COST EFFECTIVENESS OF STREAM-GAGING PROGRAM IN MICHIGAN

By D. J. Holtschlag

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CONVERSION FACTORS AND ABBREVIATIONS

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

Multiply inch-pound unit	By	To obtain metric unit
	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)

ACKNOWLEDGEMENTS

Acknowledgement is made to C. R. Whited, who developed long-term rating curves and planned hydrographer routes.

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ABSTRACT

This report documents the results of a study of the cost effectiveness of the stream-gaging program in Michigan. Data uses and funding sources were identified for the 129 continuous gaging stations being operated in Michigan as of 1984. One gaging station was identified as having insufficient reason to continue its operation. Several stations were identified for reactivation, should funds become available, because of insufficiencies in the data network.

Alternative methods of developing streamflow information based on routing and regression analyses were investigated for 10 stations. However, no station records were reproduced with sufficient accuracy to replace conventional gaging practices. A cost-effectiveness analysis of the data-collection procedure for the ice-free season was conducted using a Kalman-filter analysis. To define missing-record characteristics, cross-correlation coefficients and coefficients of variation were computed at stations on the basis of daily mean discharge. Discharge-measurement data were used to describe the gage/discharge rating stability at each station.

The results of the cost-effectiveness analysis for a 9-month ice-free season show that the current policy of visiting most stations on a fixed servicing schedule once every 6 weeks results in an average standard error of 12.1 percent for the current $718,100 budget. By adopting a flexible servicing schedule, the average standard error could be reduced to 11.1 percent. Alternatively, the budget could be reduced to $700,200 while maintaining the current level of accuracy. A minimum budget of $680,200 is needed to operate the 129-gaging-station program; a budget less than this would not permit proper service and maintenance of stations. At the minimum budget, the average standard error would be 14.4 percent. A budget of $789,900 (the maximum analyzed) would result in a decrease in the average standard error to 9.07 percent.

Owing to continual changes in the composition of the network and the changes in the uncertainties of streamflow accuracy at individual stations, the cost-effectiveness analysis will need to be updated regularly if it is to be used as a management tool. Cost of these updates need to be considered in decisions concerning the feasibility of flexible servicing schedules.

INTRODUCTION

Collection of streamflow data is a major activity of the Water Resources Division of the U.S. Geological Survey (USGS). In the United States in 1983, data were obtained from 7,152 continuous-record gaging stations and 3,924 partial-record stations (Condes de la Torre, 1983). In Michigan in 1984, data were obtained from 129 continuous-record gaging stations and 60 partial-record stations. Collection of some of these data extends back to the turn of the century.

Evaluation of stream-gaging program

The stream-gaging program is reexamined periodically to ensure that it is compatable with changes in needs, objectives, technology, and budgetary constraints. The program is presently being reexamined to define and document the most cost-effective means of furnishing streamflow data. Results of the reexamination of 129 gaging stations operated in 1984 in Michigan are given in this report.

Locations of the 129 stations are shown in figures 1 and 2. Selected data, including station number[1] and name, drainage area, period of record, and mean flow are given in table 1 (at end of report). The operating budget for streamflow data collection in fiscal year 1984 was $718,100.

Evaluation of the stream-gaging program in Michigan is divided into three parts, as follows: 1. Principal data uses for each continuous-record gaging station are identified and the availability of the data to users is categorized. 2. Less costly methods of generating streamflow data--flow-routing and multiple-regression analysis--are investigated. 3. Kalman-filtering and mathematical-programing techniques are used to define strategies for operating stations so that uncertainly in records is minimized. The results of this evaluation will be used to improve the efficiency of surface-water data collection program.

For this analysis, the ice-free period was considered separately from the ice-backwater period. During the nine-month ice-free period, uncertainty in the streamflow records is often related to vegetation growth and the deposition or scour of sediment in the channel. This uncertainty is due to changes, or shifts, in the discharge rating function as defined by discharge measurements during ice-free conditions. Uncertainty in streamflow records during ice-backwater periods is related to ice formation processes. Describing this uncertainty on the basis of under-ice discharge measurements is difficult due to greater variability in ice-backwater affects and fewer available discharge measurements. Therefore, uncertainty functions were defined for ice-free periods, thus permitting flexible field-servicing schedules during nine months of the year. A fixed-field servicing schedule will continue to be used during ice-backwater periods.

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

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[1] Station numbers used in this report are the last six digits of the standard USGS eight-digit downstream-order station number; the first two digits of the USGS station number for all stations in this report are 04.

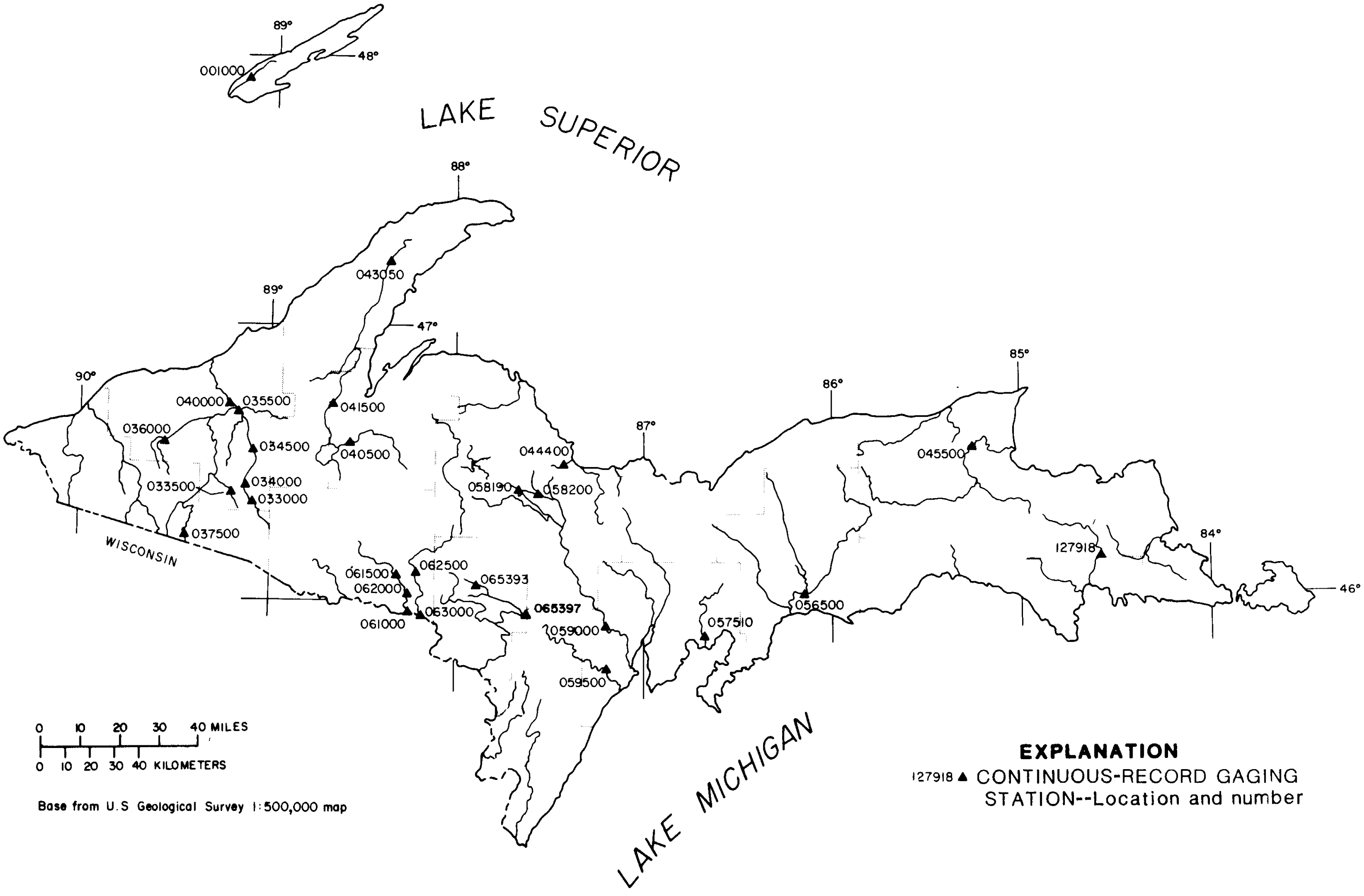


Figure 1.--Location of gaging stations in Upper Peninsula of Michigan.

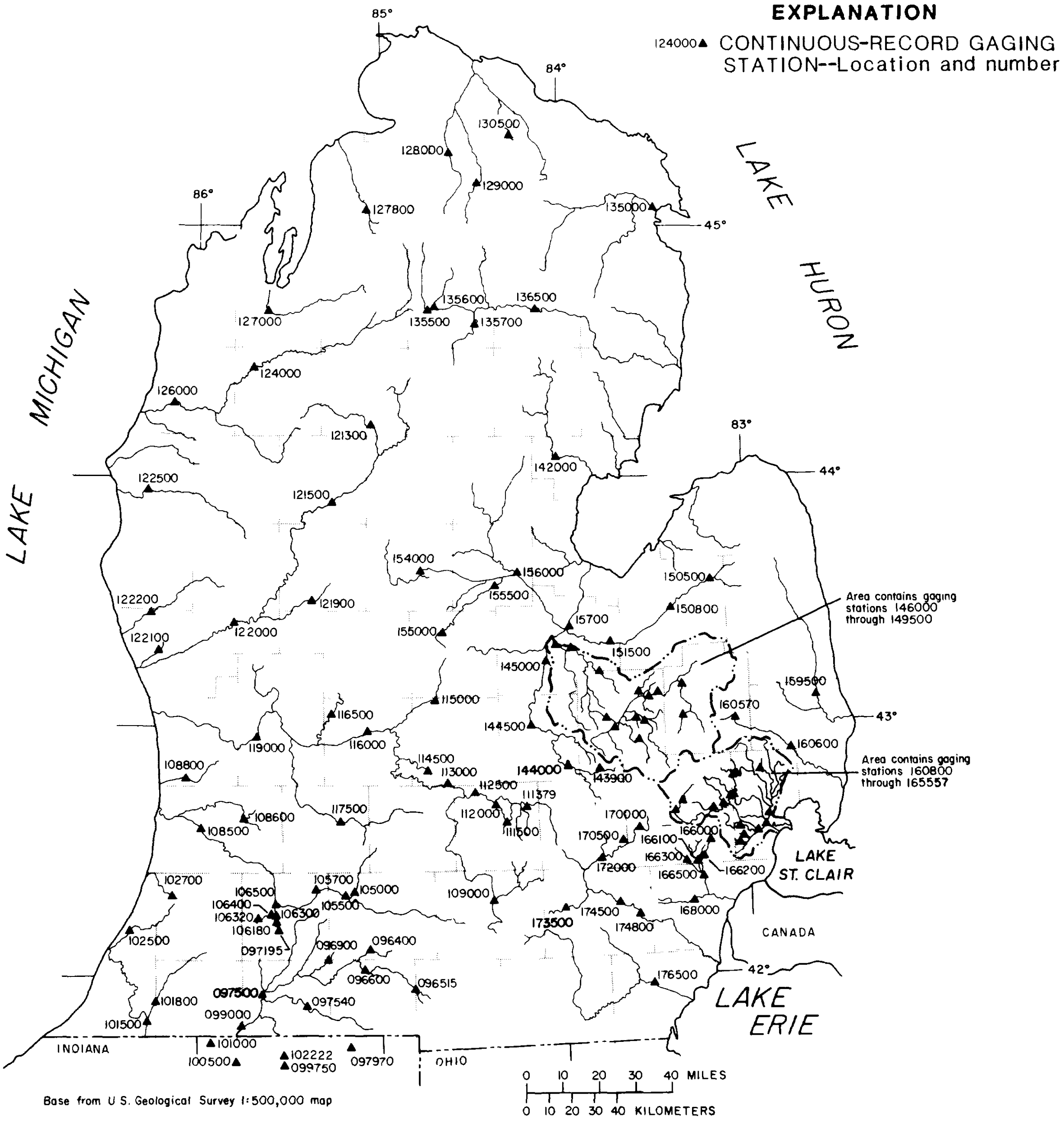


Figure 2.--Location of gaging stations in Lower Peninsula of Michigan.

Stream-Gaging Program in Michigan

The USGS entered a cooperative agreement with the State and other local units of government in 1900, and by 1902 was operating 11 continuous-record gaging stations. The data-collection program gradually declined until 1929 (figure 3) at which time only eight gaging stations were operated, primarily in connection with hydropower plant operation. In August 1930, 15 new stations were added. The number of stations increased steadily to a maximum of 200 in 1968. By 1984, the number of continuous-record gaging stations had declined to 129. Partial-record stations have been operated to supplement the gaging-station network. In 1984, 7 low-flow and 53 crest-stage partial-record stations were operated.

Three USGS offices conduct stream gaging in Michigan. A field office in Escanaba has responsibility for collection in the Upper Peninsula; a field office in Grayling collects data for the northern Lower Peninsula; and the District office in Lansing obtains data in the southern Lower Peninsula. Responsibility for data collection at some stations in the Lower Peninsula shifts between the Grayling and Lansing offices depending on (personnel) work loads.

Regular stream gaging activities vary seasonally and in response to hydrologic conditions. Generally, stations are visited and streams are measured at six-week intervals. During the nine month ice-free period, stations are visited by one person while two persons are needed when streams are ice-covered because of greater hazards and more difficult working conditions. Additional stream gaging is required during droughts and floods.

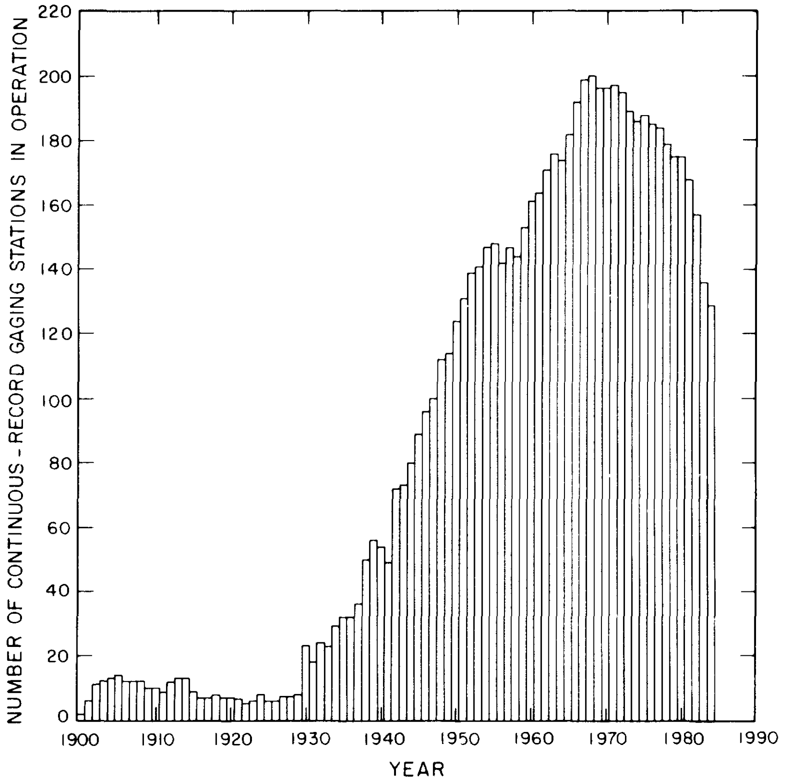


Figure 3.--History of continuous-record gaging-station operation in Michigan.

USES, FUNDING, AND AVAILABILITY OF DATA FROM CONTINUOUS-RECORD GAGING STATIONS

The relevance of a gaging station is defined by the uses made of data produced from the station. Uses of data from each station in the Michigan program were identified by a survey of known data users, and categorized into classes. The survey also documented the importance of each gaging station and identified those that may be considered for discontinuation. Date-use class, source of funding, and data availability are given in table 2 (at end of report).

Data-Use Classes

Seven data-use classes, defined below, were used to categorize each known use of data for each continuous-record gaging station in Michigan.

Regional hydrology.--Data from gaging stations in this class are used to define regional hydrology. The data must be from stations where streamflow is largely unaffected by manmade storage or diversion. In this use class, the effects of man on streamflow are limited to those caused primarily by land-use change. Large amounts of manmade storage may occur in the basin providing outflow is uncontrolled. Data from gaging stations in this class are useful in developing regionally transferable information about the relationship between basin characteristics and streamflow.

In Michigan 108 stations are included in the regional-hydrology class. Four of the stations are designated bench-mark, or index, stations. One hydrologic bench-mark station serves as an indicator of hydrologic conditions in watersheds relatively free of manmade alteration. Three index stations located in the State, are used to indicate current hydrologic conditions.

Hydrologic systems.--Data from gaging stations in this class are used to define current hydrologic conditions and the sources, sinks, and fluxes of water through hydrologic systems including regulated systems. Streamflow at the stations may include diversions and return flows. In Michigan 52 stations are included in the hydrologic-systems class. They are operated to assess the compliance of wastewater-treatment plant, hydropower plant, and reservoir operation procedures to State-issued permits. Data from stations in this class are useful for defining the interaction of water systems.

Project operation.--Data from gaging stations in this class are used, on an ongoing basis, to assist water managers in making operational decisions such as reservoir releases, hydropower operations, or diversions. Project-operation use generally implies that data are routinely available to the operators on a rapid-reporting basis. For projects on large streams, data may only be needed every few days. In Michigan 55 stations are included in the project-operation class. Of these, 15 are used to aid operators in the management of reservoirs and control structures; 24 provide data for use in hydropower production; 14 are used to assist wastewater-treatment plant operators.

Hydrologic forecasts.--Data from gaging stations in this class are used to provide information for hydrologic forecasting such as flood forecasts for a specific stream reach, forecast of inflows to reservoirs, and periodic (daily, weekly, monthly, or seasonal) flow-volume forecasts for a specific site or region. Data are used by the U.S. National Weather Service (NWS) to predict floodflows at downstream sites, by USGS to coordinate flood-measurement activities, and by communities to anticipate flooding conditions. Additionally, the NWS uses the data at some stations as input to long-range prediction models of the probability of snowmelt floods. The hydrologic-forecast class generally implies that data are routinely available to forecasters on a rapid-reporting basis. On large streams, data may only be needed every few days. In Michigan 25 stations are included in the hydrologic-forecast class.

