Prepared in cooperation with Columbia River Inter-Tribal Fish Commission

A Method for Characterizing Late-Season Low-Flow Regime in the Upper Grande Ronde River Basin, Oregon

Scientific Investigations Report 2016–5041

U.S. Department of the Interior
U.S. Geological Survey

Cover: Limber Jim Creek looking uptream from the center of the channel. This creek flows into the main stem of the Upper Grande Ronde River, supports a small population of spring Chinook salmon, and contributes relatively cold water to the main stem, where spawning is much more significant. Photograph by Monica Blanchard, Columbia River Inter-Tribal Fish Commission, 2014.

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SALLY JEWELL, Secretary

U.S. Geological Survey
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Conversion Factors

Inch/Pound to International System of Units

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	2.590	square kilometer (km^2)
	Flow rate	
inch per inch (in/in)	25.4	centimeter per centimeter (cm/cm)
inch per hour (in/h)	0.0254	meter per hour (m/h)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)

International System of Units to Inch/Pound

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Area	
square kilometer (km^2)	0.3861	square mile (mi^2)

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as

$$°C = (°F – 32) / 1.8.$$

Datums

Vertical coordinate information is referenced to North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to North American Datum of 1983 (NAD 83).

Elevation, as used in this report, refers to distance above the vertical datum.

Abbreviations

CCA	canonical correlation analysis
CRITFC	Columbia River Inter-Tribal Fish Commission
GEV	generalized extreme value
GIS	geographical information system
NED	National Elevation Database
NWIS	National Water Information System
OWRD	Oregon Water Resources Department
PCA	principal component analysis
PWM	probability-weighted moment
STATSGO	State Soil Geographic database
USGS	U.S. Geological Survey

A Method for Characterizing Late-Season Low-Flow Regime in the Upper Grande Ronde River Basin, Oregon

By Valerie J. Kelly and Seth White[1]

Abstract

This report describes a method for estimating ecologically relevant low-flow metrics that quantify late-season streamflow regime for ungaged sites in the upper Grande Ronde River Basin, Oregon. The analysis presented here focuses on sites sampled by the Columbia River Inter-Tribal Fish Commission as part of their efforts to monitor habitat restoration to benefit spring Chinook salmon recovery in the basin. Streamflow data were provided by the U.S. Geological Survey and the Oregon Water Resources Department. Specific guidance was provided for selection of streamgages, development of probabilistic frequency distributions for annual 7-day low-flow events, and regionalization of the frequency curves based on multivariate analysis of watershed characteristics. Evaluation of the uncertainty associated with the various components of this protocol indicates that the results are reliable for the intended purpose of hydrologic classification to support ecological analysis of factors contributing to juvenile salmon success. They should not be considered suitable for more standard water-resource evaluations that require greater precision, especially those focused on management and forecasting of extreme low-flow conditions.

Introduction

The Columbia River Inter-Tribal Fish Commission (CRITFC) assists four major Tribes—the Nez Perce Tribe, the Confederated Tribes of the Umatilla Indian Reservation, the Confederated Tribes of the Warm Springs Reservation of Oregon, and the Confederated Tribes and Bands of the Yakama Nation—to restore stocks of ecologically, culturally, and economically important fish populations (Columbia River Inter-Tribal Fish Commission, 2014). Funding from the Columbia Basin Fish Accords agreement between three CRITFC Tribes and Bonneville Power Administration supports efforts to evaluate recovery trends in important habitat variables for spring Chinook salmon in the Upper Grande Ronde River Basin (McCullough and others, 2014). The work described in this report is a component of this larger project, and is focused on presenting a method for characterizing low-flow regimes as a primary feature of habitat quality for salmon spawning and juvenile rearing areas during the late summer season. Low summer streamflow is implicated as one of several key limiting factors leading to the critical status of spring Chinook salmon in the project area.

This report describes a protocol for estimating ecologically relevant streamflow metrics, which can be used in classifying streams to support further analysis of factors affecting the survival of salmon in the Upper Grande Ronde River Basin. Metrics are estimated to describe streamflow variability and timing, as well as the potential for groundwater influence and intermittent flow. A primary objective of this work is to develop the capacity for CRITFC personnel to conduct characterizations of low-flow regime as needed for specific ungaged stream reaches of interest, based on the relation between landscape characteristics and streamflow at gaged streams in the region. This report provides detailed descriptions of each step of the analysis and demonstrates the application of this approach for selected streams in the CRITFC study area.

Description of Study Area

The Grande Ronde River is a tributary to the Snake River, originating in the Blue Mountains ecological province of northeastern Oregon (fig. 1). It drains the Blue Mountains to the west and northwest and the Wallowa Mountains to the southeast for a total area of about 4,000 mi^2, flowing 212 mi roughly north-northeast from the headwaters to its confluence with the Snake River at Hells Canyon. Mountainous areas where headwater streams originate peak at elevations ranging from 7,500 to 10,000 ft, and two large river valleys are defined at lower elevations by the mainstem Grande Ronde and Wallowa Rivers (elevations 2,600–2,800 and 2,800–4,700 ft, respectively) (Northwest Power and Conservation Council, written commun., 2004).

[1]Columbia River Inter-Tribal Fish Commission.

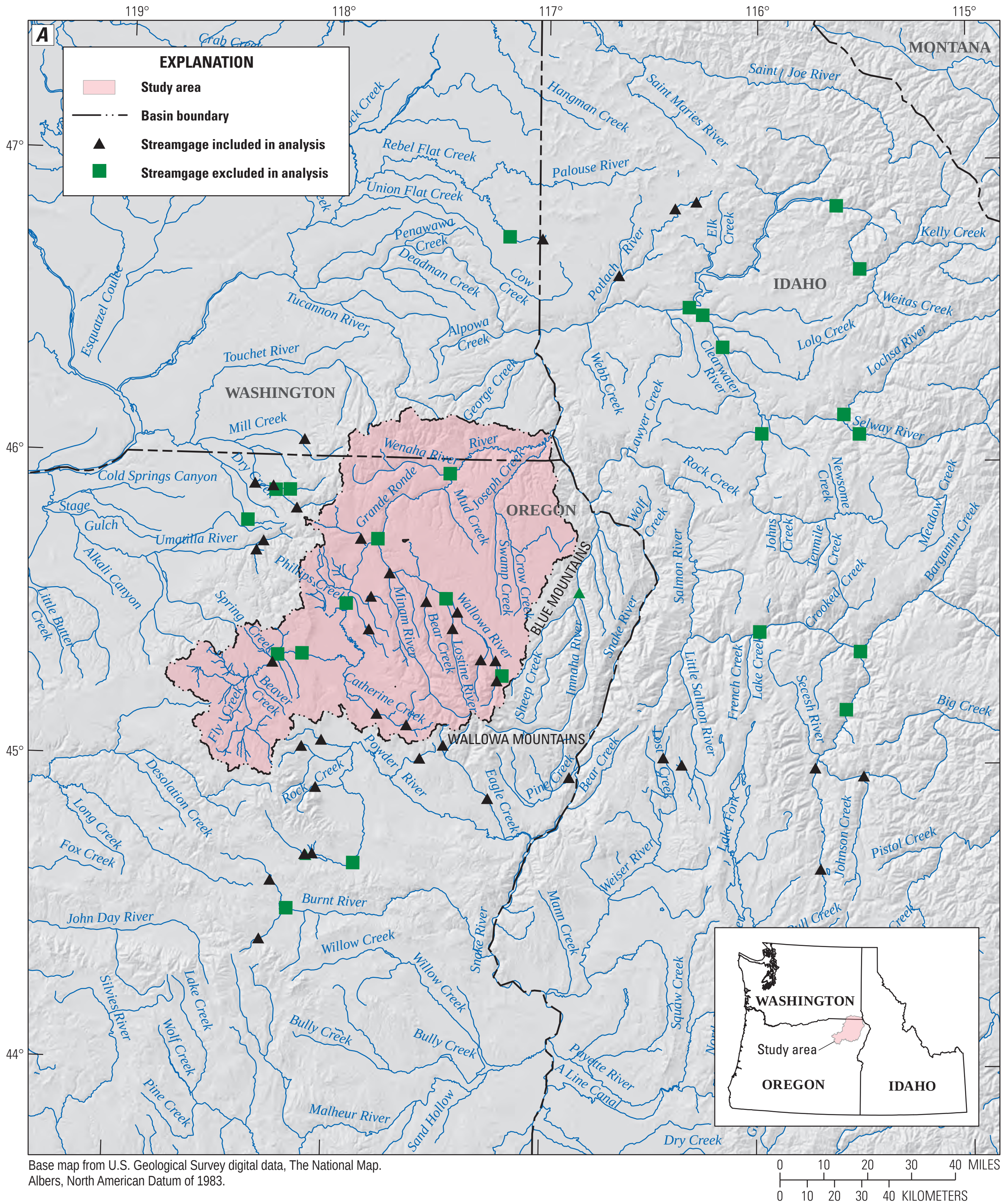
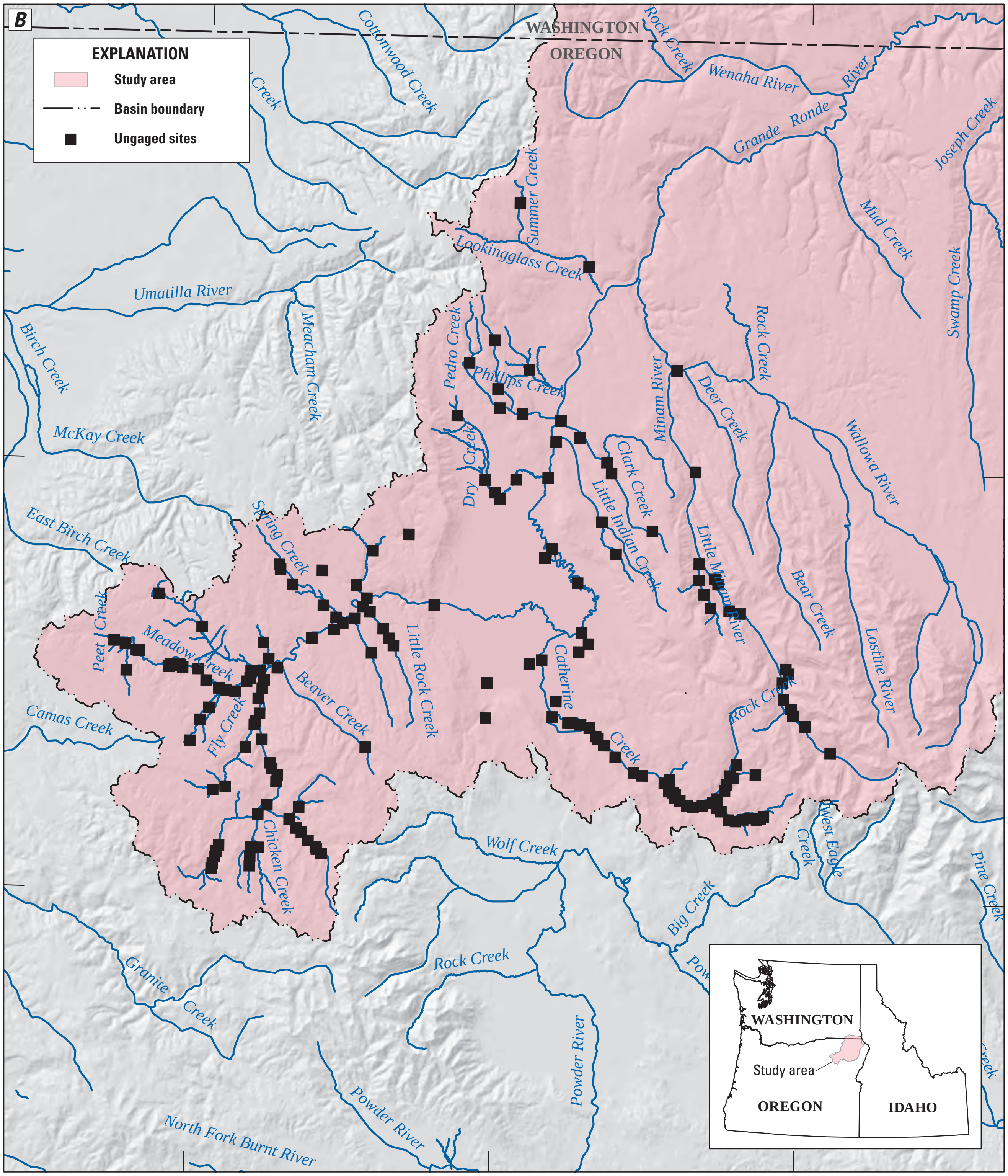


Figure 1. Locations of (*A*) all streamgages and (*B*) target ungaged sites, upper Grande Ronde River Basin, Oregon. Ungaged sites are streamgages that were excluded from further consideration if their upstream watershed area exceeded 500 mi². If two streamgages were located along the same stream, the ratio of their watershed areas was evaluated and if one watershed represented more than 0.25 of the other, the streamgage with the shorter period of record was excluded from further analysis.



Base map from U.S. Geological Survey digital data, The National Map.
Albers, North American Datum of 1983.

Figure 1.—Continued

Major tributaries include the Wenaha, Wallowa, and Minam Rivers, and Catherine and Lookingglass Creeks. Much of the upper Grande Ronde River Basin at high elevation is public land, primarily forested, whereas the lowland areas are private lands and subject to agricultural and grazing effects (McIntosh, 1992). Surface geology in the basin is dominated by Columbia River Basalt with older volcanic and granitic intrusive rocks largely confined to high elevation headwater areas; the Columbia Plateau aquifer system underlies about 75 percent of the basin (Northwest Power and Conservation Council, written commun., 2004).

Figure 1*A* presents the entire study area and includes locations of all streamgages used in this study, which were identified as suitable for regional analysis in another study focused on low flow (Risley and others, 2009). To clearly portray the streams and target sites in the upper Grande Ronde River Basin, which is a small area within the larger study area, a larger scale map is provided (fig. 1*B*). The results from this analysis should be considered applicable to any streams in the larger study area.

Climate in the Grande Ronde River Basin is influenced by the diversity of topography between high mountain ranges and deep canyons, which creates localized climatic effects. Regional climate is shielded from the maritime influence of the Pacific Ocean by the Cascade Mountains, 200 mi to the west, so that the dominant climate pattern is considered to be modified continental (Northwest Power and Conservation Council, written commun., 2004). Winters are cold and wet and summers are warm and dry, with air temperature varying according to elevation. Mean annual precipitation ranges from 14 in. in the valleys to more than 60 in. in the mountains (Northwest Power and Conservation Council, written commun., 2004). The range in elevation defines the warm snow zone (between about 2,000 and 5,000 ft of elevation) and the cold snow zone (> 5,000 ft) (Wissmar and others, 1994). Snow cover may become intermittent in the warm snow zone when temperatures between 50 and 60 °F develop during winter. These warm conditions often are associated with moderate to heavy precipitation, so that snowmelt may be coincident with rain and result in large winter floods.

Streams in the Grande Ronde River Basin are dominated by snowmelt, with peak flows occurring in spring (April–June). Timing of snowmelt runoff varies with elevation of headwaters, with earlier runoff associated with streams originating in the relatively low elevation Blue Mountains, whereas snowmelt peaks generally occur later in those arising in the higher Wallowa Mountains (written commun., Northwest Power and Conservation Council, 2004). Runoff decreases through summer and the lowest flows generally occur in August or September, sometimes extending into winter.

Importance of Low-Flow Regime to Salmon

Low flows in the upper Grande Ronde River Basin are hypothesized to be in two general categories: runoff-dominated and groundwater-dominated. The range in geology across the basin indicates two large-scale geologic zones, characterized by relatively old intrusive and volcanic deposits in the headwater areas at higher elevation and younger Columbia River Basalt farther downstream. These different rock types are presumed to be associated with contrasting patterns of groundwater storage, because older and less permeable formations generally store less water. Basaltic rocks, which tend to be more permeable, are likely to function as groundwater reserves, capturing snowmelt and storing it during the melt season, and releasing it slowly as base flow during the summer and autumn.

The extent of groundwater influence on streamflow affects habitat quality in the late summer season for stream fishes in several ways: through contributing base flow, modulating water temperature, and providing refugia from temperature extremes (Power and others, 1999). Groundwater contribution to summer base flow is beneficial because higher flows during that time provide greater volume of habitat, as well as exert a potentially significant cooling influence on stream temperature. Even a relatively small input of groundwater can provide critical protection for cold-water fishes like salmon from potentially lethal temperatures during the late summer months (Torgersen and others, 2012).

Historically, the upper Grande Ronde River supported large runs of spring Chinook salmon (*Onchorhynchus tsawytscha*) as well as summer steelhead (*O. mykiss*), although these stocks are now much reduced (McIntosh, 1992). Snake River spring Chinook salmon in the Snake River Basin, including the Grande Ronde River, were listed as threatened in 2005 under the Endangered Species Act and populations in the Grande Ronde River Basin are considered as high priority for recovery (National Oceanic and Atmospheric Administration, 2005, 2007). Natural spawning of spring Chinook salmon occurs in the upper Grande Ronde River and its primary tributaries: the Wenaha River in the lower basin, the Wallowa River in the middle basin with its tributaries the Minam and Lostine Rivers, as well as in smaller streams including Bear and Hurricane Creeks in the Wallowa Basin, Lookingglass Creek in the middle basin, and Catherine Creek in the upper basin (Columbia River Inter-Tribal Fish Commission, 1995).

