070	04085427	04085281
	04085200	-04085000	-99990050					
51	-04086600	-04086500	-88880070	-04085000	-99990050			
52	04087000	04086000	04085427	04085281	04085200			
53	-77770140	04078500	04077000	04071000	04069500	04071858	-04071500	04079000
54	-04071500							
55	04078500	04077000	04071000	04069500	04071858	04079000		
56	04071858							
57	-88880080	-77770150	05399500					
58	-88880080							
59	05399500							
60	-77770160	-04081000	-04080000	05400650	-88880090	-05400760	05402000	
61	-04081000	-04080000	-05400760					
62	-88880090							
63	05400650	05402000						
64	05402000							
65	-77770170	-04074548	-04074538	-88880100	04063700	04066000	-04067500	
66	-04074548	-04074538	-88880100	-04067500				
67	04063700	04066000						
68	-77770180	05398000	05397500					
69	05398000	05397500						
70	-77770190	04074950						
71	04074950							
72	-05395000							
73	05394500	-88880110	-77770200	05393500				
74	-88880110							
75	05394500	05393500						
76	-88880120	-77770210	-05391000					
77	-88880120	-05391000						
78	-05333500	04024430	-77770220	-04025500	-04026190	04027500	04027000	-88880130
	05356000							
79	-05333500	-04025500	-04026190					
80	-88880130							
81	04024430	04027500	04027000	05356000				
82	04024430							
83	05369500	05379500	05382000	05381000	-05380806	-77770230		
84	-05380806							
85	05369500	05379500	05382000	05381000				
86	05381000							
87	05356500	05360500	05362000	-77770240	-88880140			
88	-88880140							
89	05356500	05360500	05362000					
90	05340500	-77770250	-88880150					
91	-88880150							
92	05340500							
93	05368000	05365500	05369000	05370000	-77770260			
94	05368000	05365500	05369000	05370000				

Table 13. Additional stations considered in evaluation of routes for Wisconsin's gaging-station network operation

Station no.	Station name	Type of station[1]
04025500	Bois Brule River at Brule	Q
04026190	Sand River near Red Cliff	Q
04067500	Menominee River near McAllister	Q
04071500	Oconto River at Stiles	Q
04072490	Portage Canal at Portage	M
04073462	White Creek at Forest Glen Beach near Green Lake	Q
04074538	Swamp Creek above Rice Lake, at Mole Lake	Q
04074548	Swamp Creek below Rice Lake, at Mole Lake	Q
04080000	Little Wolf River at Royalton	Q
04081000	Waupaca River near Waupaca	Q
04084038	De Neveu Creek at Fond du Lac	Q
04085000	Fox River at Wrightstown	Q
04086500	Cedar Creek near Cedarburg	Q
04086600	Milwaukee River near Cedarburg	Q
04087159	Kinnickinnic River at Milwaukee	Q
05333500	St. Croix River near Danbury	Q
05380806	Black River at Medford	Q
05391000	Wisconsin River at Rainbow Lake near Lake Tomahawk	Q
05395000	Wisconsin River at Merrill	Q
05400760	Wisconsin River at Wisconsin Rapids	Q
05406460	Black Earth Creek at Cross Plains	Q
05406464	Rain gage site 2 near Cross Plains	RG
05406470	Brewery Creek at Cross Plains	Q
05406490	Rain gage site 3 near Black Earth	RG
05406491	Garfoot Creek near Cross Plains	Q
05425912	Beaver Dam River at Beaver Dam	M
05427965	Spring Harbor Storm Sewer at Madison	Q
05431486	Turtle Creek at Carvers Rock Road near Clinton	Q
05434510	Pecatonica River at Winslow	A
05546500	Fox River at Wilmot	Q
43471908	Rain gage at Fond du Lac	RG
77770010	Stations 05407100, 05407200, 05413400, 05414200, 05414900, 05414915	CS
77770020	Stations 05436200, 05434510	CS
77770030	Stations 05433500, 05432300	CS
77770040	Stations 05431400, 05437200, 05430403	CS
77770050	Stations 05406450, 05406459, 05406488	CS
77770060	Stations 05406488, 05403590, 05406497.5	CS
77770070	Stations 05427800, 05405600, 04072490	CS
77770080	Stations 05403610, 05403630, 05403700, 05403520, 05403550, 05404200	CS
77770090	Stations 05406800, 05387100, 05386300, 05382300, 05407400	CS
77707100	Stations 05425827, 05425700	CS
77770110	Stations 05427000	CS
77770120	Stations 05544300, 05545100, 05545200, 05548150, 04087250, 04087230, 04087200, 04087100, 05426100	CS
77770130	Stations 05423800, 04086400, 04085700, 04085300, 04085100, 04085400, 04083400	CS
77770140	Stations 04079700, 04071800, 04071700 04085030, 04081900	CS

Table 13. Additional stations considered in evaluation of routes for Wisconsin's gaging-station network operation—Continued

