Analysis of Low-Flows and Selected Methods for Estimating Low-Flow Characteristics at Partial-Record and Ungaged Sites in Western Washington

By Christopher A. Curran, Christopher P. Konrad, and Ken Eng
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### Conversion Factors

**Inch/Pound to SI**

<table>
<thead>
<tr>
<th>Multiply</th>
<th>By</th>
<th>To obtain</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Length</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>inch (in.)</td>
<td>2.54</td>
<td>centimeter (cm)</td>
</tr>
<tr>
<td>inch (in.)</td>
<td>25.4</td>
<td>millimeter (mm)</td>
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<tr>
<td>foot (ft)</td>
<td>0.3048</td>
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</tr>
<tr>
<td>mile (mi)</td>
<td>1.609</td>
<td>kilometer (km)</td>
</tr>
<tr>
<td><strong>Area</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>square mile (mi²)</td>
<td>259.0</td>
<td>hectare (ha)</td>
</tr>
<tr>
<td>square mile (mi²)</td>
<td>2.590</td>
<td>square kilometer (km²)</td>
</tr>
<tr>
<td><strong>Flow rate</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>cubic foot per second (ft³/s)</td>
<td>0.02832</td>
<td>cubic meter per second (m³/s)</td>
</tr>
<tr>
<td>inch per year (in/yr)</td>
<td>25.4</td>
<td>millimeter per year (mm/yr)</td>
</tr>
</tbody>
</table>

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

\[ ^\circ C = \left( ^\circ F - 32 \right) / 1.8 \]

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

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

Altitude, as used in this report, refers to distance above the vertical datum.
Analysis of Low-Flows and Selected Methods for
Estimating Low-Flow Characteristics at Partial-Record and Ungaged Sites in Western Washington

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Abstract

Low-flows are an important part of the natural flow regime of rivers and streams, maintaining longitudinal connectivity in the stream channel, which allows fish migration and nutrient transport, as well as the preservation of aquatic, riparian, and hyporheic (below stream-bed) ecosystems. In western Washington, competing demands between out-of-stream and in-stream water uses, as well as between the water needs of tribes and non-tribal entities, are felt most profoundly during the late summer and early fall when streamflow is generally lowest. In order to document low-flows, a regional low-flow survey of small, perennial streams was initiated by member tribes of the Northwest Indian Fisheries Commission with assistance from the U.S. Geological Survey in 2007, and repeated by the tribes during the low-flow seasons of 2008-09. This approach allows timely documentation of base-flow conditions and characteristics for small ungaged streams which, in western Washington, are underrepresented within the continuous streamflow gage network.
Low-flow measurements made at 63 partial-record and miscellaneous stream sites during surveys in 2007-09 are used with concurrent flows at continuous streamflow gaging stations (index sites) within the U.S. Geological Survey network to estimate the low-flow metric \( Q_{7,10} \) at each measurement site; \( Q_{7,10} \) is defined as the lowest average streamflow for a consecutive seven-day period that recurs on average once every 10 years. Index-site correlation methods for estimating low-flow characteristics at partial-record sites are reviewed and an empirical Monte Carlo technique is used with the daily streamflow record at 43 index sites to determine the error and bias associated with estimating the \( Q_{7,10} \) at synthetic partial-record sites using three methods: Q-ratio, MOVE.1, and Base-Flow Correlation. In general, the Q-ratio method has the lowest error and least amount of bias for 170 scenarios, with each scenario defined by the number of concurrent flow measurements between the partial-record and index sites (ranging from four to twenty) and the combination of basin attributes used to select the index site. The root-mean square error for the Q-ratio method ranged from 70 to 118 percent, depending on the scenario. The scenario with the smallest root-mean square error used four concurrent flow measurements and the basin attributes drainage area, mean annual precipitation, and base-flow-recession time constant also referred to as \( \tau \) (tau).

Preliminary regional low-flow regression equations for estimating \( Q_{7,10} \) at ungaged sites are developed from the records of daily discharge at 65 continuous gages (including 22 discontinued gages) for the purpose of evaluating basin attributes used as explanatory variables. By incorporating the base-flow-recession time constant \( \tau \) as a basin attribute in the regression equation, the root-mean square error for estimating \( Q_{7,10} \) at ungaged sites can be lowered to 73 percent (for known values of \( \tau \)), which is 11 percent less than if only drainage area and mean annual precipitation are used as explanatory variables. If partial-record sites are included in the regression data set, \( \tau \) must be estimated from pairs of discharge measurements made during continuous periods of declining low-flows. The optimum number of
measurement pairs for estimating \( \tau \) at partial-record sites is eight, which results in a lowering of the root-mean square error by 25 percent. A low-flow survey strategy that includes paired measurements at partial-record sites requires additional effort and planning beyond a standard strategy, but could be used to enhance regional estimates of \( \tau \) and potentially reduce the error of regional regression equations for estimating low-flow characteristics at ungaged sites.

**Introduction**

Low-flows are an important part of the natural flow regime of rivers and streams. Ecologically, low-flows maintain longitudinal connectivity in the stream channel, allowing fish migration and nutrient transport, as well as the preservation of aquatic, riparian, and hyporheic (below stream-bed) ecosystems. In western Washington (fig. 1), groundwater discharge, or base flow, is the primary component of low-flows in many lowland rivers and streams (Sinclair and Pitz, 1999). In mountain streams, however, meltwater from glaciers or snow fields can dominate low-flows, especially during summer months. Low-flows in western Washington typically occur during extended dry periods in the late summer and early fall, but can also occur during cold, dry periods in mid-winter, particularly at higher elevation streams. In developed areas, low-flows can be altered by many factors, including surface-water diversions, return flows, groundwater pumping, reservoir operations, and land use, all of which can influence water availability for people, fish, and ecosystems.

Native American tribes in western Washington have reserved water rights that are needed to support their growing populations, and they have treaty rights to harvestable salmon which also have water needs for successful spawning, hatching, rearing, and migration. Competing demands between out-of-stream and in-stream water uses, as well as between the water needs of tribes and non-tribal entities, are felt most profoundly in western Washington during the late summer and early fall when
streamflow is generally lowest. Information on low-flows during this time is crucial for the optimal management of water resources.

As part of a scientific framework for assessing water resources in western Washington (Konrad, 2005), the documentation of low-flow conditions in western Washington streams was identified by the Northwest Indian Fisheries Commission (NWIFC) and its member tribes as a high priority for several reasons. First, documentation of low-flow conditions can be used to map the spatial extent of perennially aquatic habitats in stream networks. These habitats support fish populations, some invertebrate taxa, and biogeochemical processes. Second, streamflow measurements under low-flow conditions can be used to identify areas and rates of groundwater discharge, which helps maintain critical thermal refugia for salmonids; information about groundwater discharge can also be used to assess the potential impact of current and future groundwater withdrawals. Sequential (paired) streamflow measurements made during a continuous period of streamflow recession can be used to characterize hydrogeologic conditions that regulate extreme low-flows. Lastly, low-flows in streams offer an opportunity for regionally-coordinated data collection and efficient regional-scale regression analysis. The results of the analysis can be extrapolated across the region to estimate streamflow under low-flow conditions with quantified error at any site.

