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Chapter B3

REGIONAL ANALYSES OF STREAMFLOW CHARACTERISTICS

By H. C. Riggs

Book 4

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PREFACE

The series of manuals on techniques describes procedures for planning and executing specialized work in water-resources investigations. The material is grouped under major subject headings called books and further subdivided into sections and chapters; section B of book 4 is on surface water.

The unit of publication, the chapter, is limited to a narrow field of subject matter. This format permits flexibility in revision and publication as the need arises.

Provisional drafts of chapters are distributed to field offices of the U.S. Geological Survey for their use. These drafts are subject to revision because of experience in use or because of advancement in knowledge, techniques, or equipment. After the technique described in a chapter is sufficiently developed, the chapter is published and is for sale by the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402.

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REGIONAL ANALYSES OF STREAMFLOW CHARACTERISTICS

By H. C. Riggs

Abstract

This manual describes various ways of generalizing streamflow characteristics and evaluates the applicability and reliability of each under various hydrologic conditions. Several alternatives to regionalization are briefly described.

Introduction

Regional analysis is concerned with extending records in space as differentiated from extending them in time. Because streamflow records are collected at only a few of the many sites where information is needed, gaging-station information must be transferred to ungaged sites. A regional analysis provides a tool for doing this. In addition, a regional analysis may produce improved estimates of the flow characteristics at the gaged sites.

The specific purposes of a regional analysis, then, are to provide estimates of the characteristics of the frequency distributions at ungaged sites and to improve estimates of the frequency distributions of flow characteristics at gaged sites. Consider, for example, a frequency curve of annual floods derived from 50 years of record. This frequency curve is an estimate of the population frequency curve; it will differ from the true curve, however, because a 50-year sample of floods is never completely representative. Frequency curves for other streams would also differ from their respective true curves. It these several curves were based on samples from the same population frequency curve and if the samples were independent of each other, then we would expect that an average of the several curves would be a better estimate of the population curve than any one of the samples. This averaging of curves can be accomplished by regional analysis.

No group, or even pair, of stream sites would have the same population frequency distribution of floods. The true distribution at a site depends on a great many factors, the principal ones being basin characteristics such as size, topography, surficial geology, and climate. Thus the variability among a group of flood frequency curves is made up of two components: chance variation due to sampling, and variation due to differences in basin characteristics. A regionalization procedure should average the chance variation but should maintain the variation due to basin characteristics. This is a difficult task because the total variation cannot be neatly separated into the two types of variation. The degree of success attained by a given method of regionalization depends on the relative sizes of the variations due to chance and those due to differences in basin characteristics, the degree of independence of the samples at the various gaging stations, the quality of the relation with basin characteristics, and the general suitability of the method.

Following sections describe and illustrate some methods of regional analysis applicable to various flow characteristics. In describing these methods, it is assumed that the frequency curves at gaging stations have been prepared by one of the methods described by Riggs (1968b) or the method recommended by Water Resources Council (1967). Background material needed for understanding some of the procedures described in this manual is available in book 4, chapter A1 of this series (Riggs, 1968a).

Procedure for Flood Peaks

Index-flood method

The index-flood method, described by Dalrymple (1960), was used for most of the regional flood-frequency analyses made by the U.S. Geological Survey prior to 1965. It consists of two parts.

The first part graphically relates mean annual flood to drainage area, and sometimes to other variables. Usually the plotted points define several different relations. On the basis of these preliminary relations, the geographic area being studied is divided into subareas such that a single relation of mean annual flood to drainage area applies to each. Thus the regionalization of the mean annual flood is attained.

The second part of the regionalization process averages the individual frequency curves to provide a regional curve. This is accomplished after expressing the flood magnitudes at selected recurrence intervals for each curve as ratios to the mean annual flood (the index flood). If some of the dimensionless individual curves are greatly different from others, the geographic area is subdivided so that each subdivision contains curves of similar shape. Then the curves in each subdivision are averaged. The subdivisions for this purpose are usually not coincident with the subareas defining the various relationships of mean annual flood to drainage area.

The index-flood method thus accomplishes the general purposes of a regionalization by relating the position of the frequency curve on the discharge scale to basin size, and by averaging the shapes of the individual curves. The method provides satisfactory results in many regions and is fairly simple to perform. The results are easy to apply to ungaged areas because usually only drainage area need be measured.

Application of the method requires arbitrary decisions as to the boundaries of subareas considered homogeneous with respect to mean annual flood or to shape of frequency curve. No subarea should be represented by fewer frequency curves than needed to define a meaningful regionalization, even though a close agreement among frequency characteristics in the subarea is not attained.

A basic assumption of the index-flood method is that the shape of the frequency curve in a homogeneous region is not related to drainage-area size or to other basin characteristics. This assumption does not appear to be justified on the basis of results from other types of analysis. Consequently, the variability in shape among dimensionless frequency curves from drainage areas of greatly differing size results both from chance and from real differences in the population frequency curves. Thus an average curve may obscure some real differences. A few published regional analyses have included suitable adjustments. Further evaluations of the index-flood method are described by Benson (1962a) and Cruff and Rantz (1965).

No example of the index-flood method is given here because one is described by Dalrymple (1960) and many others are available in published reports of the Geological Survey.

Multiple-regression method

Multiple regression is directly useful as a regionalization tool because the discharge for a given frequency level can be related to basin characteristics, leaving residuals that may be considered as due to chance. The regression line averages these residuals. Thus, in one operation, the effects of differing basin characteristics are preserved and the chance variation is averaged.

In practice, the interpretation of results from a regional regression analysis is not quite so straightforward. We know that we cannot describe all the variability due to basin characteristics by a regression. Therefore, the residuals contain both chance variation and variation due to basin characteristics, but we have no measure of the relative amounts of each.