Station no.	Station name	Type of station[1]
77770150	Stations 05395100, 05397600, 05396100	CS
77770160	Stations 05400025, 04081010, 04073400, 05401800	CS
77770170	Stations 05395020, 04074700, 04074300, 04067760, 04063688, 04067800, 04063800, 04064800, 04069700, 04074850	CS
77770180	Stations 05396300	CS
77770190	Stations 04075200	CS
77770200	Stations 05393640, 05394200	CS
77770210	Stations 05392350, 05392150, 05357360, 05357390, 05390140, 04063640, 04059900, 05390240, 05391260	CS
77770220	Stations 04024384, 04024400, 04025200, 04026200, 04026300, 04026450, 04027200, 05333100, 05335380, 05358100, 05359600	CS
77770230	Stations 05361400, 05361420, 05361600, 05370600, 05370900, 05371800, 05371920, 05378200, 05380800, 05380900, 05380970, 05382200	CS
77770240	Stations 05364000, 05364100, 05364500, 05365700, 05366500, 05367030	CS
77770250	Stations 05340300, 05367700	CS
77770260	Stations 05341900, 05367480	CS
77770270	Stations 05431400, 05437200	CS
88880010	Wells Lf-11, Lf-57, Lf-294	GW
88880020	Wells Dn-1136, Lf-78, Iw-32	GW
88880030	Wells Lf-78, Iw-32	GW
88880040	Wells Dn-1134, Dn-441, Sk-1	GW
88880050	Wells Ve-71, Mo-17	GW
88880060	Wells Ke-288, Ke-6, Ra-5	GW
88880070	Wells Mn-28	GW
88880080	Wells Ln-92	GW
88880090	Wells Ws-8	GW
88880100	Long Lake well	GW
88880110	Irma Well Ln-75	GW
88880120	Irma Well Ln-76	GW
88880130	Wells Ir-121, Wb-48	GW
88880140	Wells Br-402, EC-211, Ta-1	GW
88880150	Wells Br-8, Br-46, Br-48, Br-115, Br-153, Pk-40, Pk-75	GW
99990010	Well Dn-880	GW
99990020	Lake Kegonsa Telemark Station	A
99990030	Auxillary gage at Beloit	A
99990040	Lake stage gage	L
99990050	Reservoir gage	L

[1] A denotes a discharge station auxillary site.
CS denotes a crest-stage partial-record station.
GW denotes a ground-water site.
L denotes a lake-stage site.
M denotes a miscellaneous site.
Q denotes a discharge site where formulation of an uncertainty curve was not possible.
RG denotes a rain gage.

Route costs include the cost associated with the time spent servicing the equipment, the cost of the hydrographer's time while in transit, and any per diem costs associated with the time it takes to complete the trip. Per diem cost and transit time were estimated from past experience. Transit time was multiplied by the average hourly salary of hydrographers in each field office and added to a per diem cost of $50 to determine total route costs.

Results of K-CERA

The "Traveling Hydrographer Program" uses the uncertainty functions along with the appropriate cost data and route definitions to compute the most cost-effective way of operating the stream-gaging program. First, the current practice for operating the stream-gaging program was simulated to determine the total uncertainty associated with it. This is accomplished by fixing the number of visits made to each gaging station and selecting only the specific routes presently used to make these visits. The simulation of the current practice is strictly an accounting of all fixed, visit, and route costs; no optimization is performed. Most of the gaging stations in Wisconsin are routinely visited eight or nine times per year. The resulting average standard error per station for the current method of operation in Wisconsin is plotted as a point labeled "current operation" in figure 12.

The solid curve in figure 12 labeled "optimal practice" represents the minimum level of average uncertainty that can be obtained for a given budget with the existing instrumentation and technology. The curve was defined by executing the "Traveling Hydrographer Program" to determine optimal strategies for different budgets. Constraints on the operations other than budget were defined as described below.

Physical limitations of the method used to record data determine the minimum number of times each gaging station must be visited. The criteria used to assign a minimum-visit requirement to each gaging station are summarized in table 14. The effect of visitation frequency on the accuracy of the data and amount of lost record is taken into account in the uncertainty function.

In certain situations the hydrographer visiting a gaging station will only perform routine maintenance work and will not make a discharge measurement. The probability of making a discharge measurement during a visit was estimated by field-office personnel based on past experience and used as an input to the "Traveling Hydrographer Program". This constraint ensures that the more appropriate uncertainty related to the number of measurements, and not the number of visits, is used.

The current budget available for visiting all gaging stations considered in this analysis is $557,300. The average standard error (square root of average expected total error variance) for the stream-gaging program,