In order to document low-flows, a regional low-flow survey of small streams was initiated by NWIFC-member tribes with assistance from the U.S. Geological Survey (USGS) in 2007, and repeated by the tribes during the low-flow seasons of 2008-09. A regional low-flow survey results in streamflow data from numerous locations and watershed types over the course of a season, typically summer. The data can be efficiently analyzed to document base-flow conditions and characteristics for small ungaged streams, which are underrepresented within the continuous streamflow gage network of western Washington.
A low-flow survey supports the regional analysis of streamflow in three ways:

1) multiple measurements collected over different years can be used to estimate low-flow characteristics at a site, extend the coverage (geographic and basin-type) of the existing streamflow network, and, potentially, assess streamflow trends over time,

2) paired measurements made during a continuous period of declining streamflow (base-flow recession) can be used to estimate the base-flow-recession time constant, $\tau$, which can serve as an explanatory variable in low-flow regression models, and

3) single measurements can be used to verify regional regression estimates of low-flow characteristics at a site.

For the purposes of the analysis described in this report, four categories of stream sites are defined (Table 1): 1) an index site is a site with a continuous streamflow gaging station with 10 or more years of daily streamflow record under natural flow conditions with minimal flow contributions from glacial processes or effects of anthropogenic alteration of flow; 2) a partial-record site is a site with four or more streamflow measurements made during a period of two or more years; 3) a miscellaneous site is a site with streamflow measurements that are not continuous and the site does not qualify as a partial-record site; and 4) an ungaged site is a site without any streamflow measurements.

Low-flow measurements at partial-record and miscellaneous sites can be correlated with concurrent streamflows at selected index sites) to estimate low-flow characteristics such as the $Q_{7,10}$, which is defined as the lowest average streamflow for a consecutive seven-day period that recurs on average once every 10 years. The low-flow characteristics that are estimated at partial-record sites can be used in site-specific studies for establishing in-stream water needs or assessing the ability to meet out-of-stream demands. Partial-record sites established as part of the low-flow survey can also be incorporated into regional regression models for estimating low-flow characteristics at ungaged sites.
Purpose and Scope

The purpose of this report is to document the low-flow conditions in western Washington streams measured by NWIFC-member tribes during late-summer surveys in 2007, 2008, and 2009, to describe and evaluate methods for estimating low-flow characteristics (specifically the $Q_{7,10}$) at these sites, and to identify information needs for developing future regional regression equations for estimating low-flow characteristics at ungaged sites in western Washington.

The $Q_{7,10}$ is determined at 43 continuous streamflow gaging stations within the USGS network in western Washington that represent relatively natural and unimpaired streamflow conditions (index sites). Low-flow measurements made at partial-record and miscellaneous sites during the 2007-09 surveys are correlated with the concurrent flows at index sites, and the $Q_{7,10}$ is estimated at the partial-record and miscellaneous sites. Basin attributes (for example, drainage area and mean annual precipitation) are determined for all sites to assess gaps in the coverage (geographic and variable space) of the network. An empirical Monte Carlo technique is used to determine the error and bias associated with three commonly used index-site correlation methods for estimating low-flow characteristics ($Q$-ratio, MOVE.1 and Base-flow Correlation), and the optimal number of measurements for estimating the $Q_{7,10}$ at partial-record sites is determined. Preliminary regional low-flow regressions for estimating the $Q_{7,10}$ at ungaged sites are developed for the purpose of evaluating basin attributes used as explanatory variables. The types of future partial-record sites needed to improve regional low-flow regressions for estimating low-flow characteristics at ungaged sites in western Washington are also assessed.
Description of the Study Area

The study area is western Washington State, which extends westward from the crest of the Cascade Range (fig. 1). This region includes mountains (the Olympic Mountains and Cascade Range) as well as coastal lowlands and nearshore areas along the Pacific Ocean and Puget Sound. The Cascade Range is a magmatic arc formed by the subduction of an oceanic plate beneath the continental crust and its western assemblage of sedimentary and volcanic rocks is of Eocene through early Miocene age (Jones, 1999). The Olympic Mountains are the product of tectonic uplift caused by the subduction of the Juan de Fuca Plate beneath the North American Plate. The comparatively flat Puget Sound lowland lies within the forearc basin formed between colliding plates and has been largely shaped by numerous Pleistocene glaciations, which deposited thick layers of glacial outwash, interspersed with layers of till (Dragovich and others, 1997). The surficial geology of the basin reflects the history of mountain building, erosional and depositional processes such as landslides and lahars, and fluvial processes that erode, transport, and deposit sediment in post-glacial terrain (Linneman and others, 2007).

The climate of western Washington is maritime, with lowland areas experiencing mild, wet winters and generally cool, dry summers. The topography ranges in elevation from sea level to about 3,800 ft on average in the Olympic Mountains and about 6,200 ft on average along the crest-line of the Cascade Range. The sharp contrast in topography combined with prevailing patterns of moist wind from the Pacific Ocean create orographic lift conditions that result in higher precipitation in mountainous areas (about 200 in/yr on average) relative to lowland areas near Puget Sound (about 40 in/yr on average). Precipitation in the mountains generally occurs in the form of snow, while in the lowlands precipitation is dominated by rain. Land cover in the region is predominantly forested in mountain and upland areas, with developed and agricultural lands dominating the lowland areas. The population of western Washington is about 5 million, which is concentrated along the corridor connecting Everett,
Seattle and Tacoma (U.S. Census Bureau, 2000). Out-of-stream water use in the region is estimated at 1,350 million gallons per day with about 60 percent supplied by surface water and about 40 percent by groundwater (Lane, 2009).

**Figure 1.** Western Washington and surrounding areas.

**Previous Low-Flow Investigations**

Across the United States, numerous regional low-flow investigations have been conducted by the USGS, many for the purpose of developing regional regression equations for estimating low-flow statistics at ungaged sites (Ries and Friesz, 2000; Hortness, 2006; Funkhouser and others, 2008; Risley and others, 2009). Index-site correlation methods for estimating low-flow characteristics at partial-record sites are well-documented in many of these studies. Previous low-flow investigations in western Washington have ranged from basin- to regional-scale studies with a focus on computing low-flow frequency statistics, quantifying low-flow characteristics through various indices, or examining base-flow components of the hydrograph. Most studies in Washington State have relied heavily, if not solely, on streamflow information from USGS gaging stations that make up the national hydrologic data network. Hidaka (1973) computed low-flow indices for the Puget Sound region from frequency curves and determined that low-flow characteristics were different for mountain and lowland streams largely due to snowmelt contributions to mountain streams, and characteristics for lowland streams varied according to basin elevation. Other researchers (Collings and Hidaka, 1974; Cummans, 1977; Haushild and LaFrance, 1977; Williams and others, 1985; Curran and Olsen, 2009) calculated low-flow frequency statistics for streams in selected basins or sub-regions of western Washington. Sinclair and Pitz (1999) computed base-flow characteristics for all USGS gages in Washington and characterized the degree of streamflow alteration and the dependence of low-flows on snowmelt processes.
Methods for Analyzing Low-Flow in Western Washington Streams

In this study, low-flow surveys were conducted in western Washington on perennial streams that are not monitored as part of the USGS continuous streamflow gaging network. Because low-flows are less variable at daily or inter-annual scales than high-flows, partial-records consisting of a small number of measurements at some stream sites can be used in concert with long-term, continuous streamflow records from other sites in a regional low-flow analysis. Partial records are related to continuous records at an index site to estimate low-flow characteristics at the partial-record site, and the results are used to augment the data set available for developing regression equations for estimating low-flow characteristics at ungaged sites. Thus, partial-record sites offer an affordable way to expand the geographic coverage of sites and include combinations of basin attributes (for example, small, low-elevation streams) that are underrepresented in the stream gage network.

