EVALUATION OF SELECTED METHODS FOR DETERMINING STREAMFLOW DURING PERIODS OF ICE EFFECT

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By
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CONVERSION TABLE

For readers who prefer metric (International System) units, inch-pound units in this report may be converted by the following factors.

Multiply inch-pound unit	*By*	*To obtain metric unit*
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.590	square kilometer (km^2)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
degree Fahrenheit (°F)	0.555 – (°F –32)	degree Celsius (°C)

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ABSTRACT

Seventeen methods for estimating ice-affected streamflow are evaluated for potential use for the U.S. Geological Survey streamflow-gaging station network. The methods evaluated were identified by written responses from U.S. Geological Survey field offices and by a comprehensive literature search. The methods selected and techniques used for applying the methods are described in the report.

The methods are evaluated by comparing estimated results to data collected at three streamflow-gaging stations in Iowa during the winter of 1987–88. Discharge measurements were obtained at 1- to 5-day intervals during the ice-affected periods at the three stations to define an accurate baseline record. Discharge records were compiled for each method based on data available assuming a 6-week field schedule.

The methods are classified into two general categories, subjective and analytical, depending on whether individual judgement is necessary for method application. On the basis of results of the evaluation for the three Iowa stations, two of the subjective methods (discharge ratio and hydrographic-and-climatic comparison) were more accurate than the other subjective methods, and approximately as accurate as the best analytical method. Three of the analytical methods (index velocity, adjusted rating curve, and uniform flow) could potentially be used for streamflow-gaging stations where the need for accurate ice-affected discharge estimates justifies the expense of collecting additional field data. One analytical method (ice adjustment factor) may be appropriate for use for stations with extremely stable stage-discharge ratings and measuring sections. Further research is needed to refine the analytical methods. The discharge ratio and multiple regression methods produce estimates of streamflow for varying ice conditions using information obtained from the existing U.S. Geological Survey streamflow-gaging network.

INTRODUCTION

The U.S. Geological Survey operates continuous streamflow-gaging stations at more than 6,500 locations in the United States. Discharge at streamflow-gaging stations is normally computed using a defined relation between stream stage and stream discharge. This relation is referred to as a stage-discharge rating. The stage-discharge rating at more than one-half of the stations is affected by backwater from ice formation during part of the winter (see Appendix table A2). The most commonly used method of estimating streamflow during periods of ice cover depends on the hydrographer's judgement and is not readily adapted to automated data processing. This method evolved more than 50 years ago and does not use automated data processing techniques nor does it fully incorporate advances in the understanding of ice hydraulics. Because the method depends on individual judgement, the accuracy of ice-affected streamflow estimates had not previously been defined. The inability to automate the process of estimating ice-affected streamflow records increases streamflow gaging-station operation costs. An evaluation of proposed and other existing methods for determining streamflow during periods of ice effect was conducted by the U.S. Geological Survey.

This report presents the findings of a study that investigated methods for determining streamflow dur-

ing periods of ice effect. Selected methods were evaluated in terms of accuracy, cost, technical soundness, ice conditions, application to computers, and feasibility for use in the U.S. Geological Survey streamflow-gaging network. The accuracy of the selected methods was estimated by using data collected at three representative streamflow-gaging stations in Iowa. The findings of this study apply to streamflow-gaging stations with characteristics which are comparable to the three sites investigated.

METHODS OF STUDY

Identification of existing and proposed methods for determining streamflow during ice-affected periods was accomplished by a written survey of U.S. Geological Survey field offices and by a comprehensive literature search. The objectives of the survey were to assess the frequency and types of ice effect at streamflow-gaging stations and to identify all methods presently used by the U.S. Geological Survey to compute ice-affected streamflow record. A literature search was conducted to identify methods used for computation of ice-affected streamflow record by other countries or methods proposed by the scientific community. The identified methods were then evaluated for three selected sites in Iowa.

SURVEY

A written survey of all U.S. Geological Survey field offices was completed in June of 1987. This survey evaluated the frequency and types of ice effects at streamflow-gaging stations throughout the United States, identified methods used to compute ice-affected streamflow record, and assessed the time and cost of computing ice-affected streamflow record. The survey results indicated that ice effects occurred at streamflow-gaging stations in 44 of 50 States. Some ice effect occurred at 3,734 of 6,616 streamflow-gaging stations. Of the total ice-affected days reported, 68 percent were affected by complete surface ice cover, 17 percent by shore ice, 11 percent by anchor ice, and 4 percent by frazil ice. The computation of ice-affected streamflow record required extra computation time and increased the cost of compiling streamflow records.

Almost all offices use the hydrographic-and-climatic-comparison method to compile ice-affected streamflow record. The most frequently used data are winter discharge measurements, hydrographic comparison, air temperature and winter precipitation records, and recorded stage. The only method reported in the survey that uses a systematically applied procedure for computing ice-affected streamflow is the discharge-ratio method. Twelve districts reported at least occasional use of this method and these districts indicate it

provides reasonable results for some streamflow-gaging stations.

Several districts reported using backwater shifts as a method for verifying ice-affected streamflow record particularly during freeze-up or break-up periods. Recession curves or coefficients, stream conductivity, and index stations are considered to be important information and are used in conjunction with the hydrographic-and-climatic-comparison method by several districts. No systematic use of these methods was reported. A copy of the original survey and selected results are included in the appendix.

LITERATURE SEARCH

Methods used by other countries or proposed by the scientific community were identified through literature searches or by communications with subject authorities. Searches by subject matter were conducted at several comprehensive scientific libraries. Scientific journals and symposium proceedings related to ice studies were examined for ideas or proposed methods for determining streamflow during ice-affected periods. Personal contacts were made with subject authorities or scientific organizations which have experienced staff and recognized expertise in ice-related investigations.

Several articles proposed methods and described their use. Modifications of an author's suggested procedures were at times necessary during this study to make the method compatible with the U. S. Geological Survey streamflow-gaging network, or to adapt the method to equipment or technology presently available.

Ideas for other methods were found in articles that described or investigated other ice-related phenomenon. The specific procedures for method application were not always described in these articles; therefore procedures for method application were developed during this study.

DATA COLLECTION

The various ice conditions that typically occur in Iowa are representative of ice conditions that occur throughout much of the United States. Streams in the mid-latitude regions of the United States tend to have intermittent ice-affected periods during the winter. Warming trends during the winter months cause stream runoff to occur and frequently cause the ice cover to clear from the channel. Streams in the northern States typically have only one extended period of ice cover.

Streams in southern Iowa are affected by ice from about mid-December through late February, and warming trends occur throughout the winter. These warming trends are often long enough to cause increases in stream runoff and may cause the channel ice to clear from rivers and streams. Streams in the northern part of

the State are ice affected from early December through mid-March. Warming trends long enough to cause significant runoff are unusual during the winter months and, typically, ice cover on streams in northern Iowa remains stable throughout the winter.

Field data for evaluating the selected methods were collected during the winter of 1987–88. The meteorological conditions in Iowa during the 1987—88 winter were near normal (table 1).

Data for evaluating the selected methods were collected at three streamflow-gaging stations in Iowa (fig. 1). These stations were selected to represent a range of hydrologic and hydraulic conditions. These conditions include drainage area, channel width, mean depth, control conditions, and gage equipment. A description of the three streams and the ice periods monitored are summarized in table 2. Complete surface ice cover was the cause of backwater during most of the study period for the three test stations. Anchor ice, floating or submerged frazil ice, and shore ice were observed during some periods

Clear Creek near Coralville, Iowa

This station is located on a small tributary of the Iowa River in east-central Iowa. The Clear Creek basin is in the Southern Iowa Drift Plain (Prior, 1976). The area has mature topography with an integrated drainage of weathered glacial till overlain by a moderate to thick loess cover. The region is humid; average precipitation is 34.6 in/yr (inches per year) and average snowfall is 28.6 in/yr. The mean annual temperature is 50.2 °F and the mean January temperature is 19.8 °F (E. May, Iowa State Climatologist, written commun., 1988). The basin drainage area is 98.1 mi^2 (square miles); during winter the channel width is about 45 ft (feet) and the mean effective depth is about 0.8 ft. The streambed is composed of sand and silt and the station has a shifting low-water control. River stage is recorded using a stilling well with a digital paper-tape primary recorder and is supplemented by an analog recorder.

Des Moines River at Fort Dodge, Iowa

This station is located on the main stem of the Des Moines River in north-central Iowa. The Des Moines River basin is in the Des Moines Lobe. This area is overlain with recent glacial drift and is poorly drained. The region is humid; average precipitation is 32.3 in/yr and average snowfall is 39.5 in/yr. The mean annual temperature is 47.5 °F and the mean January temperature is 15.8 °F (E. May, Iowa State Climatologist, written commun., 1988). The basin drainage area is 4,190 mi^2; during winter the channel width is about 320 ft and the mean depth is about 1.5 ft. The streambed is composed of gravel and cobbles and the station control is stable. River stage is recorded using a stilling well with a digital paper-tape recorder.

Floyd River at James, Iowa

This station is located on a tributary to the Missouri River in northwestern Iowa. The Floyd River basin is in the Northwest Iowa Plains. This area has mature topography with an integrated drainage and is overlain with moderate to thick loess cover. The region is sub-humid; average precipitation is 25.4 in/yr and average snowfall is 31.6 in/yr. The mean annual temperature is 48.4 °F and the mean January temperature is 16.2 °F (E. May, Iowa State Climatologist, written commun., 1988). The basin drainage area is 882 mi^2; during winter the channel width is about 110 ft and the mean depth is about 0.7 ft. The streambed is composed of silt and fine sand and the station has a moderately shifting control. River stage is recorded using a mercury manometer with a digital paper-tape primary recorder and is supplemented by an analog recorder.

Data Collection Strategy

Discharge measurements were made at the three streamflow-gaging stations at 1- to 5-day intervals during periods of ice effect using standard ice-measurement techniques (Buchanan and Somers, 1969). Vertical

Table 1.—*Statewide monthly temperature, precipitation, and snowfall in Iowa for the 1987–88 winter period, and averages for the 1951–80 period*

Month	Temperature (°F)		Precipitation (inches)		Snowfall (inches)	
	1987–88 winter	1951–80 average	1987–88 winter	1951–80 average	1987–88 winter	1951–80 average[1]
December	32.9	28.6	2.61	1.85	12.4	9.5
January	15.5	16.4	.60	.76	2.6	5.0
February	15.1	19.3	.02	.52	8.9	7.8

Source: Iowa Department of Agriculture and Land Stewardship, Weather Summaries, Monthly

[1] Average monthly snowfall from E. May, Iowa State Climatologist, written. commun. (1988)

velocity profiles also were made at three locations across the measurement cross-sections by measuring point velocity at nine equal depth percentages (10, 20, ..., 80, 90 percent). A description of the appearance of the ice was recorded during each discharge measurement, and a representative block of ice was cut from the ice cover and the underside was photographed and described in the measurement notes.

Once-daily measurements of specific conductance were obtained at the gaging stations. Records of point velocity were maintained for the streamflow-gaging stations on the Des Moines River at Ft. Dodge and Clear Creek near Coralville. Point velocity record was not collected at the Floyd River at James site because only two sets of velocity monitoring equipment were available. Auxiliary gages were operated 3.0 mi (miles) downstream from the Floyd River at James and 1.9 mi downstream from Clear Creek at Coralville. Gage height was obtained at the auxiliary gages by once-daily readings from a wire-weight gage or by measuring the distance from the stream water surface to a reference point. Because section control exists for all normal winter flows at the Des Moines River at Fort Dodge, auxiliary gage height data was not collected.

DEVELOPMENT OF BASELINE RECORDS

A baseline daily streamflow record was developed for each station to evaluate the selected methods. The

EXPLANATION

▲ 05454300   Test streamflow-gaging station
and number

△ 05454000   Correlated streamflow-gaging
station and number
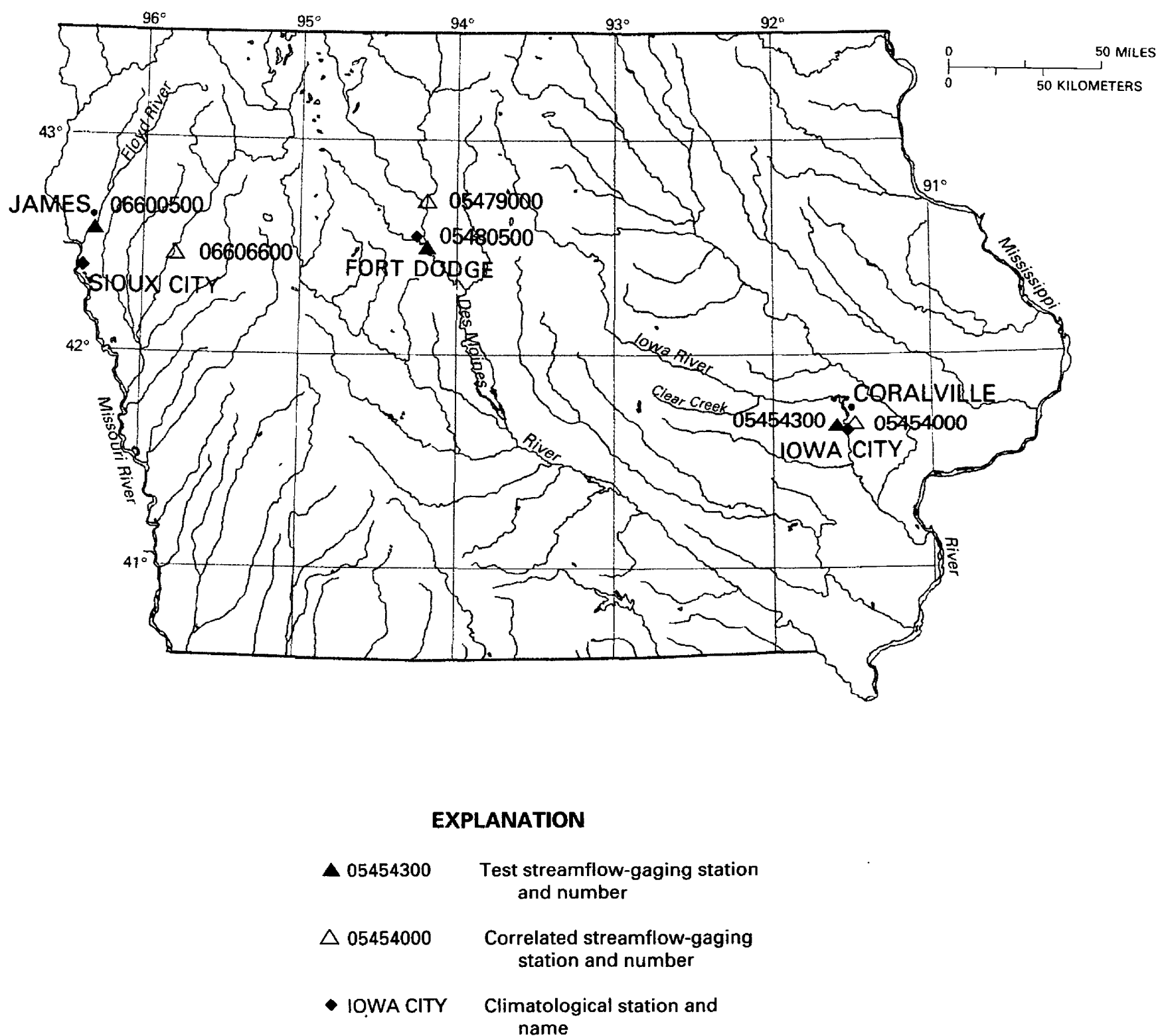
◆ IOWA CITY   Climatological station and
name

Figure 1. Location of test streamflow-gaging stations, correlated streamflow-gaging stations, and climatological stations in Iowa.

baseline record was constructed by hydrographers experienced in making ice-affected streamflow estimates and familiar with the streamflow-gaging stations and local topography. All discharge measurements and ancillary information were used to develop daily streamflow records. The frequency of the data collection significantly reduced the interpretation required to construct the ice-affected streamflow records. The daily streamflow records were reviewed by several personnel experienced in compiling and reviewing ice-affected streamflow records, and were accepted as baseline conditions. The discharge record is referred to as a baseline record because, for statistical analysis purposes, it is considered to be a correct discharge and is the basis for comparing and analyzing the selected methods. Because of the small amount of interpretation needed to compile the baseline record the discharge values are not absolute. The completed records, the discharge measurements, the indicated open-water discharge hydrographs, and climatic data are shown in figure 2. The indicated open-water discharges are the discharges computed for periods of ice effect using the stage-discharge rating without adjustments for ice effect. Because of the increased friction and reduced flow area resulting from ice cover, the indicated open-water discharge is usually greater than the actual discharge.

EVALUATION OF METHODS

Each selected method was evaluated for accuracy and other criteria related to the operation of the U.S. Geological Survey streamflow-gaging network. The accuracy evaluation included several measures of error

determined by comparing each method to the baseline streamflow record. A subset of the measurements used to compile the baseline record was used in the evaluation to simulate the usual schedule of field data collection. The evaluation also included criteria which are not readily quantified, yet are important considerations for evaluation of the selected methods, such as cost, technical soundness, ice conditions, application to computers, and feasibility of application to the U.S. Geological Survey streamflow-gaging network.

DESCRIPTION OF METHODS FOR DETERMINING STREAMFLOW DURING PERIODS OF ICE EFFECT

In this section a brief description of each method is presented. Procedures for some methods were established specifically for this study, and these procedures are described in the following sections. Each discussion concludes with a description of the data required to develop and apply the method.

The selected methods are classified into two general categories depending on whether individual judgement is necessary for method application. These two categories are referred to as subjective and analytical methods. Discharge estimates using analytical methods generally are consistent and reproducible because the results are obtained by a systematic computation. Subjective method results may vary because the methods are dependent on individual judgement. Given the same set of field data and procedures, two hydrographers working independently should compile the same

Table 2. —*Description of streamflow-gaging stations and periods of ice effect monitored during the 1987–88 winter*
[mi^2, square miles]

Station	Name	Drainage area (mi²)	Number of ice measurements	Number of ice affected days	Period(s) of ice effect
05454300	Clear Creek near Coralville, Iowa	98.1	33	66	Dec. 15–20 Dec. 31–Jan. 19 Jan. 22–Jan. 31 Feb. 2–Feb. 29
05480500	Des Moines River at Fort Dodge, Iowa	4,190	21	67	Dec. 3–Dec. 4 Dec. 15–Dec. 18 Dec. 29–Feb. 29
06600500	Floyd River at James, Iowa	882	39	79	Dec. 15–Mar. 2

results using an analytical method, but the two results may vary using a subjective method. Some analytical methods are only intended for use in one particular ice condition and may not be applicable for all ice conditions encountered at a streamflow-gaging station. Subjective methods generally can be used for all ice conditions. The first six methods are subjective; the remaining eleven methods are analytical. The discharge-ratio and backwater-shift methods were evaluated using subjective and analytical solutions.

SUBJECTIVE METHODS
Base-flow Recession

The base-flow recession method uses the normal recession rate of the nongrowing season to estimate

Figure 2A. Baseline streamflow record, indicated open-water discharges, measured discharges, and nearby climatological data for Clear Creek near Coralville, Iowa.

streamflow during ice-affected periods (Rosenberg and Pentland, 1983). The recession for a station is determined by an equation or by a graph. The equation which commonly is used to estimate recession discharge is:

$$Q_t = Q_o \, C^{\,(t-t_o)} \qquad (1)$$

where

Q_t is the discharge at time t,
Q_o is the discharge at time t_o, and
C is the recession constant.

The recession constant is defined by historical data. Discharge is computed by multiplying the discharge prior to the ice-affected period (Q_o) by the appropriate factor determined by eq. (1).

Figure 2B. Baseline streamflow record, indicated open-water discharges, measured discharges, and nearby climatological data for the Des Moines River at Fort Dodge, Iowa.