The chance variation among a group of records may be small if the records are for the same period of time and are responses to the same general weather events. Here a paradox arises. If the records are not independent, and consequently the chance variation is small, there is little to be gained by averaging the chance variation except that the regression equation can be applied to ungaged basins. Under these conditions the average is likely to be biased. On the other hand, if the records are independent and the chance variation is extremely large, the regression analysis should produce a good answer, but the quality of the results may not be recognized because of the large standard error. Thus the success of a regionalization procedure by regression analysis cannot be measured in terms of the standard error of regression alone.

However, for a given set of data, the regression equation with the smallest practical standard error should be used. Improvement of the regression equation not only reduces the standard error but reduces the portion of the standard error that is due to differences in basin characteristics.

A regional regression having a large standard error may provide a good answer if most of that standard error is due to chance variation. But since we have no way of knowing how well the regression describes the real differences among basins, we usually conclude that a relation with a large standard error has much room for improvement.

A very small standard error of regression indicates little chance variation among the records used. The practice of reducing the residual variation to near zero by assigning various coefficients to subareas of the total area represented by the regression must be based on the assumption that the residual variation is largely due to unexplained differences in basin characteristics, and thus that the chance variation is small. This assumption does not seem justified. More likely, the major part of the residual variation is due to chance.

Benson (1962a,b, 1964) discusses and shows examples of the multiple-regression method of regional analysis of flood peaks. The following example outlines the procedure.

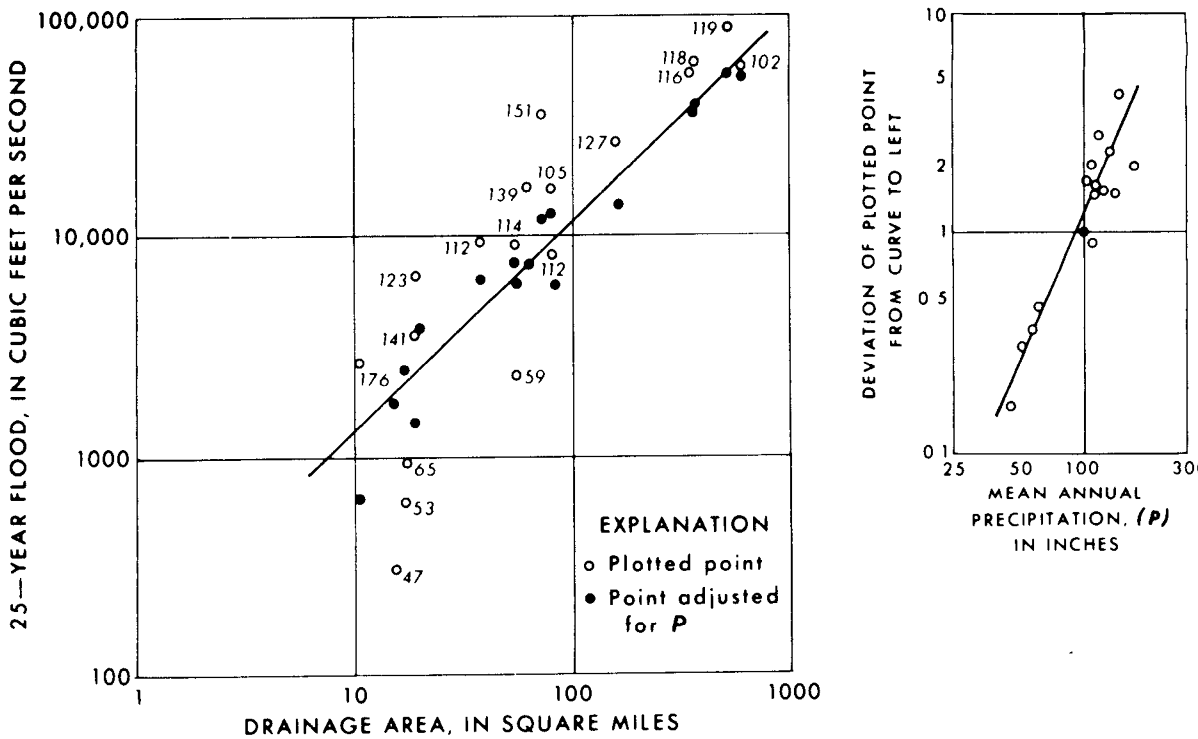
Table 1 lists the 2-, 25-, and 50-year floods, the drainage area, and the mean annual basin precipitation for gaging stations in Snohomish River basin, Washington (Collings, 1971). A graphical regression using these data is shown in figure 1 and the gage sites are shown in figure 2. See Riggs (1968a) for method of making a graphical multiple regression.

This graphical step is preliminary and may be bypassed in an analysis, but it takes little time and usually clearly indicates the suitability (or lack of suitability) of the model to be used in the mathematical fitting. In figure 1 the plotted points indicate the statistical significance of both independent variables. Standard error of the graphical regression can be estimated.

