science for a changing world

Prepared in cooperation with the Northwest Indian Fisheries Commission

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

Scientific Investigations Report 2012-5078

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

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

By Christopher A. Curran, Ken Eng, and Christopher P. Konrad

Prepared in cooperation with the Northwest Indian Fisheries Commission

Scientific Investigations Report 2012-5078

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

U.S. Department of the Interior
KEN SALAZAR, Secretary

U.S. Geological Survey
Marcia K. McNutt, Director

U.S. Geological Survey, Reston, Virginia: 2012

For more information on the USGS—the Federal source for science about the Earth, its natural and living resources, natural hazards, and the environment, visit http://www.usgs.gov or call 1–888–ASK–USGS.

For an overview of USGS information products, including maps, imagery, and publications, visit http://www.usgs.gov/pubprod

To order this and other USGS information products, visit http://store.usgs.gov

Suggested citation:
Curran, C.A., Eng, Ken, and Konrad, C.P., 2012, Analysis of low flows and selected methods for estimating low-flow characteristics at partial-record and ungaged stream sites in western Washington: U.S. Geological Survey Scientific Investigations Report 2012-5078, 46 p.

Contents

Figures

Figures—Continued

Tables

Conversion Factors and Datums

Conversion Factors

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square foot (ft^2)	0.09290	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)
	Flow rate	
foot per second (ft/s)	0.3048	meter per second (m/s)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)
cubic foot per second per square mile [$(ft^3/s)/mi^2$]	0.01093	cubic meter per second per square kilometer [$(m^3/s)/km^2$]
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)

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

°C=(°F-32)/1.8.

Datums

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).

Elevation, 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 Stream Sites in Western Washington

By Christopher A. Curran, Ken Eng, and Christopher P. Konrad

Abstract

A regional low-flow survey of small, perennial streams in western Washington was initiated by the Northwest Indian Fisheries Commission (NWIFC), NWIFC-member tribes, and Point-No-Point Treaty Council in cooperation with the U.S. Geological Survey in 2007 and repeated by the tribes during the low-flow seasons of 2008–09. Low-flow measurements at 63 partial-record and miscellaneous streamflow-measurement 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 7-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. The Q-ratio method generally 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 4 to 20) 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: basin area, mean annual precipitation, and base-flow recession time constant, also referred to as tau (τ).

Regional low-flow regression models for estimating $Q_{7,10}$ at ungaged stream sites are developed from the records of daily discharge at 65 continuous gaging stations (including 22 discontinued gaging stations) for the purpose of evaluating explanatory variables. By incorporating the base-flow recession time constant τ as an explanatory variable in the regression model, the root-mean square error for estimating $Q_{7,10}$ at ungaged sites can be lowered to 72 percent (for known values of τ), which is 42 percent less than if only basin area and mean annual precipitation are used as explanatory variables. If partial-record sites are included in the regression data set, τ must be estimated from pairs of discharge measurements made during continuous periods of declining low flows. Eight measurement pairs are optimal for estimating τ at partial-record sites, and result 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 τ and potentially reduce the error of regional regression models 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 streambed) 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 autumn, but also can 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.