Ice-affected streamflow can be estimated using a graphical solution to the base-flow recession method. An appropriate engineering curve is selected and aligned with the general recession indicated by a hydrograph of daily mean discharge values. This recession curve is drawn on the hydrograph and estimated daily discharge values are defined by this curve. The shape of the recession in prior years and winter discharge measurements during ice-affected periods are also considered in drawing the recession curve. The equation and graphical solutions to the recession curve method normally will produce similar results.

For this study, the base-flow recession method was applied using the graphical solution. The discharge for

1987-88 WINTER PERIOD

EXPLANATION

—   Baseline record

— —   Indicated open-water discharge

•   Measured discharge

|—| Open water period

◉   Measurement used for method application
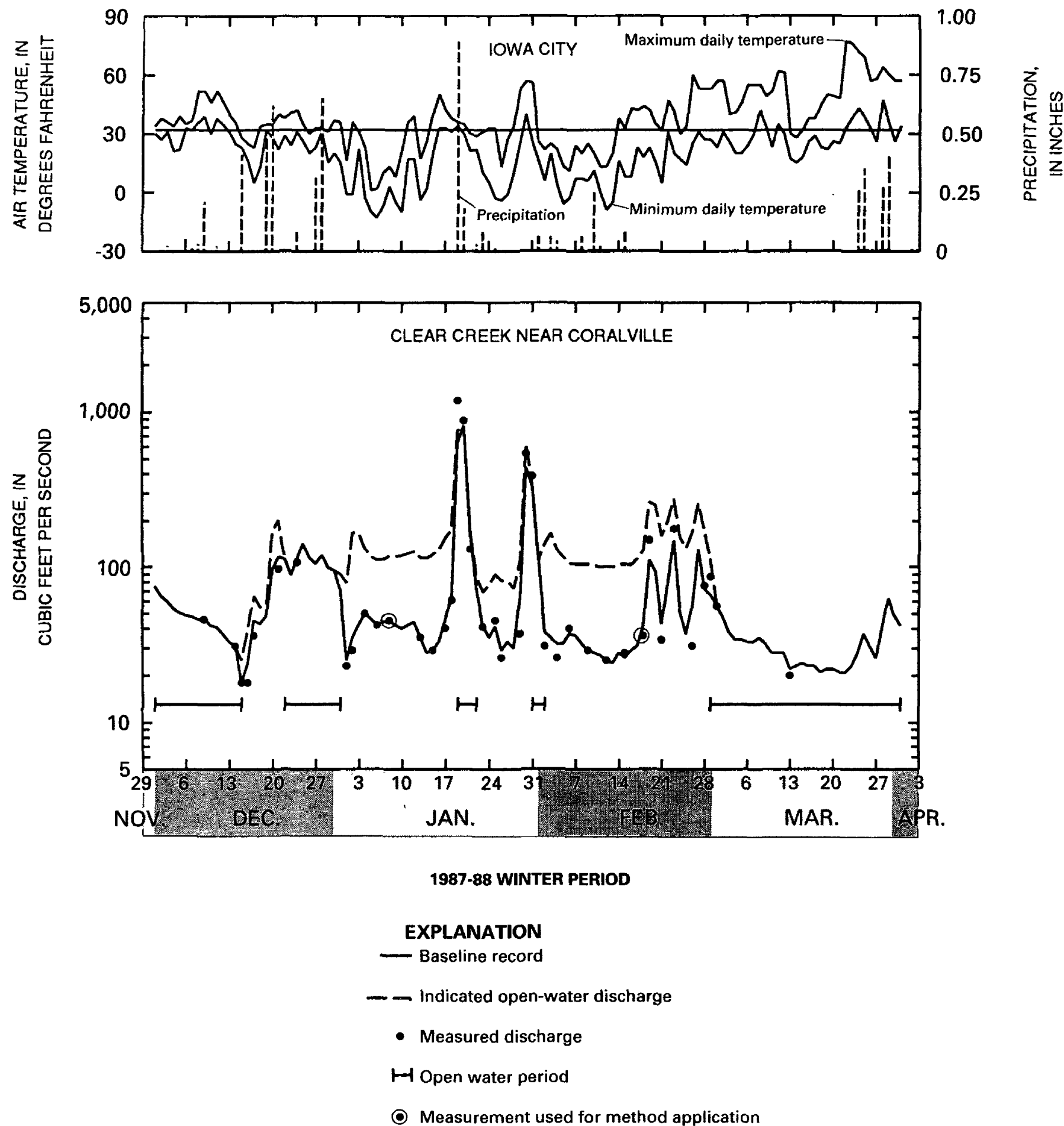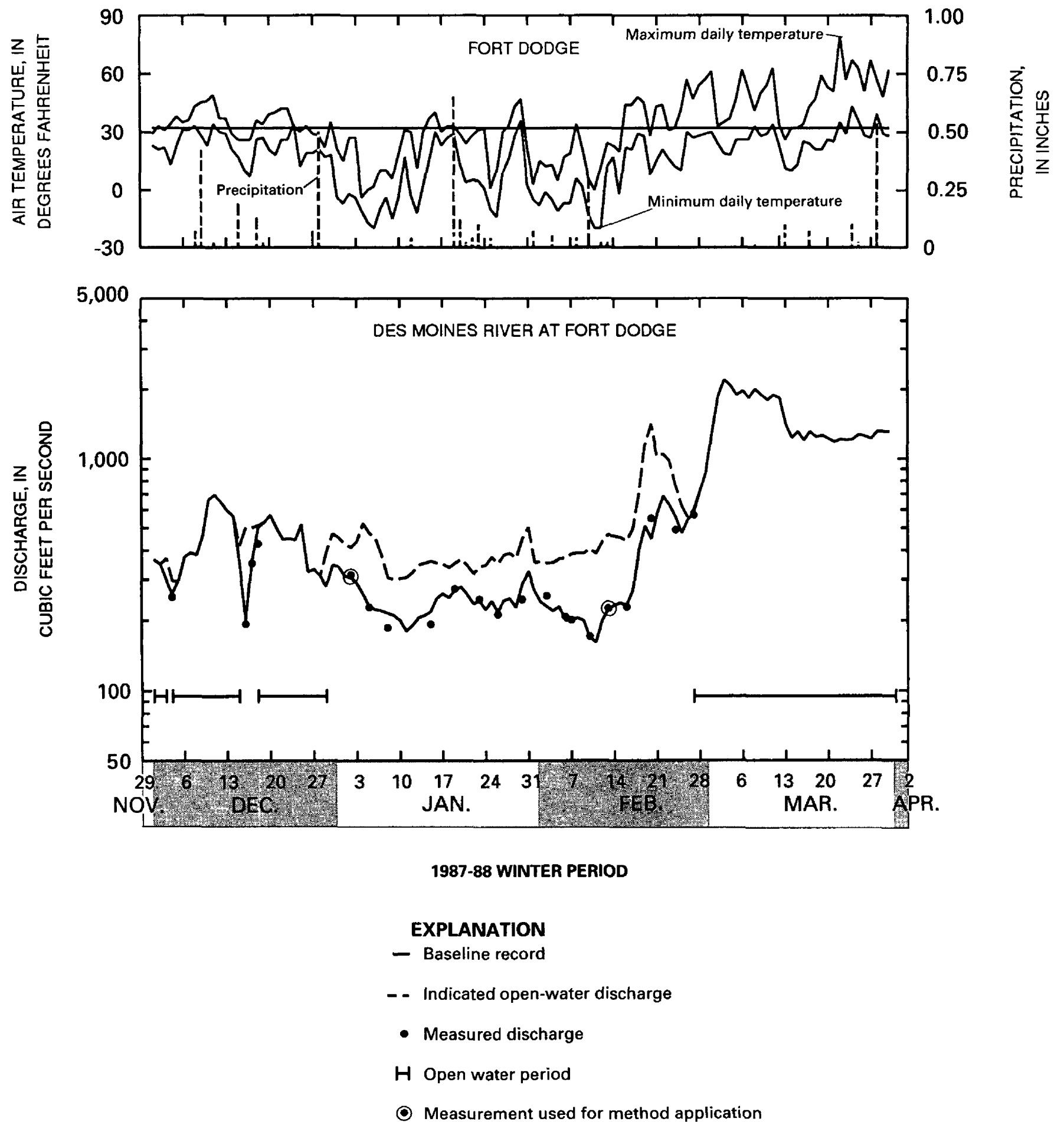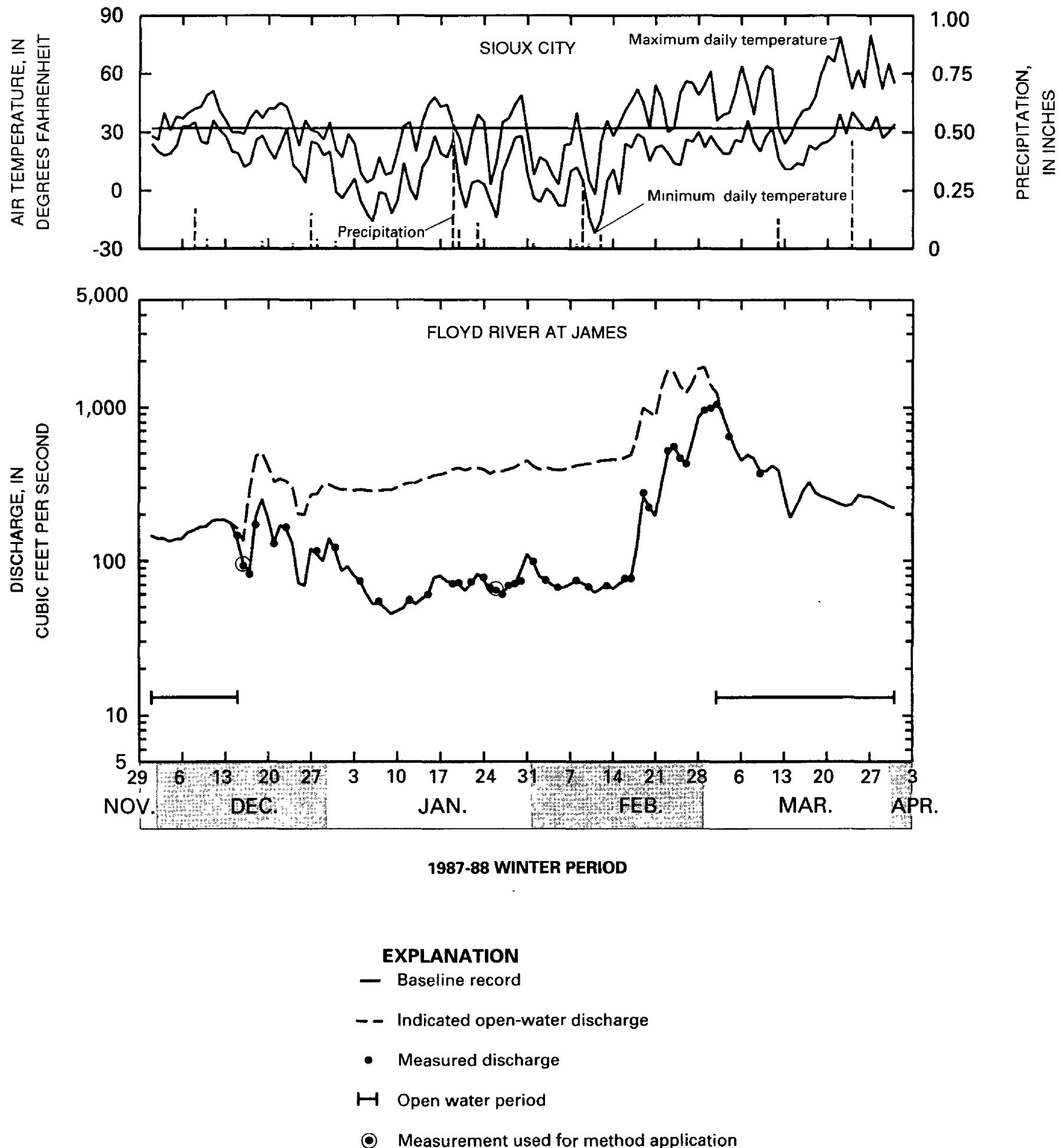
Figure 2C.   Baseline streamflow record, indicated open-water discharges, measured discharges, and nearby climatological data for the Floyd River at James, Iowa.

periods without ice effect, the indicated open-water discharges during periods of ice effect, and the maximum and minimum daily air temperatures were plotted on semilogarithmic paper. The recession curve was then drawn based on the general shape of the nongrowing season hydrograph recession. The hydrographs for the previous 2 water years were also considered in defining the recession curve. The recession curve accounted for available discharge measurements by adjusting the discharge for a few days before and after the discharge measurement or by adjusting the slope of the curve for the entire ice period depending on the hydrographer's interpretation of the cause for the discrepancy between indicated open-water discharge and the measured discharge. The curve was extended until the end of the ice period and merged with the open-water hydrograph.

Discharge Ratio

The discharge ratio method uses the ratio of measured discharge to rated discharge to adjust the indicated open-water discharge during ice-affected periods (Rosenberg and Pentland, 1983; Rantz and others, 1982). The ratio (K-factor) for each measurement is calculated by the following equation:

$$K = \frac{Q_m}{Q_r} \qquad (2)$$

where

Q_m is the measured discharge, and
Q_r is the rated discharge for the indicated gage height.

The computed K-factor for each discharge measurement is plotted on semilogarithmic paper. The plotted points are connected by modified interpolation considering the effects of changing meteorological conditions. The K-factor is merged with a value of 1.0 on the day prior to and after each ice period. The indicated open-water discharges for each ice-affected day are then adjusted by the K-factor obtained from the K-factor line.

This method can be applied using a graphical solution. Discharge measurements, the open-water periods, and indicated open-water discharges are plotted on semilogarithmic hydrograph paper. The vertical distance on the hydrograph between each ice-affected discharge measurement and the corresponding indicated open-water discharge is measured. This distance is then measured vertically from a selected reference line on the log scale corresponding to a value of 1.0, and the displaced point indicated by this measurement is marked on the plot. A factor line is then drawn through the displaced point by the same method used for the analytical solution. The indicated open-water discharges

are adjusted by measuring the distance from the reference line to the factor line and subtracting this distance from the indicated open-water discharge line. If the factor line and the K-factor line are the same, the equation and the graphical solutions will produce identical results.

For this study discharge was computed using the K-factor equation. The K-factor was computed using the ratio of the measured discharge and the indicated open-water discharge for the mean gage height during the measurement. A modified interpolated K-factor line was drawn considering meteorological records and used to adjust the indicated open-water discharges.

Backwater Shift

The backwater shift method uses the backwater computed from the open-water stage-discharge rating to estimate discharge during ice-affected periods (Rosenberg and Pentland, 1983; Rantz and others, 1982). The backwater for each discharge measurement made during ice-affected conditions is computed by subtracting the gage height indicated by the stage-discharge rating from the recorded gage height. The computed backwater shifts are plotted on hydrograph paper. A backwater curve for the ice-affected period is drawn by modified interpolation of the plotted backwater shifts, considering the effects of changing meteorological conditions on stream backwater. The backwater shift for each ice-affected day is determined from the backwater curve and is subtracted from the recorded gage height to compute the effective gage height. The discharge for the effective gage height is obtained from the stage-discharge rating and plotted on semilogarithmic hydrograph paper.

For this study the backwater shifts were computed and plotted on rectangular-coordinate paper. The backwater shift curve was drawn considering meteorological records and was merged with the shifts that were used to compute the open-water periods before and after the ice-affected period. The estimated discharge values were obtained from the stage-discharge rating and plotted on semilogarithmic hydrograph paper. The values were confirmed by comparison with the indicated open-water discharges, and the backwater curve was adjusted as necessary.

Interpolated Discharge

The interpolated discharge method (Rosenberg and Pentland, 1983) uses a modified interpolation of daily discharge for periods between discharge measurements to estimate discharge during ice-affected periods. Discharge measurements during ice-affected periods and discharges computed during open-water periods are plotted on semilogarithmic hydrograph paper. This method does not use the indicated open-water dis-

charges. Discharges for ice-affected periods are estimated and plotted on this hydrograph by interpolating between discharge measurements. This interpolation is modified considering hydrographic comparison with nearby streamflow-gaging stations and meteorological records.

For this study, ice-affected record was estimated using discharge measurements during ice-affected periods, discharge data computed for open-water periods, and the hydrograph record for one nearby hydrologically similar streamflow-gaging station.

Adjusted Discharge

The adjusted discharge method uses modified interpolation between discharge measurements to estimate daily mean discharge during ice-affected periods (Rosenberg and Pentland, 1983). Discharge measurements during ice-affected periods, the indicated open-water discharges, discharges computed during open-water periods, and local meteorological records are plotted on semilogarithmic hydrograph paper. This method does not use hydrographic comparison. Discharges for ice-affected periods between discharge measurements are estimated and plotted on this hydrograph by modified interpolation considering the other data plotted on the hydrograph.

For this study, the ice-affected record was estimated using discharge measurements during ice-affected periods, discharge data computed for open-water periods, and local meteorological records.

Hydrographic-and-Climatic Comparison

The hydrographic-and-climatic-comparison method generally is used by the U.S. Geological Survey to estimate discharge during ice-affected periods (Rantz and others, 1982). Discharge measurements, the indicated open-water discharges, meteorological information, and notes or observations on ice conditions are plotted on semilogarithmic hydrograph paper. Values of daily mean discharge are estimated and plotted on this hydrograph on the basis of discharges for periods without ice effect, the normal trend of the winter hydrograph recession, daily discharge estimates for other nearby streamflow-gaging stations, and local climatological records.

For this study, discharge was estimated using a hydrograph of open-water and indicated open-water discharges, discharge measurements, local meteorological records, and a hydrograph for one nearby hydrologically similar streamflow-gaging station.

ANALYTICAL METHODS

Prorated Discharge

The prorated discharge method uses a linear interpolation of daily discharge for periods between discharge measurements to estimate discharge during ice-affected periods. Discharge measurements during ice-affected periods and discharges computed during open-water periods are plotted on semilogarithmic hydrograph paper or are written in tabular form. Discharges for ice-affected periods are estimated by straight-line interpolation on the hydrograph or computed by linear interpolation between discharge measurements. The ice-affected days preceding and subsequent to the first and last ice-affected measurements were estimated by linear interpolation between the discharge computed for the last and first open-water day and the first and last discharge measurement.

For this study, ice-affected record was estimated using direct interpolation in tabular form

Discharge Ratio

Application of this method is the same as the subjective version of the discharge ratio method except the discharge ratio curve is drawn as a linear interpolation of the discharge ratios computed for the discharge measurements.

For this study discharge was compiled using the K-factor equation. The K-factor was computed using the ratio of the measured discharge and the indicated open-water discharge for the mean gage height during the measurement. A linear interpolation K-factor line was drawn and used to adjust the indicated open-water discharges.

Backwater Shift

Application of this method is the same as the subjective version of the backwater shift method, except the backwater shift curve is a linear interpolation between the backwater shifts indicated by the measurements.

For this study the backwater shifts were computed and plotted on rectangular-coordinate paper. A linear interpolation backwater shift curve was drawn and this curve was merged with the shifts that were used to compute the open-water periods before and after the ice-affected period. The estimated discharges were then obtained using the backwater shift curve and the stage-discharge rating.

Stage Fall

The stage-fall method uses auxiliary gage height to adjust the indicated open-water discharge for the change in stage (fall) over a given stream reach (Carey, 1967). The method uses the derived relations between gage height and discharge, and gage height and fall for the least-backwater conditions. The least backwater rating curve is drawn as the lower bound through all ice-affected discharge measurements. Carey (1967) proposed use of a third relation between the ratio of

discharge to least-backwater discharge, and the ratio of fall to least-backwater fall.

For this study, the required relations were developed using most of the discharge measurements made during the study. Discharge measurements that were not made at the usual measuring location were omitted. The use of historical data was not possible, because auxiliary gage data was not collected prior to this study. Because the discharge ratio versus fall ratio relations were not well defined, the theoretical square-root relation of discharge to fall was used (Rantz and others, 1982). The ice-affected streamflow record was computed using daily average values of gage-height, fall computed from the once-daily values of auxiliary gage height, and the derived relations.