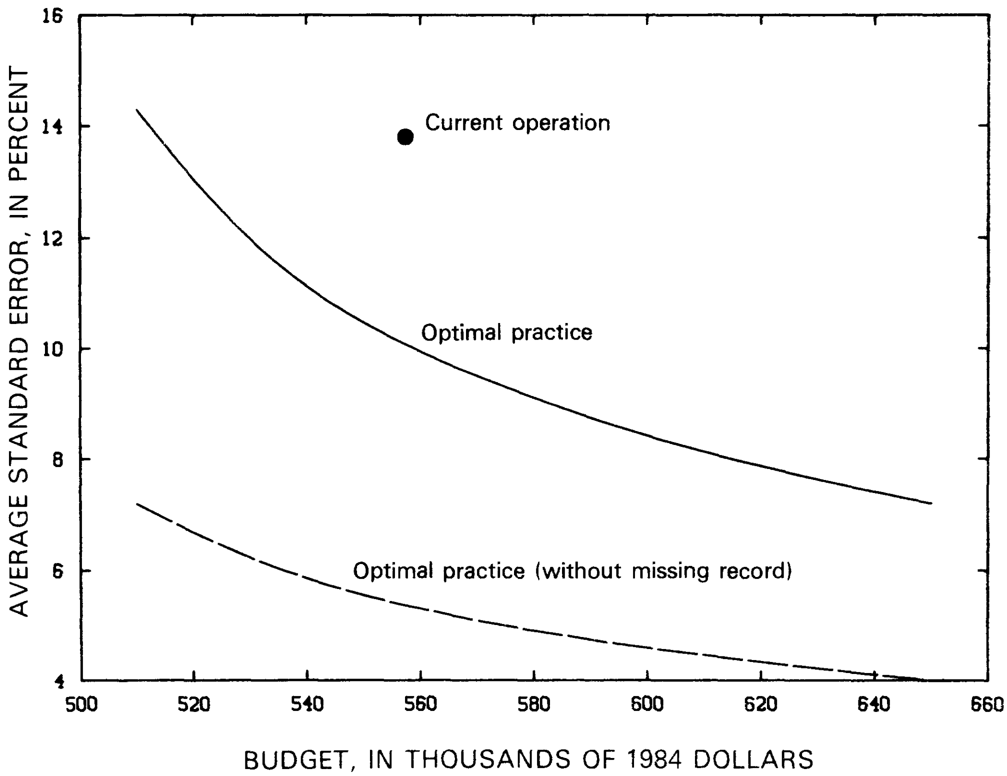

Figure 12. Temporal-average standard error per gaging station.

resulting fom the current practice for visiting the stations, is 13.8 percent (fig. 12). Site-specific standard errors corresponding to the number of measurements made at each gaging station are presented in table 15. Standard errors range from 4.6 percent for the Oconto River near Gillett (04071000) to 34.3 percent for the Yellow River at Babcock (05402000).

The standard error for the current practice is 3.7 percent greater than the 10.1 percent standard error associated with optimal practice, indicated by the solid curve at a budget of $557,300 (fig. 12 and table 15). The reduction in average standard error is achieved by visiting gaging stations having higher uncertainties more frequently and stations with lower uncertainties less frequently than the current practice (table 15). For example, although the standard error at Yahara River near Fulton (05430175) would remain nearly the same (5.6 percent versus 4.9 percent) by visiting 9 times rather than the present 12 times per year, the uncertainty at Yellow River at Babcock (05402000) would be significantly reduced (20.6 percent versus 34.3 percent) by increasing the annual number of visits to the station from 10 to 27. The slopes of the uncertainty functions for Yahara River near Fulton and Yellow River at Babcock (fig. 11) at nine measurements per year indicate that the decrease in standard error for an additional measurement at Yellow River at Babcock is much greater than the decrease expected for Yahara River near Fulton. Therefore, the cost-effective solution is to redistribute resources from gaging stations with lesser-sloped uncertainty functions to stations with steeper-sloped uncertainty functions.

The solid curve in figure 12 also indicates that the minimum budget needed to maintain the current average standard error of 13.8 percent is $518,600. This budget is determined by drawing a horizontal line through the "current practice" point parallel to the budget axis to the solid curve and dropping vertically to the budget axis.

The minimum-practicable budget (for optimal practice) is $510,000, 8.5 percent less than the current budget. Any budget less than this amount does not allow for a minimum number of visits to the gaging stations for maintenance activities. The average standard error for the minimum-practicable budget is 14.4 percent.

Visit frequencies and resulting standard errors for four budgets are presented in table 15. The two strategies presented in the third and fourth columns of table 15 are for current operations (with and without the error associated with missing record) and a current budget of $557,300.

The other four strategies show minimum-attainable standard errors for various budgets. The table indicates the change in activity at a gaging station that could be expected as the budget changes. The average standard errors for the budgets define part of the solid curve shown in figure 12. The curve extends from a minimum-practicable budget of $510,000 to $650,000 (16.6 percent more than the current budget) for which the average standard error is 7.2 percent.

The dashed curve, labeled "optimal practice (without missing record)" on figure 12, shows the average standard errors that could be obtained if perfectly reliable systems were available to measure and record the correlative data. The impacts of less-than-perfect equipment are greatest for the minimum-practicable budget of $510,000 where the average standard error increases from 7.3 percent to 14.4 percent. For a budget of $600,000, gaging stations are visited more frequently and the average standard error would increase from 4.6 percent for ideal equipment performance to 8.4 percent for the present percentage of lost record. For the current practice of visiting gaging stations, stage record that is lost due to equipment malfunction and other causes increases average standard error from 7.3 percent to 13.8 percent (see the third and fourth columns of table 15). Thus, improved equipment and maintenance activities can have a very positive impact on streamflow uncertainties throughout the range of operational budgets that possibly could be anticipated for the stream-gaging program in Wisconsin.

Technological advances in recording equipment and telemetry systems should reduce the current percentage of missing stage record. The U.S. Geological Survey currently (1984) is developing a family of data-acquisition instruments to replace existing water-stage recorders and timing devices. This family of instruments, referred to as AHDAS (Adaptable Hydrologic Data Acquisition System), has solid-state memory and "intelligent" microprocessor-control features. Hydrographers will be able to more efficiently monitor trends in stage records to determine if equipment at a gaging station is malfunctioning. The old carbon-zinc batteries have been replaced with rechargeable lead-acid batteries. Field tests have shown that the new batteries are very reliable and are expected to last from 3 to 5 years (W. P. Bartlett, Jr., W. B. Higgins, and K. V. Sharp, U.S. Geological Survey, written commun., 1983).