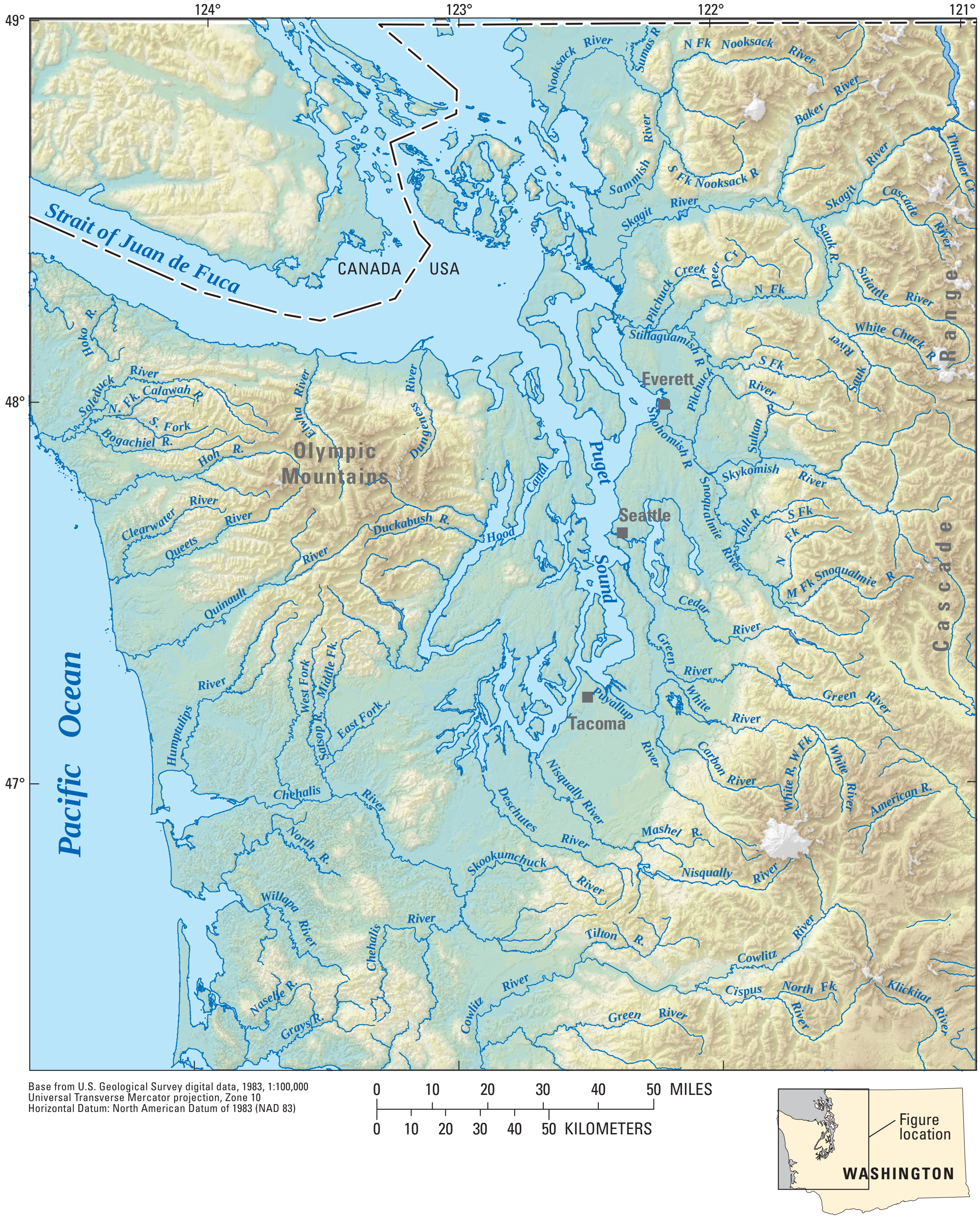


Figure 1. Study area in western Washington.

Native American tribes in western Washington have reserved water rights that are needed to support their growing populations, and the tribes have treaty rights to harvestable salmon, which also need water 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 most profound in western Washington during late summer and early autumn, 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 also can be used to assess the potential effect of current and future groundwater withdrawals. Lastly, extended periods of low flow 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.

To document low flows, a regional low-flow survey of small streams was initiated by NWIFC and NWIFC-member tribes and the Point-No-Point Treaty Council (PNPTC) in cooperation with the U.S. Geological Survey (USGS) in 2007, and repeated by the tribes during the low-flow seasons (July through September) of 2008 and 2009. 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-gaging-station network of western Washington. Of the 357 USGS-operated gaging stations with at least 10 years of continuous data, only 56 are in drainage areas less than 10 mi^2 (M.C. Mastin, U.S. Geological Survey, written commun., 2011).

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-gaging-station network, and, potentially, assess streamflow trends over time;

2. paired measurements made during a period of continuously decreasing streamflow (base-flow recession) can be used to estimate the base-flow recession time constant, τ, 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 analyses 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 and 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 2 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 at which no streamflow measurements have been made.

Low-flows measured at partial-record and miscellaneous sites can be correlated with concurrent flows at selected index sites to estimate low-flow characteristics such as the $Q_{7,10}$ (defined as the lowest average streamflow for a consecutive 7-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 also can be incorporated into regional regression models for estimating low-flow characteristics at ungaged sites.

Table 1. Definitions used to reference types of streamflow sites in western Washington used for this study.

[–, does not apply]

Type of streamflow site	Site definition	Methods for estimating low-flow characteristics	Number of base-flow measurements required to estimate low-flow characteristics	Method for determining base-flow recession time constant (τ)	Primary use in a regional-regression analysis
Index site	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.	A Log-Pearson Type III probability distribution is fit to annual or seasonal low-flow minimums determined from the daily streamflow record.	–	Computed from base-flow recession segments in the daily streamflow record.	Low-flow characteristics and basin attributes are used to develop regional regression equations.
Partial-record site	Site with four or more streamflow measurements during a period of 2 or more years.	Q-ratio Graphical MOVE.1 Base-Flow Correlation	Fewer than eight Eight to ten Eight or more Ten or more	Estimated from pairs of streamflow measurements made during periods of base-flow recession.	Low-flow characteristics and basin attributes can be used to augment information from the streamflow-gaging network in developing regional regression equations, or to verify results of regional regressions.
Miscellaneous site	Site without continuous measurements that is not a partial-record site.	Q-ratio	Fewer than eight	Estimated from pairs of streamflow measurements made during periods of base-flow recession.	Low-flow characteristics and basin attributes can be used to verify results of regional regression equations.
Ungaged site	Site with no streamflow information.	Regional regression equation	None	Estimated from regional interpolation methods.	–

