Variability of Streamflow and Precipitation in Washington

By David L. Kresch

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BRUCE BABBITT, Secretary

U.S. GEOLOGICAL SURVEY

Gordon P. Eaton, Director

For additional information write to:

District Chief
U.S. Geological Survey
1201 Pacific Avenue - Suite 600
Tacoma, Washington 98402

Copies of this report may be purchased from:

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CONVERSION FACTORS

Multiply	By	To obtain
inch (in)	2.54	centimeter
foot (ft)	0.3048	meter
acre-foot (acre-ft)	1,233	cubic meter
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer
cubic foot per second (ft^3/s)	0.02832	cubic meter per second

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ABSTRACT

This study examines the patterns of variation of streamflow and precipitation in Washington, through statistical analyses of data for 55 streamflow stations and 38 precipitation stations. Patterns of variation were evaluated using cumulative departures of monthly values from mean-monthly values, with a base period of 1937-1976. The cumulative departures for each station were rescaled (standardized) to facilitate the comparison of patterns for individual stations.

The degree of similarity between the patterns of variation for each pair of stations was determined by calculating the coefficient of correlation between them. To identify geographic regions of similarity, matrices of these coefficients were evaluated using cluster analyses. The cluster analysis of the streamflow stations defined geographic regions of similarity in southwestern, northwestern, and northeastern Washington. The cluster analysis of the precipitation stations defined only two regions of similarity—western and southeastern Washington.

In general, a higher degree of similarity was found among the patterns of variation for the streamflow stations than among the precipitation stations. A slight inverse correlation (-0.55) was found between the patterns of variation for southeastern and western Washington precipitation stations.

Cumulative departures of monthly values from mean-monthly values were used for a variety of other hydrologic applications. A water-resource-availability index was developed that provides a quantitative interpretation of present conditions in the context of historical records of streamflow and precipitation. A method was discussed for estimating monthly streamflow and precipitation at ungaged sites from monthly values at gaged sites. Two methods were described for the use of cumulative departures in determining the minimum reservoir size needed to average out wet and dry periods without the reservoir ever overfilling or emptying.

INTRODUCTION

Records of stream discharge and precipitation document that the quantity of freshwater available for use at any given location changes continuously with time. Stream discharge and precipitation vary seasonally throughout each year and from one year to the next. Periods of above- or below-average streamflow and precipitation often occur in series of consecutive years. These persistent wet or dry periods appear to be based on meteorological variations. For example, prolonged periods of water shortage (drought) during the winter occur in Washington when high pressure ridges over the State displace the Pacific storm track northward into British Columbia. Summer drought is correlated with the northward extent of the Pacific subtropical high (Graumlich, 1987, p. 28).

Water suppliers and managers need information about short- and long-term variations in streamflow and precipitation in order to ascertain whether available water supplies will satisfy present and future demands and to prevent overdevelopment in the future. Because allocations are based partly on historical data, comparison of current conditions with historical records is necessary and allows an evaluation of whether current conditions correspond to a wet, dry, or average period. Examples of persistence of above- or below-average conditions in the historical records give an indication of the potential degree and duration of similar future conditions.

Municipalities sometimes allow community development and growth to continue until water-supply limitations become apparent. Then, during extended dry periods of months or years, the water supply cannot meet demands for the water. Water shortages of certain magnitudes that extend over more than a few years cannot be remedied with water from most reservoirs in Washington because their storage capacities are too small to meet extended demands.

Background

Washington State experienced widespread water shortages in 1987 and 1988. During the summer months of these years, water stored in reservoirs for supply of municipal and irrigation needs became depleted. In many places the withdrawal of water from water-supply wells had to be curtailed for various uses and some wells went dry. Reduced streamflows hindered the passage and threatened the survival of fish in some rivers, and shorelines receded beyond the reach of docks and boat ramps in some lakes. Acute water shortages also occurred in 1977, in the early 1940's, and during the "Dust Bowl" years in the late 1920's.

The duration of extreme flooding in Washington is usually brief, generally lasting for only a few hours or days, and damages are usually endured and repaired. Above-average seasonal or annual precipitation and streamflow that persists throughout a series of years is seldom an enduring problem.

The population of Washington is increasing and expanding in both the western part of the State, where water is most plentiful, and in the drier eastern part. In the western part of the State, where approximately 75 to 80 percent of the population resides, municipal and industrial water use accounts for most of the water used. In the eastern part of the State, where more than 90 percent of the State's irrigated acreage is located, irrigation of agricultural crops accounts for most of the water used. Those who supply water or manage the apportionment of water resources try to plan and prepare for the water needs of growing populations by:

(1) Tapping sources of water not fully or previously used,

(2) Designing and implementing facilities for importing water,

(3) Designing and implementing facilities to store water from wet seasons or years for use during dry periods, and

(4) Arranging for water conservation, sharing, and allocation when water shortages occur.

Variations in the quantity of available water can affect which of these approaches are used.

The Washington State Department of Ecology (Ecology) manages and apportions the water resources of the State of Washington. Successful implementation of this responsibility requires, among other things, a knowledge of the patterns of short- and long-term variations in streamflow and precipitation. The U.S. Geological Survey (USGS), in cooperation with Ecology, conducted this study to provide some insights about the patterns of variation of these hydrologic variables in Washington.

Purpose and Scope

This report describes the results of a study of the patterns of variability of streamflow and precipitation in Washington. Records of monthly discharge at 55 streamflow stations and monthly precipitation at 38 precipitation stations were used in the study.

This study's four objectives were to: (1) determine whether Washington could be divided into geographic regions where variations in streamflow and precipitation follow similar patterns and to delineate the regions on maps; (2) develop a water-resource-availability index that places the current condition of a streamflow or precipitation station in the context of historical patterns of variation for that station; (3) develop a method for estimating monthly streamflow and precipitation at ungaged sites; and (4) describe two methods for evaluating the adequacy of the storage capacity of existing or proposed reservoirs.

It is believed that variations in streamflow and precipitation should exhibit patterns of increasing and decreasing values over time because of the typical cyclic nature of hydrologic variables. However, these patterns are difficult to discern by eye when looking at a time-series plot of monthly-mean values (fig. 1a) because of the larger and more erratic variations in month-to-month values. Monthly-mean values (henceforth referred to as monthly values) are obtained by averaging all daily-mean values during a month. Slight improvement in the detection of patterns can be obtained by plotting the departure, or difference, of each monthly value from the mean-monthly value—the average value for the month over some period of record (fig. 1b). However, the individual monthly departures scatter considerably and it is still difficult to discern patterns of dry or wet periods. The patterns become more evident, however, by plotting cumulative departures of discharge (fig. 1c) and precipitation. For example, it can be seen from the plot that 1935-45 was generally a period of below-average streamflow (a dry period), and that 1950-77 was generally a period of above-average streamflow (a wet period). Therefore, time series of cumulative departures of streamflow and precipitation records (henceforth referred to as chronologies of cumulative departure) were used in the study to exhibit patterns of dry or wet periods.

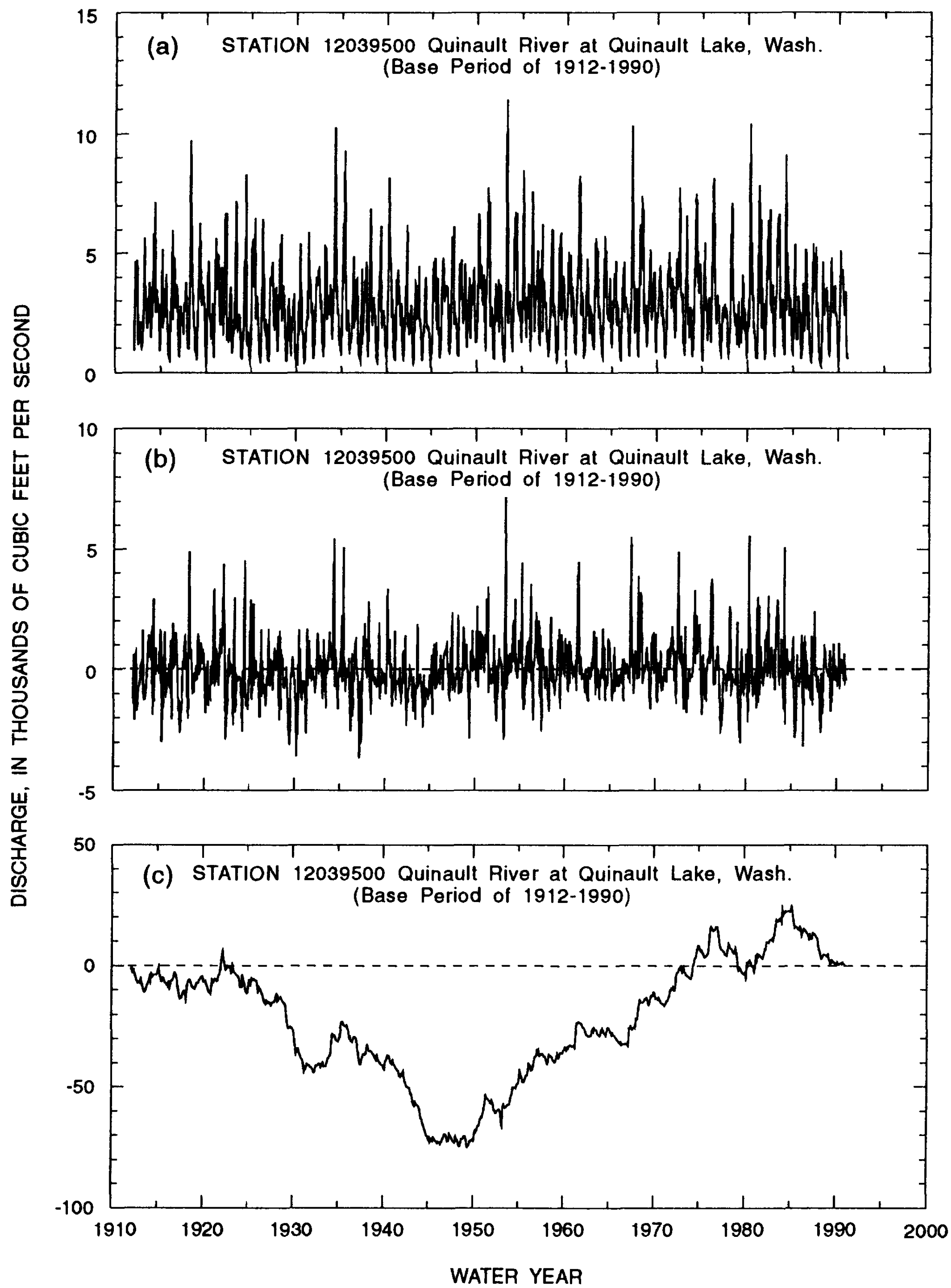

Figure 1.--Time-series plots of discharge at station 12039500. (a) monthly discharge; (b) departure of monthly discharge from mean-monthly discharge; and (c) cumulative departure of monthly discharge from mean-monthly discharge.

METHODS

Creation of Streamflow and Precipitation Data Bases

The first step in the development of information about variations in streamflow and precipitation was to create computer data bases for these two hydrologic variables. Each data base consists of a set of ASCII (American Standard Code for Information Interchange) files—one for each streamflow or precipitation station used. These station files contain monthly values of streamflow or precipitation grouped by water years[1]. (A water year is the 12-month period from October 1 of one calendar year through September 30 of the following calendar year, and it is designated by the calendar year in which September occurs. All statements in this report regarding years of record at streamflow or precipitation stations refer to water years of record.)

The criteria used to select records for USGS streamflow stations in Washington were that they (1) have continuous record throughout the base period 1937-76 (selection of base period is discussed later in report), (2) be widely distributed to adequately define variations in streamflow patterns throughout the State, and (3) represent natural conditions not significantly affected by man's activities, such as water diversion or import. There were only a few stations to represent some parts of Washington, especially eastern Washington; therefore, records from USGS stations in Oregon and Idaho and from Water Survey of Canada stations in British Columbia were also included. The stipulation that records selected should represent natural conditions was not always adhered to for eastern Washington streamflow records because of the scarcity of unaffected streams in that part of the State. Consequently, most of the eastern Washington streamflow records that were included in the data base are affected by minor regulation, diversions, or both.

The streamflow files contain monthly discharges, in cubic feet per second, for 55 streamflow stations. Thirty-two of the streamflow stations are in Washington, 15 are in Oregon, 7 are in Idaho, and 1 is in British Columbia, Canada (Water Survey of Canada, 1989). The drainage basins that contribute surface-water runoff to the streamflow measured at these stations range in size from 8.00 to 7,260 mi^2; however, only four of them exceed 2,000 mi^2. The median size of the drainage basins is 219 mi^2 and the mean size is 641 mi^2.

The precipitation files contain monthly precipitation, in inches, for 38 precipitation stations in Washington that are uniformly distributed throughout most of the State. All of the precipitation data were obtained from publications and computer data bases of the U.S. National Oceanic and Atmospheric Administration.

Computing Cumulative Departures of Monthly Values from Mean-Monthly Values

To determine cumulative departures, the mean-monthly values of streamflow or precipitation must be determined for a base period of record. The equation used to calculate mean-monthly value is

$$\bar{X}_{.j} = \left[\sum_{i=1}^{N} \Delta t_{i,j} X_{i,j}\right]\left[\sum_{i=1}^{N} \Delta t_{i,j}\right]^{-1} , \qquad (1)$$

[1]Files of monthly values for the streamflow and precipitation stations used in this study can be obtained by written request to the Washington District office of the U.S. Geological Survey at the address given on the back of the report title page. The beginning of each streamflow- or precipitation-station file contains several lines of information that specify the period of record for streamflow or precipitation data, the selected base period, the years for which departures are to be calculated, the initial value of cumulative departure, and the dimensions, scales, and units that are to be used to generate plots of cumulative departure. All of the file specifications may be modified at the discretion of the user. Modifications can be used to change the units or scale of a plot or to calculate and plot cumulative departures for an entirely different set of user-defined conditions. The ending year of record specified in a station file should be modified only if additional years of record are added to the file.

where

$X_{i,j}$ = the monthly value, expressed as a rate, of streamflow, in cubic feet per second, or precipitation, in inches per day, in month j of year i;

$\bar{X}_{\cdot j}$ = the mean-monthly value of streamflow or precipitation in month j, over the years of the base period ($\bar{X}_{\cdot,j}$ is therefore expressed as a rate in the same units as $X_{i,j}$);

$\Delta t_{i,j}$ = the time in month j of year i, in units corresponding to the rate of $X_{i,j}$ (for example, in seconds, if $X_{i,j}$ is discharge in cubic feet per second, or days, if $X_{i,j}$ is rate of precipitation in inches per day); and

N = number of years of record in the base period.

