LOW-FLOW CHARACTERISTICS OF KENTUCKY STREAMS

By Kevin J. Ruhl and Gary R. Martin

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 91-4097

Prepared in cooperation with the
KENTUCKY NATURAL RESOURCES AND
ENVIRONMENTAL PROTECTION CABINET

Louisville, Kentucky
1991

U.S. DEPARTMENT OF THE INTERIOR

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CONVERSION FACTORS

Multiply	By	To obtain
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer
cubic foot (ft^3)	0.02832	cubic meter
cubic foot per second (ft^3/s)	0.02832	cubic meter per second

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ABSTRACT

Low-flow characteristics were determined for 136 continuous-record and 212 low-flow partial-record streamflow gaging stations in Kentucky. Low-flow frequency curves were developed for the continuous-record gaging stations from daily mean streamflows for unregulated periods of 10 years or more. Through graphical correlation with data from one or more of the continuous-record stations, estimates of selected low-flow frequency values were also made at each of the partial-record stations.

Techniques are presented to estimate the 7-day 2-year and 7-day 10-year low-flow frequency values for ungaged, unregulated streams in Kentucky. These frequency values were determined at each of the continuous-record gaging stations and were related to basin characteristics and streamflow indices using multiple linear regression. The most significant variables for estimating the 7-day 2- and 10-year low-flow values from the analysis were drainage area and streamflow-variability index. The equations developed to estimate the 7-day 2-year and the 7-day 10-year low flows have a standard error of estimate of 71 and 90 percent, respectively.

INTRODUCTION

Knowledge of low-flow characteristics of Kentucky streams is important in decisions regarding water resource planning and management. Information needed to allocate waste-effluent discharges to receiving waters and to estimate surface-water availability for domestic, agricultural, industrial, and recreational supply is vital to the wise management of water resources. Certain waste-effluent discharge limits and water-supply criteria in Kentucky are based on the 7-day 10-year ($7Q_{10}$) low-flow frequency value, which is the lowest mean value of streamflow for 7 consecutive days having a 10 percent chance of not being exceeded in any year.

Even though the 7-day 2-year ($7Q_2$) low-flow frequency value is not used directly in waste-effluent discharge or water-supply criteria for the State, it provides additional insight into the flow characteristics of the stream site. The value also is important in providing additional spatial coverage in the regionalization analysis performed in this study.

As a result of increased demand for low-flow information, the U.S. Geological Survey (USGS), in cooperation with the Kentucky Natural Resources and Environmental Protection Cabinet (KNREPC), analyzed data available from the streamflow-gaging network in Kentucky to update low-flow frequency values and to derive equations to estimate these values at ungaged stream sites. Low-flow frequency values at continuous-record streamflow gaging stations were updated using data through 1987. Previous reports describing low-flow information of Kentucky streams are by Swisshelm (1974) and Sullavan (1980 and 1984). Using the updated low-flow values, equations were derived using multiple linear regression techniques to estimate low-flow frequency values at ungaged stream sites.

Purpose and Scope

This report describes the results of a study to (1) update the $7Q_2$ and $7Q_{10}$ low flows for the continuous-record streamflow-gaging stations for unregulated streamflow periods and for the low-flow partial-record gaging stations in Kentucky, and (2) develop techniques to estimate these low flows for ungaged stream sites in Kentucky.

The values reported are the $7Q_2$ and $7Q_{10}$ low flows for 136 continuous-record streamflow stations in Kentucky having 10 or more years of unregulated streamflow record. Frequency values for the continuous-record stations having less than 25 years of unregulated record were adjusted through correlation with data from stations having 25 or more years of record. This was done to adjust values for the effect that climatic variations might have on a short-term record. The $7Q_2$ and $7Q_{10}$ low flows were also determined for 212 partial-record stations in Kentucky through correlation of the partial-record station data with the data from the continuous-record stations. Data from some of the partial-record stations were correlated with data from continuous-record stations operated by the USGS in West Virginia and Tennessee.

Selected basin characteristics were determined for each of the 136 continuous- and 212 partial-record stations. These included total and contributing drainage area; main channel length, slope, and elevation; basin length and shape; and mean annual precipitation. For the continuous-record gaging stations, values of streamflow variability and streamflow recession were also determined.

Regionalization of the $7Q_2$ and $7Q_{10}$ low flows for the continuous-record stations was accomplished using multiple linear regression techniques. The basin characteristics mentioned previously, and the streamflow-variability and streamflow-recession indices were used as regressor variables in the analysis. Techniques are presented to estimate the $7Q_2$ and $7Q_{10}$ low flows at ungaged stream sites in Kentucky. Examples of the use of these techniques are also presented.

Background

Continuous-record gaging stations were first established by the USGS in Kentucky in the early 1900's. Currently (1991), the continuous-record gaging network in Kentucky includes approximately 115 stations. In the intervening time, numerous other continuous-record gaging stations have been operated and subsequently discontinued. Daily mean flows computed at 136 of these continuous-record stations were used in the determination of the $7Q_2$ and $7Q_{10}$ low flows. These stations had unregulated streamflow record for 10 or more years. Streamflow records for stations with less than 10 years of unregulated, continuous record were correlated with streamflow records from one or more of the 136 stations to obtain estimates of the $7Q_2$ and $7Q_{10}$ low flows. These sites were treated as partial-record gaging stations and are included in the 212 stations.

Partial-record gaging stations are stream sites located throughout the State where periodic streamflow measurements were made. The measured streamflow values were correlated with the concurrent daily mean flows at nearby continuous-record gaging stations to estimate selected low-flow frequency values at the partial-record station. This network of partial-record stations provided greater spatial coverage of low-flow information. Streamflow measurements were made at a few stations in the late 1940's, but a more concerted effort was made during a drought episode in the early 1950's. In the 1960's and early 1970's, additional measurements were made at these same stations and at other stations. When sufficient information was obtained at a station to estimate low-flow frequency values through correlation with a continuous-record station (usually 8 to 12 measurements), measurements were discontinued at the station and a new station was established elsewhere. This process continued until the early 1980's when the low-flow program was discontinued.

In 1987 and 1988, a limited amount of data was collected at selected partial-record stations operated in the early 1980's to verify existing correlations. Approximately 80 new low-flow partial-record stations also were established in 1988 and measurements continue to be collected at these sites. Additionally, 12 new or discontinued continuous-record stations have been either established or reactivated (1989), through a cooperative effort with the KNREPC. These stations augment the existing continuous-record gaging network used for low-flow information. Because the amount of data collected at the new stations (80 partial-record and 12 continuous-record) is limited, the data could not be incorporated into the analysis described in this report.

Previous Studies

Several reports documenting low-flow characteristics of Kentucky streams have been published. These include a report by Speer and others (1965) which describes low-flow characteristics of streams in the Mississippi Embayment. Swisshelm (1974) reported the $7Q_{10}$ low flow at 85 continuous-record and 49 partial-record gaging stations.

Information from Swisshelm (1974) was incorporated into two reports by Sullavan (1980 and 1984). The report by Sullavan (1984) contained the $7Q_2$ and $7Q_{10}$ low flows for 84 continuous-record and 203 partial-record stations in Kentucky. The report by Melcher and Ruhl (1984) is the most recent publication describing low-flow characteristics for Kentucky streams. It incorporated the information contained in Sullavan (1984) plus selected frequency values at approximately 71 additional continuous-record stations including stations with only five or more years of record.

This report updates the values contained in Melcher and Ruhl (1984) for selected low-flow frequencies based on additional information collected at the continuous-record stations and at selected low-flow partial-record stations.

Because data from the partial-record stations are correlated with data from the continuous-record stations, changes in the frequency values at the partial-record stations may also occur. Such changes are generally small. The updated values for both the continuous- and partial-record stations are included in this report.

Physiography and Geology

The physiography of the State reflects the lithology of the surface rocks in the State and is largely defined by the Cincinnati arch (fig. 1). The axis of the Cincinnati arch trends north and slightly east from south-central Kentucky to just south of the Inner and Outer Bluegrass boundary where it divides into two branches. The branches are approximately parallel but are separated by approximately 25 mi at the Ohio River (McFarland, 1950).

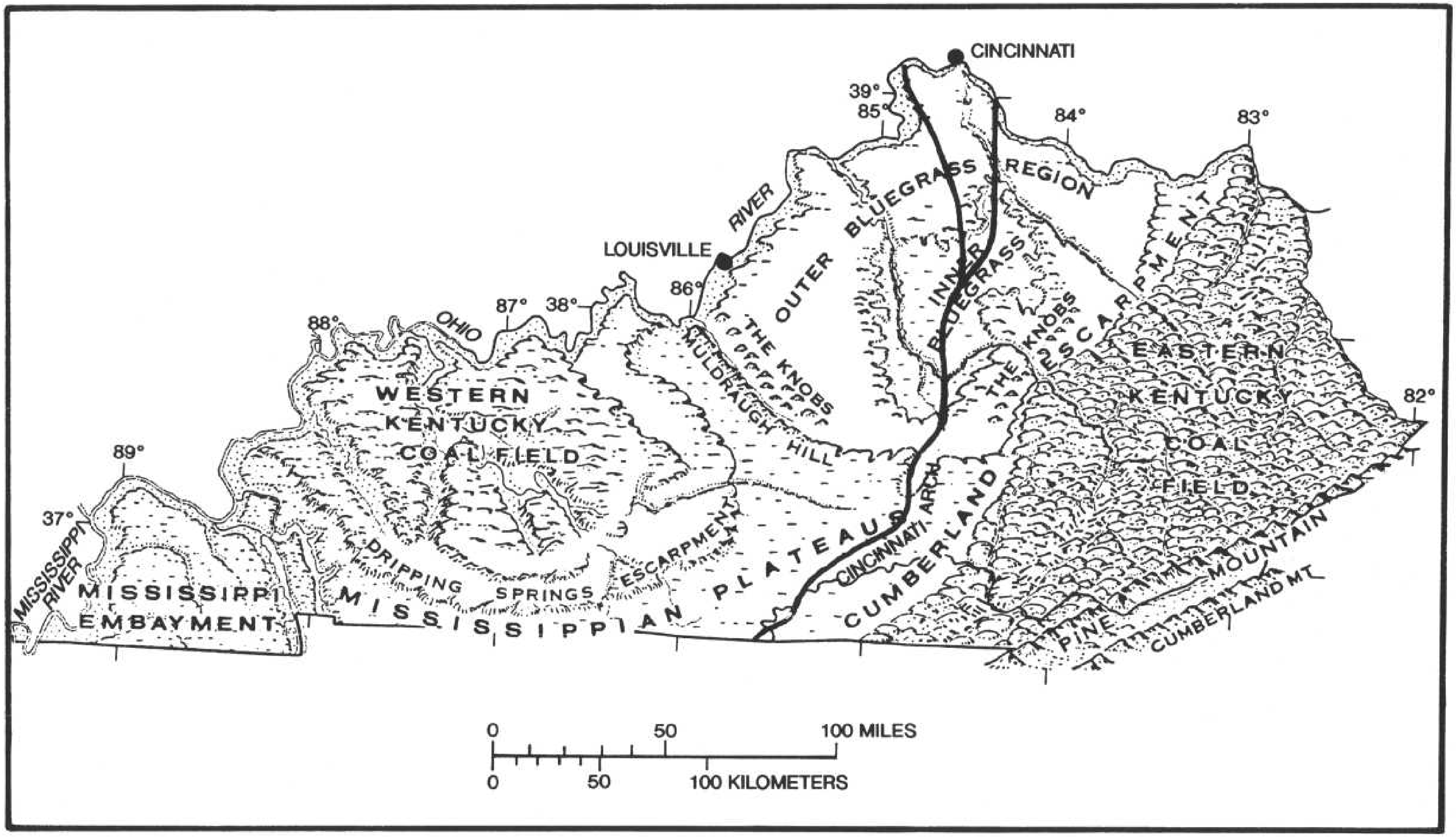
East and west from the Cincinnati arch, progressively younger rocks are exposed at the surface. The oldest exposed rocks are part of the Jessamine Dome and the areas adjacent to it. The location of this area corresponds approximately to the Inner Bluegrass region (fig. 1). These rocks consist of limestone, shale, and sandstone of Ordovician age. Narrow bands of shales and limestones of Silurian and Devonian age surround this area and correspond to the Outer Bluegrass region. An expansive area of limestone of Mississippian age (Mississippian Plateaus Region) is exposed starting at the Ohio River in northeastern Kentucky and extending southwest to the State boundary and northwest in a crescent-shaped area surrounding the Western Coal Field. The eastern boundary of this area is the Cumberland Escarpment (fig. 1). The youngest rocks are sandstones, shales, siltstones, and coals of Pennsylvanian age in eastern and northwestern Kentucky and correspond to the Eastern and Western Kentucky Coal Fields. Alluvial deposits of Cretaceous and Tertiary age occur in extreme western Kentucky in the Mississippi Embayment.

Much of the Mississippian Plateau is characterized by karst features such as sinkholes, caves, springs, and gaining and losing streams. The distribution of these features is shown in figure 2. Most well-developed karst features are located in a band originating in west-central Kentucky and extending to south-central Kentucky, southeast to the State boundary, east along the boundary, and then northeast and north (areas shown in black in figure 2). Less well-developed karst features are in central and south-central Kentucky. The streams in karst areas are characterized by sustained base flow throughout dry periods.

Climate

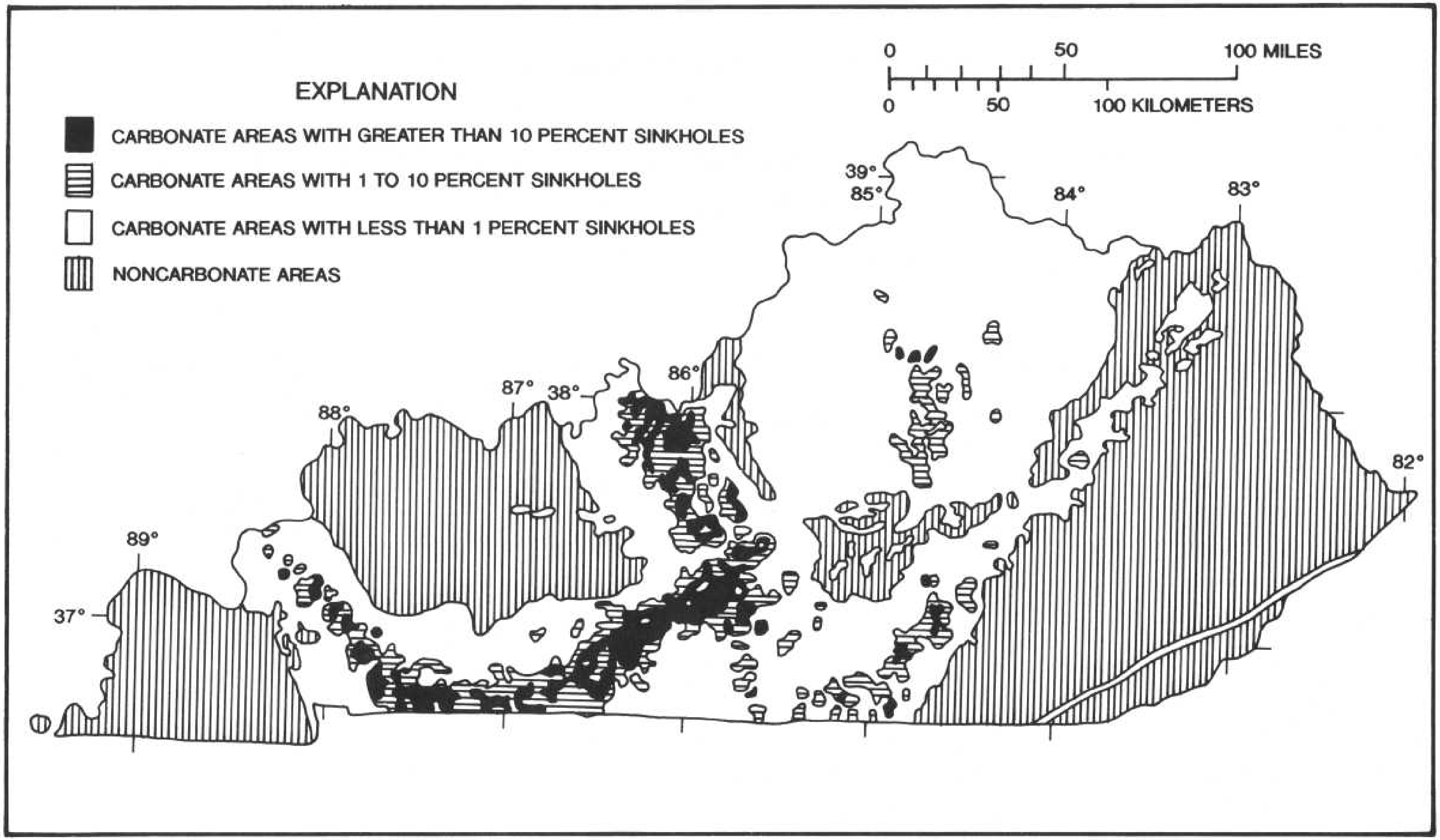
The mean annual precipitation in Kentucky ranges from about 41 to 53 in. (Conner, 1982). Rainfall generally decreases to the north, reflecting the increase in distance from the source of precipitation, which is mostly the Gulf of Mexico.

Kentucky's dry season occurs during the fall and October is the driest month. The Bermuda High, which normally resides off the coast of the southeastern United States during summer, moves inland in the fall. In



From Kentucky Geological Survey, 1980

Figure 1.--Physiographic regions in Kentucky.



From Crawford and Webster, 1986

Figure 2.--Generalized carbonate areas and surficial karst development in Kentucky.

October, the normal position of the Bermuda High is over Kentucky and Tennessee. The High retards convective activity and may deflect frontal movements away from Kentucky (Conner, 1982). As a result, streamflow depends primarily on the discharge of ground water during most of late summer and early fall.