The "best possible" average standard error that can be attained for the current budget of $557,300 using the 94 routes shown in table 14 is 5.4 percent. Stream-gaging

Table 14. Criteria for assigning a minimum number of visits

Recorder punch frequency	Minimum visits required per year
1 hour	2
30 minute	3
15 minute	5
5 minute	10

Table 15. Selected results of K-CERA analysis

Station no.	Station name	Current practice[4]: Missing record	Current practice[4]: No missing record	Budget, in thousands of 1984 dollars[5]: 510.0	530.0	557.3	600.0
		Standard error of instantaneous discharge, in percent[1] [Equivalent Gaussian Spread (EGS), in percent][2] (Annual number of visits to site)[3]					
04024430	Nemadji River near South Superior	26.4	5.8	24.9	20.0	15.9	13.9
		[6.7]	[5.8]	[6.2]	[4.8]	[3.8]	[3.3]
		(8)	(8)	(9)	(14)	(22)	(29)
04027000	Bad River near Odanah	12.5	4.7	15.8	14.4	12.5	9.8
		[4.9]	[4.7]	[6.0]	[5.6]	[4.9]	[3.9]
		(8)	(8)	(5)	(6)	(8)	(13)
04027500	White River near Ashland	10.5	7.7	12.8	11.9	10.5	8.5
		[8.0]	[7.7]	[9.6]	[9.0]	[8.0]	[6.5]
		(8)	(8)	(5)	(6)	(8)	(13)
04063700	Popple River near Fence	9.5	3.6	14.2	10.7	9.0	7.6
		[3.8]	[3.6]	[5.4]	[4.2]	[3.6]	[3.0]
		(9)	(9)	(4)	(7)	(10)	(14)
04066003	Menominee River below Pemene Creek near Pembine	11.2	1.3	16.7	12.7	10.6	9.0
		[1.5]	[1.3]	[2.2]	[1.7]	[1.4]	[1.2]
		(9)	(9)	(4)	(7)	(10)	(14)
04069500	Peshtigo River at Peshtigo	11.8	6.6	13.5	11.8	9.7	8.2
		[7.0]	[6.6]	[8.0]	[7.0]	[5.7]	[4.8]
		(8)	(8)	(6)	(8)	(12)	(17)
04071000	Oconto River near Gillett	4.6	1.2	5.4	4.6	3.8	3.2
		[1.2]	[1.2]	[1.2]	[1.2]	[1.2]	[1.1]
		(8)	(8)	(6)	(8)	(12)	(17)
04071858	Pensaukee River near Pensaukee	29.2	10.7	33.6	29.2	23.9	20.1
		[11.7]	[10.7]	[13.8]	[11.7]	[9.3]	[7.7]
		(8)	(8)	(6)	(8)	(12)	(17)
04073500	Fox River at Berlin	8.9	5.5	11.1	11.1	11.1	9.3
		[5.8]	[5.5]	[6.6]	[6.6]	[6.6]	[5.9]
		(10)	(10)	(6)	(6)	(6)	(9)
04074950	Wolf River at Langlade	4.7	3.1	9.9	8.1	7.1	6.3
		[3.2]	[3.1]	[6.8]	[5.5]	[4.7]	[4.2]
		(9)	(9)	(2)	(3)	(4)	(5)
04077000	Wolf River at Keshena Falls near Keshena	7.7	2.2	9.0	7.7	6.1	5.1
		[2.5]	[2.2]	[3.0]	[2.5]	[2.0]	[1.7]
		(8)	(8)	(6)	(8)	(12)	(17)
04078500	Embarrass River near Embarrass	7.9	2.8	9.2	7.9	6.5	5.4
		[2.8]	[2.8]	[3.2]	[2.8]	[2.4]	[2.0]
		(8)	(8)	(6)	(8)	(12)	(17)
04079000	Wolf River at New London	6.0	3.1	6.9	6.0	4.9	4.2
		[3.2]	[3.1]	[3.6]	[3.2]	[2.7]	[2.4]
		(8)	(8)	(6)	(8)	(12)	(17)
04085200	Kewaunee River near Kewaunee	24.6	8.6	26.2	21.0	17.4	14.5
		[9.6]	[8.6]	[10.2]	[8.1]	[6.6]	[5.5]
		(9)	(9)	(8)	(12)	(17)	(24)
04085281	East Twin River at Mishicot	19.4	6.7	20.7	16.6	13.8	11.5
		[7.4]	[6.7]	[8.0]	[6.3]	[5.2]	[4.4]
		(9)	(9)	(8)	(12)	(17)	(24)
04085427	Manitowoc River at Manitowoc	11.0	5.0	11.7	9.6	8.1	6.8
		[5.2]	[5.0]	[5.5]	[4.6]	[3.9]	[3.3]
		(9)	(9)	(8)	(12)	(17)	(24)
04086000	Sheboygan River at Sheboygan	18.4	3.1	19.5	16.0	13.4	11.3
		[3.2]	[3.1]	[3.4]	[2.8]	[2.3]	[2.0]
		(9)	(9)	(8)	(12)	(17)	(24)
04087000	Milwaukee River at Milwaukee	15.4	9.0	16.3	13.4	11.3	9.5
		[9.3]	[9.0]	[9.8]	[8.1]	[6.8]	[5.7]
		(9)	(9)	(8)	(12)	(17)	(24)
04087030	Menomonee River at Menomonee Falls	16.8	10.6	17.8	14.1	11.4	9.6
		[11.0]	[10.6]	[11.6]	[9.2]	[7.4]	[6.2]
		(9)	(9)	(8)	(13)	(20)	(28)
04087088	Underwood Creek at Wauwatosa	25.4	20.3	20.5	17.5	15.2	12.6
		[21.3]	[20.3]	[17.1]	[14.6]	[12.6]	[10.4]
		(9)	(9)	(15)	(21)	(28)	(41)

