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

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.

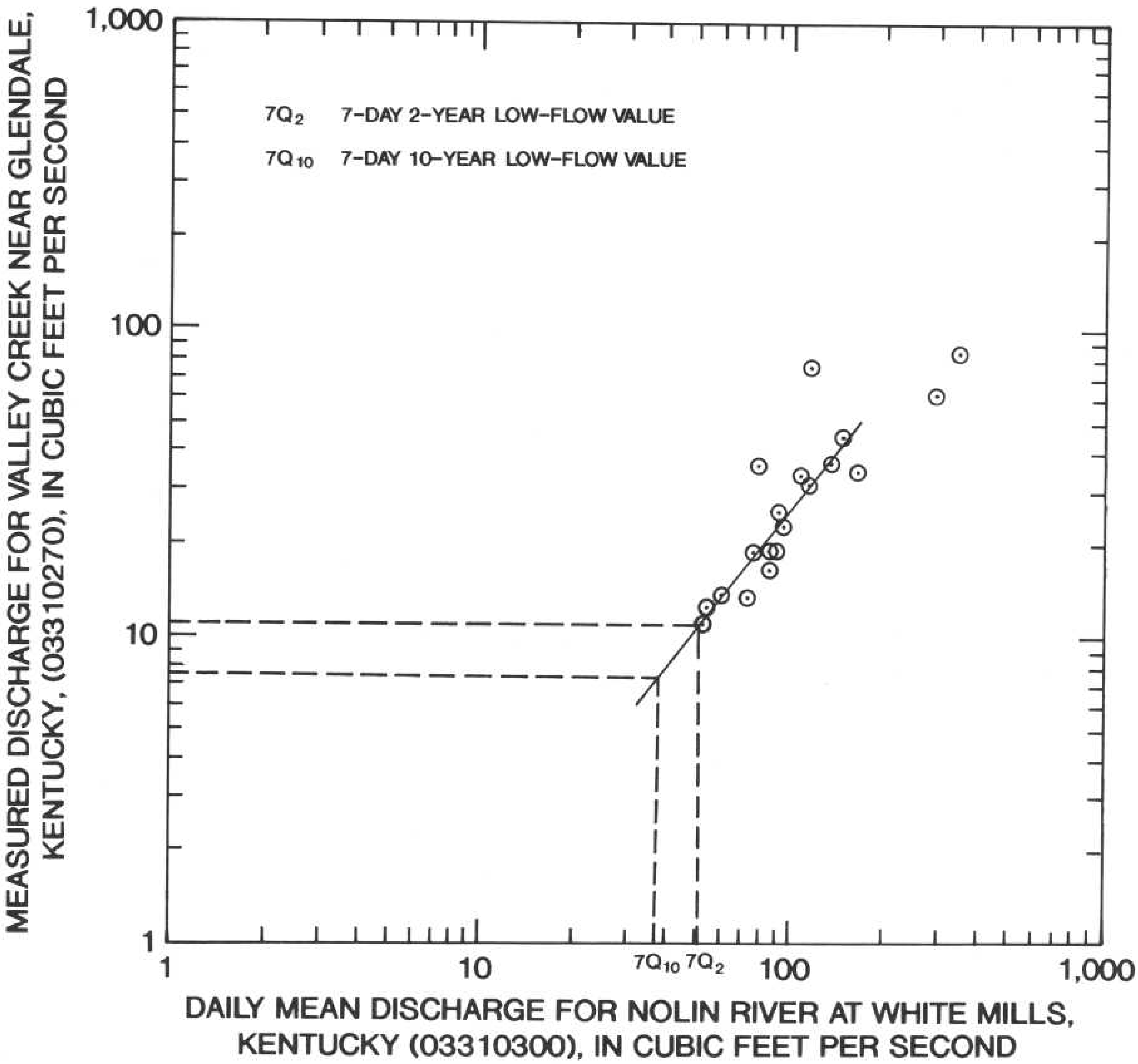

Figure 5.--Relation between base-flow measurements for Valley Creek near Glendale and concurrent daily mean flows for Nolin River at White Mills, Kentucky.