Purpose and Scope

This report documents the low-flow conditions in western Washington streams measured by NWIFC-member tribes during late-summer surveys in 2007, 2008, and 2009, describes and evaluates methods for estimating low-flow characteristics (specifically the $Q_{7,10}$) at these sites, and identifies research and data needs for developing future regional regression models 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) with a glacial meltwater component that is minimal to nonexistent. Low flows measured at partial-record and miscellaneous sites during the 2007–09 surveys are correlated with the concurrent daily-mean flows at index sites, and the $Q_{7,10}$ is estimated at the partial-record and miscellaneous sites. Basin attributes (for example, latitude and longitude, basin area, and mean annual precipitation) are determined for all sites to assess information gaps in 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 [Potter, 2001; Hirsch, 1982; and Stedinger and Thomas, 1985, respectively]), and the optimal number of measurements for estimating the $Q_{7,10}$ at partial-record sites is determined. Regional low-flow regressions for estimating the $Q_{7,10}$ at ungaged sites are developed for the purpose of evaluating explanatory variables. The types of additional partial-record sites needed to improve regional low-flow regressions for estimating low-flow characteristics at ungaged sites in western Washington also are assessed.

Description of Study Area

The study area in western Washington State 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 (as much as about 200 in/yr on average) relative to lowland areas near Puget Sound (about 40 in/yr on average). Most precipitation in the mountains occurs as snow, and 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 Mgal/d, about 60 percent of which is supplied by surface water and about 40 percent by groundwater (Lane, 2009).

Previous Low-Flow Investigations

The USGS has conducted regional-scale investigations of low flow across the United States, many for the purpose of developing regional regression models for estimating low-flow statistics at ungaged sites (Ries and Friesz, 2000; Hortness, 2006; Funkhouser and others, 2008; Risley and others, 2008). The application of index-site correlation methods for estimating low-flow characteristics at partial-record sites is well-documented in many of these studies. Previous low-flow investigations in western Washington have ranged from basin- to regional-scale, 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 collected at USGS gaging stations that are part of the national hydrologic data network. Hidaka (1973) computed low-flow indices for streams in the Puget Sound region from flow-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, 1985a, 1985b; Curran and Olsen, 2009) calculated low-flow frequency statistics for streams in selected basins or subregions of western Washington. Sinclair and Pitz (1999) computed base-flow characteristics for all USGS gaging stations 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 on perennial streams in western Washington that are not monitored as part of the USGS continuous streamflow-gaging-station network. Because low flows are less variable on an annual basis 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 in turn to augment the data set available for developing regression models for estimating low-flow characteristics at ungaged sites. Thus, partial-record sites offer an affordable way to expand the geographic coverage of low-flow information and include combinations of basin attributes (for example, small, low-elevation streams) that are underrepresented in the streamflow-gaging 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 the data from those sites were 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 models.

Index sites were initially screened on the basis of the following criteria: (1) they have 10 or more years of continuous daily streamflow record, (2) they represent perennially flowing streams or rivers with a $Q_{7,10}$ greater than zero, (3) they represent relatively natural streamflow conditions, and (4) they represent streams in which low flow is predominantly groundwater-derived (base flow), and glacier meltwater, if a contributor to streamflow, is only a minor component of flow at the site. This last criterion is necessary because glacial meltwater augments flows in many streams during the typical summer low-flow season in western Washington.

Because the number of small stream sites in the study area satisfying the first criterion was insufficient, three sites with 8 years of record and one site with 7 years also were used in the analysis. Additionally, Sinclair and Pitz (1999) identified many of the sites used in this analysis as having some potential for anthropogenic alteration or glacier meltwater contribution to base flow, but these effects were assumed to be minor at such sites. Non-USGS streamflow-gaging stations (for example, gaging stations 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 flow records, altered flow conditions at the gaging station (for example, most Ecology gaging stations monitor anthropogenic effects), or uncertainties in data quality and availability.

Basin attributes, such as basin 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 (U.S. Geological Survey, 2010). The basin attributes and low-flow characteristics for each index site are listed in table 2.

Table 2. Location, low-flow characteristics, and basin attributes for 43 index sites on streams in western Washington.

[Location of index sites are shown in figure 4. **$Q_{7,10}$:** The lowest average streamflow for a consecutive 7-day period that recurs on average once every 10 years. **Climatic year:** April 1–March 31. **Relief:** Defined as maximum minus minimum basin elevations. **Remarks:** D, minor diversion; I, minor irrigation; M, minor snowmelt; R, minor regulation (Sinclair and Pitz, 1999). **Abbreviations and symbols**: ft^3/s, cubic foot per second; mi^2, square mile; ft, foot; in., inch; τ, base-flow recession time constant]