SELECTED STREAMFLOW CHARACTERISTICS

Low-Flow Frequency

Low-flow frequency analyses are usually performed using an annual series of selected low-flow statistics, usually the lowest mean discharge for some number of consecutive days. The annual series for the determinations in this report was based on a year from April 1 to March 31. The use of this time period allowed for an analysis of an uninterrupted low-flow period. The statistic used for this study was the 7-day low flow (7Q), which is the lowest mean discharge for 7 consecutive days in a year, from April 1 through March 31.

Frequency curves were developed from this statistic, but only for the period of unregulated streamflow record for each of the continuous-record gaging stations having 10 or more years of unregulated record. Flow data collected after regulation were not used. Values for selected recurrence intervals were obtained from a frequency analysis which attempts to fit the data to a particular distribution, and were compared to values obtained from a frequency curve developed from the station data. The frequency values used in this report are the $7Q_2$ and $7Q_{10}$ low flows. These values are commonly expressed as the minimum 7-day mean discharge with an average recurrence interval of 2 and 10 years, respectively. These values are more correctly expressed as the lowest mean discharge for 7 consecutive days having a 50- and 10-percent chance, respectively, of not being exceeded in any year.

Selected low-flow frequency values were estimated at additional stream sites to provide greater spatial coverage of low-flow information. Approximately 8 to 12 streamflow measurements were made at each site during base-flow conditions. The measured streamflows for each of these sites were then correlated with concurrent daily mean streamflows from nearby continuous-record gaging stations. Estimates of selected low-flow frequency values were made at these sites based on this correlation (Riggs, 1972).

Continuous-Record Gaging Stations

Selected low-flow frequency values were determined for the period of unregulated streamflow record through 1987 at 136 continuous-record gaging stations shown in plate 1. These included the $7Q_2$ and $7Q_{10}$ low flows for the unregulated period of record at stations having 10 or more years of unregulated streamflow record. The values shown in table 1 (at the back of the report) update those values given in previous publications by Swisshelm (1974), Sullavan (1980 and 1984), and Melcher and Ruhl (1984). Additional streamflow data and the development of new analytical techniques made it necessary to update the frequency values.

Each continuous-record gaging station was first screened to determine if the station was regulated and to determine the period of unregulated record (Melcher and Ruhl, 1984). Many continuous-record gaging stations are affected by reservoir regulation, which has the affect of reducing high flows and augmenting low flows. Those stations with 10 years or more of unregulated record were retained for subsequent analysis. Values of 7Q for each year of unregulated record from April 1 to March 31 were computed using standard methods (Hutchinson, 1975; Meeks, 1983). A time series plot of these values was constructed for each station, an example of which is shown in figure 3.

Kendall's Tau, a statistic to indicate a monotonic increasing or decreasing trend in a time series, was computed for the period of record at each station using Statistical Analysis System (SAS) programs (Statistical Analysis System, 1982). At many sites, the Kendall's Tau analysis indicated that a trend did exist. If the trend resulted from changes in the watershed or human activities, the data would need to be detrended, or, possibly, only a part of the record would be used in the frequency analysis. Upon review of the plots of the 7Q with time, however, a consistent increasing pattern became apparent at many of the stations. The trend was deemed to be climatic in nature and not induced by changes within the watershed. The trend is illustrated in figure 3. The mid-1950's were characterized by many low values of 7Q, followed by another such period in the early 1960's. These periods coincide with droughts that occurred over much of the State. Starting in the late 1960's and continuing throughout the 1970's, a substantial increase in 7Q occurred and the 7Q finally decreased in the early 1980's. The substantial increase in 7Q in the 1970's, as shown in figure 3, is indicated on most of the station plots and is the source of the positive trend in most cases.

Even though no published time-series plots of annual or monthly precipitation data were available, some plots of annual precipitation were obtained from the State Climatologist's Office (Conner, written commun., 1990) which indicated increased precipitation concurrent to the periods shown in figure 3. Additionally, for the period 1951-80 (Conner, 1982), it is stated that in 1979 the maximum annual total precipitation was recorded at 41 of 73 precipitation stations in Kentucky, and the year 1972 produced 12 record highs. Other years that produced record high precipitation at one or more recording stations were 1951, 1956, 1957, 1962, 1973, 1975, 1977, and 1978. The years that these annual highs occurred coincide closely with annual high values of 7Q, as shown in figure 3. Because of the wide variability in flow conditions and the apparent absence of trend because of changes in watershed conditions, the entire period of streamflow record was used to develop the low-flow frequency curves at each station without prior adjustment for climatic trend.

The frequency curves were developed assuming a Pearson Type III distribution with log transformation (log-Pearson Type III) of the 7Q data (Meeks, 1983). While the graphical curve is considered the basic curve for annual low flows, Riggs (1972) recommends that the log Pearson Type III curve be used if it is adequate. The graphical and log Pearson Type III curves were plotted and overlain for comparison, and the log Pearson Type III curve was considered adequate for each of the 136 continuous-record stations, and no adjustments were made.

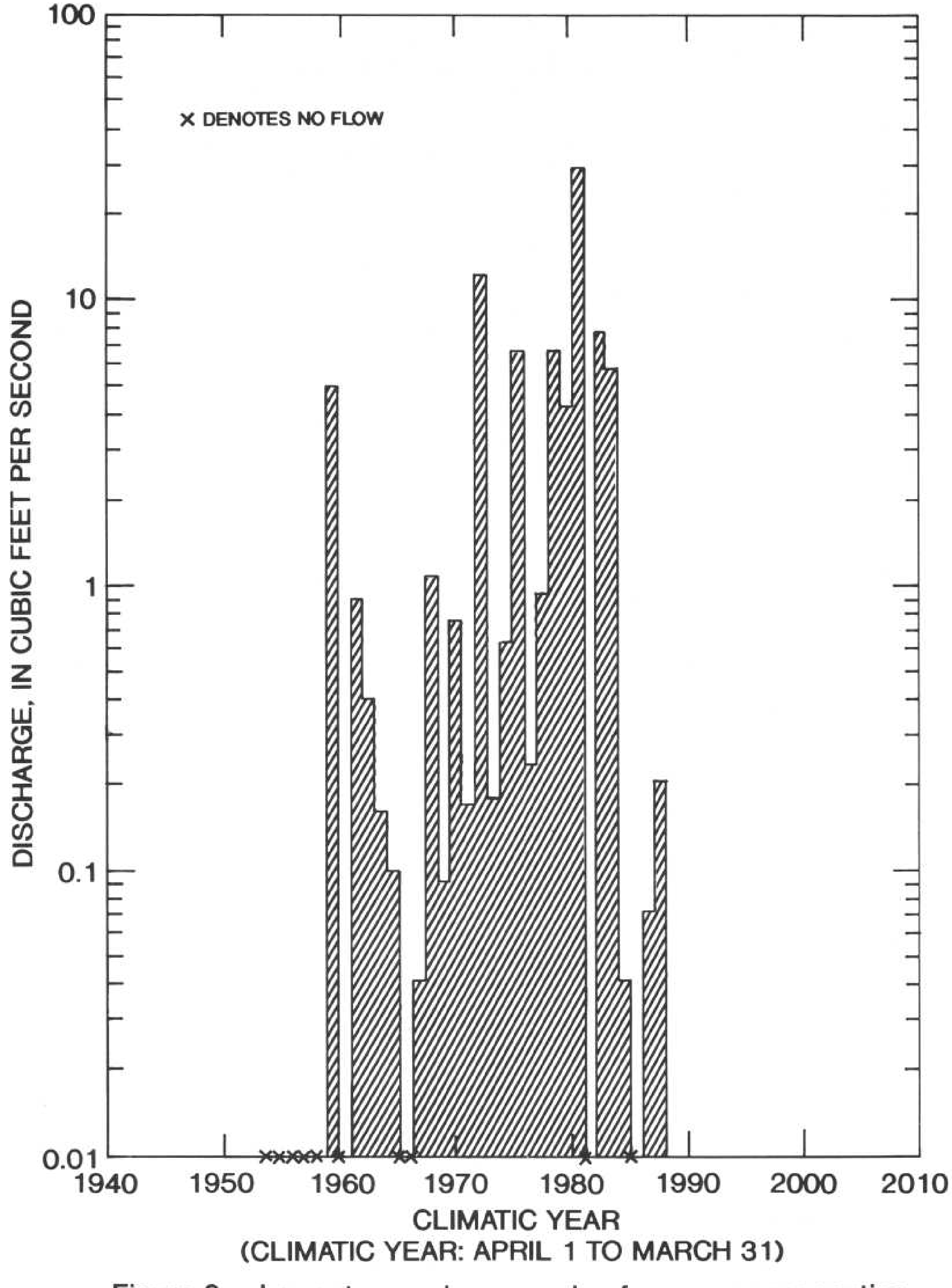


Figure 3.--Lowest annual mean value for seven consecutive days for years ending March 31, 1953-87, for Buck Creek near Shopville, Kentucky.

The log-Pearson Type III analysis uses the following relation:

$$X_T = \bar{X} + KS, \qquad (1)$$

where X_T is the T-year low flow in logarithms, $\bar{X}$ and S are the mean and standard deviation, respectively, of the annual low flows, and K is a frequency factor that is a function of skewness and recurrence interval. These factor values were obtained from Bulletin 17B (Interagency Advisory Committee on Water Data, 1982). Frequency factors are generally tabulated for use in defining a frequency curve of events having values equal to or greater than the one indicated (flood frequency analysis), but a low-flow frequency curve defines the recurrence intervals for events less than the one indicated.

Frequency curves for two of the continuous-record gaging stations are shown in figure 4. The curve for Nolin River at White Mills, Kentucky (237 mi^2) indicated a sustained base-flow even during dry periods. The station is located in the karst area of the Mississippian Plateaus physiographic region of north-central Kentucky. Conversely, the curve for Troublesome Creek at Noble, Kentucky (177 mi^2) indicated limited sustained base-flow as shown by the negative sloping curve. This site is located in the Eastern Coal Field physiographic region in southeastern Kentucky.

Many hydrologic time-series data tend to be serially correlated--that is, the current value of an attribute tends to be close in magnitude and direction to those values that immediately precede it. A technique by Tasker and Gilroy (1982) was used to increase the standard deviation of the annual events to account for this serial correlation at the continuous-record gaging stations used in the study. Unfortunately, the method could not be directly applied to stations having a $7Q_2$ or $7Q_{10}$ of zero (of which Kentucky has many), because the mean and standard deviation are computed from the logarithmic transformations of the 7Q values. The correction was determined for all other sites, with most corrections ranging between 2 to 5 percent, and some corrections being as much as 8 percent. Because the method could not be applied directly to all stations, and the results indicated little change to the computed values, no corrections were made to the low-flow frequency values for serial correlation.

As mentioned previously, plots of the annual 7-day low-flow values with respect to time indicated climate trends in the data. If no adjustment was made to the frequency analysis, the values would be biased because of flow conditions during the short time period in which they were collected. For example, a station established in the late 1960's and operated through the 1970's and early 1980's would have approximately 15 years of record. But the values from the frequency analysis would be high, or upwardly biased, compared to stations having longer periods of record because of the increased flow during the late 1960's and throughout the 1970's. This also would bias results of any partial-record station correlated with this continuous-record station. Although the correlation between the continuous-record and the partial-record station may be good, the frequency values estimated at the partial-record station would be higher than the actual value as a result of the increased frequency value at the continuous-record station. Subsequently,

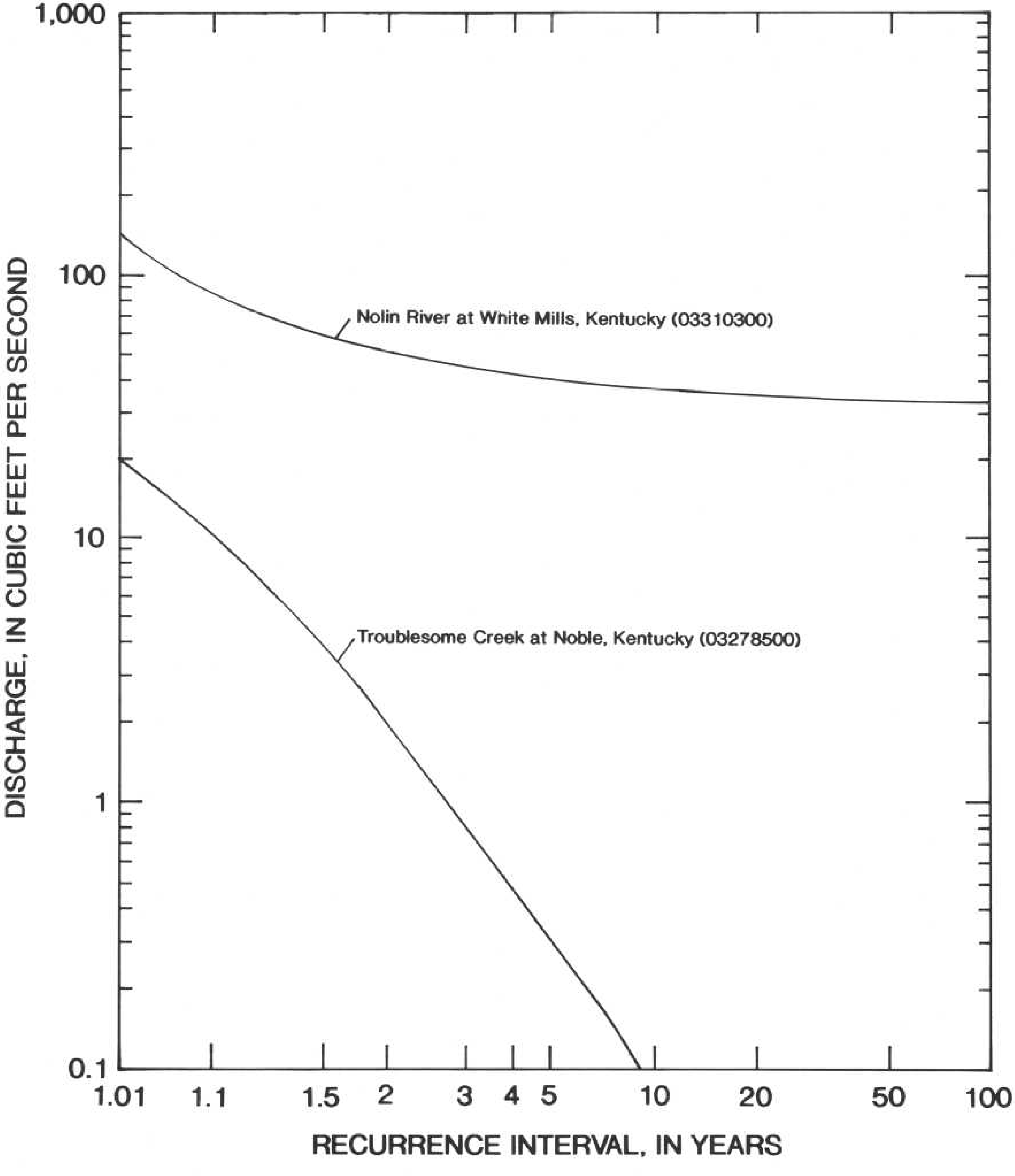


Figure 4.--Frequency curves of annual 7-day low flows for Nolin River at White Mills and Troublesome Creek at Noble, Kentucky.

regional analysis using either the continuous-record station values or both the continuous- and partial-record station values would also be biased.

Continuous-record gaging stations with less than 25 years of unregulated record (short-term stations) were correlated with the concurrent period of record for stations having 25 years or more of unregulated record (long-term stations) to adjust the frequency analysis for the climatic trend. The correlations were performed using the SAS programs (Statistical Analysis System, 1982). Using techniques outlined by Stedinger and Thomas (1985), an adjusted mean and standard deviation were obtained for the short-term station. These values were used with the station skew of the long-term station to obtain an adjusted value for selected recurrence intervals (eqn. 1). Factor values, which are a function of the skew coefficient and selected recurrence intervals, were obtained from Bulletin 17B (Interagency Advisory Committee on Water Data, 1982). Stations with a 7-day 10-year low-flow value of zero were not correlated to long-term sites. The main stem Rough River stations were correlated with Rough River near Madrid, Kentucky (03317000), which has only 20 years of continuous record. The correlation smoothed out the frequency values at the downstream main stem stations.

The frequency values at the continuous-record gaging stations are listed in table 1. Frequency values in the table for stations currently affected by regulation were for the unregulated period only, except for the Kentucky River stations at Locks 2, 4, and 6. These stations were established after the construction of Herrington Lake in 1925. For informational purposes, frequency analysis was performed for these three sites, and the entire period of record was used. Frequency values for Kentucky River stations at Lock 10 and 14 used streamflow record up to 1960, which reflected the unregulated period of record. Even though Martins Fork Lake in southeastern Kentucky had an effect on low flows at the main stem Cumberland River gaging stations, the effect of regulation was probably not significant. Therefore, the entire period of record was used in the frequency analysis for the main stem Cumberland River stations. Frequency analysis for the main stem Ohio River gaging stations was not performed because of the significant effects of regulation, which had continually increased with time throughout the basin. Stations with flows affected by local diversion, and the source of the diversion, are also noted in table 1. It is not possible to assess the degree to which these local diversions affect low flows, therefore data from these stations were not used in the regression analysis in this report, but are presented for informational purposes.