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

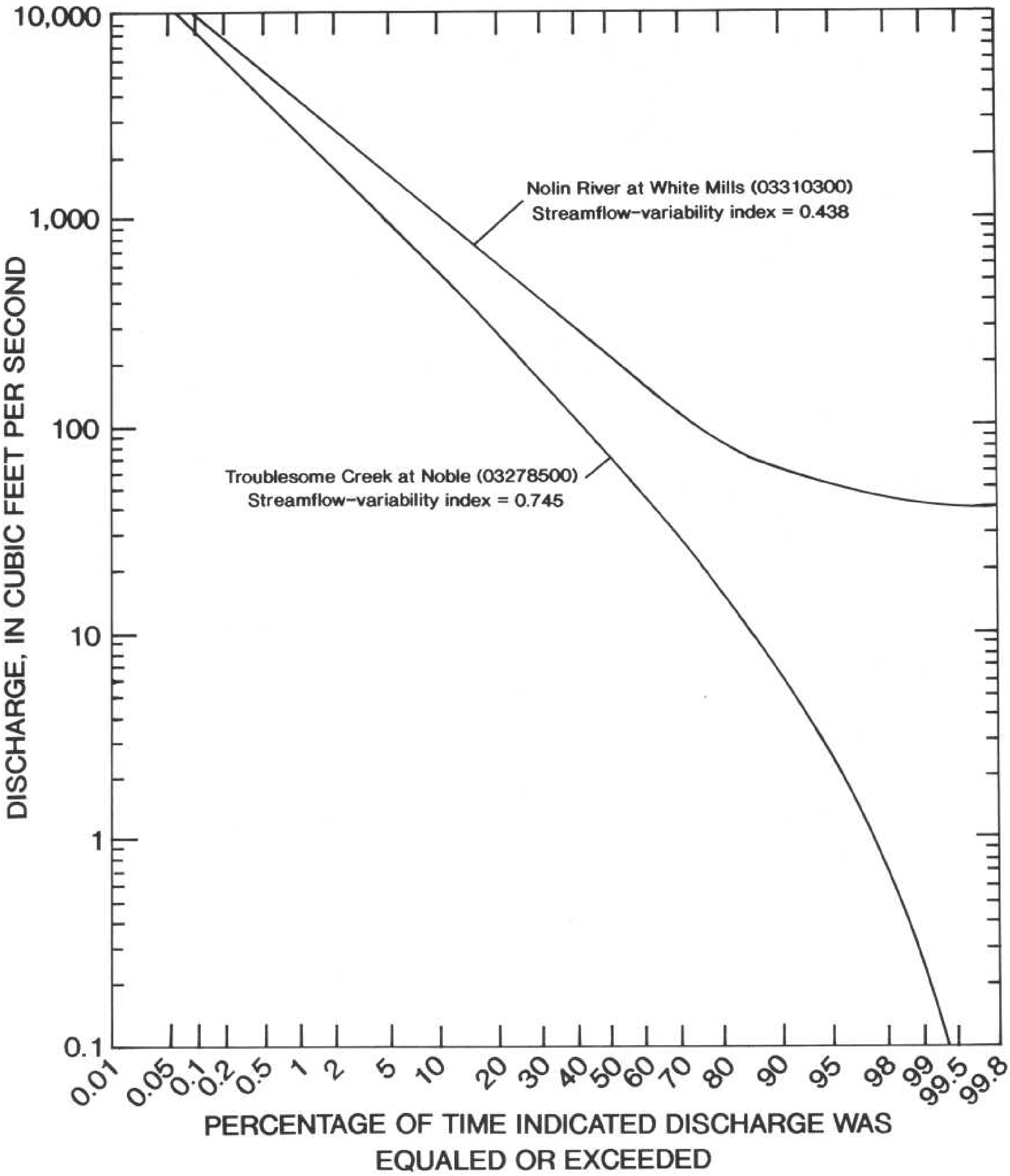

Figure 6.--Flow duration curves for Nolin River at White Mills and Troublesome Creek at Noble, Kentucky.

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

$$7Q_2 = 0.00235\ A^{1.05}\ V^{-5.62} \tag{2}$$

and

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

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 mi², and only 3 stations had drainage areas less than 10 mi².