Station name	Station No.	Latitude (decimal degrees)	Longitude (decimal degrees)	Number of climatic years of record (prior to October 1, 2007)	$Q_{7,10}$ (ft^3/s)	Mean τ (days)	Basin area (mi^2)	Mean basin elevation (ft)	Relief (ft)
Naselle River near Naselle	12010000	46.374	-123.743	77	21.9	23.1	54.8	910	2,650
Willapa River near Willapa	12013500	46.651	-123.653	50	18.2	19.8	130	707	2,830
Chehalis River near Doty	12020000	46.617	-123.278	67	20.2	21.6	113	1,290	2,800
Skookumchuck River near Vail	12025700	46.773	-122.594	39	17.2	25.2	40	2,000	3,110
Satsop River near Satsop	12035000	47.001	-123.495	77	197	32.1	296	734	3,930
Humptulips River near Humptulips	12039005	47.231	-123.974	40	104	26.2	130	1,150	4,350
Calawah River near Forks	12043000	47.960	-124.393	31	41.0	20.0	130	1,480	3,570
Hoko River near Sekiu	12043300	48.241	-124.384	22	12.8	19.1	52.2	782	2,630
Dungeness River near Sequim	12048000	48.014	-123.133	75	81.0	31.2	156	4,160	7,200
Big Quilcene River below diversion, near Quilcene	12052210	47.785	-122.980	13	21.9	33.0	49.4	3,750	6,630
Duckabush River near Brinnon	12054000	47.684	-123.012	67	48.9	24.1	66.5	3,530	6,480
North Fork Skokomish River below Staircase	12056500	47.514	-123.330	82	38.0	23.5	56.8	3,250	5,630
South Fork Skokomish River near Union	12060500	47.340	-123.280	64	70.1	29.3	76.5	1,970	4,920
Huge Creek near Wauna	12073500	47.389	-122.699	51	3.32	84.0	6.5	347	439
Deschutes near Rainier	12079000	46.852	-122.669	43	22.3	28.7	86.5	1,450	3,500
Mineral Creek near Mineral	12083000	46.744	-122.145	63	19.8	19.5	75.8	2,740	3,930
Greenwater River at Greenwater	12097500	47.153	-121.636	60	28.0	29.2	73.4	3,980	4,930
Boise Creek near Buckley	12099600	47.176	-122.018	29	3.63	25.2	16.1	1,480	3,330
Newaukum Creek near Black Diamond	12108500	47.276	-122.060	59	11.0	43.9	31.3	850	2,860
Cedar River below Bear Creek, near Cedar Falls	12114500	47.342	-121.549	48	15.8	19.5	25.7	3,520	3,550
Cedar River near Cedar Falls	12115000	47.370	-121.625	60	24.0	21.7	41.2	3,300	3,870
Rex River near Cedar Falls	12115500	47.351	-121.663	60	5.57	16.5	13.4	3,260	3,030
Taylor Creek near Selleck	12117000	47.386	-121.846	50	16.8	36.9	17.3	2,280	3,160
Issaquah Creek near Hobart	12120600	47.457	-122.005	20	7.08	29.0	18.1	1,110	2,680
Issaquah Creek near Issaquah	12121600	47.552	-122.048	43	15.5	29.0	57	919	2,950
Skykomish River near Goldbar	12134500	47.837	-121.667	78	415	18.2	535	3,450	7,740
South Fork Sultan River near Sultan	12137290	47.947	-121.627	14	6.34	18.4	11.7	3,260	3,730
Middle Fork Snoqualmie River near Tanner	12141300	47.486	-121.648	45	120	18.4	155	3,410	6,770
North Fork Snoqualmie River near Snoqualmie Falls	12142000	47.615	-121.713	65	39.8	17.5	63.9	3,050	4,740
South Fork Snoqualmie River above Alice Creek, near Garcia	12143400	47.415	-121.587	46	23.6	17.6	41.7	3,420	4,770

Table 2. Location, low-flow characteristics, and basin attributes for 43 index sites on streams in western Washington.—Continued

[Location of index sites are shown in figure 4. **$Q_{7,10}$:** The lowest average streamflow for a consecutive 7-day period that recurs on average once every 10 years. **Climatic year:** April 1–March 31. **Relief:** Defined as maximum minus minimum basin elevations. **Remarks:** D, minor diversion; I, minor irrigation; M, minor snowmelt; R, minor regulation (Sinclair and Pitz, 1999). **Abbreviations and symbols**: ft^3/s, cubic foot per second; mi^2, square mile; ft, foot; in., inch; τ, base-flow recession time constant]

Station name	Station No.	Latitude (decimal degrees)	Longitude (decimal degrees)	Number of climatic years of record (prior to October 1, 2007)	$Q_{7,10}$ (ft^3/s)	Mean τ (days)	Basin area (mi^2)	Mean basin elevation (ft)	Relief (ft)
Raging River near Fall City	12145500	47.540	-121.909	45	7.97	18.6	30.5	1,520	3,240
North Fork Tolt River near Carnation	12147500	47.712	-121.789	49	40.7	26.1	39.7	2,620	5,310
South Fork Tolt River near Index	12147600	47.707	-121.600	42	2.64	15.5	5.4	3,360	3,560
Pilchuck River near Snohomish	12155300	47.935	-122.073	13	42.1	20.3	129	870	5,240
North Fork Stillaguamish River near Arlington	12167000	48.261	-122.048	78	169	23.2	264	2,150	6,710
Newhalem Creek near Newhalem	12178100	48.656	-121.238	46	25.8	23.7	26.9	4,270	7,050
Bacon Creek below Oakes Creek, near Marblemount	12179900	48.605	-121.400	15	66.8	54.9	49.6	3,640	6,820
Sauk River above Whitechuck River, near Darrington	12186000	48.169	-121.471	81	136	19.3	154	3,860	6,870
Racehorse Creek at North Ford Road, near Kendall	12206900	48.885	-122.133	8	1.79	13.1	10.5	3,060	4,560
Warm Creek near Welcome	12207750	48.767	-121.965	8	2.58	16.7	4.3	4,270	4,040
Clearwater Creek near Welcome	12207850	48.788	-122.023	7	8.21	15.2	18.8	3,640	4,240
South Fork Nooksack River near Wickersham	12209000	48.664	-122.133	53	75.2	20.0	103	2,730	6,080
Skookum Creek above diversion, near Wickersham	12209490	48.672	-122.140	8	14.9	21.2	22.4	3,040	6,570