The $\Delta t_{i,j}$ term is included in equation 1 so that mean-monthly values calculated for February will be time-weighted according to the number of days in February each year (29 during leap years and 28 during all other years).

The base period could be defined as either the entire period of record, or a shorter period during which the mean-monthly values computed by equation 1 are considered to be representative of long-term, average conditions (avoiding over-representation of either dry or wet years). The departure from the mean, for each month j and year i, is defined as

$$D_{X_{i,j}} = X_{i,j} - \bar{X}_{\cdot,j} \quad . \tag{2}$$

A positive departure of precipitation, for example, indicates that the rate of precipitation for that month exceeds the long-term average for that month.

Let the cumulative departure be given by

$$D_X^*(t) = \sum_{t_1}^{t} \Delta t_{i,j} \, D_{X_{i,j}} \quad , \tag{3}$$

where the sum is taken over all months, j, and years, i, in the interval from specified starting time t_1 to ending time t. Note that each monthly departure $D_{X_{i,j}}$ is multiplied by the amount of time in month j of year i to convert it from a rate to an amount. The cumulative departure is thus the total of all monthly departure amounts from time t_1 to time t.

To interpret the cumulative departure, consider, for example, that $X_{i,j}$ is the monthly streamflow, in cubic feet per second, in month j of year i. Then $D_X^*(t)$ represents the excess or deficiency of total volume of flow during the time interval from t_1 to t, compared to the volume that would have flowed in the river if mean conditions had prevailed. Similarly, if $X_{i,j}$ represents the monthly rate of precipitation, in inches per day, in month j of year i, then $D_X^*(t)$ represents the excess or deficiency of total inches of precipitation compared to that which would have fallen if mean conditions had prevailed. The cumulative departure equals zero at the starting time, increases during wet periods when the monthly departures are each positive, and decreases during dry periods when the monthly departures are each negative.

Computing Rescaled Cumulative Departures

Plots of cumulative departures for precipitation and streamflow generally would be expected to exhibit similar patterns of variation because precipitation produces surface runoff to streams and recharges the aquifers that contribute to the baseflow of streams. To relate chronologies of cumulative departures for these two hydrologic variables, or even for the same variable measured at different locations, it is helpful to first rescale (standardize) the cumulative departures by dividing them by scaling factors that are characteristic of and expressed in the same units as the variables. The terminology "rescaled range" has been discussed in the literature in connection with long-term persistence in hydrologic variables (see Mandelbrot and Wallis, 1969b); rescaled cumulative departures are used in the definition of the rescaled range.

To define the scaling factor, let the volume of streamflow or inches of precipitation in month j of year i be given by

$$Q_{X_{i,j}} = \Delta t_{i,j} \, X_{i,j} \quad , \tag{4}$$

and the cumulative-annual value Q_{X_i} of streamflow or precipitation, in year i, be given by

$$Q_{X_i} = \sum_{t_{i,1}}^{t_{i,2}} \Delta t_{i,j} X_{i,j} , \qquad (5)$$

where the sums are taken over the 12 months j from the beginning of year i at time $t_{i,1}$ to the end of that year at time $t_{i,2}$.

The mean-annual value of Q_X is given by

$$\bar{Q}_X = \frac{1}{N} \sum_{i=1}^{N} Q_{X_i} , \qquad (6)$$

where N is the number of years in the base period.

Let the variance σ_X^2 of the cumulative-annual values be estimated by

$$\hat{\sigma}_X^2 = \frac{1}{N-1} \sum_{i=1}^{N} (Q_{X_i} - \bar{Q}_X)^2 . \qquad (7)$$

Then, the scaling factor S_X, which is defined as the standard deviation of the cumulative-annual values, is given by

$$S_X = \hat{\sigma}_X . \qquad (8)$$

Rescaled cumulative departures are calculated by dividing the cumulative departures $D_X^*(t)$ from equation 3 by the scaling factor S_X from equation 8. Therefore, rescaled cumulative departure is given by

$$\frac{D_X^*(t)}{S_X} = \frac{1}{S_X} \sum_{t_1}^{t} \Delta t_{i,j} D_{X_{i,j}} . \qquad (9)$$

Defining the scaling in this way results in a single factor that is applicable as each subsequent monthly departure is added to the accumulated total.

Separate computer programs STREAM.F77 and PRECIP.F77[2] calculate and plot rescaled cumulative departures for streamflow and precipitation stations. Program STREAM.F77 can also calculate and plot cumulative departures in acre-feet, rather than in dimensionless rescaled units, if desired. The cumulative departures calculated by these two programs are written to output files[3].

Interpretation of Time-Series Plots of Rescaled Cumulative Departures

Time-series plots of rescaled cumulative departure (henceforth referred to as RCD) are interpreted on the basis of the rate of change of the cumulative departures over selected time intervals. A plot that slopes downward over a time interval indicates that the hydrologic variable was below average much of the time during the interval—an indication of hydrologic drought. Similarly, a plot that slopes upward over time indicates that the hydrologic variable was above average much of the time. The rate and duration of a declining period of RCD indicates the relative severity of drought. A high rate of decline persisting for a long time indicates severe drought.

Data from several streamflow stations and precipitation stations in Washington (fig. 2) illustrate the interpretation of time-series plots of RCD. The RCD values derived from monthly discharges at one of the streamflow stations and from monthly precipitation at one of the precipitation stations are shown on figure 3. The base period 1937-76 was used for both station records and both graphs were plotted using the same departure scales and time scales to demonstrate the similarity of the RCD graphs for streamflow and precipitation. The generally decreasing trend in

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[2]Source codes for these and all other FORTRAN F77 computer programs written for this study can be obtained by written request to the Washington District office of the U.S. Geological Survey at the address given on the back of the report title page.

[3]The amount of information printed in the output files generated by computer programs STREAM.F77 and PRECIP.F77 is controlled by user response to program prompts during the interactive execution of the programs. Some program specifications, such as the number of monthly values in the last year or record, are also entered interactively in response to program prompts.

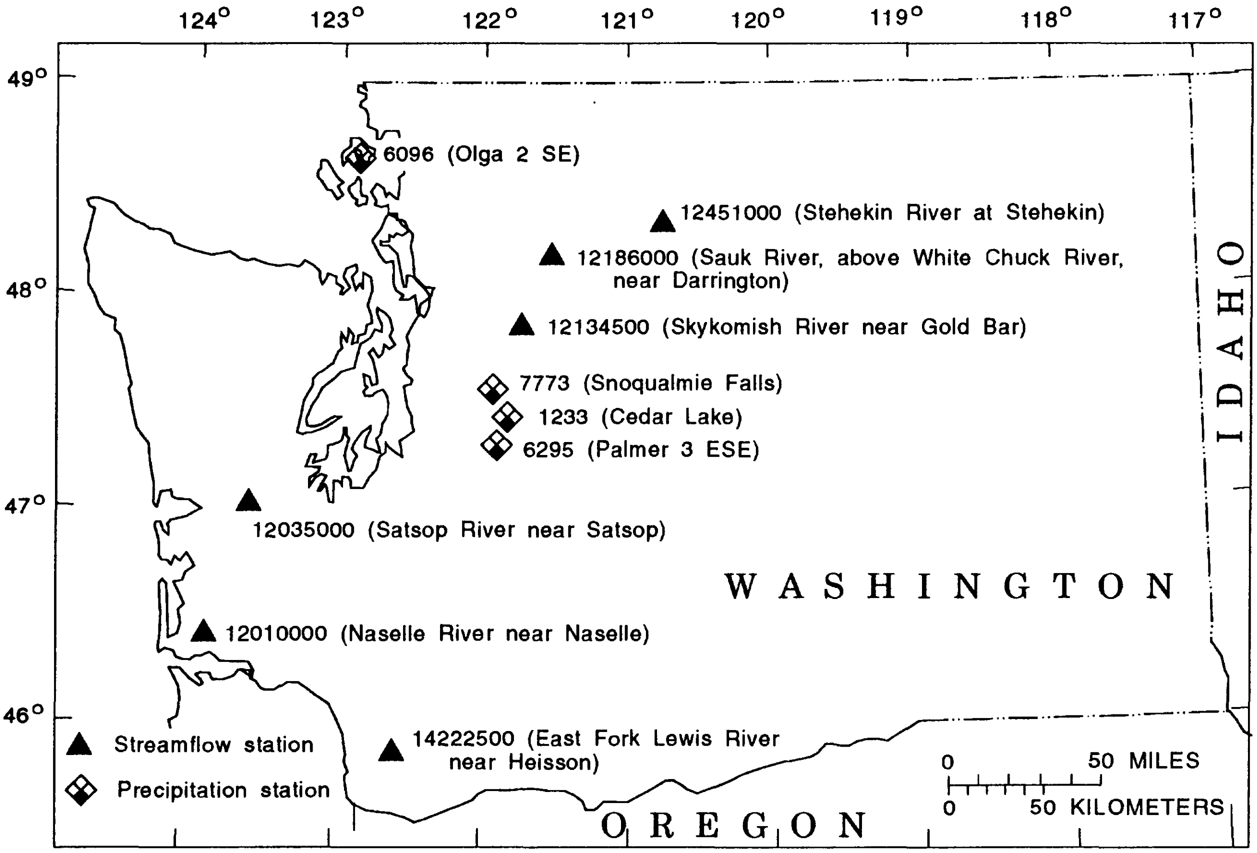

Figure 2.--Locations of streamflow and precipitation stations in Washington used to illustrate the interpretation of rescaled cumulative departures.

the RCD on both graphs during 1929-1931, 1935-1945, and 1977-1987 indicates that both streamflow and precipitation were much below normal during those years. The graphs show that the severity of droughts, indicated by the steepness and duration of the decline, vary considerably.

The base period used to calculate RCD influences the interpretation of the resulting time-series plot of the departures. The graphs on figure 4 demonstrate this for streamflow station 12134500 for base periods of 1937-76 (40 years) and 1946-86 (41 years). The graphs generally tilt relative to one another because the departures are computed (equation 2) with respect to different mean-monthly values $\bar{X}_{.,j}$, and because the graphs are set equal to zero at different beginning and ending points. The graphs have small scaling differences also because the standard deviations of the cumulative-annual values (equation 8) differ slightly.

Base-Period Selection

The first step in determining RCD values for each streamflow and precipitation record was to select a base period. The base period selected for this investigation was 1937-76. This base period, which seems to span a cycle of recent decreasing and increasing cumulative departures, was selected because (1) there are enough streamflow and precipitation stations that were operated continuously during this period to adequately define variations in streamflow and precipitation patterns throughout the State, and (2) it yields mean-monthly values and standard deviations of cumulative-annual values that represent long-term, average conditions. The mean-monthly values (equation 1) for the selected base period need to approximate long-term, average values, so that the departures (equation 2) will represent deviations from average conditions.

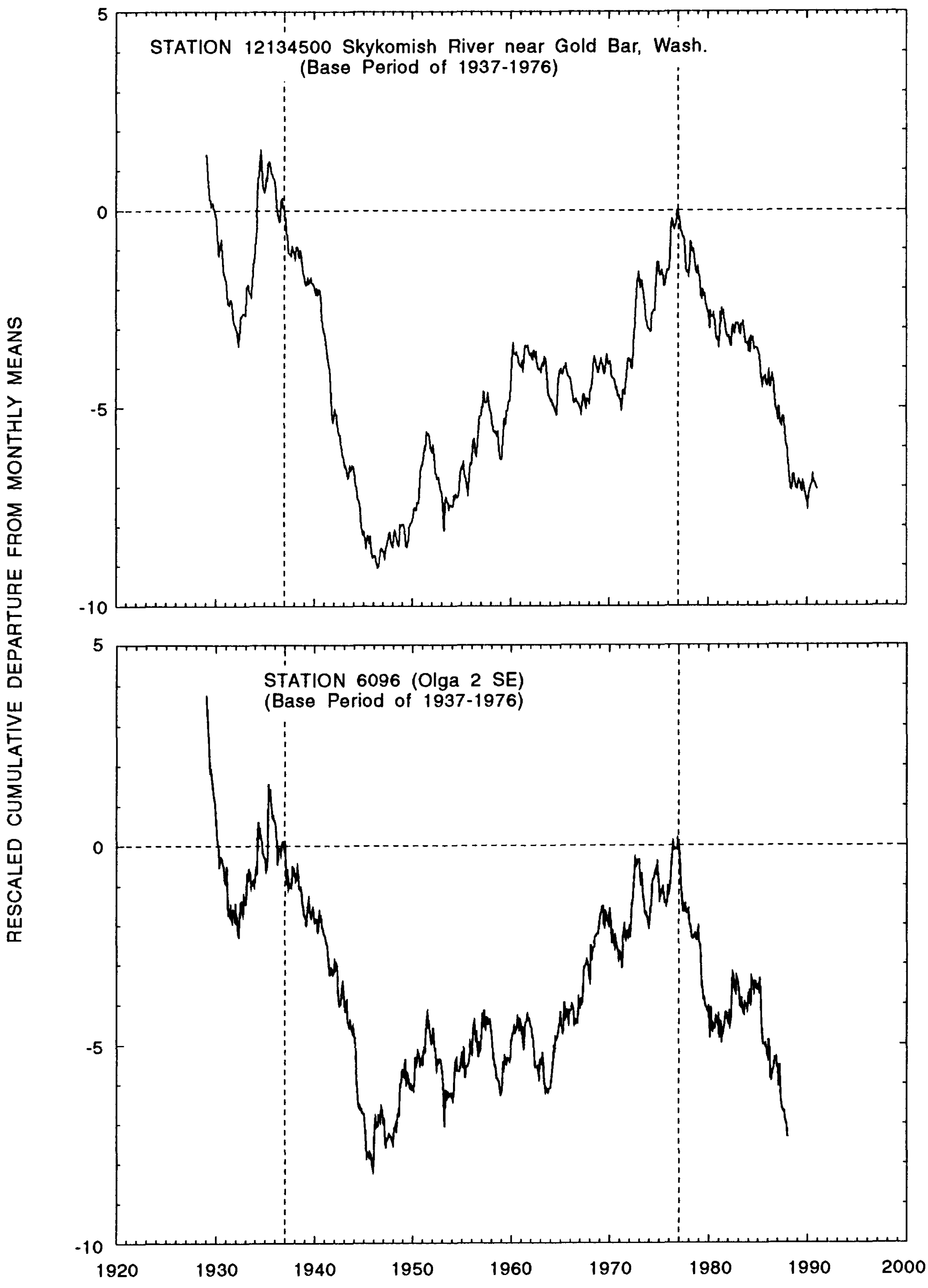

Figure 3.--Rescaled cumulative departures of streamflow at station 12134500 and precipitation at station 6096. The dashed vertical lines represent the beginning and end of the base period.