Partial-Record Gaging Stations

The $7Q_2$ and $7Q_{10}$ low flows were determined at 212 partial-record gaging stations for the study (pl. 2) and are given in table 2 at the back of the report. These values were determined through graphical correlation of streamflow records from nearby continuous-record gaging stations having similar basin characteristics and similar geology. Typically, 8 to 12 streamflow measurements were made during base flow conditions at the partial-record station, and these values were correlated with the concurrent daily mean streamflow values at one or more of the continuous-record stations (Riggs, 1972). A graphical relation was developed for the data set, with the most weight being given to points which defined that portion of the curve where the frequency estimate(s) was desired. From this relation, selected frequency values at the partial-record station were estimated using the corresponding frequency values for the continuous-record station. Information from measurements made at the partial-record stations were published in the annual compilation of surface water records for Kentucky (U.S. Geological Survey, 1962-65 and 1966-75) and in the USGS annual Water-data reports for Kentucky (1976-82, 1988).

An example of the graphical correlation technique is shown in figure 5. A line of relation was developed by graphical techniques using the measured flows at Valley Creek near Glendale, Kentucky, and the concurrent daily mean flows at Nolin River at White Mills, Kentucky (Riggs, 1972). More weight was given to points in the area of the desired low-flow frequency estimate or estimates. From frequency analysis, the $7Q_2$ and $7Q_{10}$ values at Nolin River at White Mills were 52 and 38 ft^3/s, respectively. First, locate these values on the abscissa, proceed upward to the line of relation, and then left to the ordinate to obtain estimated values of the $7Q_2$ and $7Q_{10}$ for the partial-record station. The estimated values for Valley Creek near Glendale were 11 and 7.5 ft^3/s, respectively.

These graphical relations were previously developed for most of the 212 partial-record stations listed in table 2, with the results published in Swisshelm (1974), Sullavan (1980 and 1984), and Melcher and Ruhl (1984). Therefore, the estimates of low-flow frequency values at most partial-record stations changed only as a result of a change in the values at the continuous-record station. Additional streamflow measurements or observations were available for some of the partial-record stations. Therefore, during the process of updating the frequency values at these stations, the existing graphical relation between the partial- and continuous-record stations was re-evaluated. Because of new information, some relations were modified, and 15 new graphical relations were developed for stations not previously published. These stations are included in table 2. Also included in the list of 212 partial-record stations are those continuous-record stations in Kentucky with less than 10 years of record. Daily mean flows at these sites were graphically related to daily mean flows at nearby continuous-record stations with more than 10 years of unregulated streamflow record.

Streamflow Indices

Base flow or low flow in a stream is governed by the amount and rate of ground water discharge, which is related to local geology. Although flow statistics are generally related to basin characteristics, basin characteristics usually do not adequately account for the spatial variability of low flows from one location to another. Other indices are available to account for this spatial variability, most of which relate to surface geology.

Two indices that have been useful in previous studies in quantifying the spatial variability of low-flow values are the streamflow-recession index (Bingham, 1985), and the streamflow-variability index (Friel and others, 1988). Values of these two indices were determined at each of the continuous-record stations used in this study and are given in table 1.

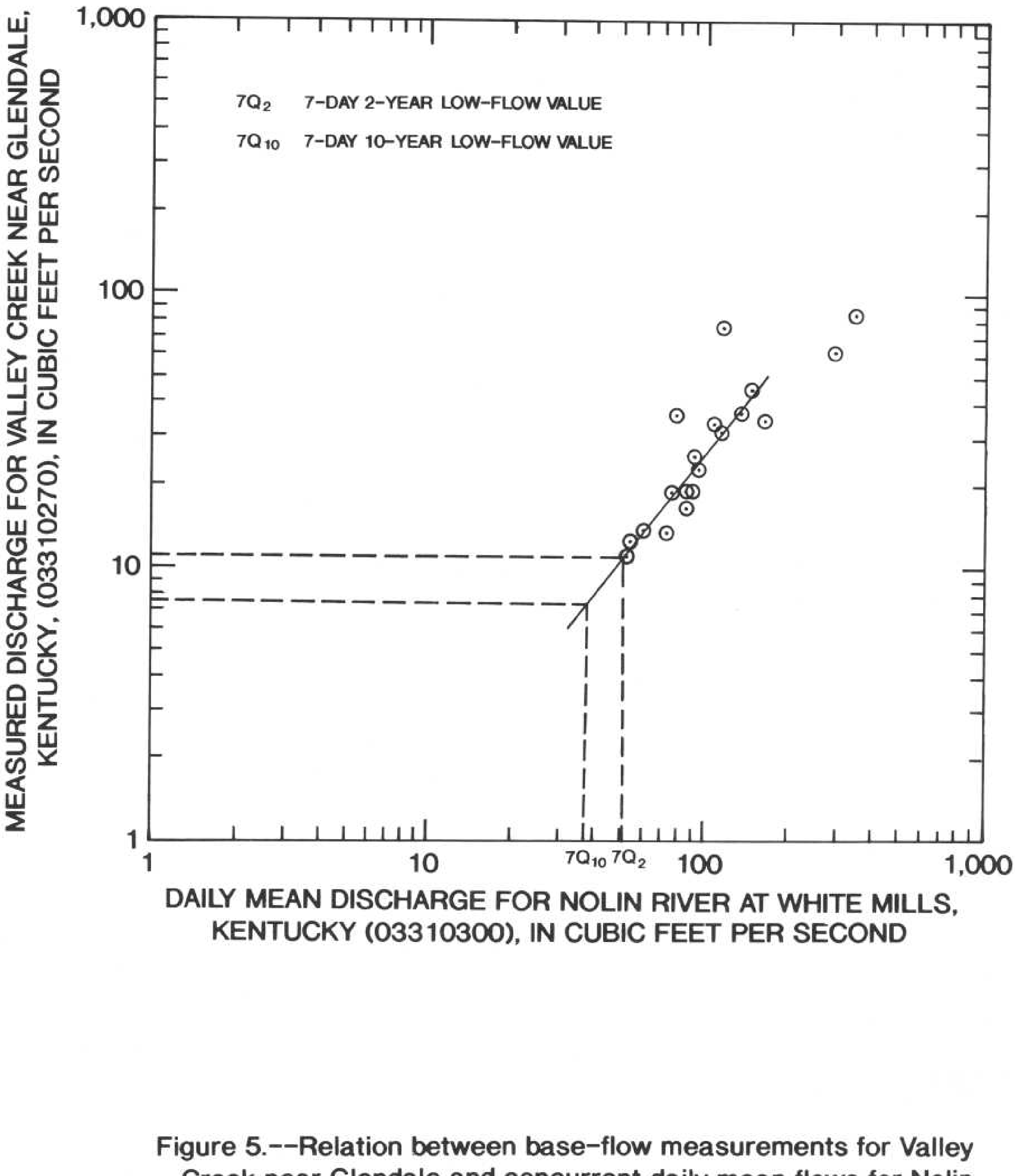


Figure 5.--Relation between base-flow measurements for Valley Creek near Glendale and concurrent daily mean flows for Nolin River at White Mills, Kentucky.

Streamflow-Recession Index

Streamflow recession is the decline in streamflow over time. When low-flow conditions exist, streamflow is normally provided by the ground-water discharge from adjacent aquifers. If low-flow conditions persist, the amount of ground-water discharge to the stream decreases as the aquifer is depleted. The streamflow recession is a measure of the decrease in streamflow (and therefore groundwater discharge) with respect to time. The streamflow-recession index is a function of the storage coefficient and transmissivity of the aquifer. However, for this report the recession index values were determined graphically from hydrograph plots of daily mean streamflows (Riggs, 1964). The value is defined as the number of days for the recession curve to proceed through a complete log cycle of the hydrograph and is expressed as days per log cycle. Areas of similar geologic settings could be expected to exhibit similar streamflow recession patterns, thus providing a means to regionalize low flow based on the geology of a particular drainage basin.

Annual hydrographs of unregulated daily mean streamflows for each continuous-record gaging station were reviewed to identify periods of base-flow recession. For hydrographs plotted on semi-logarithmic paper with streamflow on the logarithmic scale and time on the arithmetic scale, the base flow recession curve will approximate a straight line. As presented by Bingham (1985), the recession index is defined as the number of days it takes base streamflow to decrease one log cycle (one order of magnitude). For each station hydrograph selected, a line was drawn parallel to the identified base flow recession curve(s), and a value of recession index determined. Generally, three to seven annual hydrographs that included one or more well-defined recessions over the available period of record were used at each station to define the recession index. The recession index determined for each station may represent the combined effects of many different aquifers.

Use of streamflow-recession curves occurring during winter months are preferred because the effects of evaporation and evapotranspiration are minimized. However, frequent precipitation and occasional freezing often interrupt the development of a sustained recession during this period, thus limiting the number of suitable recession periods. As a result, some of the index values were determined also using recession curves developed during summer periods. The estimated recession index values for the continuous-record gaging stations are shown in table 1. Values ranged from 11 to 64 days per log cycle. The highest values were at stations located in karst regions of the State where sustained high base flows occur, but the lowest values were not confined to one specific area or geologic type and occurred at stations throughout the State.

Streamflow-Variability Index

The streamflow-variability index is an indicator of a basin's capacity to sustain base flow in a stream. The variability index is defined as the standard deviation of the logarithms of the stream discharge at selected percentiles on the flow duration curve (Lane and Lei, 1950). As with the recession index, areas of similar surface geology could be expected to correspond to similar variability index values. This would provide a means of regionalizing low flows based on geology.

The flow-duration curve is a cumulative-frequency curve that indicates the percentage of time that a given stream discharge is equaled or exceeded. The curve is developed using mean flow values over a specific time interval (daily, weekly, or monthly), either on a calendar year basis or for the total period of record (Searcy, 1959). For this study, the flow-duration curves were constructed from daily mean discharges for the entire period of unregulated record. Twenty to thirty class intervals were delineated which provided for a uniform distribution of points for the range in discharge encountered. Normally, the curves are plotted on logarithmic probability paper. The logarithmic transformed values of discharge tend to be more normally distributed than the untransformed values and usually tend to plot as a straight line. The flow-duration curves for Nolin River at White Mills and Troublesome Creek at Noble, Kentucky, are shown in figure 6. The slope of the curve for the Nolin River station was flatter than that for the Troublesome Creek curve, indicating that the base flow component at the Nolin River station was more sustained than that at the Troublesome Creek station. The streamflow-variability index was a means of quantifying this difference.

The streamflow variability was determined by first obtaining the discharges at 5-percent class intervals from 5 to 95 percent of the flow-duration curve. The standard deviation was then computed using the logarithms of each of these 19 values (Dempster, 1990). The values of variability index for the continuous-record gaging stations are in table 1 and ranged from 0.368 for Bacon Creek at Priceville to 1.502 for Obion Creek at Pryorsburg, Kentucky. The values of variability index for the stations shown in figure 6 were 0.438 for Nolin River at White Mills and 0.745 for Troublesome Creek at Noble, Kentucky. These values quantified the variability of the individual daily mean discharges relative to the mean of all discharges for the period of record. As with the recession index, the variability index for a station may represent the integrated affects of many different aquifers.

No attempt was made to adjust flow-duration curves developed from short-term records with those developed from long-term records. Because a flow-duration curve is a cumulative frequency curve based on all daily mean flows, a limited number of years of record can produce a curve representative of a long-term record. The relation is also less sensitive to extreme values because of the use of class intervals, and because the curve is not fitted to a particular distribution as are the low-flow frequency curves used to estimate values of the $7Q_2$ and $7Q_{10}$.

SELECTED BASIN CHARACTERISTICS

Flow characteristics, such as low flows, are commonly related to basin characteristics. As previously mentioned, selected basin characteristics were determined at each of the continuous- and partial-record gaging stations for use in the study. These included total and contributing drainage area; main channel length, slope, and elevation; basin length and shape; and mean annual precipitation. Most values for these parameters had been previously

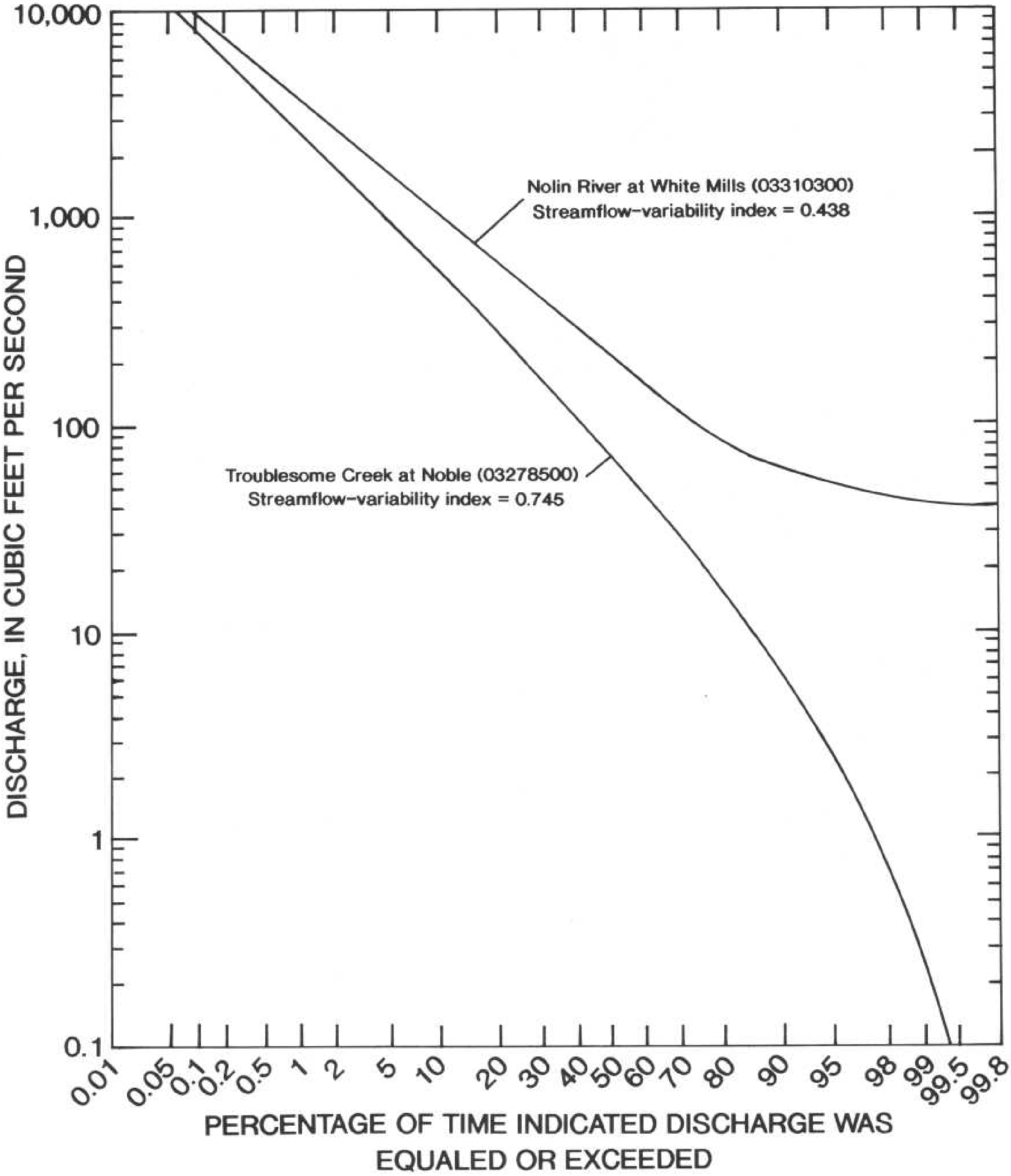


Figure 6.--Flow duration curves for Nolin River at White Mills and Troublesome Creek at Noble, Kentucky.

determined and were obtained from the basin and streamflow characteristics file of the National Water Data Storage and Retrieval System (Dempster, 1983). Values of basin characteristics that were not available from that source were determined from U.S. Geological Survey 7.5-minute topographic maps. Values of mean annual precipitation were determined from Conner (1982). Selected basin and streamflow characteristics for the continuous- and partial-record stations are in tables 1 and 2, respectively. Additional basin characteristics for most of these sites are given by Melcher and Ruhl (1984).

Basin characteristics tested for significance in the regression analysis are as follows:

1. Total drainage area, in square miles, is the area measured in a horizontal plane that is enclosed by a drainage divide.

2. Contributing drainage area, in square miles, is the total drainage area excluding any parts characterized by internal drainage.

3. Main channel length, in miles, is the length measured along the main stream channel from the gage to the basin divide, following the longest tributary.

4. Main channel slope, in feet per mile, is the ratio of the difference in elevation between points located at 10 and 85 percent of the main channel length from the gage, and the stream length between these two points.

5. Main channel elevation, in feet, is the average of the elevations determined at points located at 10 and 85 percent of the main channel length from the gage to the basin divide.

6. Basin length, in miles, is the straight line distance from the gage to the basin divide (defined by the main channel length).

7. Basin shape index is the ratio of the basin length squared to the total drainage area.

8. Mean annual precipitation, in inches, is estimated from Conner (1982).

DEVELOPMENT OF ESTIMATING EQUATIONS

Multiple linear regression was used to develop the equations to estimate the $7Q_2$ and $7Q_{10}$ low flows at ungaged stream sites. To develop these equations, the low-flow frequency values were related to a number of basin characteristics and streamflow indices. Included in the analysis were continuous-record gaging stations with 10 or more years of unregulated streamflow record, total drainage areas less than 1,500 mi^2, and flows not subject to local diversion. Graphical plots of selected basin characteristics and streamflow indices with the low-flow values indicated that logarithmic transformation of the variables would be appropriate. A coefficient of determination analysis was performed with combinations of up to six variables using SAS to determine those models having the highest coefficient. Models which produced the highest coefficient of determination were then developed and evaluated separately. A number of stations had zero values of the 7-day 2- or 10-year low flow, and could not be included in the analyses which used logarithmic transformed values. Because many of the continuous-record stations in Kentucky have zero values of the $7Q_2$ and $7Q_{10}$ low flows, the number of stations available for use in the regression analysis using logarithmic transformed values was limited. The $7Q_2$ and $7Q_{10}$ low flows were used as the response variables in the analysis. The regressor variables included basin characteristics such as total drainage area; main channel length and slope; basin length and shape; and mean annual precipitation. Also included as regressor variables in the analysis were the streamflow-recession and streamflow-variability indices.