Table 2. Location, low-flow characteristics, and basin attributes for 43 index sites on streams in western Washington.—Continued

[Location of index sites are shown in figure 4. **$Q_{7,10}$:** The lowest average streamflow for a consecutive 7-day period that recurs on average once every 10 years. **Climatic year:** April 1–March 31. **Relief:** Defined as maximum minus minimum basin elevations. **Remarks:** D, minor diversion; I, minor irrigation; M, minor snowmelt; R, minor regulation (Sinclair and Pitz, 1999). **Abbreviations and symbols**: ft^3/s, cubic foot per second; mi^2, square mile; ft, foot; in., inch; τ, base-flow recession time constant]

Station name	Station No.	Basin elevation (ft)		Percentage of basin area covered by forest	Mean annual precipitation (in.)	Mean basin slope (percent)	Percentage of basin area with slope greater than 30 percent	Percentage of basin area with north-facing slope greater than 30 percent	Remarks
		Maximum	Minimum						
Naselle River near Naselle	12010000	2,690	46	66.2	110	33.5	55.5	12.4	
Willapa River near Willapa	12013500	2,830	0	63.5	85.5	25.4	33.0	9.6	D
Chehalis River near Doty	12020000	3,130	322	73.8	93.3	34.2	55.3	16.1	
Skookumchuck River near Vail	12025700	3,830	717	61.2	71.1	33.6	54.6	18.2	
Satsop River near Satsop	12035000	3,960	29	59.5	110	20.9	26.1	5.3	
Humptulips River near Humptulips	12039005	4,470	119	78.3	156	37.0	55.6	11.5	
Calawah River near Forks	12043000	3,770	200	87.0	110	44.9	79.5	22.3	
Hoko River near Sekiu	12043300	2,660	25	69.8	122	30.2	47.1	10.0	
Dungeness River near Sequim	12048000	7,770	579	62.7	64.1	53.8	86.3	22.8	M
Big Quilcene River below diversion, near Quilcene	12052210	7,660	1,030	72.0	66.0	62.8	95.0	24.0	D
Duckabush River near Brinnon	12054000	6,750	271	65.4	110	62.8	93.2	25.0	
North Fork Skokomish River below Staircase	12056500	6,390	760	71.9	163	61.6	93.2	25.0	
South Fork Skokomish River near Union	12060500	5,030	111	76.9	138	50.9	80.5	20.3	
Huge Creek near Wauna	12073500	530	91	65.0	53.6	3.5	0.0	0.0	
Deschutes near Rainier	12079000	3,870	368	64.4	61.4	25.6	37.5	14.1	D
Mineral Creek near Mineral	12083000	5,230	1,300	63.0	96.2	35.2	63.0	15.8	
Greenwater River at Greenwater	12097500	6,690	1,750	73.9	89.4	41.6	73.3	17.7	M
Boise Creek near Buckley	12099600	3,970	639	52.5	58.9	19.1	24.5	5.4	R
Newaukum Creek near Black Diamond	12108500	3,090	225	28.8	51.4	8.6	8.4	1.1	D, I
Cedar River below Bear Creek, near Cedar Falls	12114500	5,440	1,890	71.5	116	42.9	76.6	19.6	M
Cedar River near Cedar Falls	12115000	5,440	1,580	69.5	117	44.3	79.1	21.8	M
Rex River near Cedar Falls	12115500	4,740	1,710	69.0	115	36.1	60.6	14.0	
Taylor Creek near Selleck	12117000	4,100	947	86.2	90.6	29.7	48.6	9.8	
Issaquah Creek near Hobart	12120600	2,990	306	68.6	64.7	18.2	16.9	1.8	
Issaquah Creek near Issaquah	12121600	2,990	42	66.7	60.5	19.7	22.2	5.3	D, I
Skykomish River near Goldbar	12134500	7,950	212	67.2	127	55.3	85.5	21.4	D, M
South Fork Sultan River near Sultan	12137290	5,220	1,490	60.2	90.4	63.3	92.8	25.6	
Middle Fork Snoqualmie River near Tanner	12141300	7,550	778	65.6	133	60.1	86.6	23.2	M
North Fork Snoqualmie River near Snoqualmie Falls	12142000	5,890	1,140	69.1	122	51.9	80.7	23.2	
South Fork Snoqualmie River above Alice Creek, near Garcia	12143400	6,240	1,470	62.1	118	50.7	84.2	20.0	M