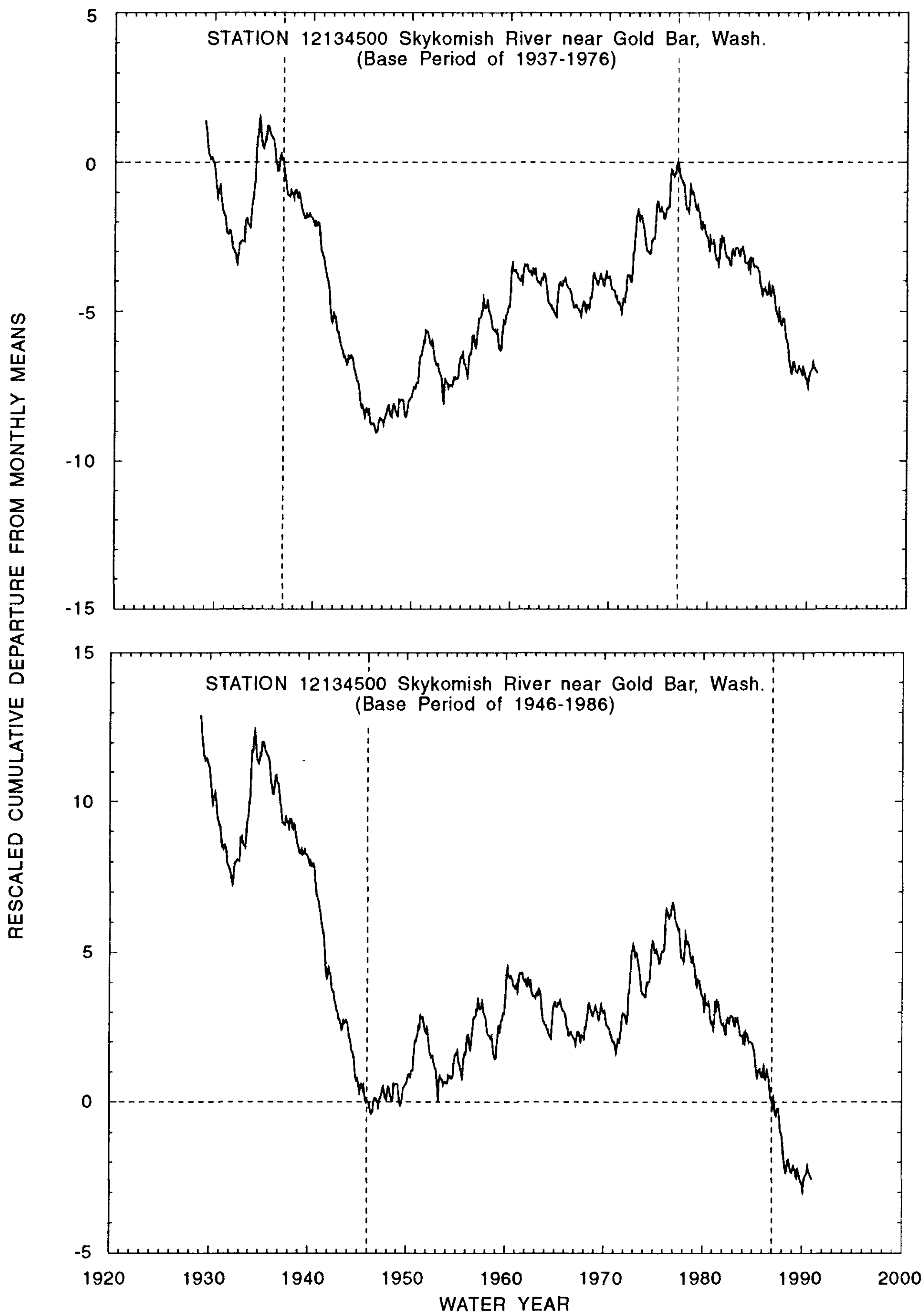

Figure 4.--Rescaled cumulative departures of streamflow at station 12134500, using two different base periods. The dashed vertical lines represent the beginning and end of the base periods.

The process of selecting the base period began with stations having the longest periods of record to increase the likelihood that the mean-monthly values at each station would approximate average conditions. Continuous records for three of the stations in the precipitation data base began in the 1870's and for twelve other stations in the 1890's. In contrast, the longest streamflow records available are those for gaging stations that were established in the 1900's and 1910's. Nevertheless, the selection of the base period was based solely on the longest streamflow records because there was more similarity among time-series plots of RCD for streamflow stations than among plots for precipitation stations. Mean-monthly discharges were calculated for both the base period 1937-76 and the period of record for many of the longest operating streamflow stations. The differences in the mean-monthly discharges were less than 10 percent for most of the stations. Differences between the standard deviations of the cumulative-annual discharges for the two periods were less than 5 percent for most of the stations.

The degree to which mean values calculated for the base period represent average conditions was further evaluated by examining some long-term precipitation records received from Lisa Graumlich (Laboratory of Tree-Ring Research, written commun., 1990) that were reconstructed from chronologies of annual tree-ring widths. The tree-ring chronologies, which were derived by Graumlich (1985), span the period 1675-1975. This 301-year period is long enough so that mean precipitation values calculated for it should represent average conditions. The mean values of the reconstructed precipitation records for the period 1937-75 are approximately 3 percent greater than means calculated for the 301-year period of record; therefore, mean streamflow and precipitation values calculated using the base period 1937-76 may represent conditions that are slightly wetter than average.

VARIABILITY OF STREAMFLOW AND PRECIPITATION

Chronologies of RCD were calculated from the monthly values of streamflow and precipitation for all station records that span the base period 1937-76. These chronologies were displayed graphically as time-series plots at uniform scales and analyzed mathematically to evaluate the variability of streamflow and precipitation.

Similarities among RCD's of streamflow and precipitation for selected stations are shown on figures 5 and 6. The streamflow graphs (fig. 5) are generally similar in magnitude and pattern, even though the stations are located on different rivers in different parts of Washington (see fig. 2 for locations). The graphs for the stations on the Skykomish, Sauk, and Stenhekin Rivers are nearly identical, even though the rivers are as much as 60 miles apart and in different drainage basins.

The graphs for the precipitation stations (fig. 6) are less similar than are the streamflow graphs, but are sufficiently similar to indicate that patterns of persistence of wet or dry periods may be similar throughout large regions of the State, independent of climatic differences. There are obvious dissimilarities among the precipitation graphs, however, and between them and the streamflow graphs (fig. 5). One possible reason is that a precipitation-station record reflects localized weather variations that often are not similar to the general weather variations over nearby drainage basins.

Cluster analyses (SAS Institute, Inc., 1985, chapter 40, pages 801-816) of the chronologies of RCD for all the stations in the streamflow and precipitation data bases were used to define geographic regions of similarity—geographic areas within which the patterns of variation of RCD's are similar. The streamflow and precipitation records were analyzed separately. The data set evaluated in each cluster analysis was a matrix of the coefficients of correlation between the chronologies of monthly RCD's for each pair of stations. Cluster analysis placed each station record in the cluster with which it has the highest squared coefficient of correlation.

Regions of Similarity Among Patterns of Variation for Streamflow Stations

Cluster analysis separated the 55 streamflow-station records into four clusters (fig. 7 and tables 1-4). The stations in clusters 1, 2, and 3 that are located in Washington define geographic regions of similarity in southwestern, northeastern, and northwestern Washington, respectively. The designation of northeastern Washington as a region of similarity is somewhat indeterminate, however, because most of the streamflow records that were used in that part of the State are affected to varying degrees by regulation, diversions, or both. Cluster 4, which contained only two stations, both located in northeastern Oregon, was not used in the determination of a region of similarity in Washington. No region(s) of similarity could be defined for southeastern Washington because that part of the State lacked a sufficient number of satisfactory gaging-station records.

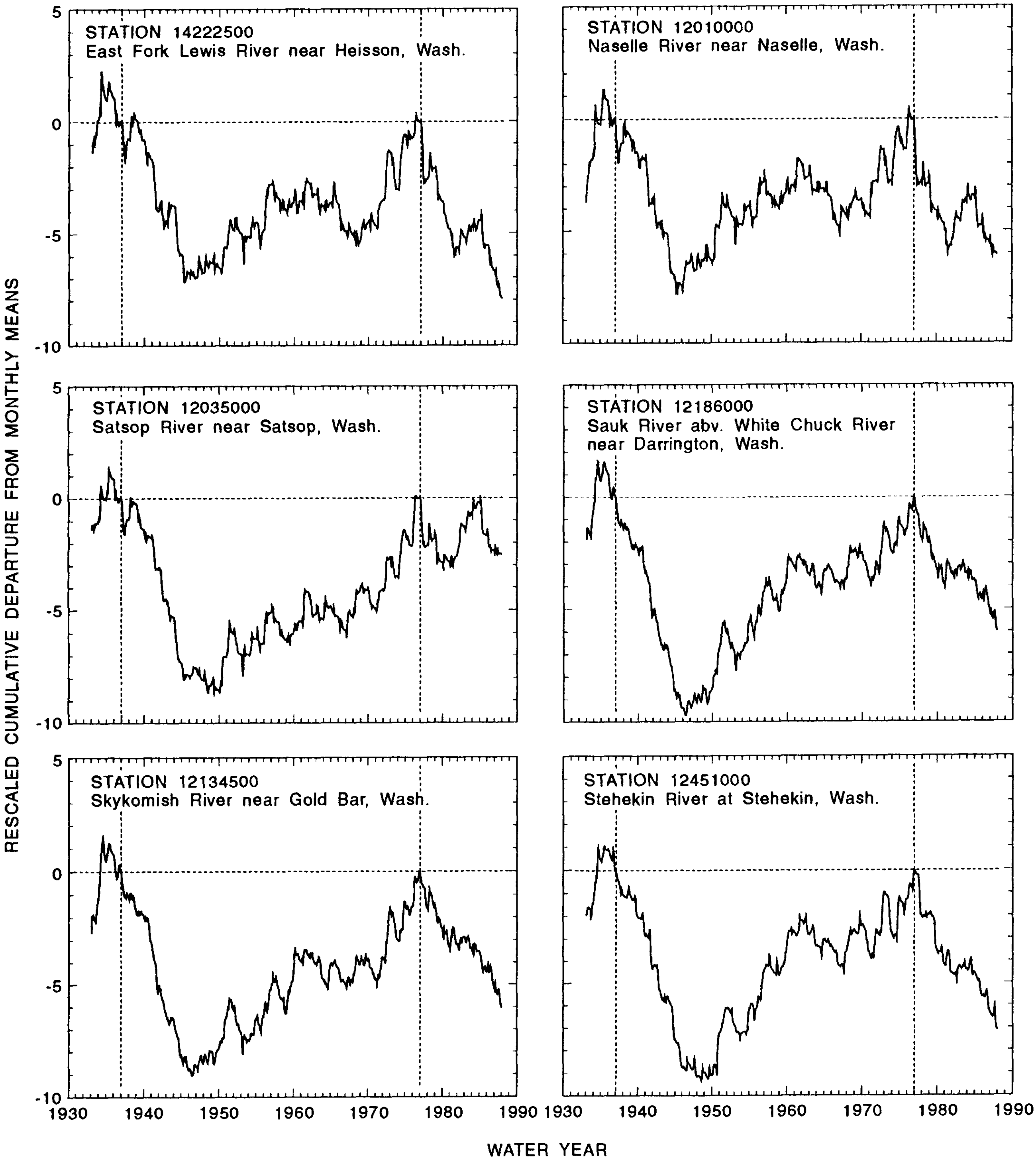

Figure 5.--Rescaled cumulative departures of streamflow at six stations in Washington, using a base period of 1937-1976. The dashed vertical lines represent the beginning and end of the base period.

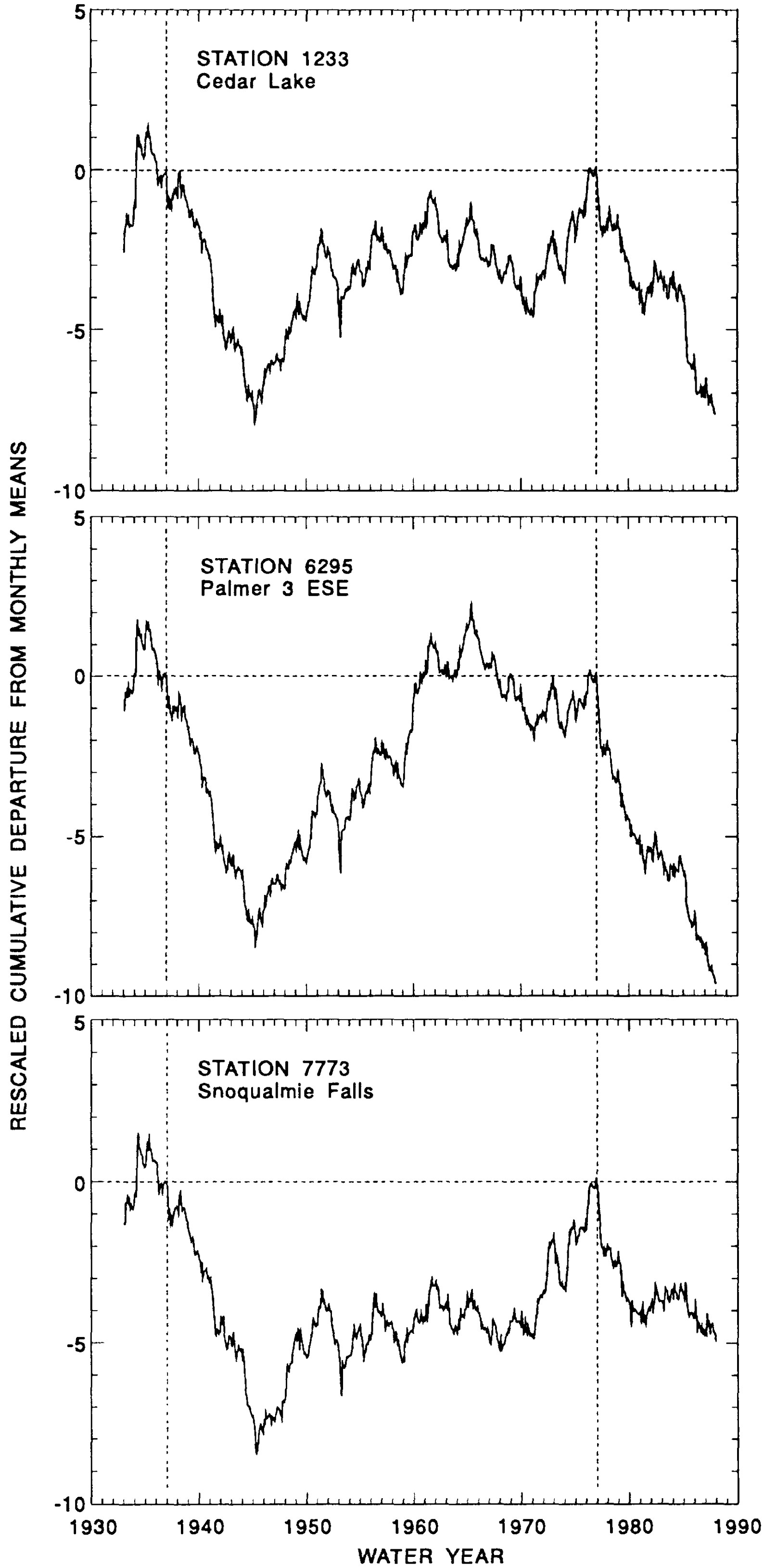

Figure 6.--Rescaled cumulative departures of precipitation at three stations in Washington, using a base period of 1937-1976. The dashed vertical lines represent the beginning and end of the base period.