Adjusted Rating Curve

The adjusted rating curve method is based on a modification of the open-water rating curve to compensate for increased slope of the rating curve due to the roughness of the ice cover. Using Manning's equation, Lavender (1984) derived the following equation relating the slope of the ice-cover rating-curve to the slope of the open-water rating-curve:

$$\frac{dH_i}{dQ} = [1 + (n_i/n_b)^{3/2}]^{2/5}\frac{dH_o}{dQ} \qquad (3)$$

where

H_o is the open-water gage height,
H_i is the ice-affected gage height,
Q is discharge,
n_b is the bed roughness, and
n_i is the ice cover roughness.

For given ice-affected discharge measurements the shift of the ice-cover rating curve can be established, thus an ice-cover rating curve can be derived from the new position and the adjusted slope.

Roughness for the ice cover and the streambed are determined by separating the vertical velocity profile into two parts. The part from the ice cover to the point of maximum velocity is influenced by the ice roughness; likewise, the bed roughness determines the shape of the velocity profile from the streambed up to the point of maximum velocity. The point of maximum velocity is determined by fitting a flexible, general two-power velocity law to the velocity data. For each part of the velocity profile, the roughness is computed from the maximum and mean velocities (Larsen, 1966; Davar and MacGougan, 1984; Gogus and Tanticlaux, 1980, 1981; Calkins and others, 1980, 1982). The composite roughness for the entire channel is computed using the Sabaneev formula (Nedzhikhovskiy, 1964; Davar and MacGougan, 1984), and averaged across the cross sec-

tion using the Pratte formula (Pratte, 1979; Davar and MacGougan, 1984).

For this study, the position of the ice-affected rating curve was determined for each discharge measurement; the shift is prorated by time for the period between measurements. Roughness ratios are computed using the vertical velocity profiles obtained during the 6-week discharge measurements, and the ratios are prorated by time between measurements. The ice-affected streamflow record is determined from the updated daily ice-affected rating curve and daily average gage height.

Conductance Correlation

The conductance correlation method is based on a statistical relation between discharge and specific conductance. Specific conductance generally is inversely related to streamflow. This is due to the higher conductance of the portion of streamflow resulting from ground-water inflow than the portion resulting from surface flow (Hem, 1985). The relation between streamflow and conductance is developed from historical data using regression analysis techniques.

For this study, measured discharge and specific conductance for the 1984–86 ice-affected periods were used to develop regression equations (table 3). Daily discharge was computed using a record of once-daily conductance values.

Multiple Regression

The multiple regression method uses a regression relation established for each site to relate ice-affected discharge to selected hydrologic and climatological variables (Fontaine, 1983). The explanatory variables used include gage height, indicated open-water discharge, concurrent daily discharge at correlated stations, maximum and minimum daily air temperature, maximum and minimum monthly air temperature, total precipitation, the previous day's total precipitation, and heating degree days for the month. Measured discharge is the dependent variable for the developed equations.

For this study the regression relations were determined using data collected for the 1977–87 ice-affected periods. The regressions were conducted using a stepwise multiple regression procedure, and were limited to four explanatory variables. For each site three correlated stations were selected; only one correlated station was used in the final equation (fig. 1). All of the regressions had significance levels less than 0.001 ($p < .001$), and standard errors that ranged from 11 to 33 percent (table 4). The ice-affected streamflow record was computed using the fitted regression equation and values of the pertinent variables.

Index Velocity

The index velocity method uses stream velocity and effective cross-sectional area of the channel to compute stream discharge (Strilaeff, 1972). The effective cross-sectional area of the channel is the difference between total cross-sectional area and the cross-sectional area of the ice cover. Velocity is monitored continuously during the ice-affected period, and effective cross-sectional area is determined at the velocity monitoring point. Discharge is computed as the product of mean velocity and effective cross-sectional area.

For this study, stream velocity was monitored using a single velocity probe located at a representative point in the stream cross-section. Mean velocity was computed by adjusting the point velocity by the ratio of mean velocity for the 6-week discharge measurements to the concurrent recorded point velocity, and the ratio was prorated by time between measurements. The relation between stage and total cross-sectional area and the cross-sectional area of the ice were defined by the discharge measurements. The cross-sectional area of the ice was prorated by time between the 6-week discharge measurements. The effective cross-sectional area was computed as the difference between total cross-sectional area and cross-sectional area of the ice cover. Mean daily discharge was computed as the product of mean velocity and effective cross-sectional area determined for the daily mean gage height.

Ice Adjustment Factor

The ice adjustment factor method uses the concept of a stable ice cover for determination of discharge. For stable conditions, the ratio of open-water to ice-cover hydraulic mean depth, the ice adjustment factor, is assumed to be constant (Santeford and Alger 1984, 1986a, 1986b; Alger and Santeford 1984, 1987). The ice-cover hydraulic mean depth is determined from an adjusted gage height and a table of gage height versus hydraulic mean depth. The recorded gage height is adjusted using the float depth to give the effective cross-sectional area.

Development of the method involves estimating float depth and the ice adjustment factor for discharge measurements. By definition, float depth is the difference between recorded gage height and the equivalent gage height resulting in the effective cross-sectional area:

$$FD = GH_r - GH_i \qquad (4)$$

where

FD is the float depth,

GH_r is the recorded gage height, and

GH_i is the equivalent ice gage height.

The ice adjustment factor is computed from the equivalent open-water hydraulic mean depth and the hydraulic mean depth corresponding to GH_i:

$$IAF = \frac{D_o}{D_i} \qquad (5)$$

where

IAF is the ice adjustment factor,

D_o is the open-water hydraulic mean depth, and

D_i is the hydraulic mean depth corresponding to GH_i.

Discharge is compiled using previously estimated float depths and ice-adjustment factors, and the recorded gage height. The equivalent ice gage height is obtained by rearranging eq. (4):

$$GH_i = GH_r - FD \qquad (6)$$

The ice-cover hydraulic mean depth is obtained from a table of hydraulic properties (gage height versus area and hydraulic mean depth). The equivalent open-water hydraulic mean depth is found by rearranging eq. (5):

$$D_o = IAF \bullet D_i \qquad (7)$$

Table 3. — *Regression equations used for the conductance correlation method*
[<, less than]

Station	Equation*	R-squared	Standard error** (percent)	Significance level (p)
Clear Creek	$Q_m = 228{,}000\ (1/K) - 346$	0.9298	40	< 0.001
Des Moines River	No significant relationship	—	—	—
Floyd River	$Q_m = 1{,}610{,}000\ (1/K) - 1{,}450$	.9812	27	< .001

* Q_m is measured discharge, in cubic feet per second, and K is specific conductance, in microsiemens per centimeter
** Expressed as a percent of the mean measured discharge

For this study the ice adjustment factor and float depth were determined for each ice-affected discharge measurement, and prorated by time between measurements. Because the cross sections changed between measurements, the tables of hydraulic properties were prorated from a measurement made before ice-cover formation and one made after spring breakup. The ice-affected streamflow record is computed using the hydraulic property and stage-discharge rating tables, the interpolated values of ice adjustment factor and float depth, and daily average values of gage height.

Pipe Flow

The pipe flow method computes streamflow under an ice cover as closed-conduit flow (Carey, 1967). The Darcy-Weisbach equation is used, with a modified friction factor based on water surface slope:

$$Q = \sqrt{\frac{8g}{f_{mod}}} \, AR^{1/2}S^{1/2} \tag{8}$$

where

  Q is discharge,

  g is the acceleration of gravity,

  f_{mod} is the modified friction factor,

  A is the effective cross-sectional area,

  R is the hydraulic radius, and

  S is the water-surface slope.

Using regression analyses, relations of f_{mod} to S and $AR^{1/2}$ to gage height are defined.

For this study the regression equations were developed using most of the measurements made during the 1987–88 ice-affected period. Discharge measurements that were not made at the usual measuring location were omitted. Water-surface slope was computed using

data from the auxiliary gage. The ice-affected streamflow record is compiled using the defined relations, the Darcy-Weisbach equation, daily mean values of gage height, and once-daily auxiliary gage height values.

Uniform Flow

The uniform flow method uses Manning's equation to compute streamflow during periods of ice effect. Bed and ice-cover roughnesses are determined from vertical velocity profiles (see the "adjusted rating curve method" section), and are prorated between measurements. The total cross-sectional area is determined using a table of cross-sectional area versus gage height. Effective cross-sectional area is computed from total area and an estimate of ice area. The hydraulic radius is determined using a table of cross-sectional area versus gage height, with gage height adjusted to give the effective flow area.

For this study, ice roughness and ice cross-sectional area were determined for each discharge measurement. Ice roughness values were distributed using a linear interpolation by time, and bed roughness was assumed to remain constant. Ice cross-sectional area was interpolated by time between measurements during the ice-affected period. The ice-affected streamflow record was computed using Manning's equation, ice and bed roughness, effective cross-sectional area, and daily average gage height.

EVALUATION OF METHODS

In this section the various methods are evaluated on the basis of accuracy and other criteria related to operation of the U.S. Geological Survey streamflow-gaging network. Accuracy was evaluated by comparing the method results to baseline data for three streamflow gaging stations in Iowa. Additional criteria include

Table 4.— *Regression equations used for the multiple regression method*

[<, less than]

Station	Equation[*]	R-squared	Standard error[**] (percent)	Significance level[***] (p)
Clear Creek	$Q_m = 0.821\ Q_i + 1.41\ T_{min} + 0.735\ Q_d + 0.752\ T_{max} - 55.8$	0.9910	23	< 0.001
Des Moines River	$Q_m = 1.52\ Q_d + 0.471\ Q_i + 5.92\ T_{min} - 23.0$	.9962	11	< .001
Floyd River	$Q_m = 1.91\ Q_i - 552\ G + 0.047\ Q_d + 4.77\ t_{max} + 5,440$	.9783	33	< .001

[*] Q_m is measured discharge, Q_i is indicated open-water discharge, Q_d is concurrent daily discharge at a correlated station, G is mean daily gage height, T_{min} is minimum monthly air temperature, T_{max} is maximum monthly air temperature, and t_{max} is maximum daily air temperature

[**] Expressed as a percent of the mean measured discharge

[***] The significance level of the regression

factors that are not easily quantified, but are important considerations that influence potential use of a method.

Several factors influence the applicability of a given method. The criteria considered in this section include the following:

(1) Accuracy — several measures of error are considered;

(2) cost — the time and difficulty required to collect data for the method, as well as data required in addition to the usual parameters collected at a gaging station;

(3) technical soundness — the theoretical basis and the assumptions that affect the reliability of the method;

(4) ice conditions — application of the method to various ice conditions;

(5) application to computers — an evaluation of whether the method could be used to compile records by automated data processing; and

(6) feasibility — applicability of the method to the existing U.S. Geological Survey streamflow-gaging network.

ACCURACY

Each selected method was used to estimate discharge at three sites in Iowa, and compared to the baseline streamflow records to assess the accuracy of each method. The evaluation of the methods was based on typical U.S. Geological Survey data-collection procedures. Because streamflow-gaging field trips are normally made at 6-week intervals, the selected methods were evaluated using only the field information for gage visits made at this interval. A 6-week field-trip interval was reconstructed based on the pattern of field trips made during the previous year. Discharge measurements that coincided with the 6-week interval were provided for the evaluation. Two discharge measurements during the ice-affected period for each of the three streamflow-gaging stations were used for evaluating each method.

The subjective methods were applied independently by three hydrographers who are experienced at making ice-affected streamflow estimates. Two of the three hydrographers are stationed in the Iowa District and are familiar with the streamflow-gaging stations used in the study and the local hydrology; the other hydrographer is stationed in the Wisconsin District and was not familiar with the streamflow-gaging stations or the local hydrology. The subjective methods were released to the test participants in the order of increasing data requirements, with a 1-week time lapse scheduled between method evaluations. All of the participants were provided with the dates of the ice-affected periods so that the evaluation would be a comparison of method accuracy rather than an evaluation of the hydrographers' ability to recognize ice effect. The analytical methods were applied by the authors because the results are not

dependent on the interpretation of the individual applying the method.

Application of the methods using different procedures or using sites with different hydrologic or hydraulic characteristics than the test sites may produce varying results. Although the hydrographers were familiar with the principles of all the methods used, they were not always familiar with method application and some improvement in the accuracy of the results may be obtained with repetitive application of the method. The test used data collected at a normal 6-week measurement schedule. The accuracy of a specific method may be improved by adjusting the timing of the schedule for that method.

Several measures of error were used to evaluate the accuracy of the methods: the percent error for the mean discharge for the ice-affected periods, the mean and standard deviation of the daily errors, and the distribution of daily errors. Statistical tests were performed to evaluate the differences between the selected methods and the baseline record.

A comparison of the estimated average discharge for the ice-affected periods with the baseline average was considered in the evaluation of the methods. Average discharge values are shown in table 5. The relative error for the daily discharge values was also computed for each method, and the results are summarized in table 6. In table 6, the relative error is defined as follows:

$$\varepsilon = \frac{Q_e - Q_b}{Q_b} \qquad (9)$$

where

ε is relative error,

Q_e is the daily estimated discharge, and

Q_b is the daily baseline discharge.

The mean relative error is an indication of the overall bias of the method, which is a consistent tendency to either over- or underestimate daily discharge. A method with a significant bias will have cumulative errors for monthly and yearly means regardless of the magnitude of the variability of the error. The distribution of relative errors for the daily discharge values are listed for selected ranges in error, and summarized in table 7. For publication purposes, daily discharge values that are within 5 percent of the true discharge are rated "excellent"; within 10 percent are rated "good"; within 15 percent are rated "fair"; records that are not within 15 percent of the true discharge are rated "poor" (Novak, 1985).

The standard deviation of the daily relative error indicates the variability in the errors. The standard deviation of the daily relative error would equal the root mean square error for each method provided the baseline record was equal to the true daily discharge and discharge was independent from day to day. Although

daily discharges are not independent and the baseline record contains some uncertainty, the standard deviation does give an indication of the variability to be expected for a given method, and can be used to compare different methods to one another. For example, the results for Clear Creek (table 6) indicate that the the errors associated with the uniform flow technique (43 percent) are considerably smaller than the

corresponding errors for the prorated discharge technique (454 percent).

The distribution of daily errors is another important consideration in the evaluation of a given method. A method may have a relatively low bias and standard deviation, however the method may provide an occasional estimate with an extremely large error. This could be caused by the inability to compute discharge for a

Table 5. — *Average discharge for the ice-affected period determined by each method and percent error compared to the average baseline discharge*

[—, not computed]

Method[1]	Clear Creek		Des Moines River		Floyd River	
	Average discharge	Percent error	Average discharge	Percent error	Average discharge	Percent error
Baseline record	68	—	290	—	170	—
Subjective methods						
Base-flow recession (1)	45	–34	260	–10	130	–24
Base-flow recession (2)	38	–44	280	–3.4	86	–49
Base-flow recession (3)	50	—26	310	6.9	160	–5.9
Discharge ratio (1)	64	–5.9	270	–6.9	130	–24
Discharge ratio (2)	65	–4.4	290	0	130	–24
Discharge ratio (3)	79	16	310	6.9	210	24
Backwater shift (1)	83	22	270	–6.9	230	35
Backwater shift (2)	77	13	310	6.9	260	53
Backwater shift (3)	74	8.8	320	10	220	29
Interpolated discharge (1)	54	–21	290	0	130	–24
Interpolated discharge (2)	92	35	270	–6.9	110	–35
Interpolated discharge (3)	87	28	290	0	140	–18
Adjusted discharge (1)	67	–1.5	280	–3.4	170	0
Adjusted discharge (2)	45	—34	260	–10	100	–41
Adjusted discharge (3)	60	—12	330	14	230	35
Hydrographic-and-climatic comparison (1)	59	–13	270	–6.9	140	–18
Hydrographic-and-climatic comparison (2)	53	—22	290	0	160	–5.9
Hydrographic-and-climatic comparison (3)	67	–1.5	270	–6.9	200	18
Analytical methods						
Prorated discharge	151	120	330	14	260	53
Discharge ratio	70	2.9	270	–6.9	280	65
Backwater shift	75	10	320	10	300	76
Stage fall	52	–24	—	—	240	41
Adjusted rating curve	76	12	280	–3.4	180	5.9
Conductance correlation	79	16	—	—	550	220
Multiple regression	119	75	340	17	380	120
Index velocity	79	16	300	3.4	—	—
Ice adjustment factor	95	40	310	6.9	220	29
Pipe flow	117	72	—	—	110	–35
Uniform flow	76	12	—	—	160	–5.9

[1] The number in parentheses indicates the hydrographer who compiled the estimated record

temporary set of ice conditions. An overall representation of the daily relative errors is shown in figure 3, and the percent distribution for selected error ranges is shown on table 7. To further aid in the interpretation of the results, the estimated and baseline hydrographs are shown in figures 4 to 6.

A comparison was made for each method to determine if the estimated daily discharges were statistically different from the baseline daily discharges. Tests for normality revealed that none of the time series followed a normal distribution, thus a nonparametric equivalent

to a paired t-test, the Wilcoxon signed-rank test (Conover, 1971), was used to test for differences between estimated and baseline discharge. The test was modified to account for serial correlation (El Shaarawi and Damsleth, 1988), and applied to the time series for each method. The results are reported in table 8, and will be discussed for each method in subsequent sections.

Statistical analyses were performed for the six subjective methods to analyze the variability of the results between the three hydrographers. Because the time series do not follow a normal distribution, the Kruskal-

Table 6. — *Statistical summary of the error between estimated daily discharge and baseline daily discharge*

[The statistics are computed over the ice-affected period(s). —, not computed.]

Method[1]	Clear Creek		Des Moines River		Floyd River	
	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation
			Subjective methods			
Base-flow recession (1)	−0.01	0.41	−0.05	0.23	−0.09	0.31
Base-flow recession (2)	−.10	.45	.09	.31	−.02	.50
Base-flow recession (3)	.06	.44	.13	.24	.16	.38
Discharge ratio (1)	.21	.36	−.02	.24	−.09	.28
Discharge ratio (2)	.19	.37	.04	.22	.00	.29
Discharge ratio (3)	.31	.52	.05	.25	.16	.30
Backwater shift (1)	.34	.48	−.12	.31	.23	.44
Backwater shift (2)	.24	.45	.02	.28	.30	.52
Backwater shift (3)	.22	.45	.09	.23	.39	.49
Interpolated discharge (1)	−.01	.28	.02	.17	−.05	.22
Interpolated discharge (2)	.33	.53	−.04	.15	−.12	.25
Interpolated discharge (3)	.43	.87	.06	.21	−.05	.23
Adjusted discharge (1)	.24	.43	−.01	.16	.03	.30
Adjusted discharge (2)	−.05	.37	−.05	.22	−.15	.27
Adjusted discharge (3)	.09	.36	.14	.22	.27	.40
Hydrographic-and-climatic comparison (1)	.13	.40	−.04	.17	−.01	.24
Hydrographic-and-climatic comparison (2)	.06	.41	.05	.21	−.02	.26
Hydrographic-and-climatic comparison (3)	.18	.41	−.03	.17	.14	.36
			Analytical methods			
Prorated discharge	2.50	4.54	.18	.28	1.11	1.93
Discharge ratio	.31	.54	−.02	.27	.71	.58
Backwater shift	.21	.54	.08	.29	.78	.72
Stage fall	.07	.34	—	—	1.63	1.26
Adjusted rating curve	.40	.54	−.01	.23	−.10	.37
Conductance correlation	.02	1.14	—	—	1.85	2.81
Multiple regression	1.14	.65	.18	.24	1.73	1.00
Index velocity	.28	.51	.04	.18	—	—
Ice adjustment factor	.48	.55	.04	.28	.32	.36
Pipe flow	.07	.79	—	—	.13	.50
Uniform flow	.35	.43	—	—	.01	.26

[1] The number in parentheses indicates the hydrographer who compiled the streamflow record.