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 mi², and 0.85 to 1,299 mi², 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 mi².

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 ft³/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 mi² 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 mi² should be determined by collecting streamflow information at the desired location.

The $7Q_{10}$ for sites with drainage areas less than 600 mi² 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

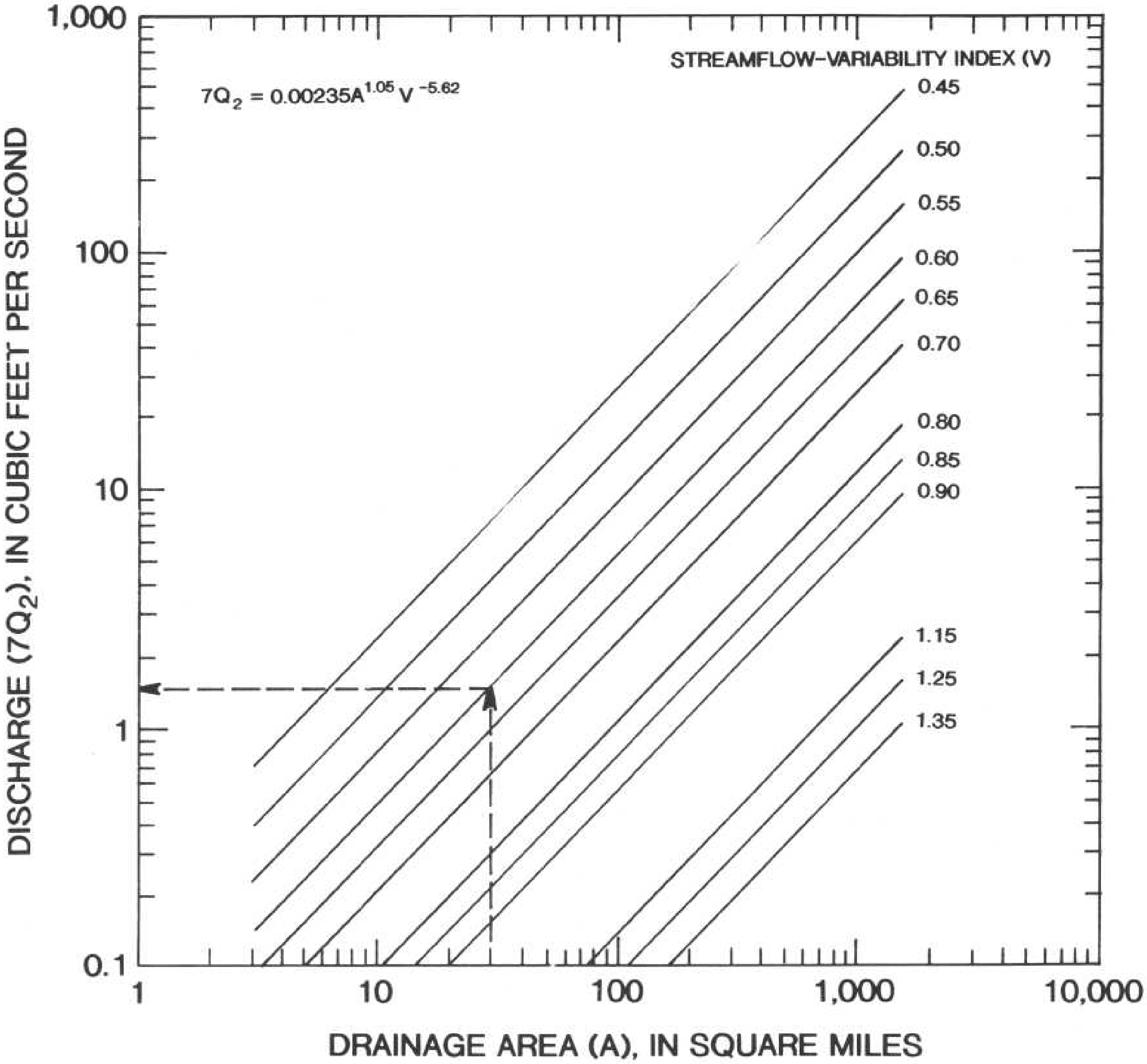

Figure 7.--Graphical solution of the 7-day 2-year low-flow estimating equation for Kentucky.