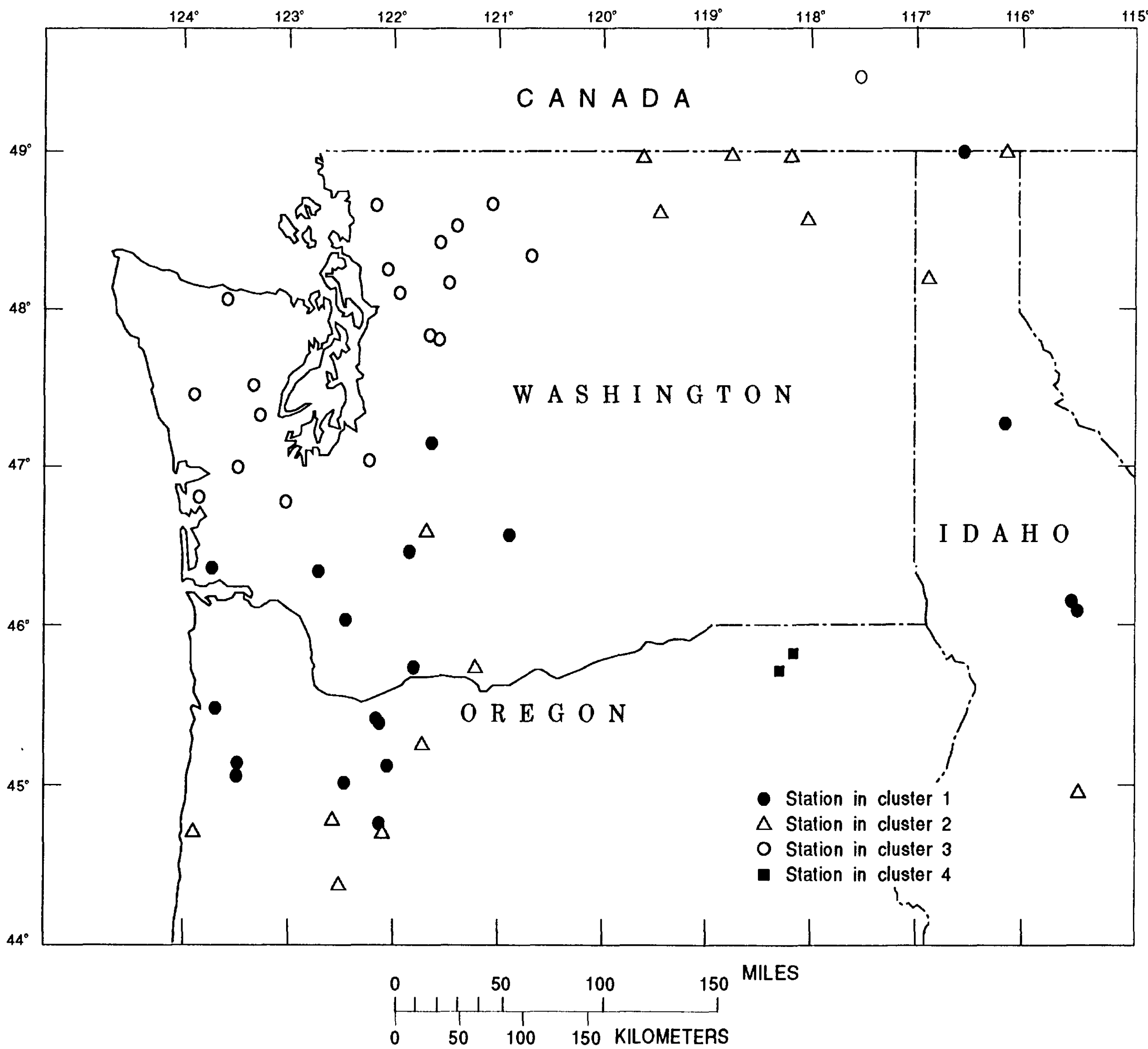

Figure 7.--Streamflow stations that describe geographic regions of similarity, as determined by cluster analysis.

Table 1.--*Streamflow stations in cluster 1*

[-, at end of year indicates the station is still in operation (as of 1991)]

Station number	Station name	Period of record (water years)	Drainage areas (square miles)	Correlation between station and cluster 1
12010000	Naselle River, near Naselle, Wash.	1929-	54.8	0.98
12097500	Greenwater River, at Greenwater, Wash.	1929-77	73.5	.94
12500500	North Fork Ahtanum Creek, near Tampico, Wash.	1932-78	68.9	.98
14128500	Wind River, near Carson, Wash.	1934-77	225	.99
14222500	East Fork Lewis River, near Heisson, Wash.	1929-	125	.97
14232500	Cispus River, near Randle, Wash.	1929-	321	.93
14242500	Toutle River, near Silver Lake, Wash.	1929-80	474	.98
12321500	Boundary Creek, near Porthill, Idaho	1928-	97	.97
12414500	St. Joe River, at Calder, Idaho	1920-	1,030	.97
13336500	Selway River, near Lowell, Idaho	1929-	1,910	.94
13337000	Lochsa River, near Lowell, Idaho	1929-	1,180	.94
14137000	Sandy River, near Marmot, Oreg.	1912-	262	.94
14141500	Little Sandy River, near Bull Run, Oreg.	1920-	22.3	.98
14179000	Breitenbush River, above French Creek, near Detroit, Oreg.	1933-87	108	.99
14192500	South Yamhill River, near Willamina, Oreg.	1935-	133	.98
14193000	Willamina Creek near Willamina, Oreg.	1935-	64.7	.99
14198500	Molalla River,above Pine Creek, near Wilhoit, Oreg.	1936-	97	.98
14209500	Clackamas River, above Three Lynx Creek, Oreg.	1922-	479	.98
14301500	Wilson River, near Tillamook, Oreg.	1932-	161	.98

Table 2.--*Streamflow stations in cluster 2*

[-, at end of year indicates the station is still in operation (as of 1991)]

Station number	Station name	Period of record (water years)	Drainage areas (square miles)	Correlation between station and cluster 2
12401500	Kettle River, near Ferry, Wash.	1929-	2,200	0.86
12404500	Kettle River, near Laurier, Wash.	1929-	3,800	.84
12409000	Colville River, at Kettle Falls, Wash.	1922-	1,007	.87
12442500	Similkameen River, near Nighthawk, Wash.	1911-	3,550	.97
12445000	Okanogan River, near Tonasket, Wash.	1929-	7,260	.95
14113000	Klickitat River, near Pitt, Wash.	1929-	1,297	.93
14226500	Cowlitz River, at Packwood, Wash.	1929-	287	.97
12306500	Moyie River, at Eastport, Idaho	1929-	570	.96
12395000	Priest River, near Priest River, Idaho	1929-	902	.93
13313000	Johnson Creek, at Yellow Pine, Idaho	1928-	213	.89
14134000	Salmon River, near Government Camp, Oreg.	1927-	8.00	.97
14178000	North Santiam River, below Boulder Creek, near Detroit, Oreg.	1929-	216	.97
14182500	Little North Santiam River, near Mehama, Oreg.	1932-	112	.97
14185000	South Santiam River, below Cascadia, Oreg.	1936-	174	.97
14305500	Siletz River, at Siletz, Oreg.	1926-	202.	.94

Table 3.--*Streamflow stations in cluster 3*

[-, at end of year indicates the station is still in operation (as of 1991)]

Station number	Station name	Period of record (water years)	Drainage areas (square miles)	Correlation between station and cluster 3
12017000	North River, near Raymond, Wash.	1927-77	219	0.98
12027500	Chehalis River, near Grand Mound, Wash.	1928-	895	.98
12035000	Satsop River, near Satsop, Wash.	1930-	299	.96
12039500	Quinault River, at Quinault Lake, Wash.	1912-	264	.98
12045500	Elwha River at McDonald Bar, near Port Angeles, Wash.	1918-	269	.99
12056500	North Fork Skokomish River, near Hoodsport, Wash.	1924-	57.2	.97
12060500	South Fork Skokomish River, near Union, Wash.	1931-84	76.3	.95
12093500	Puyallup River, near Orting, Wash.	1931-	172	.96
12133000	South Fork Skykomish River, near Index, Wash.	1911-82	355	.98
12134500	Skykomish River, near Gold Bar, Wash.	1929-	535	.99
12161000	South Fork Stillaguamish River, near Granite Falls, Wash.	1928-80	119	.98
12167000	North Fork Stillaguamish River, near Arlington, Wash.	1928-	262	.94
12175500	Thunder Creek, near Newhalem, Wash.	1930-	105	.93
12182500	Cascade River, at Marblemount, Wash.	1928-79	172	.98
12186000	Sauk River, above White Chuck River, near Darrington, Wash.	1929-	152	.97
12189500	Sauk River, near Sauk, Wash.	1928-	714	.99
12209000	South Fork Nooksack River, near Wickersham, Wash.	1933-78	103	.98
12451000	Stehekin River, at Stehekin, Wash.	1927-	321	.98

Table 4.--*Streamflow stations in cluster 4*

[-, at end of year indicates the station is still in operation (as of 1991)]

Station number	Station name	Period of record (water years)	Drainage areas (square miles)	Correlation between station and cluster 4
14010000	South Fork Walla Walla River, near Milton-Freewater, Oreg.	1931-	63	0.98
14020000	Umatilla River, above Meacham Creek, near Gibbon, Oreg.	1933-	131	.98

Visual comparison of graphs of the RCD's for selected stations considered to be representative of the three geographic regions indicate that the differences between regional patterns are relatively minor and subtle (figs. 8-10). Furthermore, the geographic regions represented by the individual gaging-station locations in each cluster overlap to varying degrees. Therefore, no attempt was made to delineate boundaries between the regions.

One measure of the statistical significance of an individual cluster is the proportion of the variance of the station records in the cluster that is explained by the first principal component of the cluster; for clusters 1, 2, and 3, they are 94, 87, and 94 percent, respectively.

The correlation between the first principal components of a pair of clusters gives a measure of their similarity. A matrix of these inter-cluster correlations between clusters 1, 2, and 3 is given below.

Cluster	1	2	3
1	1.00		
2	0.91	1.00	
3	0.94	0.80	1.00

These relatively high values of inter-cluster correlation substantiate the conclusion reached previously—by visual comparison of plots of RCD for stations from different regions—that the differences between regional patterns are relatively minor and subtle.

A measure of the degree to which each streamflow record fits the cluster with which it has been grouped is the coefficient of correlation between the record and the first principal component of the cluster (see tables 1-4). The lowest coefficient of correlation, 0.84, is for station 12404500 in cluster 2. Sixty-nine percent of the records have coefficients of correlation that are greater than 0.95.

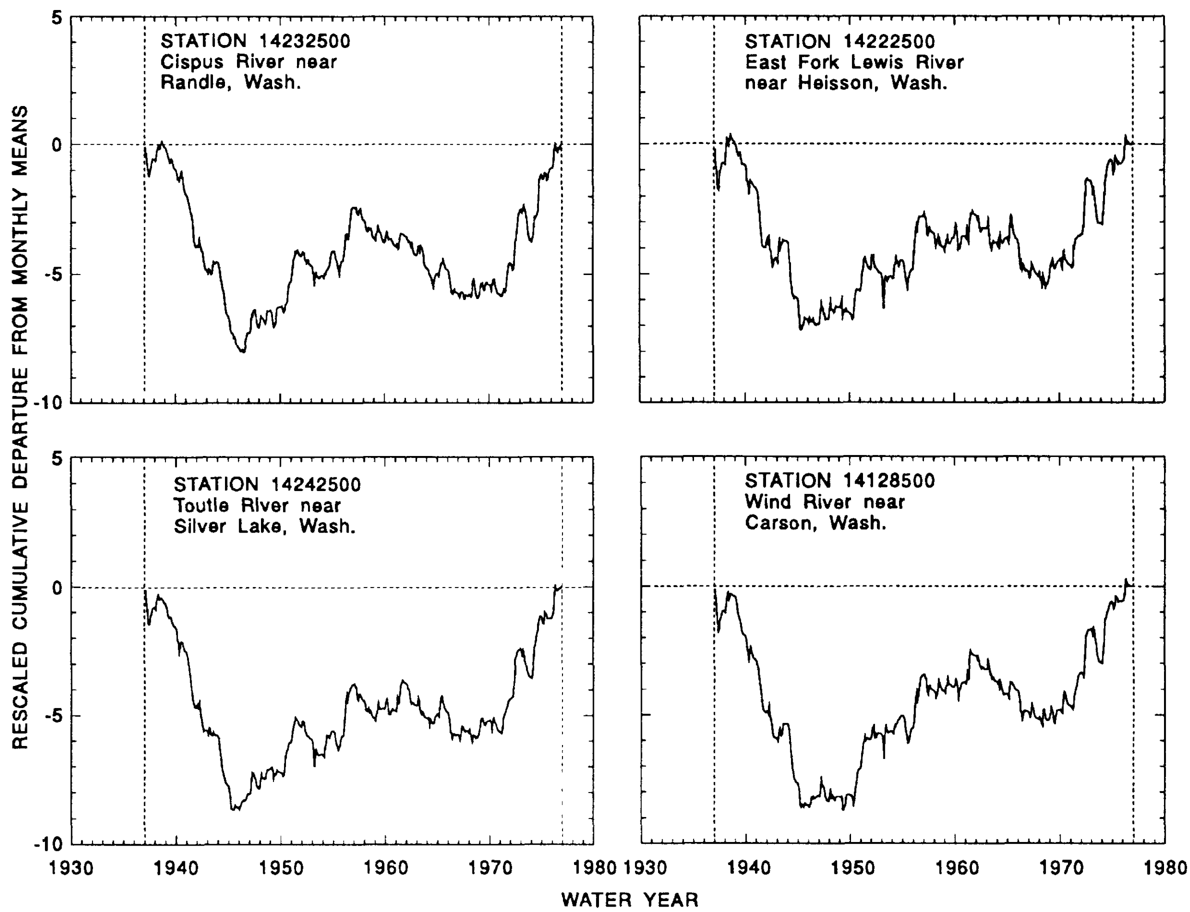

Figure 8.--Rescaled cumulative departures of streamflow at selected stations in southwestern Washington geographic region of similarity as determined by cluster analysis (cluster 1). The dashed vertical lines represent the beginning and end of the base period.