Wallis one-way analysis of variance (Conover, 1971) was used to evaluate the method results (table 9). The significance levels in this table represent the probability of a difference between the hydrographers being attributed to random chance. Thus, probabilities less than a chosen significance level (0.025) indicate inconsistent results for the three hydrographers, and probabilities that exceed the significance level indicate consistent results for the three hydrographers. For example, the three hydrographers produced statistically similar (p = .520) results for Clear Creek using the discharge ratio method, whereas the three hydrographers produced statistically different (p < .001) results using the interpolated discharge method.

The statistics included in this report are intended to be a general comparison of method accuracy, and should not be considered an absolute determination of the accuracy of each method.

SUBJECTIVE METHODS
Base-flow Recession

The base-flow recession method underestimated the baseline mean for the ice-affected periods for eight of the nine record compilations (three streams and three hydrographers). The average percent error between the method mean and the baseline mean for each stream is shown in table 5. The mean daily relative error ranged from –0.10 to 0.16 (table 6). The standard deviation of the daily relative errors ranged from 0.23 to 0.50 for the nine compilations (table 6). The relative error of the daily discharge values indicated that 15 percent of the daily values were excellent (0–5 percent error); 28 percent were good to excellent (0–10 percent error); and 39 percent were fair to excellent (0–15 percent error). Forty-three percent of the daily values had relative errors between 15 and 50 percent, and 18 percent had relative relative errors greater than 50 percent (table 7). Only one of the nine discharge records was found to be significantly different (p<.025) than the baseline discharge record (table 8). The three hydrographers' streamflow records were significantly different (p<.025) from each other for two of the three compilations, and are marginal for the other compilation (table 9).

The base-flow recession method requires a general knowledge of ice computation techniques and an understanding of streamflow recession. Each year a recession curve must be drawn or a coefficient for a recession equation must be defined. All other materials or data needed for method application are available for the existing streamflow-gaging network. The method

Table 7.—*Percentage distribution of the relative error for the daily discharge values for selected ranges in error*

[>, greater than]

Method[1]	0–5 per-cent error	5–10 per-cent error	10–15 per-cent error	15–25 per-cent error	25–50 per-cent error	>50 per-cent error	Total number of days[2]
Subjective methods							
Base-flow recession	15	13	11	19	24	18	636
Discharge ratio	17	19	13	20	21	10	636
Backwater shift	21	16	16	19	18	10	636
Interpolated discharge	20	11	11	16	20	22	636
Adjusted discharge	23	18	11	15	20	13	636
Hydrographic-and-climatic comparison	23	17	15	19	17	9	636
Analytical methods							
Prorated discharge	8	10	10	11	19	42	212
Discharge ratio	9	9	12	16	21	33	212
Backwater shift	13	10	12	16	18	31	212
Stage fall	8	4	4	10	22	52	145
Adjusted rating curve	14	14	14	14	26	18	212
Conductance correlation	0	3	1	4	17	75	145
Multiple regression	7	7	4	5	15	62	212
Index velocity	26	13	12	15	17	17	118
Ice adjustment factor	13	11	14	19	20	23	212
Pipe flow	15	12	10	19	20	24	145
Uniform flow	12	8	6	15	41	18	145

[1] The subjective methods present the combined results for all three hydrographers
[2] Number of ice-affected days available in determining the distribution of daily relative errors

is based on a uniform and predictable ice-affected recession. The method can be applied to all ice conditions except storm runoff periods. The equation solution to this method could be adapted to automated data processing, and the equation would be updated periodically. This method could be used for ice computations within the existing U.S. Geological Survey streamflow-gaging network.

The base-flow recession curve is based on the assumption that the winter recession is a smooth curve. The data collected for this study do not fully support that assumption. The frequent discharge measurements obtained for this study indicate that streamflow fluctuates on a daily basis. The winter recession, as defined by these measurements, is only a very general trend with many significant departures from the gen-

EXPLANATION

o   Value exceeding Q75 + 3.0 * IR

x   Value exceeding Q75 + 1.5 * IR

Interquartile range (IR)

Maximum value less than Q75 + 1.5 * IR
75th percentile (Q75)
Median
25th percentile (Q25)
Minimum value greater than Q25 - 1.5 * IR

x   Value less than Q25 - 1.5 * IR
o   Value less than Q25 - 3.0 * IR

Figure 3A. Summary of relative errors for selected methods applied to Clear Creek near Coralville, Iowa. (Relative error is defined in the text; the number in parentheses indicates the hydrographer who compiled the streamflow record.)

eral curve (fig. 2). The base-flow recession method probably is an oversimplification of ice-affected flow conditions, and, based on the information obtained during this study, may not be an appropriate method for compiling ice-affected streamflow record. The method may be more appropriate for use in the northernmost latitudes of the United States where winter runoff is less frequent.

Discharge Ratio

The discharge ratio method underestimated the baseline mean for the ice-affected periods for five record compilations, overestimated the mean for three compilations, and correctly computed the baseline mean for one compilation. The average percent error between the method mean and baseline mean for each stream is

EXPLANATION

o Value exceeding Q75 + 3.0 * IR
м Value exceeding Q75 + 1.5 * IR

Maximum value less than Q75 + 1.5 * IR
75th percentile (Q75)
Interquartile range (IR) Median
25th percentile (Q25)
Minimum value greater than Q25 – 1.5 * IR

ж Value less than Q25 – 1.5 * IR
o Value less than Q25 – 3.0 * IR

Figure 3*B*. Summary of relative errors for selected methods applied to the Des Moines River at Fort Dodge, Iowa. (Relative error is defined in the text; the number in parentheses indicates the hydrographer who compiled the streamflow record.)

shown in table 5. The mean daily relative error ranged from –0.09 to 0.31 (table 6). The standard deviation of the daily relative errors ranged from 0.22 to 0.52 for the nine compilations (table 6). The relative error of the daily discharge values indicated that 17 percent of the daily values were excellent (0—5 percent error); 36 percent were good to excellent (0–10 percent error); and 49 percent were fair to excellent (0—15 percent error).

Forty-one percent of the daily values had relative errors between 15 and 50 percent, and 10 percent had relative errors greater than 50 percent (table 7). Only one of the nine discharge records was significantly different (p < .025) than the baseline discharge record (table 8). The three hydrographers' streamflow records were significantly different (p < .025) from each other for one of the three compilations (table 9).

EXPLANATION

o Value exceeding Q75 + 3.0 * IR
м Value exceeding Q75 + 1.5 * IR

Maximum value less than Q75 + 1.5 * IR
75th percentile (Q75)
Interquartile range (IR)
Median
25th percentile (Q25)
Minimum value greater than Q25 - 1.5 * IR

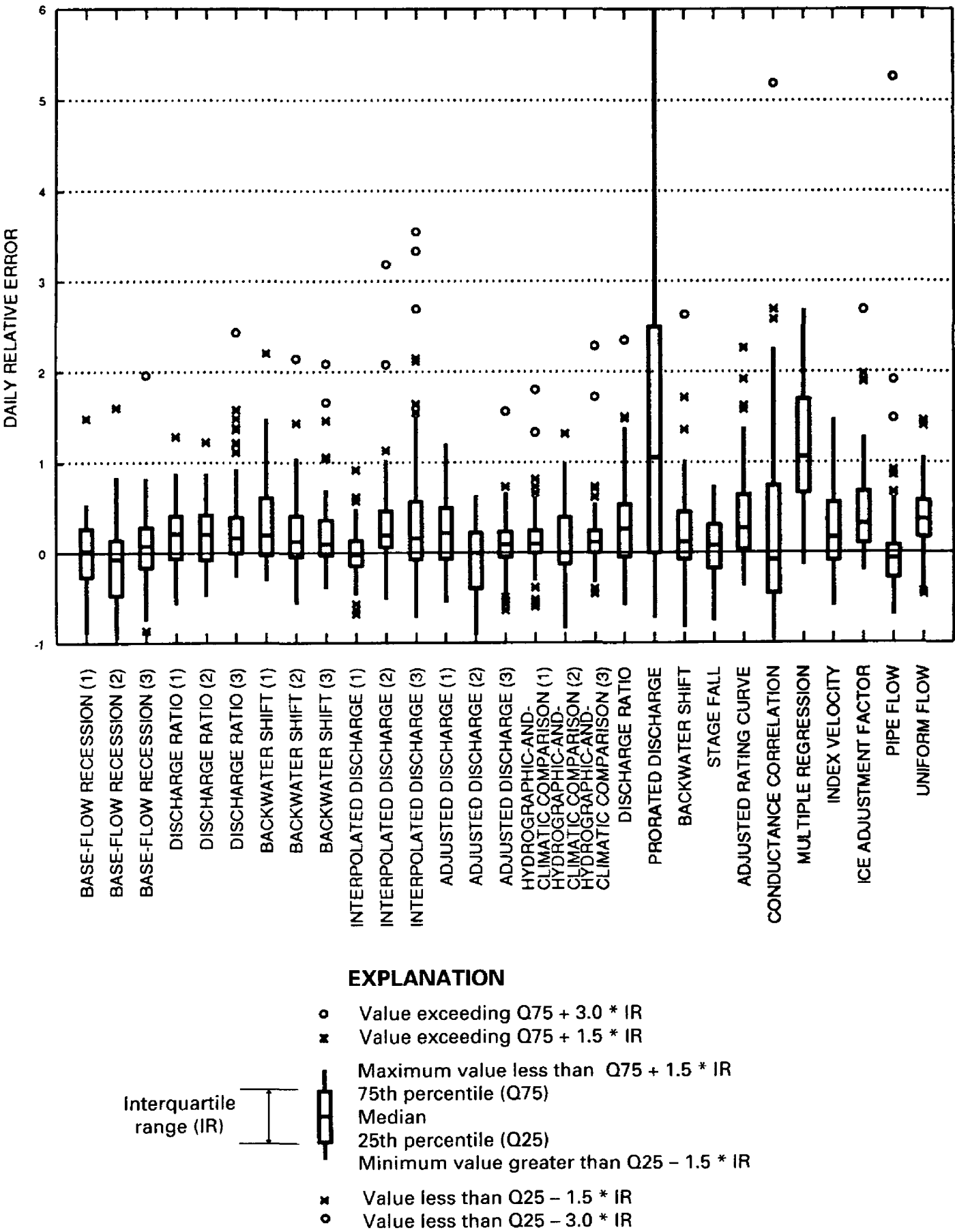м Value less than Q25 - 1.5 * IR
o Value less than Q25 - 3.0 * IR

Figure 3C. Summary of relative errors for selected methods applied to the Floyd River at James, Iowa. (Relative error is defined in the text; the number in parentheses indicates the hydrographer who compiled the streamflow record.)

The discharge ratio method requires only a general knowledge of ice-affected streamflow computation techniques. The method uses a discharge ratio curve developed for each year. All other materials or data needed for method application are available for the existing streamflow-gaging network. The method depends on individual judgment and experience in determining the effects of changing meteorological conditions on the backwater curve. The method is based on the assumption that the ratio of measured to rated discharge is representative for the periods between discharge measurements. The method can be applied to all ice conditions; however, if the discharge ratio is computed for one ice condition and used to define discharge during another condition, the results may not be reliable. The method is adaptable to automated data processing, however the discharge ratio curve would have to be manually developed. All other computations could be completed by automated methods. This method could be used for ice computations within the existing U.S. Geological Survey streamflow-gaging network.

The standard deviation of the relative error and the mean discharges for each station indicate that the results of the discharge ratio compilation for each station were similar. The Kruskal-Wallis 1-way analysis of variance (table 9) shows generally consistent results for each station, indicating that the method results are fairly reproducible. The accuracy of discharge estimates obtained by the method probably would be improved as users obtained more experience at drawing the K-factor line. The scheduling of discharge measurements for optimum definition of the discharge ratio line probably would improve the method results. Given the ease of application, the reproducibility, and the consistent and comparatively accurate results of the discharge-ratio method, the method should be considered for wider use by the U.S. Geological Survey for compiling ice-affected streamflow.

Backwater Shift

The backwater shift method underestimated the baseline mean for the ice-affected periods for one record compilation and overestimated the baseline mean for eight compilations. The average percent error between the method mean and the baseline mean for each stream is shown in table 5. The mean daily relative error ranged from –0.12 to 0.39 (table 6). The standard deviation of the daily relative errors ranged from 0.23 to 0.52 for the nine compilations (table 6). The relative error of the daily discharge values indicated that 21 percent of the daily values were excellent (0–5 percent error); 37 percent were good to excellent (0–10 percent error); and 53 percent were fair to excellent (0–15 percent error). Thirty-seven percent of the daily values

had relative errors between 15 and 50 percent, and 10 percent had relative errors greater than 50 percent (table 7). Four of the nine discharge records were significantly different (p < .025) than the baseline discharge record (table 8). The three hydrographers' streamflow records were significantly different (p < .025) from each other for one of the three compilations (table 9).

The backwater shift method requires only a general knowledge of ice-affected streamflow computation techniques. The method requires drawing a backwater shift curve for ice-affected periods. All other materials or data needed for method application are available for the existing streamflow-gaging network. The method depends on individual judgement and experience for determining the effects of changing meteorological conditions on the backwater curve. The method is based on the assumption that the stream backwater defined by discharge measurements is representative for the periods between measurements. This is the basis for the use of open-water shift application, but the variability of backwater from ice generally is greater during ice-affected periods. The method can be used for all ice conditions; however, if a backwater shift is computed for one ice condition and used to define discharge during another condition the results may not be reliable. The method is adaptable to automated data processing; however, the backwater-shift curve would have to be manually developed. This method could be used for ice computations within the existing U. S. Geological Survey streamflow-gaging network.

The backwater shifts computed for the 6-week discharge measurements observed during this study generally indicate backwater conditions exist only for a relatively brief period of time. Some improvement in the results for this method may be obtained as users become more experienced at drawing backwater curves. The scheduling of discharge measurements for optimum definition of the backwater-shift curve probably would improve the method results. The study results indicated that the backwater shift method has some value for determining discharge during storm runoff periods (figs. 4–6), but the backwater shift method is not appropriate for compiling most ice-affected streamflow record. The method may have some value in identifying outlier data estimated by another method. By computing the backwater shift for each ice-affected discharge that is estimated by another method, erroneous or impossible conditions may be identified.

Interpolated Discharge

The interpolated discharge method underestimated the baseline mean for the ice-affected periods for five record compilations, overestimated the baseline mean for two compilations and correctly computed the baseline mean for two compilations. The average percent error

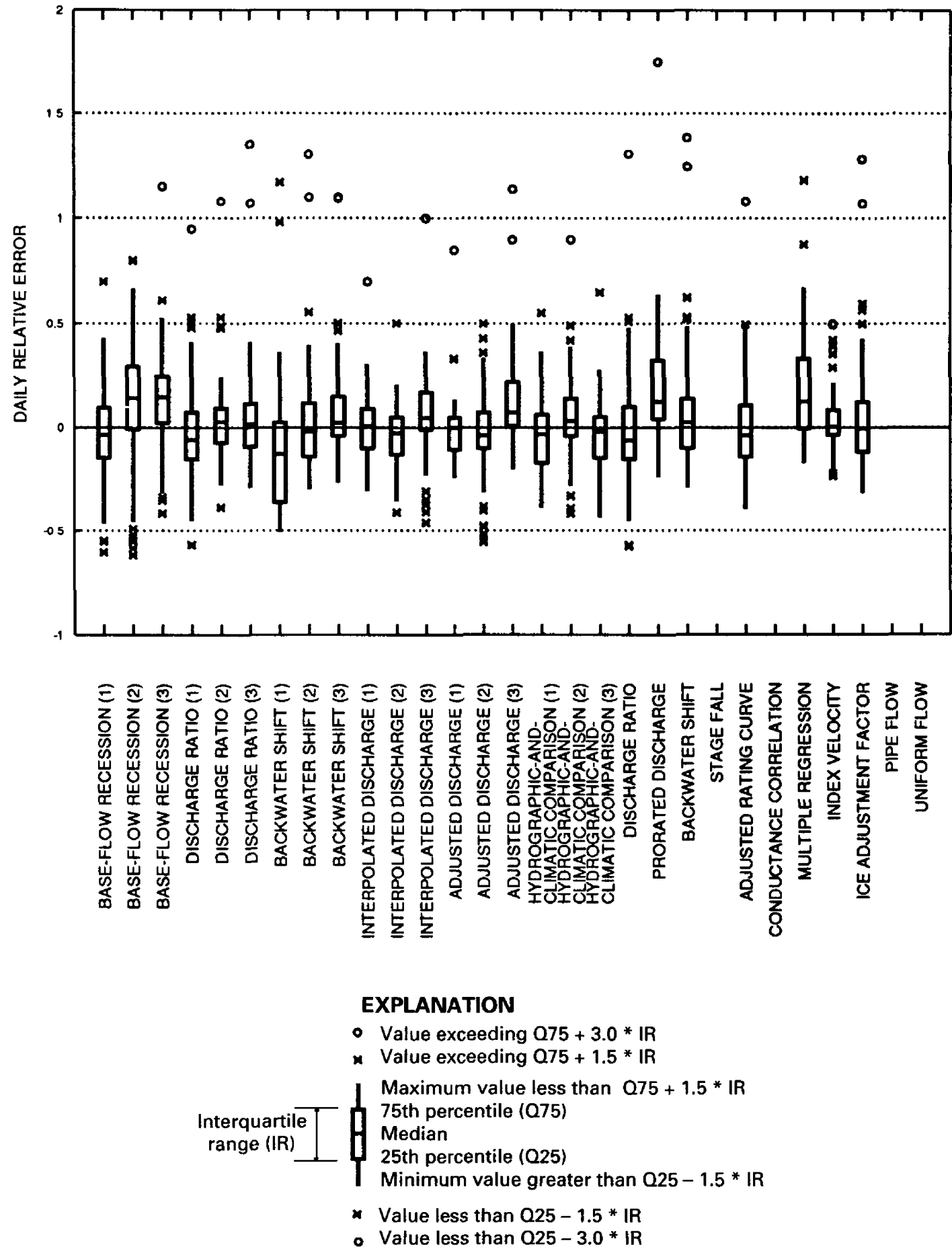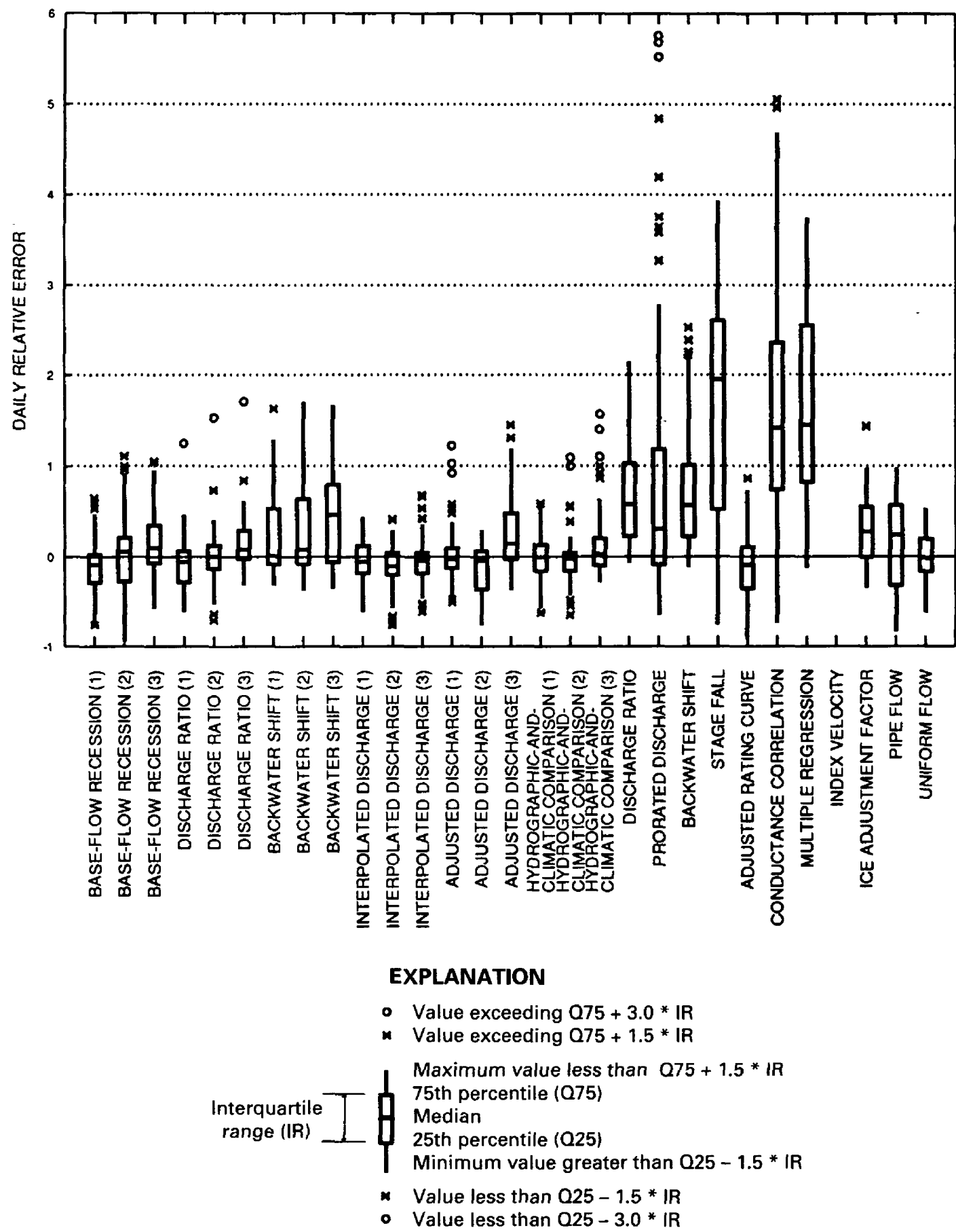between the method mean and the baseline mean for each stream is shown in table 5. The mean daily relative error ranged from —0.12 to 0.43 (table 6). The standard deviation of the daily relative errors ranged from 0.15 to 0.87 for the nine compilations (table 6). The relative error of the daily discharge values indicated that 20 percent of the daily values were excellent (0—5 percent error); 31 percent were good to excellent (0–10 percent error); and 42 percent were fair to excellent (0–15 percent error). Thirty-six percent of the daily values had relative errors between 15 and 50 percent, and 22 percent had relative errors greater than 50 percent (table 7). Two of the nine discharge records were significantly different (p < .025) than the baseline discharge record (table 8). The three hydrographers' streamflow records were significantly different (p < .025) from each other for two of the three compilations (table 9).