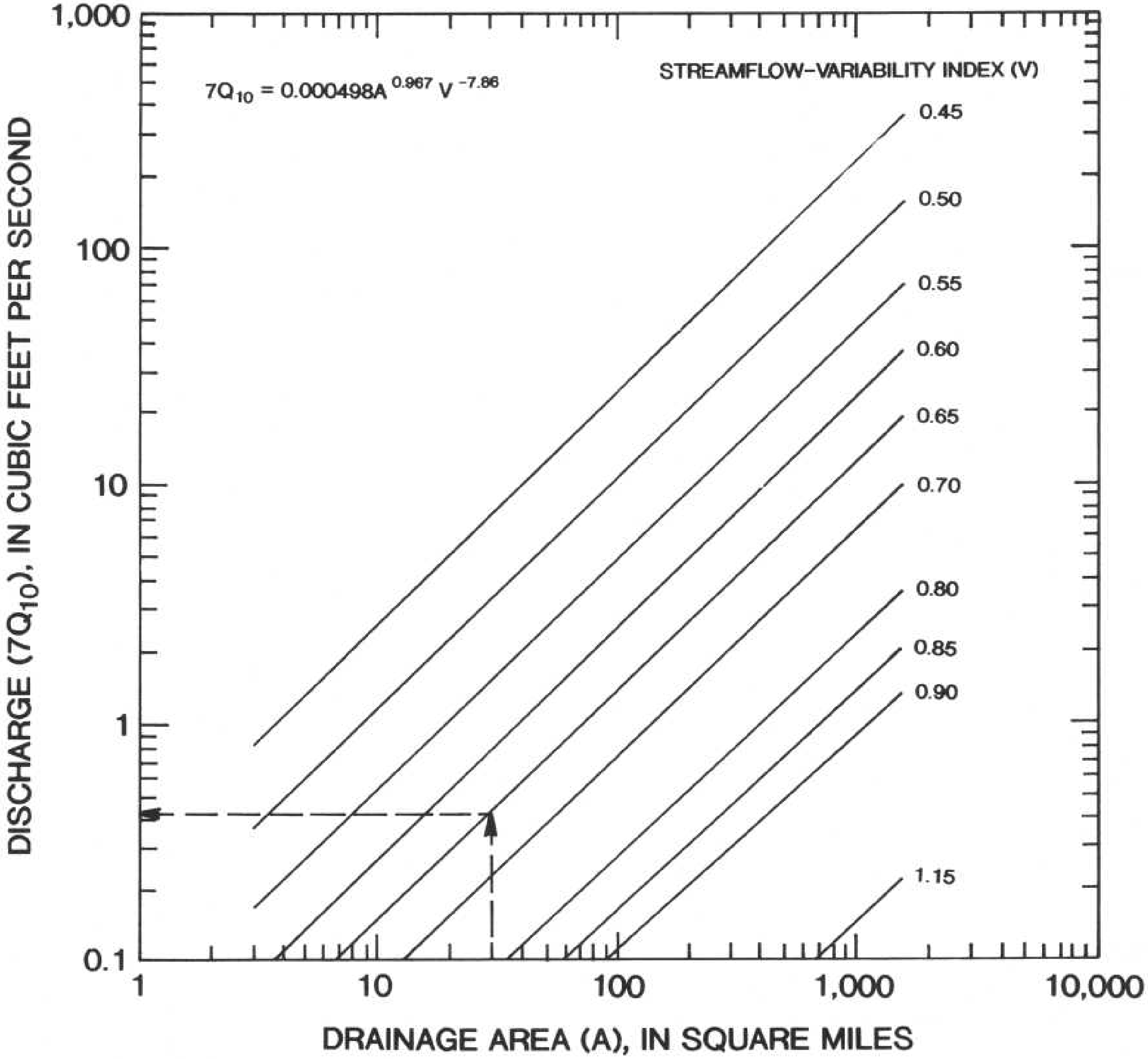

Figure 8.--Graphical solution of the 7-day 10-year low-flow estimating equation for Kentucky.