Index Sites

An index site is a site with a continuously recording streamflow gaging station that measures ‘natural’ or otherwise unimpaired (without anthropogenic alterations such as flow regulation or diversions) flow conditions in a basin, and for which a sufficient length of record exists for computing low-flow characteristics. In this study, 43 index sites were selected from the USGS streamflow gaging network in western Washington and used to:

- document regional hydrologic conditions during the low-flow surveys,
- estimate low-flow at partial-record and miscellaneous sites,
- evaluate index-site correlation methods, and
- develop preliminary regional low-flow regression equations.

Index sites were initially screened based on the criteria that they 1) have ten or more years of continuous daily streamflow record, 2) represent perennially flowing streams or rivers, 3) represent
relatively natural streamflow conditions, and 4) represent streams in which low-flow is predominantly groundwater-derived (base flow) and glacial meltwater, if present, is only a minor component of streamflow at the gage. However, due to the limited number of continuous gages in the study area that satisfied this criteria (specifically gages on smaller streams), three sites with eight years of record and one site with seven years were also used. In addition, many of the sites used in the study were identified by Sinclair and Pitz (1999) as having some potential for anthropogenic alteration or meltwater contribution to base flow, and these effects were assumed minor at such sites. Non-USGS streamflow gages (for example, gages operated by the Washington State Department of Ecology (Ecology), local governments, or tribes) were not included in this study either due to the brevity of their streamflow records, altered streamflow conditions at the gage (for example, most Ecology gages monitor anthropogenic effects), or uncertainties in data quality and availability. Also, the analyses of this study are explorative and do not require a comprehensive data set.

Basin attributes, such as drainage area, mean annual precipitation, and mean basin elevation, were determined for all 43 index sites using the USGS Washington StreamStats program, a web-based interactive tool (http://water.usgs.gov/osw/streamstats/Washington.html). The basin attributes and low-flow characteristics for each index site are listed in table 2.

Table 2. The location, low-flow characteristics, and basin attributes for 43 index sites in western Washington.

Low-Flow Characteristics

Low-flows in streams can be characterized in many ways. Typically, low-flow in a stream is assessed in terms of a minimum 7-day average of streamflow (the “7-day low-flow”) in a climatic year (April 1 – March 31). The annual series of 7-day low-flows (determined for sites with continuous daily streamflow records) is used to calculate the probability that the 7-day low-flow in any year will be less than a specified value (also referred to as the probability of non-exceedance). Tasker (1987)
recommends using a 3-parameter, Log-Pearson Type III distribution to represent the annual series of 7-day low-flows where the mean, variance, and skew of the distribution are estimated from observations (fig. 2). Extreme low-flows are usually characterized in terms of the 7-day low-flow that has a 10 percent probability of occurring in any given year (“10-year, 7-day low-flow” or $Q_{7,10}$). Although $Q_{7,10}$ is used in this report to characterize low-flows in streams, the analytical methods could be applied to alternative low-flow characteristics. For example, alternative descriptors of low-flow include the probability of zero flow (Bent and Steeves, 2006; Hortness, 2006), the magnitude of streamflow at critical times of the year (Hamilton and others, 2008), or the duration of continuous low-flow periods (Konrad and others, 2008). Cumulative distribution functions of daily streamflow (“flow-duration curves”) are useful for characterizing the range of streamflows at a site and provide information about low-flows that are exceeded most of the time (Searcy, 1959).

For convenience in this study, values of $Q_{7,10}$ were initially computed using software developed by the USGS (Ken Eng, USGS, written commun. 2007) that incorporates a conditional probability adjustment to account for streamflow records that may contain zero-flow events. Results from this program were subsequently verified with a standard USGS statistical program (SWSTAT, version 4.1). Low-flow frequency and duration statistics can be readily computed using publicly available software provided and supported by the U.S. Environmental Protection Agency (BASINS 4.0; http://water.epa.gov/scitech/datait/models/basins/b3webdwn.cfm) that retrieves USGS streamflow data from the National Water Information System (http://waterdata.usgs.gov/nwis) and performs the necessary computations.

Figure 2. An example of the annual series of 7-day low-flows fitted to the log-Pearson type III distribution for the calculation of $Q_{7,10}$, computed from the streamflow record at the USGS streamflow gaging station Huge Creek near Wauna, Washington (station no. 12073500), 1947-69, and 1977-2007.
Base-Flow Recession Time Constant, or Tau ($\tau$)

The rate of base-flow recession is an important low-flow characteristic in streams that is controlled by basin hydrogeology and the time since the last runoff event. Particularly after prolonged drought, the base-flow recession rate reveals the dependence of a stream on groundwater contributions to streamflow. Streams that are supported by relative large inflows of groundwater generally will have slower rates of base-flow recession than streams that are disconnected from, or lose water to, the groundwater system. The base-flow recession rate can be characterized as a single parameter referred to as the base-flow recession time constant, or tau ($\tau$), and expressed as:

$$\tau = \Delta t/ \ln(Q_0/Q_t),$$  \hspace{1cm} (1)

where $\tau$ is the base-flow recession time constant (in days), $\Delta t$ is the time between observations (in days) and $Q_0$ and $Q_t$ (in units of volume per time) are values of streamflow at two points in time during a continuous period of declining streamflow (Eng and Milly, 2007). Paired-measurement strategies at partial-record sites offer an efficient means for characterizing base-flow recession, because estimates of $\tau$ can be determined from two measurements of streamflow during the same low-flow period without intervening storms (Eng and Milly, 2007). It should be noted however, that such estimates of $\tau$ at partial-record sites may have substantial error due to the small number of observations, and may reflect inherent seasonality effects (for example, evapotranspiration) in some base-flow recessions (Brutsaert and Nieber, 1977).

Generally, the rate of base-flow recession can be expected to be fast ($\tau$ is small) in small basins with steep hillslopes, shallow soils, high drainage density, and aquifers with low transmissivity. Streamflow measurements in such streams must be made after long periods without precipitation or
snowmelt to provide accurate estimates of low-flow characteristics because of rapid recession rates. In contrast, the rate of base-flow recession can be expected to be slow (τ is large) in large, flat basins with deep soils, low drainage density, highly transmissive aquifers, and lakes. Estimates of low-flow characteristics are less sensitive to the timing of measurements in such streams because low-flows are relatively stable. Examples of streams with small and large values of τ in western Washington are Racehorse Creek and Satsop River, respectively (fig. 3). Eng and Milly (2007) introduced τ as a potential explanatory variable for regional low-flow regression equations, and Funkhouser and others (2008) used kriging methods to regionalize τ for interpolation at ungaged sites.