Water-quality monitoring.--Gaging stations in this class are sites where regular water-quality and sediment-transport monitoring is being conducted and where the availability of streamflow data contributes to the interpretation of quality and sediment data. In Michigan, 11 stations are included in the water-quality monitoring class. One station is designated a hydrologic bench-mark station and 10 are national stream-quality accounting network (NASQAN) stations. Water-quality data from the bench-mark station is used to indicate quality characteristics of streams that have been, and probably will continue to be, relatively free of manmade influence. Water-quality data from NASQAN gaging stations are used to assess water-quality trends of significant streams.

Research.--Data from gaging stations in this class are used for particular research studies. When there are no other needs for data at these sites, the gaging stations are discontinued. In Michigan five stations are operated to support research activities involving determination of flow under ice and affects of agricultural activities on the hydrologic cycle.

Other uses.--In addition to the data-use classes described above, 11 stations provide daily water-temperature data and 2 stations provide daily specific-conductance data.

Funding

Funds for operating gaging stations in Michigan are from:

1. Federal program.--these funds are directly allocated to the USGS.

2. Other Federal Agency (OFA) programs.--these funds are transferred to the USGS by another Federal agency.

3. Coop programs.--these funds come jointly from USGS cooperative-designated funding and from a non-Federal cooperating agency. Cooperating agency support may be in the form of direct services or cash.

4. Other non-Federal programs.--these funds are provided entirely by a non-Federal agency or a private concern under the auspices of a Federal agency. In this study, funding was limited to licensing and permitting requirements for hydropower development by the Federal Energy Regulatory Commission. Funds in this category are not matched by USGS cooperative funds.

The sources of funding identified above pertain only to the collection of streamflow data; sources of funding for other activities, such as the collection of water-quality samples, may differ from the source of funding shown in table 2. Fifteen entities currently (1984) are funding the stream-gaging program.

Data Availability

Data availability refers to the times at which data from the gaging stations may be furnished to the users. In this category, three distinct time frames exist. Data can be furnished by (1) direct-access telemetry for immediate use, (2) by periodic release of provisional data, or (3) by inclusion in the annual data report published by the USGS for Michigan. In the current (1984) Michigan program, data from 129 gaging stations are available through the annual report (Miller, Oberg, and Sieger, 1984), data from 25 stations are available by telemetry, and data from 10 stations are released on a provisional basis.

Conclusions Pertaining to Data Use

On the basis of data use, sufficient justification was found to maintain all gaging stations except one, station 162900, in the stream-gaging program. This station provides only limited data having no transfer value. Unmet data needs were noted for the River Raisin at Manchester and near Adrian, the Kalamazoo River near Comstock, the River Rouge near Rockford, and the Black River near Bessemer.

ALTERNATIVE METHODS OF DEVELOPING STREAMFLOW DATA

Another step in evaluating the stream-gaging program in Michigan is to investigate alternative methods of obtaining daily streamflow data and to identify stations where alternative methods can be used. By using such methods as flow routing and multiple-regression analysis, information about daily mean streamflow at some gaging stations may be obtained in a more cost-effective manner than by operating a continuous-record gaging station. Sites that are primary candidates for alternative methods of streamflow estimation are those that are upstream or downstream from gaging stations on the same stream. The accuracy of the estimated streamflow at such sites may be suitable because of the high redundancy of flow information between gaging stations. Similar watersheds, located in the same physiographic and climatic area, also may have potential for alternative methods.

Alternative methods of determining streamflow were considered for all gaging stations. However, on the basis of high correlation of flow records and known data uses, only 10 stations were selected. Two alternative methods--flow routing and multiple-regression analysis--were considered in the Michigan analysis. Desirable attributes of these two methods are that (1) they are computer oriented and easy to apply, (2) they have an available interface with the USGS WATSTORE Daily Values File (Hutchinson, 1975) thereby permitting easy calibration, (3) they are technically sound and generally acceptable, and (4) they provide an estimate of the accuracy of the simulated streamflow.

Flow Routing

Flow routing uses the law of conservation of mass and the relationship of storage in a reach to outflow from the reach. The reach is treated as a unit without subdivision. Hydraulics of the system are not considered. Only a few parameters are required. Input is usually a discharge hydrograph at the upstream of the reach; output is a discharge hydrograph at the downstream end. Several different flow-routing methods are available. For this analysis of Michigan streams, unit-response flow routing was used.

A unit-response flow-routing model, (Doyle and others, 1983) was used to route flow from one or more upstream sites to a downstream site. Downstream hydrographs are produced by the convolution of upstream hydrographs with their appropriate unit-response functions. The model has the capability of combining hydrographs, multiplying a hydrograph by a ratio, changing the timing of a hydrograph, and routing hydrographs through reservoirs with specified operating procedures. Calibration of the flow-routing model is achieved using observed upstream and downstream hydrographs and estimates of tributary flows.

Model options provide for the development of unit-response functions using either storage-continuity or diffusion-analogy techniques. Selection of the appropriate options depends primarily upon the variability of wave celerity (travel time) and dispersion (channel storage) throughout the range of discharges to be routed. Both storage-continuity or diffusion-analogy techniques require determination of two parameters that describe storage-discharge relationships in a given reach and traveltime of flow passing through the reach. In both techniques the two parameters are calibrated by trial and error.

In storage continuity, 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. A response function is derived by modifying a translation hydrograph technique developed by Mitchell (1962) for open channels. A triangular pulse (Keefer and McQuivey, 1974) is routed through reservoir-type storage and then transformed by a summation-curve technique to a unit response of desired duration.

In diffusion analogy, the two parameters that describe the routing reach are K_0, a wave dispersion or damping coefficient, and C_0, the floodwave celerity. K_0 controls spreading of the wave (analogous to K_s in the storage-continuity technique) and C_0 controls travel time (analogous to W_s in the storage-continuity technique). A single unit-response function, corresponding to a single linearization and determination of a single value for K_0 and C_0 , can usually be used to adequately route daily flows. If routing coefficients vary drastically with discharge, however, a single unit-response function may not provide acceptable results. Linearization about a low-range discharge may result in overestimated high flows that arrive late at the downstream site; whereas, linearization about a high-range discharge may result in low flows that are underestimated and arrive too soon. For such cases, multiple linearization (Keefer and McQuivey, 1974), which uses a family of unit-response functions can be used to represent the system. In multiple linearization, C_0 and K_0 are varied with discharge so tables of wave celerity (C_0) and dispersion coefficient (K_0) are used.

The system's response to input at the upstream end of the reach does not provide the total solution to most flow-routing problems. The unit-response method does not account for flow from the intervening area between upstream and downstream sites. Such flow may not be known or may be estimated. An estimating technique that often proves satisfactory is the multiplication of known flows at an index gaging station by a factor (for example, a drainage-area ratio).

Parameters used for a unit-response flow-routing study of six selected gaging stations are shown in table 3. For this study, a single-linearization diffusion-analogy was used.

Table 3.--Flow-routing parameters at selected gaging stations

Down-stream station	Process	First upstream station	Second upstream station	Step	Wave celerity C_0 (cubic feet per second)	Dispersion coefficient K_0 (square feet per second)	Reach length (mile)	Flow adjust-ment ratio	Reach/ process description
Portage Creek									
[a]DS1	Route	106400	--	1	1.50	73.6	2.73	1.00	West Fork Portage Creek routed to mouth
DS2	Add	106300	DS1	2	--	--	--	--	Add routed flow at DS1 to record at 106300
106500	Route	DS2	--	3	0.71	107	2.97	1.14	Portage Creek near Kalamazoo
Shiawassee River									
DS1	Route	144500	--	1	2.91	1,660	16.9	1.10	Upstream reach
145000	Route	DS1	--	2	2.73	3,400	14.3	1.08	Downstream reach
Flint River									
DS1	Route	148500	--	1	3.85	6,330	35.4	1.12	Reach between stations 148500 and 149000
149000	Add	148720	DS1	2	--	--	--	--	Add Brent Run to routed flow
Cass River									
151500	Route	150800	--	1	3.75	5,820	22.3	1.30	Wahjameha to Frankenmuth
Pine River									
155500	Route	155000	--	1	2.40	2,020	31.0	1.35	Alma to Midland
Huron River									
174800	Route	174500	--	1	2.40	1,090	9.16	1.10	Ann Arbor to Ypsilanti

[a] DS, dummy station number holding intermediate results.

Multiple-regression analysis

Multiple-regression analysis can also be used to obtain estimates of daily streamflow. Regression equations can be developed that relate daily flows (or their logarithms) at a single station to daily flows at a combination of upstream, downsteam, and tributary stations. This method, unlike the flow-routing method, is not limited to sites on streams that have upstream stations. The explanatory variables in the regression analysis can be stations from different watersheds, or downstream and tributary watersheds. Regression analysis has many of the same attributes as flow routing in that it is easy to apply, provides indices of accuracy, and is generally accepted as a good tool for estimation. The theory and assumptions of regression analysis are described in several textbooks (for example, Draper and Smith, 1966, and Kleinbaum and Kupper, 1978). Application of regression analysis to hydrologic problems is described by Riggs (1973) and Thomas and Benson (1970). Only a brief description of regression analysis is provided in this report.

A linear regression equation of the following form was developed for estimating daily mean discharges in Michigan:

$$y_i = B_0 + \sum_{j=1}^{p} B_j x_j + e_i \qquad (1)$$

where

y_i = daily mean discharge at station i (dependent variable),
x_j = daily mean discharges at nearby stations (explanatory variables),
B_0 and B_j = regression constant and coefficients, and,
e_i = the random error term.

The above equation is calibrated (B_0 and B_j are estimated) using observed values of y_i and x_j (observed daily mean discharges can be retrieved from the WATSTORE Daily Values File). Values of discharges at station j may be for the same day as discharges at station i or they may be for previous or future days, depending on whether station j is upstream or downstream of station i. Once the equation is calibrated and verified, future values of discharges at station i are estimated using observed values at station j. Regression constant and coefficients (B_0 and B_j) are tested to determine if they are significantly different from zero. A given station j should only be retained in the regression equation if its regression coefficient (B_j) is significantly different from zero. The calibration period should be representative of the range of flows that could occur at station i. The results should be examined by plotting (1) residuals e_i (difference between simulated and observed discharges) against dependent and explanatory variables in the equation, and (2) simulated and observed discharges versus time. These tests determine if the linear model is appropriate or whether some transformation of the variables is needed, and if there is any bias in the equation such as overestimating low flows. In this analyses of Michigan streams, the tests indicated that a linear model with y_i and x_j, in cubic feet per second, was appropriate.

Use of a regression relation to synthesize data at a discontinued gaging station entails a reduction in the variance of the streamflow record relative to that which would be computed from an actual record of streamflow at the site. The reduction in variance, expressed as a fraction, is approximately equal to one minus the square of the correlation coefficient that results from the regression analysis.

Parameters used for a regression-analyses study of 10 selected gaging stations are shown in table 4. Single regression equations were developed to describe the entire range of discharge.

Table 4.--Regression parameters at selected gaging stations

Station	Inter- cetp B_0	Coeffi- cient B_1	Station 1	Coeffi- cient B_2	Station 2	Coeffi- cient B_3	Station 3	Correla- tion coeffi- cient squared
063000	116.6	2.65	061000	0.57	062000	0.97	062500	0.91
101500	92.89	1.06	101000	[b]--	--	--	--	.98
106500	-17.77	1.55	106300	.89	106400	--	--	.91
119000	93.24	1.02	116000	3.47	116500	.60	117500	.97
145000	-26.93	1.13	144500	.15	[a]144500	--	--	
149000	-63.76	.99	148500	.35	[a]148500	--	--	.97
150800	25.80	.93	150800	.28	[a]150800	--	--	.97
155500	-24.58	1.36	155000	--	--	--	--	.93
165500	19.74	1.05	164000	1.31	164500	--	--	.99
174800	59.72	1.03	174500	--	--	--	--	.98

[a] Positively lagged variable

[b] Additional stations not significant in model.

Results of Data Generation by Alternative Methods

The accuracy of daily streamflow data generated by flow routing and regression analysis (table 5) varied widely among the stations examined. The percentage of days having 10 percent or less error ranged from 85 percent, based on regression analysis for station 101500, to 29 percent, based on routing analysis for station 155500. In general, the regression analysis generated more accurate data than flow routing for unregulated streams; whereas, flow routing generated more accurate data for highly regulated streams. Except for station 101500, which is too near sewage-treatment and powerplant operations for results to be meaningful, data generated by alternate methods were not sufficiently accurate to substitute for the operation of a continuous gaging station.

Table 5.--Accuracy of data generated by alternate methods
[<, less than; >, greater than]

Station	Alternate method	Mean absolute error (percent)	Simulated flows having percentage errors as follows:						Water year	
			5	10	15	20	25	25	Start	End
063000	Regression	15.9	22	42	59	71	80	20	1976	1978
101500	Regression	5.69	64	85	94	97	98	2	1980	1982
106500	Regression	9.02	38	64	82	93	96	4	1976	1978
	Routing	16.6	17	35	51	69	80	20	1976	1978
119000	Regression	6.89	50	77	90	96	98	2	1979	1981
145000	Regression	14.1	31	53	66	77	85	15	1976	1978
	Routing	11.7	28	54	72	84	91	9	1976	1978
149000	Regression	15.1	22	45	65	75	81	19	1976	1978
	Routing	10.0	37	61	79	88	93	7	1976	1978
151500	Regression	11.0	36	62	74	83	91	9	1979	1982
	Routing	12.3	26	47	66	81	90	10	1979	1982
155500	Regression	21.2	24	37	48	58	66	34	1975	1977
	Routing	25.0	13	29	45	54	63	37	1975	1977
165500	Regression	7.19	41	75	92	97	99	1	1976	1978
174800	Regression	10.4	34	58	74	86	93	7	1975	1977
	Routing	10.0	38	60	75	84	92	8	1975	1977

COST-EFFECTIVE RESOURCE ALLOCATION

K-CERA

A set of techniques called K-CERA (Kalman-filtering for cost-effective resource allocation) was developed by Moss and Gilroy (1980) to study the cost effectiveness of a network of gaging stations in the Lower Colorado River Basin. In that study, the measure of the network's effectiveness was measured in terms of the extent to which it minimized the sum of error variances in estimating annual mean discharge at each station. For the study of Michigan gaging stations, the original version of K-CERA has been modified to include, as an optional measure of effectiveness, the sums of the variances of the percentage errors of instantaneous discharges at all continuous gaging stations. Also, a procedure for dealing with missing record has been developed and incorporated into the original version. The probabilities of missing record increase as the period between service visits to a stream gage increase. Additional information on the theory or application of K-CERA is presented in Moss and Gilroy (1980) and Gilroy and Moss (1981).

Mathematical Program.--A mathematical program called the "Traveling Hydrographer" is used to optimize cost effectiveness of data-collection activities. The program attempts to allocate among gaging stations a predefined budget in such a manner that the field operation is the most cost effective possible. In this analysis, the frequency of use (number of times per year) of each of a number of routes that may be used to service gaging stations and to make discharge measurements is an available set of decisions. The range of options within the program for usage is from zero to daily for each route. A route is defined as one or more gaging stations and the least-cost travel that takes the hydrographer from his base of operation to each station and back to base. A route will have associated with it an average cost of travel and an average cost of servicing each station visited along the way.

In this part of the analysis, the first step is to define a set of practical routes. This set of routes frequently will contain the round-trip path to an individual gaging station so that the needs of that station can be considered in isolation from other stations. Another step in this part of the analysis is the determination for each gaging station of any requirements for special visits such as maintainence of recording equipment or collection of water-quality data. Such special visits are considered to be inviolable constraints in terms of the minimum number of visits to each station. A final step is to use the above to determine, on an annual basis, the number of times (N_i) that the i^{th} route for $i = 1,2,\ldots,NR$, where NR is the number of practical routes can be used so that (1) the budget for the network is not exceeded, (2) the minimum number of visits to each station is made, and (3) the total uncertainty in the network is minimized. Figure 4 shows this step in the mathematical-programing form. Figure 5 is a tabular layout of the problem.

i = route designation
j = station designation
N = number of times route is used

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

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

Such that:
Budget $\geq T_c$ ≡ total cost of operating network

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

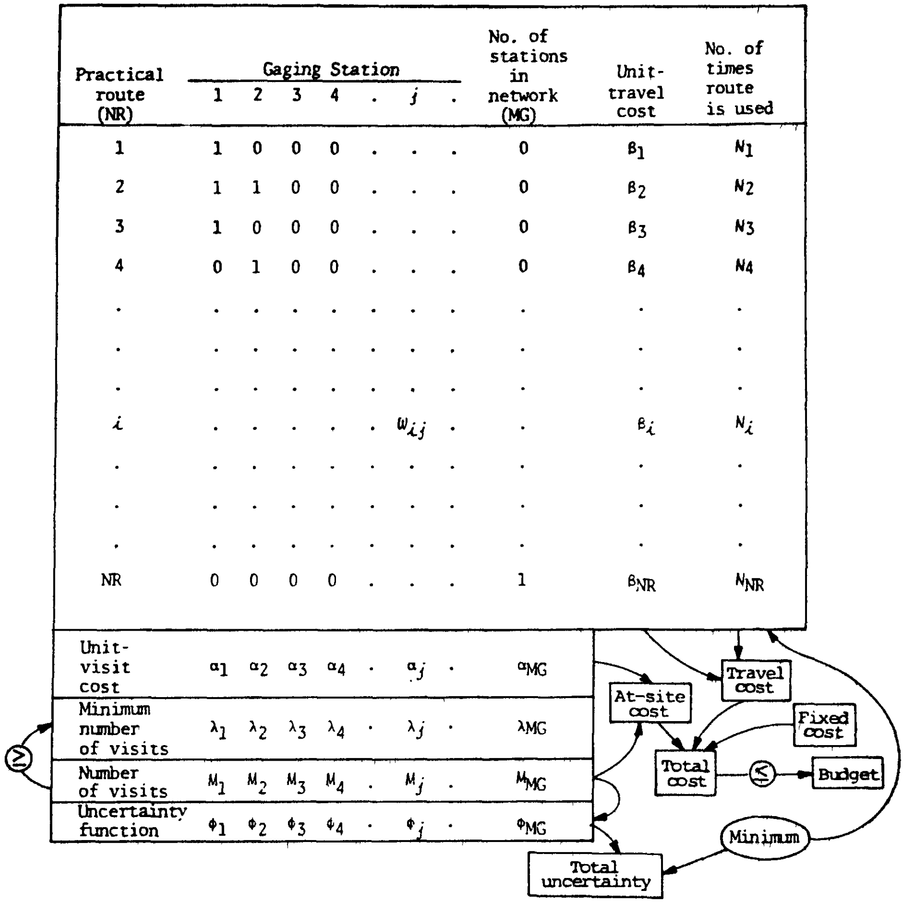
F_c ≡ fixed cost
α_j ≡ unit cost of visit to station
NR ≡ number of practical routes chosen
β_i ≡ travel cost for route i
N_i ≡ annual number of times route i is used (an element of $\underline{N}$)

and such that:

$$M_j \geq \lambda_j$$

λ_j ≡ minimum number of annual visits to station j.