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

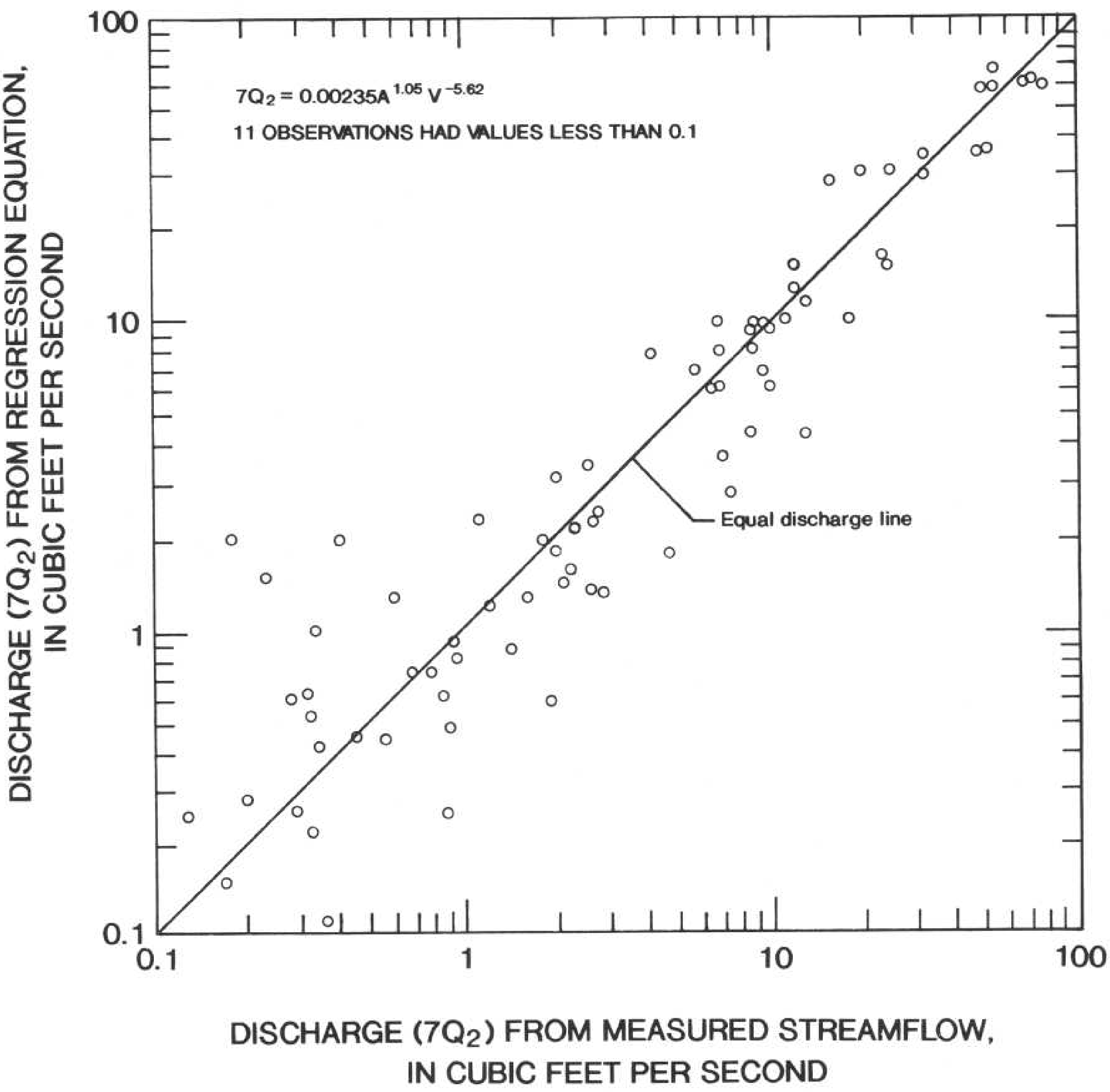

Figure 9.--Plot of 7-day 2-year low flow from measured streamflow and from regression equation for selected continuous-record gaging stations in Kentucky.