**Figure 3.** Base-flow hydrographs and corresponding values of τ calculated from a single period of base-flow recession at two USGS streamflow gaging stations in western Washington: Racehorse Creek near Kendall, 12076500 (small τ); and Satsop River near Satsop, 12021500 (large τ).

**Low-Flow Surveys**

Technical staff from the Port Gamble S’Klallam, Hoh, Squaxin Island, Tulalip, Sauk-Suiattle, Nooksack, Puyallup, and Stillaguamish tribes coordinated with the Point-No-Point Treaty Council (PNPTC), NWIFC, and USGS to conduct low-flow measurements in streams across western Washington during the late summer and early fall in 2007, 2008, and 2009. Streamflow site selections were made by tribal and agency staff based on several criteria, including the importance of the resource, accessibility, whether a site had been monitored for other purposes (for example, water quality), and whether a site represented combinations of basin attributes not represented by existing stream gages in western Washington. Sites with large diversions or return flows upstream of the gage and sites influenced by meltwater from snowfields or glaciers were avoided. Although most watersheds have been affected by land-use changes (deforestation, urban development), land use does not have a
significant effect on dry-season base-flow in western Washington, as is observed for storm-flow and wet-season base-flow (Konrad and Booth, 2005). The streamflow sites measured during the 2007-09 low-flow surveys have basin drainage areas ranging from 0.06 to 48.9 mi$^2$ and their locations are shown in figure 4.

**Figure 4.** Locations of 63 partial-record and miscellaneous streamflow sites measured during low-flow surveys conducted by member tribes of the NWIFC and the USGS from 2007-09, and 43 USGS continuous streamflow gages (index sites) in western Washington.

The overall strategy for the low-flow surveys was to make repeated measurements of streamflow at selected sites to allow estimation of low-flow characteristics and incorporation of the sites into the regional analysis as partial-record stations. In the event that multiple measurements could not be made at a site, the miscellaneous measurements under low-flow conditions would still provide information that could be used to track low-flow conditions over time and to evaluate errors in estimates of low-flows from regression analysis. The USGS conducted training prior to the surveys to assure hydrologic technicians were familiar with standard techniques for streamflow measurement (Rantz, 1982).

The measurements were made by technical staff from NWIFC-member tribes, PNPTC, and NWIFC from late July through September in 2007, 2008, and 2009, and USGS in 2007 (fig. 5). Measurements were made at least three days after measurable rainfall that caused an increase in runoff. When possible, pairs of measurements separated by at least seven days were made during a period of continuous base-flow recession to allow calculation of $\tau$ (Eq. 1). Documentation of measurements included meter type and an assessment of measurement quality. At about a third of the sites, initial measurements were repeated for verification of results and consistency in measurement procedures.
**Figure 5.** Photographs showing examples of streamflow measurements made during the 2007-09 low-flow surveys of western Washington streams: a) Squaxin Tribe technical staff measures flow on Schneider Creek, Thurston County, Washington and b) Point-No-Point Treaty Council technical staff measures flow on Thomas Creek, Kitsap County, Washington.

**Estimating Low-Flow Characteristics at Partial-Record Sites**

Estimating low-flow characteristics such as the $Q_{7.10}$ at partial-record sites is commonly done using one of several index-site correlation methods, all of which require concurrent streamflow observations from a nearby or hydrologically similar index site. The index-site correlation methods most commonly used are: graphical, MOVE.1, and Base-Flow Correlation (U.S. Geological Survey, 1985). Although well-documented in other regional low-flow studies (for example, Ries and Friesz, 2000; Funkhouser and others, 2008), for convenience these methods and an additional method, the $Q$-ratio method, are reviewed here with example calculations using results from the 2007-09 low-flow survey.

**Graphical**

First proposed by Riggs (1972), the graphical method is perhaps the easiest to use for estimating low-flow characteristics, but is also inherently biased (Stedinger and Thomas, 1985). As a result, the method is recommended only when the relation of log-transformed base-flow observations appears non-linear. Riggs (1972) recommended that the graphical method be used with eight to ten base-flow measurements made on different recessions over two or more years. To use the method, concurrent base-flow observations are plotted, usually on log-transformed axes, and a best-fit line is drawn through the observations and extended as needed to visually estimate the low-flow statistic of interest at the partial-record site (fig. 6).
Figure 6. Graphical method of estimating low-flow characteristics at a partial-record site (Dan Creek) from concurrent base-flows at an index site (USGS gaging station ID 12137290, Sultan River near Sultan, Washington) where the base-flow relation is non-linear.

Q-ratio

A relatively simple, yet robust method developed by Potter (2001) and referred to here as the Q-ratio method, is generally recommended when the number of base-flow measurements at the partial-record site is limited (fewer than eight). In this method, concurrent flow pairs (streamflow measured at the partial-record site and streamflow recorded on the same day at the index site) are tabulated and the ratio of flows is determined for each pair. The average flow ratio is then calculated and used as a multiplier with the flow statistic at the index site to estimate the statistic at the partial-record site. In equation form, the Q-ratio method is expressed as:

$$Q_p = Z(Q_l),$$  \hspace{1cm} \text{(2)}

where $Q_p$ is the estimated low-flow statistic at the partial-record site (in volume per time), $Z$ is the average flow ratio (dimensionless), and $Q_l$ is low-flow statistic at the index site (in volume per time).

The average flow ratio, $Z$, is calculated as follows:

$$Z = \frac{1}{N} \sum_{k=1}^{N} \left( \frac{Q_{p,k}}{Q_{i,k}} \right)$$  \hspace{1cm} \text{(3)}
where \( N \) is the number of pairs of concurrent base-flow observations, \( Q_{p,k} \) is the measured streamflow of the \( k^{th} \) pair at the partial-record site, and \( Q_{i,k} \) is the measured streamflow of the \( k^{th} \) pair at the index site.

As an example, the Q-ratio method was used to estimate the \( Q_{7,10} \) for a partial-record site located on Cabin Creek in the Hamma Hamma River basin in Jefferson County, Washington. Four low-flow measurements were made at this site from 2007-08 and are listed in table 3 with the concurrent flows from the USGS streamflow gaging station at Huge Creek (12073500), which was selected as the index site. Using equation 3, \( Z \) is calculated as the average ratio of the concurrent flow pairs (\( Z=3.0 \)) and following equation 2, the value of the \( Q_{7,10} \) for Huge Creek (3.32 ft\(^3\)/s) is multiplied by \( Z \) to provide an estimate of the \( Q_{7,10} \) for Cabin Creek of 9.96 ft\(^3\)/s.

**Table 3.** An example of the Q-ratio method of estimating low-flow characteristics at a partial-record site (Cabin Creek, Jefferson County, Washington) from concurrent low-flow characteristics at an index site (USGS gaging station ID 12073500, Huge Creek near Wauna, Washington).