Not all graphical regressions are as clear cut as that of figure 1. Consequently the regression is usually determined by mathematical fitting, preferably by digital computer. The computer program produces the standard

Table 1.—Data from Snohomish River basin, Washington

Station	Annual flood peak (cfs) at indicated recurrence interval (years)			Drainage area (sq mi)	Mean annual precipitation (in.)
	2	25	50		
1330. S. F. Skykomish	22,600	54,400	63,300	355	116
1335. Troublesome	920	2,760	—	10.6	176
1345. Skykomish	36,100	87,800	102,000	535	119
1350. Wallace	1,990	3,570	4,000	19.0	141
1375. Sultan	16,700	35,200	39,600	74.5	151
1410. Woods	1,210	2,300	2,580	56.4	59
1415. M. F. Snoqualmie	12,500	27,100	—	169	127
1420. N. F. Snoqualmie	7,440	16,600	19,100	64.0	139
1440. S. F. Snoqualmie	4,190	8,080	—	81.7	112
1445. Snoqualmie	26,500	63,500	—	375	118
1460. Patterson	201	309	—	15.5	47
1407. Griffin	393	944	1,120	17.1	65
1475. N. F. Tolt	5,000	9,540	—	39.2	112
1480. S. F. Tolt	3,450	6,700	—	19.7	123
1485. Tolt	7,780	16,100	17,900	81.4	105
1490. Snoqualmie	28,200	59,400	67,400	603	102
1525. Pilchuck	5,080	9,120	10,200	54.5	114
1530. L. Pilchuck	281	627	—	17.0	53



1. Graphical analysis of data from table 1.

error of estimate of the regression, significance tests of the regression coefficients, deviations of the individual points from regression, and other information in addition to the regression equation.

The model commonly used in regional analysis of flood peaks is of the form

$$\log Q_{RI} = \log a + b_1 \log X_1 + b_2 \log X_2 + b_3 \log X_3 \ldots .$$

The equation of the graphical relation of figure 1 is of the above form and is

$$\log Q_{25} = -2.28 + 0.94 \log A + 2.25 \log P,$$

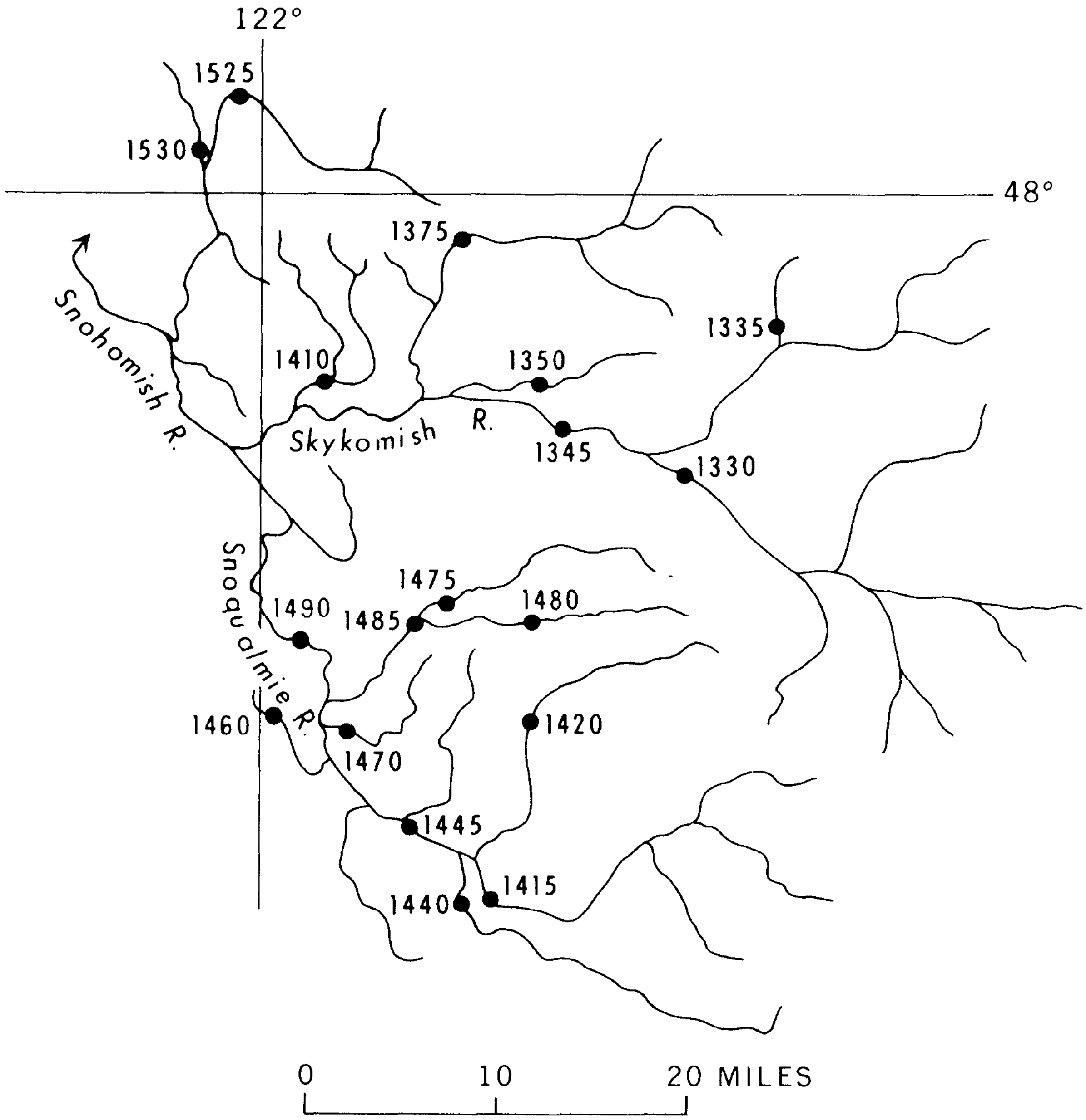
where Q_{25} is the 25-year-recurrence-interval flood in cubic feet per second (cfs), A is drainage area in square miles, and P is mean annual precipitation in inches. Using the same data in a digital computer produced the following equation

$$\log Q_{25} = -2.07 + 0.97 \log A + 2.11 \log P.$$

Both regression coefficients are highly significant, and the standard error of regression is 0.14 log units which corresponds to +38 and −28 percent. Although the coefficients in the above two regressions are appreciably different, the computed values of Q_{25} at a site by the two equations generally will be within a few percent of each other.