Table 15. Selected results of K-CERA analysis—Continued

Station no.	Station name	Standard error of instantaneous discharge, in percent[1] [Equivalent Gaussian Spread (EGS), in percent][2] (Annual number of visits to site)[3]					
		Current practice[4]		Budget, in thousands of 1984 dollars[5]			
		Missing record	No missing record	510.0	530.0	557.3	600.0
04087120	Menomonee River at Wauwatosa	23.5 [7.7] (9)	7.2 [7.2] (9)	24.9 [8.2] (8)	19.3 [6.2] (13)	15.5 [5.0] (20)	13.1 [4.2] (28)
04087204	Oak Creek at South Milwaukee	32.3 [16.7] (9)	15.0 [15.0] (9)	24.3 [12.5] (15)	20.2 [10.4] (21)	17.3 [8.9] (28)	14.1 [7.2] (41)
04087220	Root River near Franklin	25.8 [14.4] (9)	13.3 [13.3] (9)	20.0 [11.9] (15)	16.9 [10.2] (21)	14.6 [8.9] (28)	12.1 [7.4] (41)
04087233	Root River Canal near Franklin	16.5 [12.0] (9)	11.7 [11.7] (9)	17.6 [12.8] (8)	13.6 [9.9] (13)	10.9 [7.9] (20)	9.2 [6.7] (28)
04087240	Root River at Racine	19.6 [8.6] (9)	8.2 [8.2] (9)	20.8 [9.1] (8)	16.3 [7.1] (13)	13.1 [5.7] (20)	11.0 [4.8] (28)
04087257	Pike River near Racine	25.6 [11.3] (9)	10.2 [10.2] (9)	19.6 [8.4] (15)	16.5 [7.0] (21)	14.2 [6.1] (28)	11.7 [5.0] (41)
05340500	St. Croix River at St. Croix Falls	11.1 [8.3] (10)	8.0 [8.0] (10)	13.8 [8.7] (5)	12.9 [8.6] (6)	11.4 [8.3] (9)	10.6 [8.2] (12)
05356000	Chippewa River at Bishops Bridge near Winter	4.8 [3.4] (8)	3.4 [3.4] (8)	5.9 [4.2] (5)	5.5 [3.9] (6)	4.8 [3.4] (8)	3.8 [2.8] (13)
05356500	Chippewa River near Bruce	6.7 [5.2] (8)	5.2 [5.2] (8)	8.2 [6.3] (5)	7.6 [5.9] (6)	6.3 [5.0] (9)	5.3 [4.2] (13)
05360500	Flambeau River near Bruce	6.5 [4.7] (8)	4.5 [4.5] (8)	8.0 [5.6] (5)	7.4 [5.2] (6)	6.1 [4.5] (9)	5.2 [3.8] (13)
05362000	Jump River at Sheldon	17.0 [8.0] (8)	7.6 [7.6] (8)	22.0 [10.4] (5)	19.9 [9.4] (6)	15.9 [7.5] (9)	13.1 [6.2] (13)
05365500	Chippewa River at Chippewa Falls	6.6 [4.8] (8)	4.7 [4.7] (8)	7.6 [5.5] (6)	6.6 [4.8] (8)	5.4 [4.0] (12)	4.5 [3.4] (17)
05368000	Hay River at Wheeler	10.3 [4.3] (8)	4.1 [4.1] (8)	12.0 [5.0] (6)	10.3 [4.3] (8)	8.3 [3.5] (12)	7.0 [3.0] (17)
05369000	Red Cedar River at Menomonie	8.1 [5.7] (8)	5.5 [5.5] (8)	9.2 [6.4] (6)	8.1 [5.7] (8)	6.7 [4.7] (12)	5.7 [4.0] (17)
05369500	Chippewa River at Durand	7.8 [2.7] (8)	2.5 [2.5] (8)	9.4 [3.2] (6)	7.2 [2.6] (9)	6.1 [2.2] (12)	4.6 [1.8] (19)
05370000	Eau Galle River at Spring Valley	21.0 [6.3] (8)	6.1 [6.1] (8)	24.2 [7.3] (6)	21.0 [6.3] (8)	17.2 [5.2] (12)	14.4 [4.4] (17)
05379500	Trempealeau River at Dodge	13.2 [5.5] (8)	5.1 [5.1] (8)	15.3 [6.5] (6)	12.4 [5.1] (9)	10.7 [4.4] (12)	8.5 [3.5] (19)
05381000	Black River at Neillsville	26.1 [17.2] (8)	16.2 [16.2] (8)	29.1 [17.7] (6)	24.2 [16.8] (10)	21.7 [16.3] (14)	19.4 [15.5] (21)
05382000	Black River near Galesville	15.9 [10.6] (8)	10.0 [10.0] (8)	18.5 [12.4] (6)	14.9 [9.9] (9)	12.9 [8.5] (12)	10.1 [6.7] (19)
05393500	Spirit River at Spirit Falls	10.6 [7.9] (9)	7.9 [7.9] (9)	13.8 [8.7] (4)	11.5 [8.2] (7)	9.7 [7.5] (12)	8.4 [6.8] (18)