The interpolated discharge method requires only a general knowledge of ice computation techniques. All other materials or data needed for method application are available for the existing streamflow-gaging network. The method is dependent on individual judgment and experience in determining the relative importance of discharge measurements and information from hydrographic comparison. The method does not rely on recorded stage or indicated open-water discharges for making discharge estimates. Method application is, therefore, simplified, but the results probably are less reliable. The method is suitable for use in all ice conditions. Because the method depends on individual judgement rather than a systematic computation, the method is not adaptable to automated data processing. The method could be applied to the existing U.S. Geological Survey streamflow-gaging network. Because ice-affected stage is not used, the method does not consider a parameter normally recorded at streamflow-gaging stations.

The interpolated discharge method is similar to the hydrographic-and-climatic-comparison method but does not use the indicated open-water discharges. The method was included in the study to assess the relative value of the indicated open-water discharges. The indicated open-water discharges, therefore, are an important factor in improving the accuracy of ice-affected discharge estimates.

Adjusted Discharge

The adjusted discharge method underestimated the baseline mean for the ice-affected periods for six record compilations, overestimated the baseline mean for two compilations and correctly computed the baseline mean for one compilation. The average percent error between the method mean and the baseline mean for each stream is shown in table 5. The mean daily relative error ranged from —0.15 to 0.27 (table 6). The standard

deviation of the daily relative errors ranged from 0.16 to 0.43 for the nine compilations (table 6). The relative error of the daily discharge values indicated that 23 percent of the daily values were excellent (0—5 percent error); 41 percent were good to excellent (0–10 percent error); and 52 percent were fair to excellent (0–15 percent error). Thirty-five percent of the daily values had relative errors between 15 and 50 percent, and 13 percent had relative errors greater than 50 percent (table 7). Two of the nine discharge records were significantly different (p < .025) than the baseline discharge record (table 8). The three hydrographers' streamflow records were significantly different (p < .025) from each other for all three compilations (table 9), and therefore the method is not very reproducible.

The adjusted discharge method requires only a general knowledge of ice computation techniques. All other materials or data needed for method application are available for the existing streamflow-gaging network. The method depends on individual judgement and experience in determining the relative importance of discharge measurements, meteorological information and the indicated open-water discharges. Application is simplified because hydrographic comparison is not used, but the results probably are less reliable than if data from other stations were considered. The method can be applied to all ice conditions. The method is not adaptable to automated data processing because it depends on individual judgement rather than a systematic computation. The method could be applied to the existing U.S. Geological Survey streamflow-gaging network. Because the method does not consider data from other streamflow-gaging stations it does not use one of the major advantages of operating a comprehensive streamflow-gaging network.

The adjusted discharge method is similar to the hydrographic-and-climatic-comparison method but it does not use hydrographic comparison. The method was included in the study to assess the relative value of hydrographic comparison. The results indicate that hydrographic comparison is an important factor for improving the accuracy of ice-affected discharge estimates.

Hydrographic-and-climatic comparison

The hydrographic-and-climatic-comparison method underestimated the baseline mean for the ice-affected periods for seven record compilations, overestimated the mean for one compilation, and correctly computed the baseline mean for one compilation. The average percent error between the method mean and the baseline mean for each stream is shown in table 5. The mean daily relative error ranged from –0.04 to 0.18 (table 6). The standard deviation of the daily relative errors ranged from 0.17 to 0.41 for the nine compila-

Figure 4A.   Hydrographs for Clear Creek near Coralville showing baseline daily mean discharge and daily mean discharge estimated by subjective methods.

tions (table 6). The relative error of the daily discharge values indicated that 23 percent of the daily values were excellent (0–5 percent error); 40 percent were good to excellent (0–10 percent error); and 55 percent were fair to excellent (0–15 percent error). Thirty-six percent of the daily values had relative errors between 15 and 50 percent, and 9 percent had relative errors greater than 50 percent (table 7). Only one of the nine discharge

Figure 4B. Hydrographs for Clear Creek near Coralville showing baseline daily mean discharge and daily mean discharge estimated by analytical methods.

records was significantly different (p < .025) than the baseline discharge record, although two were marginal (table 8). The three hydrographers' streamflow records were significantly different (p < .025) from each other for two of the three compilations (table 9).

The hydrographic-and-climatic-comparison method requires knowledge of ice-affected streamflow computation techniques. All other materials or data needed for method application are available for the existing streamflow-gaging network. The method is dependent on individual judgement and experience in determining the relative importance of discharge measurements, meteorological information, indicated open-water discharges, and information from hydrographic comparison. The method is suitable for application under all ice conditions. The method is not adaptable
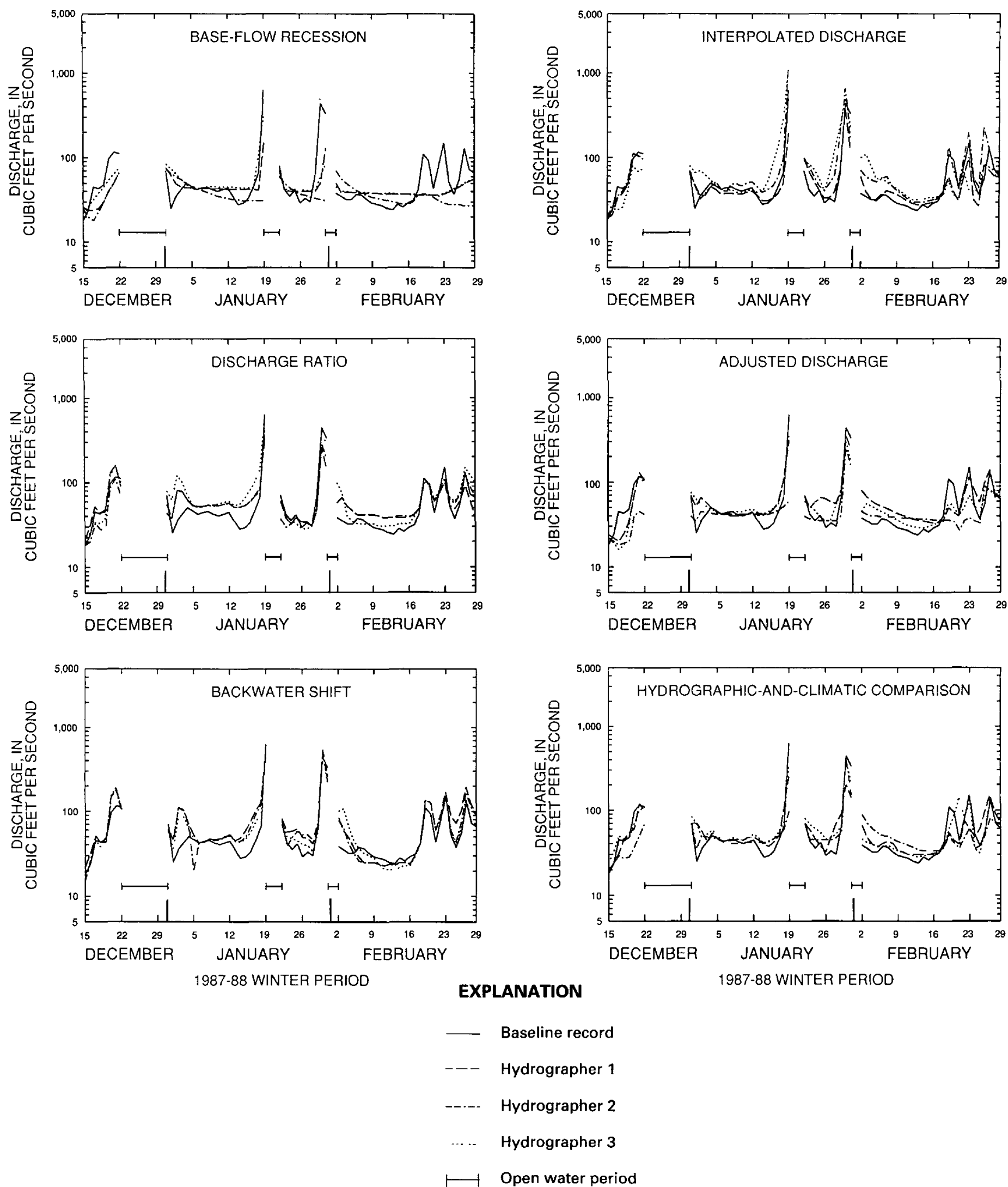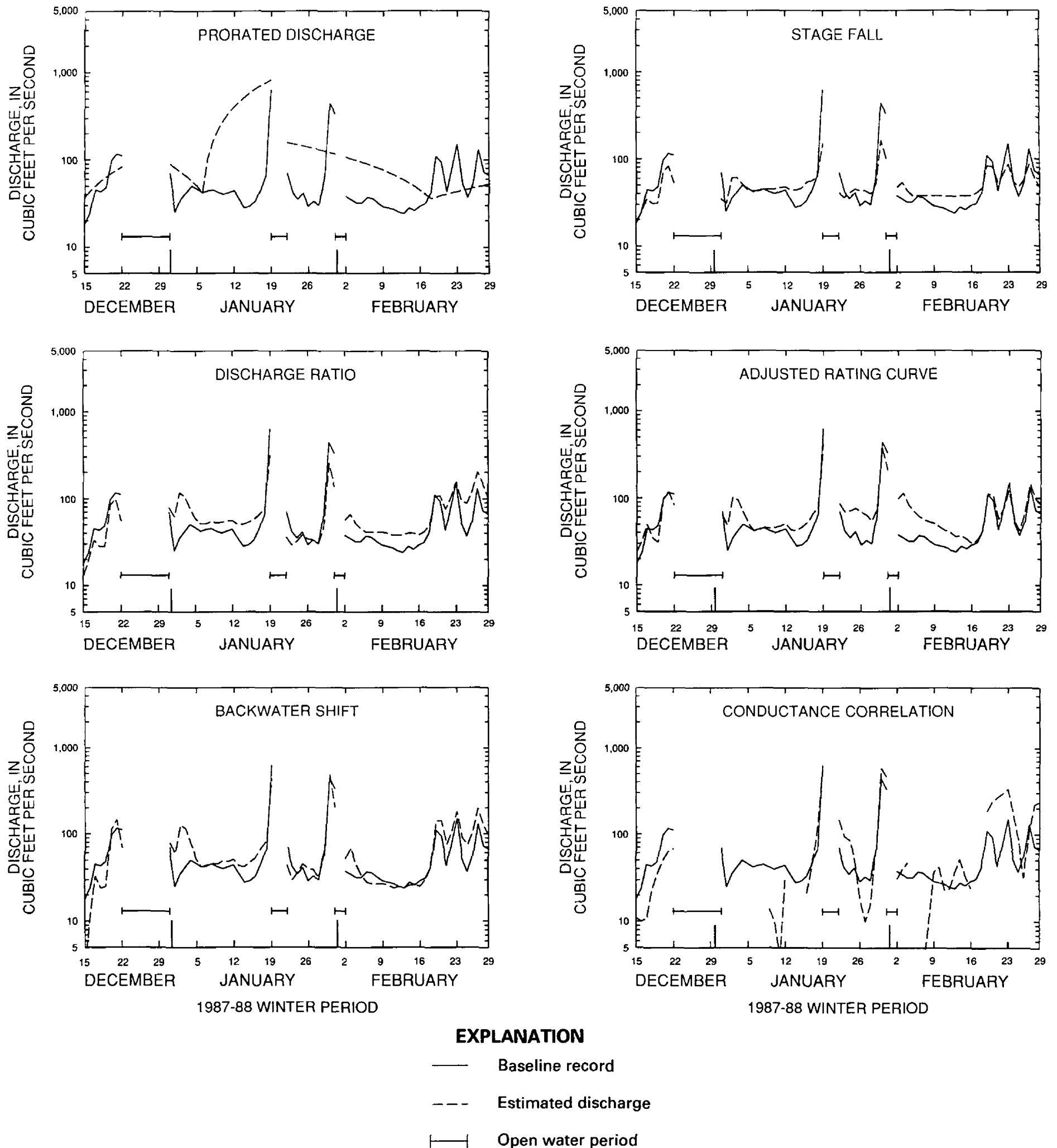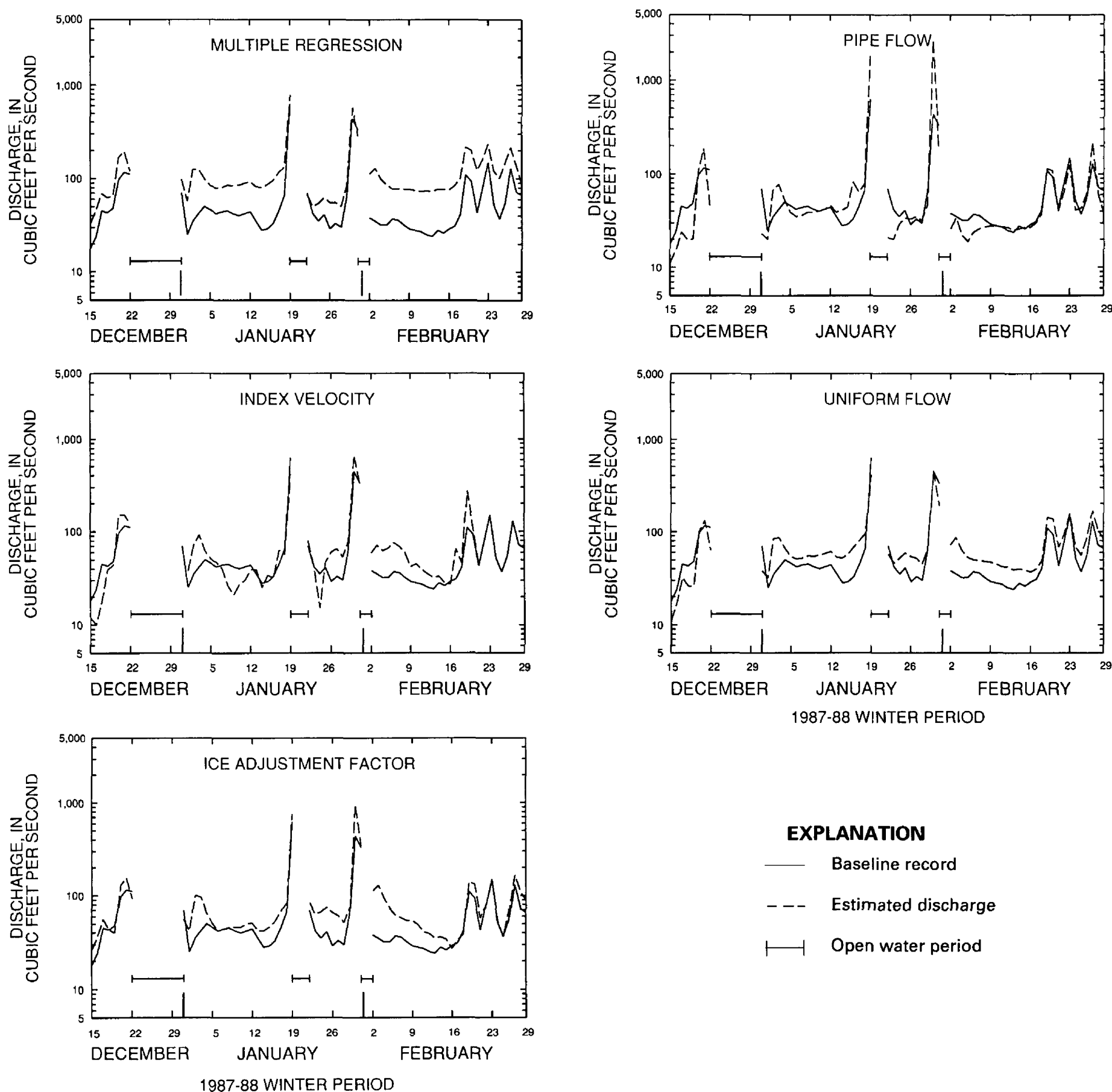

Figure 4C. Hydrographs for Clear Creek near Coralville showing baseline daily mean discharge and daily mean discharge estimated by analytical methods.

to automated data processing because it depends on individual judgement rather than a systematic computation. The method is applicable to the existing U. S. Geological Survey streamflow-gaging network.

The hydrographic-and-climatic-comparison method produced more reliable results compared to the other subjective methods, and results comparable with the best analytical methods. This is the only method the test hydrographers were experienced with prior to this study. Experience may have been a factor in the results of this study.

ANALYTICAL METHODS

Prorated Discharge

The prorated discharge method overestimated the baseline mean for the ice-affected periods for all three record compilations. The average percent error between the method mean and the baseline mean for each stream is shown in table 5. The mean daily relative error ranged from 0.18 to 2.5 (table 6). The standard deviation of the daily relative errors ranged from 0.28 to 4.54 for the three compilations (table 6). The relative error of the daily discharge values indicated that 8 percent of the daily values were excellent (0–5 percent error); 18 percent were good to excellent (0–10 percent error); and 28 percent were fair to excellent (0–15 percent error). Thirty percent of the daily values had relative errors between 15 and 50 percent, and 42 percent had relative errors greater than 50 percent (table 7). One of the three discharge records was significantly different (p < .025) than the baseline discharge record (table 8).