Figure 4.--Schematic of mathematical-programming form of the optimization of the routing of hydrographers



Practical route (NR)	Gaging Station 1	2	3	4	.	j	.	No. of stations in network (MG)	Unit-travel cost	No. of times route is used
1	1	0	0	0	.	.	.	0	β_1	N_1
2	1	1	0	0	.	.	.	0	β_2	N_2
3	1	0	0	0	.	.	.	0	β_3	N_3
4	0	1	0	0	.	.	.	0	β_4	N_4
.	.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.	.
i	.	.	.	.	.	ω_{ij}	.	.	β_i	N_i
.	.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.	.
NR	0	0	0	0	.	.	.	1	β_{NR}	N_{NR}
Unit-visit cost	α_1	α_2	α_3	α_4	.	α_j	.	α_{MG}		
Minimum number of visits	λ_1	λ_2	λ_3	λ_4	.	λ_j	.	λ_{MG}		
Number of visits	M_1	M_2	M_3	M_4	.	M_j	.	M_{MG}		
Uncertainty function	Φ_1	Φ_2	Φ_3	Φ_4	.	Φ_j	.	Φ_{MG}		

Figure 5.--Tabular form of optimization of routing of hydrographers

In figure 5, the zero-one matrix (ω_{ij}) defines a route in terms of stations that comprise it. A value of one in row i and column j indicates that gaging station j will be visited on route i; a value of zero indicates that it will not. Unit travel costs (B_i) are per-trip costs for hydrographer's traveltime, cost of servicing each station visited along the specified route, and related per diem and for operation, maintenance, and rental of vehicles. The sum of the products of B_i and N_i for $i=1,2,\ldots,NR$ is the total annual travel cost associated with the set of decisions $= (N_1, N_2, \ldots, N_{NR})$.

The unit-visit cost (α_j) is the average service and maintenance costs incurred on a visit to a station plus the average cost of making a discharge measurement. Minimum visit constraint is denoted by row λ_j, $j=1,2,\ldots, MG$, where is the number of gaging stations. Row M_j, $j=1,2,\ldots,MG$ specifies the number of visits to each station. M_j is the sum of the products of ω_{ij} and N_i for all i and must equal or exceed λ_j for all j if N is to be a feasible solution to the problem. Total uncertainty in the estimates of discharges of 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 $j=1,2,\ldots,MG$.

The total cost expended at the stations is equal to the sum of the products of unit-visit cost (α_j) and annual number of visits (M_j) for all stations (j). Cost of record computation, documentation, and publication is assumed to be influenced negligibly by the number of visits to a station and is considered along with overhead as a fixed cost. Total cost of operating the network equals the sum of travel costs, at-site costs, and fixed costs. Total costs must be less than or equal to the budget.

The steepest decent search used to solve the decision problem does not guarantee a true optimum solution (Moss and Gilroy, 1980). However, a locally optimum set of values for N obtained with this technique define an efficient strategy for operating the network. True optimum strategy cannot be defined unless all undominated, feasible strategies are tested.

Description of Uncertainty Functions

As noted earlier, uncertainty in streamflow records is measured in this study as the average relative variance of estimation of instantaneous discharges. The accuracy of a streamflow estimate depends on how that estimate was obtained. Three situations are considered in this study: (1) streamflow is estimated from measured discharge and correlative data using a stage-discharge relation (rating curve), (2) the streamflow record is reconstructed using secondary data at nearby stations because primary correlative data are missing, and (3) primary and secondary data are unavailable for estimating streamflow. The variances of the errors of the estimates of flow that would be employed in each situation were weighted by the fraction of time each situation is expected to occur. Thus the average relative variance would be

$$\bar{V} = \varepsilon_f V_f + \varepsilon_r V_r + \varepsilon_e V_e \qquad (2)$$

with

$$1 = \varepsilon_f + \varepsilon_r + \varepsilon_e \qquad (3)$$

where

$\bar{V}$ is the average relative variance of the errors of streamflow estimates,
ε_f is the fraction of time that the primary recorders are functioning,
V_f is the relative variance of the errors of flow estimates from primary recorders,
ε_r is the fraction of time that secondary data are available to reconstruct streamflow records given that the primary data are missing,
V_r is the relative variance of the errors of estimation of flows reconstructed from secondary data,
ε_e is the fraction of time that primary and secondary data are not available to compute streamflow records, and
V_e is the relative error variance of the third situation.

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

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

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

where

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

where

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

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

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

The variance of the observed residuals z(t) is

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

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

If the recorder at the primary site fails and there are no concurrent data at other sites that can be used to reconstruct the missing record at the primary site, there are at least two ways of estimating discharges at the primary site. A recession curve could be applied from the time of recorder stoppage until the gage was once again functioning or the expected value of discharge for the period of missing data could be used as an estimate. The expected-value approach is used in this study to estimate V_e, the relative error variance during periods of no concurrent data at nearby stations. If the expected value is used to estimate discharge, the value that is used should be the expected value of discharge at the time of year of the missing record because of the seasonality of the streamflow processes.

The variance of streamflow, which also is a seasonally varying parameter, is an estimate of the error variance that results from using the expected value as an estimate. Thus the coefficient of variation squared $(C_v)^2$ is an estimate of the required relative error variance V_e. Because C_v varies seasonally and the times of failures cannot be anticipated, a seasonally averaged value of C_v is used:

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

where

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

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

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

The variance V_r of the relative error during periods of reconstructed streamflow records is estimated on the basis of correlation between records at the primary site and records from other gaged nearby sites. The correlation coefficient ρ_c between the streamflows with seasonal trends removed at the site of interest and detrended streamflows at the other sites is a measure of the goodness of their linear relationship. The fraction of the variance of streamflow at the primary site that is explained by data from the other sites is equal to $\rho_c{}^2$. Thus, the relative error variance of flow estimates at the primary site obtained from secondary information will be

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

Because errors in streamflow estimates arise from three different sources with widely varying precisions, the resultant distribution of those errors may differ significantly from a normal or log-normal distribution. This lack of normality causes difficulty in interpretation of the resulting average estimation variance. When primary and secondary data are unavailable, the relative error variance V_e may be very large. This could yield correspondingly large values of $\bar{V}$ in equation (2) even if the probability that primary and secondary information are not available, ε_e, is quite small.

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

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

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

Application of K-CERA in Michigan

Missing record probabilities.--As previously discussed, statistical characteristics of missing stage or other correlative data for computation of streamflow records can be defined by a single parameter, k, (equation 4), where the average time to failure is $1/k$. To estimate $1/k$ in Michigan, a 3-year period of actual data collection was used. During the period, there was little change in technology and gaging stations were visited once every 6 weeks. During the ice-free portion of the period, the average amount of lost record was 3.2 percent (J.B. Miller, oral commun., 1984). However, the percentage of loss varied among offices and station types (table 6). The highest percentage of lost record determined for the 1981 through 1983 period was 31.6 for bubble gages in the Grayling office. However, this figure is based on only six station-years of record. Only one bubble gage is currently operated by the Grayling office. No lost record was accumulated for bubble gages in the Escanaba office during the 1981-1983 ice-free period based on 18 station years of record. Values of $1/k$ from table 6 were used to determine ε_f, ε_r, and ε_e for each of the 129 gaging stations as a function of the individual frequencies of visit.

Table 6.--Missing record characteristics during ice-free seasons, 1981 - 1983

Office	Type of sensor	Record loss (percent)	Time to recorder malfunction (days)
Escanaba	Float	1.58	1,270
	Bubble-gage	0.00	--
Grayling	Float	4.54	433
	Bubble-gage	31.6	52
Lansing	Float	2.39	835
	Bubble-gage	8.49	225

Coefficient of variation and cross-correlation coefficient. --To compute values of V_e and V_r, daily streamflow records for each of the 129 gaging stations were retrieved from WATSTORE (Hutchinson, 1975). The records are for the last 30 years or the part of the last 30 years for which daily streamflow values are stored. For each station that had data for 3 or more complete water years the value of C_v was computed and various options were explored to determine maximum ρ_c. For stations that only had data for less than 3 water years, values of C_v and ρ_c were estimated subjectively. In addition to other nearby stations, some stations had other means by which streamflow data could be reconstructed during downtime. At several stations, records from nearby hydropower plants have rated their turbines to determine discharge through them so that these flow records can be used for streamflow reconstruction. A ρ_c value of 0.95 was estimated for stations near hydropower plants based on analysis of selected stations. Parameters for each station and the auxiliary records that gave the highest cross-correlation coefficient are listed in table 7 (at the end of the report).

Kalman Filtering.--Variance V_f was determined for each of the 129 gaging stations. This required: (1) long-term rating analysis and computation of residuals of measured discharges from the long-term rating, (2) time-series analysis of residuals to determine input parameters for Kalman-filter analysis of streamflow records, and (3) computation of error variance V_f as a function of the time-series parameters, the discharge-measurement-error variance, and the frequency of discharge measurements.

Definition of long-term rating functions was complicated by the fact that most Michigan streams are affected by ice backwater for about 3 months each year. Therefore, rating functions were defined for the 9-month open-water periods rather than for the entire year. Ratings were not defined for ice-backwater periods. Instead, it was assumed that discharge measurements during these periods would continue to be made at fixed intervals. Therefore, all measures of variance reported apply only to open-water periods.

Long-term rating functions were defined by pairs of stage and discharge values assembled in a rating table. Estimation of discharge for stages not explicitly defined at rating points was carried out by linear interpolation between the logarithms of the designated rating points. Residuals from the long-term rating were determined by subtracting logarithms of rated discharges from logarithms of measured discharges. For residuals, the mean was compared to the variance to ensure that the mean was not significantly different than zero. Ratings with the mean of the residuals significantly different than zero are biased.

Long-term rating functions were initially estimated on the basis of existing rating tables and modified, as necessary, by graphical inspection. Stage offsets (Rantz and others, 1982) were applied to linearize the stage/discharge relationship. The rating table determined for station 096400, table 8, is based on a -0.5 ft offset. Table 9 shows measured discharge data and computed residuals. The relationship between long-term rating points and discharge data is shown on figure 6.

Table 8.--Long-term 9-month open-water rating for station 096400

Stage (feet)	Discharge (cubic feet per second)
1.50	32.8
3.90	405
5.80	1,325

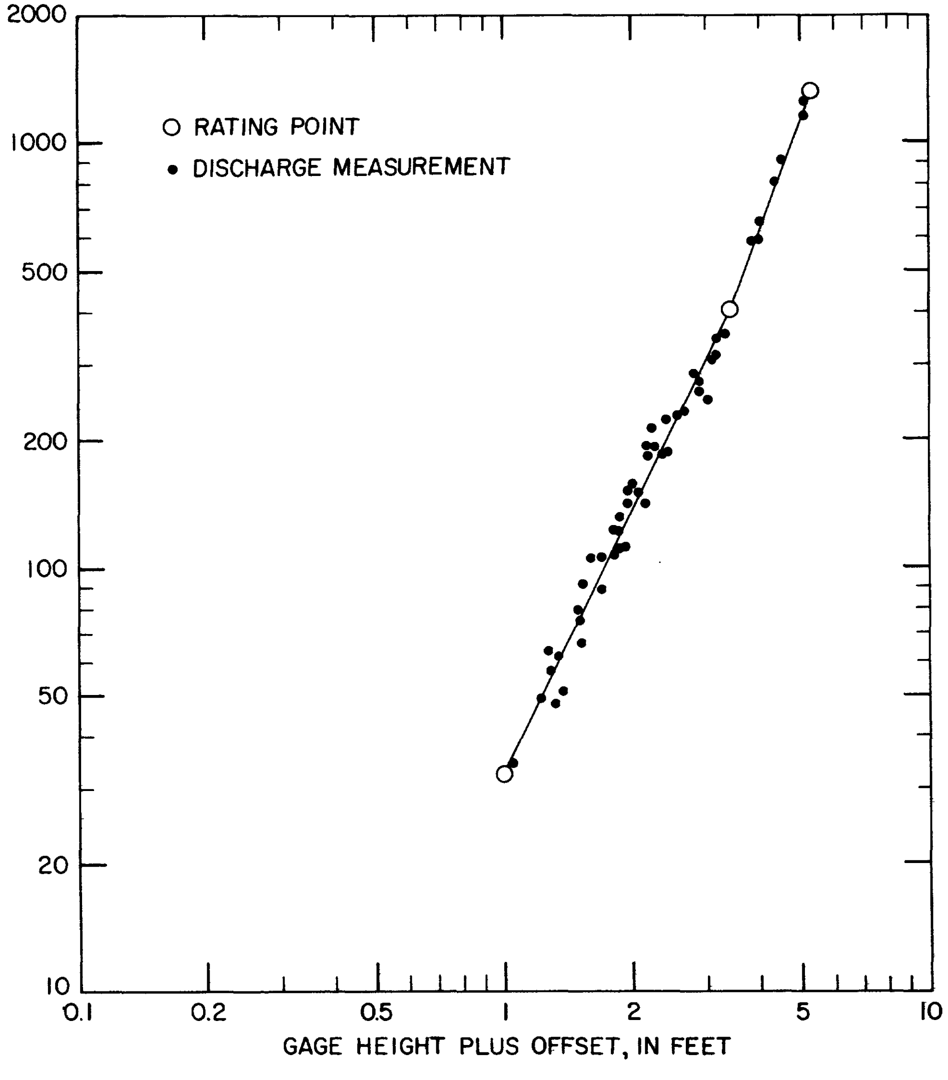


Figure 6.--Stage discharge rating for station 096400.

Table 9.--Discharge and computed residuals for station 096400

Measurement number	Date of measurement	Gage height (feet)	Measured discharge (cubic feet per second)	Log_{10} measured discharge (cubic feet per second)	Log_{10} Residual (cubic feet per second)
166	Oct. 19, 1976	1.82	47.9	1.680	-0.083
167	Nov. 22, 1976	1.89	50.8	1.705	-.103
170	Mar. 4, 1977	3.19	232	2.365	-.033
171	Apr. 7, 1977	3.86	358	2.553	-.043
172	May 12, 1977	2.38	131	2.117	.038
173	June 13, 1977	1.98	79.3	1.899	.033
174	July 19, 1977	1.55	34.5	1.537	-.021
175	Aug. 22, 1977	1.72	48.7	1.687	-.005
176	Oct. 3, 1977	2.37	111	2.045	-.028
177	Oct. 31, 1977	2.02	66.2	1.820	-.068
178	Dec. 6, 1977	2.63	141	2.149	-.041
181	Mar. 27, 1978	4.83	815	2.911	.026
182	May 2, 1978	3.08	229	2.359	-.001
183	June 8, 1978	2.34	122	2.086	.026
184	June 28, 1978	5.02	905	2.956	.019
185	July 18, 1978	2.44	153	2.184	.077
186	Aug. 15, 1978	1.83	62.0	1.792	.022
187	Sep. 18, 1978	2.57	150	2.176	.011
188	Oct. 26, 1978	2.20	88.2	1.945	-.043
189	Nov. 30, 1978	2.32	108	2.033	-.016
192	Mar. 12, 1979	4.42	590	2.770	-.001
193	Apr. 16, 1979	3.81	351	2.545	-.038
194	May 29, 1979	2.46	155	2.190	.074
195	May 29, 1979	2.45	151	2.178	.067
196	July 10, 1979	2.10	106	2.025	.090
197	Aug. 3, 1979	2.03	91.9	1.963	.068
198	Sep. 10, 1979	1.79	63.8	1.804	.061
199	Oct. 9, 1979	1.84	61.0	1.785	.008
200	Nov. 14, 1979	2.01	75.6	1.878	-.004
201	Jan. 2, 1980	3.39	275	2.439	-.023
203	Feb. 25, 1980	2.94	224	2.350	.038
204	Apr. 3, 1980	3.68	349	2.542	-.004
205	May 15, 1980	2.73	213	2.328	.097
206	June 26, 1980	2.68	194	2.287	.076
207	July 31, 1980	2.50	158	2.198	.064
208	Sep. 4, 1980	3.68	319	2.503	-.044
209	Oct. 10, 1980	2.37	122	2.086	.012
210	Nov. 13, 1980	2.41	112	2.049	-.043
211	Dec. 18, 1980	2.88	183	2.262	-.026
213	Feb. 23, 1981	4.50	650	2.812	.017
214	Mar. 30, 1981	2.77	191	2.281	.033
215	May 22, 1981	3.31	289	2.460	.023
216	June 11, 1981	3.58	309	2.489	-.029
217	July 13, 1981	2.45	141	2.149	.037
218	Aug. 19, 1981	2.69	181	2.257	.042
219	Sep. 23, 1981	3.36	260	2.414	-.038
220	Oct. 28, 1981	3.51	250	2.397	-.100
221	Dec. 9, 1981	2.93	186	2.269	-.038
223	Mar. 3, 1982	2.83	183	2.262	-.007
224	Mar. 18, 1982	5.58	1,170	3.068	-.002
225	Mar. 18, 1982	5.57	1,250	3.096	.023
226	Apr. 14, 1982	4.34	594	2.773	.025
227	May 19, 1982	2.77	193	2.285	.038
228	June 23, 1982	3.05	228	2.357	.007
229	Aug. 3, 1982	2.20	106	2.025	.036
230	Sep. 14, 1982	1.77	56.7	1.753	.024

The time series of residuals (in logarithmic units) is used to compute sample estimates of q and β by determining the best fit autocovariance function to the time series of residuals. Measurement variance (r) is determined from estimates of accuracy made by hydrographers at the time of the measurement (table 10). The measurement variance at a station was computed as the mean measurement variance for all discharge measurements used in defining the long-term rating.