Table 2. Location, low-flow characteristics, and basin attributes for 43 index sites on streams in western Washington.—Continued

[Location of index sites are shown in figure 4. **$Q_{7,10}$:** The lowest average streamflow for a consecutive 7-day period that recurs on average once every 10 years. **Climatic year:** April 1–March 31. **Relief:** Defined as maximum minus minimum basin elevations. **Remarks:** D, minor diversion; I, minor irrigation; M, minor snowmelt; R, minor regulation (Sinclair and Pitz, 1999). **Abbreviations and symbols**: ft^3/s, cubic foot per second; mi^2, square mile; ft, foot; in., inch; τ, base-flow recession time constant]

Station name	Station No.	Basin elevation (ft)		Percentage of basin area covered by forest	Mean annual precipitation (in.)	Mean basin slope (percent)	Percentage of basin area with slope greater than 30 percent	Percentage of basin area with north-facing slope greater than 30 percent	Remarks
		Maximum	Minimum						
Raging River near Fall City	12145500	3,500	256	68.9	77.1	22.0	24.2	6.9	D, I
North Fork Tolt River near Carnation	12147500	5,970	665	66.2	96.7	63.7	63.7	13.5	
South Fork Tolt River near Index	12147600	5,420	1,860	71.5	128	61.6	90.7	29.4	
Pilchuck River near Snohomish	12155300	5,280	43	64.2	51.9	14.6	15.9	3.2	
North Fork Stillaguamish River near Arlington	12167000	6,820	105	76.1	83.1	37.7	58.2	16.2	D
Newhalem Creek near Newhalem	12178100	8,110	1,060	60.4	118	66.5	96.1	22.0	M
Bacon Creek below Oakes Creek, near Marblemount	12179900	7,250	434	53.1	112	64.8	91.7	14.9	M
Sauk River above Whitechuck River, near Darrington	12186000	7,800	926	67.6	143	61.0	89.9	21.8	M
Racehorse Creek at North Fork Road, near Kendall	12206900	4,970	420	81.8	89.5	49.3	89.5	34.5	
Warm Creek near Welcome	12207750	6,760	2,720	73.0	115	51.5	85.5	22.0	
Clearwater Creek near Welcome	12207850	5,900	1,660	78.3	113	47.0	83.5	20.6	
South Fork Nooksack River near Wickersham	12209000	6,460	382	71.1	91.4	39.8	69.9	18.5	M
Skookum Creek above diversion, near Wickersham	12209490	6,990	421	67.7	94.1	42.9	75.0	16.6	

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), rather than a water year (October 1–September 30), to ensure the continuity of data during typical low-flow periods (which commonly occur in late summer). 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, in which the mean, variance, and skew of the distribution are computed from the annual series (fig. 2). 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 quantifying the percentage of flows that exceed specific low flows of interest (Searcy, 1959).

Values of $Q_{7,10}$ for this study were initially computed using software developed by the USGS (Ken Eng, U.S. Geological Survey, written commun., 2007) that incorporates a conditional probability adjustment to account for streamflow records that may contain zero-flow events. Results of analyses made with 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 (2011; BASINS 4.0) that retrieves USGS streamflow data from the National Water Information System (U.S. Geological Survey, 2011a) and performs the necessary computations.