The prorated discharge method does not require any special knowledge or skill except for simple linear interpolation. All other materials or data needed for method application are available for the existing streamflow-gaging network. The method can be applied under all ice conditions. This method is adaptable to automated data processing because it is based on linear interpolation of measured discharge. The method could be applied to the existing U. S. Geological Survey streamflow-gaging network. Because the prorated discharge method does not use relevant data that is collected at most streamflow-gaging stations, the results probably will not be as reliable as the results of methods that use more stream parameters.

The prorated discharge method was included in the study to compare the results of the other methods with the results of linear discharge proration. The prorated discharge method is not recommended for compiling ice-affected streamflow record.

Discharge Ratio

The discharge ratio method underestimated the baseline mean for the ice-affected periods for one record

compilation and overestimated the baseline mean for two compilations (three streams). The average percent error between the method mean and the baseline mean for each stream is shown in table 5. The mean daily relative error ranged from —0.02 to 0.71 (table 6). The standard deviation of the daily relative errors ranged from 0.27 to 0.58 for the three compilations (table 6). The relative error of the daily discharge values indicated that 9 percent of the daily values were excellent (0—5 percent error); 18 percent were good to excellent (0–10 percent error); and 30 percent were fair to excellent (0–15 percent error). Thirty-seven percent of the daily values had relative errors between 15 and 50 percent, and 33 percent had relative errors greater than 50 percent (table 7). One of the three discharge records was significantly different (p < .025) than the baseline discharge record (table 8).

The discharge ratio method requires only a general knowledge of ice-affected streamflow computation techniques. The method uses a discharge ratio curve developed each year. All other materials or data needed for method application are available for the existing streamflow-gaging network. The method is based on the assumption that the ratio of measured to rated discharge is representative for the periods between discharge measurements. The method can be used for all ice conditions; however, if the discharge ratio is computed for one ice condition and used to define discharge during another condition, the results may not be reliable. The method is adaptable to automated data processing. The discharge ratio line could be computed using automated data processing because the discharge ratio line is developed by linear interpolation. Linear interpolation of the discharge ratio line may cause obviously anomalous results during changing ice conditions. This method could be used for ice computations within the existing U.S. Geological Survey streamflow-gaging network.

The discharge ratio method was included in the study to compare the results of an analytical solution of this method with a subjective solution. Collection of discharge measurements for optimum definition of the discharge ratio line probably would improve the method results. The subjective solution produced more reliable results than the analytical solution, therefore the analytical discharge ratio method is not recommended for compiling ice-affected streamflow record.

Backwater Shift

The backwater shift method overestimated the baseline mean for all three record compilations. The average percent error between the method mean and the baseline mean for each stream is shown in table 5. The mean daily relative error ranged from 0.08 to 0.78 (table 6). The standard deviation of the daily relative

Figure 5A. Hydrographs for the Des Moines River at Fort Dodge showing baseline daily mean discharge and daily mean discharge estimated by subjective methods.

errors ranged from 0.29 to 0.72 for the three compilations (table 6). The relative error of the daily discharge values indicated that 13 percent of the daily values were excellent (0—5 percent error); 23 percent were good to excellent (0—10 percent error); and 35 percent were fair to excellent (0—15 percent error). Thirty-four percent of the daily values had relative errors between 15 and 50 percent, and 31 percent had relative errors greater than 50 percent (table 7). One of the three discharge records was significantly different (p < .025) than the baseline discharge record (table 8).

The backwater shift method requires only a general knowledge of ice-affected streamflow computation techniques. The method requires drawing a backwater shift curve for ice-affected periods. All other materials or data needed for method application are available for the existing streamflow-gaging network. The method is based on the assumption that the stream backwater defined by discharge measurements is representative for the periods between measurements. This is the basis for the use of open-water shift application, but the variability of backwater from ice generally is greater during ice-affected periods. The method can be used for all ice conditions; however, if a backwater shift is computed for one ice condition and used to define discharge during another condition, the results may not be reli-

EXPLANATION

——— Baseline record

– – – Estimated discharge

|———| Open water period

Figure 5B. Hydrographs for the Des Moines River at Fort Dodge showing baseline daily mean discharge and daily mean discharge estimated by analytical methods.

able. Linear interpolation of the backwater curve may cause obviously anomalous results during changing ice conditions. The method is adaptable to automated data processing. The backwater curve could be computed using automated data processing because the backwater curve is determined by linear interpolation. The method could be used for ice computations within the existing U.S. Geological Survey streamflow-gaging network.

The backwater shift method was included in the test to compare the results of an analytical solution of this method with a subjective solution. The subjective solution produced more reliable results than the analytical solution, therefore the analytical backwater shift method is not recommended for compiling ice-affected streamflow record.

Stage Fall

The stage-fall method overestimated the baseline mean for the ice affected periods for one record compilation and underestimated the mean for the other compilation. The average percent error between the method mean and the baseline mean for each stream is shown

in table 5. The mean daily relative errors were 0.07 and 1.63 (table 6). The standard deviations of the daily relative errors were 0.34 and 1.26 (table 6). The relative error of the daily discharge values indicated that 8 percent of the daily values were excellent (0–5 percent error); 12 percent were good to excellent (0–10 percent error); and 16 percent were fair to excellent (0–15 percent error). Thirty-two percent of the daily values had relative errors between 15 and 50 percent, and 52 percent had relative errors greater than 50 percent (table 7). Neither of the two discharge records were significantly different (p < .025) from the baseline streamflow record (table 8).

The stage fall method requires a general knowledge of slope stations and regression analysis. Determination of the least-backwater rating and subsequent least-fall curve requires some hydrologic judgement. Imperfectly defined curves reduced the reliability of the method for the sites examined. The method is empirical; however, it uses slope station concepts, which are widely accepted. The method appears to be applicable to all ice conditions, but would be most suitable for complete ice
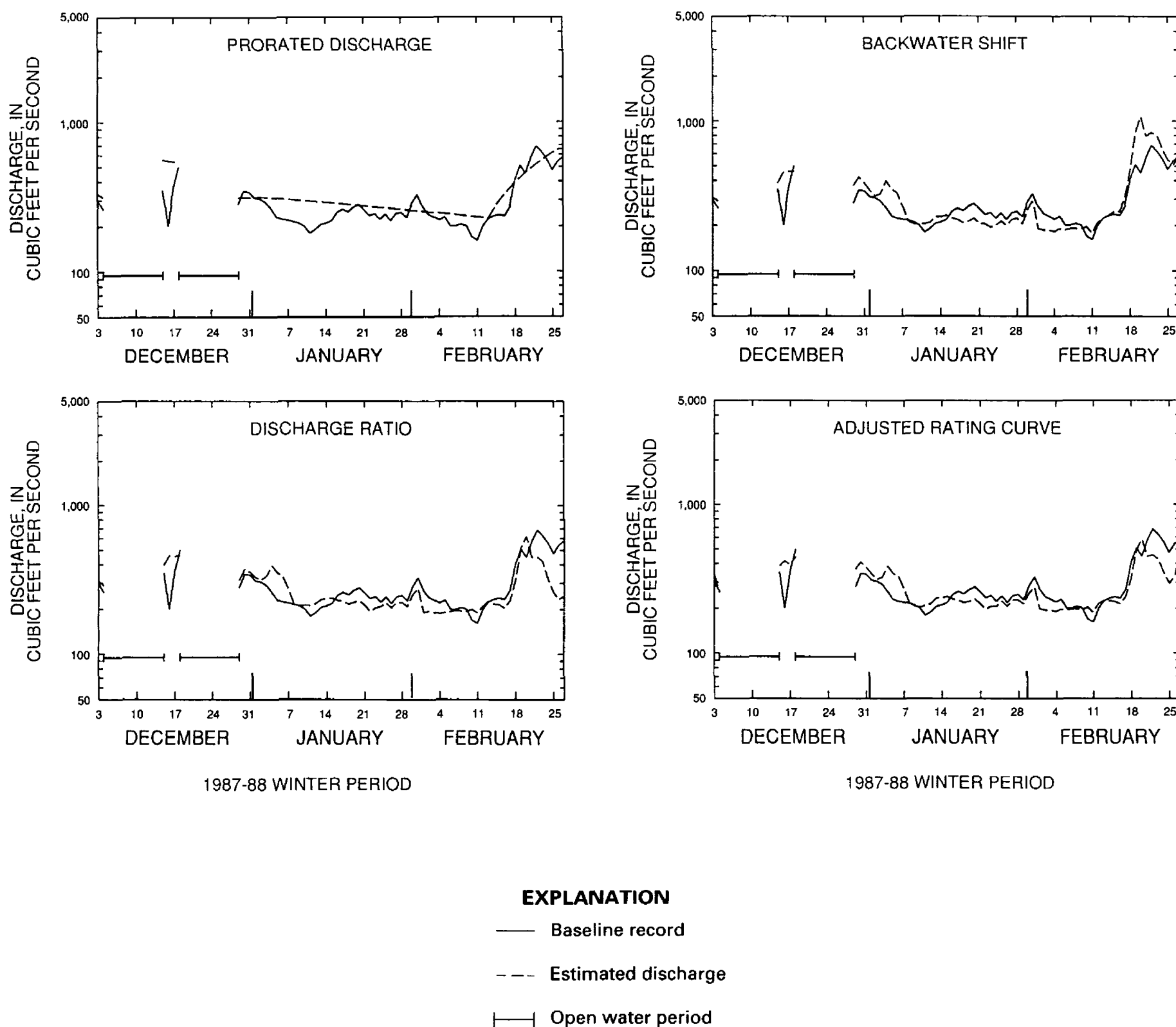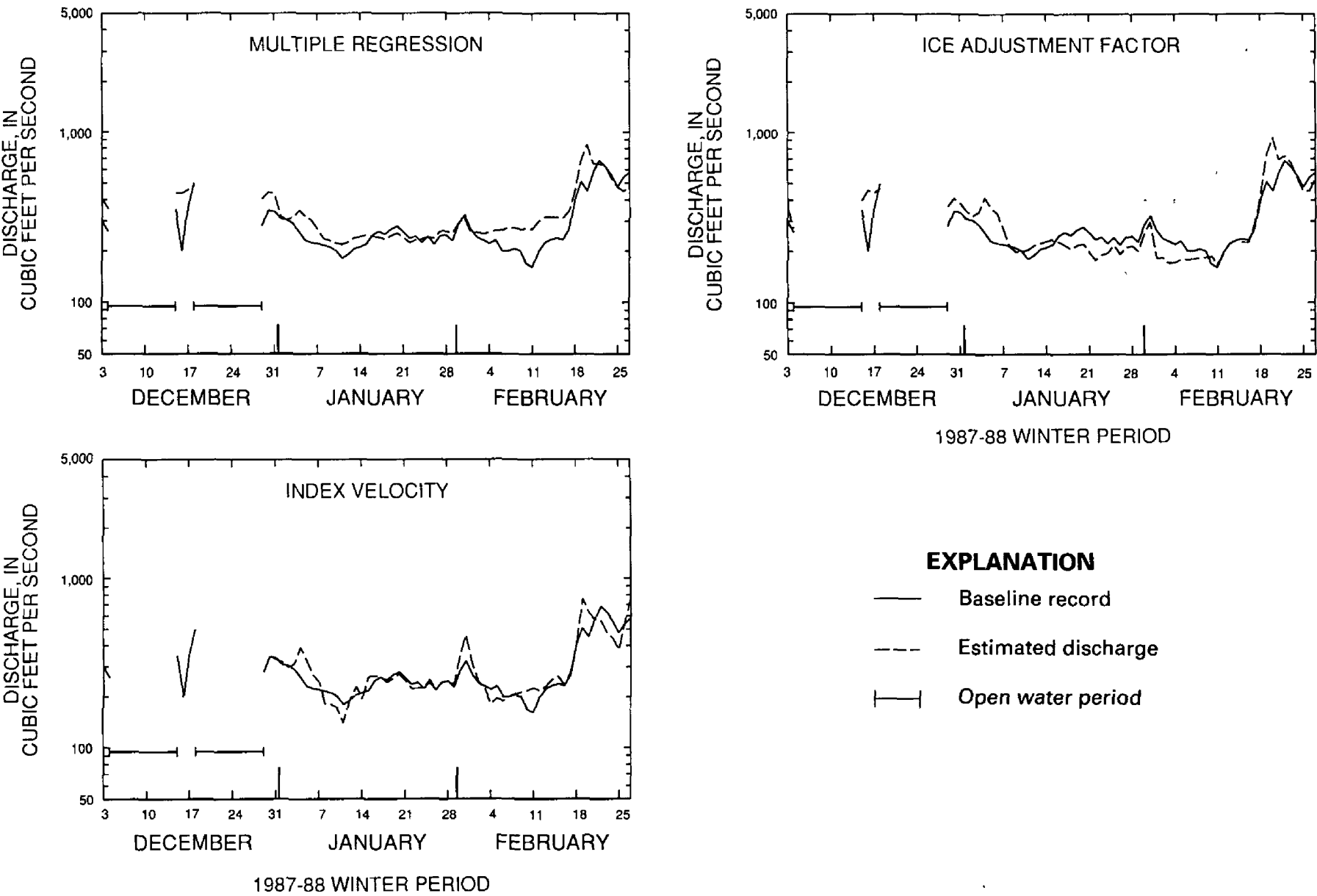

Figure 5C.   Hydrographs for the Des Moines River at Fort Dodge showing baseline daily mean discharge and daily mean discharge estimated by analytical methods.

cover. The method is easily adapted to computers either through regression relations or table interpolation, and the resulting discharge values could be computed for the time unit used to record gage height for the streamflow-gaging station. Implementation throughout the U.S. Geological Survey streamflow-gaging network would require auxiliary gage height data, and increased measurement frequency for at least two winters to define the necessary curves. The auxiliary gage height data would require either continuous gage-height monitoring or the use of observers to obtain daily gage-height values.

The results of the test of the stage -fall method are not directly comparable to the results for the other methods because complete record is not available for all three stations, and the frequent measurement data collected during this study was used for the regression analyses. The method worked well for Clear Creek, but produced poor results for the Floyd River. The location of the auxiliary gage for the Floyd River could account for the poor results. The method requires an auxiliary gage to establish the fall in the control section; if the auxiliary gage is outside of the control section, the results will be unreliable. The stage-fall method is not recommended for compiling ice-affected streamflow record.

Adjusted Rating Curve

The adjusted rating curve method overestimated the baseline mean for the ice affected periods for one record compilation and underestimated the mean for the other two compilations. The average percent error between the method mean and the baseline mean for each stream is shown in table 5. The mean daily relative error ranged from –0.10 to 0.40 (table 6). The standard deviation of the daily relative errors ranged from 0.23 to 0.54 (table 6). The relative error of the daily discharge values indicated that 14 percent of the daily values were excellent (0—5 percent error); 28 percent were good to excellent (0—10 percent error); and 42 percent were fair to excellent (0—15 percent error). Forty percent of the daily values had relative errors between 15 and 50 percent, and 18 percent had relative errors greater than 50 percent (table 7). One of the three discharge records was significantly different ($p < .025$) from the baseline streamflow record (table 8).

The adjusted rating curve method requires a general knowledge of ice computation techniques, open channel hydraulics, and familiarity with vertical velocity profiles and curve fitting techniques. Determination of the ice and bed roughness requires a basic knowledge of hydraulics and curve fitting techniques. The estimation of the roughness ratio and the proration of the roughness ratio between measurements reduces the reliability of the method. Because the method uses a roughness ratio to compute discharge, it is probably only valid for a complete surface ice cover. The method is easily adapted to automated data processing and the resulting discharge values could be computed for the time unit used to record gage height for the streamflow-gaging station. Implementation throughout the U. S. Geological Survey streamflow-gaging network would require that vertical velocity profiles be obtained for at least 3 vertical locations during each ice-affected discharge measurement.

The adjusted rating curve method produced reasonable results, although several methods were better for all three streams. This method shows that accounting for the roughness of the ice is an improvement over the backwater shift (analytical) method. The method could be improved through a better understanding of the changes in shift and ice roughness over time. The adjusted rating curve method is recommended for further study for use in the U.S. Geological Survey streamflow-gaging network.

Conductance Correlation

The conductance correlation method overestimated the baseline mean for the ice-affected periods for both record compilations. The average percent error between the method mean and the baseline mean for each compilation is shown in table 5. The mean daily relative errors were 0.02 and 1.85 (table 6). The standard deviations of the daily relative errors were 1.14 and 2.81 (table 6). The relative error of the daily discharge values indicated that less than one percent of the daily values were excellent (0—5 percent error); 3 percent were good to excellent (0–10 percent error); and 4 percent were fair to excellent (0–15 percent error). Twenty-one percent of the daily values had relative errors between 15 and 50 percent, and 75 percent had relative errors greater than 50 percent (table 7). One of the two discharge records was significantly different ($p < .025$) from the baseline streamflow record (table 8).

The conductance correlation method requires knowledge of basic regression techniques. The regression relation would require periodic update. The reliability of the method is a function of the estimated regression equation. For the three sites considered, the regression results were variable (table 3). One site failed to produce a statistically significant regression, therefore data for this station was not compiled. The method is based on a statistical relation between discharge and stream conductance. Although the form of the regression relation may be site-specific, the general concept should be widely applicable to different ice conditions. The method is adaptable to automated data processing because it uses an equation. Implementation of the conductance correlation method throughout the U.S.

Figure 6A. Hydrographs for the Floyd River at James showing baseline daily mean discharge and daily mean discharge estimated by subjective methods.

Geological Survey network would require continuous specific conductance monitoring or the use of observers to obtain daily conductance values.

Although the conductance correlation method performed poorly, it produced reasonable discharge values during higher flows for Clear Creek (fig. 4). At lower flows the regression relation is not sufficiently sensitive to accurately reflect small changes in discharge. However, the method has some merit in reproducing higher flows, and perhaps could be used in conjunction with another method. Use of a method to scale the data to the 6-week discharge measurements would improve the accuracy of the conductance correlation method (Melcher, 1988)

Multiple Regression

The multiple regression method overestimated the baseline mean for the ice-affected periods for all three

Figure 6B. Hydrographs for the Floyd River at James showing baseline daily mean discharge and daily mean discharge estimated by analytical methods.

record compilations. The average percent difference between the method mean and the baseline mean for each stream is shown in table 5. The mean daily relative error ranged from 0.18 to 1.73, with a mean of 1.02 (table 6). The standard deviation of the daily relative errors ranged from 0.24 to 1.00, with a mean of 0.63 (table 6). The relative error of the daily discharge values indicated that 7 percent of the daily values were excellent (0–5 percent error); 14 percent were good to excellent (0–10 percent error); and 18 percent were fair to excellent (0–15 percent error). Twenty percent of the daily values had relative errors between 15 and 50 percent, and 62 percent had relative errors greater than 50 percent (table 7). All three of the discharge records were significantly different (p < .025) from the baseline streamflow record (table 8).