This table is continued on the following page →

Table 15. Selected results of K-CERA analysis—Continued

Station no.	Station name	Current practice[4] Missing record	Current practice[4] No missing record	Budget, in thousands of 1984 dollars[5] 510.0	530.0	557.3	600.0
		Standard error of instantaneous discharge, in percent[1] [Equivalent Gaussian Spread (EGS), in percent][2] (Annual number of visits to site)[3]					
05394500	Prairie River near Merrill	13.6 [11.3] (9)	11.0 [11.0] (9)	18.6 [15.2] (4)	15.1 [12.5] (7)	11.9 [10.0] (12)	9.9 [8.2] (18)
05397500	Eau Claire River at Kelly	13.2 [2.8] (9)	2.6 [2.6] (9)	18.2 [3.8] (5)	14.1 [2.9] (8)	11.4 [2.4] (12)	10.1 [2.2] (15)
05398000	Wisconsin River at Rothschild	6.2 [4.9] (9)	4.9 [4.9] (9)	7.6 [5.7] (5)	6.4 [5.1] (8)	5.5 [4.5] (12)	5.0 [4.1] (15)
05399500	Big Eau Pleine River near Stratford	29.1 [11.7] (8)	11.3 [11.3] (8)	23.9 [9.9] (12)	20.1 [8.5] (17)	16.6 [7.1] (25)	13.3 [5.7] (39)
05400650	Little Plover River at Plover	7.8 [3.5] (10)	3.3 [3.3] (10)	10.7 [4.5] (5)	9.8 [4.2] (6)	9.2 [4.0] (7)	7.8 [3.5] (10)
05402000	Yellow River at Babcock	34.3 [15.0] (10)	13.9 [13.9] (10)	31.3 [13.5] (12)	25.3 [10.8] (18)	20.6 [8.7] (27)	17.3 [7.3] (38)
05403500	Lemonweir River at New Lisbon	8.0 [8.0] (9)	8.0 [8.0] (9)	8.2 [8.2] (4)	8.1 [8.1] (6)	8.1 [8.1] (8)	8.0 [8.0] (11)
05404000	Wisconsin River near Wisconsin Dells	10.8 [1.2] (9)	1.1 [1.1] (9)	16.7 [2.0] (4)	13.5 [1.5] (6)	11.5 [1.3] (8)	9.8 [1.1] (11)
05405000	Baraboo River near Baraboo	33.1 [4.5] (9)	3.2 [3.2] (9)	26.1 [3.2] (14)	21.1 [2.5] (21)	17.5 [2.0] (30)	14.1 [1.6] (45)
05406500	Black Earth Creek at Black Earth	8.0 [6.8] (12)	6.8 [6.8] (12)	12.3 [10.6] (5)	10.4 [9.0] (7)	8.7 [7.5] (10)	7.2 [6.1] (15)
05407000	Wisconsin River at Muscoda	6.4 [2.6] (9)	2.5 [2.5] (9)	13.4 [5.5] (2)	9.6 [3.9] (4)	8.6 [3.5] (5)	6.8 [2.8] (8)
05408000	Kickapoo River at LaFarge	5.6 [3.7] (9)	3.6 [3.6] (9)	9.7 [6.4] (3)	9.7 [6.4] (3)	8.4 [5.5] (4)	6.9 [4.5] (6)
05410500	Kickapoo River at Steuben	6.3 [4.4] (9)	4.3 [4.3] (9)	6.3 [4.4] (9)	5.4 [3.8] (12)	4.9 [3.4] (15)	4.0 [2.8] (23)
05413500	Grant River at Burton	18.2 [4.4] (9)	3.9 [3.9] (9)	18.2 [4.4] (9)	15.4 [3.7] (12)	13.5 [3.3] (15)	10.6 [2.6] (23)
05414000	Platte River near Rockville	13.2 [5.6] (9)	5.3 [5.3] (9)	13.2 [5.6] (9)	11.3 [4.8] (12)	10.0 [4.3] (15)	8.0 [3.5] (23)
05415000	Galena River at Buncombe	16.3 [4.2] (9)	4.0 [4.0] (9)	16.3 [4.2] (9)	14.1 [3.6] (12)	12.6 [3.2] (15)	10.1 [2.6] (23)
05424082	Rock River at Hustisford	16.6 [11.5] (9)	11.0 [11.0] (9)	18.0 [11.8] (7)	15.2 [11.1] (12)	13.7 [10.6] (17)	12.0 [9.7] (27)
05425500	Rock River at Watertown	19.1 [16.4] (9)	15.9 [15.9] (9)	21.4 [18.4] (7)	16.6 [14.3] (12)	14.0 [12.0] (17)	11.1 [9.5] (27)
05426000	Crawfish River at Milford	16.3 [4.1] (9)	3.8 [3.8] (9)	18.6 [4.4] (7)	14.6 [3.8] (11)	12.9 [3.4] (14)	9.9 [2.8] (23)
05426031	Rock River at Jefferson	15.2 [12.2] (9)	11.3 [11.3] (9)	16.5 [12.7] (7)	14.3 [11.8] (11)	13.3 [11.4] (14)	11.5 [10.3] (23)