Snake River spring Chinook salmon life history is of the stream type, where juveniles remain in fresh water for 1 year before they migrate to the ocean. Adults re-enter fresh water in late winter and early spring and move upstream to relatively high elevation areas where they rely on cool and deep pool habitat before spawning in late summer and early autumn. The most important flow-related effects on salmon in the basin include the loss of pool habitat and extreme water temperatures during the late summer season (Wissmar and others, 1994), both of which depend on the relative influence of groundwater during late-season base flow conditions.

Approach

Analysis of streamflow patterns is frequently based on annual streamflow frequency information that, in the United States, is supplied primarily by data from the U.S. Geological Survey (USGS) streamflow database. The necessary data are available only for sites where long-term streamgages are located, however, and many streams are not gaged. Regional frequency analysis provides a way to estimate the frequency distribution for various low-flow metrics at ungaged sites, based on pooled data from streamgages within a homogeneous region (Riggs, 1973; Stedinger and others, 1993). In this study, an index procedure was used, whereby the regional frequency curve was scaled by a site-specific scaling factor (termed the "index flow," for example the mean peak- or low-flow value for the site) (Hosking and Wallis, 1993). This curve defines the dimensionless frequency distribution for the region, from which specific quantile estimates for ungaged sites can be determined on the basis of estimated values for the index flow for those sites. The steps involved in regional index-flow analysis include (1) identification of homogeneous regions, (2) selection and estimation of a regional frequency distribution, and (3) estimation of index flow.

A critical assumption for any index-flow procedure is that the scaled frequency distributions for all sites within the region are similar. Geographically contiguous regions frequently have been defined according to physiographic and political boundaries and assumed to be homogeneous, although they do not always correspond to similarities across the region in hydrologic response (Simmers, 1975). For this analysis, a "region of influence" approach was used to group sites according to watershed features that are presumed to control streamflow characteristics (Wiltshire, 1986). In this approach to regionalization, every site potentially has a unique set of basins defined as its hydrological "region" that is not required to be spatially contiguous (Burn, 1990a, 1990b; Zrinji and Burn, 1994) (fig. 2). These sites are selected from the correspondence between selected hydrologic and watershed characteristics, as determined by canonical correlation analysis (CCA) (Ribeiro-Correa and others, 1995). CCA is a multivariate statistical technique in which each entity is measured on two sets of variables and provides a measure of how strongly the two sets are related to each other (Tabachnick and Fidell, 2001). In this analysis, the two sets of variables include (1) the target streamflow metrics and (2) watershed attributes that have been determined to correlate strongly with the attributes. The analysis produces pairs of canonical variates that represent a combination of the associated variables across all sites, each of which contains a canonical score for each site with the highest correlation with the score for that site in the other set. The relation between these variates then provides a way to estimate the streamflow metrics from watershed data for sites where no hydrologic data are available. By measuring the same attributes for watersheds of the ungaged target streams and determining the corresponding canonical scores, the associated scores on the hydrologic vector can be identified. An ellipsoidal region around each hydrologic score can be quantified with a defined level of confidence based on a chi-squared distribution. This region identifies the gaged watersheds that compose the corresponding so-called hydrologic neighborhood or site-specific region for the target site. Data from each region are then combined to produce a regional probability curve to describe low-flow conditions for each target site.

A key element of any regionalization technique is to select the appropriate frequency distribution to describe the individual frequency curves for the gaged sites and the regional frequency curves for the ungaged sites. Because of the focus on extreme events, the generalized extreme value (GEV) distribution, based on probability-weighted moments (PWMs), was selected for this analysis (Greenwood and others, 1979; Landwehr and Matalas, 1979; Hosking and others, 1985). This procedure is flexible and easy to implement, and has proven to be especially reliable when regions are not homogeneous (Lettenmaier and others, 1987). Additionally, after a comparison of six theoretical distributions for minimum flows, the PWM/GEV distribution was determined to have the best performance (Onoz and Bayazit, 1999; Vicente-Serrano and others, 2012). For these reasons, this approach was selected as appropriate for this analysis.

This method differs from the usual USGS technique of estimating low-flow conditions, which is based on multiple linear regressions within presumed homogeneous contiguous regions (for example, Risley and others, 2009). This approach does not estimate a coherent regional probability curve but instead provides individual estimates for selected quantile elements of a probability curve. Furthermore, in the standard USGS approach flows typically are augmented to provide estimates of flow magnitude unaffected by human activity such as water withdrawals. Because the intent of this project was to estimate existing low-flow conditions, augmented flows were not used in this analysis. No attempt was made to compare the performance of these different methods.

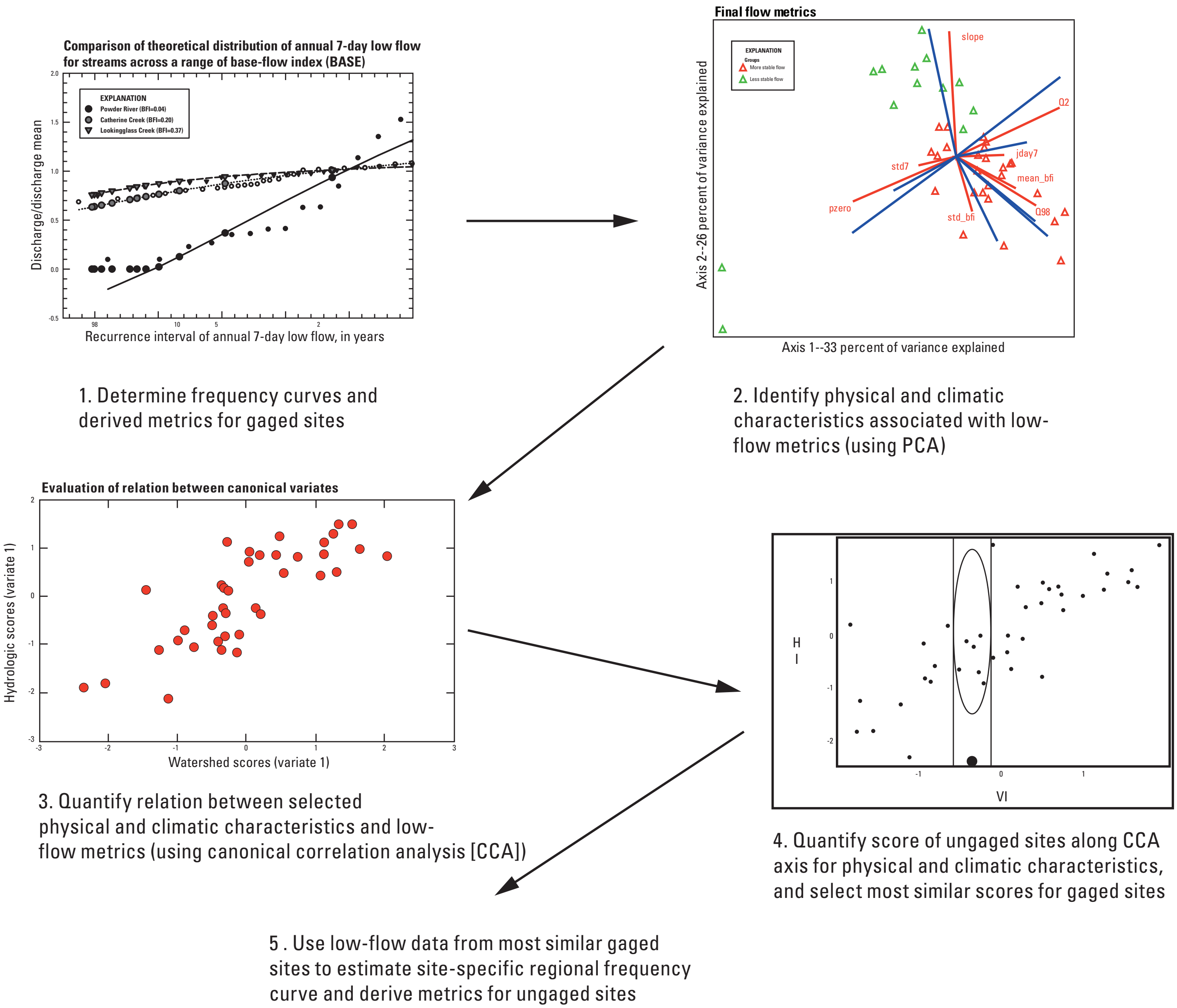


Figure 2. Conceptual diagram showing overview of approach to regionalization used for the upper Grande Ronde River Basin, Idaho, Oregon, and Washington.

Data Assembly

Streamflow Data

Previous work by Risley and others (2009), estimating low-flow frequency statistics for unregulated streams in Oregon, provided the first estimation of a set of streamgages suitable for this analysis. Daily mean streamflow data were obtained from the USGS National Water Information System (U.S. Geological Survey, 2012) and from the online data service provided by the Oregon Water Resources Department (OWRD) (2012) for those streamgages (N=61) identified in Risley and others (2009) as Region 6, which they assumed to represent a homogeneous hydrologic region containing the Grande Ronde River. These streamgages were further augmented by additional OWRD streamgages (N=14) on streams that were not included in Region 6 for the Risley and others (2009) analysis. Streamgages were excluded from further consideration if their upstream watershed area exceeded 500 mi^2, the largest watershed included as a target CRITFC ungaged site. Additionally, if two streamgages were located along the same stream, the ratio of their watershed areas was evaluated, and if one watershed represented more than 0.25 of the other, the streamgage with the shorter period of record was excluded from further analysis.

The daily data were first subset to include data only for the late-season summer period (Julian days 200–300, mid-July through most of October), prior to determining the annual 7-day minimum flow for each year of record. Once these data were compiled, in order to conform to the assumptions of stationarity for the frequency analysis, they were evaluated for temporal trend as defined by Kendall's tau-b ($p<0.01$). Trend analysis proceeded in an iterative process in an attempt to maximize the period of record. First, the data for the entire period of record were evaluated. For streamgages where no trend was observed, the entire dataset was included in the regional analysis. Second, for streamgages with a significant trend, a subset of the data was evaluated again to determine if a shorter period of record would be suitable for the regional analysis. The period of record was first limited to the record beginning in 1960 and subsequently for the record beginning in 1980. All streamgages with a significant trend over the entire period of record continued to show trends over these shorter periods. Sites were further limited so that each was associated with a minimum of 10 years of record. Based on this screening, 39 suitable streamgages were selected for analysis (table 1).

Table 1. Final set of streamgages used in analysis, upper Grande Ronde River Basin, Idaho, Oregon, and Washington.

[**Agency:** USGS, U.S. Geological Survey; OWRD, Oregon Water Resources Department]

Streamgage No.	Agency	Name	Period of record
13251300	USGS	West Branch Weiser River near Tamarack ID	1959–1977
13269300	USGS	North Fork Burnt River near Whitney OR	1964–1980
13270800	USGS	South Fork Burnt River above Barney Creek, near Unity OR	1963–1981
13275100	USGS	Powder River above Phillips Lake near Sumpter OR	1967–1980
13275200	USGS	Deer Creek above Phillips Lake near Sumpter OR	1967–1999
13281200	USGS	Rock Creek near Haines OR	1976–1999
13282400	USGS	Anthony Creek below North Fork near North Powder OR	1962–1978
13283600	USGS	Wolf Creek above Wolf Creek Reservoir near North Powder OR	1973–2000
13285900	USGS	Big Creek below Burn Creek near Medical Springs OR	1962–1979
13287200	USGS	West Eagle Creek below Jim Creek near Baker OR	1967–1986
13288200	USGS	Eagle Creek above Skull Creek near New Bridge OR	1957–2011
13290190	USGS	Pine Creek near Oxbow OR	1966–1996
13310500	USGS	South Fork Salmon River near Knox ID	1928–1960
13310700	USGS	South Fork Salmon River near Krassel Ranger Station ID	1966–2011
13313000	USGS	Johnson Creek at Yellow Pine ID	1928–2011
13315500	USGS	Mud Creek near Tamarack ID	1937–1959
13318500	USGS	Grande Ronde River near Hilgard OR	1937–1956
13319900	OWRD	North Fork Catherine Creek near Medical Springs OR	1992–2013
13320000	USGS	Catherine Creek near Union OR	1911–1996
13323600	OWRD	Indian Creek near Imbler OR	1938–1950
13323700	OWRD	North Fork Clarks Creek near Elgin OR	1966–1983
13324300	USGS	Lookingglass Creek near Looking Glass OR	1982–2009
13325001	OWRD	East Fork Wallowa + powerplant tailrace	1924–1983
13327500	OWRD	Wallowa River at Joseph OR	1903–1991
13329500	OWRD	Hurricane Creek near Joseph OR	1915–1978
13329770	OWRD	Wallowa River above Cross County Canyon OR	1995–2009
13330000	USGS	Lostine River near Lostine OR	1912–2011
13330500	USGS	Bear Creek near Wallowa OR	1995–2013
13331500	USGS	Minam River near Minam OR	1912–2011
13341300	USGS	Bloom Creek near Bovill ID	1959–1971
13341400	USGS	East Fork Potlatch River near Bovill ID	1959–1971
13341500	USGS	Potlatch River at Kendrick ID	1945–1960
13346800	USGS	Paradise Creek at University of Idaho at Moscow ID	1978–2011
14010000	USGS	South Fork Walla Walla River near Milton OR	1907–1991
14011000	USGS	North Fork Walla Walla River near Milton OR	1930–1969
14011800	USGS	Couse Creek near Milton-Freewater OR	1964–1978
14013500	USGS	Blue Creek near Walla Walla WA	1939–1971
14020000	USGS	Umatilla River above Meacham Creek near Gibbon OR	1933–2011
14020300	USGS	Meacham Creek at Gibbon OR	1975–2011

Watershed Characteristics

Numerous candidate watershed characteristics were obtained for each streamgage and CRITFC site, including drainage area, topography, precipitation, soil characteristics, underlying geology, and several metrics of watershed shape and aspect. All watershed characteristics were extracted from geographical information system (GIS) databases using Arc Macro Language programs written for Arc/Info by Environmental Systems Research Institute, Inc. Drainage area was determined by digitizing watershed boundaries using 1:24,000 USGS topographic maps. Elevation was determined from data from the USGS National Elevation Database (NED), with 30-meter resolution; further evaluation of elevation was based on the proportion of each watershed within selected elevation ranges. Annual precipitation was calculated as the sum of area-weighted estimates, based on raster precipitation data for monthly mean precipitation totals (1961–90), with 2-km resolution (Daly and others, 1994). Precipitation intensity metrics for selected recurrence intervals were calculated from raster data, including both local (site-specific) and watershed-wide characteristics (Hershfield, 1961; National Oceanic and Atmospheric Administration, 1973). Soil permeability and water capacity were described by the sum of area-weighted values for the watershed, based on data from the State Soil Geographic (STATSGO) database (Schwarz and Alexander, 1995). Metrics of watershed shape were determined by the Basinsoft program (Harvey and Eash, 1996). Data to describe aspect direction were derived as the mean overall deviation of the watershed from the south in degrees. Watershed characteristics evaluated in this analysis are described in appendix A; data used to describe watershed characteristics for streamgage sites are presented in appendix B.

Characterization of Late-Season Low-Flow Regime

Streamflow Frequency Analysis

Frequency analysis provides a way to assign probabilities to the occurrence of low-flow events of a specified size based on fitting a theoretical probability distribution to the measured data. The use of theoretical distributions provides an objective method for deriving estimates of metrics that succinctly describe the streamflow regime, based on parameters that are determined directly from the annual data series. These include measures to describe location (that is, mean), scale (that is, standard deviation), and skew (that is, shape). Annual data are ranked and assigned a plotting position that approximates the associated probability, and the theoretical curve is estimated based on this position and appropriate parameters.

Frequency analysis of annual 7-day low-flow data from gaged sites was based on an index-flow procedure, using PWM estimators of the GEV distribution (Hosking and others, 1985). The GEV distribution of any random variable (*x*) is described by

$$F(x) = exp\left\{-\left[1-\frac{g(x-u)}{a}\right]^{\frac{1}{g}}\right\}, \tag{1a}$$

where

g $\neq 0$.

$$F(x) = exp\left\{-exp\left[-\left(\frac{x-u}{a}\right)\right]\right\}, \tag{1b}$$

where

g = 0, and

u, a, and g represent parameters of location, scale, and shape or skew, respectively.

For this analysis, the probability-weighted moments (M_j) for each site were first determined as

$$M_j = \frac{1}{n}\sum_{i=1}^{n}\left(p_i^j, Q_i\right), \text{for } j = 0,1,2, \tag{2}$$

where

p_i =(i-0.35)/n is the plotting position estimate of $F(Q)$ and

Q_i is the series of annual 7-day minimum streamflow.

For this analysis, the series was ordered from smallest to the largest so that the plotting position (p_i) represents Px(x), the probability of an event equal to or smaller than the designated value (Gordon and others, 1992).

Next, the PWMs for each site were normalized by their mean ($M_j^* = M_j - M_0$). The parameters of the GEV distribution were estimated as follows:

$$c = \frac{2M_1 - M_0}{3M_2 - M_0} - \frac{\log 2}{\log 3} \tag{3a}$$

$$g = 7.8590c + 2.9554c^2 \tag{3b}$$

$$a = \frac{(2M_1 - M_0)g}{\Gamma(1+g)(1-2^{-g})} \tag{3c}$$

$$u = M_0 + a\left[\Gamma(1+g) - 1\right]/g . \tag{3d}$$

Finally, the selected quantiles (T-year flow events) of the GEV distribution were determined by

$$Q_T^* = \frac{\left\{1 - \left[-ln\left(1 - \frac{1}{T}\right)\right]^g\right\}}{g} \quad (4)$$

where

$g \neq 0$.