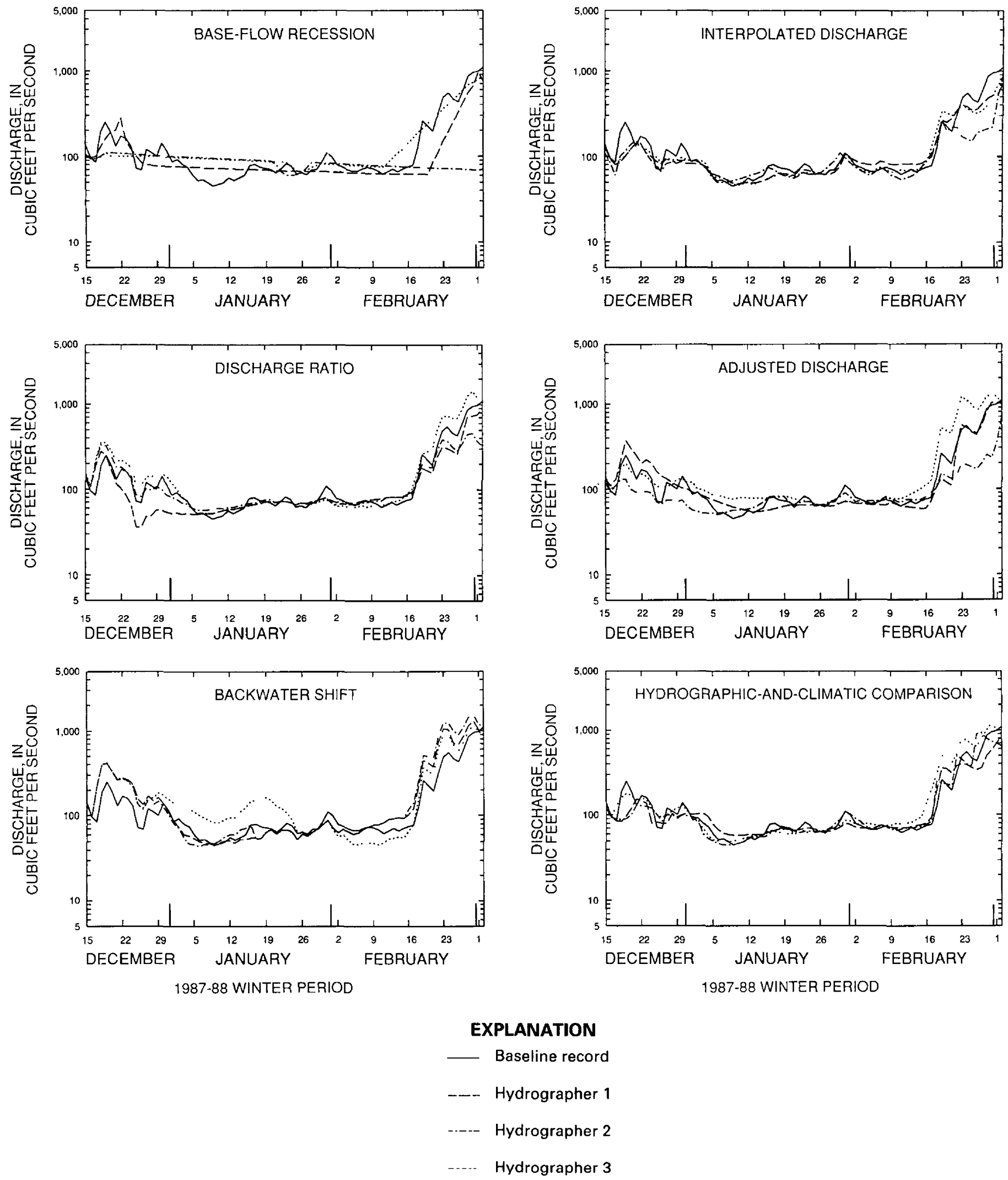The multiple regression method requires knowledge of advanced regression techniques. The method

Figure 6C.   Hydrographs for the Floyd River at James showing baseline daily mean discharge and daily mean discharge estimated by analytical methods.

is based on a statistical relation between the dependent and independent variables. The accuracy of the method depends on the development of an accurate regression equation. The results of the regression analyses for the three streams were variable (table 4). The method would only be applicable to the ice conditions that were present during the discharge measurements used to establish the regression relations. Because the method uses an equation, the results are reproducible and the method is adaptable to automated data processing. Implementation throughout the U.S. Geological Survey network would require the appropriate climatological data for each site and compiled data for the correlated stations.

The application of the multiple regression method made no attempt to incorporate the information from the 6-week discharge measurements into the estimation process. The method generally reproduced the shape of

Table 8.—*Significance levels for the difference between estimated discharge for each method and the baseline discharge*

Method[1]	Significance level[2]		
	Clear Creek	Des Moines River	Floyd River
	Subjective methods		
Base-flow recession (1)	0.565	0.187	**0.014**
Base-flow recession (2)	.120	.307	.682
Base-flow recession (3)	.831	.051	.458
Discharge ratio (1)	.052	.160	.057
Discharge ratio (2)	.139	.522	.723
Discharge ratio (3)	**.007**	.475	.156
Backwater shift (1)	**.001**	**.014**	.349
Backwater shift (2)	**.007**	.941	.239
Backwater shift (3)	**.003**	.115	**.036**
Interpolated discharge (1)	.228	.897	.433
Interpolated discharge (2)	**<.001**	.078	**.007**
Interpolated discharge (3)	.146	.146	.152
Adjusted discharge (1)	.070	.206	.885
Adjusted discharge (2)	.362	.163	**.004**
Adjusted discharge (3)	.281	**.006**	.141
Hydrographic-and-climatic comparison (1)	.051	.058	.512
Hydrographic-and-climatic comparison (2)	.883	.451	.083
Hydrographic-and-climatic comparison (3)	**.025**	.167	.525
	Analytical methods		
Prorated discharge	.152	**.006**	.255
Discharge ratio	.066	.312	**.018**
Backwater shift	.080	.494	**.024**
Stage fall	.897	—	.106
Adjusted rating curve	**.003**	.308	.659
Conductance correlation	.605	—	**.009**
Multiple regression	**<.001**	**.006**	**.001**
Index velocity	.057	.364	—
Ice adjustment factor	**<.001**	.965	**.040**
Pipe flow	.299	—	.944
Uniform flow	**.001**	—	.878

[1] The number in parentheses indicates the hydrographer who compiled the streamflow record.
[2] Significance level of the modified Wilcoxon test. Methods found to be statistically different from the baseline data at the 5 percent level appear in bold print.

the hydrograph, but tended to consistently over or underestimate the discharge (figs. 4–6). Use of a method to scale the data to the 6-week discharge measurements would improve the accuracy of the multiple regression method (Melcher, 1988). Continued use of the method would result in greater experience in determining relevant variables for the regression equations, and could improve the accuracy of the method. The accuracy could be further improved by increasing the discharge measurement frequency at the correlated stations. Further study of the multiple regression method is warranted.

Index Velocity

The index velocity method overestimated the baseline mean for the ice-affected periods for both record compilations. The average percent error between the method mean and the baseline mean for each stream is shown in table 5. The mean daily relative errors were 0.04 and 0.28 (table 6). The standard deviations of the daily relative errors were 0.51 and 0.18 (table 6). The relative error of the daily discharge values indicated that 26 percent of the daily values were excellent (0–5 percent error); 39 percent were good to excellent (0–10 percent error); and 51 percent were fair to excellent (0–15 percent error). Thirty-two percent of the daily values had relative errors between 15 and 50 percent, and 17 percent had relative errors greater than 50 percent (table 7). Neither of the two discharge records were significantly different (p < .025) than the baseline discharge record (table 8).

The index velocity method requires a general knowledge of ice computation techniques, the use and maintenance of velocity monitoring equipment, and an understanding of the basic hydraulic principles of open-channel flow. The method is based on the principle that discharge is the product of mean velocity and cross-sectional area. The variation of the spatial distribution of velocity during periods of ice effect causes the relation between measured velocity and mean velocity to vary. The method can be used for all ice conditions; however, in this study the most reliable velocity data was obtained during complete ice cover. The method is adaptable to automated data processing and the resulting discharge values could be computed for the time unit used to record gage height and velocity for the streamflow-gaging station. Velocity data is difficult to obtain during anchor-ice conditions or for streams with a mean depth less than 1 ft. The use of this method throughout the existing U.S. Geological Survey network would require a large capital investment to purchase velocity monitoring equipment. Future advances in velocity monitoring equipment and technology may make this method more suitable for widespread use.

The results of the test of the index velocity method are not directly comparable to the results for the other methods because complete record is not available for the Floyd River at James, and because malfunctioning equipment resulted in some missing record for the other two sites (figs. 4 and 5). The results of the study indicate that the index velocity method can produce satisfactory results. Many of the field and office procedures for applying this method were developed for this study. Repetitive use of this method probably would result in improvements in these procedures, make the method easier to use, and may improve the reliability of the results. Improvements in method accuracy probably could be obtained as field personnel became more experienced with the velocity monitoring equipment. An improvement in the velocity record may also be obtained by using equipment that monitors an integrated stream velocity. The index velocity method may be an appropriate method for use where the need for accurate discharge estimates during ice-affected periods justifies the expense of collecting additional field data.

Ice Adjustment Factor

The ice adjustment factor method overestimated the baseline mean for the ice-affected periods for all three record compilations. The average percent error between the method mean and the baseline mean for each stream is shown in table 5. The mean daily relative error ranged from 0.04 to 0.48 (table 6). The standard deviation of the daily relative errors ranged from 0.28 to 0.55 (table 6). The relative error of the daily discharge values indicated that 13 percent of the daily values were excellent (0–5 percent error); 24 percent were good to excellent (0–10 percent error); and 38 percent were fair to excellent (0–15 percent error). Thirty-nine percent of the daily values had relative errors between 15 and 50 percent, and 23 percent had relative errors greater than 50 percent (table 7). One of the three discharge records was significantly different (p < .025) from the baseline streamflow record (table 8).

The ice adjustment factor method requires knowledge of open-channel hydraulics and general ice computation procedures. Proration of the float depth and ice adjustment factor reduces the reliability of the method. The method is based on a simplification of Manning's equation. The method was developed for periods of stable ice cover; thus application to other conditions could be unreliable. The method is easily adapted to automated data processing and the resulting discharge values could be computed for the time unit used to record gage height for the streamflow-gaging station. Implementation to the U.S. Geological Survey network would require hydraulic geometry tables before and after each winter, and a reasonable procedure

Table 9.—*Results from the Kruskal-Wallis one-way anaylsis of variance comparing the record compilations by the three hydrographers to the baseline record for each method*

[<, less than]

Method	Significance level (p)[1]		
	Clear Creek	Des Moines River	Floyd River
Base-flow recession	0.071	<0.001	0.001
Discharge ratio	.520	.040	<.001
Backwater shift	.264	<.001	.515
Interpolated discharge	<.001	.002	.222
Adjusted discharge	.001	<.001	<.001
Hydrographic-and-climatic comparison	.138	.008	.013

[1] Methods where the three hydrographers were found to be statistically different from each other at the 5 percent level (p < .025) appear in bold print.

for determining float depth and ice adjustment factor between measurements.

In general, the ice adjustment factor method should only be applied to conditions with a stable stage-discharge rating and stable hydraulic geometry characteristics. Many of the sites in the U.S. Geological Survey streamflow-gaging network do not have stable stage-discharge ratings. Failure of the method to accurately reproduce the streamflow records for this study can be attributed primarily to the instability of the sites chosen (H. Santeford, Michigan Tech. Univ., written commun.). The ice adjustment factor method may be appropriate for use where the need for accurate discharge estimates during ice-affected periods justifies the expense of the additional data tabulation, and for stations with stable stage-discharge ratings.

Pipe Flow

The pipe-flow method overestimated the baseline mean for the ice-affected periods for one record compilation and underestimated the mean for the other compilation. The average percent error between the method mean and the baseline mean for each stream is shown in table 5. The mean daily relative errors were 0.07 and 0.13 (table 6). The standard deviations of the daily relative errors were 0.50 and 0.79 (table 6). The relative error of the daily discharge values indicated that 15 percent of the daily values were excellent (0–5 percent error); 27 percent were good to excellent (0–10 percent error); and 37 percent were fair to excellent (0–15 percent error). Thirty-nine percent of the daily values had relative errors between 15 and 50 percent, and 24 percent had relative errors greater than 50 percent (table 7). Neither of the two discharge records were significantly different (p < .025) from the baseline streamflow record (table 8).

The pipe flow method requires knowledge of general hydraulic principles, regression analysis techniques and statistical judgement. The method is based on accepted hydraulic principles, although the regression relations result in an empirical component. Imperfect regression relations diminish the reliability of the method. Because of the pipe-flow analogy, the method is strictly applicable to complete ice-cover conditions, and would work best for stable conditions. This method is directly applicable to automated data processing because equations are used, and the resulting discharge values could be computed for the time unit used to record gage height for the streamflow-gaging station. Implementation throughout the U.S. Geological Survey streamflow-gaging network would require auxiliary gage height data and the development of the regression relations based upon one or two winters with increased measurement frequency. The auxiliary gage-height data would require either continuous monitoring or the use of observers to obtain daily gage-height values.

The results for the pipe flow method are not directly comparable to the results for the other methods because complete record is not available for all three stations, and the frequent measurement data collected during this study were used for the regression analyses. The method produced reasonable results for Clear Creek, yet performed poorly for the Floyd River. The location of the auxiliary gage for the Floyd River probably accounted for the poor results. The pipe flow method is not recommended for use in the U.S. Geological Survey streamflow-gaging network.

Uniform Flow

The uniform-flow method overestimated the baseline mean for the ice-affected periods for one record compilation and underestimated the mean for the

other compilation. The average percent error between the method mean and the baseline mean for each stream is shown in table 5. The mean daily relative errors were 0.01 and 0.35 (table 6). The standard deviations of the daily relative errors were 0.26 and 0.43 (table 6). The relative error of the daily discharge values indicated that 12 percent of the daily values were excellent (0–5 percent error); 20 percent were good to excellent (0–10 percent error); and 26 percent were fair to excellent (0–15 percent error). Fifty-six percent of the daily values had relative errors between 15 and 50 percent, and 18 percent had relative errors greater than 50 percent (table 7). One of the two discharge records was significantly different (p < .025) from the baseline streamflow record (table 8).

The uniform-flow method requires knowledge of open-channel hydraulics, vertical velocity profiles, and general curve fitting techniques. Several assumptions are required for the computation of roughness, and the proration of roughness and ice area between measurements reduces the reliability of the method. The method is based on Manning's equation. The method probably is suitable only for a surface ice-cover condition. The method is easily adapted to automated data processing and the resulting discharge values could be computed for the time unit used to record gage height for the streamflow-gaging station. Implementation throughout the U. S. Geological Survey streamflow-gaging network would require auxiliary gage-height data, and complete vertical velocity profiles for at least three locations during each ice-affected discharge measurement. The auxiliary gage-height data would require either continuous-stage monitoring or the use of observers to obtain once-daily gage-height values.

The results of the test of the uniform-flow method are not directly comparable to the results for the other methods because complete record is not available for all three stations. The method produced excellent results, demonstrating low daily error standard deviations for both sites, although Clear Creek showed a positive bias in the daily errors. The method could be improved through a better understanding of changes in ice roughness and ice thickness. Incorporation of a general ice accretion/ablation model (Yapa and Shen, 1986) would improve the ice area and roughness characterizations over time. The uniform-flow method may be appropriate for use where the need for accurate discharge estimates during ice-affected periods justifies the expense of collecting additional field data.

NEEDS FOR FUTURE STUDY

The characteristics of ice and ice-affected streamflow need further study. Several of the methods applied in this study could be improved by better characterization of the ice thickness and roughness over time. An improved understanding of ice accretion/ablation rates and its incorporation into these methods is required. For this study, uniform rates of ice accretion and ice roughness changes were assumed for application of several methods (adjusted rating curve, index velocity, ice adjustment factor, and uniform flow). If more were known about these changes, these corrections could be applied more realistically, and the results for these methods would be more reliable.

On the basis of frequent measurement data collected at the three stations during this study, discharge varied more than expected. A study to consider the meteorological and environmental factors affecting the variability of streamflow under an ice cover is warranted. The relative importance of these factors needs to be understood for reliable use of multiple regression to estimate ice-affected streamflow.

The frequent measurements at the three stations indicate that streamflow is reduced by 40–50 percent during the initial freeze-up period. The conditions affecting the magnitude and duration of the streamflow reductions due to freeze up need to be better understood.

The frequent measurements made during this study indicate backwater conditions vary throughout the ice-affected periods. There is a need to better understand the nature of backwater from various ice conditions, the variation of backwater over time for more widespread conditions, and the factors that cause backwater from ice to vary. The reliability of the results of methods that are based on an estimate of backwater (backwater shift, adjusted rating curve) would be significantly improved if the processes affecting backwater from ice were better understood.

Rantz and others (1982) noted that the accuracy of ice-affected discharge estimates could be improved by using the discharge-ratio method to provide discharge estimates and then verifying these estimates using the hydrographic and climatic comparison method. On the basis of the results of this study, the authors concur with this suggestion. The study results indicate that the discharge-ratio method can produce reasonable discharge estimates and would be a reliable method for making initial discharge estimates. Any anomalous or outlier data obtained from the application of the discharge-ratio method could be identified and corrected using the hydrographic-and-climatic-comparison method. The discharge estimates could be further refined by computing the backwater shifts for the daily discharge estimates and inspecting these shifts for reasonable continuity. This procedure could be applied to the U.S. Geological Survey network without obtaining any new field data and could be adapted to automated data processing techniques. The implemen-

tation of this procedure probably would improve the consistency and accuracy of ice-affected streamflow estimates.

SUMMARY AND CONCLUSIONS

Ice affects the stage-discharge relation for some portion of the winter at more than one-half of the streamflow-gaging stations operated by the U.S. Geological Survey. Ice-affected discharge usually is estimated using a method that is dependent on the judgment of the hydrographer and is not adaptable to automated data processing. To improve the reliability of estimates of ice-affected streamflow and the efficiency of processing streamflow record, proposed and existing methods for estimating ice-affected discharge records were evaluated for possible use by the U.S. Geological Survey.

Seventeen methods used for computing ice-affected discharge records were identified by a written survey of U.S. Geological Survey field offices and by a literature search. The methods were classified into two general categories for evaluation. Methods that require judgement are categorized as subjective methods. Methods that are based on a systematic computation are categorized as analytical methods. The methods were evaluated by applying the methods to data collected at three stations in Iowa during the winter of 1987–88. A baseline data set was compiled by collecting data needed for application of the seventeen methods and making discharge measurements at 1- to 5-day intervals at the three stations. The discharge records for each method were compiled by simulating a normal 6-week field schedule. The subjective methods were independently applied by three hydrographers. The analytical methods were applied by the authors.

Each method was evaluated for subjective factors including method costs, technical soundness, applicability to various ice conditions, compatibility with automated data processing, and suitability for use in the existing U.S. Geological streamflow-gaging network. The methods were evaluated for accuracy by comparing the results for the seventeen methods with the baseline data set.

The discharge ratio and hydrographic-and-climatic-comparison methods generally produced more reliable results than the other subjective methods. Based on the results of this study, the base-flow recession method may not be appropriate for use in compiling ice-affected streamflow records. A comparison of the results for the interpolated discharge method, which does not use indicated open-water discharge, and the adjusted discharge method, which does not use hydrographic comparison, showed similar results, and indicated the following:

(1) The relative value of the use of hydrographic comparison and indicated open-water discharges are considered to be about equal.

(2) Comparing the results of the interpolated discharge, adjusted discharge, and hydrographic-and-climatic-comparison methods, the use of both indicated open-water discharges and hydrographic comparison improves the accuracy of ice-affected discharge estimates.

On the basis of a non-parametric analysis of variance, two methods (adjusted discharge and base-flow recession) showed significant differences in the records worked by the individual hydrographers. The hydrographic-and-climatic comparison and interpolated discharge methods each had a moderate degree of subjectivity, whereas the discharge ratio and backwater shift methods were the most consistent.

The index velocity, adjusted rating curve, and uniform flow methods generally produced more reliable results than the other analytical methods considered. The adjusted rating curve method was slightly more accurate at reproducing the mean discharge for the entire ice period, whereas the uniform flow and index velocity methods were slightly better at reproducing the daily discharges. The ice adjustment factor and discharge ratio methods worked reasonably well for the Des Moines River (the most stable of the three streams), and probably would provide reasonable results for situations with a stable geometry and stage-discharge rating. The analytical prorated discharge, discharge ratio, backwater shift, stage fall, and pipe flow methods are not recommended for use in compiling ice-affected streamflow record.

Based on the results of the evaluation for the three Iowa stations, the discharge ratio and hydrographic-and-climatic-comparison methods were more accurate than the other subjective methods, and about as accurate as the best analytical method. The index-velocity method, the adjusted rating curve method, and the uniform flow method could potentially be used for streamflow-gaging stations where the need for accurate ice-affected discharge estimates justifies the expense of collecting additional field data. The use of these methods may not be appropriate for certain ice conditions. The ice adjustment factor method may be appropriate for use for stations with extremely stable stage-discharge ratings and measuring sections. Further research is needed to refine these methods. The discharge ratio method and multiple regression method may produce reliable estimates of streamflow for varying ice conditions using information obtained from the existing U.S. Geological Survey streamflow-gaging network. Improvements in the accuracy of the results of some of the methods may be obtained as users obtain more experience at method application.