**MOVE.1**

The Maintenance of Variance Extension, Type 1 (MOVE.1) method (Hirsch, 1982) is often used for extending the length or filling missing periods of streamflow record at a continuous gage. However, the method can also be used to estimate low-flow frequency or duration statistics at a partial-record site. Also referred to as the line of organic correlation, MOVE.1 is preferred over more common linear regression techniques, such as ordinary least squares, because it preserves the inherent variance of streamflow data at the partial-record site and results in an estimate of streamflow that is less biased. This method is recommended when eight or more base-flow measurements exist at a partial-record site and
requires concurrent flows from a hydrologically similar index site. The MOVE.1 method follows the equation:

\[
\hat{Y} = \bar{Y} + \frac{s_y}{s_x} (\hat{X} - \bar{X}),
\]

where \(\hat{Y}\) is the estimated low-flow statistic (transformed to log units) at the partial-record site, \(\bar{Y}\) is the average of the base-flow measurements (log units) at the partial-record site, \(s_y\) and \(s_x\) are the standard deviations of the log transformed base flows at the partial record site and index site, respectively, \(\hat{X}\) is the low-flow statistic (log units) at the index site, and \(\bar{X}\) is the average of concurrent flows (log units) at the index site.

As an example, MOVE.1 was used to estimate the Q\(_{7,10}\) for a partial-record site located on Dan Creek in the Sauk River basin of Snohomish County, Washington. Ten low-flow measurements were made at this site from 2007-09 and are listed in table 4 with concurrent flows at the USGS streamflow gaging station at South Fork Sultan River (12137290), which was selected as the index site. All streamflow values are log-transformed (in this example, base-10 is used) and the mean values are calculated for Dan Creek and South Fork Sultan River as 0.746 (\(\bar{Y}\)) and 1.49 (\(\bar{X}\)), respectively. Similarly, the standard deviations are calculated from the log-transformed streamflow values at each site as 0.134 (\(s_y\)) and 0.149 (\(s_x\)). The log-transformed Q\(_{7,10}\) for the South Fork Sultan River \(\hat{X}\) is 0.802 (or 6.34 ft\(^3\)/s) and, applying Eq. 1, the log-transformed Q\(_{7,10}\) for Dan Creek (\(\hat{Y}\)) is 0.123 (or 1.33 ft\(^3\)/s).

**Table 4.** An example of the MOVE.1 method for estimating the Q\(_{7,10}\) at a partial-record site (Dan Creek, Snohomish County, Washington) from concurrent low-flows at an index site (USGS gaging station ID 12137290, South Fork Sultan River near Sultan, Washington).
Base-Flow Correlation

The Base-Flow Correlation method (Stedinger and Thomas, 1985) was developed as an unbiased technique for estimating low-flow frequency statistics at partial-record sites. The method assumes a Log-Pearson Type III distribution for the annual time series of d-day low-flows (for example, the seven consecutive-day low-flow, or \( Q_7 \)) at both the partial-record sites and index sites, and an equal skew coefficient for the distribution of \( Q_7 \) at both sites. For reliable results, a minimum of 10 base-flow measurements at a partial-record site is recommended when using this method (U.S. Geological Survey, 1985). For example, an estimate of the \( Q_7 \) with a recurrence interval of ten years (\( Q_{7,10} \)) is calculated for the partial-record site using the Base-Flow Correlation method as outlined by Funkhouser and others (2008):

\[
\log_{10}(\hat{Q}_{7,10}) = \hat{\mu}_p + K_p \hat{\sigma}_p, \tag{5}
\]

where \( \hat{\mu}_p \) is the estimated mean of the annual \( Q_7 \) at the partial-record site, \( K_p \) is the log-Pearson Type III standard deviate for a recurrence interval of ten years, and \( \hat{\sigma}_p \) is the estimated standard deviation of the annual \( Q_7 \) time-series at the partial-record site. To estimate \( \hat{\mu}_p \) and \( \hat{\sigma}_p \), a simple linear regression between the log-transformed concurrent flows at the partial-record site and index site is performed to obtain the regression coefficients \( \beta_1 \) (slope) and \( \beta_0 \) (intercept). These coefficients are further used to estimate \( \hat{\mu}_p \) and \( \hat{\sigma}_p \) as follows:

\[
\hat{\mu}_p = \beta_0 + \beta_1 m_i \tag{6}
\]

and

\[
\hat{\sigma}_p = \sqrt{\beta_1^2 s_i^2 + s_e^2 \left[ 1 - \frac{s_i^2}{(n_b-1)s_e^2} \right]} \tag{7}
\]
where, $m_i$ and $s_i^2$ are the mean and variance of the annual $Q_7$ time series at the index site, $s_c^2$ is the variance of the concurrent flows at the index site, $n$ is the number of base-flow measurements at the partial-record site, and $s_e^2$ is the square of the standard error of the regression among log-transformed concurrent flows at the partial-record site and index site. Example calculations demonstrating the Base-Flow Correlation method are presented in appendix A.

**Empirical Monte Carlo Technique for Evaluating Index-Site Correlation Methods**

The performance of three index-site correlation methods (Q-ratio, MOVE.1, Base-Flow Correlation) and the optimal number of base-flow measurements to use for each method was evaluated using an empirical Monte Carlo technique in MATLAB computing software (The MathWorks Inc., 2008). Required inputs for the program are the daily streamflow records for a user-defined number of index sites, and the low-flow characteristic (such as the $Q_{7,10}$) and basin attributes for each site. The program identifies base-flow recession segments of the hydrograph for all index sites, subject to user-defined criteria such as the hydrologic season, minimum duration of recession segments, minimum streamflow that defines a peak, and the number of days since the peak to begin recession segments (the latter is needed to differentiate between short- and long-time base-flow response [Brutsaert and Nieber, 1977]). In the analysis, index sites are sequentially simulated as partial-record sites (hereafter referred to as ‘synthetic partial-record sites’), wherein a user-defined number of observations (daily streamflow values from the continuous record) are randomly selected from recession segments. These observations are then paired with concurrent streamflows at an index site and the $Q_{7,10}$ (or other low-flow statistic) is estimated using the methods of Q-ratio, MOVE.1, and Base-Flow Correlation. The index site used for correlating concurrent flows was selected from the pool of other sites on the basis of basin attribute similarity. The sequence of randomly selecting concurrent streamflows (within user-defined constraints) was repeated 500 times, and with each iteration an estimate of $Q_{7,10}$ was generated for each index site.
using the three correlation methods. Residual error was then determined for each correlation method by comparing the estimated $Q_{7.10}$ with the observed value determined from the streamflow record. The average error and bias associated with estimating the $Q_{7.10}$ value at each index site were computed for each correlation method under scenarios that varied with the combination of basin attributes and the number of observations.

In addition to evaluating correlation methods to estimate $Q_{7.10}$ values, the MATLAB program also calculated the base-flow-recession time constant, $\tau$, at each index site (Eng and Milly, 2007). The calculation of $\tau$ was performed as part of the empirical Monte Carlo analysis for each index site using a number of observation pairs (ranging from 2 to 10) defined by the user for each scenario. Discharge observation pairs were selected along randomly selected base-flow recession segments, and equation 1 was used to calculate $\tau$. Because the value of $\tau$ is based on a limited number of observations, a more robust estimate, $\tau_{\text{ideal}}$, was obtained for each index site based on 500 observation pairs from randomly selected recession segments. The values of $\tau$ calculated from 2 to 10 observation pairs for each index site were compared with $\tau_{\text{ideal}}$ to determine the optimum number of streamflow measurements for reliably estimating $\tau$ at partial-record sites.