In a common procedure several regressions are computed, the first one including all basin and climatic characteristics considered applicable. A "step-backward" computer program will make the first computation, eliminate the least significant variable and recompute the regression, then continue the elimination process until only one independent variable remains. Differences in the standard errors of the various regressions indicate the degree of improvement obtained by inclusion of each independent variable. For examples, see table 6 of Thomas and Benson (1970).

A preferable approach is to carefully select a few variables having clear physical relationships to the flood peak and to compute the regression equation and check the regression coefficients for significance. A computer program called "step-forward" regression will



2. Map of Snohomish River stream system showing location of gaging stations listed in table 1.

select the most highly related variable and test it for significance; then select the next most highly related variable, compute the regression on the two, and test for significance; then proceed similarly until all the significant variables are included in the regression. A following "Model and Parameters" section covers the selection of independent variables in more detail.

Using the data of table 1, regressions for the 2- and 50-year flood have been defined by computer. They are

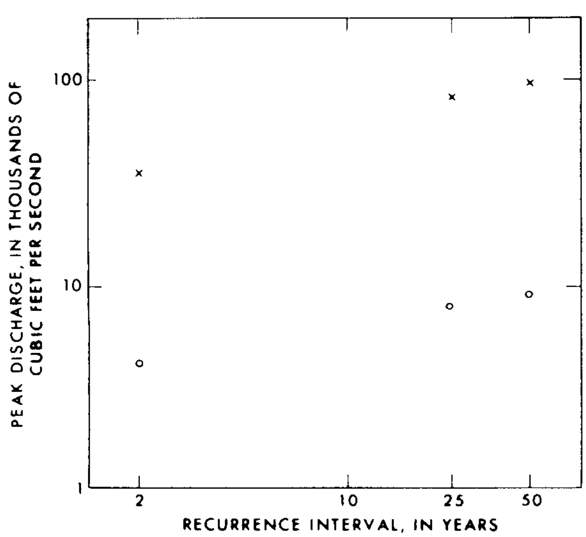
$$\log Q_2 = -2.07 + 0.954 \log A + 1.96 \log P$$

$$\log Q_{50} = -2.07 + 0.955 \log A + 2.16 \log P,$$

for which the standard errors are 0.16 and 0.12 log units respectively. All regression coefficients are statistically significant at the 1 percent level. The standard error of log Q_{50} is smaller than that of either log Q_2 or log Q_{25}, probably because the regression for log Q_{50} is based on only 10 stations whose records may be less independent than are the records for the 18 stations used in the other regressions. It should not be assumed that Q_{50} can be estimated more closely than the others because it has the smallest standard error.

Equations applied to a specific site to obtain discharges corresponding to several recurrence intervals may not produce points that lie on a smooth curve. To check the equations for the Snohomish River example, assume a basin of 300 square miles with a mean annual precipitation of 150 inches. The 2-, 25-, and 50-year flood peaks computed by slide rule are 35,500, 83,000, and 97,600 cfs respectively. These are plotted in figure 3 along with results from a 300-square-mile basin having 50 inches of precipitation. The results appear to be consistent.

A frequency curve could be drawn to average the computed points, but this is usually not justified unless a set of equations produces a large-recurrence-interval flood which is smaller than one computed for a smaller recurrence interval. This condition does not appear possible with the equations derived for this example, although it can occur with equations from some analyses.



3. Plot of computed floods for hypothetical basins.

The object of a regional study usually is to define the floods corresponding to two or three recurrence intervals at ungaged sites, not to define the entire frequency curve. The 2-year flood and the mean annual flood (2.33-yr) are of limited interest.

Regionalization of characteristics of the frequency distribution

Both the index-flood method and the regression method regionalize peak discharges at specific recurrence intervals; in the above example separate regressions were made for floods at the 2-, 25- and 50-year recurrence intervals. These discharges at individual sites were selected from the station frequency curves which may be either graphically or analytically defined.

If the station frequency curves are obtained by analytically fitting the same theoretical frequency distribution to data for each station, the differences among those frequency curves can be described by the differences in the computed parameters of the theoretical distribution. A two-parameter distribution can be described by its mean and variance (or standard deviation). A three-parameter distribution will require an index of skewness in addition to the mean and variance.

Then a regionalization procedure might consist of relating separately the mean, the variance, and the skewness to basin characteristics by the regression method. These three parameters, estimated from the regression equations for a specific site will define the regionalized frequency curve not only in the defined range but also beyond that range where its use is not justified. In practice, regressions are computed for the mean and for the standard deviation only. A mean value of skew is usually applied to a region of considerable size because the computed skew from an individual record is highly unreliable. Regionalization of parameters of the frequency curve is described by Beard (1962, section 7). Fitting of station data to a Pearson Type III distribution is described in book 4, chapter A2 of "Techniques of Water Resources Investigations" (Riggs 1968b) and by Water Resources Council (1967).

Use of short records on small streams

The usual regional analysis is based on some long records and some short ones. Records of floods from small drainage areas are usually short; consequently even the 10-year flood may be poorly defined. In this case a regional analysis by one of the methods previously described will tend to produce results of low reliability. On the other hand, there may be more independence among the records for small streams than among those for large streams; if so, this should lead to increased reliability.