The presence of zero flow values was managed by adjusting probabilities based on the theorem of total probability (Haan, 2002). All the probability was assumed to be accounted for simply by the sum of the probability of flow equal to zero plus the probability of flow greater than zero. Based on this assumption, the frequency distribution for each site was first determined for all 7-day low-flow values greater than zero. The resulting probabilities were then adjusted by the fraction of non-zero values in the data for that site, effectively shifting the frequency curve along the probability axis to reflect the probability of zero flow (Gordon and others, 1992).

A probability plot correlation test was done to determine how well the sample data from each streamgage fit the GEV distribution (Stedinger and others, 1993). This test is based on the correlation *r* between the ranked sample data and the corresponding estimated values based on their plotting positions. Values of *r* close to 1 indicate a close correspondence between the data and the theoretical distribution.

Streamflow metrics were determined for each site, either directly from the frequency curve or calculated from the time-series data (table 2; appendix C).

Canonical Correlation Analysis

Canonical correlation analysis (CCA) was used to analyze the relation between selected watershed characteristics and streamflow metrics (fig. 2). The method is comparable to multiple regressions with sets of variables on both sides of the equation. These sets of variables are combined to produce multivariate dimensions that maximize the linear relation between the two sets of variables (Tabachnick and Fidell, 2001). The solution depends both on the correlations among variables *in each set* (which are best minimized) and on correlations among variables *between the sets* (which are best maximized).

The CCA was done between selected sets of watershed variables and sets of streamflow metrics using SAS CANCORR (SAS Institute, Inc., 1989). Where appropriate, watershed variables were normalized (for example, maximum January temperature) to the maximum value to improve normality of distribution and linearity of relation between variables. Variables for each set were selected on the basis of principal component analysis (PCA) ordination of streamflow metrics, using the Euclidian distance measure (McCune and Mefford, 1999) (fig. 2). All data were first normalized to the maximum value to account for differences in scale.

Table 2. Definitions of ecologically relevant streamflow metrics to describe a low-flow regime.

Streamflow metric	Short definition	Description
Q	Mean annual 7-day low-flow magnitude	Mean annual 7-day low flow over period of record
Q_2	Index of low-flow stability (normalized 7-day 2-year flow)	7-day low flow magnitude expected to occur once in 2 years/mean annual 7-day low flow
Q_{98}	Index of low-flow variability (normalized 7-day 98-year low flow)	7-day low flow magnitude expected to occur once in 98 years/mean annual 7-day low flow
Jday	Low-flow timing (mean Julian day, onset of annual 7-day low flow)	Average Julian day for onset of annual 7-day low flow over period of record
BASE	Baseflow index (mean annual 7-day low flow/mean annual flow)	Average annual 7-day low flow over period of record/average annual flow over same period of record
pzero	Percent zero flow	Percent of time that annual 7-day low flow was zero over period of record

Estimation of Metrics for Ungaged Sites

The estimation of metrics for ungaged sites was based on a regionalization process that assumes regions of similar watershed characteristics determined to be associated with low-flow metrics from gaged sites provide appropriate inference for similar associations for the ungaged sites. Accordingly, the results from CCA provided the basis for identification of site-specific regions for each ungaged site based on comparable watershed attributes.

Using output from the CCA of gaged sites, scores on the first two canonical watershed variates were determined for each ungaged site using SAS SCORE (SAS Institute, Inc., 1989). The distance between gaged sites and each target ungaged site along the watershed variate was identified by Mahalonobis distance, a multivariate distance measure that conforms to a chi-square distribution. This distribution was evaluated for canonical watershed scores (v_0) for each ungaged site along the first two canonical variates according to the following:

$$\left(w-\backslash\Lambda v_0\right)'\left(I_p-\backslash\Lambda v_0\right)^{-1}\left(w-\backslash\Lambda v_0\right)\leq X^2_{a,p} \quad (5)$$

where

w is the score on the hydrologic variate for each gaged site,

Λ is the eigenvalue, or squared canonical correlation between the pair of canonical variates, and

I_p is the $p \times p$ identify matrix (p = 2) (Ouarda and others, 2001).

Regions were defined by 90 percent confidence when possible, with a further requirement to contain a minimum of three sites; for some sites, it was necessary to limit confidence to obtain the minimum number of sites.

Once the site-specific regions were determined for each ungaged site, the regional PWMs were calculated as weighted averages of the PWMs for the gaged sites with each region:

$$M_{j_r} = \frac{\sum_{k=1}^{K} n_k M_j^*}{\sum_{k=1}^{K} n_k}, \; j = 0,1,2, \quad (6)$$

where the denominator is the total number of years of record for the region. Regional average PWMs were used to estimate the parameters of the GEV distribution based on equation 3(a–d), and quantiles of the regional GEV distribution were calculated using regional parameter values and equation 4. Streamflow metrics were derived directly from the regional frequency curve for each ungaged site, as described in table 2. Metrics describing timing (mean for Julian day [Jday]) of onset of annual 7-day low flow and base-flow index (mean for BASE) were estimated from data for each site-specific region. The percent of zero flow (pzero) was estimated directly from the regional frequency curve.

Quantifying Uncertainty in Estimates

An evaluation of the errors in the regionalization process on the metrics estimated for the ungaged sites was provided by two additional analyses. First, cross-validation of data from the gaged sites was done to evaluate how well frequency distributions derived from regions defined by CCA compared with those derived from observed data. Watershed scores for gaged sites were used to generate regions for each gaged site considered separately, each of which was excluded from inclusion in the potential pool of sites for the region. Regional frequency curves were derived for each gaged site from those regions in the same manner used for ungaged CRITFC sites and the differences between the metrics derived from these regional curves and those determined from the individual frequency curves were evaluated.

Second, the standard error of the estimate for the selected quantiles were determined according to the method described in Rosbjerg and Madsen (1995). The mean and variance of each T-year event estimator (for example, Q/Q_m) were first approximated by:

$$E\{x_T\} = \frac{a}{g}\left(1 - K_T^g\right) + u - \frac{a}{N}\left\{Bw_{23} + \left[\frac{1}{2g}K_T^g\left(lnK_T\right)^2 - \frac{1}{g}B\right]w_{33}\right\} \quad (7)$$

$$Var\{x_T\} = \frac{a^2}{N}\left[w_{11} + A\left(Aw_{22} + 2w_{12}\right) + B\left(Bw_{33} - 2w_{13} - 2w_{23}\right)\right] \quad (8)$$

where

a, g, and u are from equation 3(b–d),

N is the total number of years of record for all sites within the site-specific region,

$K_T = -ln\left(1 - \frac{1}{T}\right)$ and

A and B were determined as follows:

$$A = \frac{1}{g}\left(1 - K_T^g\right) \quad (9)$$

$$B = \frac{1}{g^2}\left(1 - K_T^g\right) + \frac{1}{g}K_T^g lnK_T \quad (10)$$

The terms w_{ij} are elements of the asymptotic covariance matrix of the PWM estimators of the GEV parameters, and were derived by Hosking and others (1985) for several values of g; the values used in this analysis were based on a mean value of g of -0.4 (Rosbjerg and Madsen, 1995) (table 3).

Finally, the standard errors associated with each T-year event estimator (or quantile) were determined as $\sqrt{var\{x_T\}} \big/ \sqrt{N}$.

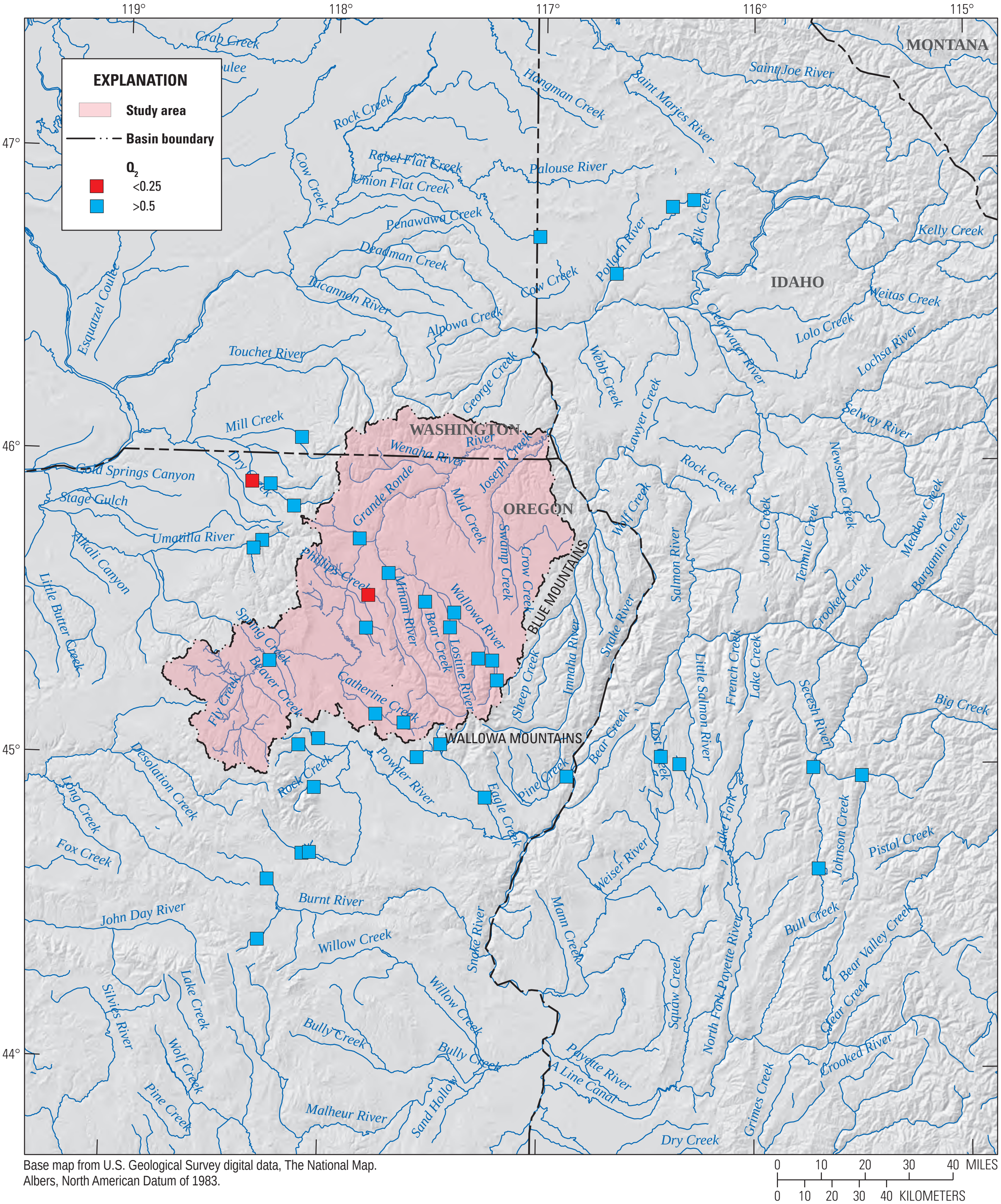
Table 3. Selected elements of the asymptotic covariance matrix.

[w_{ij}, represents the covariance between the ith and jth elements]

g	w_{11}	w_{11}	w_{11}	w_{11}	w_{11}	w_{11}
0.4	1.2433	-0.1205	0.3592	0.6368	0.3329	0.5880

Streamflow Metrics for Gaged Sites

Results for selected streamflow metrics for gaged sites are shown in figures 3–7 and appendix C. Results for Q_2, which is defined as the ratio of the 2-year 7-day low flow magnitude and the mean annual 7-day low-flow magnitude (both defined for the summer period only, Julian day 200–300), provides a unitless measure of the stability of common low-flow conditions. Results suggest that low flow is fairly stable for all gaged sites (fig. 3). Only two sites were associated with Q_2 values less than 0.25, and the remainder were associated with Q_2 values greater than 0.85. Variability was greater for Q_{98} across the range of gaged sites, which is defined as the ratio of the 98-year 7-day low-flow magnitude and the mean annual 7-day low-flow magnitude. This metric is assumed to represent a measure of extreme low-flow conditions (and thereby an indication of the variability in low flow) (fig. 4). Fourteen sites were associated with Q_{98} values less than 0.25, indicating that extreme low-flow conditions represent a significant reduction from mean flow conditions. Results for the mean timing of onset of annual 7-day low-flow conditions show that only four gaged sites were associated with early mean onset of low flow (prior to September 1); most sites were associated with low-flow onset after September 15 (fig. 5). For base flow index, results indicate that only four gaged sites are subject to relatively high influence of groundwater, as measured by BASE values greater than 0.4 (fig. 6). The remainder of the sites were roughly divided between those with BASE values between 0.1 and 0.4 (N=18), suggesting a slight tendency for groundwater input, and those associated with BASE values less than 0.1 (N=17), suggesting little influence of groundwater. The probability of zero flow was zero for most gaged sites, with only two sites showing any probability of intermittent flow (fig. 7).



Base map from U.S. Geological Survey digital data, The National Map.
Albers, North American Datum of 1983.

Figure 3. Estimated ratio of the 2-year 7-day low flow magnitude and the mean annual 7-day low-flow magnitude (Q_2) for gaged sites, Idaho, Oregon, and Washington.