**Basin-Attribute Selection**

A total of 16 basin attributes were considered for the purposes of index-site selection within the Monte Carlo analysis as well as for serving as explanatory variables in preliminary regional low-flow regressions (described in section Analysis of Low-Flow in Western Washington Streams). Basin attributes were selected to represent physical and climatic parameters within the region that might explain observed variations in base flow. The USGS Washington StreamStats program \( (http://water.usgs.gov/osw/streamstats/Washington.html) \) was used to delineate basin areas and determine 10 of the 16 basin attributes for all of the index sites. Four basin attributes pertaining to
surficial geology were determined from simplified geologic maps of the Puget Sound and Pacific Coast
sub-regions (Jones, 1999). Geographic proximity was determined from the locations (latitude and
longitude) of index sites, and the base-flow recession time constant ($\tau$) was determined from the
empirical Monte Carlo program, as previously described. Basin attributes were screened for multi-
collinearity, and where strong correlations were found between two attributes (for example, mean
annual precipitation and mean basin elevation), only one attribute was retained for further analysis. The
five basin attributes considered in the empirical Monte Carlo analysis were: drainage area (A), mean
annual precipitation (P), geographic proximity (G), percentage of basin area covered with surficial
geology classified as ‘coarse sediments’ (S), and $\tau$. All basin-attribute types and data sources used in
this study are in table 5.

Table 5. Basin attributes and data sources used for index-site selection in the empirical Monte Carlo Analysis and
for developing preliminary regional low-flow regressions.

**Index-Site Selection**

The selection of an index site for correlating with each synthetic partial-record site was done
within the empirical Monte Carlo analysis on the basis of basin similarity. To quantify basin similarity,
the Euclidean distance (measured in basin-attribute variable space) was calculated between the synthetic
partial-record site and all index sites considered in the analysis. The index site nearest the synthetic
partial-record site, in basin-attribute variable space (minimum Euclidean distance), was selected.

The Euclidean distance was calculated as:

$$R_{ij} = \sum_{k=1}^{k} \left( \frac{(\log X_{1,i} - \log X_{1,j})^2}{\sigma^2(\log X_1)} + \cdots + \frac{(\log X_{k,i} - \log X_{k,j})^2}{\sigma^2(\log X_k)} \right).$$

(8)
where $R_{ij}$ is the Euclidean distance (dimensionless), $i$ is the basin delineated upstream of the partial-record site, $j$ is the index-site basin, $k$ is the number of basin attributes, $X_{k,i}$ is value of the $k^{th}$ basin attribute for the partial-record basin, $X_{k,j}$ is value of the $k^{th}$ basin attribute at the index-site basin, and $\sigma^2_{\log X_k}$ is the variance of the log-transformed values of the $k^{th}$ basin attribute for all potential index sites considered.

**Analysis of Low-Flow in Western Washington Streams**

In western Washington, the monthly mean streamflow at the 43 index sites used in this study is generally lowest from July through September (fig. 7). The annual minimum streamflow generally occurs during this period, with the specific date depending on summer storm patterns and the long-term recession associated with decreasing aquifer recharge in the late spring and early summer. Annual minimum streamflows are relatively stable year-to-year, ranging from about 70 to 130 percent of the median annual minimum streamflow at most gages. On a unit-area basis, annual minimum streamflow ranges from 0.2 to 2 ft³/mi² for the period of record at index sites, with a median of about 0.7 ft³/mi². Streamflow at the index sites for the July-September period was about average in 2007, above average in 2008, and generally below average in 2009 (fig. 8). Streamflows exceeded about 90 percent of the time are roughly equivalent to the median 7-day low-flow at index sites (fig. 9). Likewise, streamflows exceeded about 99 percent of the time are roughly equivalent to the $Q_{7,10}$.

**Figure 7.** Monthly mean streamflow as a fraction of annual streamflow at 43 index sites in western Washington.

**Figure 8.** Monthly mean streamflow at 43 index sites during July-September in 2007-2009 as a fraction of long-term monthly mean streamflow in western Washington.
Figure 9. Streamflows (A) exceeded 90 percent of the time versus median 7-day low-flow, and (B) exceeded 99 percent of the time versus $Q_{7,10}$.

Results of the 2007, 2008, and 2009 Low-Flow Surveys

Streamflow was measured at 63 streams on 66 days in 2007, 2008, and 2009. A total of 283 measurements were made, of which 42 were duplicate verification measurements. The number of measurements made at each stream ranged from 1 to 10. Pairs of measurements made during the same base-flow-recession period for estimating $\tau$ were made at 25 sites. Because rainfall varies across the region and is often localized during summer, measurements were made on different days at different sites. The median unit-area streamflow of all measurements was 0.5 ft$^3$/mi$^2$ with a range from 0.06 to 16 ft$^3$/mi$^2$. The $Q_{7,10}$ was estimated using the Q-ratio method at miscellaneous sites and at partial-record sites with fewer than eight measurements. The MOVE.1 method was used at partial-record sites if eight or more measurements were made and concurrent flow pairs were reasonably correlated (Pearson’s rho greater than or equal to 0.8); otherwise, the Q-ratio method was used. All partial-record and miscellaneous sites where streamflow was measured during the low-flow surveys are listed in table 6, and the measurements and ancillary information are tabulated in Appendix B. Basin attributes were determined for all partial-record and miscellaneous sites using Washington Streamstats (http://water.usgs.gov/osw/streamstats/Washington.html) and are listed in table 7.

Table 6. The location, number of measurements, and estimates of $\tau$ and $Q_{7,10}$ at partial-record and miscellaneous sites (shown in fig. 4) established by NWIFC-member tribes and the USGS as part of the low-flow surveys conducted in western Washington during 2007-09.
Table 7. The location and basin attributes for partial-record and miscellaneous sites (shown in fig. 4) established by NWIFC-member tribes, PNPTC, NWIFC and the USGS as part of low-flow surveys conducted in western Washington during 2007-09.

Partial-record and miscellaneous sites established during the low-flow surveys occupy unique basin-attribute variable space that is not represented by the existing streamflow gaging network in western Washington. In general, these sites have smaller drainage areas that generate less runoff and have correspondingly lower values of \( Q_{7,10} \) (fig. 10). By incorporating these sites into the streamflow network, regional regression equations will be able to more accurately estimate low-flow characteristics at these types of ungaged stream sites.

Figure 10. The relation between low-flow characteristics \( (Q_{7,10}) \) and selected basin attributes (drainage area times mean annual precipitation) of index sites and partial-record sites in western Washington.