Table 10.--Measurement variance

[ft^3/s, cubic feet per second; <, less than; >, greater than]

Measurement classification	Error bounds (percent)	Average error (percent)	Measurement variance $\log_{10}(\mathrm{ft}^3/\mathrm{s})$
Excellent	<2	1.0	0.00002
Good	<5	3.5	.00023
Fair	<8	6.5	.00080
Poor	>8	12	.00270

As perviously discussed, q and β can be expressed as the process variance of the shifts from the rating curve and the 1-day autocorrelation coefficient of these shifts. Table 11 (at end of report) presents a summary of the autocovariance analysis expressed in terms of 1-day autocorrelation, measurement variance, and process variance. Process variance is computed as the difference between the variance of the residuals about the long-term rating function and the measurement variance. The measurement variance is based on the measurement rating given in the field by the hydrographer. Occasionally, the measurement variance was greater than the variance of the residuals which resulted in a negative process variance. Since the process variance is non-negative definite, the measurement variance seems to be overestimated at some sites with stable controls. In these cases, process variance was set equal to 0.010 and autocorrelation was set to 0.0. The affect of differing values of 1-day autocorrelation coefficient on autocovariance functions are shown on figure 7 for selected stations.

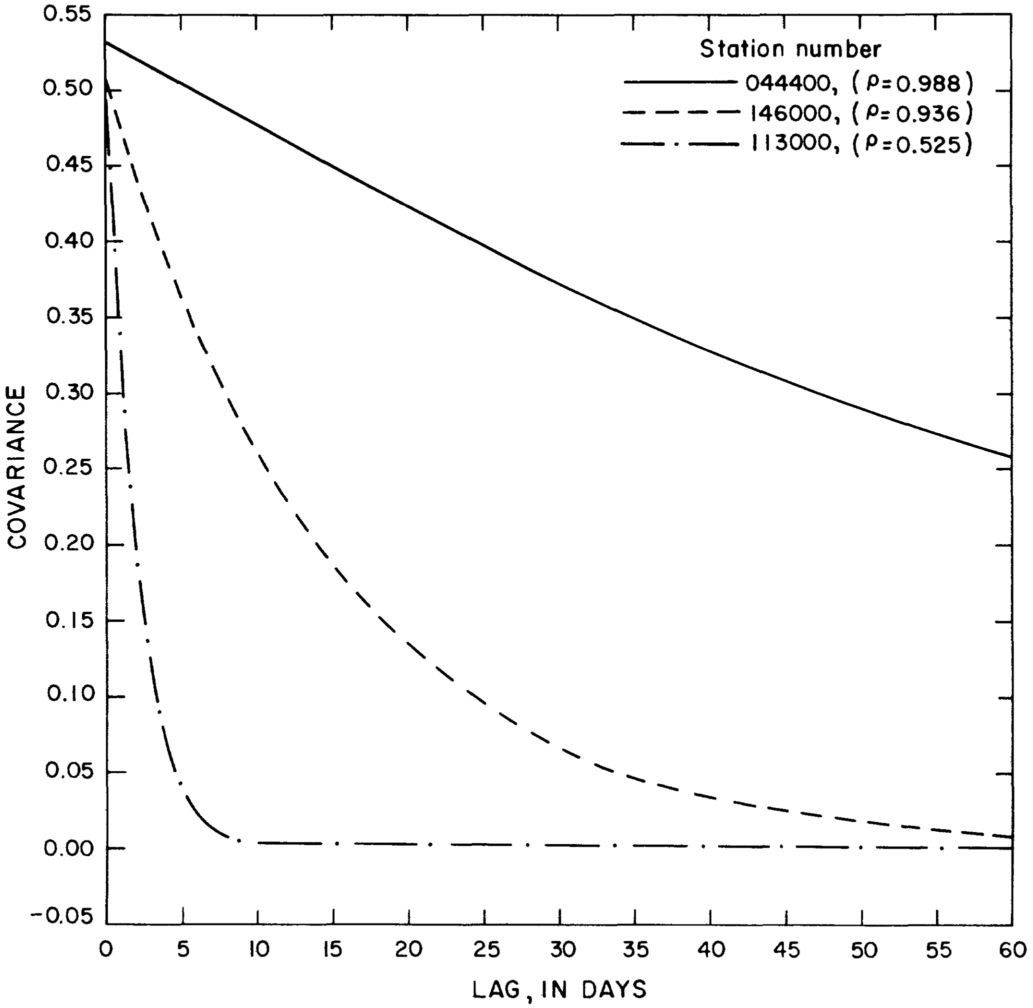


Figure 7.--Autocovariance functions for 9-month open-water season at selected stations.

Autocovariance parameters (table 11), and data from the definition of missing record probabilities (table 7), are used jointly to define uncertainty functions for each gaging station. Uncertainty functions give the relationship of total-error variance to the number of visits and discharge measurements. Stations for which autocovariance functions were previously given present typical examples of uncertainty functions and are shown in figure 8. These functions are based on the assumption that a measurement was made during each visit to the station. Due to difficult measuring and rating conditions at stations 162900 and 164300, the descriptions of the uncertainty functions were not thought to adequately describe streamflow variability. Therefore, the contribution of these stations to the standard error of the network was not included.

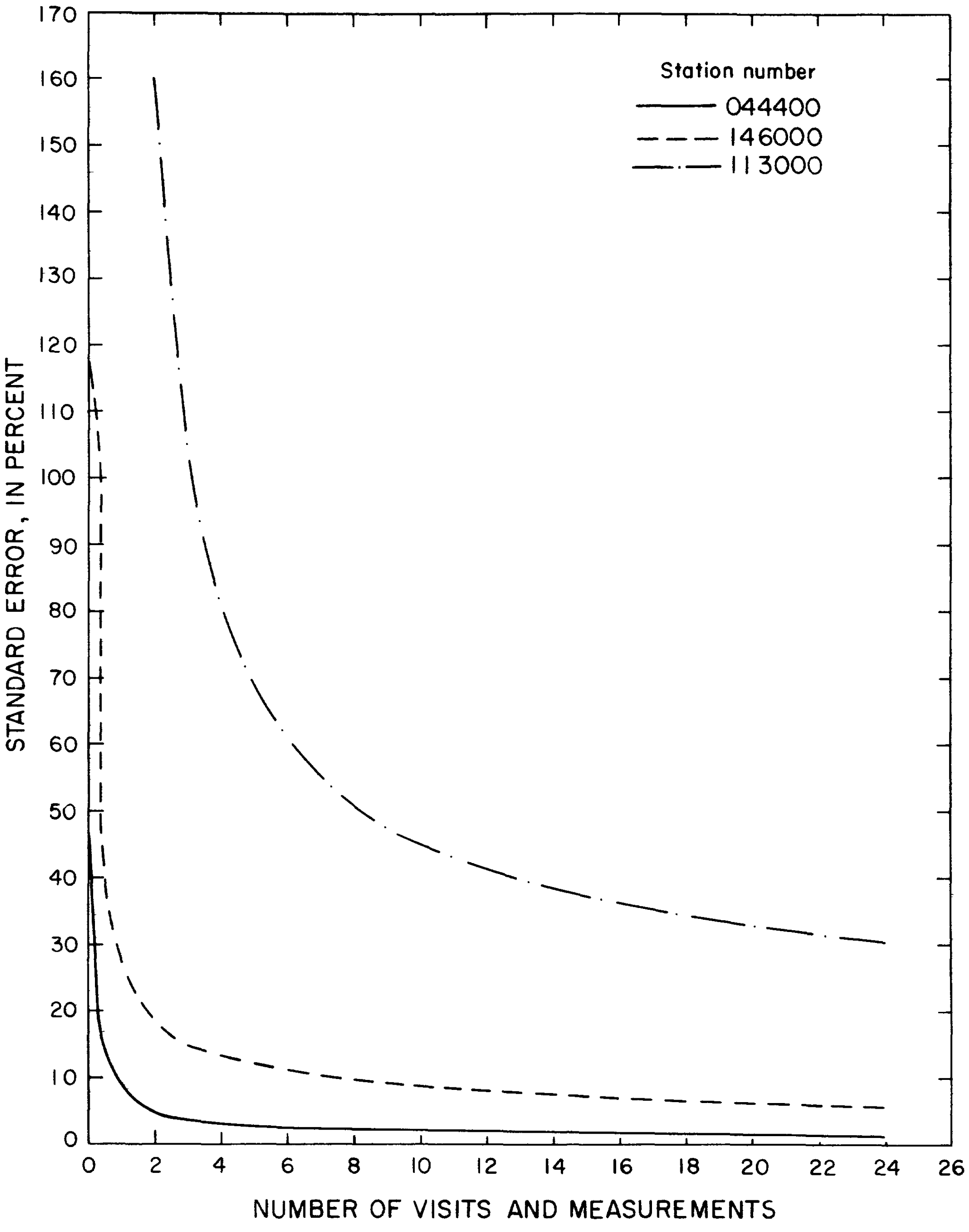


Figure 8.--Uncertainty functions for 9-month open-water season at selected stations.

Twenty-eight feasible routes were selected for visiting the 129 gaging stations after consultation with personnel in the Hydrologic Data Section of the Michigan district and after review of uncertainty functions. These routes are usable for current operating practices, for alternatives that were under consideration as future possibilities, for visits to certain key individual stations, and for visits to grouped stations where levels of uncertainty indicated more frequent visits might be useful. The routes and stations visited are summarized in table 12.

Table 12.--Practical routes and gaging stations visited

Route number	Stations visited on route						
1	059000						
2	045500						
3	058200	057814	057813	044400	057800		
4	057510	056500					
5	063000	061000	062000	062500	065393	061500	
6	033000	033500	034500	035500	036000	037500	
7	043050	041500	040500	040000			
8	001000						
9	059500						
10	062000	037500	035500	041500	057800	065393	
11	057800	065393					
12	176500						
13	108600	108500	108800	102700	102500	101800	099000
	097540	101500					
14	145000	149000	160570	159500	160600	148140	147500
	146063	146000	148500	143900	144500		
15	096515	096600	096900	106300	105500	105000	096400
	106320	106400	106500	105700	117500		
16	119000	116500	116000	115000	114500	111500	112000
	111379	113000					
17	172000	170500	170000	166000	166100	166200	166300
	166500	168000	174800	174500	176500	109000	
18	164500	164000	162900	162010	163400	161540	161800
	161580	164100	164300	161100	160800	160900	
19	112500						
20	172000	170500	166300	166200	166500	162010	162900
	163400	161100	161800	164300	164100	161580	160800
	160900						
21	166200	162900	163400	164300	160800		
22	127800	128000	130500	129000			
23	142000						
24	150500	150800	151500	156000	155500	155000	154000
25	155000	155500					
26	121500	121300					
27	135500	135600	135700	136500			
28	121900	122000	122100	122200	122500	126000	124000
	127000						

Costs associated with the routes given in table 12 for visiting gaging stations were determined. Route costs include the vehicle cost associated with driving the number of miles it takes to cover the route, the cost of the hydrographer's time while in transit, the cost to inspect the gaging station, and any per diem associated with the time it takes to complete the trip.

Fixed costs of station operation include equipment rental, batteries/-electricity, data processing and storage, computer charges, maintenance, collection of record during ice-cover periods, and miscellaneous supplies, analysis and supervisory charges. Average fixed costs were applied to each station.

Visit costs are those associated with paying the hydrographer for the time actually spent at a station making a discharge measurements. These costs vary from station to station as a function of the difficulty and time required to make the discharge measurement. Average visit times are calculated for each station based on an analysis of discharge measurement data. This time was then multiplied by the average hourly salary of hydrographers in the Michigan district to determine total visit costs.

K-CERA results.--In applying the Traveling Hydrographer program to computing the most cost-effective way of operating Michigan's gaging station program, the first step was to simulate the current practice and determine the total uncertainty associated with it. To accomplish this, the number of visits to each station and the routes used to make the visits were related to District offices in Escanaba, Grayling, and Lansing. Resulting average error of estimation for the current practice at each office and for District as a whole is plotted as a point in figures 9 through 12. The solid line on the figures represents the minimum-average-standard error for a given budget using existing instrumentation and technology. The line was defined by several computer simulations using different budgets. Table 13 (at end of report) lists some of the results of the K-CERA analysis. Constraints on gaging-station operation, other than budget, are described below.

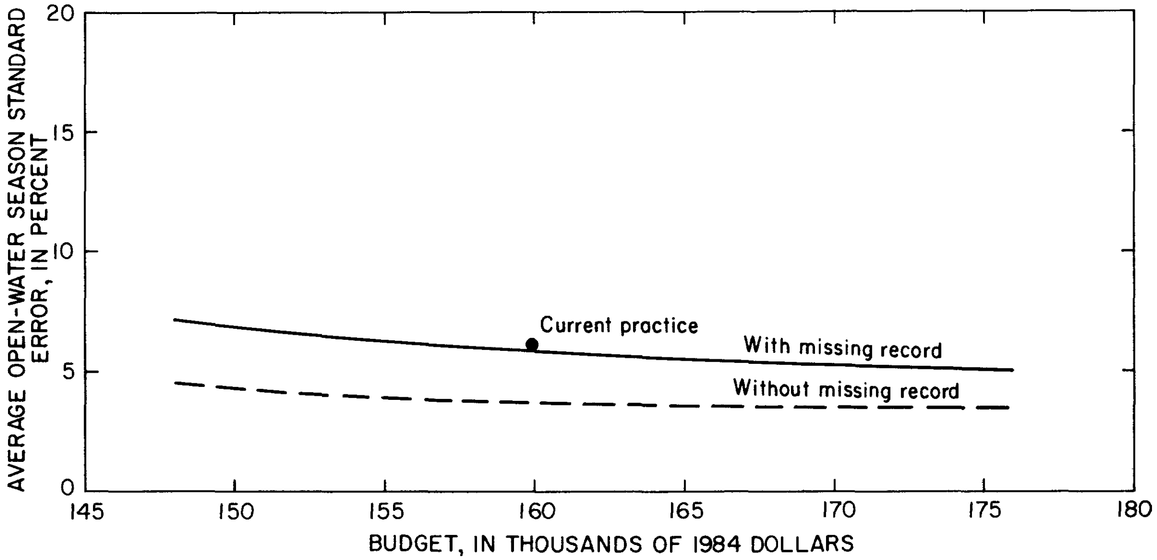


Figure 9.--Average standard error per gaging station in the Escanaba field office for 9-month open-water season

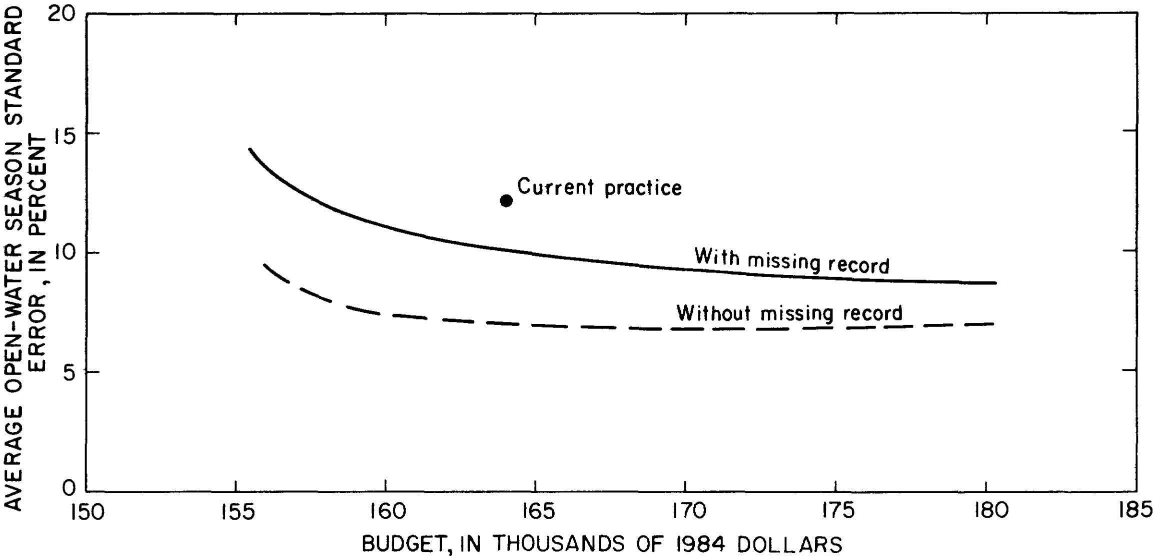


Figure 10.--Average standard error per gaging station in the Grayling field office for 9-month open-water season