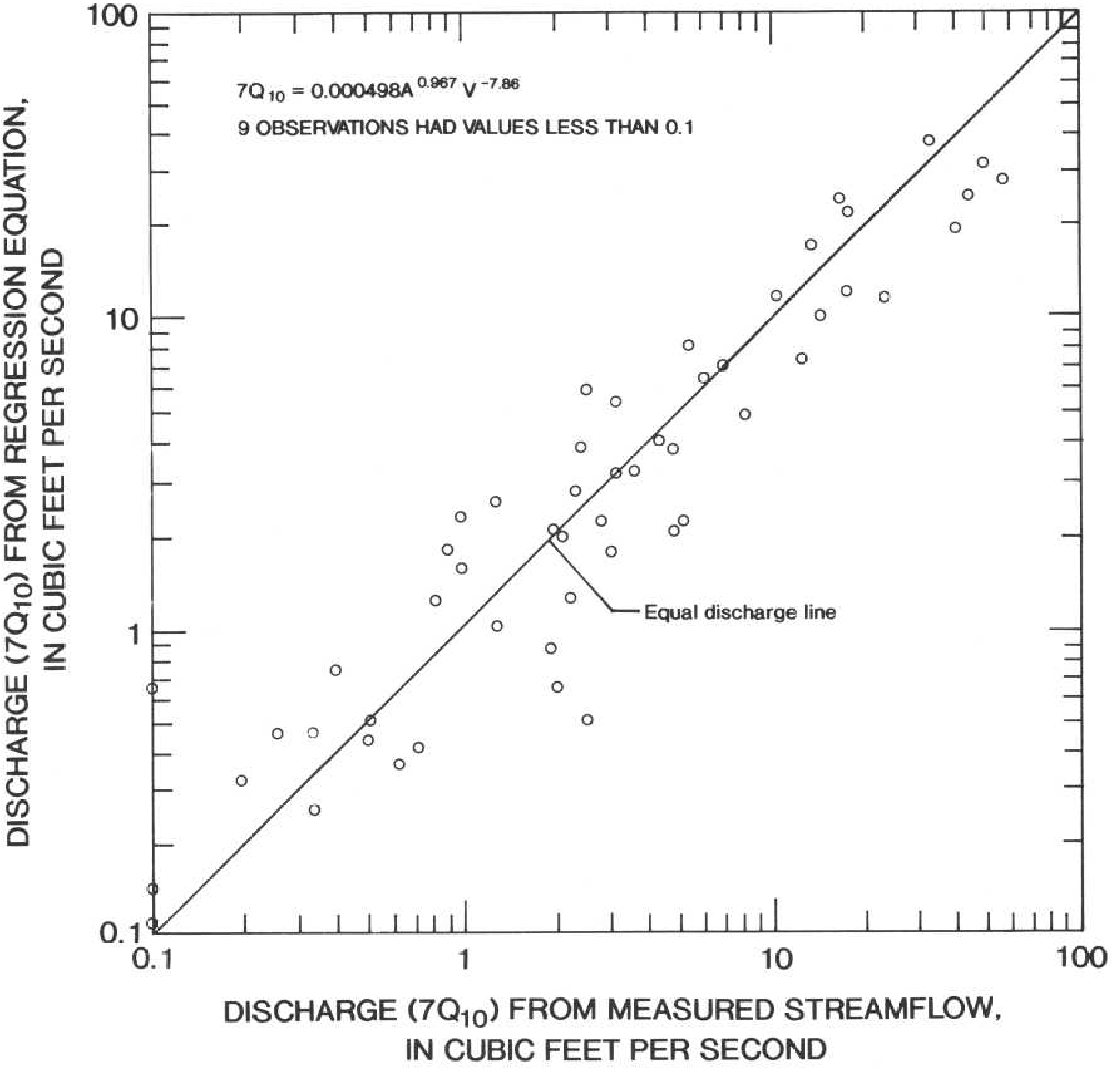

Figure 10.--Plot of 7-day 10-year low flow from measured streamflow and from regression equation for selected continuous-record gaging stations in Kentucky.

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

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