The conterminous United States is covered by regional flood-frequency analyses, generally based on data for the larger streams. Since those analyses were made, 10 or more years of record have become available at many small-basin crest-stage gage sites, and the demand for flood frequency characteristics of small streams has greatly increased. The short records on small streams could be used with the records from larger areas to produce another regional analysis, one that would encompass the whole range of drainage area sizes. Such a procedure probably would give the best answer, but one which would more or less duplicate the available results for the larger drainage areas. Furthermore, 5 years from now one might be justified in reanalyzing the records from the small areas, and this would call for another general analysis, resulting in more duplication (or confusion).

Therefore, it is sometimes desirable to produce a regional analysis limited to small drainage areas, one that will not duplicate or conflict to any substantial extent with recently published analyses. This can be done in several ways.

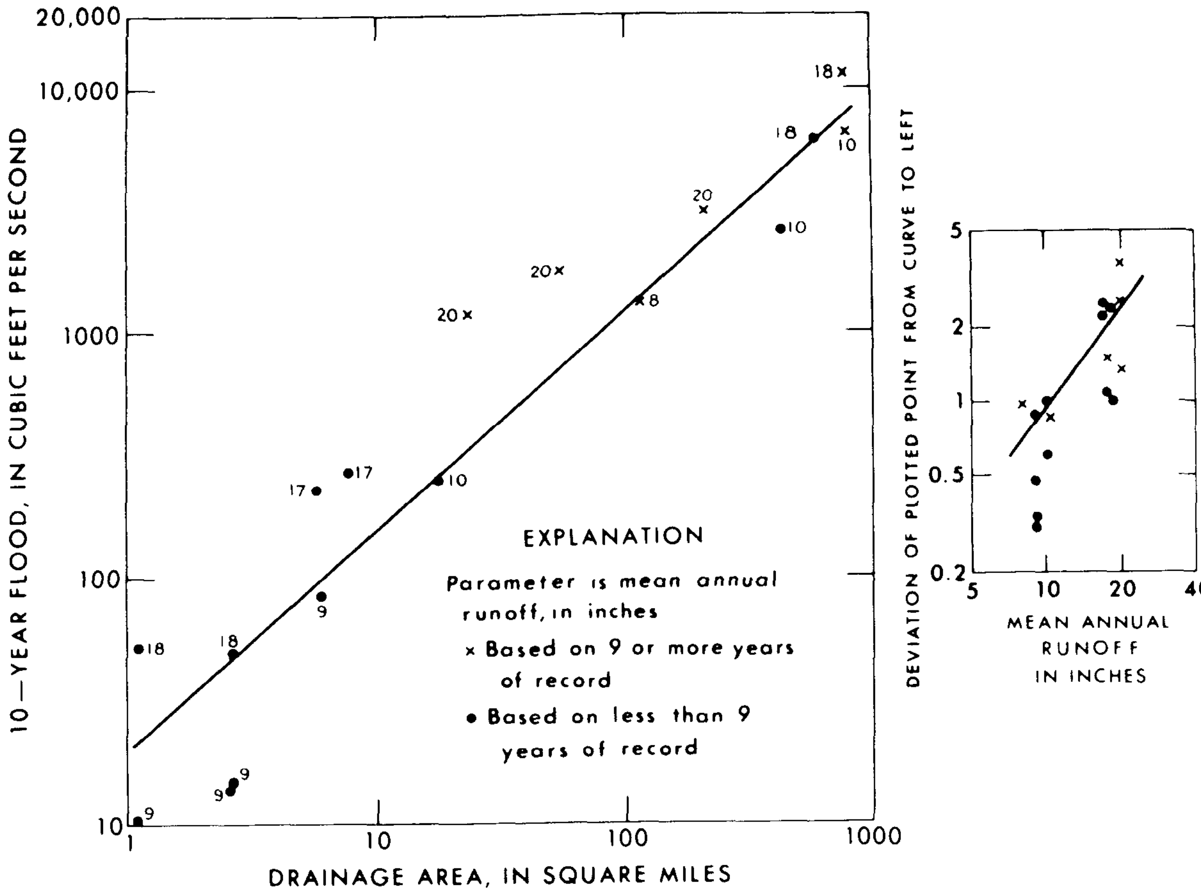
Given a regional analysis by the index-flood method, the defined relations can be extrapolated to small drainage areas. If the mean annual floods for the crest-stage stations check the extrapolated curves, the existing regional analysis may be considered applicable to small drainage areas. If not, the curves should be modified as indicated.

Likewise, regression equations from an existing regional analysis may be checked against data from small drainage areas. If this check indicates that those equations are not applicable, and if time and money are limited, a regression analysis applicable only to small drainage areas could be made. Because of the short records available, such a regression usually will have a large standard error. Graphical regression may be adequate. An example, given in figure 4, is based on data used by Boner and Omang (1967). Note that some of the small 10-year floods based on short records have been given little weight in defining the relation of figure 4. Some of the 10-year floods at the larger drainage areas are defined by many years of record and are used to tie this relation into one based on records for large streams.

At many sites on small streams, both flood hydrographs and the causative rainfalls at short time intervals (15 minutes or so) are being collected. After a few years, these data should be adequate to calibrate a hydrologic basin model such as the one described by Dawdy, Lichty, and Bergmann (1972). Then a long record of precipitation can be used to synthesize additional flood peaks. These synthetic peaks can be combined with those of record to define the frequency curve to recurrence intervals of 50 years or more. Using frequency curves defined to that length, a standard regionalization process should give good results. The practicability of the method depends on obtaining a good relation between floods and precipitation and on the availability of an applicable long precipitation record.