Table 15. Selected results of K-CERA analysis—Continued

Station no.	Station name	Current practice[4] Missing record	No missing record	Budget, in thousands of 1984 dollars[5] 510.0	530.0	557.3	600.0
		Standard error of instantaneous discharge, in percent[1] [Equivalent Gaussian Spread (EGS), in percent][2] (Annual number of visits to site)[3]					
05426250	Bark River near Rome	8.8 [4.7] (9)	4.4 [4.4] (9)	9.4 [5.0] (8)	7.3 [3.8] (13)	5.9 [3.1] (20)	5.0 [2.6] (28)
05427570	Rock River at Indianford	19.3 [19.3] (15)	19.2 [19.2] (15)	23.6 [23.6] (10)	18.2 [18.1] (17)	15.6 [15.5] (23)	12.6 [12.5] (35)
05427948	Pheasant Branch at Middleton	28.6 [27.0] (24)	26.7 [26.7] (24)	30.7 [28.3] (15)	26.2 [25.0] (39)	21.3 [20.6] (82)	16.9 [16.4] (147)
05429500	Yahara River near Mc Farland	15.1 [12.1] (17)	11.8 [11.8] (17)	19.6 [16.2] (10)	15.1 [12.1] (17)	12.7 [10.1] (24)	10.5 [8.4] (35)
05430150	Badfish Creek neary Cooksville	6.8 [6.6] (15)	6.5 [6.5] (15)	8.1 [7.9] (10)	6.4 [6.2] (17)	5.5 [5.3] (23)	4.5 [4.4] (35)
05430175	Yahara River near Fulton	4.9 [2.2] (12)	2.1 [2.1] (12)	6.4 [2.7] (7)	5.6 [2.5] (9)	5.6 [2.5] (9)	4.7 [2.1] (13)
05430500	Rock River at Afton	7.3 [5.0] (9)	4.8 [4.8] (9)	7.3 [5.0] (9)	6.7 [4.7] (11)	6.7 [4.7] (11)	5.8 [4.2] (15)
05432500	Pecatonica River at Darlington	8.3 [4.8] (9)	4.7 [4.7] (9)	11.2 [6.2] (5)	9.4 [5.3] (7)	7.8 [4.6] (10)	6.4 [3.8] (15)
05433000	East Branch Pecatonica River near Blanchardville	10.4 [6.6] (9)	6.3 [6.3] (9)	14.3 [8.9] (5)	11.9 [7.5] (7)	9.8 [6.3] (10)	7.9 [5.1] (15)
05434500	Pecatonica River at Martintown	6.9 [6.0] (9)	5.9 [5.9] (9)	9.9 [8.4] (4)	9.0 [7.8] (5)	6.9 [6.0] (9)	6.0 [5.3] (12)
05436500	Sugar River near Brodhead	8.3 [5.9] (9)	5.8 [5.8] (9)	11.8 [8.0] (4)	10.7 [7.4] (5)	8.3 [5.9] (9)	7.2 [5.2] (12)
05543830	Fox River at Waukesha	18.3 [9.4] (9)	8.9 [8.9] (9)	19.4 [9.9] (8)	15.3 [7.8] (13)	12.4 [6.3] (20)	10.5 [5.3] (28)
05544200	Mukwonago River at Mukwonago	16.8 [4.9] (9)	4.1 [4.1] (9)	17.8 [5.4] (8)	13.9 [3.9] (13)	11.2 [3.1] (20)	9.5 [2.6] (28)
Average per station[6]		13.8	7.3	14.4	11.9	10.1	8.4

[1] Square root of the expected total variance of the percentage errors of estimated instantaneous discharge (V_T).
[2] Nearly two-thirds of the errors in instantaneous discharge will be within ±EGS percent of the reported value.
[3] Visits made during ice-free period.
[4] Current practice and associated errors for 1984 budget of $557,300. Effects of missing stage record are indicated by comparing columns labeled "missing record" and "no missing record".
[5] Optimal practice and associated errors that minimize the sum of total variance of the percentage errors of estimated instantaneous discharge (V_T), for all gaging stations, for the stated budget.
[6] Square root of the average total variance of the percentage errors of estimated instantaneous discharge, in percent.

resources must be optimally distributed among the gaging stations and all of the instrumentation at the gaging stations must provide accurate hydrographic record for the entire year (ice-free period) to attain this standard error. The only way to further reduce the average standard error is to define additional routes that have not been considered and/or to reduce the relative variance of errors associated with the stage-discharge rating (V_f) at gaging stations having high standard errors of instantaneous discharge.

A majority of the discharge measurements considered in the Kalman-filter definition of variance for a gaging station were made during low- to medium-flow conditions. The low range of many stage-discharge ratings is subject to considerable shifting due to transient changes in streambed geometry, intermittent debris jams, or seasonal aquatic plant growth. The high end of a rating is often much more stable. The standard errors presented in table 15 are more representative of low to medium discharges. Kalman filtering can be used to determine the standard error associated with the high end of a rating; however, the long intervals of time (more than 80 days) between high-flow measurements would preclude an accurate determination of the 1-day autocorrelation coefficient (*RHO*) for a time series of high-flow rating residuals.

Ice-related backwater conditions were not included in the Kalman-filter definition of variance for stage-discharge ratings. Additional analyses would have to be performed to determine the standard errors for ice-affected instantaneous discharge.

Conclusions Pertaining to the K-CERA Analysis

The information presented in table 12, especially the standard error and EGS for instantaneous discharge associated with the current practice for visiting gaging stations, should be critically evaluated in terms of required accuracy for intended use. The accuracy of instantaneous discharge at gaging stations where the EGS is excessive may not be sufficient for the intended use of the streamflow data. The long-term stage-discharge ratings for those stations should be reviewed to determine the range in discharge that is sufficiently accurate for the intended data use.

The average annual percentage of missing hydrographic record attributable to equipment malfunctions at gaging stations is high. Technological advances in recording equipment and telemetry systems should reduce the current percentage of missing record. Accurate records of the amounts and causes of missing record encountered in the future should be maintained to monitor the performance of the equipment.

An observer or telemetry system should be considered as an auxiliary source of hydrographic data at gaging stations where accurate records of streamflow data are needed, and the error contribution from missing record is excessive (for example, difference between standard error with and without missing record missing for the current practice of visiting the stations exceeds 15 percent).

The "Traveling Hydrographer Program" should be used as a management tool to evaluate the sensitivity of route selection and gaging station visit frequency to changes in budget and minimum-visit constraints and to determine if routes are economically and operationally feasible.

SUMMARY

The U.S. Geological Survey surface-water data-collection program in Wisconsin began in the late 1800's with the establishment of four gaging stations. With the start of the cooperative surface-water data program in 1913, the number of gaging stations increased to 11. By 1938 the number of gaging stations had increased to 58 and reached a maximum of 135 in 1979. In 1984 there were 89 active continuous record gaging stations in Wisconsin.