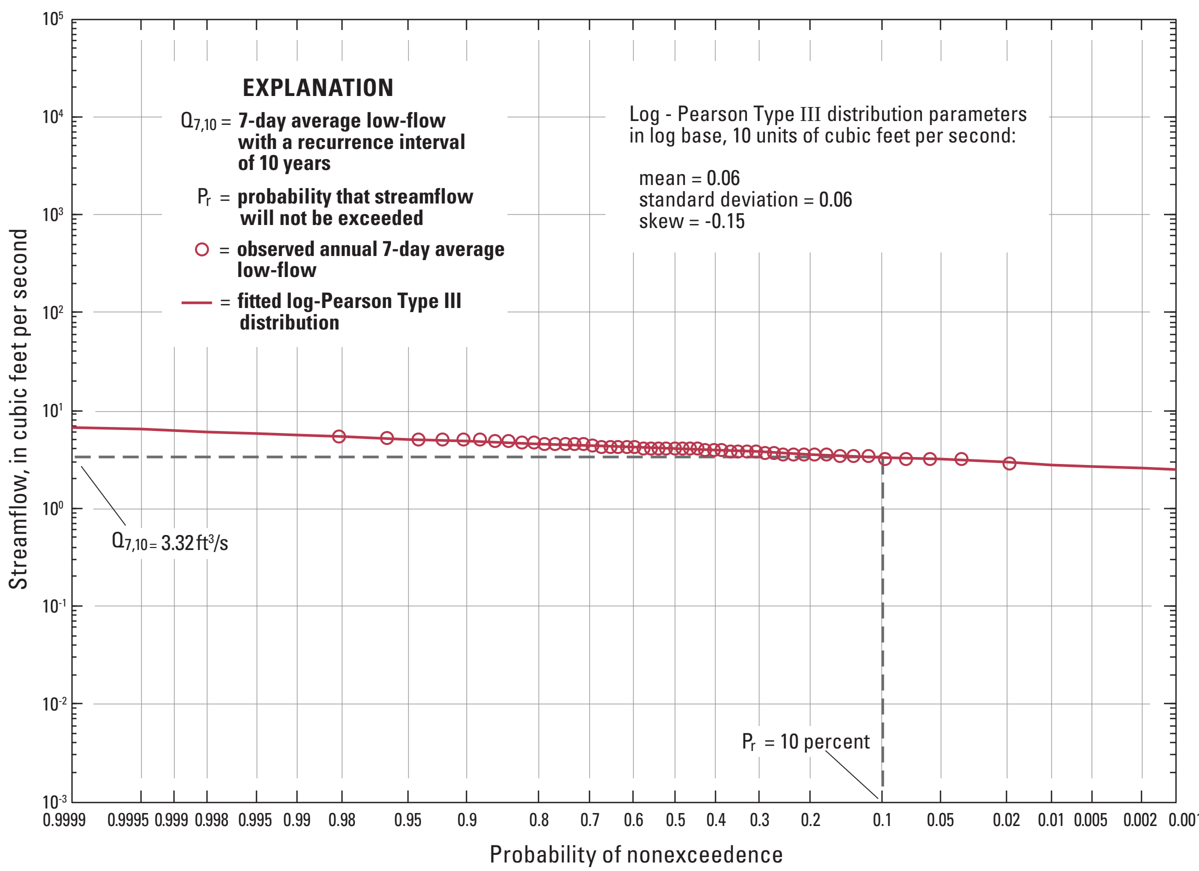


Figure 2. Example of the annual series of 7-day low flows fitted to the log-Pearson type III distribution for the calculation of $Q_{7,10}$, computed from the streamflow record at the streamflow-gaging station Huge Creek near Wauna, Washington (U.S. Geological Survey station No. 12073500), 1947–69 and 1977–2007.

Base-Flow Recession Time Constant, or Tau (τ)

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 streamflow on groundwater inflow to the channel. Streams that are supported by relatively large inflows of groundwater generally will have slower rates of base-flow recession than streams that are hydraulically 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 (τ), and expressed as:

$$\tau = \Delta t / ln\left(Q_0 / Q_t\right), \quad (1)$$

where τ is the base-flow recession time constant (in days), Δt 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 period of continuously decreasing streamflow (Eng and Milly, 2007). Thus, the value of τ can be readily estimated 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 τ 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 rapid (τ is small) in small basins with steep hillslopes, shallow soils, high drainage density, and aquifers with low transmissivity. Streamflow in such basins is sensitive to precipitation events; therefore, low-flow measurements should be made during periods without precipitation or snowmelt to ensure accurate estimates of low-flow characteristics. In contrast, the rate of base-flow recession can be expected to be slow (τ is large) in large, gently sloping 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 the Satsop River, respectively (fig. 3). Eng and Milly (2007) introduced τ as a potential explanatory variable for regional low-flow regression models, and Funkhouser and others (2008) used kriging methods to regionalize τ for interpolation at ungaged sites.