Defining the flow characteristic

The better the frequency curves which form the basis for the regionalized relation, the better that relation will be. Therefore, some effort should be made to improve the frequency curves. Where data are available, the rainfall-runoff approach described above can be used. Another method, utilizing historical data is described by Dalrymple (1960). Sometimes the definition of a frequency curve can be improved by correlation with a longer record, but this procedure generally results in improvement only if the correlation coefficient between the two records is greater



4. Graphical regression of 10-year floods defined from short records, Kootenai River basin, Montana.

than about 0.8. However, under certain conditions improvement can be obtained at smaller values of the correlation coefficient (Matalas and Jacobs, 1964).

The improvement of a frequency curve by correlation with a longer record is obviously desirable if one is concerned only with characteristics at that site. But use of such a modified frequency curve in a regional analysis may not improve the result over that obtained by use of the unmodified curve, the reason being that the flood experience at the two sites may not be independent. Because the regionalization process attempts to average that part of the variability due to random occurrences of weather, a substantial extension of a frequency curve on the basis of another one already included in the analysis will tend to duplicate the experience at the site of the longer record. This duplication may bias the result of the regional analysis. As an extreme example, consider a region containing 20 records of 10 years and one record of 50 years, and assume that each of the short records is adequately correlated with the concurrent part of the long record to justify extension to 50 years. If the 20 records were all for the same 10-year period, the upper part of the regionalized curve would be nearly identical to the individual curve for the 50-year period of record (given the same basin characteristics). Now suppose that given the same data, a regionalization based on unextended frequency curves was made. This would still lean heavily on the long record for the higher recurrence intervals and might not be too much different at 20 years and below because of the high correlation among all records. So which result is the better? There is little basis for a decision, but because the difference in results likely would be small, we probably would select the method using the unextended frequency curves that requires less work.

More commonly the short records in a region are not closely correlated with longer ones; in practice few short records will be found that meet the criterion for extension. Thus a decision on whether to extend or not to extend may be required only infrequently.

Frequency data for use in a regional analysis are often based on records for a selected period of years, called a base period. Adjustment of all records to a base period requires that parts of long records be discarded and that short records be extended. The objective of using a base period is to obtain a group of records all affected by the same weather occurrences so that the differences among the frequency characteristics are largely due to differences in basin characteristics. This objective may or may not be met depending on the particular streamflow characteristic being studied and on the size of the region considered.

The records for a base period should produce a regional regression relation with a smaller standard error than would records for periods of various lengths. However, the purpose of a regionalization is to average the variability due to random weather occurrences. The more samples (in time) used the more likely will the average represent long-term conditions. But use of a base period minimizes the number of independent events and thus may produce a biased result.

Ordinarily the flood-frequency characteristics should be defined by all the record available at each site. If an extension of a record is made to improve the definition of the frequency curve, the extension should cover the entire length of the longer record, not just a part of it.

Lack of independence of flood occurrences at the various sites used in a regional analysis has two effects: (1) The variability of the slope of the regression line is reduced, and (2) the variability of the intercept is increased; that is, the slope of the regional relation is better defined because of a dependence among stations but its position is less well defined (Matalas and Benson, 1961). For example, suppose that all the stations in a region are affected by the same storms, that the 20-year flood is defined at each station, and that these 20-year floods are related to basin characteristics. The resulting regression equation may describe very well the relative effects of the various basin characteristics on flood magnitude, but we do not know whether the magnitude is that of a 20-year flood or of one having a very different recurrence interval because we have essentially only one sample of flood experience.

In most parts of the United States, the longer flood records can not be considered homogeneous because of man-made changes in the flow regimen. It has been proposed that a hydrologic basin model be used to adjust the annual floods of record to undeveloped basin conditions. This would add considerable information for use in a regional analysis. Of course the results of the regional analysis would not apply to that particular stream under its existing pattern of regulation.

Model and parameters

The regression model used in regional flood-frequency analyses is of the form

$$Q_n = a\, A^b B^c C^d \ldots .$$

the log transform of which is linear. Selection of suitable independent variables is often made on a statistical basis; that is, many variables are used in preliminary regressions and those that lack statistical significance are discarded. This practice occasionally results in the retention of a variable whose effect in the regression does not conform to known hydrologic principles. Usually the effect of such a variable on the result is trivial (a few percent reduction in standard error). The fact that the particular variable does not appear in regressions for other areas may indicate that it does not exert an effect of practical significance.

It seems desirable to select in advance those variables which are expected, on the basis of previous work, to have practical significance. However, some commonly used and widely accepted variable may not prove significant in a particular regression if the range in that variable is small. For example, channel slope is a significant basin characteristic in some regional frequency analyses, but if all streams in a region have very similar slopes, the slope characteristic will not be significant, either statistically or practically.

The significant variables found in 10 published regional flood-frequency regressions are shown in table 2. The four most common variables are drainage area, main-channel slope, percentage of basin area covered by lakes and swamps, and mean annual precipitation. Mean annual runoff appears only once; mean annual precipitation could have been substituted for it because the two are highly related. Only four of the 11 remaining variables appear more than once.

Because of the relatively high intercorrelation among certain of the so-called independent variables and because most of these variables are only crude indexes of the characteristic being described, we may question whether the ones infrequently reported as significant are really so. Ordinarily the first four variables in table 2 will reduce the standard error very close to the practical minimum.

The regression model previously described was used for each of the 10 analyses referred to in table 2. However, that model is not adequate for semiarid regions of large relief. For example, consider a stream which rises in the high mountains and flows onto a plain. The 10-year flood will increase with drainage area to the base of the mountains and from that point on may decrease, or at least not increase at the same rate as in the upper part of the basin. If channel slope is included in a regression using data from such streams, the computed effect of drainage area will depend to some extent on the way channel slope is defined; the usual definition is not adequate to describe a major break in the channel profile. Thus a better model for regional analysis is needed for such regions.