For the initial regression analysis, the basin characteristics and the station values of streamflow recession and variability were used. The most statistically significant models to estimate both the $7Q_2$ and $7Q_{10}$ low flows included the logarithmic transformed values of both drainage area (total) and streamflow variability. Values of streamflow variability were then mapped for the State. Even though gaging stations with either a $7Q_2$ or $7Q_{10}$ of zero were not included in the regression analysis, the value of streamflow variability for these stations was used to aid in the mapping of the variability index boundaries. A geologic map of Kentucky at a 1:250,000 scale (McDowell and others, 1981) was also used to help define the boundaries. Also available was a map showing the station location, the station streamflow-variability index, and the approximate basin drainage. These maps were used to assign a variability index value to areas of similar surface geology. The results of the mapping effort are shown in plate 1. The categories of variability index resulting from the mapping were 0.45, 0.50, 0.55, 0.60, 0.65, 0.70, 0.80, 0.85, 0.90, 1.15, 1.25, and 1.35.

For some locations, the geologic map at the 1:250,000 scale did not provide sufficient detail to delineate certain variability index boundaries. At these locations, USGS 7.5-minute geologic quadrangle maps were used to provide a more detailed delineation on the basis of surficial geology. One such area was the Inner Bluegrass region where most of the region was assigned a value of 0.85, but the northwestern section was assigned a value of 0.70 (fig. 1 and pl. 1). Streamflow variability for the gaging stations in the two areas indicated a difference and the geologic quadrangle maps for the area were examined. From inspection of the maps, the larger area (0.85 variability index) corresponded to the Frier Limestone and also to the Tanglewood and Clays Ferry Limestone. The northwestern area (0.70 variability index) corresponded mostly to the Grier Limestone. Therefore these two areas were assigned separate index values. In west-central Kentucky, the area defined by 0.45 variability index (pl. 1) consisted of slumped shale, sandstones, and conglomerate mixed with residual soil from weathered limestone. From nearby gaging station information, rocks in this area had greater water-bearing capacity than the surrounding rocks of the Ste. Genevieve Limestone and St. Louis Limestone and were, therefore, assigned a value lower than 0.55. Station records also indicated that a 0.45 value of variability index was warranted in the south-central area of the State underlain by the Cumberland Formation and the Louisville Limestone. After a review of geologic quadrangle maps for the Mississippi Embayment (fig. 1 and pl. 1) in conjunction with gaging-station information, areas containing mostly loess were assigned a streamflow-variability index of 0.50, whereas those consisting mostly of sand, gravel, and clay were assigned values of 0.60 or 0.70. In the report by Bingham (1985), which describes low-flow characteristics for Tennessee streams, separate estimating equations were developed for the Mississippi Embayment. However, for this study, adequate streamflow information was not available to make such a determination or to produce a separate set of estimating equations.

Subsequent regression analyses used the mapped values of streamflow variability and selected basin characteristics. The best equations for estimating the $7Q_2$ and $7Q_{10}$ low flows again contained the logarithmic transformed values of both the drainage area and the streamflow-variability index.

Estimating Equations

The estimating equations developed for the $7Q_2$ and $7Q_{10}$ were based on multiple linear regression analysis using records from 79 and 52 continuous-record gaging stations, respectively. This method assumes that the regressor and predictor variables fit a linear regression model. The best three models for estimating the two recurrence intervals contained the logarithms of the streamflow-variability index as a regressor variable. The best three models for both recurrence intervals, in order of predictive power, contained the logarithms of the streamflow-variability index and the logarithms of (1) drainage area, (2) main channel length, and (3) basin length, respectively. When additional attributes were included in these models, they were insignificant at the 0.05 level. Also, the variance inflation factor ranged from 15 to 20 for these models, indicating a high degree of multicolinearity. The variance inflation factor is a measure of the effect of the dependencies among the regressors on the variance of the terms (Montgomery and Peck, 1982). Because of the limited number of gaging stations available for the analysis, 10 partial-record stations were included. These stations all had positive values of $7Q_2$ and $7Q_{10}$, were distributed spatially throughout the State, and were typical in drainage area size of most of the partial-record stations (38 to 126 mi^2). This number of sites was chosen to provide additional information for the analysis, while still giving the most emphasis in the analysis to the values developed from the continuous-record stations.

The best estimating equations resulting from the multiple linear regression analyses using the logarithmic transformed data are

$$7Q_2 = 0.00235\ A^{1.05}\ V^{-5.62} \qquad (2)$$

and

$$7Q_{10} = 0.000498\ A^{0.967}\ V^{-7.86}, \qquad (3)$$

where $7Q_2$ and $7Q_{10}$ are the 7-day 2- and 10-year recurrence interval values, respectively, in cubic feet per second; A is the total drainage area, in square miles; and V is the streamflow-variability index. The assumption is made that the predictor and regressor variables fit a linear regression model. Equation 2 has a coefficient of determination of 0.92 and a standard error of estimate of 71 percent. Equation 3 has a coefficient of determination of 0.86

and a standard error of estimate of 90 percent. The coefficient of determination is a measure of the linearity of a relation on a scale from 0 to 1.00 (Montgomery and Peck, 1982). The standard error is a measure of the predictive power of the model and was determined using the root-mean-square error from the model output and information from Tasker (1978). All variables were significant to the 0.01 level in both models. The residual plots for equations 2 and 3 indicated no drastic changes in variance throughout the range of values of the regressor variables used in the analysis.

The values of $7Q_2$ and $7Q_{10}$ are sensitive to the value of variability index because the exponent of the variability index term in both models is high. Other models were developed using the logarithmic transformed values of drainage area and the untransformed values of streamflow-variability index. These models would have decreased the sensitivity to variability index, but these models were not as powerful in predictive capability as equations 2 and 3 and were, therefore, not used.

The estimating equations should be used only for sites having drainage areas within the range of those available to develop the relations. For equation 2, the total drainage area values ranged from 0.67 to 1,299 mi^2. The distribution of drainage areas used to develop equation 2 are shown by size in the following table.

Range in drainage area (mi^2)	Number of stations in analysis
< 25	13
26-50	9
51-100	18
101-250	18
251-500	12
501-1,000	15
1,001-1,500	4
	89

Caution should be exercised when using equation 2 for small drainage areas. Only 2 stations had drainage areas less than 2.5 mi^2, and 6 stations had drainage areas less than 10 mi^2.

For equation 3, the drainage area values ranged from 0.85 to 1,299 mi^2. The distribution of total drainage areas by size used to develop equation 3 are shown in the following table.

Range in drainage area (mi^2)	Number of station in analysis
< 25	5
26-50	5
51-100	12
101-250	12
251-500	10
501-1,000	15
1,001-1,500	3
	62

Again, caution should be exercised when using equation 3 for very small drainage areas. Only 1 station had a drainage area less than 3.5 mi^2, and only 3 stations had drainage areas less than 10 mi^2.

The solution to equations 2 and 3 can also be determined graphically. Figure 7 is the graphical presentation of equation 2 and figure 8 is the graphical presentation of equation 3.

Limitations and Accuracy

The techniques presented in this report can be used to estimate the $7Q_2$ and $7Q_{10}$ values at ungaged stream sites in Kentucky not subject to regulation or significantly affected by local diversion. These equations were developed from stations having measured attribute values within a certain range and are not recommended for use if the stream site has attribute values outside that range. The equations developed to estimate the $7Q_2$ and $7Q_{10}$ low flows were based on stations with total drainage areas ranging from 0.67 to 1,299 mi^2, and 0.85 to 1,299 mi^2, respectively. Caution should be used in estimating the $7Q_2$ and $7Q_{10}$ low flows at sites with drainage areas less than about 3 or greater than about 1,500 mi^2.

Because the estimating equations were developed from the logarithmic transformed data, a value of zero cannot be computed directly. However, a value for $7Q_2$ or $7Q_{10}$ of 0.05 ft^3/s or less computed using these equations should be considered zero. As indicated in figure 8, the $7Q_{10}$ at sites with drainage areas less than 3 mi^2 should be considered zero except in variability index areas of either 0.45, 0.50, or 0.55 (pl. 1). These areas are characterized by karst features (fig. 2). Low-flow values for sites in these areas with drainage areas less than 3 mi^2 should be determined by collecting streamflow information at the desired location.

The $7Q_{10}$ for sites with drainage areas less than 600 mi^2 that are contained entirely within streamflow-variability-index areas with values of 1.25 or 1.35, should be considered zero (pl. 1). These areas are the Western Kentucky Coal Field region and most of the Outer Bluegrass region (fig. 1). Curves for estimating the $7Q_{10}$ for sites in these areas do not appear in figure 8 because they are outside the range of the values shown.

Caution should be used in applying the estimating techniques in areas where much of the base streamflow is contributed by springs. Delineation of the drainage area in such instances is uncertain. Caution should also be used in applying the equations to areas where the surface rocks are mainly limestone because flow in solutionally enlarged fractures may significantly alter streamflow for short stream reaches. One such case of a karst discontinuity is along Sinking Creek in Breckinridge County, Kentucky. Four partial-record gaging stations are located along a reach of Sinking Creek: stations 03303195, 03303198, 03303200, and 03303205 (pl. 2). The $7Q_2$ and $7Q_{10}$ low flows for the first two sites were nonzero, and increased in the downstream direction (table 2). However, the flow traveled beneath the surface at the third site, Sinking Creek near Irvington (03303200), resulting in a value of zero for the $7Q_2$ and $7Q_{10}$. At the fourth site, the flow

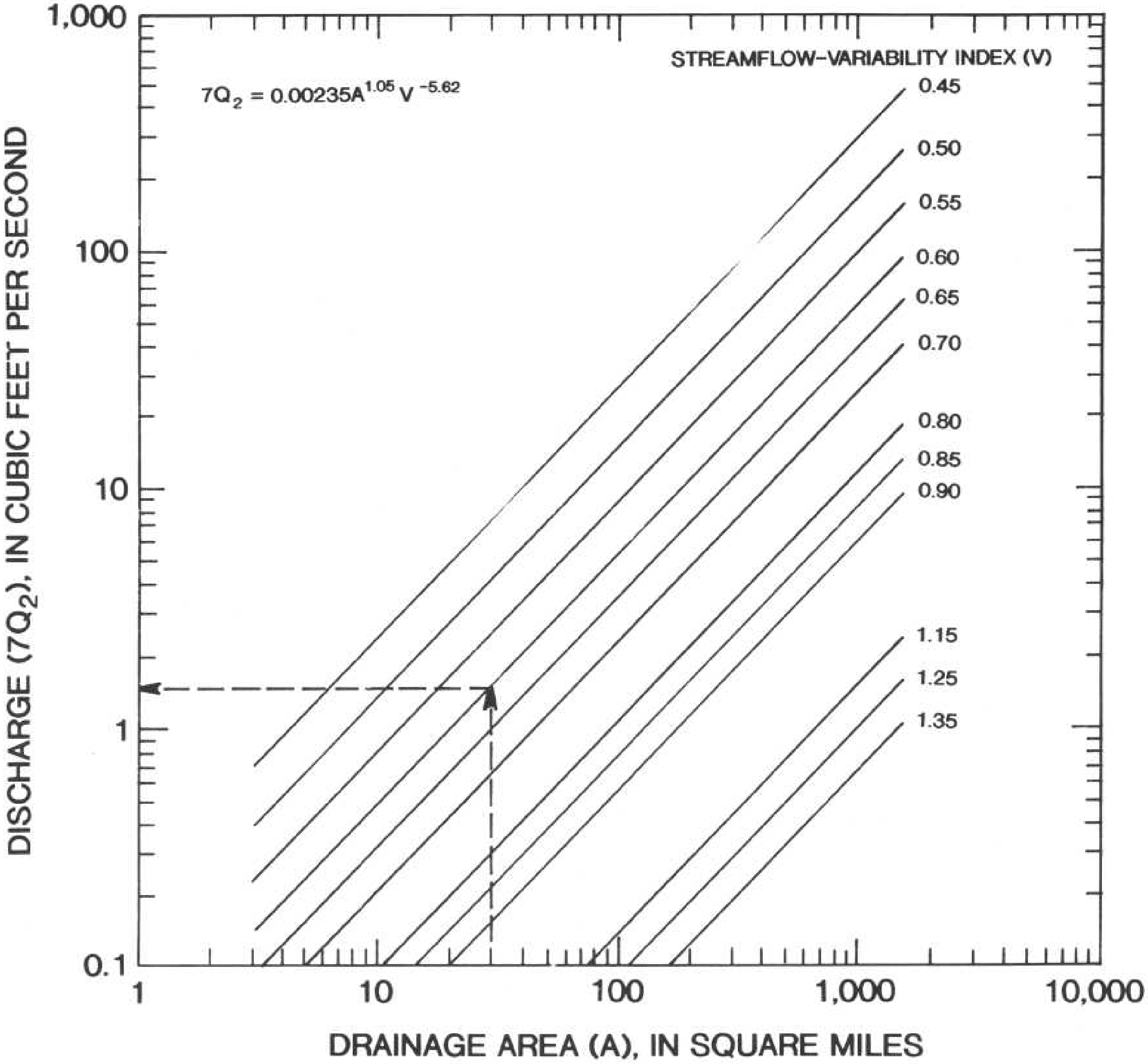


Figure 7.--Graphical solution of the 7-day 2-year low-flow estimating equation for Kentucky.

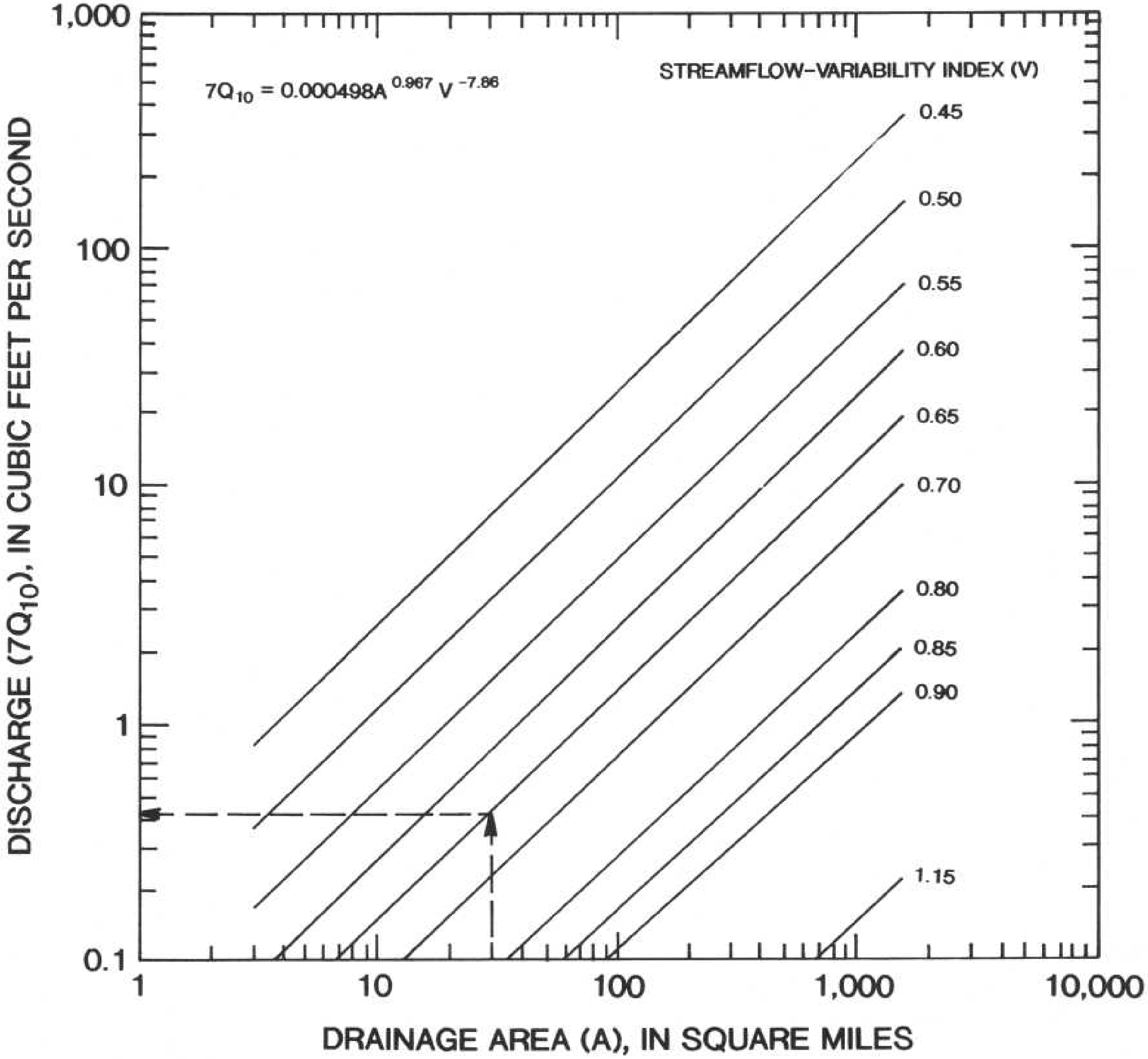


Figure 8.--Graphical solution of the 7-day 10-year low-flow estimating equation for Kentucky.

resurfaced, and the $7Q_2$ and $7Q_{10}$ low flows had increased from those observed at the second station. The regional estimating techniques presented here will not account for a condition, as described, where sinking streams are present.