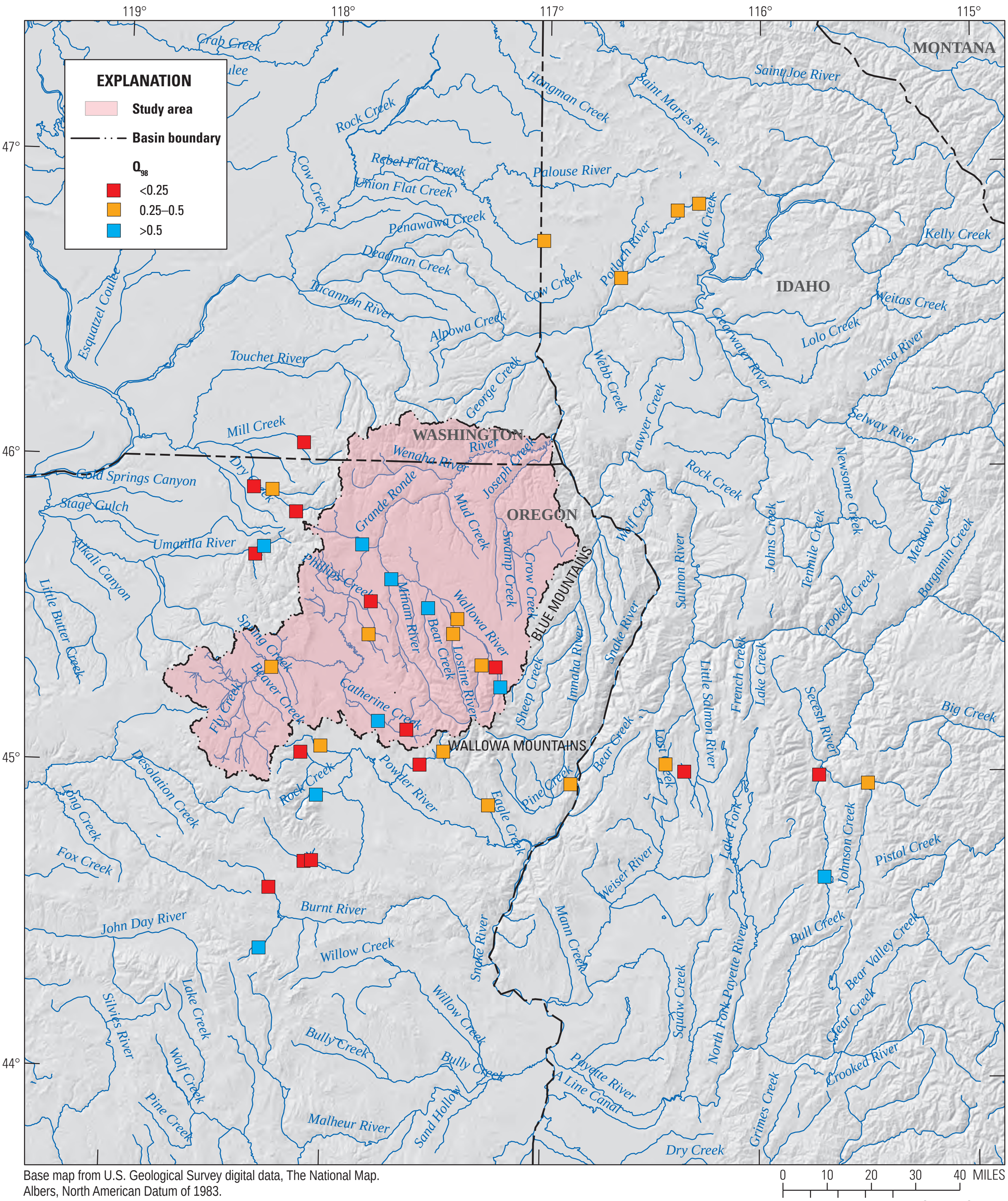
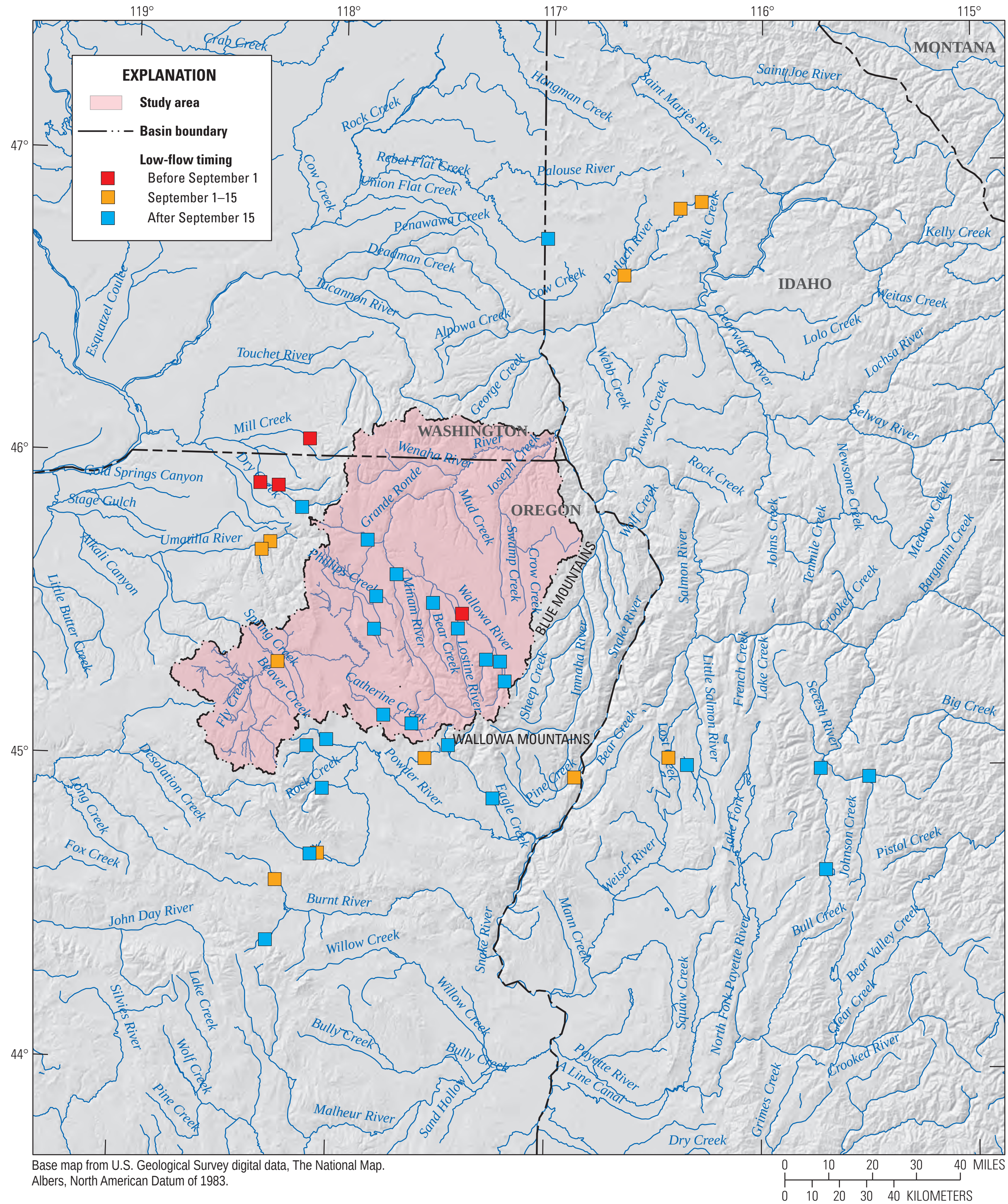
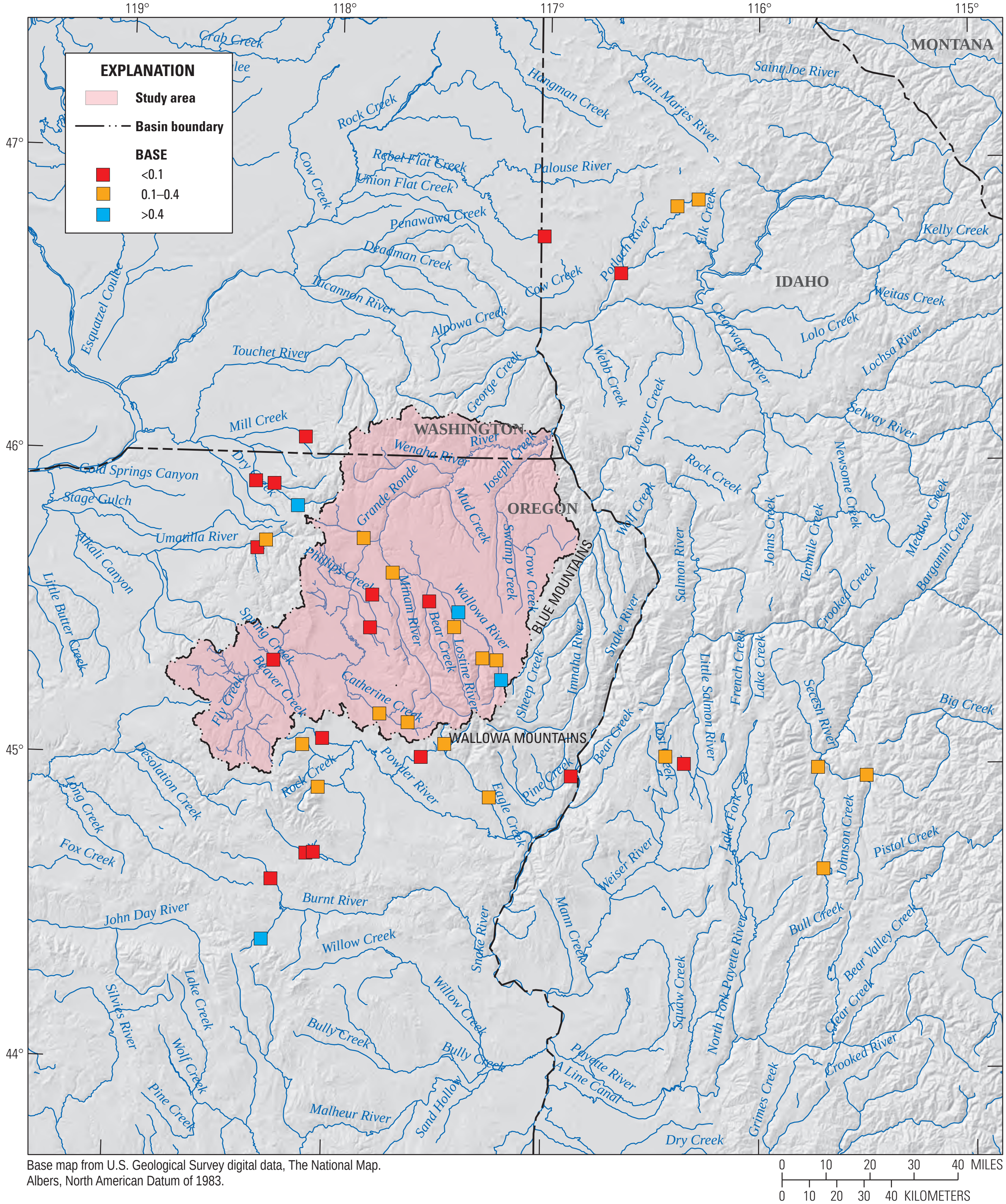


Figure 4. Estimated ratio of the 98-year 7-day low-flow magnitude and the mean annual 7-day low-flow magnitude (Q_{98}) for gaged sites, Idaho, Oregon, and Washington.



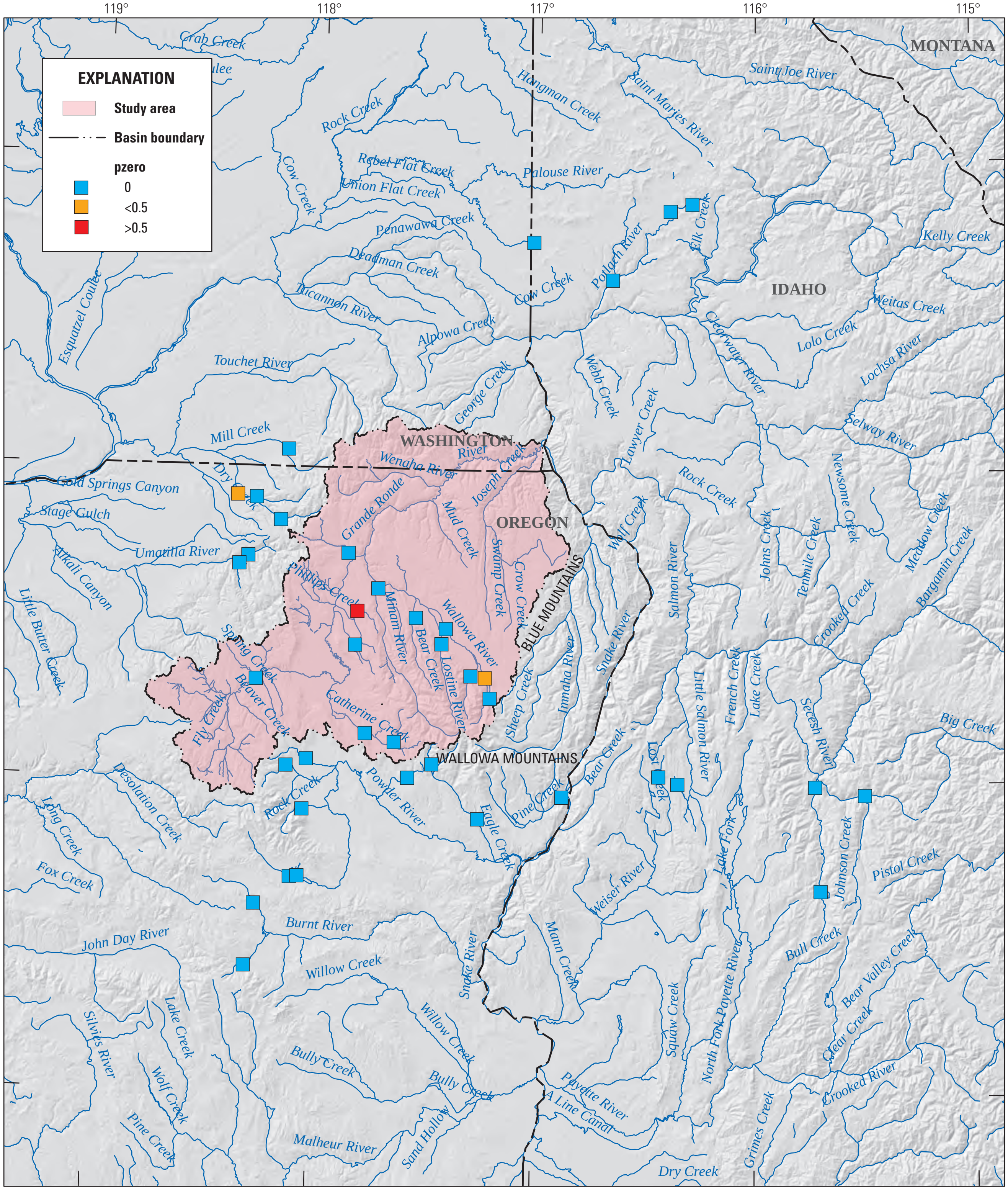
Base map from U.S. Geological Survey digital data, The National Map.
Albers, North American Datum of 1983.

Figure 5. Mean timing of onset of low-flow for gaged sites, Idaho, Oregon, and Washington.



Base map from U.S. Geological Survey digital data, The National Map.
Albers, North American Datum of 1983.

Figure 6. Estimated base-flow index (BASE) for gaged sites, Idaho, Oregon, and Washington.



Base map from U.S. Geological Survey digital data, The National Map.
Albers, North American Datum of 1983.

Figure 7. Probability of zero flow (pzero) for gaged sites, Idaho, Oregon, and Washington.

Canonical Correlation Analysis

Examination of correlations of the flow metrics with the PCA ordination provided the justification for identification of two relatively independent (that is, non-redundant) dimensions of low-flow regime—one identified with a measure of low-flow variability (Q_{98}) and one identified with a measure of low-flow timing (Jday) (fig. 8). The selection of watershed variables was based on examination of a joint plot, which portrayed the direction and strength of the correlation between the two sets of variables. The variables selected showed the strongest linear relation with the ordination structure of the hydrologic regime, and included mean annual precipitation, maximum January temperature, and stream density (figs. 9–12). An additional consideration, which limited the total number of variables for CCA was the relatively small number of gaged sites (Tabachnick and Fidell, 2001). The distribution of these watershed variables across the study area are shown in figures 10–12.

Results from the canonical correlation analysis indicate that the first canonical correlation was significant ($P<0.0001$) and accounted for a large proportion of the variation (table 4), whereas the second variate was not significant ($p=0.13$). The first canonical correlation was high (0.8) and accounted for 64 percent of overlapping variance (squared canonical correlation) (fig. 13). The second canonical correlation was less (0.4), accounting for an additional 15 percent of overlapping variance. These results indicate that only the first pair of canonical variates were strongly related. Full results for canonical correlation are presented in appendix D.

Final flow metrics

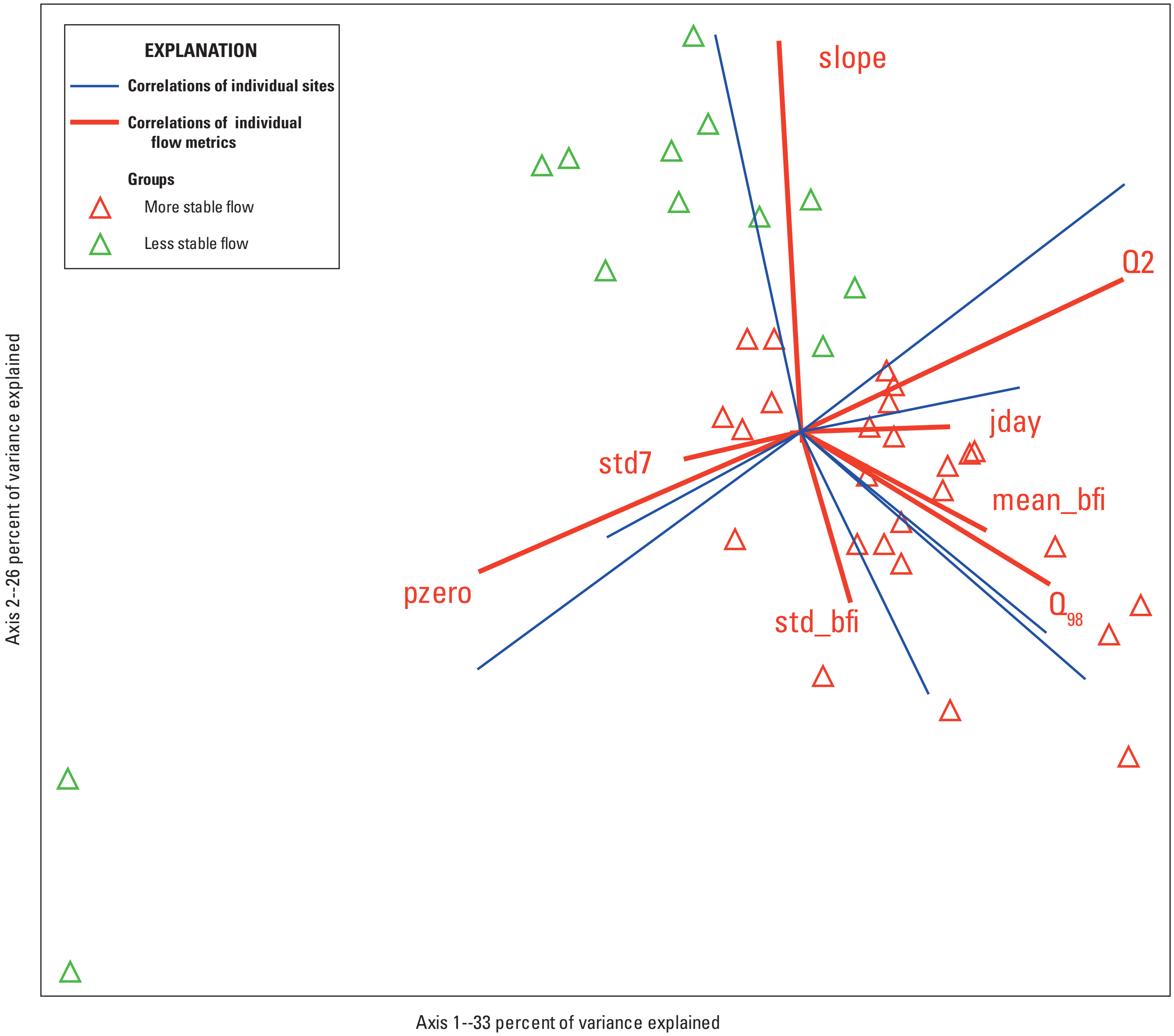


Figure 8. Ordination plot showing principal component ordination of flow metrics.