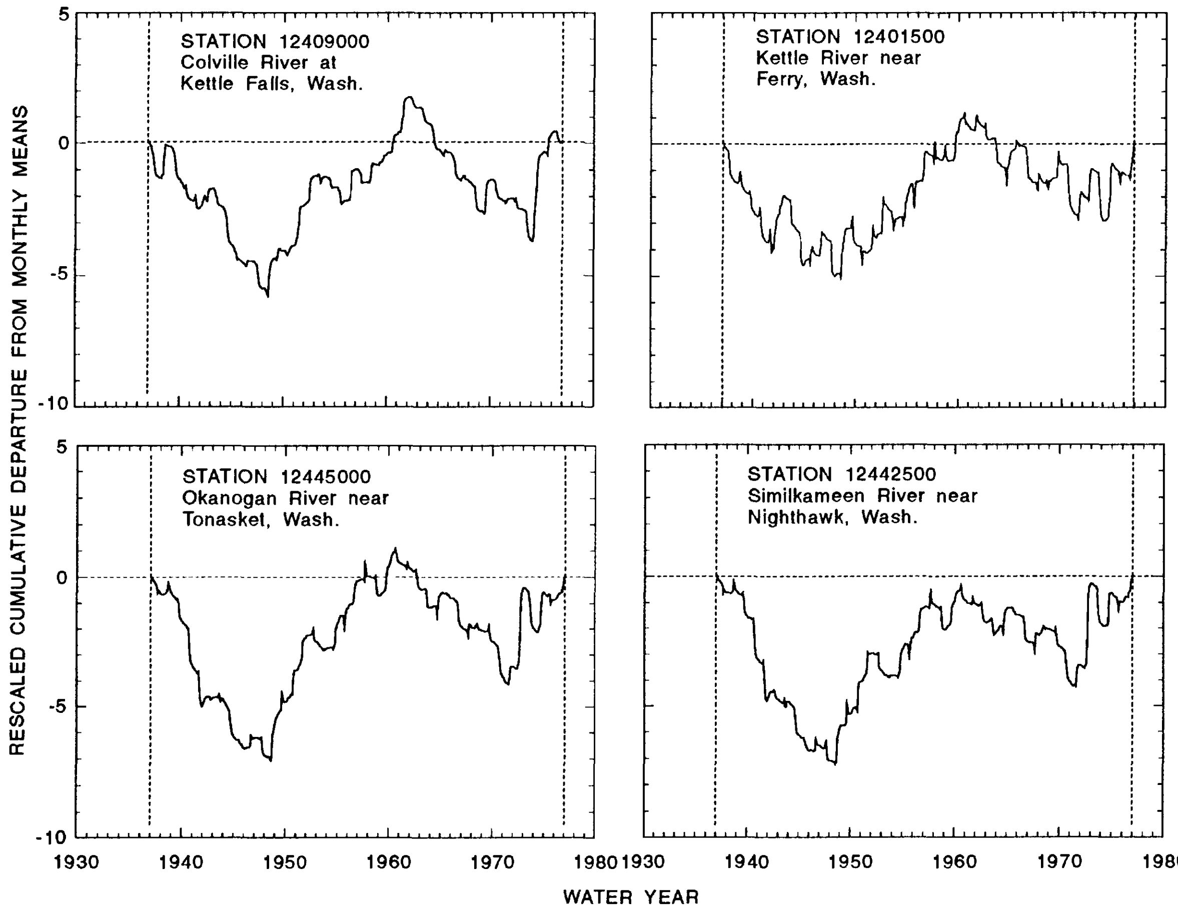

Figure 9.--Rescaled cumulative departures of streamflow at selected stations in northeastern Washington geographic region of similarity as determined by cluster analysis (cluster 2). The dashed vertical lines represent the beginning and end of the base period.

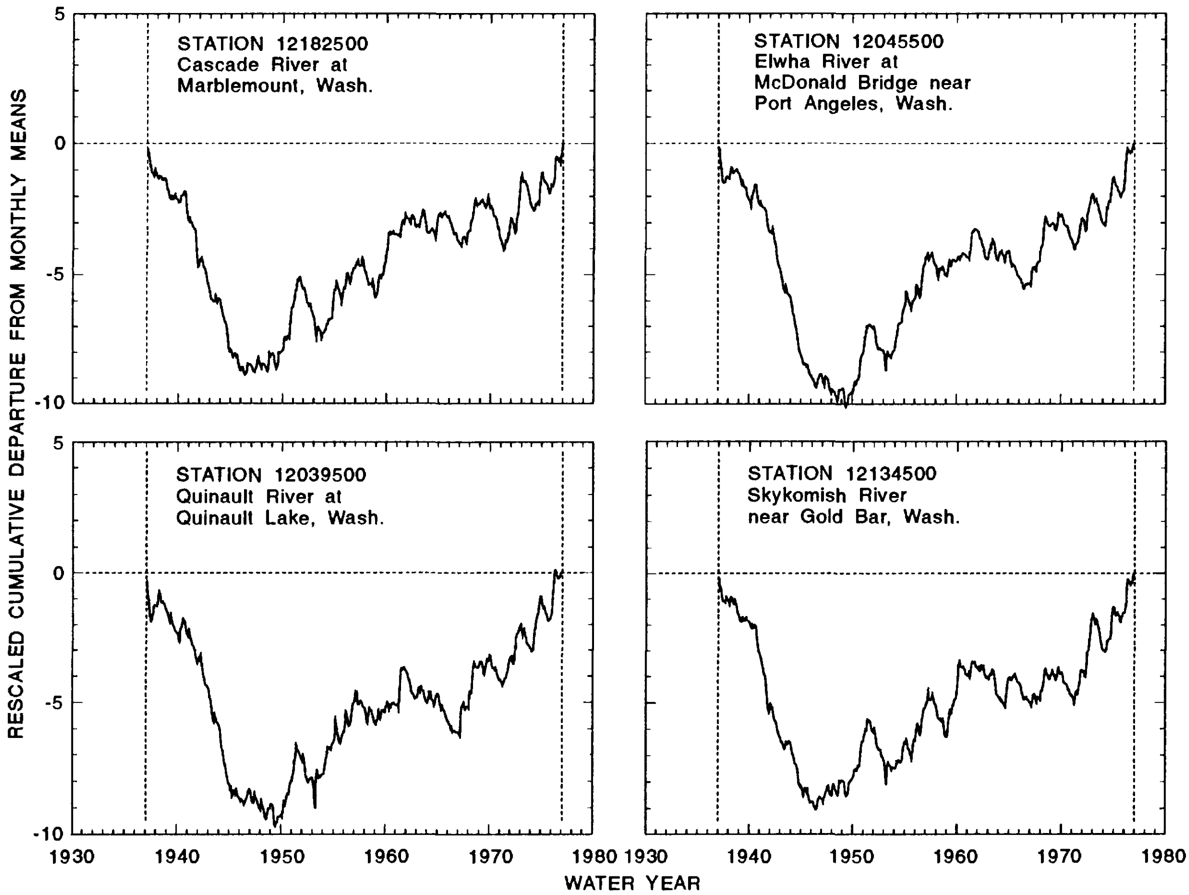

Figure 10.--Rescaled cumulative departures of streamflow at selected stations in northwestern Washington geographic region of similarity, as determined by cluser analysis (cluster 3). The dashed vertical lines represent the beginning and end of the base period.

Regions of Similarity Among Patterns of Variation for Precipitation Stations

Cluster analysis separated the 38 precipitation-station records into four clusters; however, the geographic areas covered by the locations of the stations in the four clusters overlap each other considerably (fig. 11). The stations in clusters 1 and 3 (henceforth referred to as cluster 1) define a western Washington region of similarity, and the stations in clusters 2 and 4 (henceforth referred to as cluster 2) define a southeastern Washington region of similarity (fig. 12 and tables 5 and 6). Inter-cluster correlations (discussed later) support this grouping of the stations into just two composite clusters. Graphs of the RCD's for selected stations considered to be representative of the two regions of similarity are shown on figures 13 and 14.

The patterns of variation among precipitation records generally are less similar than those for streamflow records. One indication of this is that the proportions of variance explained by the two composite clusters (76 and 80 percent) are somewhat lower than those for the streamflow record clusters, which ranged from 87 to 94 percent. Even if the results of the four-cluster analyses could have been used to define regions of similarity for the precipitation stations, the proportions of variance explained by the individual clusters would still have ranged from only 81 to 87 percent. Also, the degree to which the precipitation records fit the clusters with which they have been grouped is lower than that for streamflow records. The lowest coefficient of correlation between any of the precipitation records and the two composite clusters in which they were placed is 0.67, and only 16 percent of the records have correlations greater than 0.95. If the four-cluster analyses could have been used, the lowest coefficient of correlation would have increased to 0.81, but still only 26 percent of the records would have had correlations of greater than 0.95. By comparison, 69 percent of the streamflow records have correlations of greater than 0.95 with the clusters in which they were placed.

A matrix of the inter-cluster correlations between the four clusters into which the precipitation station records were initially separated is given below.

Cluster	1	2	3	4
1	1.00			
2	-0.61	1.00		
3	0.84	-0.24	1.00	
4	-0.62	0.84	-0.47	1.00

The relatively high inter-cluster correlation of 0.84 between clusters 1 and 3 and between clusters 2 and 4 supports combining the stations into just two composite clusters to define two regions of similarity.

The negative inter-cluster correlations between clusters 1 and 2, 1 and 4, 2 and 3, and 3 and 4 reveal an apparent inverse correlation between the western Washington stations (clusters 1 and 3) and the southeastern Washington stations (clusters 2 and 4). This also held true in the two-cluster analysis, where the inter-cluster correlation was -0.55. These findings indicate that, statistically, there is a tendency for persistent periods of above-average precipitation in western Washington to correspond with persistent periods of below-average precipitation in southeastern Washington, and conversely.

The apparent inverse relation between the patterns of variation of precipitation in southeastern and western Washington is illustrated by the superimposed graphs of rescaled cumulative departure shown on figure 15. The patterns of rises and falls in the two graphs have many similarities, but there are also several short periods of 1 to 5 years during which the departures for one station are predominantly above average whereas the departures for the other station are predominantly below average.

Evaluation of the reason(s) for the inverse precipitation relation for southeastern and western Washington is beyond the scope of this report, but it could reflect changes in the direction of the jet stream caused by climatic conditions such as El Niño .

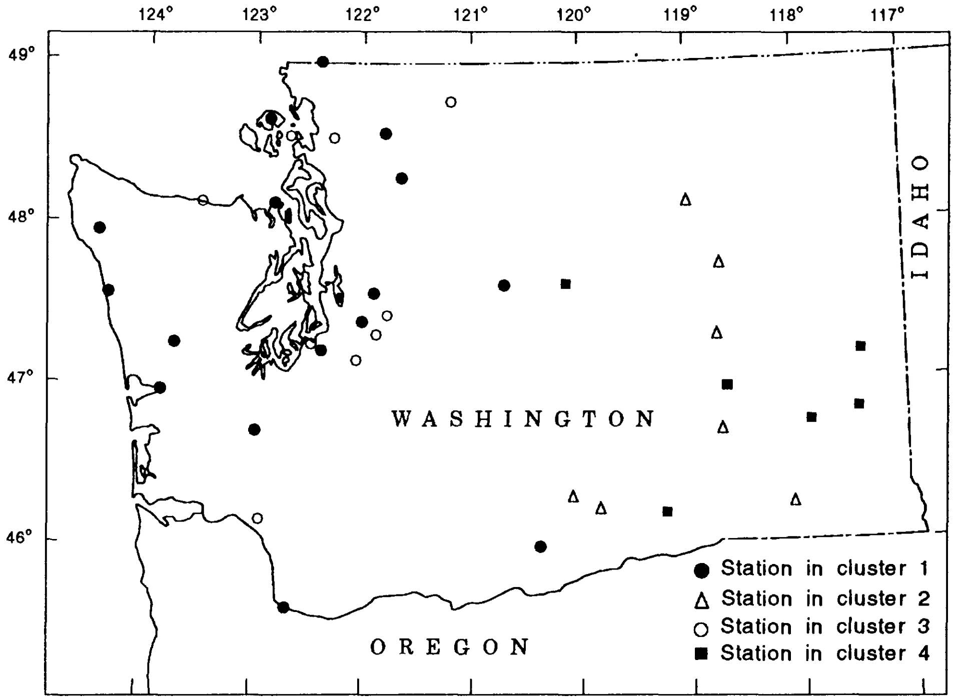

Figure 11.--Precipitation stations that have similar patterns of variation of rescaled cumulative departure, as determined by cluster analysis.

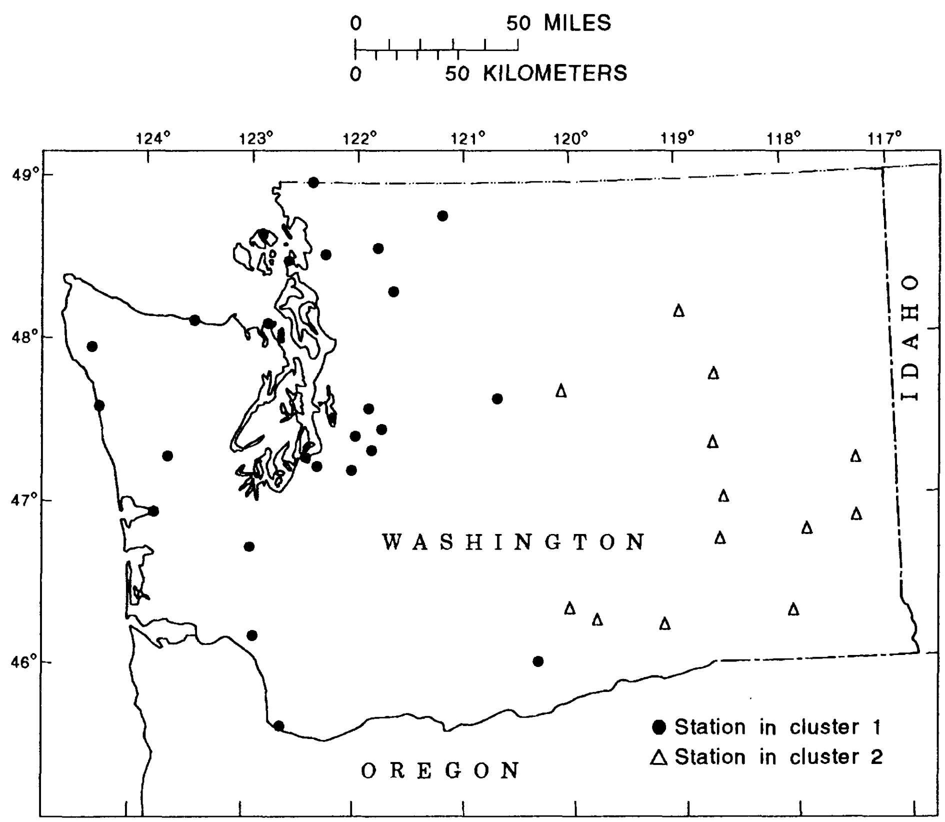

Figure 12.--Precipitation stations that describe geographic regions of similarity, as determined by cluster analysis.