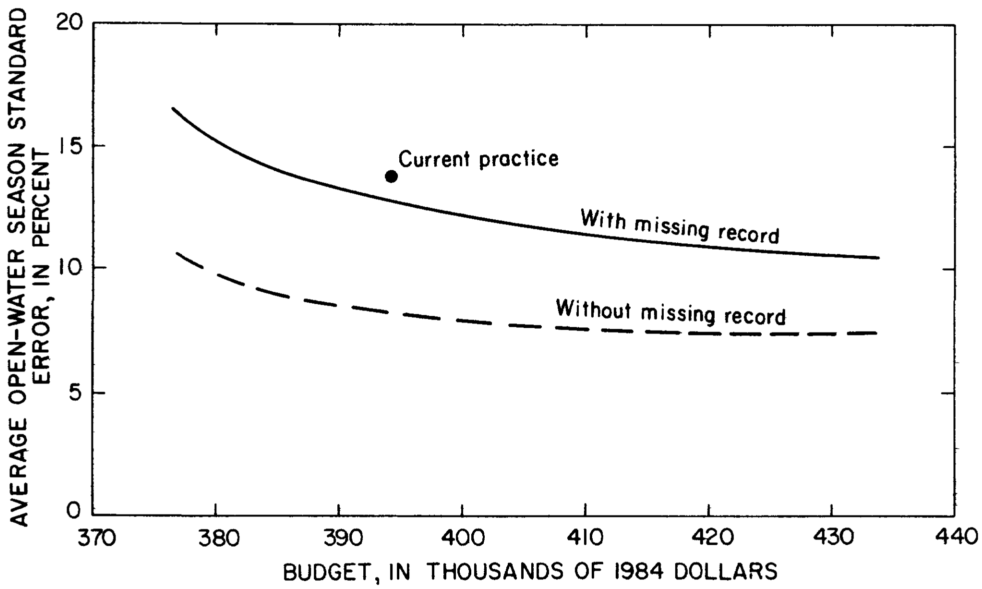


Figure 11.--Average standard error per gaging station in the Lansing district office for 9-month open-water season

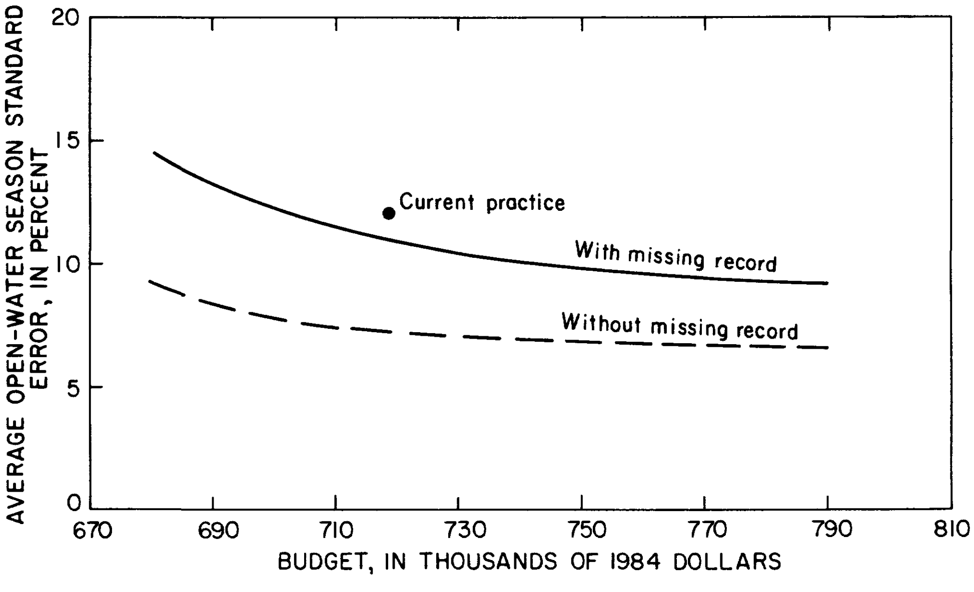


Figure 12.--Average standard error per gaging station in the Michigan district for 9-month open-water season

To determine the minimum number of times each station must be visited, consideration was only given to the physical limitations of the method used to record data. The affect of visitation frequency on the accuracy of the data and the amount of lost record is taken into account in the uncertainty analysis. A minimum requirement of four visits to a station per open-water season was determined on the basis of limitations of the batteries used to drive recording equipment, capacities of the uptake spools on the digital recorders, the need to conduct water-quality sampling, ground water well inspections, crest-stage gage inspections and discharge measurements, and low-flow site measurements. A minimum requirement of four visits during the open-water season was applied to all stations. Uncertainty curves were flattened at 15 visits per gaging station during the open-water season to prevent the cost of any particular station from exceeding reasonable limits.

Results of the K-CERA analysis in figures 9 through 12 and table 13 are predicated on a discharge measurement being made each time a station is visited. In other words, at least four measurements per open water season. Under current policy some stations are measured only twice during open-water season.

Figures 9 through 12 and table 13 are based on various assumptions (previously discussed) concerning both the time series of shifts to the stage-discharge relationship and the methods of record reconstruction. Where a choice of assumptions was available, the assumption chosen was one that would not underestimate the magnitude of the error variances.

Under the current situation, a $718,100 budget is used to operate a 129 gaging stations having an average standard error of estimate of streamflow of 12.1 percent (ranging from 0.32 percent at station 040000 to 39.0 percent at station 155500). By changing the field activities of the stream-gaging program, a reduced budget of $700,200 would result in about the same average standard error. The standard error would range from 0.36 at station 040000 to 28.2 percent at station 162010. If the $718,100 budget were retained, a change in field activities could reduce the average standard error to 11.1 percent (ranging from 0.35 for station 040000 to 27.9 percent for station 108800).

The minimum budget required to operate the 129-station program is $680,200; a smaller budget would not permit proper service and maintenance of the stations. Under the minimum budget, the average standard error is 14.4 percent (from 0.37 at station 04000 to 45.2 at station 155500).

Under revised field schedules, a 10 percent increase in budget could result in a 25 percent reduction in average standard error. A budget of $789,900 would result in an average standard error of 9.07 percent (ranging from 0.27 for station 040000 to 25.6 percent for stations 155500). The larger budget results in a significant improvement in accuracy of streamflow records.

Improved equipment can have a positive impact on reducing streamflow uncertainties throughout the range of operational budgets analyzed. For the minimum operational budget of $680,200 and no equipment malfunction, the average standard error would be 9.38 percent (shown by the curve "without missing record" on figures 9 through 12). For a budget of $789,900 and no equipment malfunction, the average standard error would be 6.53 percent.

Conclusion from K-CERA Analysis

Results of the K-CERA analysis for a 9-month open-water season are:

1. Average standard error of gaging-station network under the current $718,100 budget could be reduced about 1 percent by changing field activities. The change would result in some increases and some decreases in accuracy of records at individual sites.

2. Average standard error could be maintained at its present level of 12.1 percent with a reduced budget of about $680,200 as long as the composition of gaging stations and the characteristics of the uncertainty functions at each station remains unchanged.

3. The K-CERA analysis will need to be updated continually to be used as a management tool because composition of the network and uncertainty functions change with time. Therefore, the cost effectiveness of continuing the K-CERA analysis should be considered.

4. Funding for stations with unacceptable accuracies for the data uses should be renegotiated with the data users.

5. Schemes for reducing amount of missing record, for example increased use of local gaging station observers and satellite relay of data, should be explored and evaluated as to their cost effectiveness.

SUMMARY

Currently (1984), 129 continuous-record gaging stations are operated in Michigan at a cost of $718,200. In an analysis of the uses made of the data, it was determined that all stations except one should be retained in the program for the forseeable future. In addition, to meet data needs, stations should be installed or reactivated on River Raisin near Manchester and Adrian; on Kalamazoo River near Comstock; on Rogue River near Rockford; on Black River near Bessemer, on Presque Isle River near Marenisco, and Iron River at Caspian, to correct insufficiencies in the streamflow data network.

Ten stations were selected to evaluate the possibility of developing streamflow data by using flow routing and multiple-regression analysis. Both methods are less expensive than field collection of data; however, the accuracy of the data developed was unsatisfactory for present data needs. Should data needs change, these alternate methods may be appropriate for generating streamflow data.

A cost-effective resource-allocation analysis of the surface-water data-collection network for a 9-month open-water season indicates that the current (1984) network could be made more effecient by a change in field operations and budget. Standard error could be reduced if the present budget is retained but field operations are changed. Changes in field operations, however, could permit reducing the budget about 2.5 percent and still retain the present standard error. Implementation of flexible field schedules of visits for future networks will require continuation of the cost-effective resource allocation analysis. Costs associated with this analysis should be included in any decisions concerning the feasibility of flexible scheduling.

A major component of error in streamflow records is caused by loss of record at primary gaging stations. Upgrading equipment and developing strategies to minimize record loss seem to be key actions that can be taken to improve reliability and accuracy of streamflow data.

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TABLES

Table 1.--Selected hydrologic data for active gaging stations

Station number	Station name	Drainage area (square miles)	Period of record (water years)	Mean discharge (cubic feet per second)
001000	Washington Creek at Windigo	13.2	1965-	17.4
033000	Middle Branch Ontonagon River near Paulding	164	1942-	174
033500	Bond Falls Canal near Paulding	[a]--	1942-	142
034500	Middle Branch Ontonagon River near Trout Creek	203	1942-	67.1
035500	Middle Branch Ontonagon River near Rockland	671	1942-	532
036000	West Branch Ontonagon River near Bergland	162	1942-	176
037500	Cisco Branch Ontonagon River at Cisco Lake Outlet	50.7	1944-	47.5
040000	Ontonagon River near Rockland	1,340	1942-	1,425
040500	Sturgeon River near Sidnaw	171	1913-15, 1943-	217
041500	Sturgeon River near Alston	346	1932-41, 1943-	423
043050	Trap Rock River near Lake Linden	28.0	1967-	45.4
044400	Carp River near Negaunee	51.4	1961-	61.4
045500	Tahquamenon River near Tehquamenon Paradise	790	1953-	938
056500	Manistique River near Manistiqúe	1,100	1938-	1,446
057510	Sturgeon River near Nahma Junction	183	1967-	209
057800	Middle Branch Escanaba River at Humboldt	46.0	1959-	61.5
057813	Greenwood Diversion near Greenwood	[a]--	1973-	[b]9.22
057814	Greenwood Release near Greenwood	67.4	1973-	[b]27.1
058200	Schweitzer Creek near Palmer	23.6	1961-	[b]16.7
059000	Escanaba River at Cornell	870	1903-13, 1951-	891
059500	Ford River near Hyde	450	1955-	388
061000	Brule River near Florence, Wics.	389	1914-16, 1944-	362
061500	Paint River at Crystal Falls, Wics.	597	1944-	602

Table 1.--Selected hydrologic data for active gaging stations--Continued

Station number	Station name	Drainage area (square miles)	Period of record (water years)	Mean discharge (cubic feet per second)
062000	Paint River near Alpha	631	1952-	175
062500	Michigamme River near Crystall Falls	656	1944-	711
063000	Menominne River near Florence	1,780	1914-	1,817
096400	St. Joseph River near Burlington	201	1963-	173
096515	Hog Creek near Allen	48.7	1970-	43.6
096600	Coldwater River near Hodunk	293	1963-	253
096900	Nottawa Creek near Athens	162	1967-	147
097195	Gourdneck Canal near Schoolcraft	[a]--	1966-72, 1983-	3.78
097540	Prairie River near Nottawa	106	1963-	92.9
099000	St. Joseph River at Mottville	1,866	1924-	1,584
101500	St. Joseph River at Niles	3,666	1931-	3,259
101800	Dowagiac River at Sumnerville	255	1961-	286
102500	Paw Paw River at Riverside	390	1952-	444
102700	South Branch Black River near Bangor	83.6	1966-	106
105000	Battle Creek at Battle Creek	241	1931, 1933-	200
105500	Kalamazoo River near Battle Creek	824	1937-	660
105700	Augusta Creek near Augusta	38.9	1965-	43.2
106180	Portage Creek at Portage	16.5	1983-	[b]19.0
106300	Portage Creek near Kalamazoo	22.4	1965-	40.5
106320	West Fork Portage Creek near Oshtemo	13.0	1972-	7.23
106400	West Fork Portage Creek at Kalamazoo	18.7	1959-	9.94
106500	Portage Creek at Kalamazoo	46.8	1948-58, 1974-	54.2
108500	Kalamazoo River near Fennville	1,600	1929-36, 1938-	1,419

Table 1.--Selected hydrologic data for active gaging stations--Continued

Station number	Station name	Drainage area (square miles)	Period of record (water years)	Mean discharge (cubic feet per second)
108600	Rabbit River near Hopkins	71.4	1966-	57.0
108800	Macatawa River near Zeeland	65.8	1961-	65.5
109000	Grand River at Jackson	174	1935-	122
111379	Red Cedar River near Williamston	163	1975-	102
111500	Deer Creek near Dansville	16.3	1954-	10.6
112000	Sloan Creek near Williamston	9.34	1954-	5.70
112500	Red Cedar River at East Lansing	355	1902-04, 1931-	206
113000	Grand River at Lansing	1,230	1901-06, 1935-	834
114500	Lookingglass River near Eagle	281	1944-	173
115000	Maple River at Maple Rapids	434	1944-	256
116000	Grand River at Ionia	2,840	1931, 1951-	1,899
116500	Flat River near Smyrna	528	1951-	432
117500	Thornapple River at Hastings	385	1945-	314
118000	Thornapple River near Hastings	773	1952-82, 1983-	[b]570
119000	Grand River at Grand Rapids	4,900	1901-06, 1931-	3,572
121300	Clam River at Vogel Center	243	1966-	124
121500	Muskegon River at Evert	1,450	1931, 1934-	998
121900	Little Muskegon River near Morley	138	1967-	126
122000	Muskegon River at Newaygo	2,350	1908-15, 1916-20, 1931-	1,968
122100	Bear Creek near Muskegon	14.8	1966-	16.5
122200	White River near Whitehall	406	1957-	433
122500	Pere Marquette River at Scottville	681	1939-	667
122400	Manistee River near Sherman	900	1903-16, 1931, 1934-	1,055

Table 1.--Selected hydrologic data for active gaging stations--Continued

Station number	Station name	Drainage area (square miles)	Period of record (water years)	Mean discharge (cubic feet per second)
126000	Manistee River near Manistee	1,780	1952-	2,001
127000	Boardman River near Mayfield	182	1952-	191
127800	Jordan River near East Jordan	67.9	1967-	187
127918	Pine River near Rudyard	184	1972-	236
128000	Sturgeon River near Wolverine	198	1942-	218
129000	Pigeon River near Vanderbilt	62.6	1950-	77.7
130500	Black River near Tower	311	1943-	270
135000	Thunder Bay River near Alpena	1,238	1980-	[b]1,137
135500	Au Sable River at Grayling	110	1943-	74.2
135600	East Branch Au Sable River at Grayling	76.0	1958-	43.9
135700	South Branch Au Sable River near Luzerne	401	1967-	221
136500	Au Sable River at Mio	1,100	1952-	984
142000	Rifle River near Sterling	320	1937-	308
143900	Shiawassee River at Linden	81.2	1968-	60.3
144500	Shiawassee River at Owosso	538	1931-	333
145000	Shiawassee River near Fergus	637	1940-	422
146000	Farmers Creek near Lapeer	55.3	1933-	30.3
146063	South Branch Flint River near Columbiaville	221	1980-	[b]140
147500	Flint River near Otisville	530	1953-	302
148140	Kearsley Creek near Davison	99.4	1966-	69.8
148500	Flint River near Flint	956	1932-	588
149000	Flint River near Fosters	1,188	1940-	741
150500	Cass River at Cass City	359	1948-	204
150800	Cass River at Wahjamega	645	1969-	409

Table 1.--Selected hydrologic data for active gaging stations--Continued

Station number	Station name	Drainage area (square miles)	Period of record (water years)	Mean discharge (cubic feet per second)
151500	Cass River at Frankenmuth	841	1908-09, 1935-36, 1939-	485
154000	Chippewa River near Mount Pleasant Mich.	416	1931, 1933-	307
155000	Pine River at Alma	286	1931-	215
155500	Pine River near Midland	390	1934-38, 1948-	298
156000	Tittabawassee River at Midland	2,400	1936-	1,678
157000	Saginaw River at Saginaw	6,060	1904, 1908-19, 1929-30, 1943-	[c]--
159500	Black River near Fargo	480	1944-	281
160570	North Branch Belle River at Imlay City	18.0	1965-	11.3
160600	Belle River at Memphis	151	1963-	85.6
160800	Sashabaw Creek near Drayton Plains	20.9	1960-	12.3
160900	Clinton River near Drayton Plains	79.2	1960-	50.2
161100	Galloway Creek near Auburn Heights	17.9	1960-	10.0
161540	Paint Creek at Rochester	70.9	1960-	51.5
161580	Stony Creek near Romeo	25.6	1965-	17.2
161800	Stony Creek near Washington	68.2	1958-	41.8
162010	Red Run near Warren	[a]--	1980-	[b]31.8
162900	Big Beaver Creek near Warren	[a]--	1959-	[b]6.95
163400	Plum Brook at Utica	16.5	1965-	13.1
164000	Clinton River near Fraser	444	1947-	374
164100	East Pond Creek at Romeo	21.8	1958-	15.3
164300	East Branch Coon Creek at Armada	13.0	1959-	6.66
164500	North Branch Clinton River near Mount Clemens	199	1947-	121
165500	Clinton River at Mount Clemens	734	1934-	530

Table 1.--Selected hydrologic data for active gaging stations--Continued

Station number	Station name	Drainage area (square miles)	Period of record (water years)	Mean discharge (cubic feet per second)
166000	River Rouge at Birmingham	33.3	1950-	15.3
166100	River Rouge at Southfield	87.9	1958-	60.2
166200	Evans Ditch at Southfield	9.49	1958-	8.24
166300	Upper River Rouge at Farmington	17.5	1958-	11.9
166500	River Rouge at Detroit	187	1931-	115
167000	Midddle River Rouge near Garden City	99.9	1931-33, 1947-77, 1984-	69.0
168000	Lower River Rouge at Inkster	83.2	1947-	52.5
170000	Huron River at Milford	132	1948-	97.7
170500	Huron River near New Hudson	148	1948-	112
172000	Huron River near Hamburg	308	1952-	211
174500	Huron River at Ann Arbor	729	1904-	456
174800	Huron River at Ypsilanti	807	1974-	583
176500	River Rasin near Monroe	1,042	1937-	722

[a] Drainage area indeterminate
[b] Flow regulated, discharge based on 1983 water year only
[c] Estuary flow. Mean flow unknown

Table 2.--Data-use class, source of funding, and data availability

	Data-use class							Source of funding			
Station	Regional hydrology	Hydrologic systems	Project operation	Hydrologic forcasts	Water quality monitoring	Research	Other	Federal	Other federal agencies	Coop	Frequency of data availability
001000	H,M,L	Y,HB			HB:Q		T	HB			A
033000	H,M,L	Y	HP							DNR	A
033500		Y	HP							DNR	A
034500		Y	HP							DNR	A
035500	H	Y	HP							DNR	A
036000		Y	HP							DNR	A
037500		Y	HP							DNR	A
040000	H	Y	HP		N-Q					DNR	A
040500	H,M,L	Y,I				MTU				DNR	A,P
041500	H,M	Y	HP							DNR	A
043050	H,M,L						T			DNR	A
044400		Y	R-M							DNR	A
045500	H,M,L				N-Q			NQ			A
056500	H,M,L									DNR	A
057510	H,M,L					MTU				DNR	A,P
057800	H,M,L	Y	R-M							DNR	A
057813		Y	R-M							DNR	A
057814		Y	R-M							DNR	A
058200		Y	R-M							DNR	A
059000	H,M,L				N-B			NQ			A
059500	H,M,L				N-Q					DNR	A
061000	H,M	Y	HP							DNR	A,P
061500	H,M	Y	HP							DNR	A,P
062000		Y	HP							DNR	A,P
062500		Y	HP							DNR	A,P
063000		Y	HP							DNR	A,P
096400	H,M,L									DNR	A
096515	H,M,L		WD							DNR	A
096600	H,M,L									DNR	A
096900	H,M,L									DNR	A
097195		Y	R-C							CP	A
097540	H,M,L									DNR	A
099000	H,M		HP	NWS						DNR	A,TEL
101500	H,M				N-B		T,C	NQ			A
101800	H,M,L									DNR	A
102500	H,M,L							AE			A
102700	H,M,L									DNR	A
105000	H,M,L									HWY	A
105500	H,M									HWY	A
105700	H,M,L									DNR	A
106180	H,M,L	Y	R-C							CP	A
106300	H	Y	R-C							CP	A
106320	H,M,L	Y	MWS							CoK	A
106400	H	Y	MWS							CoK	A
106500	H	Y	WD				T			DNR	A
108500	H,M		HP							DNR	A
108600	H,M,L									DNR	A
108800	H,M,L									DNR	A
109000	H		WD							HWY	A
111379	H,M,L			NWS		MTU				DNR	A,TEL,P
111500	H,M,L					MSU				DNR	A
112000	H,M,L					MSU				DNR	A
112500	H,M,L	Y,I		NWS						HWY	A,P,TEL
113000	H,M		WD	NWS						HWY	A,TEL
114500	H,M,L									HWY	A

See footnotes at end of table.