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Appendix

SURVEY SENT TO U.S. GEOLOGICAL SURVEY OFFICES AND SELECTED RESULTS

42

DISTRICT_____ COMPLETED BY_____

1. Within each of the following climatic categories, defined by annual runoff, how many gages in your District are in the listed subcategories? These subcategories are defined by the number of days in which backwater from ice affects the normal stage discharge relation. Base the number of days on a typical year. Most Districts will have gages listed in only one or two climatic categories. The sum of the gages listed in the table should equal the total number of gages in your District.

	Less than 2 inch of annual runoff (arid)	.2 to 2 inches of annual runoff (semiarid)	2 to 5 inches of annual runoff (subhumid)	Greater than 5 inches of annual runoff (humid)
Number of gages with:				
No ice-affected days	____	____	____	____
1-5 days of ice effect/year	____	____	____	____
6-15 days of ice effect/year	____	____	____	____
16-45 days of ice effect/year	____	____	____	____
46-90 days of ice effect/year	____	____	____	____
91-150 days of ice effect/year	____	____	____	____
Greater than 150 days of ice effect/year	____	____	____	____

2. Within your District, approximately what percent of the total number of days in which the stage discharge relation is affected by ice is caused by the following conditions? If more than one condition exists simultaneously at a gaging station, consider only the predominant condition. (Your total percent should equal 100 percent.) (Descriptions of these ice conditions can be found in Water-Supply Paper 2175, volume 2, pages 360-363.)

_____ frazil ice   _____ surface ice

_____ anchor ice   _____ shore ice

3. Describe briefly the normal methods used by your District for determining discharge during periods of ice effect.

4. Describe any techniques used by your District for determining discharge during ice-affected periods which you think are unusual or have special merit.

5. Describe any formal projects or backyard efforts which your office has initiated or completed related to evaluating discharge during ice-affected periods. Briefly describe your efforts and conclusions or include a copy of any reports with your response to this questionnaire.

6. The following types of data are commonly used as the basis for determining discharge during periods of backwater from ice. Please mark an "X" next to the data which are NORMALLY used by your office when computing or estimating stream discharge affected by backwater from ice.

_____digital stage record   _____stream velocity record

_____discharge measurements   _____correlation with other stations

_____recession curves or coefficients   _____backwater shifts

_____discharge ratios   _____measurements of ice thickness

_____ice roughness   _____graphic stage record

_____air temperature   _____winter precipitation records

_____snowcover records   _____index stations

_____hydrographic comparison   _____observer information

_____other, please describe_____

7. How important is the availability of analog stage record for determining discharge during ice-affected periods?

_____necessary   _____useful   _____unnecessary

8. In your District, what is the frequency of discharge measurements made during ice-affected periods?_____

9. Estimate, for your District, how many total hours of additional time are used to process streamflow data for periods of ice effect. Estimate the additional field time necessary for data collection and office time to compute, check, and review ice-affected periods. "Additional" refers to the extra time necessary to determine streamflow during ice-affected periods compared with computing streamflow by the normal open-water method.

_____total hours of field time   _____total hours of office time

10. For the gages in your District affected by backwater from ice, how important is the winter record in terms of data use? In other words, to what degree do users of the data consider accuracy of daily values during winter record to be important? Estimate the percent of ice-affected gages in the following categories:

Percent of winter record where accuracy is

_____extremely important   _____important
_____very important   _____not important

11. Data sets are needed to evaluate the available methods for computing discharge during ice-affected periods. Does your District have any stations in which discharge is defined by frequent discharge measurements during the ice-affected period (e.g., measurements at 7-10 day frequency)? Describe stations and data.

Table A1. --- <u>Summary of responses to survey question 1. Number of gages with ice-affected days, categorized by inches of runoff, listed by categories of number of days of ice effect per year</u>

	<.2 in. of annual runoff	.2 to 2 in. of annual runoff	2 to 5 in. of annual runoff	>5 in. of annual runoff	Total gages
Number of gages with:					
No ice-affected days	77	234	239	2,343	2,893
1-5 days of ice effect/year	9	81	42	468	600
6-15 days of ice effect/year	11	100	64	480	655
16-45 days of ice effect/year	13	136	72	789	1,010
46-90 days of ice effect/year	1	89	131	575	796
91-150 days of ice effect/year	4	194	146	212	556
More than 150 days of ice effect/year	106	0	15	3	88
Total	115	849	697	4,955	6,616

Table A2 --- <u>Summary of responses to survey question one. Summary of days of ice-effect for stream-gaging stations,</u> <u>by district</u>

DISTRICT	TOTAL NUMBER STREAM-GAGING STATIONS	NUMBER OF STATIONS WITH ICE-AFFECTED DAYS	TOTAL DAYS OF ICE EFFECT	PERCENT OF TOTAL DAYS WITH ICE EFFECT
ALABAMA	78	0	0	0.00
ALASKA	88	86	9976	31.06
ARKANSAS	49	0	0	0.00
ARIZONA	80	21	343	1.17
CALIFORNIA	500	50	1140	0.62
COLORADO	295	286	21063	19.56
CONNECTICUT	48	48	528	3.01
FLORIDA	285	0	0	0.00
GEORGIA	108	18	54	0.14
HAWAII	107	0	0	0.00
IDAHO	228	140	5640	6.78
ILLINOIS	135	127	5786	11.74
INDIANA	167	148	6413	10.52
IOWA	118	114	7178	16.67
KANSAS	142	128	1896	3.66
KENTUCKY	104	80	1480	3.90
LOUISIANA	70	0	0	0.00
MAINE	44	35	2967	18.53
MARYLAND, DELAWARE	100	85	1315	3.60
MASSACHUSETTS	72	40	1193	4.54
MICHIGAN	129	98	5413	11.50
MINNESOTA	83	78	9743	32.16
MISSISSIPPI	86	8	24	0.08
MISSOURI	107	55	1698	4.35
MONTANA	161	137	9159	15.59
NEBRASKA	144	134	7309	13.91
NEVADA	96	79	1589	4.53
NEW HAMPSHIRE, VERMONT	70	65	3005	11.76
NEW JERSEY	100	40	280	0.77
NEW MEXICO	145	116	3722	7.03
NEW YORK	184	160	6408	9.54
NORTH CAROLINA	159	30	274	0.47
NORTH DAKOTA	73	73	9210	34.57
OHIO	125	100	2900	6.36
OKLAHOMA	120	85	455	1.03
OREGON	259	109	678	0.62
PENNSYLVANIA	246	218	6159	6.86
PUERTO RICO	49	0	0	0.00
RHODE ISLAND	15	6	139	2.54
SOUTH CAROLINA	120	0	0	0.00
SOUTH DAKOTA	110	95	9765	24.32
TENNESSEE	105	60	180	0.47
TEXAS	386	35	169	0.12
UTAH	180	152	8606	13.10
VIRGINIA	82	56	488	1.63
WASHINGTON	196	91	1078	1.51
WEST VIRGINIA	70	61	971	3.80
WISCONSIN	97	91	8780	24.80
WYOMING	101	96	10223	27.73
	======	======	======	======
	6,616	3,734	175,397	8.09

Table A3. --- Summary of responses to question two. Number of days of ice effect for each type of ice (Rantz and others, 1982), by district

DISTRICT	DAYS OF FRAZIL	DAYS OF ANCHOR	DAYS OF SURFACE	DAYS OF SHORE
ALABAMA	0	0	0	0
ALASKA	100	199	9,278	399
ARKANSAS	0	0	0	0
ARIZONA	86	17	171	69
CALIFORNIA	0	0	1,140	0
COLORADO	1,053	5,266	8,425	6,319
CONNECTICUT	0	53	396	79
FLORIDA	0	0	0	0
GEORGIA	0	49	5	0
HAWAII	0	0	0	0
IDAHO	1,128	1,692	2,256	564
ILLINOIS	116	174	3,934	1,562
INDIANA	0	834	4,874	705
IOWA	215	359	5,814	790
KANSAS	0	285	1,326	285
KENTUCKY	74	1,184	74	148
LOUISIANA	0	0	0	0
MAINE	0	148	2,225	594
MARYLAND, DELAWARE	66	263	723	263
MASSACHUSETTS	0	191	787	215
MICHIGAN	0	271	4,601	541
MINNESOTA	487	487	8,282	487
MISSISSIPPI	0	0	1	23
MISSOURI	255	255	1,018	170
MONTANA	92	275	8,243	549
NEBRASKA	731	0	5,847	731
NEVADA	0	0	1,192	397
NEW HAMPSHIRE , VERMONT	150	300	2,104	451
NEW JERSEY	0	0	140	140
NEW MEXICO	0	372	2,233	1,117
NEW YORK	192	1,923	3,204	1,089
NORTH CAROLINA	0	219	0	55
NORTH DAKOTA	0	0	9,210	0
OHIO	290	580	580	1,450
OKLAHOMA	0	5	364	86
OREGON	13	88	102	475
PENNSYLVANIA	123	1,047	4,003	986
PUERTO RICO	0	0	0	0
RHODE ISLAND	0	22	117	0
SOUTH CAROLINA	0	0	0	0
SOUTH DAKOTA	0	488	8,789	488
TENNESSEE	0	72	0	108
TEXAS	25	25	51	68
UTAH	430	861	5,594	1,721
VIRGINIA	15	88	117	268
WASHINGTON	21	140	162	755
WEST VIRGINIA	126	0	0	845
WISCONSIN	351	175	6,322	1,932
WYOMING	1,022	1,533	5,112	2,556
========	========	========	========	========
	7,161	19,940	118,816	29,480
	4%	11%	68%	17%

Table A4 --- <u>Summary of responses to survey question six. Data used for estimating streamflow during ice-affected periods, by district</u>

DISTRICT	DS	DM	RC	DR	IR	AT	SR	HC	SV	CS	BS	MT	GS	WP	IS	OI	TOTAL
ALABAMA																	0
ALASKA		X	X	X		X	X	X		X			X	X	X	X	11
ARKANSAS																	0
ARIZONA	X	X				X		X		X			X	X			7
CALIFORNIA		X				X		X		X			X	X		X	7
COLORADO	X	X		X		X	X	X		X	X	X	X	X	X	X	13
CONNECTICUT	X	X				X		X		X			X	X	X		8
FLORIDA																	0
GEORGIA																	0
HAWAII																	0
IDAHO	X	X		X		X		X		X			X	X	X	X	10
ILLINOIS	X	X	X	X		X	X	X		X		X	X	X	X	X	13
INDIANA	X	X				X	X	X		X			X	X		X	9
IOWA	X	X		X		X		X		X	X		X	X	X	X	11
KANSAS	X	X				X	X	X			X		X	X	X	X	10
KENTUCKY		X				X	X	X			X		X	X			7
LOUISIANA																	0
MAINE	X	X				X		X		X				X			6
MARYLAND, DELAWARE	X	X				X	X	X		X	X		X	X	X		10
MASSACHUSETTS	X	X		X				X					X	X	X		7
MICHIGAN	X	X		X		X	X	X		X			X	X	X	X	11
MINNESOTA	X	X				X	X	X		X			X	X	X	X	10
MISSISSIPPI																	0
MISSOURI	X	X				X		X		X	X		X	X	X		9
MONTANA	X	X				X	X	X		X			X	X	X	X	10
NEBRASKA	X	X				X	X	X			X		X	X		X	9
NEVADA	X	X				X		X						X			5
NEW HAMPSHIRE,VERMONT	X	X				X		X		X			X	X	X	X	9
NEW JERSEY	X	X				X		X		X				X	X	X	8
NEW MEXICO	X	X				X		X		X			X	X	X		8
NEW YORK	X	X	X	X		X	X	X		X	X		X	X	X	X	13
NORTH CAROLINA		X				X		X					X				4
NORTH DAKOTA	X	X	X	X		X		X					X	X		X	9
OHIO	X	X	X	X		X		X		X			X	X	X	X	11
OKLAHOMA	X	X				X	X	X		X			X	X		X	9
OREGON	X	X				X		X					X	X			6
PENNSYLVANIA	X	X	X			X	X	X		X			X	X	X	X	11
PUERTO RICO																	0
RHODE ISLAND	X	X		X				X					X	X		X	7
SOUTH CAROLINA																	0
SOUTH DAKOTA	X	X				X	X	X		X	X		X	X	X	X	11
TENNESSEE	X	X				X		X		X			X	X			7
TEXAS	X	X	X			X		X		X			X	X		X	9
UTAH	X	X				X	X	X		X				X	X		8
VIRGINIA	X	X				X		X		X	X	X	X	X	X	X	11
WASHINGTON	X	X				X		X					X	X			6
WEST VIRGINIA		X				X		X		X	X		X				6
WISCONSIN	X	X	X			X	X	X					X	X	X	X	10
WYOMING	X	X		X		X	X	X					X	X	X	X	10
	==	==	==	==	==	==	==	==	==	==	==	==	==	==	==	==	====
	35	40	8	12	0	38	18	40	0	28	11	3	36	38	24	25	356

DS	digital stage record	SV	stream velocity record
DM	discharge measurements	CS	correlation w/other stations
RC	recession curves or coefficients	BS	backwater shifts
DR	discharge ratios	MT	measurements of ice thickness
IR	ice roughness	GS	graphic stage record
AT	air temperature	WP	winter precipitation records
SR	snowcover records	IS	index stations
HC	hydrographic comparison	OI	observer information

Table A5 --- <u>Summary of responses to survey question seven. Importance of analog stage record for completing ice-affected streamflow record, by district</u>

DISTRICT	NECESSARY	USEFUL	UNNECESSARY
ALABAMA			
ALASKA	X		
ARKANSAS			
ARIZONA		X	
CALIFORNIA		X	
COLORADO		X	
CONNECTICUT		X	
FLORIDA			
GEORGIA			
IDAHO	X		
ILLINOIS		X	
INDIANA	X		
IOWA	X		
KANSAS	X		
KENTUCKY	X		
LOUISIANA			
MAINE			X
MARYLAND, DELAWARE		X	
MASSACHUSETTS	X		
MICHIGAN	X		
MINNESOTA	X	X	
MISSISSIPPI			
MISSOURI		X	
MONTANA		X	
NEBRASKA		X	
NEVADA	X		
NEW HAMPSHIRE, VERMONT	X		
NEW JERSEY		X	
NEW MEXICO		X	
NEW YORK		X	
NORTH CAROLINA	X		
NORTH DAKOTA		X	
OHIO		X	
OKLAHOMA		X	
OREGON		X	
PENNSYLVANIA	X	X	
PUERTO RICO			
RHODE ISLAND	X		
SOUTH CAROLINA			
SOUTH DAKOTA		X	
TENNESSEE		X	
TEXAS		X	
UTAH		X	
VIRGINIA		X	
WASHINGTON		X	
WEST VIRGINIA		X	
WISCONSIN		X	
WYOMING	X		
	======	======	======
	15	26	1

Table A6 --- Summary of responses to survey question nine. Additional office and field hours used to compute streamflow during ice-affected periods, by district

DISTRICT	FIELD HOURS	OFFICE HOURS	HOURS USED PER ICE DAY (FIELD + OFFICE HOURS ÷ TOTAL DAYS OF ICE)
ALABAMA	0	0	—
ALASKA	300	350	0.07
ARKANSAS	0	0	—
ARIZONA	220	450	1.95
CALIFORNIA	200	200	0.35
COLORADO	400	450	0.04
CONNECTICUT	96	48	0.27
FLORIDA	0	0	—
GEORGIA	0	0	0.00
HAWAII	0	0	—
IDAHO	1,080	960	0.36
ILLINOIS	280	285	0.10
INDIANA	270	540	0.13
IOWA	488	635	0.16
KANSAS	128	192	0.17
KENTUCKY	0	100	0.07
LOUISIANA	0	0	—
MAINE	140	350	0.17
MARYLAND, DELAWARE	80	80	0.12
MASSACHUSETTS	186	568	0.63
MICHIGAN	200	500	0.13
MINNESOTA	540	2,000	0.26
MISSISSIPPI	0	0	0.00
MISSOURI	200	100	0.18
MONTANA	950	3,900	0.53
NEBRASKA	1,352	610	0.27
NEVADA	300	250	0.35
NEW HAMPSHIRE, VERMONT	300	400	0.23
NEW JERSEY	23	95	0.42
NEW MEXICO	100	400	0.13
NEW YORK	990	1,420	0.38
NORTH CAROLINA	0	0	0.00
NORTH DAKOTA	800	400	0.13
OHIO	1,000	1,500	0.86
OKLAHOMA	20	45	0.14
OREGON	285	512	0.76
PENNSYLVANIA	650	600	0.20
PUERTO RICO	0	0	—
RHODE ISLAND	16	56	0.52
SOUTH CAROLINA	0	0	—
SOUTH DAKOTA	160	340	0.05
TENNESSEE	200	250	2.50
TEXAS	10	80	0.53
UTAH	200	100	0.03
VIRGINIA	10	56	0.14
WASHINGTON	215	388	0.56
WEST VIRGINIA	240	120	0.37
WISCONSIN	740	670	0.16
WYOMING	900	900	0.18
	=====	=====	====
	14,269	20,900	0.30

Table A7 --- <u>Summary of responses to survey question ten. Relative importance of stream-gaging station data, by</u> district

DISTRICT	EXTREMELY IMPORTANT	VERY IMPORTANT	IMPORTANT	NOT IMPORTANT	TOTAL STATIONS WITH ICE-AFFECT
ALABAMA	0	0	0	0	0
ALASKA	3	7	62	14	86
ARKANSAS	0	0	0	0	0
ARIZONA	8	11	2	0	21
CALIFORNIA	0	0	25	25	50
COLORADO	14	72	157	43	286
CONNECTICUT	0	0	48	0	48
FLORIDA	0	0	0	0	0
GEORGIA	0	0	0	18	18
HAWAII	0	0	0	0	0
IDAHO	14	28	98	0	140
ILLINOIS	0	4	76	47	127
INDIANA	7	22	119	0	148
IOWA	5	45	10	54	114
KANSAS	0	0	128	0	128
KENTUCKY	0	0	80	0	80
LOUISIANA	0	0	0	0	0
MAINE	4	24	7	0	35
MARYLAND, DELAWARE	0	0	77	8	85
MASSACHUSETTS	0	20	20	0	40
MICHIGAN	5	10	83	0	98
MINNESOTA	9	16	43	10	78
MISSISSIPPI	0	0	0	8	8
MISSOURI	0	0	55	0	55
MONTANA	0	0	82	55	137
NEBRASKA	0	0	134	0	134
NEVADA	0	0	79	0	79
NEW HAMPSHIRE, VERMONT	6	52	7	0	65
NEW JERSEY	0	4	12	24	40
NEW MEXICO	0	0	46	70	116
NEW YORK	10	48	56	46	160
NORTH CAROLINA	0	0	0	30	30
NORTH DAKOTA	0	73	0	0	73
OHIO	0	0	100	0	100
OKLAHOMA	0	0	85	0	85
OREGON	6	0	76	27	109
PENNSYLVANIA	6	22	72	118	218
PUERTO RICO	0	0	0	0	0
RHODE ISLAND	0	3	3	0	6
SOUTH CAROLINA	0	0	0	0	0
SOUTH DAKOTA	57	10	9	19	95
TENNESSEE	0	0	60	0	60
TEXAS	0	0	35	0	35
UTAH	0	8	137	7	152
VIRGINIA	0	0	56	0	56
WASHINGTON	4	0	64	23	91
WEST VIRGINIA	0	0	0	61	61
WISCONSIN	0	2	86	3	91
WYOMING	=9	29	48	10	96
	=====	=====	====	=====	=====
	167	510	2,337	720	3,734
	4%	14%	63%	19%	