Accuracy of the estimating equations is expressed as a standard error of estimate, in percent. The standard error was computed from the difference between station data and estimates of low-flow values from the regression equations (Tasker, 1978). The $7Q_2$ and $7Q_{10}$ low-flow estimating equations were developed using the mapped values of streamflow variability and have a standard error of estimate of 71 and 90 percent, respectively. The $7Q_2$ and $7Q_{10}$ low-flow estimating equations were developed using data from 79 and 52 continuous-record gaging stations, respectively. Data from 10 partial-record gaging stations was also used to develop each regression equation. Continuous-record gaging stations with a zero flow value for a particular recurrence interval were not used in that analysis. Figures 9 and 10 show the comparison between the $7Q_2$ and $7Q_{10}$ low flows developed from measured flows and flows estimated using the regression equations. More emphasis was placed on developing and refining the $7Q_{10}$ estimating equation than the $7Q_2$ estimating equation. As shown in figure 9, the $7Q_2$ estimating equation tends to slightly underpredict throughout most of the range in discharge.

Equations 2 and 3 were used to estimate the $7Q_2$ and $7Q_{10}$ at the 212 partial-record stations, and the values are given in table 2. Estimates of the $7Q_2$ and $7Q_{10}$ were determined to two significant figures to the nearest tenth. Values equal to or less than 0.05 ft³/s were rounded to zero. The standard error was computed using the data set from the 212 partial-record stations except Sinking Creek near Irvington, which was the station at the point of a sinking stream, and the 10 partial-record stations used in developing the regression equations. The set was used as verification data, and the resulting values of standard error of prediction for the $7Q_2$ and $7Q_{10}$ low-flow estimating equations was 76 and 91 percent, respectively. Because many of the predicted values of $7Q_2$ and $7Q_{10}$ were zero, the relation

$$SE = \left[\frac{1}{N} \sum_{i=1}^{j} \left[\frac{O_i - P_i}{\frac{O_i + P_i}{2}} \right]^2 \right]^{0.5}$$

was used to compute the standard error instead of

$$SE = \left[\frac{1}{N} \sum_{i=1}^{j} \left[\frac{O_i - P_i}{P_i} \right]^2 \right]^{0.5} ,$$

where SE is the standard error of prediction, in percent; N is the number of observations; O_i is the observed value of $7Q_2$ or $7Q_{10}$, in ft³/s, for the ith station; and P_i is the predicted value of $7Q_2$ or $7Q_{10}$, in ft³/s, from either equation 2 or 3, respectively, for the ith station.

The possibility of dividing by zero when the numerator was a nonzero value was thereby eliminated. The $7Q_2$ and $7Q_{10}$ low flows estimated from correlation

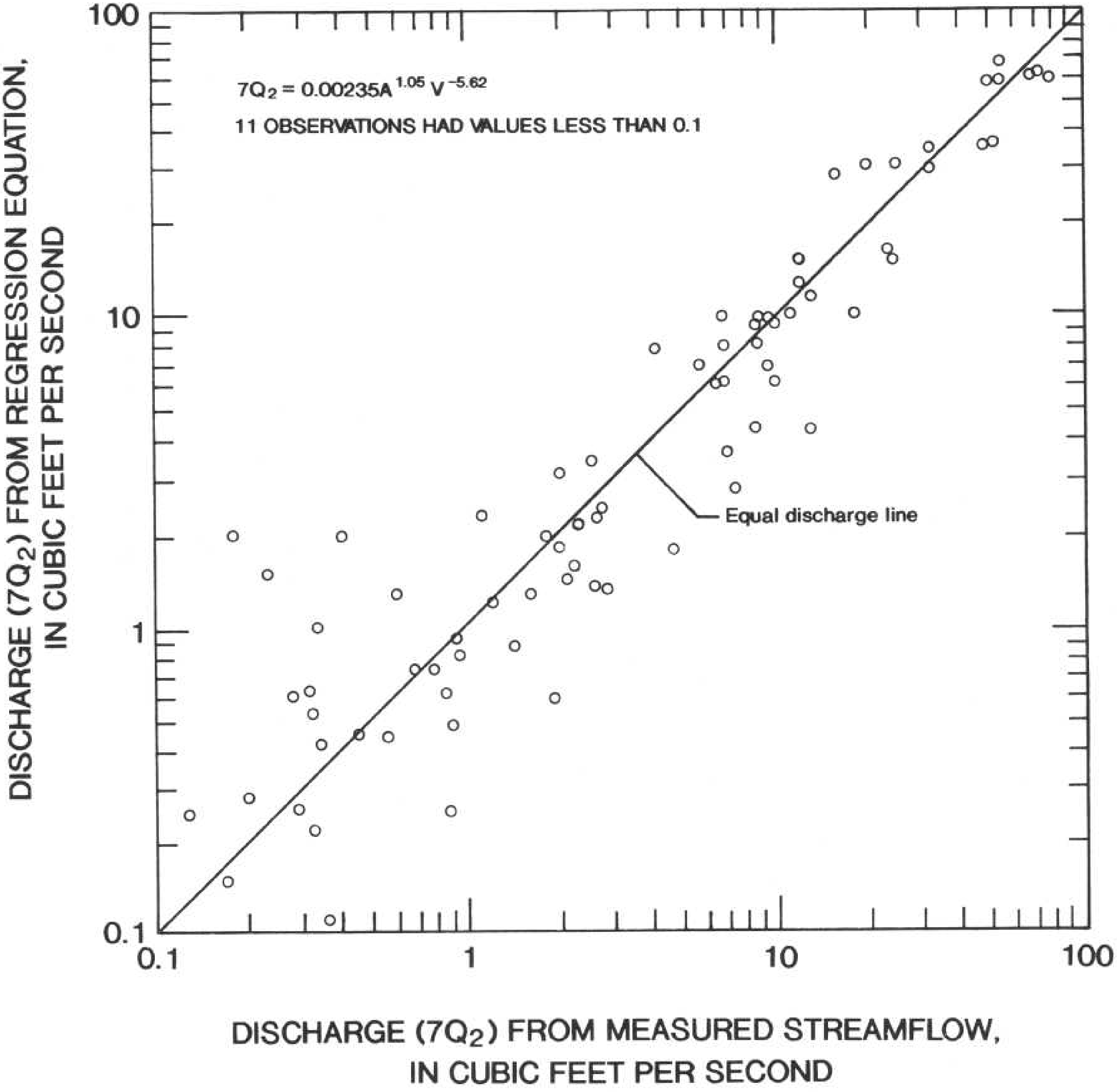


Figure 9.--Plot of 7-day 2-year low flow from measured streamflow and from regression equation for selected continuous-record gaging stations in Kentucky.

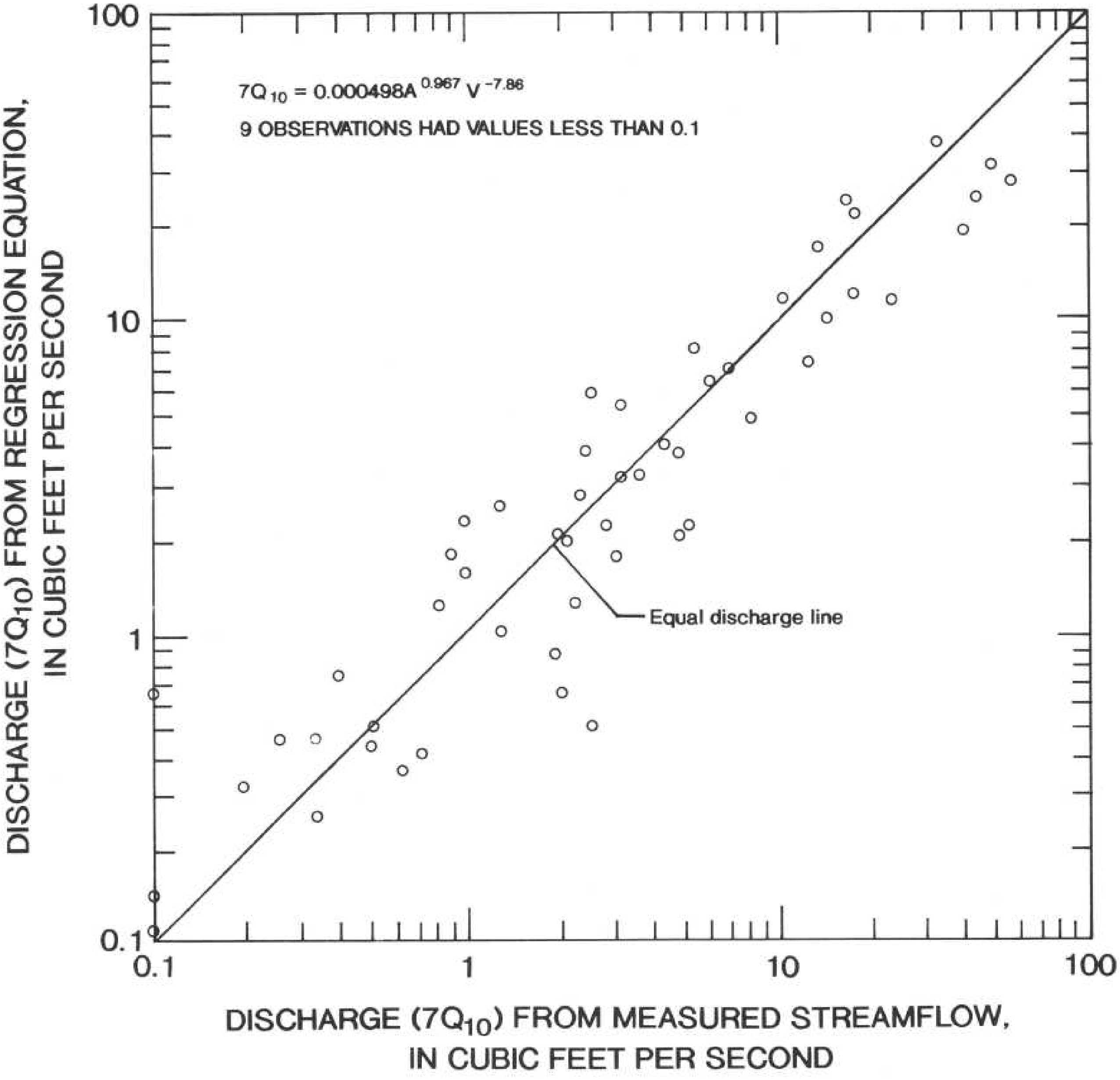


Figure 10.--Plot of 7-day 10-year low flow from measured streamflow and from regression equation for selected continuous-record gaging stations in Kentucky.

methods and from the regression equations are given in table 2. Also included in table 2 are the drainage area and mapped streamflow variability for each partial-record station. Figures 11 and 12 show the relation between the $7Q_2$ and $7Q_{10}$ low flows estimated from correlation techniques and estimated using the regression equations. The $7Q_2$ estimating equation tends to slightly underpredict for stations having observed discharge values above about 2 ft^3/s. Figures 11 and 12 both show considerable scatter in estimates below about 1.0 ft^3/s which becomes more pronounced the closer the estimates are to 0.1 ft^3/s.

ESTIMATING LOW-FLOW FREQUENCY VALUES AT STREAM SITES IN KENTUCKY

Stream Sites With Gage Information

Sites at Gage Locations

Estimates of low-flow values are presented for 136 continuous-record and 212 partial-record stations. When an estimate of low-flow is required at a stream site, the first step should be to scan tables 1 and 2 to determine whether low-flow frequency values have previously been estimated. This is the primary source for a low-flow estimate at a stream site.

Sites near Gage Locations

If information is available for the stream where an estimate is desired, but not at the specific location, a weighting procedure can be employed (Carpenter, 1983). The first constraint to the use of this method is that the drainage area of the ungaged site differ by no more than 50 percent from that of the gaged site (either a continuous- or partial-record station). The second constraint to the use of this method is that the entire drainage basin where the estimate is desired be within the same variability-index area (pl. 1). This second constraint is important because the method assumes a linear relation between the flow values at the gaged and ungaged sites. This is not a valid assumption if the gaged and ungaged sites are affected by different basin characteristics.

The first step in using the weighting procedure is to verify that the above two constraints are not violated. Obtain the low-flow value at the gage site from either table 1 or 2 (from column labeled "From graphical correlation") and also estimate the value at the gaged site using either equation 2 or 3, whichever is appropriate. Compute the correction factor at the gaged site (C_g) as the ratio of the observed low-flow value from table 1 or 2 to the estimated value from either equation 2 or 3. This correction factor will now be used to compute a correction factor at the ungaged site based on the difference in drainage area between the gaged and ungaged site by

$$C_u = C_g - \frac{2\Delta A}{A_g} (C_g - 1) , \qquad (4)$$

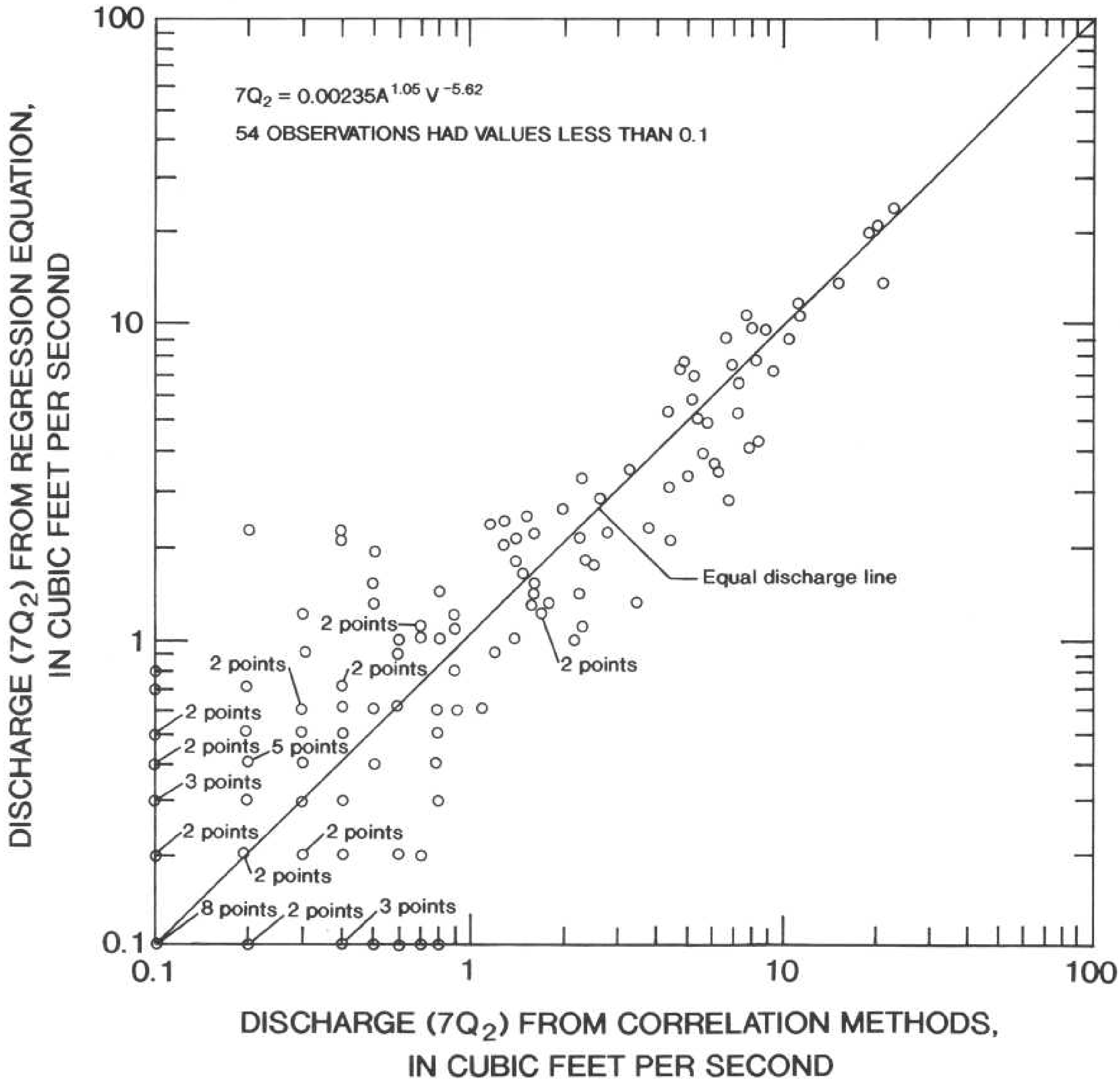


Figure 11.--Plot of 7-day 2-year low flow from correlation methods and from regression equation for selected partial-record gaging stations in Kentucky.