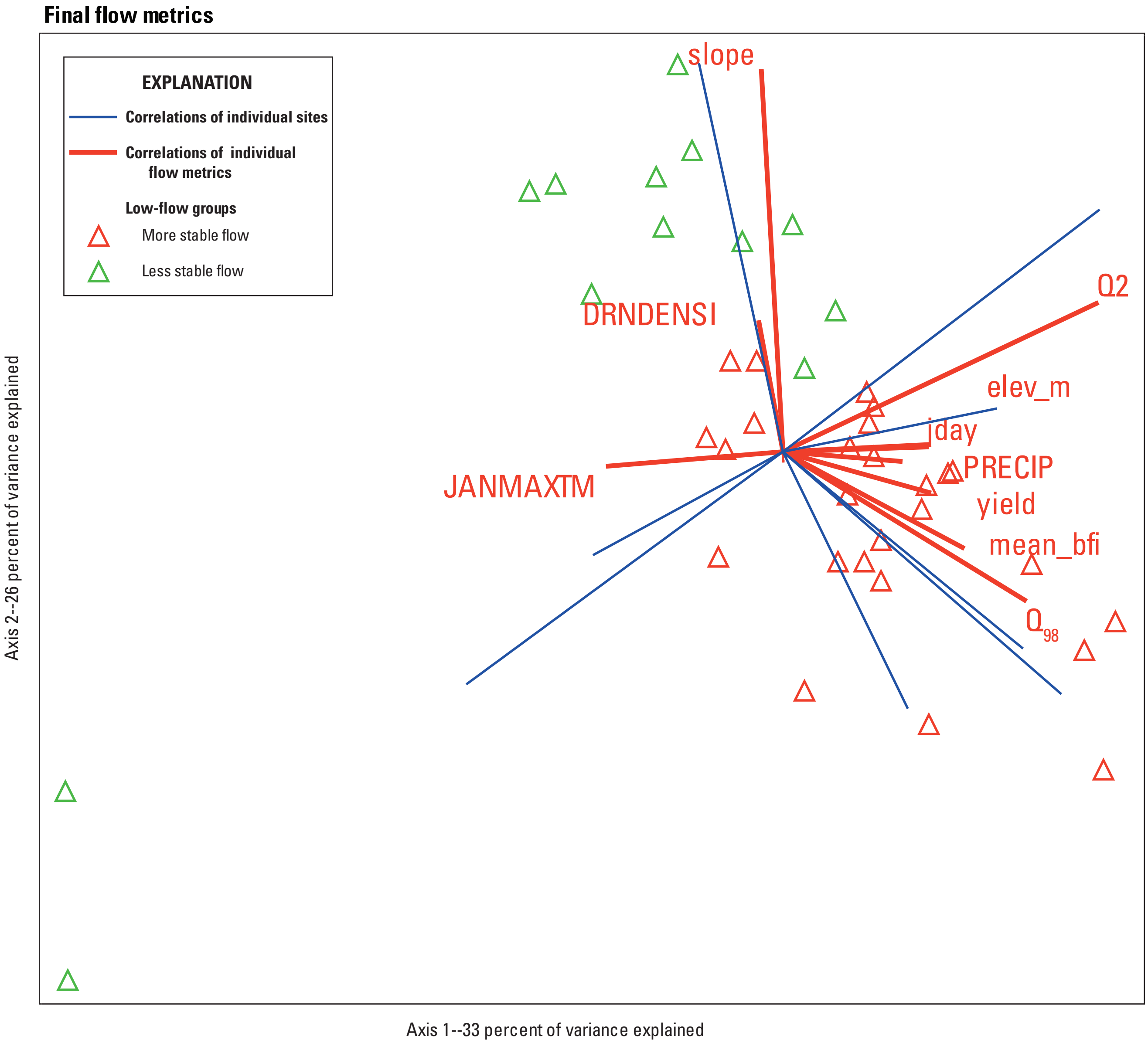
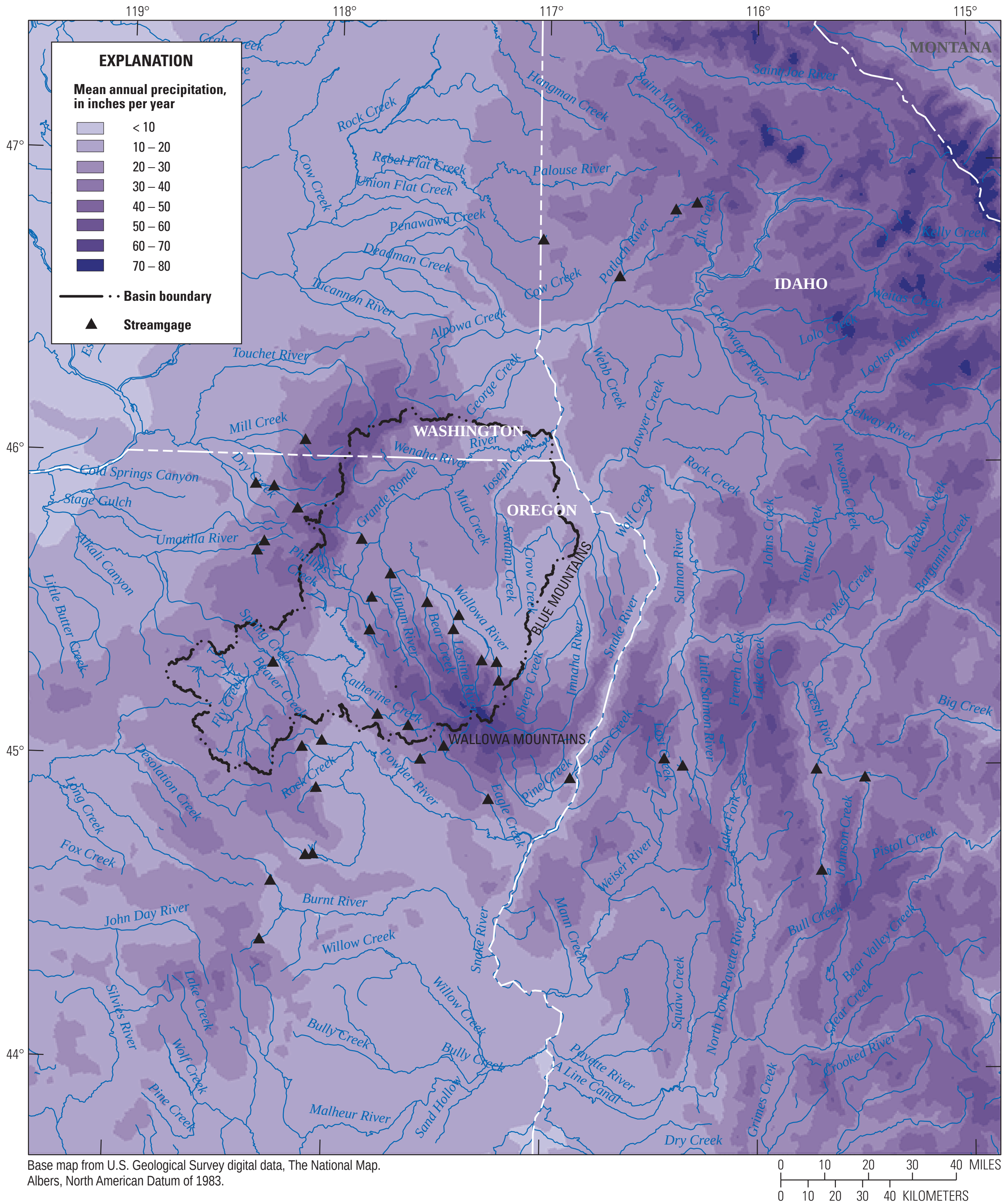
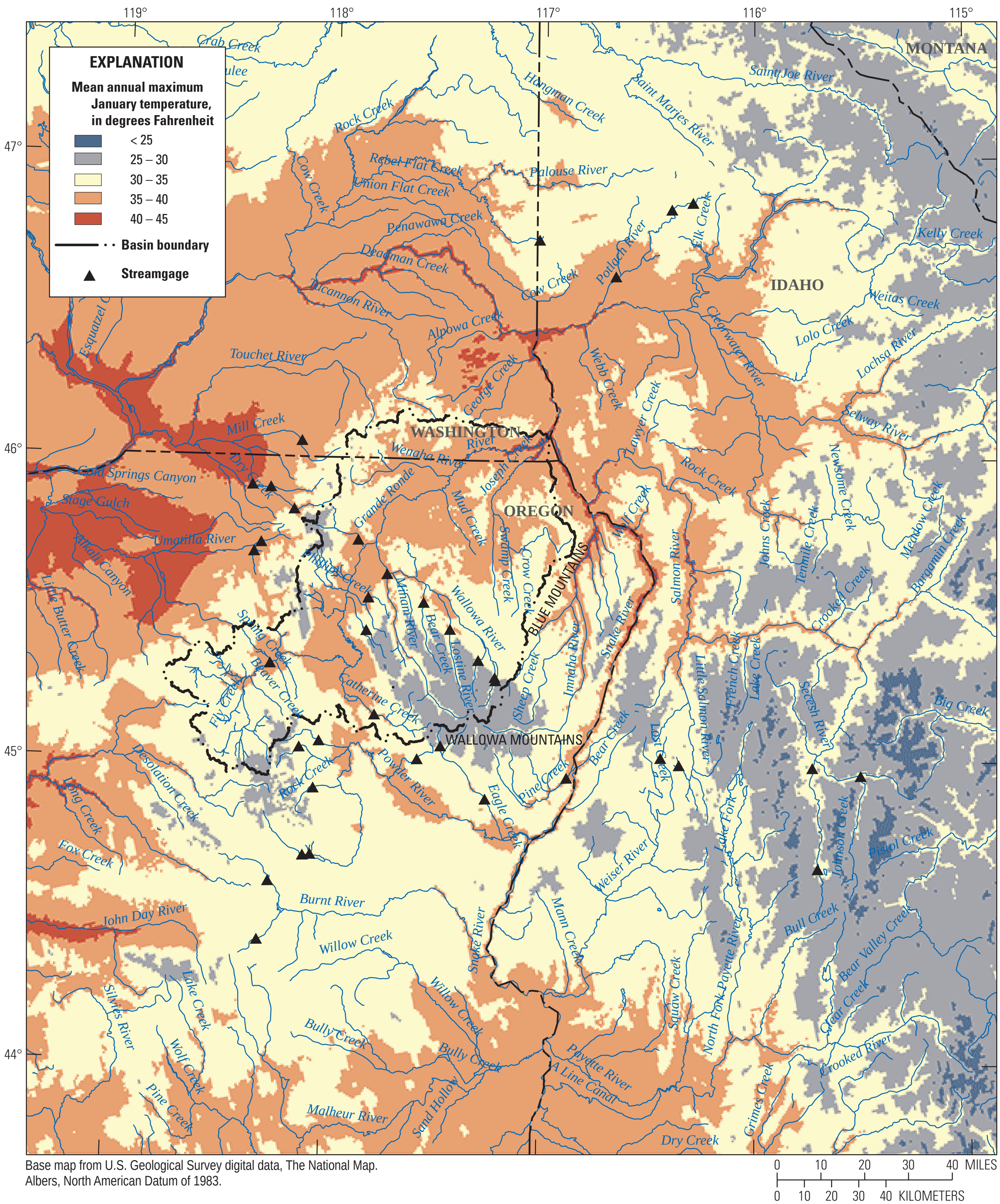


Figure 9. Joint plot showing watershed attributes on ordination of flow metrics.



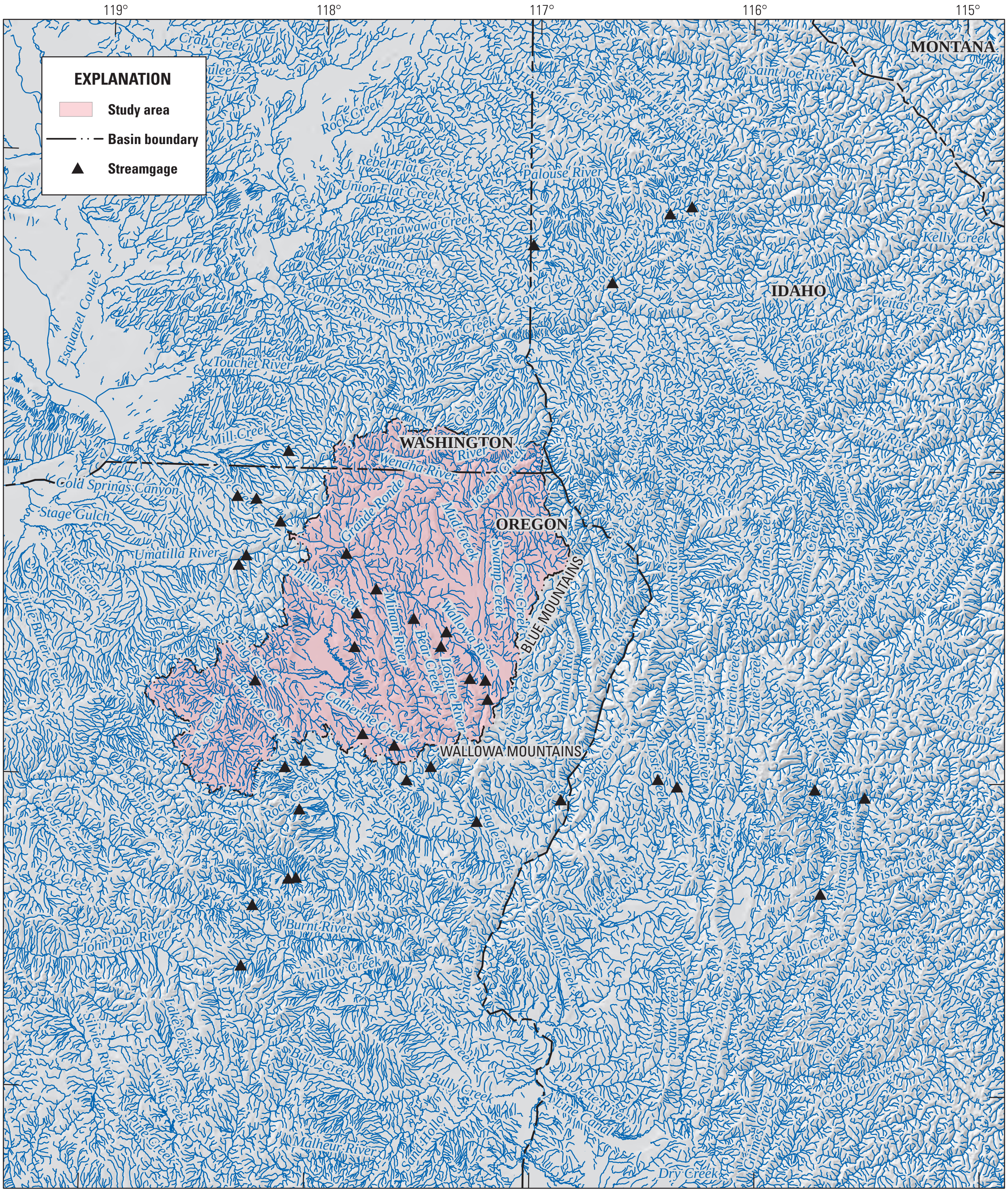
Base map from U.S. Geological Survey digital data, The National Map.
Albers, North American Datum of 1983.

Figure 10. Streamgage locations and mean annual precipitation in the study area, upper Grande Ronde River Basin, Idaho, Oregon, and Washington.



Base map from U.S. Geological Survey digital data, The National Map.
Albers, North American Datum of 1983.

Figure 11. Streamgage locations and mean annual maximum January temperature in the study area, upper Grande Ronde River Basin, Idaho, Oregon, and Washington.



Base map from U.S. Geological Survey digital data, The National Map.
Albers, North American Datum of 1983.

0 10 20 30 40 MILES
0 10 20 30 40 KILOMETERS

Figure 12. Streamgage locations and stream density in the study area, upper Grande Ronde River Basin, Idaho, Oregon, and Washington.

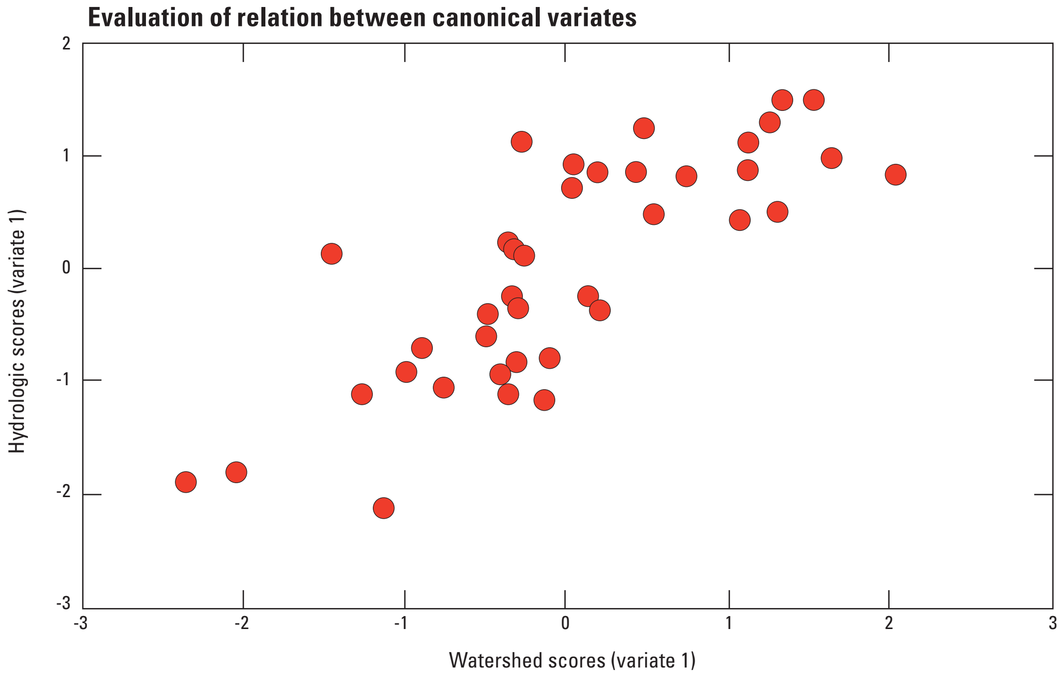


Figure 13. Relation between hydrologic and watershed scores for first canonical variate.