Table 5.--*Precipitation stations in cluster 1*

[All stations are located in Washington; -, at end of year indicates the station is still in operation (as of 1991)]

Station index number	Station name	Period of record (water years)	Correlation between station and cluster 1
0008	Aberdeen	1891-	0.88
0013	Aberdeen 20 NNE	1927-	.94
0176	Anacortes	1893-	.83
0668	Bickleton	1928-	.82
0945	Buckley 1 NE	1913-	.92
1233	Cedar Lake	1903-	.79
1276	Centralia	1890-	.95
1484	Clearbrook	1903-	.93
1496	Clearwater	1896-1910, 1928-	.67
1679	Concrete Ppl Fish Stn.	1906-1916, 1925-	.93
1992	Darrington Ranger Stn.	1912-	.96
2157	Diablo Dam	1922-	.97
2914	Forks 1 E	1907-	.86
4486	Landsburg	1903-	.95
4572	Leavenworth 3 S	1915-	.89
4769	Longview	1925-	.96
6096	Olga 2 SE	1890-	.93
6295	Palmer 3 ESE	1925-	.69
6624	Port Angeles	1878-	.88
6678	Port Townsend	1874-	.68
6803	Puyallup 2 W Exp. St.	1914-	.98
7507	Sedro Woolley	1897-	.90
7773	Snoqualmie Falls	1899-	.95
8286	Tacoma City Hall	1879-1981	.88
8773	Vancouver 4 NNE	1850-1868, 1889-1892; 1898-	.73

Table 6.--*Precipitation stations in cluster 2*

[All stations are located in Washington; -, at end of year indicates the station is still in operation (as of 1991)]

Station index number	Station name	Period of record (water years)	Correlation between station and cluster 2
1586	Colfax 1 NW	1881-1883, 1892-	0.93
2030	Dayton 1 WSW	1880-1885, 1891-	.91
3546	Hatton 9 SE	1906-	.91
4154	Kennewick	1885-1887, 1894-	.89
4338	La Crosse	1884-1901, 1908-	.71
4679	Lind 3 NE	1897-1906, 1917-	.89
5832	Nespelem 2 S	1915-	.97
6039	Odessa	1904-	.93
6768	Prosser 4 NE	1913-	.83
7180	Rosalia	1893-	.95
8207	Sunnyside	1895-	.96
9012	Waterville	1890-	.81
9238	Wilbur	1900-	.85

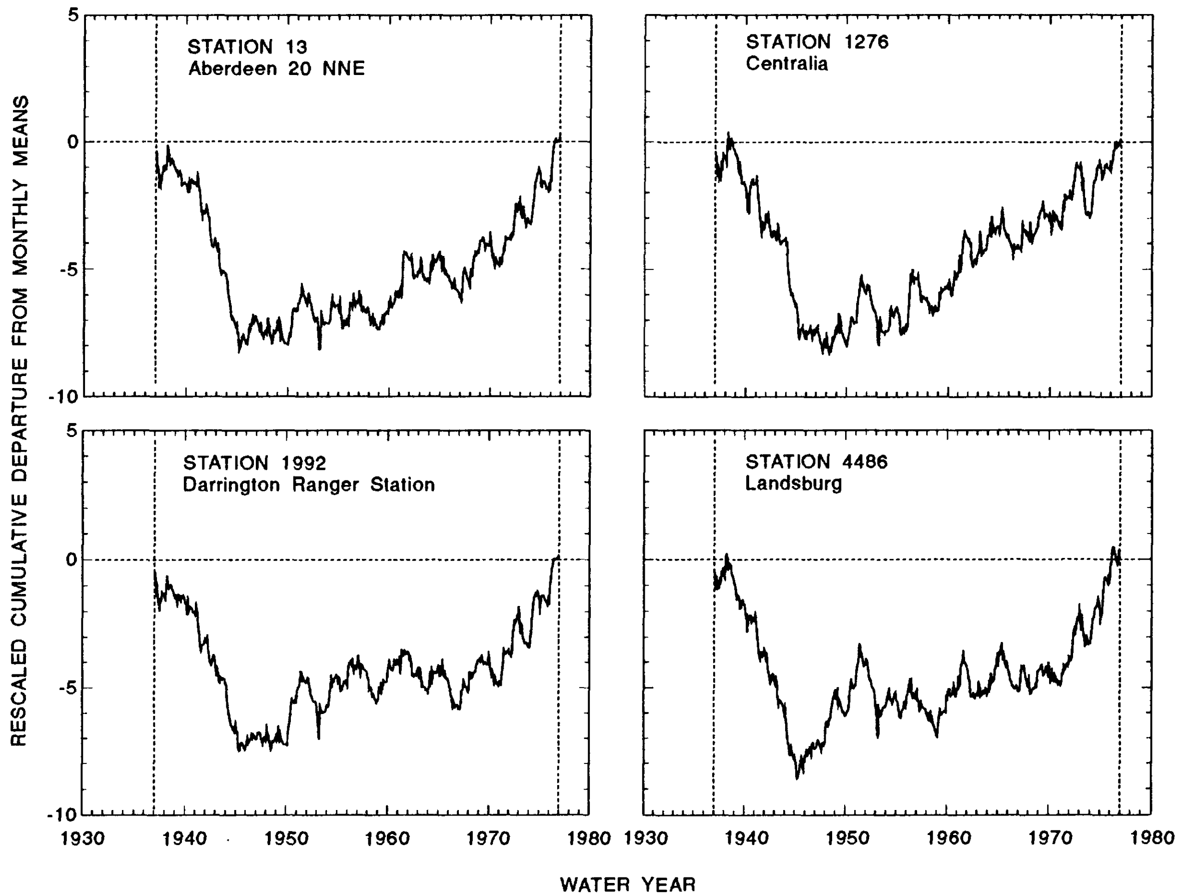

Figure 13.--Rescaled cumulative departures of precipitation at selected stations in western Washington geographic region of similarity, as determined by cluster analysis (cluster 1). The dashed vertical lines represent the beginning and end of the base period.

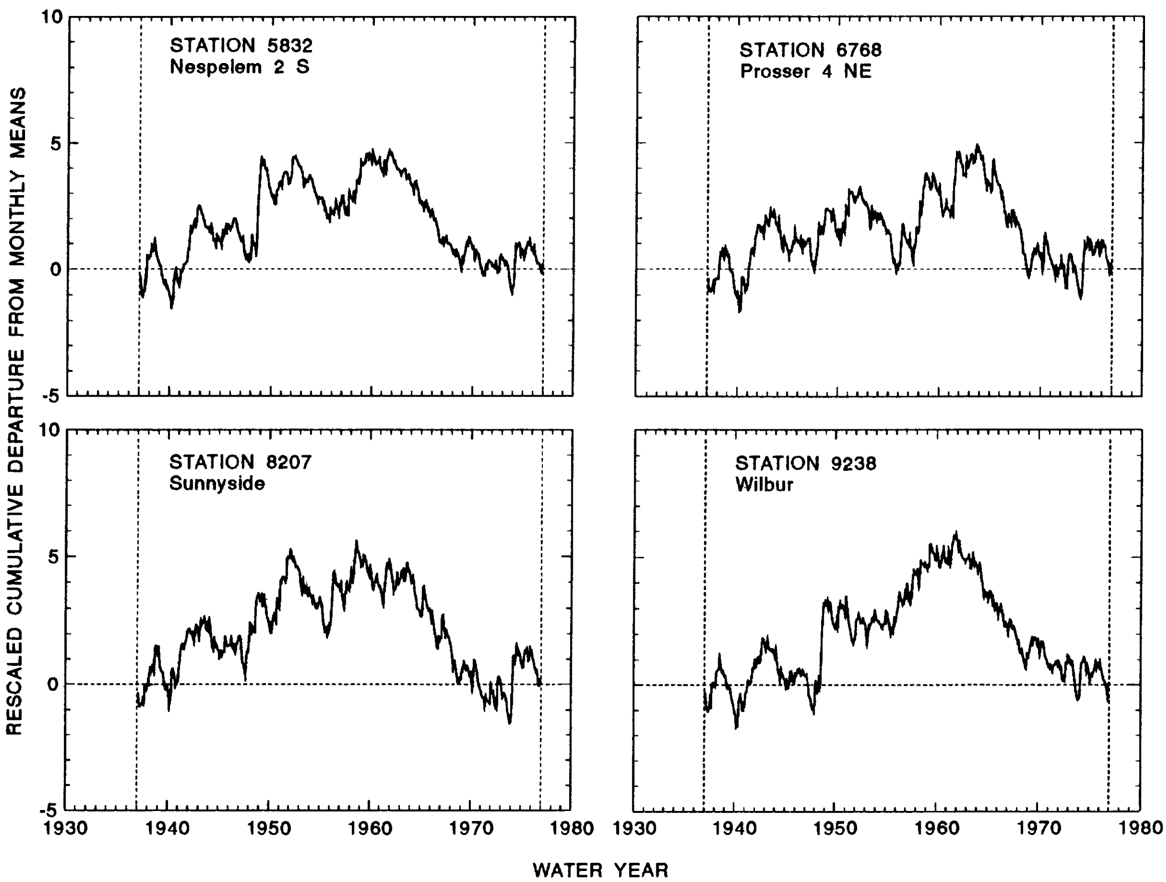

Figure 14.--Rescaled cumulative departures of precipitation at selected stations in southeastern Washington geographic region of similarity, as determined by cluster analysis (cluster 2). The dashed vertical lines represent the beginning and end of the base period.

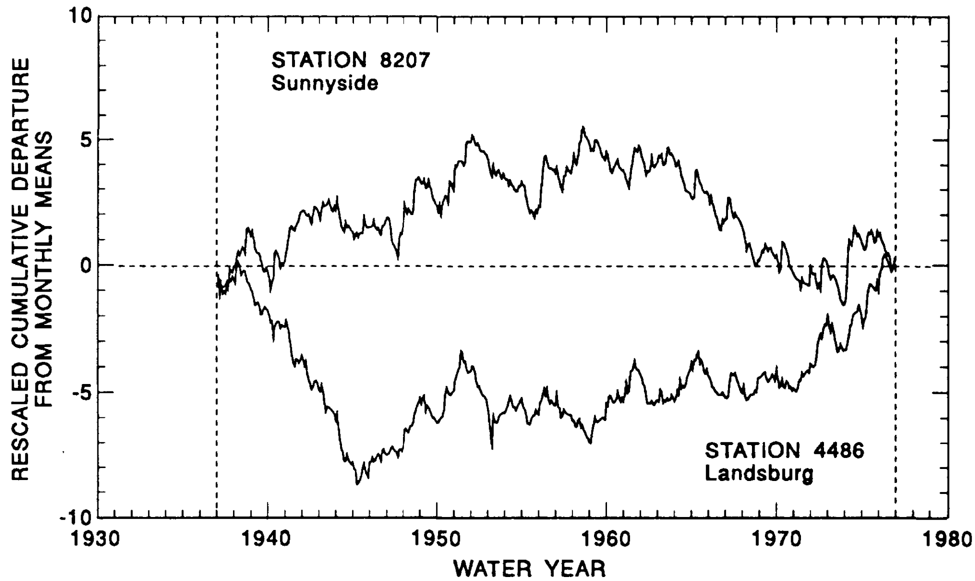

Figure 15.--Rescaled cumulative departures of precipitation at two stations, using a base period of 1937-1976. Station 8207 is in eastern Washington and Station 4486 is in western Washington. The dashed vertical lines represent the beginning and end of the base period.

ESTIMATES OF MONTHLY STREAMFLOW AND PRECIPITATION AT UNGAGED SITES

In some applications, it would be desirable to estimate streamflow or precipitation at ungaged sites from streamflow or precipitation data for gaged sites within the same geographic region of similarity. For example, a city might want to build a reservoir in an ungaged basin to increase the water supply. If a history of streamflow and precipitation could be estimated for the basin, the city could make informed decisions about the desirability of building the reservoir, about reservoir size, and about how the reservoir would have functioned during the dry and wet periods already experienced.

An equation for estimating streamflow or precipitation at an ungaged site could be derived by using RCD's (equation 9). Suppose that two sites have monthly precipitaiton or streamflow values $Y_{i,j}$ and $X_{i,j}$. The RCD's D^*_Y/S_Y and D^*_X/S_X for the two sites are identical for all times t if, and only if, $D_{Y_{i,j}}/S_Y$ equals $D_{X_{i,j}}/S_X$ for all months j and years i. Letting $Y_{i,j}, \bar{Y}_{i,j}$ and S_Y be the monthly values, mean-monthly values, and standard deviation of the cumulative-annual values for an ungaged site, and letting $X_{i,j}, \bar{X}_{i,j}$ and S_X be the corresponding values for a gaged sited in the same region of similarity, equality for all times of the rescaled cumulative departures thus means that

$$\frac{Y_{i,j} - ,\bar{Y}_{i,j}}{S_Y} = \frac{X_{i,j} - \bar{X}_{i,j}}{S_X} \quad . \qquad (10)$$

Solving equation 10 for the monthly precipitation or streamflow $Y_{i,j}$ at the ungaged site in terms of the other variables in the equation results in the following equation, which provides an estimate in terms of the historical data for the selected gaged site, and estimates of the mean-monthly values $\bar{Y}_{i,j}$ and the standard deviation S_Y for the base period, at the ungaged site.

$$Y_{i,j} = ,\bar{Y}_{i,j} + \left(\frac{S_Y}{S_X}\right)(X_{i,j} - \bar{X}_{i,j}) \quad . \qquad (11)$$

Equation 11 is related closely to the "line of organic correlation" (Hirsch and Gilroy, 1984). The line of organic correlation is symmetric; therefore, it is the same regardless of which variable is the dependent variable.