Table 2.--Data-use class, source of funding, and data availability--Continued

Station	Data-use class							Source of funding			Frequency of data availability
	Regional hydrology	Hydrologic systems	Project operation	Hydrologic forcasts	Water quality monitoring	Research	Other	Federal	Other federal agencies	Coop	
115000	H,M,L									HWY	A
116000	H,M			NWS				AE			A,TEL
116500	H,M,L			USGS				AE			A,TEL
117500	H,M,L			NWS						HWY	A,TEL
118000	H,M,L		HP							DNR	A
119000	H,M,L			NWS				CBR			A,TEL
121300	H,M,L									DNR	A
121500	H,M,L	Y,I	HP				T			DNR	A,P
121900	H,M,L						T			DNR	A
122000			HP	NWS						DNR	A,TEL
122100	H,M,L		WD							DNR	A
122200	H,M,L									DNR	A
122500	H,M,L						T			HWY	A
124000	H,M		HP							DNR	A
126000			HP							DNR	A
127000			HP							HWY	A
127800	H						T			HWY	A
127918	H,M,L									DNR	A
128000	H,M,L						T	AE			A
129000	H,M									DNR	A
130500			HP							DNR	A
135000					N-B		T,C	NQ			A
135500	H,M,L		HP							DNR	A
135600	H,M,L									DNR	A
135700	H,M,L						T			DNR	A
136500			HP							DNR	A
142000	H,M,L				N-Q					DNR	A
143900	H,M		WD							CoG	A
144500	H			NWS						DNR	A,TEL
145000	H,M,L								COE		A
146000	H,M,L		WD							DNR	A
146063	H,M,L		R-C	USGS						CoG	A,TEL
147500	H		R-C	CF						DNR	A,TEL
148140	H,M,L			USGS						DNR	A,TEL
148500	H,M		WD	NWS						DNR	A,TEL
149000	H,M,L								COE		A
150500	H,M,L							AE			A
150800	H,M,L		WD	NWS						DNR	A,TEL
151500	H,M,L									DNR	A
154000	H,M			NWS						DNR	A,TEL
155000	H,M		WD							DNR	A
155500	H,M							AE			A
156000	H,M		WD	NWS						DNR	A,TEL
157000	H			NWS	N-Q				COE		A,TEL
159500	H,M,L									HWY	A
160570	H,M,L		WD							CI	A
160600	H,M,L									DNR	A
160800	H,M,L	Y								CoO	A
160900	H,M,L	Y								CoO	A
161100	H,M,L	Y								CoO	A
161540	H,M,L	Y								CoO	A
161580	H,M,L	Y	R-C							HC	A
161800	H	Y	R-C							HC	A
162010	Y			USGS				AE			A,TEL
162900	Y									CoM	A

See footnotes at end of table.

Table 2.--Data-use class, source of funding, and data availability--Continued

Station	Data-use class							Source of funding			Frequency of data availability
	Regional hydrology	Hydrologic systems	Project operation	Hydrologic forcasts	Water quality monitoring	Research	Other	Federal	Other federal agencies	Coop	
163400	H,M,L	Y								CoM	A
164000	H,M,L	Y	WD	NWS				AE			A,TEL
164100	H,M,L	Y								CoM	A
164300	H,M,L	Y								CoM	A
164500	H,M,L	Y		NWS				AE			A,TEL
165500	H,M,L	Y		NWS	N-Q			AE			A,TEL
166000	H,M,L	Y								CoO	A
166100	H,M,L	Y								CoO	A
166200	H,M,L	Y								CoO	A
166300	H,M,L	Y								CoO	A
166500	H,M,L	Y		NWS						DNR	A,TEL
167000	H,M,L	Y		NWS						DNR	A,TEL
168000	H,M,L	Y								HWY	A
170000	H,M,L	Y	R-C							HC	A
170500	H	Y	R-C							HC	A
172000	H,M,L	Y	R-C							HC	A
174500		Y	WD					AE			A
174800		Y								HWY	A
176500	H,M,L			CM	N-Q					DNR	A,TEL

A	Published in the annual water resources data report.
AE	Army Engineers Replacement.
C	Minimum, maximum, and mean daily specific conductance data.
CF	City of Flint, Mich.
CI	Imlay City, Mich.
CM	City of Monroe, Mich.
CP	City of Portage, Mich.
CBR	Collection of basic records.
CoG	Genessee County, Mich.
CoK	Kalamazoo County, Mich.
CoM	Macomb County, Mich.
CoO	Oakland County Drain Commission.
COE	U.S. Army Corps of Engineers.
DNR	Michigan Department of Natural Resources, Water Management Div.
H	High-flow characteristics defined.
HB	Hydrologic benchmark station.
HB:Q	Hydrologic benchmark station, sampled quarterly.
HC	Huron-Clinton Metropolitan Authority.
HP	Required by State of Michigan for operation of hydropower plant.
HWY	Michigan State Department of Highways.
I	Long-term index gaging station.
L	Low-flow characteristics defined.
M	Mean and mean monthly flow characteristics defined.
MSU	Michigan State University.
MTU	Michigan Technological University, flow under ice study.
MWS	Municipal water supply.
NQ	National stream-quality accounting network station-Nasqan.
N-B	Nasqan station, sampled bimonthly.
N-Q	Nasqan station, sampled quarterly.
NWS	U.S. National Weather Service - flood forcasting.
P	Provisional data available periodically.
R-A	Reservoir management in connection with agricultural activities.
R-M	Reservoir management in connection with mining operations.
R-C	Reservoir management in connection with recreational uses.
T	Minimum, maximum and mean daily water temperature data.
TEL	Telemetry equipment at station provides real-time data.
USGS	U.S. Geological Survey, used in coordinating flood measurements.
WD	Waste disposal.
Y	Station meets categorical requirement.

Table 7.--Characteristics of record reconstruction

Station number	Station name	C_v	ρ_c	Source of reconstructed records
001000	Washington Creek at Windigo	115	0.66	043050 057800
033000	Middle Branch Ontonagon River near Paulding	45	.89	061500 057800
033500	Bond Falls Canal near Paulding	93	.95	Power plant records
034500	Middle Branch Ontonagon River near Trout Creek	52	.95	Power plant records
035500	Middle Branch Ontonagon River near Rockland	81	.78	033000 040500
036000	West Branch Ontonagon River near Bergland	100	.95	Power plant records
037500	Cisco Branch Ontonagon River at Cisco Lake Outlet	93	.95	Power plant records
040000	Ontonagon River near Rockland	72	.95	Power plant records
040500	Sturgeon River near Sidnaw	94	.89	057800 061500 057510
041500	Sturgeon River Near Alston	70	.95	Power plant records
043050	Trap Rock River near Lake Linden	82	.77	040500 001000
044400	Carp River near Negaunee	46	.95	Power plant records
045500	Tahquamenon River near Tehquamenon Paradise	57	.84	056500
056500	Manistique River near Manistique	49	.90	045500 057510
057510	Sturgeon River near Nahma Junction	62	.90	059500 056500
057800	Middle Branch Escanaba River at Humboldt	88	.83	040500
057813	Greenwood Diversion near Greenwood	74	.95	Power plant records
057814	Greenwood Release near Greenwood	40	.95	Power plant records
058200	Schweitzer Creek near Palmer	103	.95	Power plant records
059000	Escanaba River at Cornell	65	.91	059500 057800
059500	Ford River near Hyde	95	.91	057510 059000
061000	Brule River near Florence, Wisc.	41	.87	061500 033000
061500	Paint River at Crystal Falls	58	.95	Power plant records

Table 7.--Characteristics of record reconstruction--Continued

Station number	Station name	C_v	ρ_c	Source of reconstructed records
062000	Paint River near Alpha	99	0.90	Power plant records
062500	Michigamme River near Crystall Falls	58	.95	Power plant records
063000	Menominne River near Florence	44	.95	Power plant records
096400	St. Joseph River near Burlington,	68	.94	096600
096515	Hog Creek near Allen	85	.89	096600
096600	Coldwater River near Hodunk	83	.94	096400
096900	Nottawa Creek near Athens	53	.90	096400 105500
097195	Gourdneck Canal near Schoolcraft	73	.06	105700
097540	Prairie River near Nottawa	57	.92	096600
099000	St. Joseph River at Mottville	49	.90	101500
101500	St. Joseph River at Niles	46	.90	099000
101800	Dowagiac River at Sumnerville	35	.79	102500
102500	Paw Paw River at Riverside	41	.86	108500 101800
102700	South Branch Black River near Bangor	82	.63	117500
105000	Battle Creek at Battle Creek	75	.94	105500 117500
105500	Kalamazoo River near Battle Creek	53	.92	105000 108500
105700	Augusta Creek near Augusta	36	.81	105500 101800
106180	Portage Creek at Portage	32	.85	Estimated
106300	Portage Creek near Kalamazoo	23	.84	106500 101800
106320	West Fork Portage Creek near Oshtemo	35	.81	106400
106400	West Fork Portage Creek at Kalamazoo	36	.81	106320
106500	Portage Creek at Kalamazoo	29	.84	106300
108500	Kalamazoo River near Fennville	42	.85	105500
108600	Rabbit River near Hopkins	80	.75	102700

Table 7.--Characteristics of record reconstruction--Continued

Station number	Station name	C_v	ρ_c	Source of reconstructed records
108800	Macatawa River near Zeeland	199	0.74	108600 102700
109000	Grand River at Jackson	68	.86	096400 113000
111379	Red Cedar River near Williamston	84	.80	112500 113000
111500	Deer Creek near Dansville	175	.92	112000
112000	Sloan Creek near Williamston	211	.92	112500 111500
112500	Red Cedar River at East Lansing	123	.94	113000 111379
113000	Grand River at Lansing	88	.95	116000 112500
114500	Lookingglass River near Eagle	108	.89	116000
115000	Maple River at Maple Rapids	150	.89	116000 114500
116000	Grand River at Ionia	92	.97	119000 113000
116500	Flat River near Smyrna	50	.84	119000 116000
117500	Thornapple River at Hastings	82	.82	112500 115000
119000	Grand River at Grand Rapids	70	.96	116000
121300	Clam River at Vogel Center	44	.86	121500 125500
121500	Muskegon River at Evert	52	.84	121300
121900	Little Muskegon River near Morley	52	.86	122100
122000	Muskegon River at Newaygo	45	.95	Power plant records
122100	Bear Creek near Muskegon	88	.76	122200
122200	White River near Whitehall	42	.89	122500
122500	Pere Marquette River at Scottville	34	.89	122200
124000	Manistee River near Sherman	20	.82	125500 126000
126000	Manistee River near Manistee	24	.95	Power plant records
127000	Boardman River near Mayfield	25	.75	124000
127800	Jordan River near East Jordan	18	.76	128000

Table 7.--Characteristics of record reconstruction--Continued

Station number	Station name	C_v	ρ_c	Source of reconstructed records
127918	Pine River near Rudyard	80	0.70	057510
128000	Sturgeon River near Wolverine	27	.89	129000 127800
129000	Pigeon River near Vanderbilt	34	.87	128000 127800
130500	Black River near Tower	43	.83	129500
135000	Thunder Bay River near Alpena	58	.95	Power plant records
135500	Au Sable River at Grayling	22	.93	135600
135600	East Branch Au Sable River at Grayling	28	.93	135500
135700	Au Sable River near Au Sable	30	.78	135600
136500	Au Sable River at Mio	23	.90	135500 135700
142000	Rifle River near Sterling	54	.94	140500 138500
143900	Shiawassee River at Linden	70	.87	144500 160900
144500	Shiawassee River at Owosso	108	.96	145000
145000	Shiawassee River near Fergus	116	.96	145000
146000	Farmers Creek near Lapeer	117	.87	147500 148500
146063	South Branch Flint River near Columbiaville	63	.62	148500
147500	Flint River near Otisville	101	.87	148500
148140	Kearsley Creek near Davison	158	.70	Estimated
148500	Flint River near Flint	104	.96	147500 149000
149000	Flint River near Fosters	109	.95	148500
150500	Cass River at Cass City	190	.92	151500
150800	Cass River at Wahjamega	136	.92	151500
151500	Cass River at Frankenmuth	149	.94	150500 150800
154000	Chippewa River near Mount Pleasant	67	.87	156000 155000
155000	Pine River at Alma	76	.94	155500 154000

Table 7.--Characteristics of record reconstruction--Continued

Station number	Station name	C_v	ρ_c	Source of reconstructed records	
155500	Pine River near Midland	88	0.92	155000	
156000	Tittabawassee River at Midland	101	.89	154000	155500
159500	Black River near Fargo	208	.76	160600	
160570	North Branch Belle River at Imlay City	121	.84	160600	
160600	Belle River at Memphis	152	.90	160570	
160800	Sashabaw Creek near Drayton Plains	100	.86	164000	164100
160900	Clinton River near Drayton Plains	70	.82	160800	
161100	Galloway Creek near Auburn Heights	137	.86	163400	164500
161540	Paint Creek at Rochester	74	.90	160800	161580
161580	Stony Creek near Romeo	96	.91	161800	164100
161800	Stony Creek near Washington	85	.85	161540	161580
162010	Red Run near Warren	110	.60	162900	163400
162900	Big Beaver Creek near Warren	207	.73	163400	163400
163400	Plum Brook at Utica	146	.86	162900	166000
164000	Clinton River near Fraser	87	.96	165500	
164100	East Pond Creek at Romeo	96	.91	161540	161580
164300	East Branch Coon Creek at Armada	244	.85	164500	
164500	North Branch Clinton River near Mount Clemens	177	.88	160600	164000
165500	Clinton River at Mount Clemens	105	.96	164000	
166000	River Rouge at Birmingham	129	.92	166100	
166100	River Rouge at Southfield	135	.92	166000	
166200	Evans Ditch at Southfield	177	.78	166100	166300
166300	Upper River Rouge at Farmington	131	.93	166000	166100
166500	River Rouge at Detroit	149	.94	166100	168000

Table 7.--Characteristics of record reconstruction--Continued

Station number	Station name	C_v	ρ_c	Source of reconstructed records	
168000	Lower River Rouge at Inkster	195	0.86	166500	
170000	Huron River at Milford	61	.93	172000	170500
170500	Huron River near New Hudson	55	.93	172000	
172000	Huron River near Hamburg	59	.96	170500	174500
174500	Huron River at Ann Arbor	72	.86	174800	
174800	Huron River at Ypsilanti	57	.86	174500	
176500	River Rasin near Monroe	126	.73	174500	166500

Table 11.--One-day-lag autocorrelation and measurement and process variances based on analysis of autocovariance

Station number	Station name	Autocorrelation	Measurement variance $(\log_{10})^2*10^3$	Process variance $(\log_{10})^2*10^3$
001000	Washington Creek at Windigo	0.988	0.346	2.328
033000	Middle Branch Ontonagon River near Paulding	.992	.373	0.219
033500	Bond Falls Canal near Paulding	.0	.283	.010
034500	Middle Branch Ontonagon River near Trout Creek	.611	.260	.193
035500	Middle Branch Ontonagon River near Rockland	.975	.414	2.996
036000	West Branch Ontonagon River near Bergland	.979	.309	.221
037500	Cisco Branch Ontonagon River at Cisco Lake Outlet	.649	.537	.506
040000	Ontonagon River near Rockland	.983	.486	.006
040500	Sturgeon River near Sidnaw	.0	.545	.010
041500	Sturgeon River Near Alston	.621	.280	1.064
043050	Trap Rock River near Lake Linden	.986	.228	1.642
044400	Carp River near Negaunee	.987	.345	.539
045500	Tahquamenon River near Tehquamenon Paradise	.0	.354	.010
056500	Manistique River near Manistique	.987	.295	.035
057510	Sturgeon River near Nahma Junction	.0	.446	.010
057800	Middle Branch Escanaba River at Humboldt	.711	.545	2.224
057813	Greenwood Diversion near Greenwood,	.981	.219	.405
057814	Greenwood Release near Greenwood	.0	.501	.010
058200	Schweitzer Creek near Palmer	.0	.573	.010
059000	Escanaba River at Cornell	.976	.340	.083
059500	Ford River near Hyde	.0	.414	.010
061000	Brule River near Florence, Wisc.	.0	.356	.010
061500	Paint River at Crystal Falls	.985	.515	.143