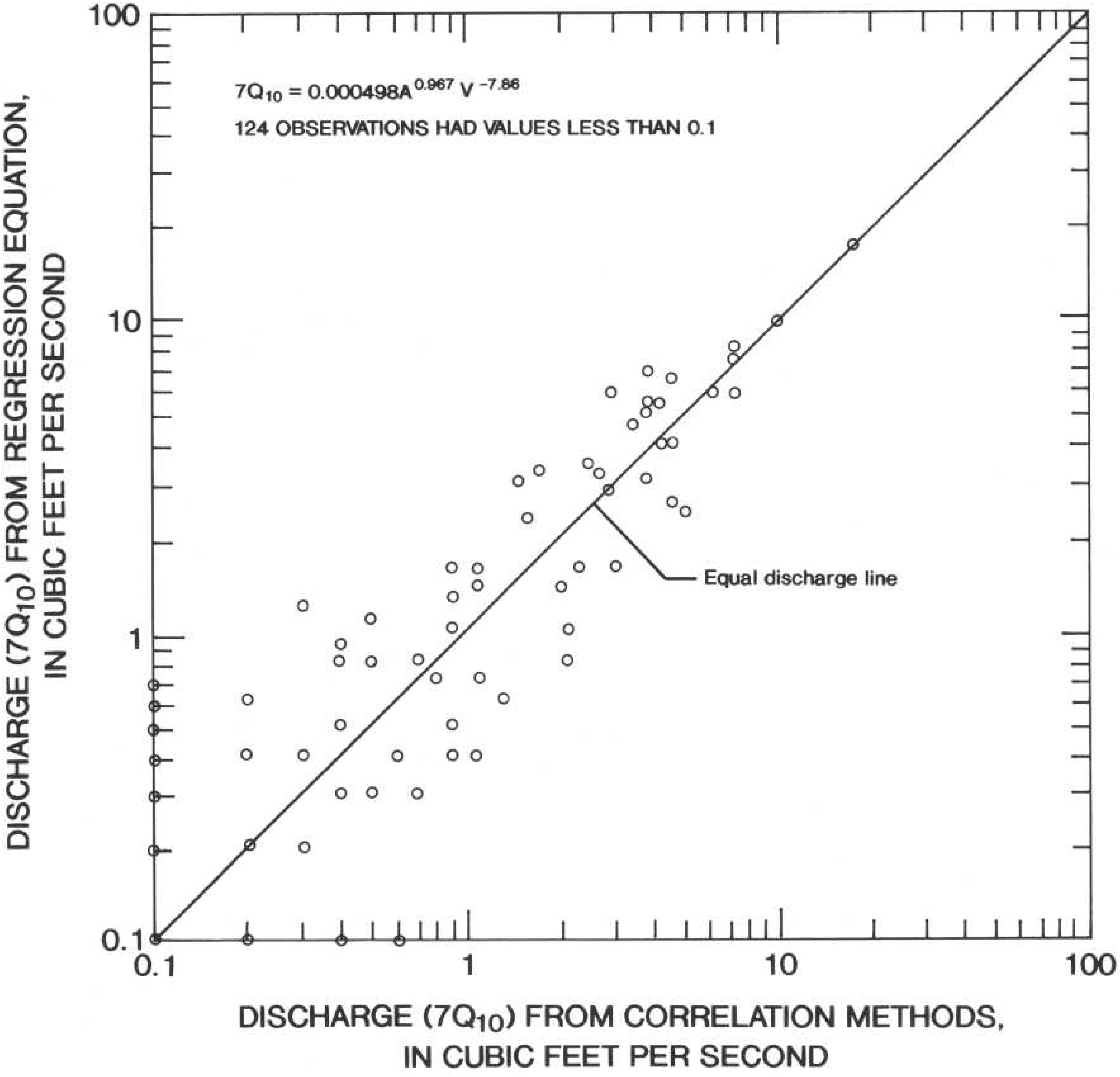


Figure 12.--Plot of 7-day 10-year low flow from correlation methods and from regression equation for selected partial-record gaging stations in Kentucky.

where

C_u is the correction factor for the ungaged site;
C_g is the correction factor for the gaged site;

A is the absolute value of the difference in drainage area between the gaged and ungaged site, in square miles; and
A_g is the drainage area of the gaged site, in square miles.

Compute the estimated discharge at the ungaged site using either equation 2 or 3 and multiply this value by the correction factor, C_u from equation 4, to obtain the weighted value of low-flow at the ungaged site. The equation is

$$Q_w = C_u Q_u , \quad (5)$$

where

Q_w is the weighted discharge determined at the ungaged site, in cubic feet per second;
C_u is the correction factor for the ungaged site (from equation 4); and
Q_u is the regression estimate of low flow from either equation 2 or 3, in cubic feet per second.

As the difference in drainage area between the gaged and ungaged site approaches 50 percent, the value of C_u approaches 1, and no longer has an effect on the regression estimate at the ungaged site.

Sites Between Gage Locations

If a low-flow estimate is desired between two gage locations on the same stream, the value can be estimated by straight-line interpolation, using the low-flow values and corresponding drainage areas at the two gaged sites. As with the previous method, the technique should not be used where the reach extends over, or is drained by more than one variability-index boundary. When this condition exists, the relation is not linear between the two gaged sites.

Stream Sites With No Gage Information

If no streamflow information is available at the desired stream site or at a nearby stream site on the same stream so that the estimating methods in the previous section cannot be used, then equations 2 and 3 can be used directly to estimate low-flow values. These equations, or the curves shown in figures 7 and 8, can be used to estimate values of the $7Q_2$ and $7Q_{10}$ at ungaged, unregulated stream sites in Kentucky. A value of 0.05 ft^3/s or less, using either equation 2 or 3, should be considered zero.

Total drainage area of the site of interest should be obtained from USGS 7.5-minute topographic maps. The drainage areas for many sites along streams in Kentucky are listed in Bower and Jackson (1981). Streamflow variability is obtained from plate 1. The percent of total drainage area within each streamflow-variability index area will also need to be determined. Examples of numerical and graphical procedures for obtaining the estimated $7Q_2$ and $7Q_{10}$ values from basins lying entirely within one index area and those in two or more index areas are given in the following sections.

Sites With Drainage Basins in One Index Area

The numerical solution for obtaining the $7Q_2$ and $7Q_{10}$ values at an ungaged site that is entirely within the same streamflow-variability index area is computed using the following method. Determine the total drainage area of the site from USGS 7.5-minute topographic maps and the streamflow variability from plate 1. Substitute the values into equations 2 and 3 below. The example assumes the site has a total drainage area of 155 mi^2 and is entirely within the variability index area of 0.70.

$$7Q_2 = 0.00235\ A^{1.05}\ V^{-5.62} \quad \text{(Equation 2)}$$

$$7Q_2 = 0.00235\ (155)^{1.05}(0.70)^{-5.62}$$

$$7Q_2 = 0.00235\ (199)(7.42)$$

$$7Q_2 = 3.5\ ft^3/s$$

$$7Q_{10} = 0.000498\ A^{0.967}\ V^{-7.86} \quad \text{(Equation 3)}$$

$$7Q_{10} = 0.000498\ (155)^{0.967}(0.70)^{-7.86}$$

$$7Q_{10} = 0.000498\ (131)(16.5)$$

$$7Q_{10} = 1.1\ ft^3/s$$

A graphical solution can be obtained from the curves shown in figures 7 and 8. Enter the plot on the abscissa scale at 155 mi^2 and proceed upward to the 0.70 streamflow-variability index curve. From there, proceed to the ordinate scale to obtain the estimated $7Q_2$ and $7Q_{10}$ value.

Sites With Drainage Basins in More Than One Index Area

If the drainage area for a desired site location includes more than one variability index area, the following method is used to estimate the $7Q_2$ and $7Q_{10}$ values. Determine the total drainage area of the site and percent of the drainage basin located within each of the streamflow-variability index areas. For this example, assume that an estimate of the $7Q_{10}$ is desired for a 300 mi^2 basin having 65 percent of the drainage area within a variability index area of 0.90. The remaining 35 percent is contained in an area having a variability index of 0.70. The numerical solution is as follows. First, obtain a value for the $7Q_{10}$ as if all of the basin were contained in the 0.70 variability index area, and perform the following computation:

$$7Q_{10} = 0.000498\ A^{0.967}\ V^{-7.86} \quad \text{(Equation 3)}$$

$$7Q_{10} = 0.000498\ (300)^{0.967}(0.70)^{-7.86}$$

$$7Q_{10} = 0.000498\ (249)(16.5)$$

$$7Q_{10} = 2.0\ ft^3/s$$

Assume the entire area lies within the 0.90 variability index area and compute the flow.

$$7Q_{10} = 0.000498\ A^{0.967}\ V^{-7.86}$$

$$7Q_{10} = 0.000498\ (300)^{0.967}(0.90)^{-7.86}$$

$$7Q_{10} = 0.000498\ (249)(2.29)$$

$$7Q_{10} = 0.28\ ft^3/s$$

To obtain a solution, multiply each flow value computed above by the corresponding percent of basin drainage area and sum the resulting values to determine the weighted average low-flow estimate.

$$\begin{aligned} 2.0\ ft^3/s\ (0.65) &= 1.30 \\ 0.28\ ft^3/s\ (0.35) &= \underline{0.10} \\ \text{weighted average } 7Q_{10} &= 1.40 \quad \text{or} \quad 1.4\ ft^3/s \end{aligned}$$

A graphical solution using the curves in figures 7 and 8 can be obtained using the same method. First, obtain values of the $7Q_2$ or $7Q_{10}$ for each variability index using the entire drainage area from either figure 7 or 8, whichever is appropriate. Multiply the values obtained from the graph by the percent of total drainage area corresponding to that variability index and sum the results to obtain the weighted average low-flow estimate.

The $7Q_{10}$ for stream sites with drainage areas less than 3 mi^2 should be considered zero, unless the site is located in a variability index area of 0.45, 0.50, or 0.55 (pl. 1). Streamflow information should be collected at sites in these index areas with drainage areas less than 3 mi^2 to determine low-flow values. The $7Q_{10}$ should be considered zero for stream sites draining areas less than 600 mi^2 in variability index areas of either 1.25 or 1.35. These areas coincide with the Western Kentucky Coal Field and the Outer Bluegrass physiographic regions (fig. 1). Streamflow information should be collected at sites when the $7Q_2$ or $7Q_{10}$ estimated from equations 2 or 3 is between 0.1 and 1.0 ft^3/s. Considerable scatter was evident in figures 9 through 12 for low-flow estimates in this range.

SUMMARY

Low-flow characteristics were determined for 136 continuous- and 212 low-flow partial-record streamflow-gaging stations in Kentucky. Values of the 7-day low flow for the unregulated streamflow record of 10 years or more were used to construct frequency curves at the continuous-record stations. These curves were compared to output from the Log Pearson Type III frequency analysis and in all cases there was good agreement; therefore, the results from the Log Pearson Type III analysis were used. Because of climatic trends in the station data, the frequency values for stations with less than 25 years of record were adjusted through correlation techniques to stations having 25 or more years of record. Selected frequency values previously estimated at 212 partial-record stations were reviewed. The values were estimated using graphical correlation techniques with one or more of the continuous-record gaging stations.

Techniques to estimate the $7Q_2$ and $7Q_{10}$ low flows at ungaged stream sites in Kentucky were developed from the available data. The estimating equations use drainage area and the streamflow-variability index as the regressor variables. The streamflow variability at a station is the standard deviation of the logarithms of the daily mean flows taken at selected percentiles from the flow-duration curve. The streamflow variability reflects the influence of surficial geology observed by the spatial variation of stream base flow. The $7Q_2$ and $7Q_{10}$ estimating equations have a standard error of 71 and 90 percent, respectively. Ten of the 212 partial-record gaging stations also were used to develop the estimating equations. Data from the remaining partial-record sites were used as verification data resulting in a standard error of prediction of the $7Q_2$ and $7Q_{10}$ low flows of 76 and 91 percent, respectively.

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Table 1.--Streamflow characteristics for selected continuous-record gaging stations in Kentucky

[mi^2, square miles; ft^3/s, cubic feet per second; LD, local diversion; --, value not determined]

Station number	Station name	Regu- lated	Period of unreg- ulated record (water year)	Years of record in analysis	Drainage area (mi^2)	Station streamflow- variability index	Station streamflow- recession index (days/log cycle)	7-day 2-year low flow (ft^3/s)	7-day 10-year low flow (ft^3/s)	Source of regulation and start date, or type of diversion and location
03208000	Levisa Fork Below Fishtrap Dam	Yes	1938-68	29	392	0.655	18	8.6	1.3	Fishtrap Lake, 10/68
03209500	Levisa Fork at Pikeville	Yes	1937-64	27	1,232	.634	19	25	5.2	Flannagan Lake, 03/65
03210000	Johns Creek near Meta	No	1941-87	46	56.3	.720	19	.68	0	
03212000	Paint Creek at Staffordsville	No	1950-75	25	103	.734	18	1.6	.20	
03212500	Levisa Fork at Paintsville	Yes	1915-16 1929-49	21	2,144	.647	22	50	16	Dewey Lake, 05/50
03215500	Blaine Creek at Yatesville	No	1915-18 1938-75	39	217	.750	20	2.7	.52	
03216500	Little Sandy River at Grayson	Yes	1938-67	29	400	.705	27	6.9	2.8	Grayson Lake, 03/68
03216540	East Fork Little Sandy River near Fallsburg	No	1973-87	14	12.2	1.063	18	0	0	
03216800	Tygarts Creek at Olive Hill	No	1957-87	30	59.6	.829	22	.34	.02	
03217000	Tygarts Creek near Greenup	LD	1940-87	46	242	.767	18	2.4	.34	Upstream power plant
03237900	Cabin Creek near Tollesboro	No	1972-87	15	22.4	.926	17	.02	0	
03248500	Licking River near Salyersville	No	1939-87	48	140	.711	28	2.1	0	
03249500	Licking River at Farmers	Yes	1939-73	33	827	.676	25	18	4.8	Cave Run Lake, 12/73
03250000	Triplett Creek at Morehead	No	1941-80	39	47.5	.878	19	.38	0	
03250100	North Fork Triplett Creek near Morehead	No	1967-87	19	84.7	.913	19	.28	0	
03250500	Licking River near Blue Lick Springs	No	1938-59	21	1785	.761	22	30	7.6	
03251000	North Fork Licking River near Lewisburg	No	1946-87	40	119	1.247	20	.04	0	
03251500	Licking River at McKinneysburg	Yes	1924-26 1938-73	35	2,326	.732	25	35	10	Cave Run Lake, 12/73
03252000	Stoner Creek at Paris	LD	1953-87	34	239	.828	22	1.5	.58	Waste disposal, Paris
03252500	South Fork Licking River at Cynthiana	LD	1938-87	49	621	.856	22	3.4	1.2	Municipal supply, Cynthiana

Table 1.--Streamflow characteristics for selected continuous-record gaging stations in Kentucky--Continued

[mi^2, square miles; ft^3/s, cubic feet per second; LD, local diversion; --, value not determined]

Station number	Station name	Regulated	Period of unregulated record (water year)	Years of record in analysis	Drainage area (mi^2)	Station streamflow-variability index	Station streamflow-recession index (days/log cycle)	7-day 2-year low flow (ft^3/s)	7-day 10-year low flow (ft^3/s)	Source of regulation and start date, or type of diversion and location
03253500	Licking River at Catawba	Yes	1915-17	45	3,000	0.741	26	49	13	Cave Run Lake, 12/73
03254400	North Fork Grassy Creek near Piner	No	1968-83	15	13.6	.984	31	0	0	
03277450	Carr Fork near Sassafras	Yes	1964-75	10	60.6	.704	23	.92	0	Carr Fork Lake, 01/76
03277500	North Fork Kentucky River at Hazard	Yes	1940-76	34	466	.627	29	8.8	2.1	Carr Fork Lake, 01/76
03278000	Bear Branch near Noble	No	1955-73	18	2.21	.917	18	0	0	
03278500	Troublesome Creek near Noble	No	1950-81	31	177	.745	24	2.0	.06	
03280000	North Fork Kentucky River at Jackson	Yes	1928-31 1938-75	39	1,101	.645	24	24	3.1	Carr Fork Lake, 01/76
03280600	Middle Fork Kentucky River near Hyden	LD	1958-87	29	202	.701	22	2.3	0	Municipal supply, Hyden
03280700	Cutshin Creek at Wooton	No	1958-87	29	61.3	.698	21	.86	.10	
03281000	Middle Fork Kentucky River at Tallega	Yes	1931-32 1940-60	20	537	.724	20	6.9	.84	Buckhorn Lake, 12/60
03281040	Red Bird River near Big Creek	No	1972-87	14	155	.667	24	2.2	.67	
03281100	Goose Creek at Manchester	No	1965-87	22	163	.703	25	1.8	.26	
03281500	South Fork Kentucky River at Booneville	No	1925-31 1940-87	53	722	.705	21	11	1.0	
03282000	Kentucky River at Lock 14 at Heidelberg	Yes	1926-31 1938-60	25	2,657	.688	21	46	12	Buckhorn Lake, 12/60
03282500	Red River at Hazel Green	No	1954-87	33	65.8	.764	20	.45	0	
03283000	Stillwater Creek at Stillwater	No	1954-73	19	24	.889	20	.08	0	
03283500	Red River at Clay City	LD	1931-32 1938-87	50	362	.606	27	12	3.8	Waste disposal, Stanton, municipal supply, Clay City

Table 1.--Streamflow characteristics for selected continuous-record gaging stations in Kentucky--Continued

[mi^2, square miles; ft^3/s, cubic feet per second; LD, local diversion; --, value not determined]

Station number	Station name	Regulated	Period of unregulated record (water year)	Years of record in analysis	Drainage area (mi^2)	Station streamflow-variability index	Station streamflow-recession index (days/log cycle)	7-day 2-year low flow (ft^3/s)	7-day 10-year low flow (ft^3/s)	Source of regulation and start date, or type of diversion and location
03284000	Kentucky River at Lock 10 near Winchester	Yes	1908-60	51	3,955	0.663	23	101	35	Buckhorn Lake, 12/60
03284300	Silver Creek near Kingston	LD	1968-83	15	28.6	.641	23	.78	.28	Waste disposal, Berea
03284500	Kentucky River at Lock 8 near Camp Nelson	Yes	1939-60	20	4,414	.672	23	141	44	Buckhorn Lake, 12/60
03285000	Dix River at Danville	No	1943-87	44	318	.939	23	.56	0	
03287000	Kentucky River at Lock 6 near Salvisa	Yes	1926-87 1/	61	5,102	.578	--	294	133	Herrington Lake, 11/25
03287500	Kentucky River at Lock 4 at Frankfort	Yes	1926-87 1/	58	5,411	.563	--	323	172	Herrington Lake, 11/25
03288000	North Elkhorn Creek near Georgetown	No	1950-83	34	119	.786	22	1.4	0	
03288500	Cave Creek near Fort Spring	No	1953-72 1977	20	2.53	.752	26	.05	0	
03289000	South Elkhorn Creek at Fort Spring	No	1950-87	37	24	.707	36	.90	0	
03289500	Elkhorn Creek near Frankfort	LD	1915-18 1940-83	46	473	.603	27	22	6.8	Intrabasin transfer, and waste disposal, Lexington
03290000	Flat Creek near Frankfort	No	1952-71	20	5.63	1.207	14	0	0	
03290500	Kentucky River at Lock 2 at Lockport	Yes	1926-87 1/	55	6,180	.560	--	393	202	Herrington Lake, 11/25
03291000	Eagle Creek at Sadieville	No	1941-75	33	42.9	1.488	18	0	0	
03291500	Eagle Creek at Glencoe	No	1915-18 1928-31 1938-77	42	437	1.341	16	.13	0	
03292460	Harrods Creek near LaGrange	No	1968-87	19	24.1	.973	17	.09	0	