The same is not true of regression. Regression lines are tilted in such a way as to reduce variability in the dependent variable (the "regression effect" of variance reduction in the estimated values). These concepts are illustrated graphically on figure 16. On this figure, the data points (X_i, Y_i) are measured annual-mean discharges of the East Fork Lewis River (X_i) and the Sauk River (Y_i). All three lines go through the common point $(\bar{X}, \bar{Y})$, where $\bar{X}$ and $\bar{Y}$ are the arithmetic mean values of the annual-mean discharges for the East Fork Lewis and Sauk Rivers, respectively.

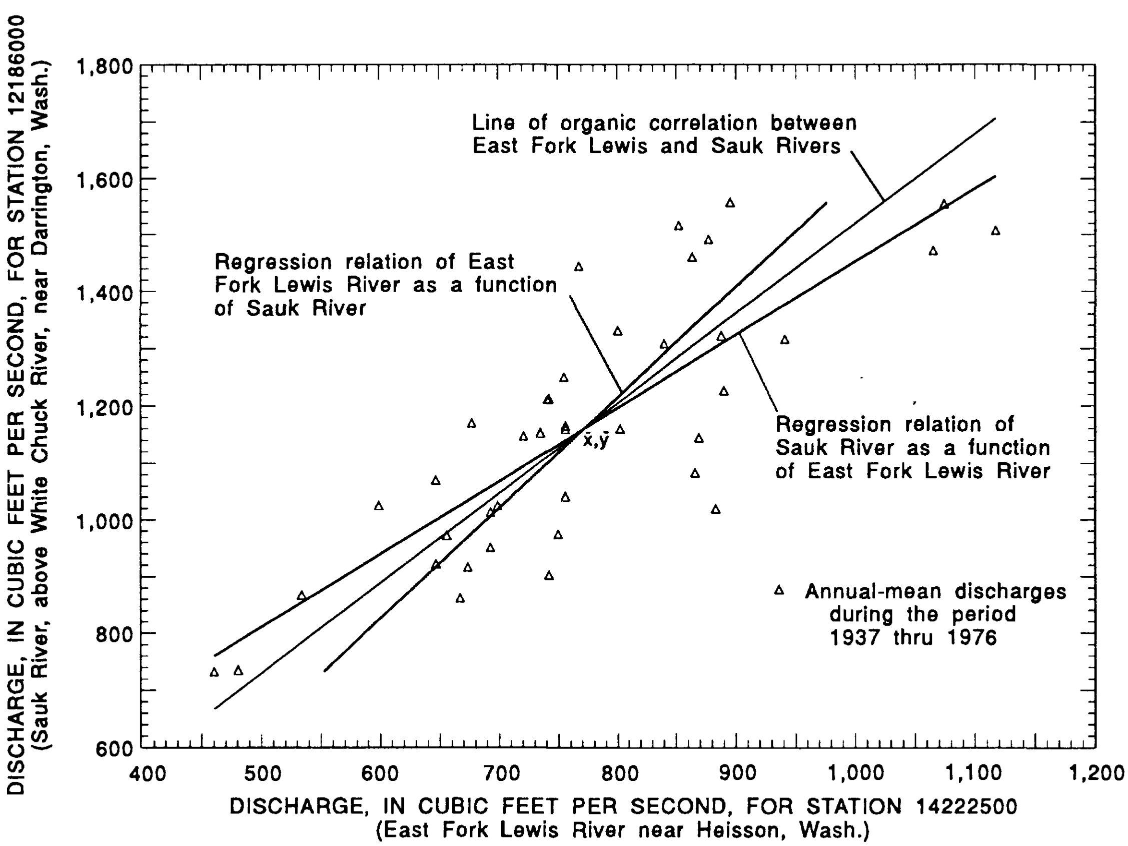

Figure 16.--Regression relations and line of organic correlation between annual-mean discharges at streamflow stations on the Sauk and East Fork Lewis Rivers, Washington.

Because the line of organic correlation avoids the "regressive effect" of variance reduction in estimated values, it is recommended for application in cases such as this where (a) characterization of a relation between two variables is sought, and (b) multiple values of one variable are estimated from multiple observations of another variable.

Computer program SIMULATE.F77 uses equation 11 to simulate monthly discharges for an ungaged streamflow site from monthly discharges for a gaged site. The relative accuracy of this method can be illustrated by comparing the record of monthly discharges for a gaging-station site with discharges simulated for the same site. Therefore, monthly discharges for station 14128500 (Wind River near Carson, Wash.) for the period 1937-76 were simulated from monthly discharges for station 14242500 (Toutle River near Silver Lake, Wash.) using program SIMULATE.F77. The simulated discharges were expected to closely match the actual discharges for the Wind River because the stations are both in the same region of similarity (cluster 1, southwestern Washington) and because the coefficient of correlation between the RCD's for the two stations (0.96) is high. The mean-monthly discharges and the standard deviation of the cumulative-annual discharges for the Wind River were calculated from the station record for the Wind River. In a real application, the mean-monthly discharges and standard deviation for the ungaged streamflow site would not be available, and consequently they would have to be estimated. These values could be estimated by the use of regional regression equations on variables such as basin area and mean-annual precipitation.

The cumulative differences between the simulated and actual monthly discharges for the Wind River are illustrated by the graphs of RCD shown on figure 17. Forty-nine percent of the simulated discharges were within 15 percent of the actual discharges, 72 percent were within 25 percent, and 95 percent were within 50 percent. The maximum percentage difference between simulated and actual monthly discharges was 91 percent in October 1952. The maximum percentage difference between simulated and actual annual-mean discharges was 21 percent in 1939 and the average percentage difference between them was 6 percent.

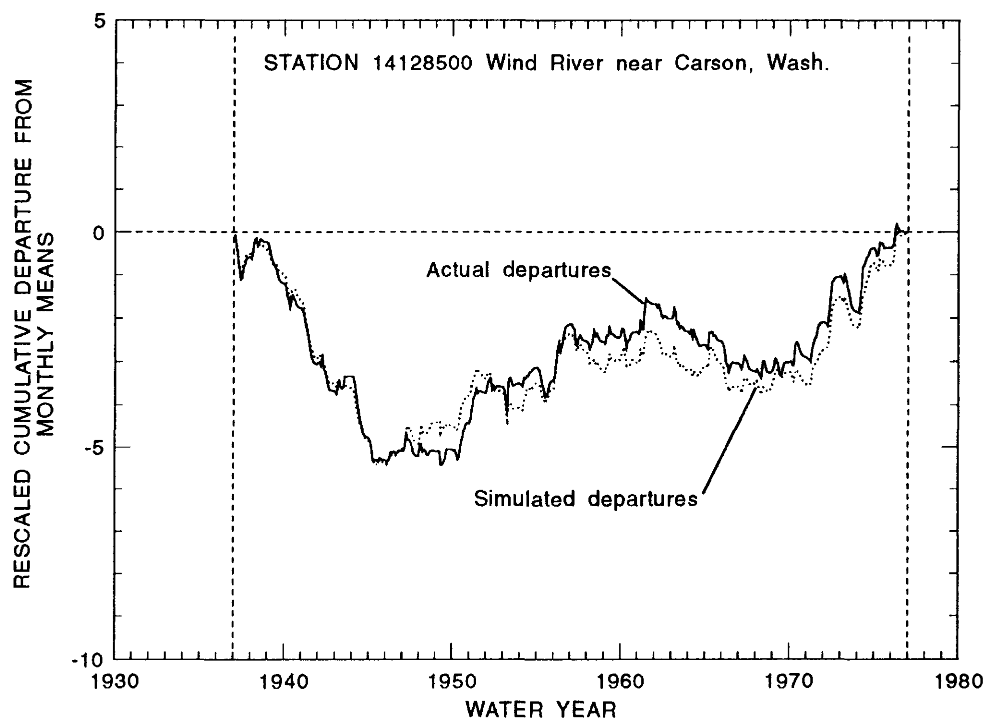

Figure 17.--Rescaled cumulative departures of streamflow at station 14128500, using a base period of 1937-1976. Simulated rescaled cumulative departures based on record of monthly discharges for station 14242500 (Toutle River near Silver Lake, Wash.). The dashed-vertical lines represent the beginning and end of the base period.

WATER-RESOURCE-AVAILABILITY INDEX

For water suppliers and managers to apportion available water resources effectively, they need to be able to evaluate current conditions in the context of the hydrologic history of an area. One objective of this study was to develop a water-resource-availability index that would provide a quantitative interpretation of present conditions relative to prior conditions. Such an index, although it does not quantify the amount of ground water or surface water available for use, does give an indication of the relative deficiency or abundance of these sources of water.

One well-known and widely used index, which was developed in the 1960's, is the Palmer Drought Severity Index (PDSI). The PDSI, which is a measure of agricultural drought, focuses on the quantity of moisture present in the root zone of agricultural crops, and therefore it is not indicative of the relative deficiency or abundance of water in the underlying aquifers that commonly are the primary source of water for agricultural, industrial, and domestic uses. The availability of water in the sense of recharge that has reached these aquifers over the last several years determines the magnitude of base-flow discharge in most streams and also the amount that can be pumped to the surface.

The water-resource-availability index (WRAI) developed in this study is defined for a given month and year as the summation of time-weighted, rescaled, monthly departures during the preceding 3-year period. The equation for the index, where the sums are taken over the 3 year period from $n = 0$ for the last month in the period to $n = 35$ for the first month in the period, is given by

$$WRAI = \sum_{n=0}^{35} W(n) \frac{D_X(n)}{S_X}, \qquad (1)$$

where

$W(n)$ = the weight factor given by $\left(1 - \frac{n}{36}\right)^2$ for month n,

$D_X(n)$ = the rescaled departure for month n, and

S_X = the standard deviation of the cumulative-annual values.

Index values are calculated using rescaled departures, rather than actual streamflow or precipitation departures, to place them all on an equivalent scale. Therefore, indices from both streamflow and precipitation records yield compatible values and allow a more uniform index.

The finite memory of 3 years used in the definition of the index was arbitrarily selected but it does have a physical significance in the hydrologic system, in that reservoirs, soil moisture, ground-water levels, and so on, are most affected by the most recent few years of streamflow and precipitation. For example, the hydrologic system can largely recover from the effects of a drought by the occurrence of several wetter-than-normal years.

The weight factor was derived empirically to estimate the effect that each of the previous 36 monthly rates of streamflow and precipitation would have on the current water-resource availability.

The WRAI for a given month indicates the relative deficiency or abundance in streamflow or precipitation during the preceding 3-year period. Positive index values indicate periods of relative abundance and negative index values indicate periods of relative deficiency. A plot of index values calculated for the entire period of record at a given gaging station can be used to identify historical periods of relative water abundance or deficiency and to evaluate current conditions in terms of the historical record at the station. Separate computer programs, INDEX.F77 and PRECIP.INDEX.F77, calculate and plot index values for streamflow and precipitation records. These programs generate time-series plots of the index values and also provide two sets of summary statistics. One set lists the minimum index value during the period of record analyzed and the percentage of time that the index was less than selected negative values. The other set lists the maximum index value and the percentage of time that the index was greater than selected positive values.

As an example, program INDEX.F77 generated time-series graphs of index values (fig. 18) for the records of the same six streamflow stations graphed previously (fig. 5).

The historically highest index values for five of the six stations occurred during the 1934 water year. The maximum index values at those stations during that year ranged from +2.23 to +3.30. The highest index value at the sixth station (+2.02 at station 12035000) occurred during the 1951 water year; however, the highest value during the 1934 water year at that station was only slightly lower at +1.83.

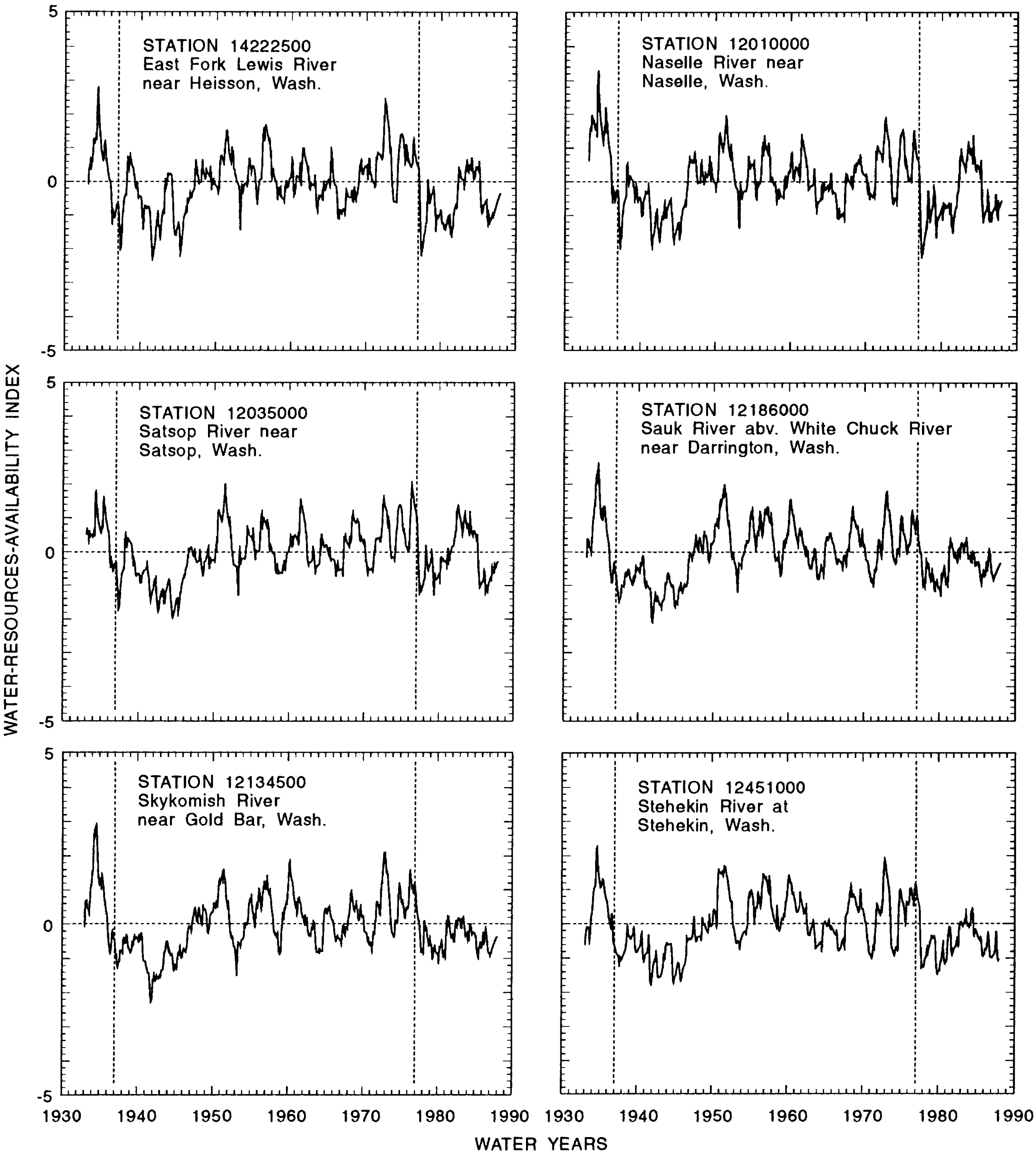

Figure 18.--Water-resources-availability index values for six streamflow stations in Washington, using a base period of 1937-1976. The dashed vertical lines represent the beginning and end of the base period.