The first formal evaluation of the Wisconsin stream-gaging program was conducted by Campbell and Dreher (1975). This study is part of a 5-year nationwide effort by the U.S. Geological Survey to evaluate the operation of the gaging stations it maintains. This evaluation consists of three steps: (1) identification of streamflow data use, funding, and availability, (2) examination of less costly alternative methods for determining daily mean discharge in lieu of stream gaging, and (3) evaluation of the cost effectiveness of the current stream-gaging program.

Current use of streamflow data collected at each gaging station was determined by a survey of known data users, including agencies that do not participate in funding the stream-gaging program. Data uses were categorized into eight classes: Regional hydrology, hydrologic systems, legal obligations, planning and design, project operation, hydrologic forecasts, water-quality monitoring, and research.

Streamflow data at 63 stations are used to develop regionally transferable information about surface-water hydrology. Twenty-two stations are used to monitor current hydrologic conditions, and are classified in the hydrologic systems category. No gaging stations are operated to satisfy legal obligations. The planning and design category includes seven stations used to provide data for the planning and design of projects. The Army Corps of Engineers uses data from 11 gaging stations to operate dams on the Mississippi and Fox Rivers; these stations are classified in the project operation category. Thirty-one stations are used for flood prediction, and constitute the hydrologic forecast category. Nine gaging stations, all NASQAN sites, are used to assess water-quality trends in Wisconsin. These stations make up the water-quality monitoring group. No gaging stations are operated to provide data for research-type activities.

Four gaging stations are maintained solely or in part by Army Engineer Replacement funds. Nine gaging stations are maintained in part by funds allocated directly to the Wisconsin district from the U.S. Geological Survey headquarters. Twenty-seven gaging stations are supported by funds from other Federal agencies. Six gaging stations are supported by funds from other non-Federal agencies. The coop program provides funds for the remaining 48 gaging stations.

Three gaging stations were selected for evaluation of alternative methods of streamflow generation. A unit-response, convolution flow-routing model was used to estimate daily mean streamflow at two sites, while a statistical model was used for the third. Discharge was computed over periods ranging from 9 to 21 years; the first half of the record was used for model calibration, whereas the last portion of the record was used for model verification.

Based on the evaluation of data use and the evaluation of alternative methods to stream gaging, no gaging stations in the 1984 stream-gaging program in Wisconsin should be deactivated. All 89 stations were included in the third step of the stream-gaging program evaluation.

The U.S. Geological Survey developed the Kalman-Filtering for Cost-Effective Resource Evaluation (K-CERA) methodology to aid in evaluating its stream-gaging programs. The methodology identifies the uncertainty (error) of instantaneous discharge resulting from (1) variability of streamflow, (2) methods used by the U.S. Geological Survey to determine discharge, and (3) realistic financial and operational constraints.

The K-CERA method does not reflect the procedure used in Wisconsin to compute disharge, thus it is likely that the standard errors would differ from the values presented in the report. The majority of discharges considered in the determination of uncertainty are for low- to medium-flow conditions, thus the standard errors presented in this report are more representative of these conditions. In addition, the effects of ice-related backwater conditions were not considered in this study.

The current practice for operating the stream-gaging program uses an annual budget of $557,300 (1984 dollars). The present (1984) theoretical average standard error of the instantaneous discharge for all gaging stations is 13.8 percent. This average standard error could be maintained with a budget of $518,600, if the current practice for visiting the gaging stations is drastically altered. Perhaps more importantly, the average standard error would be reduced to 10.1 percent by utilizing the current budget in an optimal manner. Furthermore, the average standard error could be reduced to 7.3 percent if all missing record is eliminated, and the network is operated optimally.

A minimum budget of $510,000 is needed to optimally visit all gaging stations a minimum number of 2, 3, 5, or 10 times per year, depending on the type of instrumentation at a gaging station. The resultant average standard error associated with this minimum-practicable budget is 14.4 percent.

The loss of primary stage record and other correlative data at the gaging stations is a major component of error in streamflow records. For 50 percent of the stations in Wisconsin, primary stage record is unavailable up to 5 percent of the time, or approximately 18 days per year. This lost record increases the average standard error associated with instantaneous discharge from 7.3 to 13.8 percent, for the current practice of visiting gaging stations.

As a result of the three-step evaluation of the Wisconsin stream-gaging program, the following recommendations are offered:

1. Formal surveys of gaging station data use should be conducted at intervals of 5 years or less.
2. No gaging stations should be deactivated for the purpose of using alternative methods for estimating daily mean streamflow in lieu of stream gaging.
3. The U.S. Geological Survey and cooperating agencies should periodically review streamflow records of network gaging stations to ensure that highly correlated streamflows are not being measured without due cause.
4. Long-term stage-discharge ratings at gaging stations where the EGS (error) of instantaneous discharge is excessive should be reviewed to determine the range in discharge that is sufficiently accurate for intended data use.
5. The average annual percentage of missing hydrographic record attributable to equipment malfunctions at the gaging stations should be reduced through the use of state-of-the-art recording and telemetry equipment.
6. Improved records of the amount and cause of missing record should be compiled and maintained.
7. Observers or telemetry systems should be considered for gaging stations where accurate records for the full range of discharge are needed, streamflow is highly variable, and unstable controls for stage-discharge ratings exist.
8. The "Traveling Hydrographer Program" should be used as a management tool to evaluate the feasibility of new routes and the impacts of changing budgets or operational constraints.

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