Table 11.--One-day-lag autocorrelation and measurement and process variances based on analysis of autocovariance--Continued

Station number	Station name	Auto-correlation	Measurement variance $(\log_{10})^2*10^3$	Process variance $(\log_{10})^2*10^3$
062000	Paint River near Alpha	0.971	0.432	1.722
062500	Michigamme River near Crystall Falls	.0	.303	0.010
063000	Menominne River near Florence	.0	.329	.010
065393	East Branch Sturgeon River near Felch	.953	.353	2.990
065397	East Branch Sturgeon River at Hardwood	.0	.400	.010
096400	St. Joseph River near Burlington,	.980	.259	1.830
096515	Hog Creek near Allen	.982	.321	3.605
096600	Coldwater River near Hodunk	.980	.405	.948
096900	Nottawa Creek near Athens	.980	.792	31.760
097195	Gourdneck Canal near Schoolcraft	.982	.893	31.360
097540	Prairie River near Nottawa	.978	.371	2.135
099000	St. Joseph River at Mottville	.974	.283	.057
101500	St. Joseph River at Niles	.939	.379	.936
101800	Dowagiac River at Sumnerville	.0	.251	.056
102500	Paw Paw River at Riverside	.965	.361	.339
102700	South Branch Black River near Bangor	.982	.295	.602
105000	Battle Creek at Battle Creek	.964	.403	.328
105500	Kalamazoo River near Battle Creek	.943	.467	.636
105700	Augusta Creek near Augusta	.981	.263	.137
106180	Portage Creek at Portage	.0	.400	.010
106300	Portage Creek near Kalamazoo	.990	.266	2.224
106320	West Fork Portage Creek near Oshtemo	.974	.434	.742

Table 11.--One-day-lag autocorrelation and measurement and process variances based on analysis of autocovariance--Continued

Station number	Station name	Auto-correlation	Measurement variance $(\log_{10})^2*10^3$	Process variance $(\log_{10})^2*10^3$
106400	West Fork Portage Creek at Kalamazoo	0.947	0.289	0.443
106500	Portage Creek at Kalamazoo	.974	.324	1.030
108500	Kalamazoo River near Fennville	.976	.321	.539
108600	Rabbit River near Hopkins	.982	.245	2.701
108800	Macatawa River near Zeeland	.996	.340	44.000
109000	Grand River at Jackson	.963	.384	.131
111379	Red Cedar River near Williamston	.966	.425	3.260
111500	Deer Creek near Dansville	.973	.509	3.766
112000	Sloan Creek near Williamston	.968	.531	3.607
112500	Red Cedar River at East Lansing	.627	.342	.713
113000	Grand River at Lansing	.597	.390	.525
114500	Lookingglass River near Eagle	.956	.298	.523
115000	Maple River at Maple Rapids	.626	.412	4.882
116000	Grand River at Ionia	.0	.397	.434
116500	Flat River near Smyrna	.970	.273	1.075
117500	Thornapple River at Hastings	.955	.291	.693
119000	Grand River at Grand Rapids	.976	.505	1.600
121300	Clam River at Vogel Center	.974	.276	.935
121500	Muskegon River at Evert	.971	.334	.421
121900	Little Muskegon River near Morley	.961	.270	.635
122000	Muskegon River at Newaygo	.899	.398	.026
122100	Bear Creek near Muskegon	.986	.279	4.292

Table 11.--One-day-lag autocorrelation and measurement and process variances based on analysis of autocovariance--Continued

Station number	Station name	Autocorrelation	Measurement variance $(\log_{10})^2*10^3$	Process variance $(\log_{10})^2*10^3$
122200	White River near Whitehall	0.992	0.434	0.420
122500	Pere Marquette River at Scottville	.962	.323	.070
124000	Manistee River near Sherman	.0	.289	.010
126000	Manistee River near Manistee	.970	.432	.456
127000	Boardman River near Mayfield	.991	.270	1.241
127800	Jordan River near East Jordan	.968	.350	.310
127918	Pine River near Rudyard	.623	.421	.136
128000	Sturgeon River near Wolverine	.990	.289	.421
129000	Pigeon River near Vanderbilt	.0	.350	.010
130500	Black River near Tower	.945	.277	.082
135000	Thunder Bay River near Alpena	.0	.400	.010
135500	Au Sable River at Grayling	.977	.307	.081
135600	East Branch Au Sable River at Grayling	.974	.361	.403
136500	Au Sable River at Mio	.0	.326	.010
142000	Rifle River near Sterling	.541	.323	.010
143900	Shiawassee River at Linden	.938	.359	2.857
144500	Shiawassee River at Owosso	.983	.263	9.305
145000	Shiawassee River near Fergus	.987	.480	6.058
146000	Farmers Creek near Lapeer	.935	.266	.506
146063	South Branch Flint River near Columbiaville	.0	.241	.010
147500	Flint River near Otisville	.965	.244	1.088
148140	Kearsley Creek near Davison	.985	.248	6.403

Table 11.--One-day-lag autocorrelation and measurement and process variances based on analysis of autocovariance--Continued

Station number	Station name	Auto-correlation	Measurement variance $(\log_{10})^2*10^3$	Process variance $(\log_{10})^2*10^3$
148500	Flint River near Flint	0.954	0.426	0.549
149000	Flint River near Fosters	.0	2.425	.010
150500	Cass River at Cass City	.932	.624	1.994
150800	Cass River at Wahjamega	.967	.327	.858
151500	Cass River at Frankenmuth	.978	.346	.661
154000	Chippewa River near Mount Pleasant	.982	.263	2.799
155000	Pine River at Alma	.624	.364	7.920
155500	Pine River near Midland	.973	.459	66.850
156000	Tittabawassee River at Midland	.990	.267	2.214
159500	Black River near Fargo	.946	.478	.334
160570	North Branch Belle River at Imlay City	.0	.400	.010
160600	Belle River at Memphis	.967	.366	5.338
160800	Sashabaw Creek near Drayton Plains	.973	.364	18.620
160900	Clinton River near Drayton Plains	.980	.295	.900
161100	Galloway Creek near Auburn Heights	.986	.448	30.120
161540	Paint Creek at Rochester	.980	.272	.777
161580	Stony Creek near Romeo	.982	.315	14.120
161800	Stony Creek near Washington	.984	.286	8.635
162010	Red Run near Warren	.979	.867	14.670
162900	Big Beaver Creek near Warren	.981	1.380	246.100
163400	Plum Brook at Utica	.0	.400	.010
164000	Clinton River near Fraser	.916	.416	1.060

Table 11.--One-day-lag autocorrelation and measurement and process variances based on analysis of autocovariance--Continued

Station number	Station name	Autocorrelation	Measurement variance $(\log_{10})^2*10^3$	Process variance $(\log_{10})^2*10^3$
164100	East Pond Creek at Romeo	0.990	0.368	17.150
164300	East Branch Coon Creek at Armada	.941	1.036	67.890
164500	North Branch Clinton River near Mount Clemens	.616	.423	1.231
165500	Clinton River at Mount Clemens	.0	.400	.010
166000	River Rouge at Birmingham	.0	.880	.010
166100	River Rouge at Southfield	.972	.275	2.358
166200	Evans Ditch at Southfield	.991	.824	55.310
166300	Upper River Rouge at Farmington	.862	.644	2.483
166500	River Rouge at Detroit	.586	.582	4.076
168000	Lower River Rouge at Inkster	.946	.805	2.261
170000	Huron River at Milford	.980	.304	1.260
170500	Huron River near New Hudson	.983	.519	15.730
172000	Huron River near Hamburg	.976	.354	12.180
174500	Huron River at Ann Arbor	.991	.624	1.575
174800	Huron River at Ypsilanti	.597	.586	.167
176500	River Rasin near Monroe	.984	.499	1.224

Table 13.--Results of K-CERA analysis

	Standard error of instantaneous discharge, in percent [Equivalent Gaussian spread] (Number of visits per open-water season to site)					
Station number	Current operation	Budget, in thousand of 1984 dollars				
		680.2	700.2	718.1	754.0	789.9
001000	12.8 [5.09] (6)	15.7 [6.13] (4)	14.0 [5.55] (5)	12.8 [5.09] (6)	11.9 [4.73] (7)	10.5 [4.21] (9)
033000	3.20 [2.78] (6)	3.95 [1.63] (4)	3.20 [1.35] (6)	3.20 [1.35] (6)	2.76 [1.18] (8)	2.46 [1.06] (10)
033500	4.86 [2.36] (6)	5.92 [2.38] (4)	4.86 [2.36] (6)	4.86 [2.36] (6)	4.30 [2.34] (8)	3.95 [2.34] (10)
034500	6.87 [3.21] (6)	8.12 [3.27] (4)	6.87 [3.21] (6)	6.87 [3.21] (6)	6.14 [3.16] (8)	5.65 [3.13] (10)
035500	7.84 [7.82] (6)	9.03 [9.00] (4)	7.39 [7.38] (7)	7.00 [6.98] (8)	6.36 [6.35] (10)	5.88 [5.86] (12)
036000	2.04 [2.04] (6)	2.35 [2.35] (4)	2.04 [2.04] (6)	2.04 [2.04] (6)	1.84 [1.84] (8)	1.67 [1.67] (10)
037500	5.64 [5.13] (6)	6.16 [5.21] (4)	5.50 [5.09] (7)	5.40 [5.06] (8)	5.25 [5.01] (10)	5.14 [4.95] (12)
040000	0.32 [0.32] (6)	0.37 [0.37] (4)	0.36 [0.36] (5)	0.35 [0.35] (5)	0.30 [0.30] (7)	0.27 [0.27] (9)
040500	6.03 [0.75] (6)	7.49 [0.76] (4)	6.64 [0.75] (5)	6.64 [0.75] (5)	5.56 [0.74] (7)	4.88 [0.74] (9)
041500	7.96 [7.46] (6)	8.38 [7.58] (4)	7.96 [7.46] (6)	7.84 [7.42] (7)	7.65 [7.33] (9)	7.52 [7.26] (11)

Table 13.--Results of K-CERA analysis--Continued

Standard error of instantaneous discharge, in percent
[Equivalent Gaussian spread]
(Number of visits per open-water season to site)

Station number	Current operation	Budget, in thousand of 1984 dollars				
		680.2	700.2	718.1	754.0	789.9
043050	8.42 [4.68] (6)	10.2 [5.62] (4)	9.19 [5.07] (5)	9.19 [5.07] (5)	7.81 [4.36] (7)	6.90 [3.88] (9)
044400	2.86 [2.61] (6)	3.48 [3.09] (4)	3.12 [2.82] (5)	2.86 [2.61] (6)	2.65 [2.43] (7)	2.49 [2.30] (8)
045500	4.27 [0.75] (6)	5.26 [0.76] (4)	5.26 [0.76] (4)	5.26 [0.76] (4)	5.26 [0.76] (4)	5.26 [0.76] (4)
056500	3.02 [0.68] (6)	3.77 [0.80] (4)	3.34 [0.73] (5)	3.34 [0.73] (5)	2.79 [0.63] (7)	2.59 [0.59] (8)
057510	3.81 [0.75] (6)	4.73 [0.76] (4)	4.19 [0.75] (5)	4.19 [0.75] (5)	3.52 [0.74] (7)	3.29 [0.74] (8)
057800	12.4 [10.7] (6)	13.4 [11.0] (4)	11.8 [10.6] (8)	11.2 [10.3] (12)	10.9 [10.1] (14)	10.8 [10.1] (15)
057813	4.31 [2.68] (6)	5.30 [3.14] (4)	4.73 [2.89] (5)	4.31 [2.68] (6)	3.98 [2.52] (7)	3.72 [2.38] (8)
057814	1.84 [1.37] (12)	2.46 [0.75] (4)	2.18 [0.75] (5)	1.99 [0.75] (6)	1.84 [0.74] (7)	1.73 [0.74] (8)
058200	4.80 [0.75] (6)	6.09 [0.76] (4)	5.33 [0.75] (5)	4.80 [0.75] (6)	4.40 [0.74] (7)	4.09 [0.74] (8)
059000	4.49 [1.35] (6)	5.54 [1.56] (4)	5.54 [1.56] (4)	4.49 [1.35] (6)	4.15 [1.28] (7)	3.46 [1.10] (10)
059500	6.34 [0.75] (6)	7.86 [0.76] (4)	5.14 [0.74] (9)	4.87 [0.74] (10)	4.11 [0.74] (14)	4.11 [0.74] (14)

Table 13.--Results of K-CERA analysis--Continued

Standard error of instantaneous discharge, in percent
[Equivalent Gaussian spread]
(Number of visits per open-water season to site)

Station number	Current operation	Budget, in thousand of 1984 dollars				
		680.2	700.2	718.1	754.0	789.9
061000	2.99	3.66	2.99	2.99	2.60	2.45
	[0.75]	[0.76]	[0.75]	[0.75]	[0.74]	[0.74]
	(6)	(4)	(6)	(6)	(8)	(9)
061500	3.04	3.80	3.04	3.04	2.61	2.45
	[1.49]	[1.76]	[1.49]	[1.49]	[1.32]	[1.26]
	(6)	(4)	(6)	(6)	(8)	(9)
062000	8.72	10.4	8.16	7.68	6.95	6.65
	[6.46]	[7.41]	[6.10]	[5.79]	[5.29]	[5.08]
	(6)	(4)	(7)	(8)	(10)	(11)
062500	2.78	3.50	2.78	2.78	2.39	2.25
	[0.75]	[0.76]	[0.75]	[0.75]	[0.74]	[0.74]
	(6)	(4)	(6)	(6)	(8)	(9)
063000	2.17	2.70	2.17	2.17	1.88	1.78
	[0.75]	[0.76]	[0.75]	[0.75]	[0.74]	[0.74]
	(6)	(4)	(6)	(6)	(8)	(9)
065393	9.70	10.6	8.55	7.72	7.05	7.05
	[9.70]	[10.6]	[8.55]	[7.72]	[7.05]	[7.05]
	(6)	(4)	(9)	(12)	(15)	(16)
096400	6.91	8.35	8.35	7.54	6.43	5.42
	[5.74]	[6.78]	[6.78]	[6.21]	[5.37]	[4.57]
	(6)	(4)	(4)	(5)	(7)	(10)
096515	9.91	12.0	12.0	10.8	9.21	7.75
	[7.72]	[9.21]	[9.21]	[8.39]	[7.19]	[6.08]
	(6)	(4)	(4)	(5)	(7)	(10)
096600	6.47	8.00	8.00	7.12	5.98	4.99
	[4.22]	[4.96]	[4.96]	[4.55]	[3.96]	[3.39]
	(6)	(4)	(4)	(5)	(7)	(10)
096900	23.7	27.9	27.9	25.6	22.2	18.8
	[23.7]	[27.8]	[27.8]	[25.6]	[22.2]	[18.7]
	(6)	(4)	(4)	(5)	(7)	(10)
097540	7.44	8.82	8.82	8.04	6.55	5.66
	[6.51]	[7.61]	[7.61]	[6.99]	[5.76]	[4.99]
	(6)	(4)	(4)	(5)	(8)	(11)

Table 13.--Results of K-CERA analysis--Continued

Standard error of instantaneous discharge, in percent
[Equivalent Gaussian spread]
(Number of visits per open-water season to site)

Station number	Current operation	Budget, in thousand of 1984 dollars				
		680.2	700.2	718.1	754.0	789.9
099000	3.83 [1.16] (6)	4.79 [1.35] (4)	4.79 [1.35] (4)	4.23 [1.24] (5)	3.28 [1.04] (8)	2.78 [0.91] (11)
101500	7.56 [0.84] (6)	9.81 [0.91] (4)	9.81 [0.91] (4)	8.49 [0.86] (5)	6.32 [0.81] (8)	5.22 [0.79] (11)
101800	3.73 [0.76] (6)	4.58 [0.77] (4)	4.58 [0.77] (4)	4.09 [0.76] (5)	3.24 [0.75] (8)	2.77 [0.74] (11)
102500	4.73 [3.12] (6)	5.64 [3.53] (4)	5.64 [3.53] (4)	5.12 [3.31] (5)	4.17 [2.83] (8)	3.62 [2.51] (11)
102700	11.1 [3.26] (6)	13.6 [3.86] (4)	13.6 [3.86] (4)	12.2 [3.53] (5)	9.63 [2.87] (8)	8.23 [2.50] (11)
105000	6.48 [3.11] (6)	7.95 [3.51] (4)	7.95 [3.51] (4)	7.10 [3.28] (5)	6.00 [2.94] (7)	5.03 [2.59] (10)
105500	9.93 [5.27] (6)	12.4 [6.00] (4)	12.4 [6.00] (4)	11.0 [5.60] (5)	9.14 [4.99] (7)	7.60 [4.41] (10)
105700	3.91 [1.61] (6)	4.79 [1.89] (4)	4.79 [1.89] (4)	4.28 [1.73] (5)	3.62 [1.51] (7)	3.03 [1.30] (10)
106300	4.95 [4.60] (6)	5.94 [5.55] (4)	5.94 [5.55] (4)	5.38 [5.02] (5)	4.59 [4.26] (7)	3.90 [3.60] (10)
106320	5.26 [4.17] (6)	6.19 [4.79] (4)	6.19 [4.79] (4)	5.67 [4.45] (5)	4.94 [3.93] (7)	4.24 [3.41] (10)
106400	5.24 [3.98] (6)	6.06 [4.39] (4)	6.06 [4.39] (4)	5.60 [4.18] (5)	4.96 [3.82] (7)	4.33 [3.43] (10)