Table 4. Canonical correlation analysis results.

[**Symbols:** >, greater than; <, less than. **P**, probability value associated with the F statistic]

Variate	Canonical correlation	Squared canonical correlation	P
1	0.8	0.64	< 0.0001
2	0.4	0.15	0.06

Estimation of Streamflow Metrics for Ungaged Sites

The relation between selected watershed characteristics and streamflow metrics that was derived from CCA was used to select subsets (or hydrologic neighborhoods) of gaged sites to serve as the basis for generating regional low-flow frequency curves for ungaged sites. The selection of these hydrologic neighborhoods was based on similarity of watershed characteristics between gaged and ungaged sites. The distribution of selected watershed characteristics alongside ungaged sites within the upper Grande Ronde River Basin are shown in figures 14–16.

Each assignment of a gaged site to an ungaged site was associated with a probability value that described the likelihood of that association. The range of probability associated with the selection of site-specific regions for ungaged sites, limiting outliers to the 5th and 95th percent is shown in figure 17. Although most probabilities were close to 0.90 (median=0.86), 5 percent were associated with a confidence level less than 0.65. The list of gaged sites in each site-specific region and the associated probability are listed in appendix E; watershed data for selected characteristics for ungaged sites used in regional analysis and estimated flow metrics are presented in appendix F. The distribution of estimated streamflow metrics for ungaged sites in the Upper Grande Ronde River Basin is shown in figures 18–22.

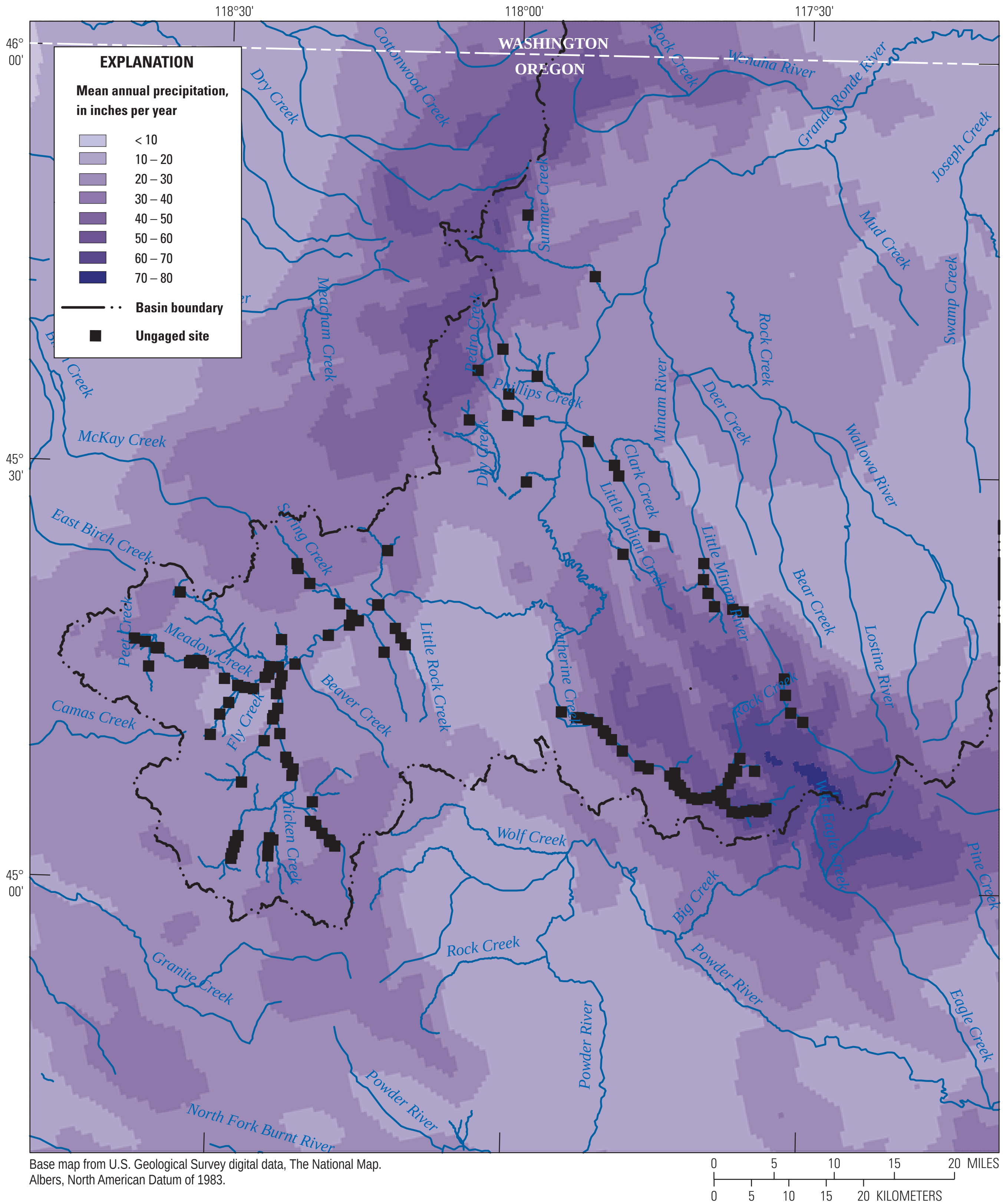


Figure 14. Mean annual precipitation, upper Grande Ronde River Basin, Oregon.

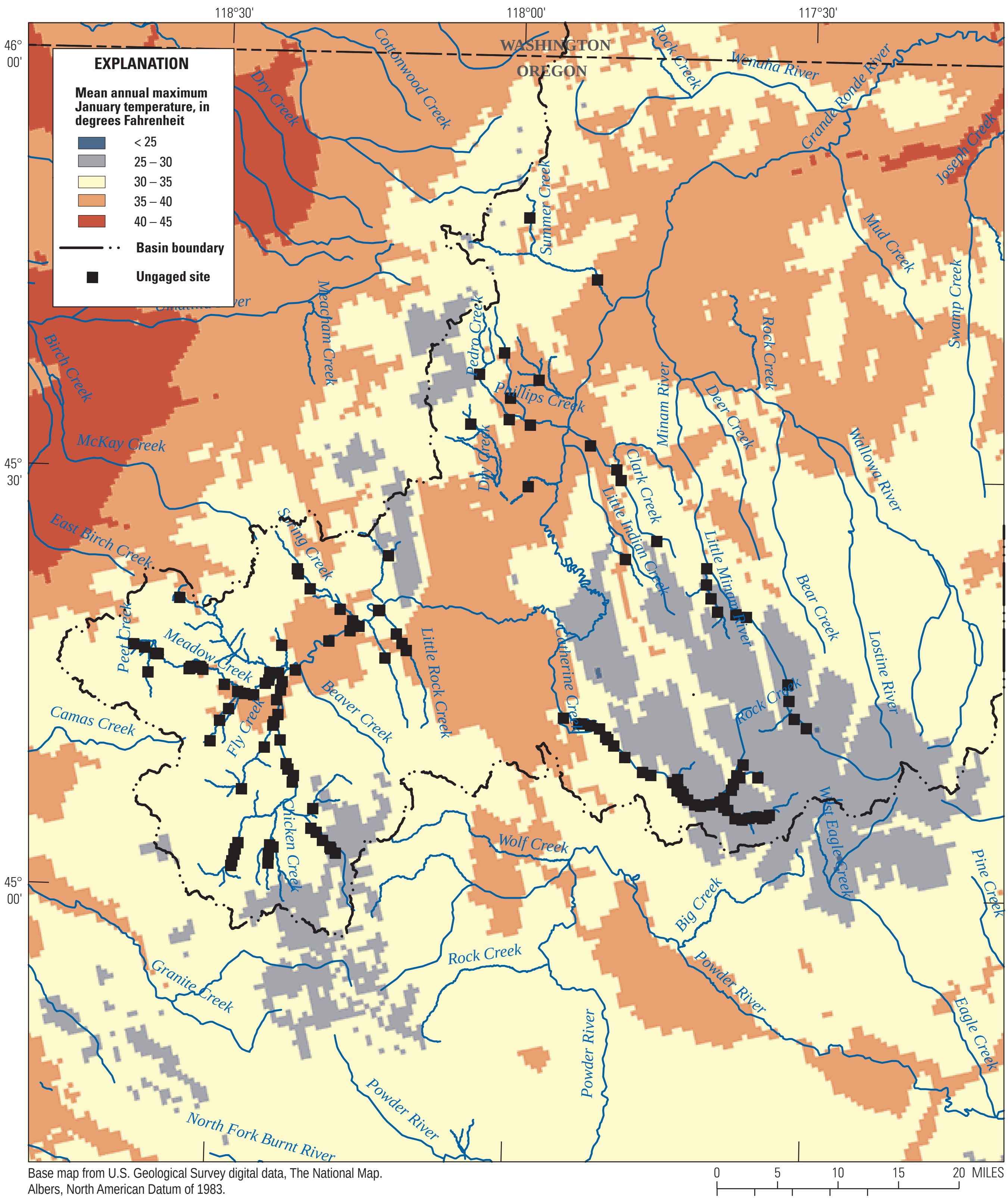
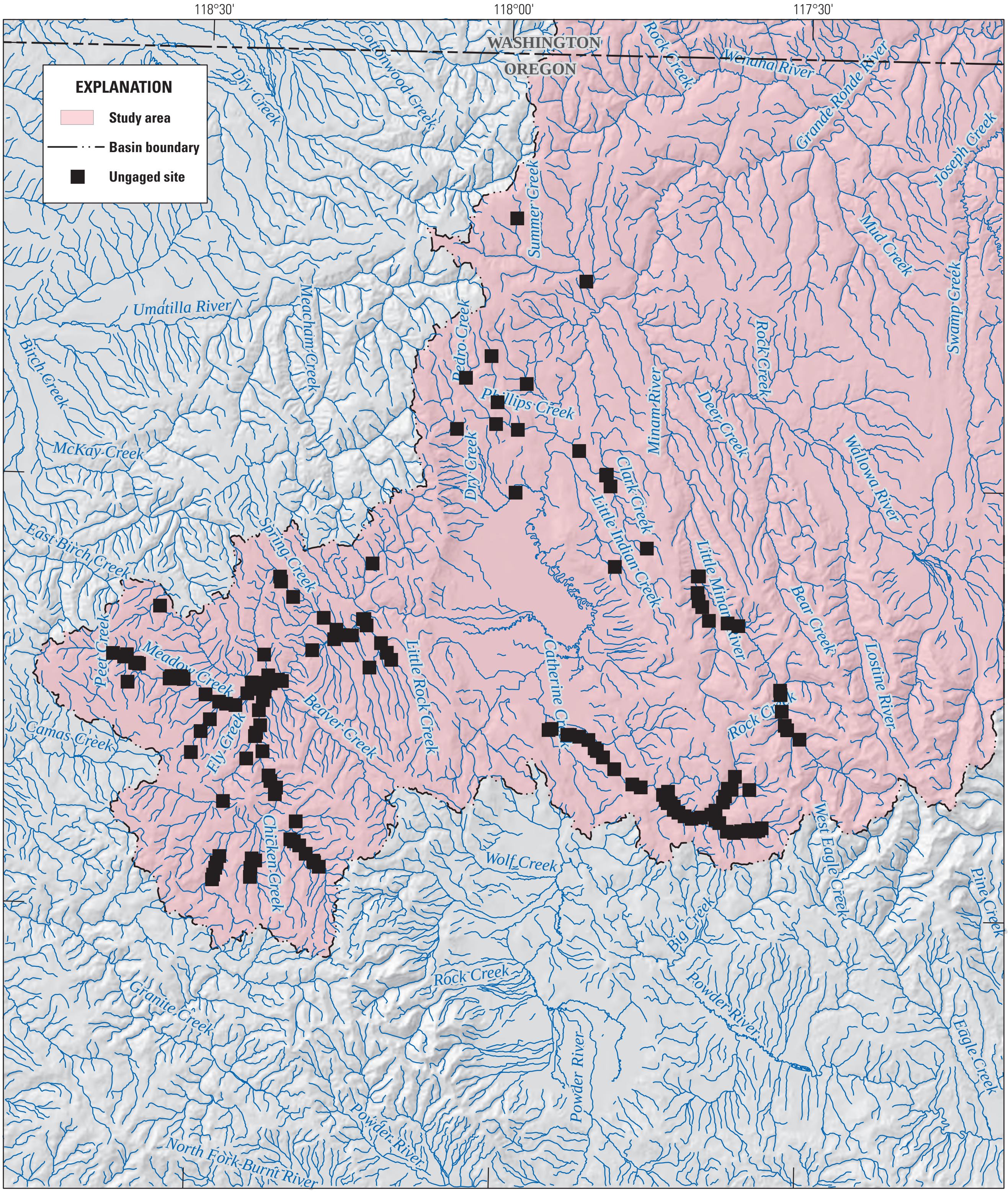


Figure 15. Locations of ungaged sites and mean annual maximum January temperature, upper Grande Ronde River Basin, Oregon.



Base map from U.S. Geological Survey digital data, The National Map.
Albers, North American Datum of 1983.

0 5 10 15 20 MILES
0 5 10 15 20 KILOMETERS

Figure 16. Locations of ungaged sites and stream density, upper Grande Ronde River Basin, Oregon.

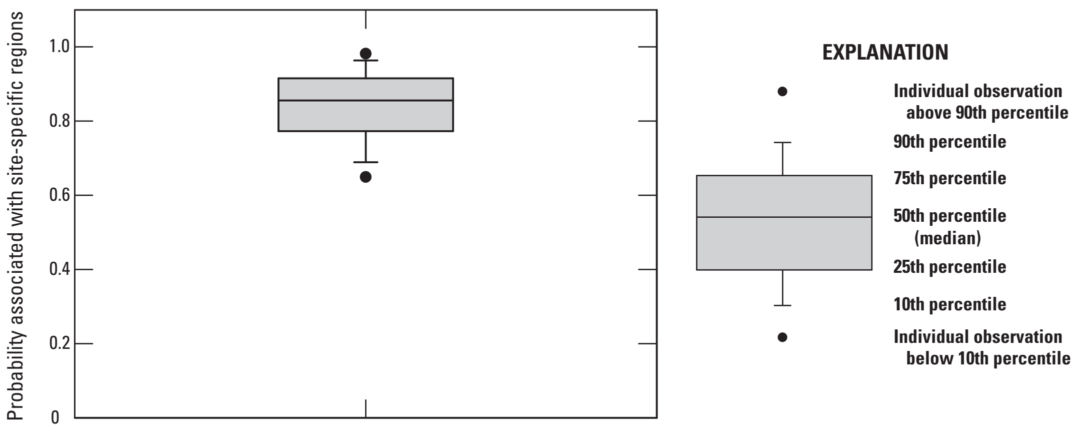


Figure 17. Range of probability for site-specific regions.