It is desirable practice to plot the residuals from a regional regression analysis on a map to check for possible geographical bias. Where a substantial bias is indicated by this test, a "geographical factor" is sometimes introduced into the regression equation to compensate for the bias. Before doing this, the analyst should realize that a geographical bias does not necessarily indicate that the regional relation is inadequate; there may have been much higher flood experience in one part of the region than in another during the period of record used. If possible one should identify the reasons for the bias and incorporate them in the analysis rather than use a geographic factor.

Regardless of the region being studied, the analyst should select his model and the relevant variables on the basis of knowledge of the system, leaving little of the selection process to be defined by the data. Snyder and Stall (1966) support this approach by writing:

> The extreme versatility of numerical methods and computing machines has sometimes led man into the pitfall of relying solely on these methods and machines. This occurs when an analysis of a set of data is made without reference to past knowledge, under

Table 2.—Independent variables used in 10 regional flood-frequency analyses

Variable	1	2	3	4	5	6	7	8	9	10
Drainage area	X	X	X	X	X	X	X	X	X	X
Main-channel slope	X	X	X	X	X					
Percentage of basin covered by lakes and swamps	X		X	X				X	X	
Mean annual precipitation		X					X		X	X
Mean annual runoff								X		
T-year 24-hour rainfall	X		X							
Average degrees below freezing in January	X									
Orographic factor	X									
Elevation		X								X
Number of thunderstorm days		X	X							
Main-channel length			X							
Ratio of runoff to precipitation			X							
Mean annual snowfall				X						
Average number of wet days per year					X					
Shape factor						X				
Geographical factor								X	X	

the erroneous assumption that the structure of the model is revealed by a particular set of data. The contribution that prior knowledge can make to understanding of the present problem or process is excluded by this practice, which also is inefficient and the frequent cause of incorrect conclusions. By such a practice man abdicates much of his responsibility and the research process loses the crucial elements of intelligence and logic that only man can contribute.

In general the extent of a region encompassed by a regional analysis should be limited to that in which the same variables are considered effective throughout. For example, Benson (1964) found it necessary to separate the western Gulf of Mexico basins into two parts, one dominated by thunderstorms and widespread tropical storms, and another in which snowmelt is the principal flood producer.

Reliability of a regionalization

The reliability of a regional frequency relation cannot be determined precisely but can be approximated. Suppose we have thirty 10-year flood records, that we define the 10-year flood from each, that we relate these 10-year floods to drainage area by regression, and that the standard error of the regression is 0.2 log unit. Now let us estimate the 10-year flood from this regression for a drainage area that is the mean of all the drainage areas used. What are the confidence limits of that estimate? If we consider that we are estimating the 10-year flood that we would expect to define from 10 years of record, then the 67 percent confidence limits would be one standard error of regression, plus the standard error of the mean, above and below the estimate. But we assume the regression performs a regionalization function; ideally that the differences due to basin characteristics are removed by drainage area and that the remaining variability is due to random errors in defining the 10-year floods at each site. If these assumptions are met, the estimate of the true 10-year flood defined would have a standard error of

$$S/\sqrt{N} = 0.2/\sqrt{30} = 0.037 \text{ log units},$$

equivalent to about 9 percent.

The standard error, based on regression, of an estimated 10-year flood in the above example would be much greater than 9 percent because (1) the 30 individual 10-year floods used to define the regression are not entirely independent, (2) the differences among 10-year floods due to basin characteristics are not completely explained by drainage area (nor would they be by any group of basin variables), and (3) estimates for drainage areas other than the mean drainage area would have a larger theoretical error than the estimate for the mean drainage area. Even though the samples are random, it is possible that they are also biased because the weather experience in one 10-year period may not represent long-term conditions. This additional source of error due to bias cannot be stated statistically.

The above discussion should lead to the conclusion that the standard error of an estimate from a regional analysis lies somewhere between the standard error, S, and $S/\sqrt{N}$. That the error is substantially less than S is indicated by comparing Benson's (1960) results with Irza's (1966). Benson drew 100 samples of 10 years each from one distribution and found that about 80 percent of the 10-year floods defined by those 10-year records were within 25 percent of the true value (actually Benson showed that 80 percent of 10-yr floods estimated from 8-yr records would be within 25 percent of correct). Irza related the 10-year flood, defined from 8 years of record, to several basin characteristics and found the standard error of regression to be +100 percent and −49 percent, that is, 67 percent of the items were within that range. Benson's 100-sample study and Irza's regional analysis are analogous if the regional analysis is assumed to have removed the variability of floods due to differences in basin characteristics; that is, the standard error of the 10-year flood (not the 10-yr flood defined from 10 yr of record) from Irza's equation is less than the computed standard error.

Regionalizing Flood Stages

Flood stages corresponding to selected recurrence intervals are needed for planning structures on or near a stream. The usual approach is to estimate the discharge from a regional relation and to compute the stage from this discharge and a channel survey. A simpler though less accurate method relates stream depth to discharge or to basin characteristics (see Thomas, 1964, and Gann, 1968). A more comprehensive study was made by Stall and Yang (1970) in which stream depth (and other measures of channel geometry) were related to flow frequency and drainage area. All three of the above-referenced studies are based on the pioneering work on channel geometry by Leopold and Maddock (1953).

Procedures for Other Flow Characteristics

Multiple regression has been used to regionalize mean annual flows, mean monthly flows, annual minimum flows, annual flood volumes, and some other characteristics. Thomas and Benson (1970) described a study of relations for estimating streamflow characteristics from drainage-basin characteristics in four hydrologically differing regions of the United States. An even more comprehensive use of the multiple-regression method for regionalization of flow characteristics was performed in each State of the conterminous United States during 1970. Results of this study are given in a series of reports, generally one for each State; a typical one is by Collings (1971).