Table 13.--Results of K-CERA analysis--Continued

Standard error of instantaneous discharge, in percent
[Equivalent Gaussian spread]
(Number of visits per open-water season to site)

Station number	Current operation	Budget, in thousand of 1984 dollars				
		680.2	700.2	718.1	754.0	789.9
106500	5.40 [4.86] (6)	6.26 [5.59] (4)	6.26 [5.59] (4)	5.78 [5.19] (5)	5.08 [4.59] (7)	4.38 [3.96] (10)
108500	5.03 [3.44] (6)	6.03 [3.98] (4)	6.03 [3.98] (4)	5.46 [3.68] (5)	4.40 [3.05] (8)	3.80 [2.67] (11)
108600	10.9 [6.66] (6)	13.2 [7.97] (4)	13.2 [7.97] (4)	11.9 [7.22] (5)	9.49 [5.82] (8)	8.12 [4.98] (11)
108800	25.5 [11.8] (6)	31.3 [14.7] (4)	31.3 [14.7] (4)	27.9 [13.0] (5)	22.1 [10.2] (8)	18.8 [8.63] (11)
109000	6.16 [1.98] (6)	7.61 [2.24] (4)	7.61 [2.24] (4)	6.77 [2.10] (5)	5.69 [1.88] (7)	4.75 [1.66] (10)
111379	12.6 [9.49] (6)	14.8 [10.8] (4)	14.8 [10.8] (4)	12.6 [9.49] (6)	11.1 [8.52] (8)	9.67 [7.46] (11)
111500	15.5 [9.44] (6)	19.0 [11.0] (4)	19.0 [11.0] (4)	15.5 [9.44] (6)	13.5 [8.39] (8)	11.5 [7.29] (11)
112000	17.8 [9.73] (6)	21.9 [11.2] (4)	21.9 [11.2] (4)	17.8 [9.73] (6)	15.5 [8.72] (8)	13.2 [7.60] (11)
112500	10.2 [6.22] (6)	12.1 [6.38] (4)	11.0 [6.29] (5)	11.0 [6.29] (5)	9.20 [6.12] (8)	10.2 [6.22] (6)
113000	7.80 [5.34] (6)	9.08 [5.46] (4)	9.08 [5.46] (4)	7.80 [5.34] (6)	7.13 [5.25] (8)	6.55 [5.16] (11)
114500	9.34 [4.15] (6)	11.5 [4.62] (4)	11.5 [4.62] (4)	9.34 [4.15] (6)	8.09 [3.78] (8)	6.93 [3.38] (11)

Table 13.--Results of K-CERA analysis--Continued

Standard error of instantaneous discharge, in percent
[Equivalent Gaussian spread]
(Number of visits per open-water season to site)

Station number	Current operation	Budget, in thousand of 1984 dollars				
		680.2	700.2	718.1	754.0	789.9
115000	19.8 [16.3] (6)	21.8 [16.6] (4)	21.8 [16.6] (4)	19.8 [16.3] (6)	18.7 [16.0] (8)	17.7 [15.7] (11)
116000	6.85 [4.95] (6)	7.99 [5.03] (4)	7.99 [5.03] (4)	6.85 [4.95] (6)	6.30 [4.91] (8)	5.86 [4.88] (11)
116500	6.91 [5.21] (6)	8.18 [5.99] (4)	8.18 [5.99] (4)	6.91 [5.21] (6)	6.12 [4.68] (8)	5.30 [4.09] (11)
117500	9.54 [4.79] (6)	11.5 [5.35] (4)	11.5 [5.35] (4)	10.4 [5.04] (5)	8.89 [4.57] (7)	7.53 [4.04] (10)
119000	6.77 [5.85] (6)	8.07 [6.77] (4)	8.07 [6.77] (4)	6.77 [5.85] (6)	5.94 [5.19] (8)	5.13 [4.53] (11)
121300	7.22 [4.74] (6)	8.74 [5.57] (4)	7.87 [5.10] (5)	7.87 [5.10] (5)	5.96 [4.00] (9)	5.19 [3.51] (12)
121500	7.46 [3.37] (6)	9.19 [3.92] (4)	8.19 [3.62] (5)	8.19 [3.62] (5)	6.07 [2.85] (9)	5.25 [2.53] (12)
121900	7.74 [4.51] (6)	9.41 [5.15] (4)	9.41 [5.15] (4)	9.41 [5.15] (4)	7.19 [4.27] (7)	6.07 [3.73] (10)
122000	4.21 [1.15] (6)	5.48 [1.23] (4)	5.48 [1.23] (4)	5.48 [1.23] (4)	3.83 [1.12] (7)	3.09 [1.03] (10)
122100	15.2 [7.79] (6)	18.6 [9.57] (4)	18.6 [9.57] (4)	18.6 [9.57] (4)	14.0 [7.20] (7)	11.7 [5.98] (10)
122200	5.26 [2.01] (6)	6.62 [2.47] (4)	6.62 [2.47] (4)	6.62 [2.47] (4)	4.82 [1.87] (7)	3.97 [1.57] (10)

Table 13.--Results of K-CERA analysis--Continued

Standard error of instantaneous discharge, in percent
[Equivalent Gaussian spread]
(Number of visits per open-water season to site)

Station number	Current operation	Budget, in thousand of 1984 dollars				
		680.2	700.2	718.1	754.0	789.9
122500	4.16 [1.50] (6)	5.22 [1.72] (4)	5.22 [1.72] (4)	5.22 [1.72] (4)	3.83 [1.42] (7)	3.17 [1.24] (10)
124000	2.84 [0.78] (6)	3.51 [0.81] (4)	3.51 [0.81] (4)	3.51 [0.81] (4)	2.63 [0.77] (7)	2.21 [0.76] (10)
126000	3.92 [3.46] (6)	4.63 [3.95] (4)	4.63 [3.95] (4)	4.63 [3.95] (4)	3.68 [3.28] (7)	3.15 [2.84] (10)
127000	5.05 [3.45] (6)	6.14 [4.22] (4)	6.14 [4.22] (4)	6.14 [4.22] (4)	4.69 [3.19] (7)	3.94 [2.68] (10)
127800	3.95 [2.97] (6)	4.65 [3.41] (4)	4.65 [3.41] (4)	4.26 [3.17] (5)	4.26 [3.17] (5)	3.95 [2.97] (6)
127918	2.63 [2.63] (6)	2.65 [2.65] (4)	2.65 [2.65] (4)	2.65 [2.65] (4)	2.65 [2.65] (4)	2.65 [2.65] (4)
128000	3.69 [2.18] (6)	4.59 [2.65] (4)	4.59 [2.65] (4)	4.07 [2.38] (5)	4.07 [2.38] (5)	3.69 [2.18] (6)
129000	4.18 [2.57] (10)	5.66 [0.81] (4)	3.89 [0.77] (8)	3.66 [0.76] (9)	3.66 [0.76] (9)	3.30 [0.76] (11)
130500	6.10 [1.80] (6)	7.56 [2.03] (4)	7.56 [2.03] (4)	6.71 [1.91] (5)	6.71 [1.91] (5)	6.10 [1.80] (6)
135500	2.55 [1.37] (6)	3.21 [1.61] (4)	3.21 [1.61] (4)	3.21 [1.61] (4)	2.82 [1.48] (5)	2.82 [1.48] (5)
135600	4.06 [3.12] (6)	4.92 [3.63] (4)	4.92 [3.63] (4)	4.92 [3.63] (4)	4.42 [3.34] (5)	4.42 [3.34] (5)

Table 13.--Results of K-CERA analysis--Continued

Standard error of instantaneous discharge, in percent
[Equivalent Gaussian spread]
(Number of visits per open-water season to site)

Station number	Current operation	Budget, in thousand of 1984 dollars				
		680.2	700.2	718.1	754.0	789.9
135700	4.52	5.58	5.58	5.58	4.96	4.96
	[0.78]	[0.81]	[0.81]	[0.81]	[0.79]	[0.79]
	(6)	(4)	(4)	(4)	(5)	(5)
136500	2.73	3.45	3.45	3.45	3.03	3.03
	[0.78]	[0.81]	[0.81]	[0.81]	[0.79]	[0.79]
	(6)	(4)	(4)	(4)	(5)	(5)
142000	7.23	7.23	7.23	7.23	7.23	6.27
	[0.24]	[0.24]	[0.24]	[0.24]	[0.24]	[0.24]
	(4)	(4)	(4)	(4)	(4)	(5)
143900	11.6	13.0	11.6	11.1	9.28	8.52
	[10.4]	[11.3]	[10.4]	[10.0]	[8.52]	[7.84]
	(6)	(4)	(6)	(7)	(12)	(15)
144500	12.6	15.2	12.6	11.7	8.94	8.03
	[11.7]	[14.1]	[11.7]	[10.9]	[8.38]	[7.53]
	(6)	(4)	(6)	(7)	(12)	(15)
145000	17.2	22.8	17.2	15.5	10.9	9.41
	[9.36]	[11.6]	[9.36]	[8.61]	[6.50]	[5.76]
	(6)	(4)	(6)	(7)	(12)	(15)
146000	11.1	13.6	11.1	10.3	7.98	7.17
	[4.47]	[4.89]	[4.47]	[4.31]	[3.68]	[3.40]
	(6)	(4)	(6)	(7)	(12)	(15)
146063	16.0	19.6	16.0	14.9	11.3	10.1
	[0.84]	[0.91]	[0.84]	[0.82]	[0.78]	[0.77]
	(6)	(4)	(6)	(7)	(12)	(15)
147500	9.98	12.1	9.98	9.28	7.17	6.44
	[5.56]	[6.32]	[5.56]	[5.27]	[4.26]	[3.87]
	(6)	(4)	(6)	(7)	(12)	(15)
148140	20.9	25.5	20.9	19.3	14.8	13.2
	[9.50]	[11.5]	[9.50]	[8.78]	[6.73]	[6.03]
	(6)	(4)	(6)	(7)	(12)	(15)
148500	7.24	8.93	7.24	6.70	5.16	4.64
	[4.29]	[4.78]	[4.29]	[4.08]	[3.40]	[3.12]
	(6)	(4)	(6)	(7)	(12)	(15)

Table 13.--Results of K-CERA analysis--Continued

Standard error of instantaneous discharge, in percent
[Equivalent Gaussian spread]
(Number of visits per open-water season to site)

Station number	Current operation	Budget, in thousand of 1984 dollars				
		680.2	700.2	718.1	754.0	789.9
149000	5.82 [0.75] (6)	7.50 [0.77] (4)	5.82 [0.75] (6)	5.31 [0.75] (7)	3.91 [0.74] (12)	3.47 [0.74] (15)
150500	21.3 [9.27] (6)	26.8 [10.2] (4)	21.3 [9.27] (6)	16.3 [7.97] (10)	14.2 [7.31] (13)	13.3 [6.94] (15)
150800	14.7 [5.00] (6)	18.7 [5.82] (4)	14.7 [5.00] (6)	11.0 [4.06] (10)	9.51 [3.62] (13)	8.80 [3.39] (15)
151500	15.8 [3.86] (6)	20.2 [4.59] (4)	15.8 [3.86] (6)	11.7 [3.06] (10)	10.1 [2.72] (13)	9.31 [2.55] (15)
154000	10.8 [7.04] (6)	13.2 [8.50] (4)	10.8 [7.04] (6)	8.39 [5.50] (10)	7.35 [4.83] (13)	6.85 [4.50] (15)
155000	21.1 [20.6] (6)	21.9 [21.0] (4)	19.8 [19.6] (15)	19.8 [19.6] (15)	19.8 [19.6] (15)	19.8 [19.6] (15)
155500	39.0 [38.8] (6)	45.2 [44.7] (4)	25.6 [25.5] (15)	25.6 [25.5] (15)	25.6 [25.5] (15)	25.6 [25.5] (15)
156000	12.3 [4.80] (6)	15.5 [5.93] (4)	12.3 [4.80] (6)	9.26 [3.69] (10)	8.03 [3.22] (13)	7.45 [3.02] (15)
159500	22.8 [3.51] (6)	28.0 [3.86] (4)	22.8 [3.51] (6)	21.1 [3.36] (7)	16.0 [2.83] (12)	14.3 [2.60] (15)
160570	11.1 [0.76] (6)	13.8 [0.77] (4)	11.1 [0.76] (6)	10.2 [0.75] (7)	7.73 [0.74] (12)	6.90 [0.74] (15)
160600	16.3 [11.9] (6)	19.4 [13.7] (4)	16.3 [11.9] (6)	15.2 [11.2] (7)	11.8 [8.91] (12)	10.6 [8.05] (15)

Table 13.--Results of K-CERA analysis--Continued

	Standard error of instantaneous discharge, in percent [Equivalent Gaussian spread] (Number of visits per open-water season to site)					
Station number	Current operation	Budget, in thousand of 1984 dollars 680.2	700.2	718.1	754.0	789.9
160800	22.0 [20.7] (6)	25.5 [24.0] (4)	17.6 [16.5] (10)	16.9 [15.9] (11)	15.6 [14.6] (13)	14.6 [13.7] (15)
160900	7.78 [4.10] (6)	9.49 [4.84] (4)	6.76 [3.63] (8)	5.78 [3.14] (11)	5.54 [3.02] (12)	5.54 [3.02] (12)
161100	22.5 [19.8] (6)	27.2 [24.0] (4)	19.5 [17.1] (8)	16.6 [14.5] (11)	15.9 [13.9] (12)	15.9 [13.9] (12)
161540	7.06 [3.82] (6)	8.66 [4.50] (4)	8.66 [4.50] (4)	8.66 [4.50] (4)	8.66 [4.50] (4)	8.66 [4.50] (4)
161580	16.3 [15.0] (6)	19.5 [17.9] (4)	14.2 [13.0] (8)	12.1 [11.1] (11)	11.7 [10.7] (12)	11.7 [10.7] (12)
161800	13.5 [11.4] (6)	16.2 [13.7] (4)	11.8 [9.89] (8)	10.1 [8.48] (11)	9.66 [8.10] (12)	9.66 [8.10] (12)
162010	32.3 [18.2] (6)	38.9 [22.4] (4)	28.2 [15.7] (8)	24.2 [13.2] (11)	23.2 [12.6] (12)	23.2 [12.6] (12)
163400	27.2 [24.6] (6)	29.0 [25.1] (4)	25.6 [23.9] (10)	25.3 [23.8] (11)	24.8 [23.6] (13)	24.5 [23.3] (15)
164000	7.96 [6.74] (6)	9.04 [7.13] (4)	9.04 [7.13] (4)	9.04 [7.13] (4)	9.04 [7.13] (4)	9.04 [7.13] (4)
164100	14.2 [12.5] (6)	17.3 [15.2] (4)	12.3 [10.8] (8)	10.4 [9.11] (11)	9.99 [8.72] (12)	9.99 [8.72] (12)
164500	16.3 [8.18] (6)	19.5 [8.39] (4)	19.5 [8.39] (4)	19.5 [8.39] (4)	19.5 [8.39] (4)	19.5 [8.39] (4)

Table 13.--Results of K-CERA analysis--Continued

Standard error of instantaneous discharge, in percent
[Equivalent Gaussian spread]
(Number of visits per open-water season to site)

Station number	Current operation	Budget, in thousand of 1984 dollars				
		680.2	700.2	718.1	754.0	789.9
166000	8.99 [0.76] (6)	11.4 [0.77] (4)	11.4 [0.77] (4)	9.99 [0.76] (5)	8.24 [0.75] (7)	6.77 [0.75] (10)
166100	11.8 [7.53] (6)	14.4 [8.71] (4)	14.4 [8.71] (4)	13.0 [8.08] (5)	11.0 [7.08] (7)	9.21 [6.08] (10)
166200	27.8 [21.4] (6)	34.1 [26.4] (4)	21.5 [16.3] (10)	19.6 [14.8] (12)	17.6 [13.6] (16)	17.6 [14.7] (21)
166300	13.8 [10.9] (6)	15.7 [11.4] (4)	12.8 [10.6] (8)	11.5 [9.92] (12)	10.8 [9.48] (15)	10.8 [9.73] (18)
166500	17.8 [14.9] (6)	19.6 [15.2] (4)	16.8 [14.7] (8)	15.8 [14.4] (12)	15.3 [14.2] (15)	15.3 [14.4] (18)
168000	19.2 [9.10] (6)	23.3 [10.0] (4)	23.3 [10.0] (4)	20.9 [9.51] (5)	17.9 [8.71] (7)	15.1 [7.76] (10)
170000	6.29 [4.89] (6)	7.60 [5.75] (4)	7.60 [5.75] (4)	6.86 [5.28] (5)	5.86 [4.58] (7)	4.94 [3.90] (10)
170500	15.3 [15.1] (6)	18.1 [18.0] (4)	13.4 [13.3] (8)	11.0 [10.9] (12)	9.92 [9.79] (15)	9.92 [9.82] (18)
172000	15.8 [15.7] (6)	18.4 [18.2] (4)	14.0 [13.9] (8)	11.6 [11.5] (12)	10.5 [10.3] (15)	10.5 [10.4] (18)
174500	7.24 [3.89] (6)	8.91 [4.71] (4)	8.91 [4.71] (4)	7.95 [4.24] (5)	6.69 [3.62] (7)	5.60 [3.06] (10)
174800	10.7 [3.32] (6)	13.4 [3.58] (4)	13.4 [3.58] (4)	11.8 [3.43] (5)	9.81 [3.25] (7)	8.14 [3.11] (10)

Table 13.--Results of K-CERA analysis--Continued

Standard error of instantaneous discharge, in percent
[Equivalent Gaussian spread]
(Number of visits per year to site)

Identification	Current operation	Budget, in thousands of 1984 dollars				
		680.2	700.2	718.1	754.0	789.9
176500	14.3 [9.96] (12)	14.3 [6.54] (8)	13.3 [3.93] (8)	12.6 [3.73] (9)	11.4 [3.39] (11)	10.1 [3.03] (14)

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