Results of the Empirical Monte Carlo Analysis

The \( Q_{7,10} \) is estimated at 43 synthetic partial-record sites using each of the three correlation methods (Q-ratio, MOVE.1, and Base-Flow Correlation) in 170 scenarios, where each scenario is defined by the number of streamflow observations (ranging from four to 20) or observation pairs (ranging from two to ten), and the combination of basin attributes used to select an index site. For example, in one scenario the \( Q_{7,10} \) is estimated at each of the 43 synthetic partial-record sites using only four streamflow observations, and the index site is selected based on similarity in the basin attributes of A, P and G; for another scenario, three pairs of observations (each pair from the same base-flow recession segment) and only the basin attribute \( \tau \) are used. To allow the calculation of \( \tau \) as a basin attribute, half of the scenarios contain streamflow observation pairs \( (Q_j \text{ and } Q_{j+1}) \), separated by J number of days) from the same randomly selected base-flow recession segment.
In all scenarios, the root-mean square error (RMSE) expressed as a percentage is calculated from the difference between the estimated $Q_{7,10}$ (derived from the average of 500 repeated applications of Q-ratio, MOVE.1, and Base-Flow Correlation) and the $Q_{7,10}$ calculated from the continuous daily record at each of the 43 index sites. In general, as the number of concurrent streamflow observation increases, the RMSE decreases for the MOVE.1 and Base-Flow Correlation methods, but changes comparatively little for the Q-ratio method (fig. 11). Of the three correlation methods, Q-ratio results in the smallest RMSE for almost all scenarios; the optimum number of observations for the Q-ratio method is four, with only slight reductions in the RMSE with additional observations.

**Figure 11.** The performance (expressed as root-mean square error, RMSE) of three correlation methods (Q-ratio, MOVE.1, and Base-Flow Correlation) in estimating the $Q_{7,10}$ at partial-record sites in western Washington, using different scenarios defined by the number of streamflow observations (n) and the combination of basin attributes used to select an index site.

The overall bias (defined herein as the observed minus the estimated value) for each correlation method was calculated as the arithmetic average of the bias for all estimates of $Q_{7,10}$ in a scenario (fig. 12). In general, the correlation method that had the largest absolute bias for each scenario was Base-Flow Correlation, while Q-ratio had the smallest absolute bias. In addition, both MOVE.1 and Base-Flow Correlation had consistently negative bias (estimates of $Q_{7,10}$ were larger than observed values), whereas Q-ratio had consistently positive bias (estimates of $Q_{7,10}$ were smaller than observed values). In estimating low-flow statistics, methods that have smaller bias are obviously preferred, but the preferred direction of bias (and hence the definition of a conservative estimate) depends on how the estimated flow statistic will be used.
Incorporating \( \tau \) and Partial-Record Sites into Regional Low-Flow Regressions

Previous studies have demonstrated the value of including \( \tau \) as a basin attribute in regional regression equations for estimating low-flow characteristics at ungaged sites (for example, Bingham, 1986; Vogel and Kroll, 1992; and Funkhouser and others, 2008). For basins with continuous gages, a reliable estimate of \( \tau \) is readily determined from the daily streamflow record. Where the continuous gage network is not well represented, either in geographic or regression-variable space, estimates of \( \tau \) can be determined at partial-record sites to extend coverage of the network. For partial-record sites, \( \tau \) can be estimated using equation 1, with measurements pairs made on the receding limb of the hydrograph during base-flow conditions. In developing partial-record sites, however, there is uncertainty as to where sites should be located (and what types of basins to include) and, once a site is established, how many measurements are needed to reliably estimate \( \tau \).

To answer these questions, provisional regression equations are developed for the sole purpose of evaluating the benefits of including \( \tau \) as an explanatory variable (which has implications for the types of streams to measure as well as their geographic locations) and determining the optimum number of observations for estimating \( \tau \) at partial-record sites. Provisional regression equations for estimating the \( Q_{7,10} \) at ungaged sites are developed using the basin attributes of A, P and \( \tau \) as explanatory variables and the \( Q_{7,10} \) derived from 65 continuous gages (the 43 index sites and 22 discontinued gages) in western Washington with seven or more years of daily streamflow record. Three regression equations using an
ordinary least-squares method (which is considered sufficient for purposes of the analysis) are evaluated using the performance metric of RMSE expressed as a percentage (fig. 13). The three regression equations estimate $Q_{7,10}$ as a function of drainage area ($A$), as a function of $A$ and mean annual precipitation ($P$), and as a function of $A$, $P$, and $\tau$ as follows:

$$Q_{7,10} = 0.15A^{1.27}, \quad R^2 = 0.74, \quad (9)$$

$$Q_{7,10} = 8.48 \times 10^{-4}(A^{1.17} P^{1.23}), \quad R^2 = 0.79, \quad (10)$$

$$Q_{7,10} = 6.47 \times 10^{-6}(A^{0.968} P^{1.16} \tau^{1.68}), \quad R^2 = 0.90, \quad (11)$$

where $Q_{7,10}$ is streamflow in cubic feet per second, $A$ is basin drainage area in square miles, $P$ is mean annual precipitation in inches, $\tau$ is the base-flow recession time constant in days, and $R^2$ is the coefficient of determination. In the empirical Monte Carlo analysis, $\tau$ was calculated from 500 randomly sampled observation pairs to obtain the best estimate ($\tau_{\text{ideal}}$), and from a much smaller number of observation pairs ranging from 1 to 10 to represent the estimate at a partial-record site.

**Figure 13.** The performance (expressed as root-mean square error, RMSE) of regression equations for estimating the $Q_{7,10}$ at ungauged sites in western Washington, using different combinations of basin attributes, including $\tau$, and numbers of paired streamflow measurements.

In general, the RMSE of the regression equations decreases as the number of explanatory variables increases, and the fraction of variation explained by the regressions ($R^2$) increases with additional variables. For example, the regression equation that uses only $A$ as an explanatory variable has an RMSE of 133 percent, and the regression equation that uses $A$ and $P$ as explanatory variables has an RMSE of 114 percent. By incorporating $\tau$ as a third explanatory variable, the RMSE is further reduced to possibly as small as 72 percent, depending on the number of paired streamflow
measurements that were used to determine \( \tau \). The optimum number of measurement pairs for estimating \( \tau \) at partial-record sites is eight, beyond which the RMSE is not reduced significantly.

The ability of regional regression equations to accurately estimate low-flow characteristics at ungaged sites over a large range of stream types and geography depends on the comprehensiveness of coverage of the regional streamflow network. Regression equations will generally provide poor estimates of low-flow characteristics at ungaged sites with basin attributes that are unique or not represented in the data set from which the regressions were developed. Partial-record sites with reliable estimates of \( \tau \) can be easily added to extend the coverage of basin-attribute variable space that is represented by a continuous streamflow gaging network, and thereby increase the ability of the regression equations to accurately estimate flow at ungaged sites. Preliminary estimates of \( \tau \) at partial-record sites established in the recent low-flow surveys suggest that basin-attribute variable space is extended by incorporating partial-record sites (fig. 14) and that including small streams in the streamflow network is important in developing regional regression equations for estimating low-flow characteristics at ungaged sites.

**Figure 14.** The coverage of basin-attribute variable space defined by basin area and \( \tau \) for index sites and partial-record sites established during 2007-09 low-flow surveys in western Washington.