The lowest index values occurred during the 1941 water year at stations 12186000, 12451000, 12134500, and 14222500 and ranged from -1.78 to -2.29. The lowest index value at station 12035000 (-1.96) occurred in 1944. The lowest index value at station 12010000 (-2.28), and the second lowest at station 14222500 (-2.23) occurred during the 1977 water year, a year in which 34 of the 39 counties in Washington were designated as emergency drought-impact areas (Governor's Ad Hoc Executive Water Emergency Committee, 1977, p. 37). During a severe drought in 1952, minimum index values ranged from -0.55 to -1.51 at the six stations.

EVALUATION OF RESERVOIR SIZES

Chronologies of cumulative departures for streamflow stations can be useful for assessing the adequacy of the storage capacity of existing or proposed reservoirs. The cumulative departures must be in acre-feet for their use in this application. The maximum cumulative departure of streamflow for a given stream, minus the minimum, over a given period yields the approximate minimum size of reservoir that would be necessary on the stream to average out wet and dry periods and provide monthly releases equal to the mean-monthly values of inflow during the period without it ever overfilling or emptying (see Mandelbrot and Wallis, 1969a, fig.1, p. 243). The determination of the minimum reservoir size is approximate because the method does not consider potential losses of stored water due to leakage and evaporation.

Minimum reservoir sizes thus determined using the half-century of data available for many streams in Washington are impractically large; therefore, smaller reservoirs might already exist or be considered for construction. During extended dry periods such reservoirs could not completely mitigate the effects of a drought, and during extended wet periods, they could not store all of the water flowing into them and could at times allow excessive, possibly damaging, flows downstream. However, examining reservoirs in the context of the chronology of streamflow records provides managers with information about how to best manage them in such cases where outflow cannot be completely averaged. Streamflow-record chronologies are also useful in deciding how much use of the reservoir's capacity to allow, taking into account extended dry periods.

Two examples using hypothetical streamflow records are given to illustrate the determination of minimum reservoir contents and minimum reservoir sizes. Both records are 80 years long (1911-90) and the monthly discharge, in cubic feet per second, was assumed to remain constant at the rates given below for all months during the indicated years.

	Monthly discharge	
Years	Example 1	Example 2
1911-25	200	100
1926-45	75	225
1946-55	250	50
1956-75	125	225
1975-85	225	75
1986-90	50	250

Computer program STREAM.F77 calculated the cumulative departures of monthly discharge from mean-monthly discharge, in acre-feet, for the two examples, and generated the time-series graphs that are shown on figure 19. The mean-monthly discharge for the 80-year period of record for each month of the year for both examples is 150 ft^3/s (9,050 acre-ft/month).

In example 1, the maximum cumulative departure (+543,000 acre-ft) occurred in 1926, and the minimum cumulative departure (-543,000 acre-ft) occurred in 1946 (fig. 19a). The difference between the maximum and minimum cumulative departures during 1926-46, a period of below-average streamflow, gives the minimum reservoir contents (1,086,000 acre-ft) that would be needed at the time of the maximum cumulative departure in 1926 so that monthly releases could be maintained at the rate of the mean-monthly inflow (150 ft^3/s) throughout the period without emptying the reservoir.

In example 2, the minimum cumulative departure (-543,000 acre-ft) occurred in 1926, and the maximum cumulative departure (+543,000 acre-ft) occurred in 1946 (fig. 19b). In this example, 1926-46 is a period of above-average streamflow and the difference between the maximum and minimum cumulative departures (1,086,000 acre-ft) gives the minimum size of reservoir that would be needed so that the release of a monthly outflow of 150 ft^3/s could be maintained throughout the period of record without the reservoir ever overfilling. This minimum reservoir size is correct only if the reservoir is assumed to be empty at the time of the minimum cumulative departure in 1926.

If program STREAM.F77 is used to examine the size of an existing reservoir, the initial cumulative departure at the beginning of the period of calculation should be set equal to the actual reservoir contents at that time, so that the value of the cumulative departure at any given time is representative of actual reservoir contents.

Another method of sizing reservoirs is known as the "residual mass curve method" (see Shaw, 1988, p. 460). The minimum size of reservoir determined by this method is less than the size determined by the method described previously. This method is illustrated by reference to figure 19a. In this method, the reservoir is assumed to be full at points A (1926) and B (1956). The difference between the mean-monthly inflow to the reservoir (9,050 acre-ft/month) and the slope of the line from A to B—the "residual yield line"—(1,000 acre-ft/month) gives the rate of release (8,050 acre-ft/month) from the reservoir. The minimum reservoir capacity (846,000 acre-ft) required to provide this continuous rate of release is given by the difference in cumulative departure between points C (303,000 acre-ft) and D (-543,000 acre-ft).

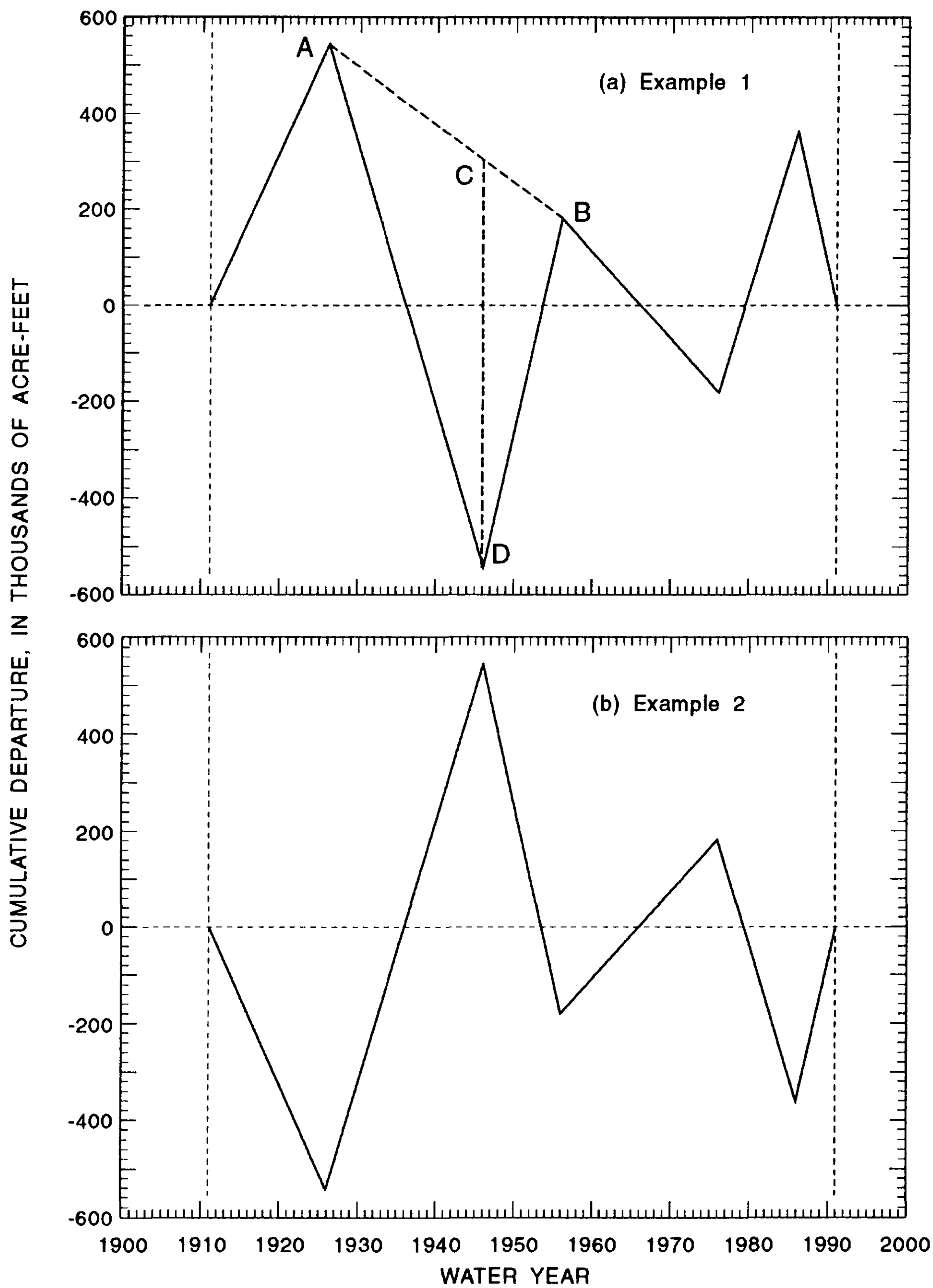

Figure 19.--Monthly cumulative departures of streamflow for two hypothetical streamflow records, using a base period of 1911-1990. During the period 1926-46, which is bounded by maximum and minimum cumulative departures, streamflow is (a) below average and (b) above average. The letters A, B, C and D in (a) identify data points used in the description of the "residual mass curve method" of sizing reservoirs. The dashed vertical lines represent the beginning and end of the base period.

SUMMARY AND CONCLUSIONS

Water suppliers and managers need information on short- and long-term variations in streamflow and precipitation to ascertain whether water supplies are adequate to satisfy present and future demands. Two data bases, one containing streamflow data and the other containing precipitation data, were used to analyze these variations. The streamflow data base contains monthly discharge data for 55 streamflow stations. Thirty-two of the streamflow stations are in Washington, 15 are in Oregon, 7 are in Idaho, and 1 is in British Columbia, Canada. The precipitation data base contains monthly precipitation data for 38 precipitation stations in Washington.

Patterns of variation in monthly records of streamflow and precipitation were observed by examining time series of cumulative departure (chronologies) of monthly values from mean-monthly values. A base period of 1937-1976, which represents long-term, average conditions, was used to calculate mean-monthly values. To more easily compare chronologies of cumulative departure for two or more stations, the cumulative departures were rescaled (standardized) by dividing each one by the standard deviation of the cumulative-annual values.

Computer programs STREAM.F77 and PRECIP.F77 (1) calculate mean-monthly values of streamflow and precipitation for the base period, (2) calculate departures of monthly values of these variables from the mean-monthly values, (3) accumulate the departures over time, and (4) standardize these chronologies of cumulative departure into chronologies of rescaled cumulative departure (RCD). These programs also generate plot files that can be used to create time-series plots of RCD's.

The degree of similarity between the chronologies of RCD for each pair of either streamflow or precipitation stations was determined by calculating the coefficient of correlation between them. Matrices of these coefficients were created for all of the stations in the two data bases. These matrices were evaluated using cluster analyses to identify geographic regions of similarity.

Cluster analysis of the streamflow-station matrix grouped the stations into four clusters. Three of the clusters define geographic regions of similarity in southwestern, northwestern, and northeastern Washington. The other cluster, which contains only two stations, both located in northeastern Oregon, was not used in the determination of a geographic region of similarity in Washington.

Cluster analysis of the precipitation-station matrix grouped the stations into four clusters, but defined only two geographic regions of similarity—western and southeastern Washington—because the geographic areas represented by the clusters overlapped considerably. The analysis also revealed an apparent inverse correlation between patterns of precipitation in southeastern and western Washington. This indicates that there is a tendency for persistent periods of above-average precipitation in western Washington to correspond with persistent periods of below-average precipitation in southeastern Washington, and conversely.

There generally is a higher degree of similarity among the patterns of variation for the streamflow stations than for the precipitation stations. The proportions of variance explained by the first principal components of the clusters in the analysis of the streamflow stations ranged from 87 to 94 percent, whereas the proportions explained by the clusters in the analysis of the precipitation stations ranged from 76 to 80 percent. Furthermore, the coefficients of correlation between streamflow-station chronologies and the clusters with which they were grouped were greater than 0.95 for 69 percent of the stations, whereas only 16 percent of the precipitation-station chronologies had coefficients of correlation that were greater than 0.95.

A water-resource-availability index (WRAI) was developed that provides a quantitative interpretation of present conditions in the context of historical records of streamflow and precipitation. The index value for a given month and year is calculated as the summation of time-weighted, rescaled, monthly departures during the preceding 3-year period. Computer programs INDEX.F77 and PRECIP.INDEX.F77 calculate and plot the chronologies of index values for streamflow and precipitation stations.

A method was developed to estimate monthly streamflow and precipitation at ungaged sites from monthly values at gaged sites. The method uses mean-monthly values and the standard deviation of the cumulative-annual values for both the gaged and ungaged sites. Computer program SIMULATE.F77 facilitates use of the method to estimate monthly discharges at ungaged streamflow sites. The relative accuracy of the method was illustrated by estimating, for the period 1937-76, monthly discharges for streamflow station 14128500 (Wind River near Carson, Wash.) from monthly discharges for station 14242500 (Toutle River near Silver Lake, Wash.). The estimated discharges were expected to closely match the actual discharges for the Wind River because the two stations are in the same region of similarity (cluster 1, southwestern Washington) and because the coefficient of correlation between them

(0.96) is high. Forty-nine percent of the simulated discharges were within 15 percent of the actual discharges, 72 percent were within 25 percent, and 95 percent were within 50 percent. The maximum percentage difference between simulated and actual monthly discharges was 91 percent in October 1952. The maximum percentage difference between simulated and actual annual-mean discharges was 21 percent in 1939 and the average percentage difference between them during 1937-76 was 6 percent.

Chronologies of cumulative departure for streamflow records can be used to examine the adequacy of the storage capacity of existing or proposed reservoirs. The maximum cumulative departure, in acre-feet, for a given stream, minus the minimum, over a given period, yields the approximate minimum size of reservoir that would be necessary to average out wet and dry periods and provide monthly outflows that are equal to the mean-monthly values of inflow without the reservoir ever overfilling or becoming completely depleted. Hypothetical examples were given to illustrate the use of computer program STREAM.F77 to make such calculations.

Another method of sizing reservoirs—the "residual mass curve method"—was briefly described. Minimum reservoir capacities determined by this method are less than those determined by the other method described.

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