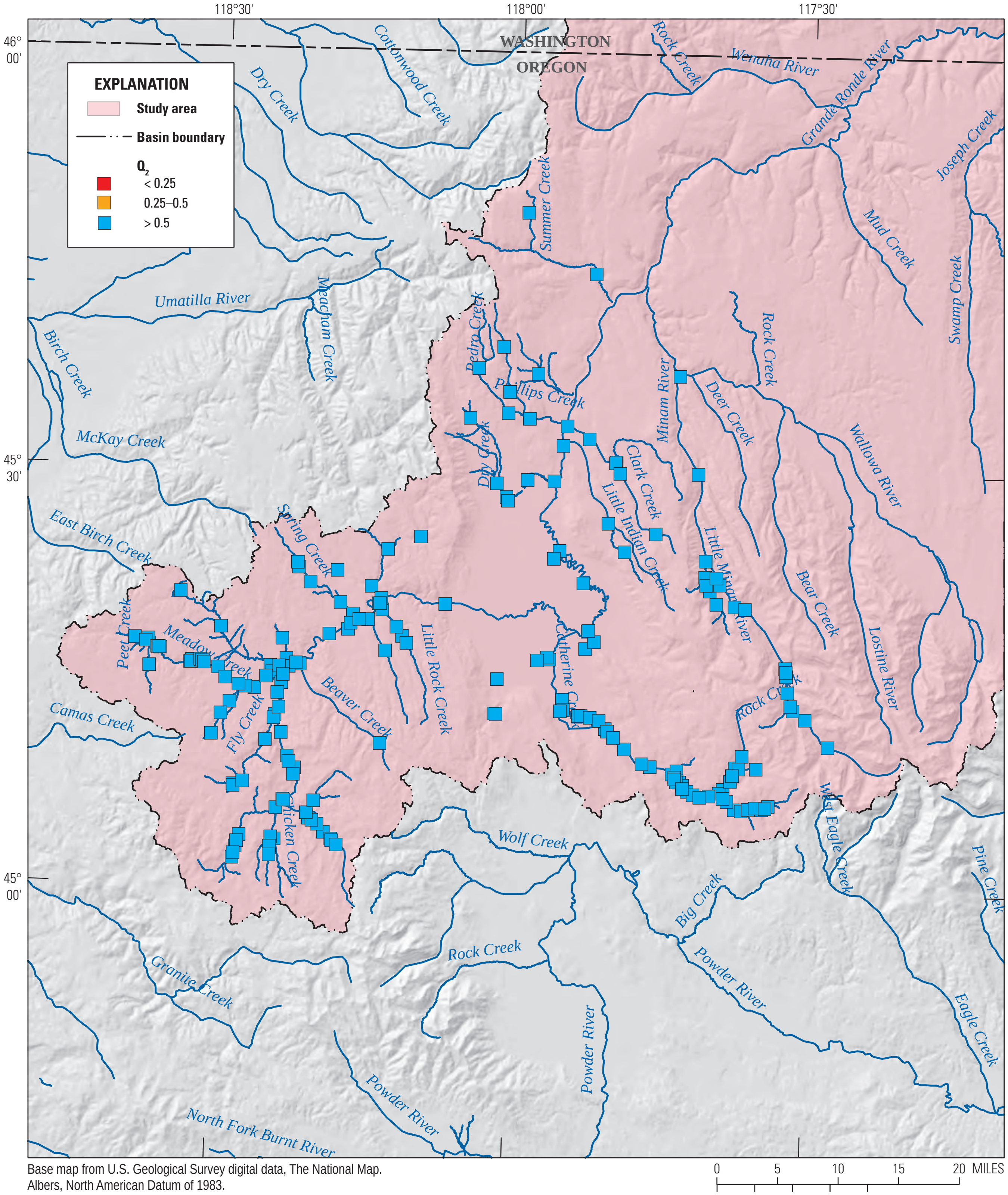
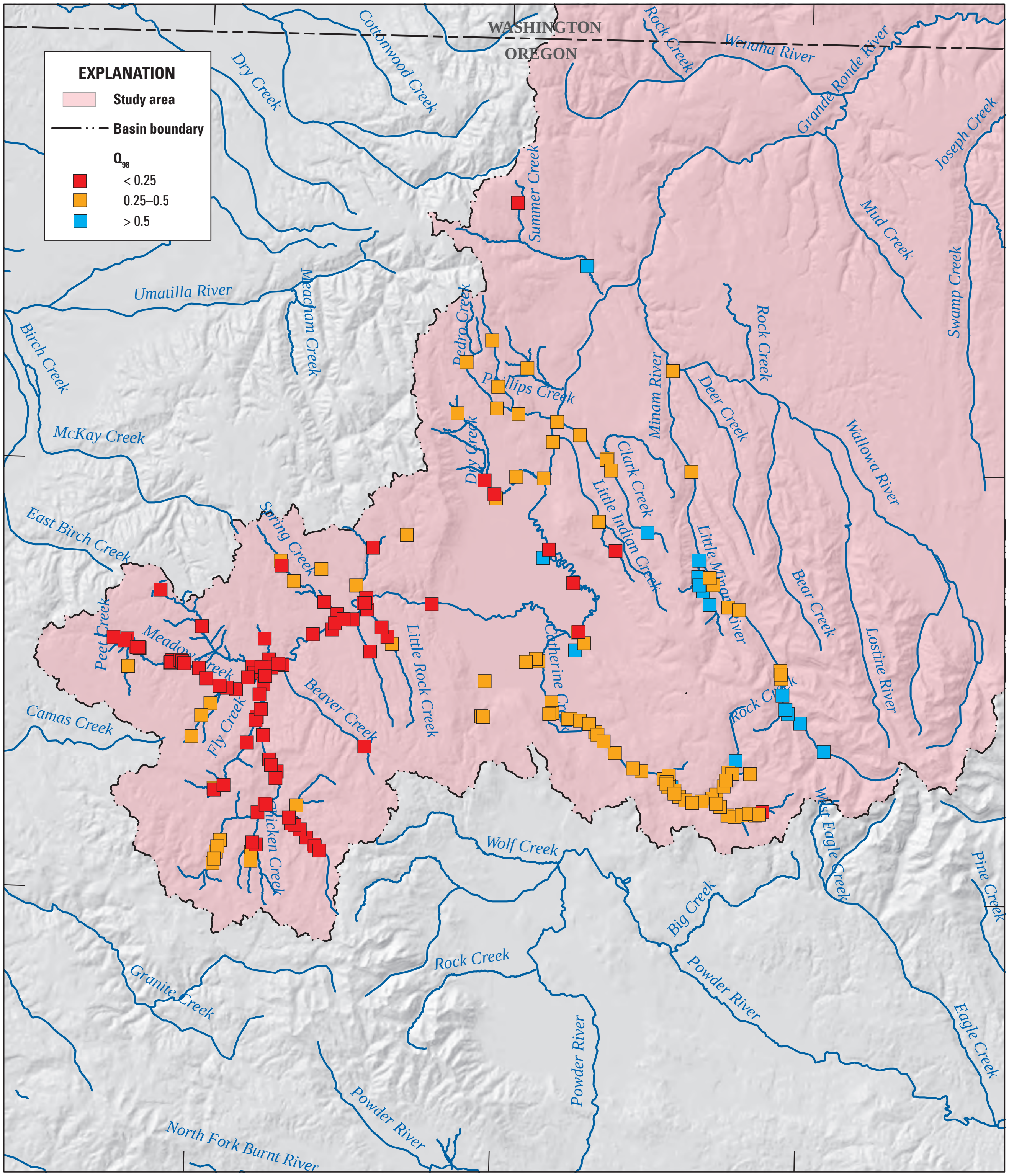
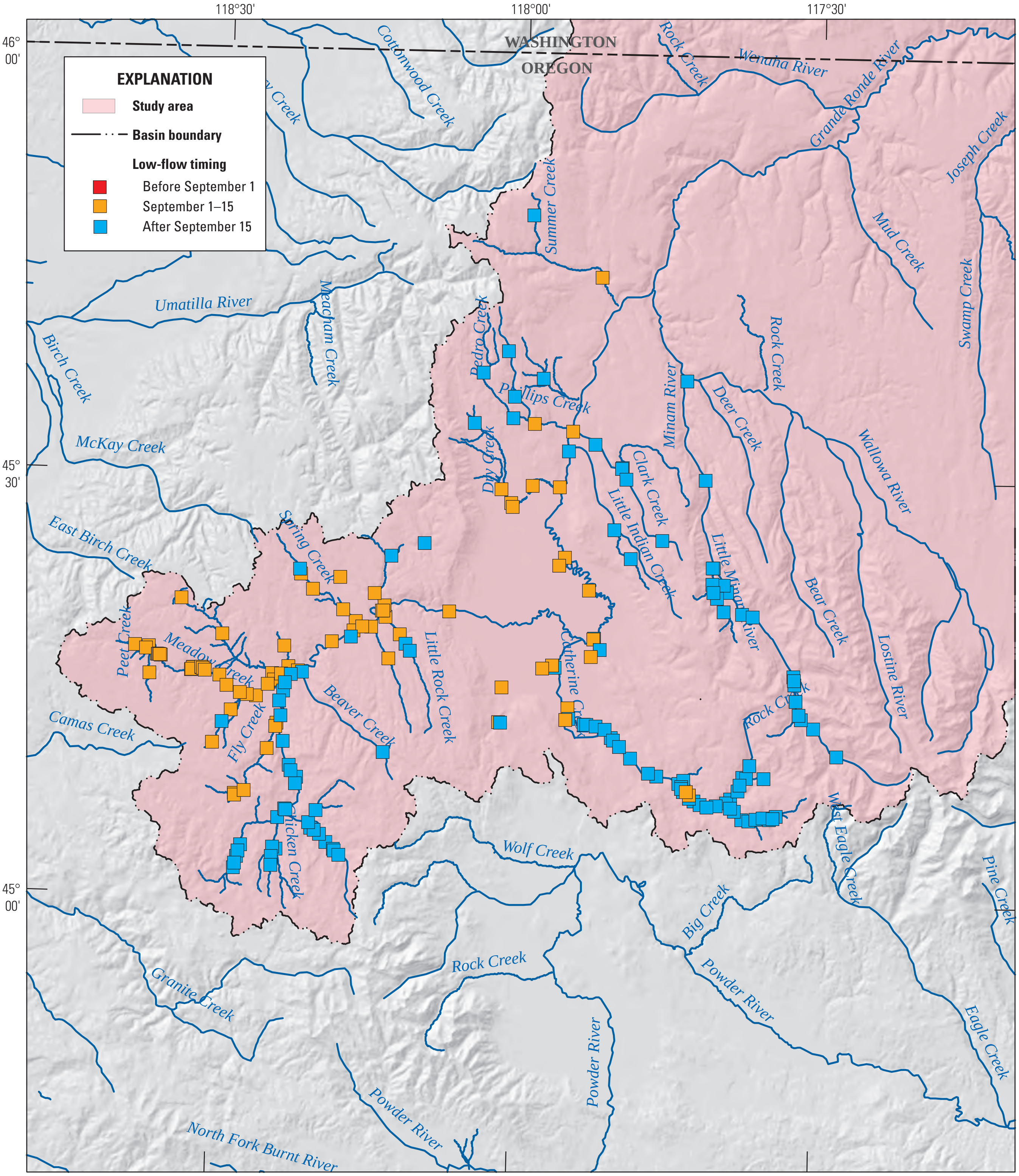


Figure 18. Estimated ratio of the 2-year 7-day low flow magnitude and the mean annual 7-day low-flow magnitude (Q_2) for ungaged sites, upper Grande Ronde River Basin, Oregon.



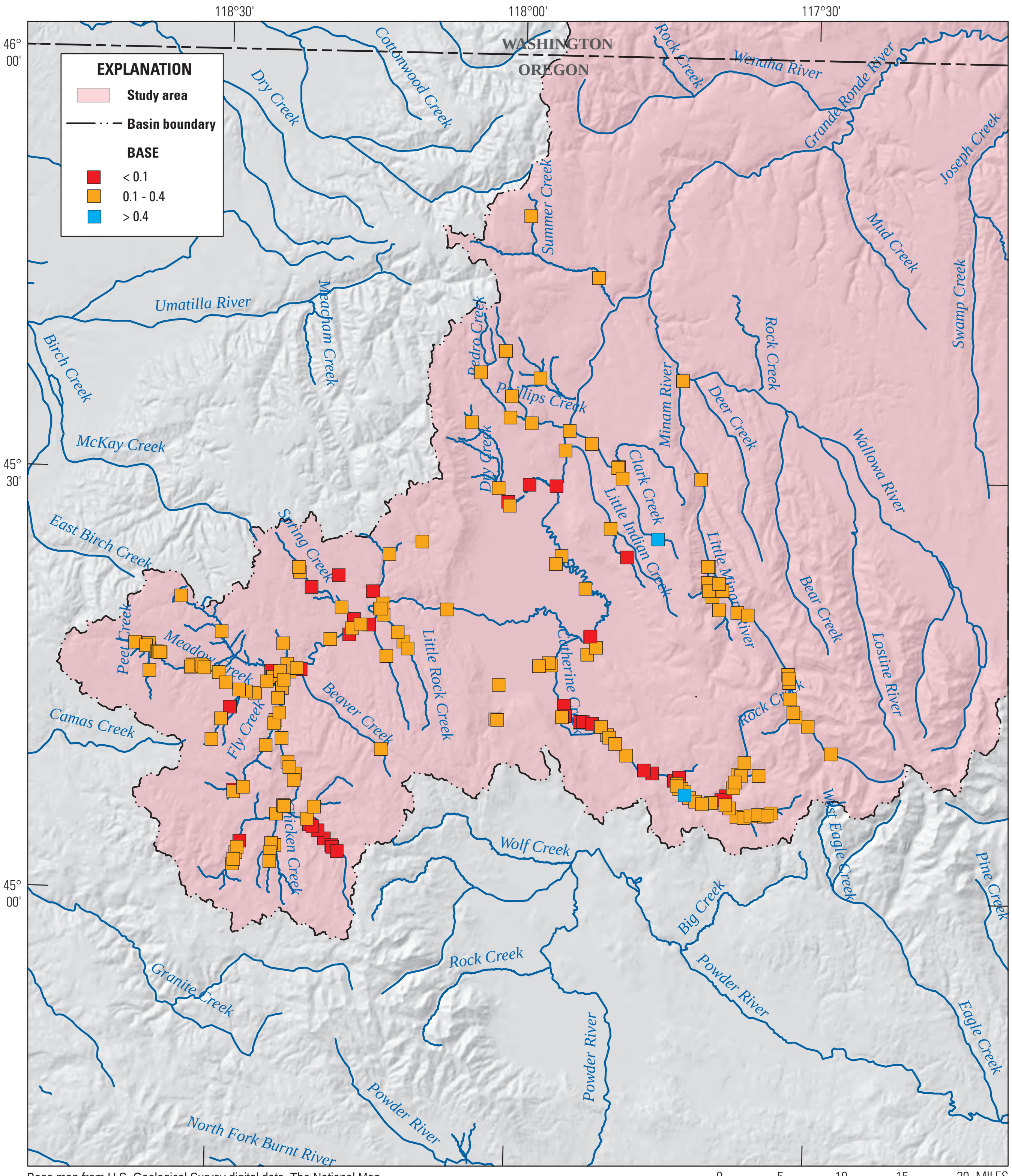
Base map from U.S. Geological Survey digital data, The National Map.
Albers, North American Datum of 1983.

Figure 19. Estimated ratio of the 98-year 7-day low-flow magnitude and the mean annual 7-day low-flow magnitude (Q_{98}) for ungaged sites, upper Grande Ronde River Basin, Oregon.



Base map from U.S. Geological Survey digital data, The National Map.
Albers, North American Datum of 1983.

Figure 20. Estimated timing of onset of low flow for ungaged sites in Upper Grande Ronde River Basin, Oregon.



Base map from U.S. Geological Survey digital data, The National Map.
Albers, North American Datum of 1983.

Figure 21. Estimated base-flow index (BASE) for ungaged sites, upper Grande Ronde River Basin, Oregon.