A low-flow survey strategy that includes measurements of \( \tau \) at partial-record sites requires additional effort and planning, but has the potential to reduce the error of regional regression equations for estimating low-flow characteristics at ungaged sites. However, as Vogel and Kroll (1992) point out, regression equations that include \( \tau \) as an explanatory variable present a problem in that an estimate of \( \tau \) must first be made at the ungaged site. To accomplish this, previous researchers have mapped \( \tau \) on a regional scale using interpolation (Bingham, 1986) and more specifically, kriging methods (Funkhouser
and others (2008). Regionalization of low-flow characteristics through regression also assumes stationarity of watershed and climatic conditions and does not account for potential trends in streamflow (Milly and others, 2008).

Summary

As part of a scientific framework for assessing water resources in western Washington (Konrad, 2005), the documentation of low-flow conditions in western Washington streams was identified by the Northwest Indian Fisheries Commission (NWIFC) and its member tribes as a high priority. In order to document low-flows, a regional low-flow survey of small streams was initiated by NWIFC-member tribes with assistance from the USGS in 2007, and repeated by the tribes during the low-flow seasons of 2008-09. This approach allows timely documentation of base-flow conditions and characteristics for small ungaged streams which, in western Washington, are underrepresented within the continuous streamflow gage network.

In this report, low-flow measurements made at partial-record sites during the 2007-09 surveys are compared to the recorded flows and low-flow characteristics ($Q_{7,10}$) at continuous gages in the USGS streamflow network. The basin attributes (for example, drainage area and mean annual precipitation) of continuous gages in the network are used to identify index sites for estimating the $Q_{7,10}$ at partial-record sites, and to assess gaps in the spatial coverage of the network. An empirical Monte Carlo technique is used to determine the error and bias associated with three index-site correlation methods ($Q$-ratio, MOVE.1, and Base-Flow Correlation) for estimating low-flow characteristics. Preliminary regional low-flow regressions for estimating the $Q_{7,10}$ at ungaged sites are developed for the purpose of evaluating basin attributes used as explanatory variables, and in particular the base-flow-recession time constant, $\tau$. 
Streamflow was measured at 63 streams during the low-flow seasons in 2007, 2008, and 2009 and the number of measurements made at each stream ranged from 1 to 10. Pairs of measurements made during the same base-flow-recession period for estimating \( \tau \) were made at 25 sites. The \( Q_{7,10} \) was estimated at these sites using the Q-ratio and MOVE.1 methods. Partial-record and miscellaneous sites established during the low-flow surveys occupy unique basin-attribute variable space that is not represented by the existing streamflow gaging network in western Washington. In general, these sites have smaller drainage areas, generate less runoff and have correspondingly lower values of \( Q_{7,10} \).

The accuracy of index-site correlation methods (Q-ratio, MOVE.1 and Base-Flow Correlation) in estimating the \( Q_{7,10} \) at 43 index sites was determined using an empirical Monte Carlo technique for different scenarios, which were defined by the number of streamflow observations and the combination of basin attributes used to select an index site. Of the three correlation methods, Q-ratio has the smallest root-mean square error (RMSE) ranging from 70 to 118 percent for all of the scenarios, and the optimum number of observations is four, with only slight reductions in RMSE gained by additional observations.

By incorporating \( \tau \) as a basin attribute in the regression equation, the RMSE for estimating \( Q_{7,10} \) at ungaged sites can be lowered to as much as 73 percent, 11 percent lower than if only drainage area and mean annual precipitation are used. In practice, if partial-record sites are included in the regression data set, \( \tau \) must be estimated from pairs of base-flow-recession measurements. In this case, the optimum number of measurement pairs for estimating \( \tau \) at partial-record sites is eight. A low-flow survey strategy that includes measurements of \( \tau \) at partial-record sites requires additional effort and planning, but has the potential to reduce the error of regional regression equations for estimating low-flow characteristics at ungaged sites.
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References Cited


U.S. Census Bureau, 2000, Census 2000, accessed on May 5, 2010 at url
http://factfinder.census.gov/servlet/GCTTable?_bm=y&-geo_id=04000US53&-
_box_head_nbr=GCT-PH1&-ds_name=DEC_2000_SF1_U&-redoLog=false&-
mt_name=DEC_2000_SF1_U_GCTPH1_ST7&-format=ST-2


Appendix A: Example of Base-Flow Correlation Method for Estimating Low-Flow Characteristics at Partial-Record Sites

The following is an example of using the Base-Flow Correlation Method (Stedinger and Thomas, 1985) to estimate the Q_{7,10} at a partial-record site, for which data and derived coefficients are shown in table 8. In this example, ten low-flow measurements were made at Dan Creek from 2007-09. Concurrent flows are obtained from an index site with similar basin attributes, South Fork Sultan River near Sultan, Washington (12137290), and all streamflow values are log-transformed. A least-squares regression equation is developed with the concurrent flows at the partial-record and index sites, and the coefficients $\beta_0$ and $\beta_1$ are the resulting intercept and slope, respectively, of the regression. The time series of annual 7-day low-flows (Q_7) is determined at the index site, the values are log-transformed, and the coefficient $m_i$ is calculated as the mean. The coefficient $\mu_p$, is the estimated mean (log-transformed) of the Q_7 at the partial-record site and is calculated using eq. 6.

The variance ($s_i^2$) is calculated for the Q_7 time series at the index site and also for the concurrent base flows at the index site ($s_c^2$). The number of concurrent base flow pairs is $n_b$, and the square of the standard error from the previously performed regression of concurrent flows is $s_c^2$. The estimate of the standard deviation of the Q_7 at the partial-record site, $\sigma_p$, is then calculated using eq. 7.

In this example, the known value of Q_{7,10} for the index site is 6.34 ft^3/s based on 14 years of continuous streamflow record. A log-Pearson Type III distribution is assumed for the Q_7 time series at the index site and the standard deviate, $K_i$, (if not already known) is determined for the index site, by modifying eq. 5 to solve for $K_i$, given the values of $m_i$ and the square root of $s_i^2$ previously determined:

$$K_i = \frac{\log_{10}(Q_{7,10}) - m_i}{s_i}$$  \hspace{1cm} \text{(eq. A1)}.
The standard deviate for the partial-record site ($K_p$) is assumed equal to $K_i$, and using eq. 5, the estimated $Q_{7,10}$ for the partial-record site Dan Creek is calculated as 1.80 ft$^3$/s.

Table 8. An example of the Baseflow Correlation method for estimating the $Q_{7,10}$ at a partial-record site (Dan Creek, Snohomish County, Washington) from concurrent flows at an index site (USGS gaging station ID 12137290, South Fork Sultan River near Sultan, Washington).


During the low-flow surveys conducted in 2007-09, a total of 283 streamflow measurements were made by NWIFC-member tribes, the PNPTC, NWIFC and USGS (2007 only). Measurements were made in perennial streams that are not part of the USGS streamflow gaging network, using a variety of current-meter types, and following streamflow-measurement methods outlined by Rantz (1982). All measurements are listed in table 9.

Table 9. Streamflow measurements made during the 2007-09 low-flow survey conducted by NWIFC-member tribes, PNPTC, NWIFC and the USGS in western Washington.