Table 1.--Streamflow characteristics for selected continuous-record gaging stations in Kentucky--Continued

[mi^2, square miles; ft^3/s, cubic feet per second; LD, local diversion; --, value not determined]

Station number	Station name	Regulated	Period of unregulated record (water year)	Years of record in analysis	Drainage area (mi^2)	Station streamflow-variability index	Station streamflow-recession index (days/log cycle)	7-day 2-year low flow (ft^3/s)	7-day 10-year low flow (ft^3/s)	Source of regulation and start date, or type of diversion and location
03292500	South Fork Beargrass Creek at Louisville	LD	1939-40 1944-53 1954-62 1970-83	27	17.2	0.665	28	0.43	0	Waste disposal, Louisville
03293000	Middle Fork Beargrass Creek at Louisville	LD	1944-87	42	18.9	.521	24	1.6	.31	Waste disposal, Louisville
03295000	Salt River near Harrodsburg	No	1953-73	20	41.4	1.173	20	0	0	
03295500	Salt River near Van Buren	No	1939-82	43	196	.944	21	.29	0	
03297500	Plum Creek at Waterford	No	1954-74	20	31.8	1.309	16	0	0	
03298000	Floyds Fork at Fisherville	No	1944-87	42	138	1.262	23	.07	0	
03298500	Salt River at Shepherdsville	Yes	1938-82	43	1,197	.876	19	2.6	.06	Taylorsville Lake, 01/83
03299000	Rolling Fork near Lebanon	No	1938-87	49	239	.947	23	.60	0	
03300000	Beech Fork near Springfield	No	1953-72	19	85.9	1.204	20	0	0	
03300400	Beech Fork at Maud	No	1972-87	14	436	.790	33	.89	.02	
03301000	Beech Fork at Bardstown	No	1939-74	34	669	.913	21	1.9	.20	
03301500	Rolling Fork near Boston	No	1938-87	48	1,299	.773	33	13	2.5	
03302000	Pond Creek near Louisville	LD	1944-87	42	64	.550	28	5.0	.88	Waste disposal, Louisville
03304500	McGills Creek near McKinney	No	1951-71	19	2.14	1.101	21	0	0	
03305000	Green River near McKinney	No	1951-73	21	22.4	1.135	25	0	0	
03306500	Green River at Greensburg	Yes	1939-68	29	736	.716	28	9.4	2.0	Green River Lake, 02/69
03307000	Russell Creek near Columbia	No	1940-87	47	188	.575	30	8.6	2.2	
03307100	Russell Creek near Gresham	No	1965-75	10	265	.571	32	10	3.0	
03307500	South Fork Little Barren River at Edmonton	No	1941-72	30	18.3	1.270	24	0	0	
03308500	Green River at Munfordville	Yes	1915-23 1928-31 1938-68	40	1,673	.568	32	112	71	Green River Lake, 02/69
03309000	Green River at Mammoth Cave	Yes	1938-50	11	1,983	--	--	148	100	Green River Lake, 02/69

Table 1.--Streamflow characteristics for selected continuous-record gaging stations in Kentucky--Continued

[mi^2, square miles; ft^3/s, cubic feet per second; LD, local diversion; --, value not determined]

Station number	Station name	Regu-lated	Period of unreg-ulated record (water year)	Years of record in analysis	Drainage area (mi^2)	Station streamflow-variability index	Station streamflow-recession index (days/log cycle)	7-day 2-year low flow (ft^3/s)	7-day 10-year low flow (ft^3/s)	Source of regulation and start date, or type of diversion and location
03309500	McDougal Creek near Hodgenville	No	1953-71	17	5.34	0.610	26	0.17	0	
03310000	North Fork Nolin River at Hodgenville	No	1941-73	31	36.4	.824	24	.33	0	
03310300	Nolin River at White Mills	No	1960-87	27	357	.438	53	52	38	
03310400	Bacon Creek near Priceville	No	1960-87	27	85.4	.368	62	9.0	5.9	
03310500	Nolin River at Wax	No	1937-62	25	600	.474	64	72	47	
03311000	Nolin River at Kyrock	Yes	1931-32 1939-50 1961-62	12	703	.478	48	78	53	Nolin Lake, 03/63
03311500	Green River at Lock 6 at Brownsville	Yes	1925-31 1938-62	29	2,762	.527	34	250	158	Nolin Lake, 03/63
03311600	Beaverdam Creek at Rhoda	No	1973-87	14	10.9	.553	45	.79	.34	
03312000	Bear Branch near Leitchfield	No	1950-71	21	30.8	.886	19	.32	0	
03312500	Barren River near Pageville	No	1939-63	24	531	.493	42	55	31	
03313000	Barren River near Finney	Yes	1942-50 1961-63	10	942	.511	38	69	42	Barren River Lake, 03/64
03313500	West Bays Fork at Scottsville	No	1951-72	21	7.47	.572	29	.33	.08	
03314000	Drakes Creek near Alvaton	No	1940-71	31	478	.528	49	32	17	
03314500	Barren River at Bowling Green	Yes	1938-63	25	1,849	.547	34	105	62	Barren River Lake, 03/64
03315500	Green River at Lock 4 at Woodbury	Yes	1938-62	24	5,404	.543	32	403	260	Nolin Lake, 03/63
03316000	Mud River near Lewisburg	No	1940-72	32	90.5	.860	25	1.1	0	
03316500	Green River at Paradise	Yes	1940-50 1961-63	13	6,183	.553	37	443	326	Nolin Lake, 03/63
03317000	Rough River near Madrid	No	1938-59	20	225	--	--	14	9.5	
03317500	North Fork Rough River near Westview	No	1954-73	19	42	.834	21	.18	0	
03318000	Rough River near Falls of Rough	LD	1940-56	11	454	--	22	15	10	Mill, Falls of Rough
03318200	Rock Lick Creek near Glenn Dean	No	1957-71	14	20.1	.852	18	0	0	

Table 1.--Streamflow characteristics for selected continuous-record gaging stations in Kentucky--Continued

[mi², square miles; ft³/s, cubic feet per second; LD, local diversion; --, value not determined]

Station number	Station name	Regu-lated	Period of unreg-ulated record (water year)	Years of record in analysis	Drainage area (mi²)	Station streamflow-variability index	Station streamflow-recession index (days/log cycle)	7-day 2-year low flow (ft³/s)	7-day 10-year low flow (ft³/s)	Source of regulation and start date, or type of diversion and location
03318500	Rough River at Falls of Rough	Yes	1950-59	10	504	0.669	22	16	10	Rough River Lake, 10/59 and mill
03318800	Caney Creek near Horse Branch	No	1957-87	30	124	1.311	19	0	0	
03319000	Rough River near Dundee	Yes	1940-59	18	757	.701	22	20	14	Rough River Lake, 10/59
03320000	Green River at Lock 2 at Calhoun	Yes	1930-59	28	7,566	.590	32	505	338	Rough River Lake, 10/59
03320500	Pond River near Apex	No	1940-87	46	194	1.287	23	.04	0	
03321350	South Fork Panther Creek near Whitesville	No	1968-83	15	58.2	.973	25	0	0	
03322360	Beaverdam Creek near Corydon	No	1972-87	15	14.3	1.357	25	0	0	
03383000	Tradewater River at Olney	No	1940-87	45	255	--	20	.33	0	
03384000	Rose Creek at Nebo	No	1952-70	18	2.10	1.209	11	0	0	
03400500	Poor Fork at Cumberland	No	1940-87	47	82.3	.488	33	9.4	4.6	
03401000	Cumberland River near Harlan	Yes	1940-87 2/	47	374	.523	33	32	13	Martins Fork Lake, 01/79
03402000	Yellow Creek near Middlesboro	LD	1940-87	47	60.6	.554	31	5.2	2.5	Waste disposal, Middlesboro
03403000	Cumberland River near Pineville	Yes	1938-75 1980-87 2/	43	809	.566	32	50	16	Martins Fork Lake, 01/79 and upstream power plant
03403500	Cumberland River at Barbourville	Yes	1923-31 1948-87 2/	47	960	.578	30	55	17	Martins Fork Lake, 01/79 and municipal supply, Barbourville
03403910	Clear Fork at Saxton	No	1968-87	18	331	.514	28	12	2.5	
03404000	Cumberland River at Williamsburg	Yes	1951-87 2/	36	1,607	.575	24	73	22	Martins Fork Lake, 01/79
03404500	Cumberland River at Cumberland Falls	Yes	1907-11 1915-87 2/	73	1,977	.605	22	87	23	Martins Fork Lake, 01/79
03404820	Laurel River at Municipal Dam at Corbin	LD	1974-87	13	140	1.011	--	0	0	Municipal supply, Corbin
03404900	Lynn Camp Creek at Corbin	No	1974-87	13	53.8	.624	24	1.2	.73	
03405000	Laurel River at Corbin	LD	1922-24 1942-73	31	201	.871	18	1.8	.61	Municipal supply, Corbin
03406000	Wood Creek near London	No	1954-71	17	3.89	.535	25	.37	.27	
03406500	Rockcastle at Billows	No	1936-87	50	604	.687	25	12	3.5	

Table 1.--Streamflow characteristics for selected continuous-record gaging stations in Kentucky--Continued

[mi^2, square miles; ft^3/s, cubic feet per second; LD, local diversion; --, value not determined]

Station number	Station name	Regu-lated	Period of unreg-ulated record (water year)	Years of record in analysis	Drainage area (mi^2)	Station streamflow-variability index	Station streamflow-recession index (days/log cycle)	7-day 2-year low flow (ft^3/s)	7-day 10-year low flow (ft^3/s)	Source of regulation and start date, or type of diversion and location
03407100	Cane Branch near Parkers Lake	No	1956-66 1974	10	0.67	0.574	19	0.03	0	
03407300	Helton Branch near Greenwood	No	1956-74	18	.85	.461	18	.12	.09	
03407500	Buck Creek near Shopville	No	1953-87	34	165	.958	26	.23	0	
03410500	South Fork Cumberland River near Sterns	No	1943-87	44	954	.598	23	49	22	
03411000	South Fork Cumberland River near Nevelsville	No	1915-50	33	1,271	--	--	56	23	
03411500	Cumberland River at Burnside	Yes	1914-50	35	4,865	--	--	184	84	Martins Fork Lake, 01/79
03412500	Pitman Creek at Somerset	No	1953-72	18	31.3	.771	24	.31	.04	
03413200	Beaver Creek near Monticello	No	1969-83	14	43.4	.617	25	2.3	1.3	
03435140	Whippoorwill Creek near Claymour	No	1973-87	13	20.8	1.033	22	.06	0	
03437500	South Fork Little River at Hopkinsville	No	1950-73	23	46.5	.753	31	.94	.34	
03438000	Little River near Cadiz	No	1940-87	47	244	.535	33	23	12	
03438070	Muddy Fork Little River near Cerulean	No	1968-83	14	30.5	1.158	20	.01	0	
03610000	Clarks River at Murray	No	1952-71	19	89.7	1.343	15	0	0	
03610500	Clarks River near Benton	No	1938-73	34	227	.711	29	4.1	2.3	
03610545	West Fork Clarks River near Brewers	No	1969-83	14	68.7	.531	25	2.5	1.0	
03611260	Massac Creek near Paducah	No	1972-87	15	14.6	.724	17	.20	.10	
07022500	Perry Creek near Mayfield	No	1953-65 1968-72	15	1.72	1.085	--	0	0	
07023000	Mayfield Creek at Lovelaceville	No	1938-72	33	212	.516	17	13	7.9	
07023500	Obion Creek at Pryorsburg	No	1951-73	21	36.8	1.502	18	0	0	
07024000	Bayon De Chien near Clinton	No	1940-78 1984-87	41	68.7	.472	34	9.8	6.9	

1/ Includes effect of regulation by Herrington Lake

2/ Includes effect of regulation by Martins Fork Lake

Table 2.--Drainage area, streamflow-variability index, and low-flow characteristics estimated from graphical correlation and from regression equations for selected low-flow partial-record gaging stations in Kentucky

[mi², square miles; ft³/s, cubic feet per second]

Station number	Station name	Drainage area (mi²)	Streamflow-variability index	7-day 2-year low flow (ft³/s): From graphical correlation	7-day 2-year low flow (ft³/s): From regression equation[1/]	7-day 10-year low flow (ft³/s): From graphical correlation	7-day 10-year low flow (ft³/s): From regression equation[2/]
03207965	Dicks Fork at Phyllis	6.2	0.70	0	0.1	0	0
03209400	Elkhorn Creek near Elkhorn City	48.8	.69	1.7	1.2	.1	.4
03209460	Shelby Creek at Shelbiana *	112	.70	2.7	2.4	.4	.8
03209600	Right Fork Beaver Creek at Wayland	73.9	.70	1.5	1.6	0	.5
03209700	Beaver Creek at Martin	228	.70	6.0	5.1	.9	1.6
03209890	Middle Creek near Prestonsburg	62.1	.70	.5	1.3	0	.4
03211500	Johns Creek near Van Lear	206	.80	1.6	2.2	.4	.5
03211945	Open Fork Paint Creek near Relief	25.5	.80	.4	.2	.1	.1
03213600	Knox Creek at Argo	95.9	.70	.4	2.1	.1	.7
03213790	Big Creek near Hatfield	59.1	.80	1.1	.6	0	.1
03214400	Wolf Creek ar Pilgrim	62.8	.80	.6	.6	0	.2
03214700	Rockcastle Creek at Inez	63.1	.80	.8	.6	0	.2
03214730	Rockcastle Creek at Clifford	121	.80	1.7	1.2	0	.3
03215362	Blaine Creek above Cains Creek near Blaine	64.7	.80	.4	.6	0	.2
03215410	Blaine Creek near Blaine	119	.80	.9	1.2	.1	.3
03216190	Little Sandy River near Sandy Hook	35.7	.70	.2	.7	0	.3
03216438	Little Fork Little Sandy River near Willard	58.1	.80	.3	.6	0	.1
03216480	Little Fork Little Sandy River near Grayson	132	.79	1.6	1.5	.2	.4
03216570	East Fork Little Sandy River near Argillite	138	.80	2.2	1.4	.4	.3
03216935	Tygarts Creek near Kehoe	124	.85	1.2	.9	.2	.2
03216965	Buffalo Creek below Grassey Creek at Kehoe	54.6	.85	.1	.4	0	.1
03237225	Kinniconick Creek near Kinniconick	60.1	1.01	.3	.2	0	0
03237230	Kinniconick Creek near Rugless	112	.93	.3	.6	0	.1
03237246	Laurel Fork near Camp Dix	57.0	.85	.2	.4	0	.1
03237285	Salt Lick Creek near Vanceburg	47.5	1.15	0	.1	0	0
03237985	Cabin Creek near Plumville	57.6	1.15	0	.1	0	0
03238620	Bracken Creek near Augusta	28.8	1.25	0	0	0	0
03238660	Locust Creek near Augusta	41.7	1.35	0	0	0	0
03248170	Licking River at Fredville	40.3	.80	.2	.4	0	.1
03248250	Licking River at Royalton	76.7	.80	.6	.8	0	.2
03248540	Middle Fork near Salyersville	45.7	.80	.3	.4	0	.1
03248685	Elk Fork near West Liberty	59.4	.80	.9	.6	0	.1
03248730	Caney Creek near West Liberty	41.4	.80	.2	.4	0	.1
03248815	Blackwater Creek near Ezel	38.3	.70	.1	.8	0	.3
03248855	North Fork Licking River near Wrigley	33.7	.70	.4	.7	.3	.2
03250240	Slate Creek near Owingsville	185	1.15	.2	.3	0	0
03250320	Rock Lick Creek near Sharkey	4.01	1.15	0	0	0	0
03250330	Fox Creek near Hillsboro	110	1.15	0	.1	0	0
03250470	Fleming Creek near Hilltop	77.2	1.25	0	.1	0	0
03250640	Johnson Creek at Piqua	72.4	1.35	0	0	0	0

Table 2.--Drainage area, streamflow-variability index, and low-flow characteristics estimated from graphical correlation and from regression equations for selected low-flow partial-record gaging stations in Kentucky--Continued

[mi², square miles; ft³/s, cubic feet per second]