In most humid regions mean flow is closely related to drainage area and mean annual precipitation. Thomas and Benson (1970) found a standard error of regression of 14.4 percent using those two variables in Potomac River; they reduced it further by including channel length and mean annual snowfall. Standard errors of 10 to 15 percent have been attained in other humid regions.

In semiarid regions of large relief the relation of mean flow to drainage area and precipitation may not be usable because of (1) the great range in precipitation with elevation, (2) the lack of good information on precipitation, and (3) the strong influence of geology on mean flow. For example, the standard error of the regression equation for mean flow in New Mexico is 53 percent (Borland, 1970).

In certain humid regions a satisfactory regionalization of mean flows is not attainable because of the movement of ground water across topographic divides. Some regions exhibiting this condition are the Umpqua River basin in Oregon, the Red Rock River basin in Montana, and the Balcones Fault region in Texas.

Although the principles of regional analysis apply to all flow characteristics, the application to low flows is least successful because of the greater dependence of low flows on basin characteristics that are imperfectly known and that cannot be described by simple indexes. Geology is the chief basin characteristic, other than drainage area, controlling the size of low flows in a region of homogeneous climate. Evapotranspiration, especially from the channels and flood plains, also has a substantial effect on low flows in many basins.

Most reported attempts at regionalization of low flows on a statewide basis have been unsuccessful. Forty-seven Geological Survey districts participated in and reported on their comprehensive regionalization studies in 1970. Most districts reported either standard errors of low flows in excess of 100 percent (average of plus and minus percentages) or that no meaningful relation was derived. A notable exception was Connecticut; there the 7-day 10-year low flow was related to drainage area, channel slope, mean basin elevation, and percentage of basin covered by stratified drift, with a standard error of 68 percent (Thomas and Cervione, 1970). This small standard error (relative to those found in most regions) resulted from the inclusion of the fourth parameter. In a previous paper, Thomas (1966) reported large unit base flows from stratified drift and very small ones from till, the predominant surficial glacial deposit.

Regionalization of low flows in a few geologically homogeneous regions of limited extent has produced useful results. A "Techniques of Water-Resources Investigations" on low flow investigations now (1972) being prepared, will consider regionalization of low flows in more detail.

Regionalizing Draft-Storage Relations

Methods of regionalizing draft-storage relations are described by Riggs (1966). Applications of these methods are reported by Patterson (1967) in Arkansas and Skelton (1971) in Missouri. These procedures are not true regionalizations because one or two of the variables required at each site of application are flow characteristics which must be estimated from another regional relation or from discharge information at the site.

Transferring a regional draft-storage relation to an ungaged site may be preferable to estimating the flow characteristics at that site by other means and then defining the draft-storage characteristics from the estimated flow characteristics. The former method seems to require less work and certainly requires less of the user of the report.

Alternatives to Regionalization

The section on "Procedures for Other Flow Characteristics" described some conditions for which regionalization will not provide satisfactory results. Although it may be possible to improve the regression results substantially in some regions by collecting additional precipitation data, making field geologic studies, and devising better hydrologic models, the time and cost required generally make these approaches impractical. Therefore other methods of defining flow characteristics at ungaged sites are needed. Some of these other methods differ from a true regionalization in that they require field information at each "ungaged" site.

Channel-geometry method

Moore (1968) and Hedman (1970) have shown that mean annual flow is closely related to the width and average depth of a selected cross section of the stream channel. Selection of the proper cross section requires some field training, but experienced men can very closely match each other's results. In a recent investigation by Moore and Hedman (personal commun., 1971), the channel widths and mean depths were measured on 53 perennial streams in the mountain region of Colorado. These data were related to the respective mean flows with a standard error of about 18 percent. This derived relation can be used to estimate mean flow at any site in the region at which the channel width and average depth are obtained.

Channel measurements also may be used similarly to estimate floods of selected recurrence intervals. Data at gaging stations in Nevada, California, Arizona, and Kansas have been collected and analyzed for this purpose. In addition, flood-peak characteristics of the 53 streams in the mountain region of Colorado have been related to channel dimensions. Results of these two analyses indicate the usefulness of this method on both perennial and ephemeral streams in the western United States. The channel geometry method has no advantage, however, over regression on basin characteristics in humid regions of moderate relief.

Mean flow from monthly measurements

Another method of defining mean flow of a stream requires discharge measurements near the middle of each month for 1 year (Riggs, 1969). These measured flows are related to concurrent daily mean flows at a nearby gaging station, using a separate relation for each month. Several trials of the method in the western United States, using gaging station records, indicate that the annual mean for 1 year may be estimated within about 10 percent from 12 monthly measurements. An estimate of the long-term mean, based on a relation between means for that year and the corresponding long-term means at gaging stations in the vicinity, is somewhat less accurate.

Defining mean runoff by elevation zones

Riggs and Moore (1965) used streamflow records to define mean annual runoff in inches from 1,000-ft zones of elevation in a hydrologically homogeneous region. A solution, made by trial and error, is possible only when the gaged basins encompass different proportions of area in the various elevation zones.

Low-flow characteristics from base-flow measurements

Discharge measurements of low flows at an ungaged stream site may be related to concurrent flows at a nearby gaging station at which the low-flow frequency curve is defined. The low-flow characteristics at the gaging station then can be transferred through that relation to obtain estimates of the characteristics at the measurement site. The method is widely applicable. Examples are given by Riggs (1965, 1970).

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