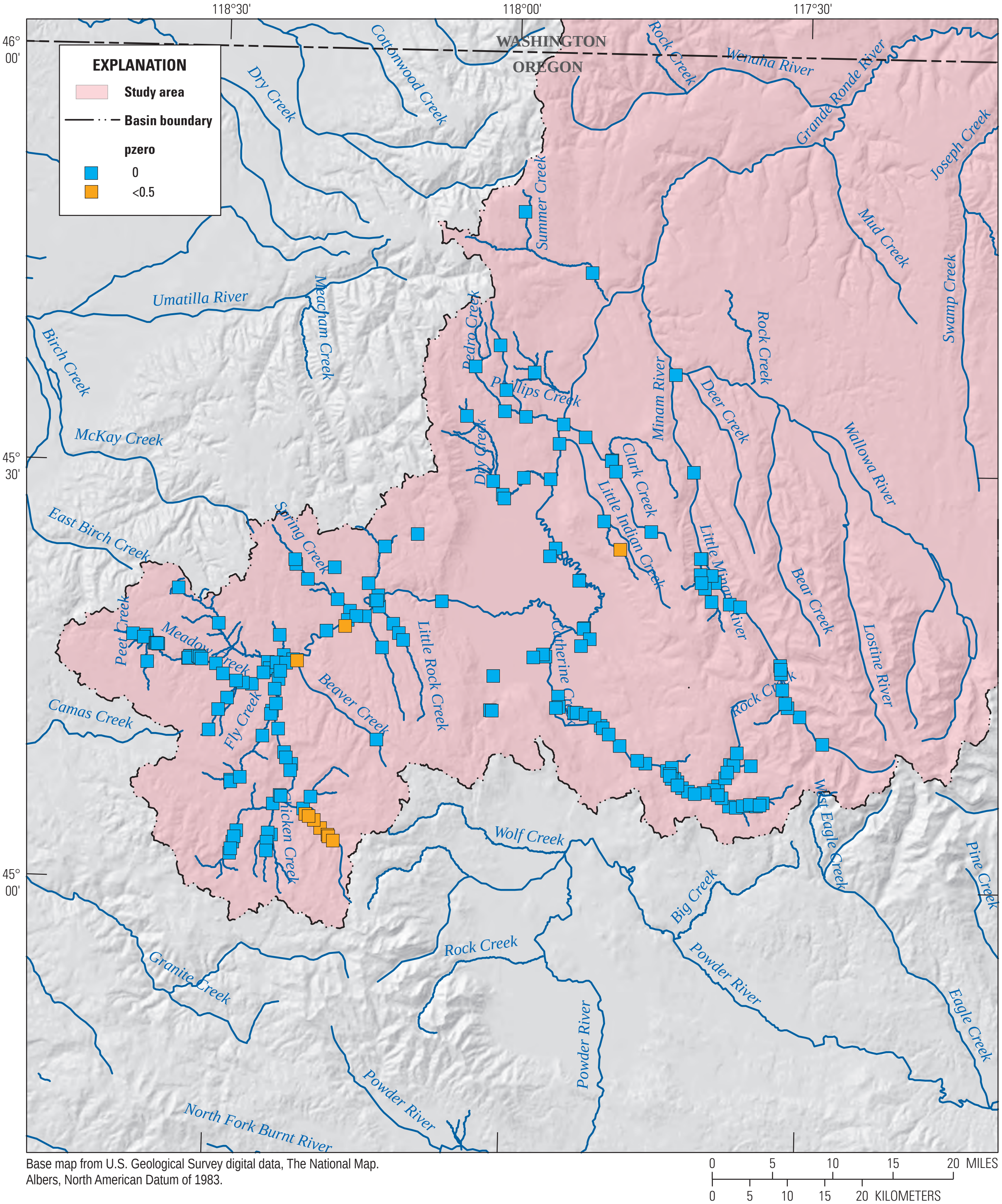
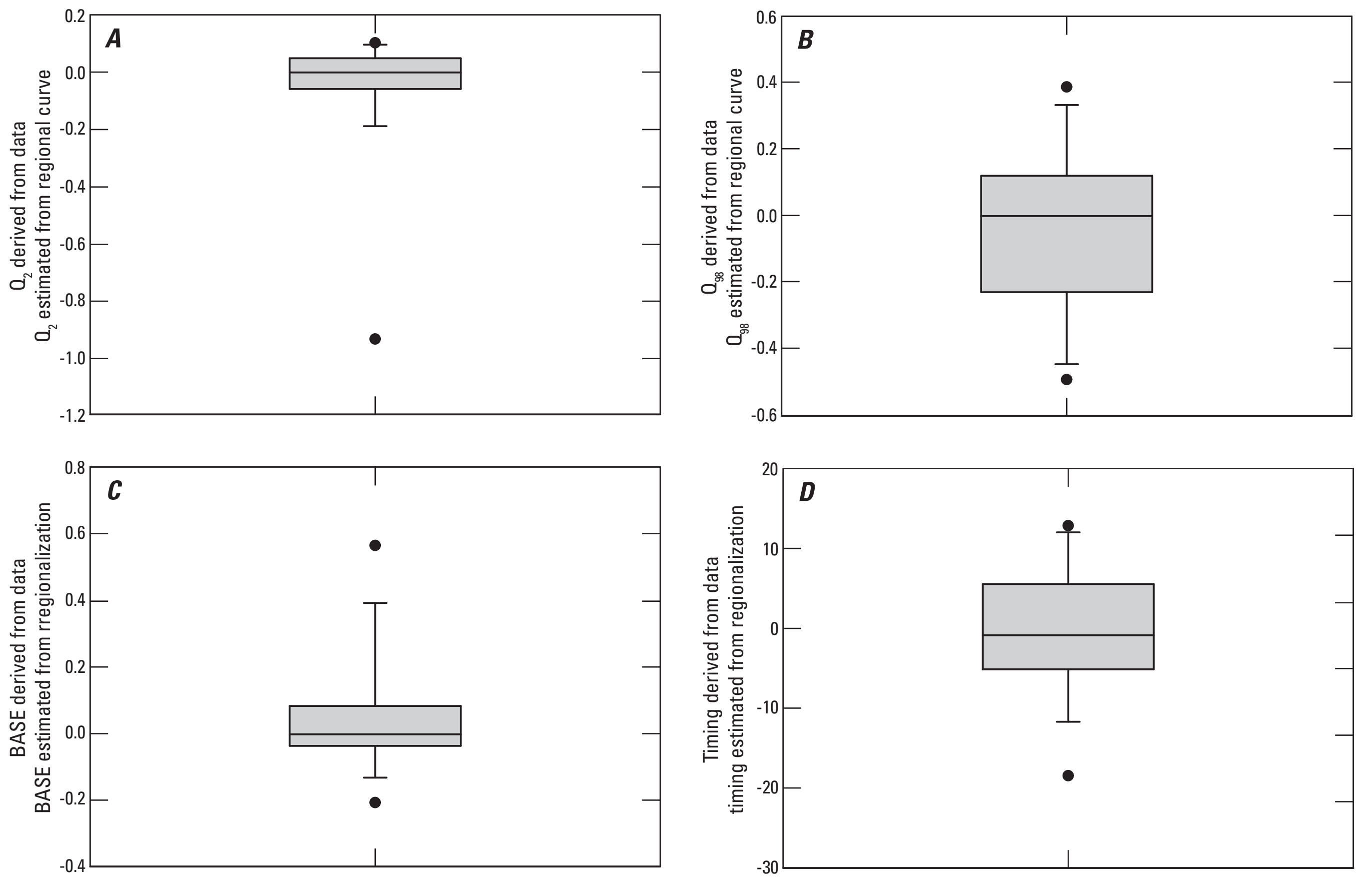


Figure 22. Estimated probability of zero flow (pzero) for ungaged sites, upper Grande Ronde River Basin, Oregon.

Quantifying Uncertainty

Many sources of uncertainty are associated with estimates of flow characteristics in the absence of streamgage data. The cross-validation analysis provides a means to compare estimates derived from the regionalization process with those derived directly from streamflow data, and thereby provide some context for assessing the reliability of the estimates for ungaged sites. Results from the cross-validation analysis of metrics derived from measured data and those estimated by the regionalization process are presented in figure 23. These results indicate that Q_{98} was estimated within ±0.4 by the regionalization process for 75 percent of the gaged sites; the median difference between estimated and measured metrics was close to zero although a slight tendency was shown for estimates to be larger than measured metrics. Because the estimated values of Q_{98} are normalized by mean annual flow, larger values for this metric represent an extreme low-flow condition that is closer to the mean annual 7-day low flow; this means that smaller values of Q_{98} indicate a higher degree of variability. Results for BASE show a closer correspondence in general with a contrasting pattern—estimated values were generally within ±0.05 for 75 percent of the gaged sites with a tendency to be smaller than measured metrics. Finally, results for the timing of onset of annual 7-day low-flow conditions indicate that estimates were generally within ±10 days for 75 percent of the gaged sites.

Standard errors provide a measure of the precision of each T-year event estimator (or quantile), and are presented in figure 24. These errors indicate that greatest precision is associated with the quantiles expected to occur more frequently (median for Q_2=0.003, median for Q_{98}=0.007).



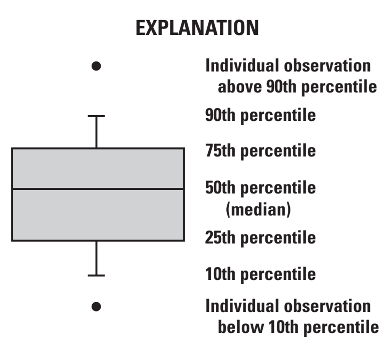


Figure 23. Cross-validation results for low-flow analysis. Results show difference between metrics derived from regional and individual frequency curves for streamgages.

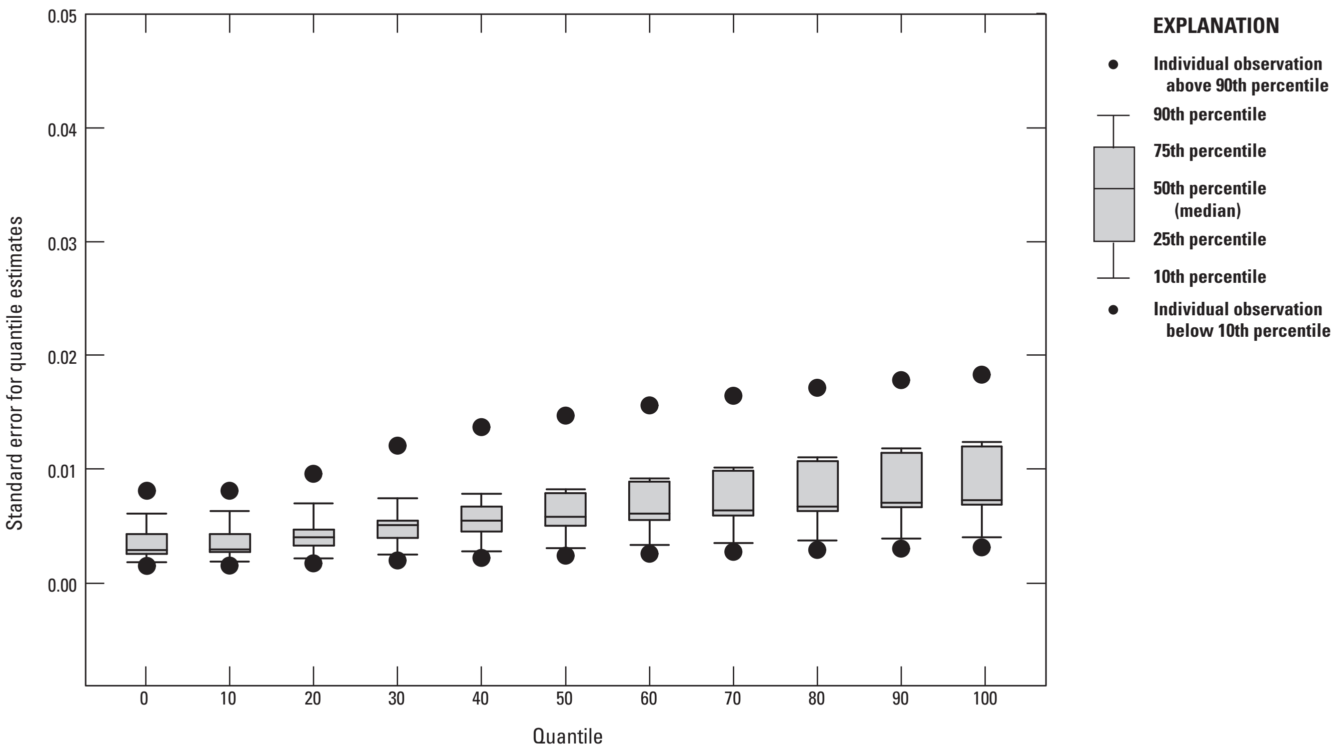


Figure 24. Standard errors for quantiles estimated for ungaged sites, upper Grande Ronde River Basin, Oregon.

Reliability and Limitations

This report presents a protocol for estimation of flow metrics for ungaged sites based on regional analysis of data from streamgages and watershed characteristics. Interpretation of these results is beyond the scope of this analysis. Nevertheless, any regional analysis is associated with an unavoidable level of uncertainty in the estimates, which should be considered carefully in order to understand the limitations of the analysis. This uncertainty arises partly because of the inherent difficulties in the probabilistic approach, especially when focused on the long-term distribution of events from comparatively short-term data series. Any probabilistic analysis of streamflow distribution increases in reliability when based on long periods of record, ideally more than 20 years, which were not available for this analysis. Another source of error is the regionalization process itself, even when focused on site-specific hydrologic neighborhoods to define regions as was done in this analysis, especially given the assumption of sufficient similarity within regions that are defined by a small number of attributes. For this analysis, additional uncertainty occurs as a result of the relatively small number of streamgages in the study area. Accordingly, the evaluation of errors associated with the streamflow metrics is a critical element of this protocol.

The first component of the analysis subject to potential error is the selection of streamflow data and the subsequent application of the GEV theoretical frequency distribution to describe the components of the low-flow regime for streamgages. As mentioned in the section, "Data Assembly," data were screened to simultaneously eliminate any temporal trend ($p<0.01$) and maximize the period of record, with a minimum of 10 years. This screening allowed the basic assumptions of the distribution to be met by focusing on a relatively "ideal" set of sites. In the process, however, sites were excluded where streamflow was most likely to be influenced by significant human activity, a major factor in causing temporal trend. As a result, the metrics generated by this analysis should be considered less reliable for those watersheds that are similar to the excluded gaged sites, especially regarding human impact. Because of the limitations of the frequency analysis, as well as the data that are currently available for human water use, it is not possible to accurately describe the nature of these errors or the sites that may be most affected. The fact that these metrics do not well describe the effect of human modification of low-flow regime represents an important source of uncertainty in the analysis.

Additional error is associated with the regionalization component of the analysis, including both the correspondence between watershed and streamflow attributes determined by CCA, and the subsequent assignment of site-specific regions for ungaged sites based on watershed characteristics. The uncertainty associated with CCA is described by the canonical correlation results presented in appendix D, and graphically by the relation between canonical variates (fig. 13). The CCA results indicated that the first canonical variate explained most of the variability in the watershed and flow data (64 percent). A generally strong correspondence was observed between the first pair of canonical variates, indicating that a moderately high degree of confidence is warranted for the characterization of the multivariate relation between the selected hydrologic and watershed variables. The analysis is limited, however, by the selection of variables that are included, and especially by the assumption of linearity and independence among them. Although an attempt was made to focus on non-redundant streamflow metrics and watershed characteristics that are strongly and linearly correlated, it is unrealistic to presume that the available data perfectly describe the complex array of factors that determine low-flow regime.

Further errors are associated with the process of region definition, and essentially represent the lack of similarity in key watershed attributes between gaged and ungaged sites. These are described by the probabilities associated with each site-specific region represented in figure 17 and appendix E, and reflect differences in the range of confidence among the ungaged sites. In other words, the probabilities represent how close of a correspondence exists within the watershed context defined by the selected characteristics between the gaged site and the target ungaged site. Most probability values are greater than 0.8 indicating a high degree of correspondence, although a small number of regions for ungaged sites were associated with probabilities less than 0.65 (appendix E), presumably reflecting the lack of similarity of those watersheds with gaged sites.

An evaluation of the effect of these errors in the regionalization process on the metrics estimated for ungaged sites was provided by two additional analyses. First, cross-validation analysis of data from gaged sites was conducted to evaluate how well frequency distributions derived from site-specific regions defined by CCA compared with those derived from measured data. Watershed scores for gaged sites were used to generate regions, and regional frequency curves were then derived from those regions in the same manner used for ungaged sites. The differences between the metrics derived from these regional curves and those determined from the individual frequency distributions show generally close agreement between the two sets of metrics, with median differences consistently close to 0 (fig. 23). Moderately large differences were determined for Q_{98}, ranging generally between ±0.2, reflecting the general uncertainty associated with these extreme flow events. Differences for BASE sometimes also were relatively large, as much as 0.6, with estimates tending to be biased relatively low compared to metrics derived from the data. Differences for the timing of the onset of low flow were generally within ±7–14 days or 1–2 weeks. These results suggest that (1 estimates for Q_{98} (a measure of low-flow variability) may be underrepresenting the true level of variability; (2) estimates for BASE (a measure of the potential for groundwater influence) also may be underestimated; and (3) estimates for the timing of the onset of low-flow conditions are fairly reliable, generally within less than 2 weeks.

Another measure of uncertainty in the metrics estimated for ungaged sites is the standard error of the estimate for the selected quantile (fig. 24). These results indicate the greatest uncertainty is associated with the more extreme flow event (Q_{98}), although most errors were low (< 0.01). Errors associated with the 2-year low-flow event (Q_2) were essentially nil, indicating a high degree of confidence can be associated with these metrics.

Summary and Conclusions

The estimates for low-flow metrics provided here are based on a regionalization approach that uses multivariate analysis in the form of a canonical correlation analysis (CCA) to determine site-specific regions (or hydrologic neighborhoods). These regions were explicitly based on comparability in watershed characteristics that are associated with the distribution of selected low-flow metrics. This approach was selected because it was assumed to provide an advantage over regionalization techniques where all sites within a contiguous region show the same characteristics of low-flow distribution.

Analysis of streamflow metrics for gaged sites showed that measures of variability based on extreme 7-day low-flow conditions (Q_{98}), measures of the potential for groundwater influence (BASE), and measures of the timing of the onset of annual 7-day low-flow conditions were relatively independent. These metrics were strongly correlated with mean annual precipitation, maximum January temperature, and stream density in the watershed. The CCA provided the means to select gaged sites in watersheds that were most closely similar to the target ungaged sites in terms of these characteristics, with probabilities that were generally greater than 0.8, reflecting a high degree of correspondence. Results for cross-validation and standard errors for the estimates indicate that measures that describe more extreme conditions show a higher degree of uncertainty.

The various components of this analysis represent a series of abstractions from measured data to derived metrics. Because of the nature of the problem, that is, the description of low-flow regime for sites without streamflow data, these metrics are necessarily based on a range of assumptions. Although founded on an empirical base and well-developed theoretical techniques, each step in the analysis provides an opportunity for some level of uncertainty to enter into the final result. These uncertainties have been minimized to the greatest extent possible, and yet it is not possible to eliminate uncertainty completely. As a result, the estimates derived from this analysis should not be assumed appropriate for other types of water-resource evaluations, especially those focused on management and forecasting of extreme flow conditions that require greater precision. Nonetheless, the estimates can be considered suitable for the stated purpose, which is the hydrologic classification of stream systems to support ecological analysis.

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Appendixes

The appendixes are Microsoft© Excel files and can be dlownloaded at http://dx.doi.org/10.3133/sir20165041.

Appendix A. Description of Watershed Characteristics for Gaged Sites Evaluated in Regional Frequency Analysis of Low-Flow Regime

Appendix B. Data for Watershed Characteristics for Gaged Sites Evaluated in Regional Frequency Analysis of Low-Flow Regime

Appendix C. Data for Streamflow Metrics for Gaged Sites Evaluated in Regional Frequency Analysis of Low-Flow Regime

Appendix D. Results from Canonical Correlation Analysis

Appendix E. Gaged Sites in Site-Specific Regions for Ungaged Sites, with Associated Probability

Appendix F. Watershed Data and Estimated Metrics for Ungaged Sites

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