Station number	Station name	Drainage area (mi²)	Streamflow-variability index	7-day 2-year low flow (ft³/s) From graphical correlation	7-day 2-year low flow (ft³/s) From regression equation[1/]	7-day 10-year low flow (ft³/s) From graphical correlation	7-day 10-year low flow (ft³/s) From regression equation[2/]
03251400	North Fork Licking River at Milford	286	1.35	0.1	0.2	0	0
03252188	Grassy Lick Creek near Sharpsburg	40.6	1.35	0	0	0	0
03252300	Hinkston Creek near Carlisle	154	1.35	.4	.1	0	0
03252940	Fork Lick Creek at Morgan	50.2	1.35	0	0	0	0
03254460	Grassy Creek at Demossville	119	1.35	0	.1	0	0
03277100	Gunpowder Creek near Union	50.2	.90	.3	.3	.1	0
03277300	North Fork Kentucky River at Whitesburg *	66.4	.67	4.7	1.8	2.0	.7
03277340	North Fork Kentucky River at Blackey	131	.68	6.1	3.7	2.0	1.4
03277360	Rockhouse Creek near Letcher	51.5	.70	.9	1.1	.3	.4
03277370	Line Fork at Defeated Creek	40.8	.70	.9	.8	.4	.3
03277411	North Fork Kentucky River at Cornettsville	322	.80	6.6	3.5	2.1	.8
03277835	Troublesome Creek at Dwarf	59.9	.80	.5	.6	0	.2
03277915	Balls Fork at Ary	45.4	.80	.2	.4	0	.1
03279400	Quicksand Creek at Lunah	101	.80	.6	1.0	0	.2
03279700	Quicksand Creed at Quicksand	203	.80	2.3	2.1	.1	.5
03280551	Middle Fork Kentucky River at Asher	70.6	.80	.4	.7	0	.2
03280570	Greasy Creek at Napier	37.7	.80	.2	.4	0	.1
03280590	Greasy Creek at Haskinton	95.0	.80	.8	1.0	0	.2
03281016	Red Bird River near Spring Creek	52.7	.80	.8	.5	.2	.1
03281030	Red Bird River at Big Creek	125	.80	1.8	1.3	.5	.3
03281065	Goose Creek at Gooserock	49.6	.80	.3	.5	0	.1
03281080	Collins Fork near Bluehole	51.9	.80	.1	.5	0	.1
03281200	South Fork Kentucky River at Oneida	486	.80	4.4	5.4	.3	1.2
03281350	Sexton Creek at Taft (Below Bungeon Branch)	71.0	.72	.8	1.4	.1	.4
03282045	Sturgeon Creek near Heidelberg	96.4	.70	.4	2.1	0	.7
03282135	South Fork Station Camp Creek near Drip Rock Post Office	41.4	.85	.4	.3	0	.1
03282170	Station Camp Creek at Wagersville	115	.84	.7	1.0	0	.2
03282190	Red Lick Creek near Station Camp	69.5	1.05	.2	.2	0	0
03283100	Red River near Pine Ridge	142	.79	1.4	1.8	0	.5
03283830	Muddy Creek at Doylesville	63.8	1.15	.2	.1	0	0
03283995	Otter Creek near Ford	63.5	1.15	.4	.1	0	0
03284100	Boone Creek at Grimes Mill Road near Locust Grove	41.8	.85	.1	.3	0	.1
03284415	Paint Lick Creek at Paint Lick	54.4	1.15	0	.1	0	0
03284450	Paint Lick Creek near McCreary	97.6	1.21	0	.1	0	0
03284495	Sugar Creek near Buckeye	41.5	1.35	0	0	0	0
03284720	Dix River above Copper Creek near Crab Orchard	43.5	1.15	.1	.1	0	0
03284750	Dix River below Copper Creek near Crab Orchard	70.6	1.15	.1	.1	0	0
03284800	Dix River near Stanford	160	1.15	.2	.2	0	0
03284935	Hanging Fork Creek near Stanford	46.9	1.15	0	.1	0	0
03284995	Hanging Fork Creek near Hubble	91.1	1.15	0	.1	0	0

Table 2.--Drainage area, streamflow-variability index, and low-flow characteristics estimated from graphical correlation and from regression equations for selected low-flow partial-record gaging stations in Kentucky--Continued

[mi^2, square miles; ft^3/s, cubic feet per second]

Station number	Station name	Drainage area (mi^2)	Streamflow-variability index	7-day 2-year low flow (ft^3/s) From graphical correlation	7-day 2-year low flow (ft^3/s) From regression equation[1/]	7-day 10-year low flow (ft^3/s) From graphical correlation	7-day 10-year low flow (ft^3/s) From regression equation[2/]
03287130	Clear Creek near Mortonsville	61.6	0.85	0.1	0.4	0	0.1
03287550	Benson Creek at Frankfort	107	1.35	.1	.1	0	0
03288260	Cane Run near Georgetown	45.4	.85	0	.3	0	.1
03288450	North Elkhorn Creek at Switzer	265	.91	3.1	2.3	.1	.5
03290420	Sixmile Creek near Defoe	42.6	1.35	0	0	0	0
03290490	Sixmile Creek near Lockport	76.5	1.35	0	0	0	0
03290675	Drennon Creek at Drennon Springs	82.5	1.35	0	0	0	0
03291110	Eagle Creek near New Columbus	124	1.35	0	.1	0	0
03291270	Eagle Creek near Holbrook	258	1.35	.1	.1	0	0
03291490	Tenmile Creek at Folsom	68.4	1.35	0	0	0	0
03291700	Little Kentucky River near Bedford	73.2	1.08	.1	.2	0	0
03292100	Corn Creek near Bedford	27.5	.90	.1	.1	0	0
03295290	Salt River at Fox Creek	131	1.35	.5	.1	0	0
03295580	Beech Creek near Taylorsville	53.2	1.35	0	0	0	0
03295610	Salt River at Taylorsville	359	1.35	.7	.2	0	0
03295800	Brashears Creek near Finchville	147	1.25	.6	.1	0	0
03295900	Brashears Creek at Taylorsville	262	1.29	.6	.2	0	0
03295985	Simpson Creek near Taylorsville	57.3	1.25	0	0	0	0
03296500	Plum Creek near Wilsonville	19.1	1.25	0	0	0	0
03297000	Little Plum Creek near Waterford	5.15	1.25	0	0	0	0
03297700	Cox Creek near Highgrove	95.8	1.25	0	.1	0	0
03298710	North Rolling Fork near Gravel Switch	66.2	.90	0	.3	0	.1
03298760	North Rolling Fork at Bradfordsville	95.7	.90	.2	.5	0	.1
03298865	Big South Fork at Bradfordville	59.6	.90	.1	.3	0	.1
03300300	Chaplin River Sharpsville	140	1.35	0	.1	0	0
03300390	Chaplin River at Chaplin	262	1.35	.4	.1	0	0
03300498	Cartwright Creek at Fredericktown	82.3	1.25	.2	.1	0	0
03300780	Hardins Creek near Holy Cross	57.8	1.25	.1	0	0	0
03302100	Otter Creek at Grahamton	88.4	.55	7.3	7.4	4.6	4.2
03302150	Doe Run near Brandenburg Station	52.7	.55	8.4	4.3	5.1	2.5
03303195	Sinking Creek at Rosetta	36.0	.56	2.0	2.7	1.1	1.6
03303198	Sinking Creek at Dents Bridge near Irvington	66.1	.56	5.5	5.2	2.9	3.0
03303200	Sinking Creek near Irvington	86.7	.55	0	7.3	0	4.1
03303205	Sinking creek near Lodiburg	125	.56	8.2	10	4.3	5.5
03303445	Blackford Creek near Hawesville	71.8	1.22	0	.1	0	0
03303450	Blackford Creek near Maceo	111	1.26	0	.2	0	0
03305500	Green River near Mount Salem	36.3	1.06	0	.1	0	0
03305520	Green River at Middleburg	66.5	.98	.1	.3	0	0
03305660	Green River near Dunnville	221	.86	1.3	2.4	.2	.6
03305720	South Fork near Dunnville	71.0	.70	.5	1.5	0	.5

Table 2.--Drainage area, streamflow-variability index, and low-flow characteristics estimated from graphical correlation and from regression equations for selected low-flow partial-record gaging stations in Kentucky--Continued

[mi^2, square miles; ft^3/s, cubic feet per second]

Station number	Station name	Drainage area (mi^2)	Streamflow-variability index	7-day 2-year low flow (ft^3/s) From graphical correlation	7-day 2-year low flow (ft^3/s) From regression equation[1/]	7-day 10-year low flow (ft^3/s) From graphical correlation	7-day 10-year low flow (ft^3/s) From regression equation[2/]
03305760	Goose Creek at Dunnville	51.6	0.70	2.3	1.1	0.9	0.4
03305865	Casey Creek at Casey Creek	74.7	.82	.5	.9	.1	.2
03305945	Robinson Creek at Acton	48.4	.83	.4	.5	.2	.2
03306690	Russell Creek near Joppa	62.9	.70	3.5	1.3	.9	.5
03306850	Russell Creek at Columbia *	126	.70	7.5	2.8	1.9	.9
03307215	Big Pitman Creek near Bengal	47.7	.70	1.4	1.0	.4	.3
03307295	Big Pitman Creek near Summersville	126	.70	2.7	2.7	.4	.9
03307400	Big Brush Creek near Summersville	45.7	.59	7.0	2.8	2.3	1.6
03307600	South Fork Little Barren River at Sulpher Well	97.9	.70	4.5	2.1	1.1	.7
03307730	East Fork Little Barren River near Sulpher Well	87.4	.70	.5	1.9	.1	.6
03307800	Little Barren River near Monroe	244	.68	8.6	7.9	1.5	3.1
03309100	Wet Prong Buffalo Creek near Mammoth Cave	2.26	.60	.8	.1	.6	.1
03310078	South Fork Nolan River at Mathers Mill	49.6	.49	4.8	7.4	2.9	6.0
03310160	Nolin River near Glendale	185	.54	24	24	18	17
03310270	Valley Creek near Glendale	90.1	.54	11	9.1	7.5	5.9
03310380	Bacon creek at Highway 31W at Bonnieville *	53.5	.52	6.4	6.0	4.2	4.0
03310600	Dog Creek near Mammoth Cave	8.12	.60	.5	.4	.1	.2
03311100	Bylew Creek near Mammoth Cave	5.16	.75	.7	.1	.4	0
03312100	Bear Creek near Roundhill	137	.87	1.6	1.4	.6	.4
03312200	Line Creek at Gamaliel *	64.0	.70	2.8	1.4	.5	.5
03312395	Salt Lick Creek at Ackersville	118	.66	7.6	5.4	1.7	3.4
03312400	Barren River near Ackersville	296	.64	22	14	7.3	8.3
03312680	Skaggs Creek near Glasgow	141	.70	4.5	3.1	.9	1.0
03312765	Beaver Creek at Highway 31E near Glasgow	49.6	.55	5.8	4.0	1.6	2.4
03313860	Middle Fork Drakes Creek at Drake	124	.68	3.4	3.5	1.1	1.4
03313900	Trammel Creek near Scottsville	93.4	.64	8.6	4.3	4.7	2.7
03315515	Welch Creek near Morgantown	59.5	1.17	0	.1	0	0
03315610	Indian Camp Creek near Aberdeen	61.2	1.35	0	0	0	0
03315810	Muddy Creek at Dunbar	94.3	1.28	0	0.1	0	0
03316200	Wolflick Creek near Lewisburg	116	.20	.3	1.2	0	.5
03316640	Pond Creek near Martwick	125	1.30	0	.1	0	0
03316815	Rough River at Vertrees *	45.3	.55	7	3.7	5.0	2.2
03319540	Adams Fork near Dundee	48.9	.99	0	.2	0	0
03320770	West Fork Pond River Near White Plains	81.0	1.35	.1	0	.1	0
03321280	East Fork Deer Creek near Sebree	44.7	1.35	0	0	0	0
03321290	Deer Creek near Sebree	122	1.35	0	.1	0	0
03321370	South Fork Panther Creek near Masonville	109	1.35	0	.1	0	0
03321410	North Fork Panther Creek near Masonville	88.3	1.35	0	0	0	0
03321450	Panther Creek near Curdsville	344	1.35	.3	.2	0	0
03322180	Cane Creek near Henderson	56.0	1.35	0	0	0	0

Table 2.--Drainage area, streamflow-variability index, and low-flow characteristics estimated from graphical correlation and from regression equations for selected low-flow partial-record gaging stations in Kentucky--Continued

[mi^2, square miles; ft^3/s, cubic feet per second]

Station number	Station name	Drainage area (mi^2)	Streamflow-variability index	7-day 2-year low flow (ft^3/s) From graphical correlation	7-day 2-year low flow (ft^3/s) From regression equation[1/]	7-day 10-year low flow (ft^3/s) From graphical correlation	7-day 10-year low flow (ft^3/s) From regression equation[2/]
03322350	Highland Creek near Waverly	62.3	1.35	0	0	0	0
03322400	Highland Creek near Uniontown	166	1.35	.1	.1	0	0
03382600	Tradewater River at Pooles Mill Branch near Dawson Springs	60.4	1.35	0	0	0	0
03382685	Tradewater River at Murphy Ford near Dawson Springs	94.3	1.35	0	.1	0	0
03383755	Clear Creek at Highway 70 near Richland	17.0	1.35	0	0	0	0
03383900	Clear Creek at Watson Branch near Coiltown	78.8	1.35	0	0	0	0
03384050	Clear Creek at Highway 293 near Providence	197	1.35	.1	.1	0	0
03384100	Tradewater River at Montezuma Branch near Providence	605	1.35	.8	.4	0	0
03384110	Piney Creek near Blackford	60.8	1.35	0	0	0	0
03384154	Craborchard Creek at Clay	86.6	1.35	.1	0	0	0
03384360	Crooked Creek near Marion	47.4	1.35	.1	0	0	0
03400585	Poor Fork at Ross Point	142	.55	12	12	4.7	6.6
03400700	Clover Fork at Evarts *	82.4	.55	5.7	6.9	2.4	3.9
03400985	Martins Fork at Harlan	116	.55	9.4	9.8	3.9	5.4
03401500	Yellow Creek Bypass at Middlesboro	35.3	.65	.7	1.1	.2	.4
03402230	Yellow Creek near Ferndale	99.5	.58	7.6	6.6	3.8	3.2
03402480	Clear Creek at Clear Creek Springs *	38.5	.55	2.0	3.1	.9	1.9
03402850	Left Fork Straight Creek at Cary	33.7	.80	.8	.3	.4	.1
03402852	Straight Creek at Straight Creek	89.8	.73	2.2	1.0	.7	.3
03403180	Stinking Creek at Dewitt	49.1	.80	.1	.5	0	.1
03403255	Road Fork Creek at Dewitt	25.2	.80	0	.2	0	.1
03403530	Richland Creek near Barbourville	27.7	.70	0	.6	0	.2
03404200	Jellico Creek Near Williamsburg	103	.70	.2	2.2	0	.7
03404390	Marsh Creek near Whitley	72.0	.68	2.4	1.8	.8	.7
03404688	Laurel River near Lily	52.3	.70	0	1.1	0	.4
03404810	Little Laurel River near Lily	42.4	.68	.7	1.1	.1	.4
03405700	South fork Rockcastle River near Peoples *	95.1	.70	.4	2.1	.1	.7
03405818	Middle fork Rockcastle River near Parrot	79.0	.68	1.4	2.1	.4	.8
03405842	Horse Lick Creek near Lamero	61.7	.65	1.3	2.0	.7	.8
03405868	Roundstone Creek at Hummel	52.9	.62	2.8	2.3	2.1	1.0
03406330	Skegg Creek near Billows	55.9	.62	1.5	2.5	.5	1.2
03407000	Rockcastle River at Rockcastle Springs	745	.71	21	21	3.9	6.8
03407200	West Fork Cane Branch at Parkers Lake	.26	.65	0	0	0	0
03407425	Buck Creek near Woodstock	73.0	.97	.1	.7	0	.2
03410900	Little South Fork Cumberland River near Oil Valley	98.2	.64	2.3	3.4	.9	1.3
03412700	Fishing Creek near Hogue	59.8	.70	1.6	1.3	1.1	.4
03413345	Otter Creek near Susie	67.1	.60	5.1	3.4	3.0	1.6
03414080	Crocus Creek near Bakerton	108	.70	1.2	2.4	.5	.8
03414175	Marrowbone Creek near Grider	80.9	0.70	2.5	1.7	1.3	.6
03435063	Red River near Schochoh	127	.55	12	11	6.3	5.9

Table 2.--Drainage area, streamflow-variability index, and low-flow characteristics estimated from graphical correlation and from regression equations for selected low-flow partial-record gaging stations in Kentucky--Continued

[mi², square miles; ft³/s, cubic feet per second]

Station number	Station name	Drainage area (mi²)	Streamflow-variability index	7-day 2-year low flow (ft³/s): From graphical correlation	7-day 2-year low flow (ft³/s): From regression equation 1/	7-day 10-year low flow (ft³/s): From graphical correlation	7-day 10-year low flow (ft³/s): From regression equation 2/
03435100	Red River near Adairville	229	0.55	20	20	10	10
03435265	Whipoorwill Creek at Dot *	115	.55	6.7	9.7	3.1	5.4
03435380	Elk Fork Near Hadensville	88.5	.55	10	7.4	4.5	4.2
03436190	West Fork Red River near St. Elmo	162	.55	16	14	7.5	7.5
03438167	Dry Creek near Lamasco	34.6	.55	0	2.8	0	1.7
03438170	Eddy Creek near Lamasco	71.7	.55	5.4	5.9	2.7	3.4
03438470	Livingston Creek near Dycusburg	112	.55	6.9	9.5	3.9	5.2
03609710	Cypress Creek near Possum Trot	40.1	.70	0	.8	0	.3
03610585	West Fork Clarks River at Kaler	150	.60	5.0	7.9	2.5	3.5
03613000	Humphrey Creek at Lanceter	44.2	.70	.3	.9	.1	.3
07022600	Mayfield Creek at Mayfield	95.1	.60	0	4.9	0	2.3
07023700	Obion Creek near Arlington	203	.60	8.0	11	3.5	4.7

1/ $7Q_2 = 0.00235 A^{1.05} V^{-5.62}$

2/ $7Q_{10} = 0.000498 A^{0.967} V^{-7.86}$

* Station used in regression analysis to develop estimating equations

Low-flow characteristics of Kentucky streams

U.S. Geological Survey
Water-Resources Investigations Report 91-4097

ERRATA

Page	Line	Correction Needed		
31	4	A	to	ΔA
32	32	0.90	to	0.70
32	33	0.70	to	0.90