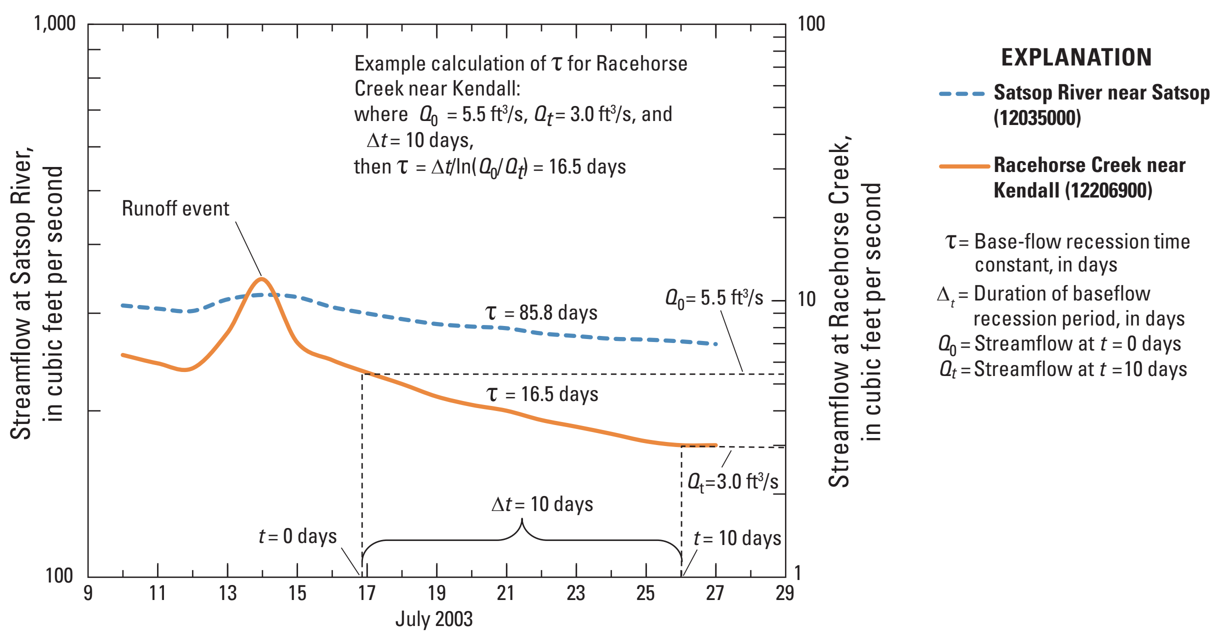


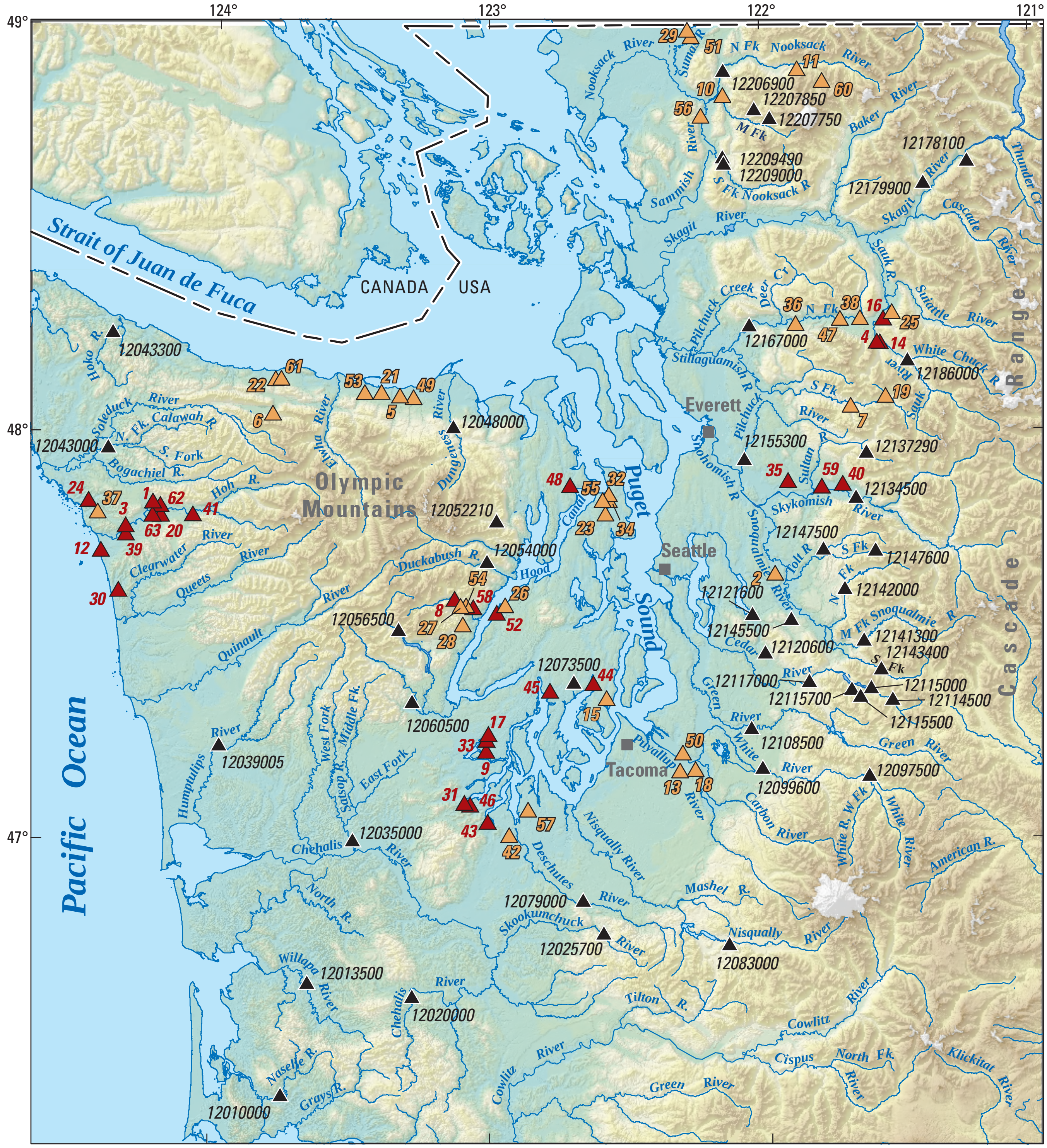
Figure 3. Base-flow hydrographs and corresponding values of τ calculated from a single period of base-flow recession at two U.S. Geological Survey streamflow-gaging stations in western Washington, Satsop River near Satsop, 12035000 (large τ) and Racehorse Creek near Kendall, 12206900 (small τ).

Low-Flow Surveys

Technical staff from the Port Gamble S'Klallam, Hoh, Squaxin Island, Tulalip, Sauk-Suiattle, Nooksack, Puyallup, and Stillaguamish tribes and the PNPTC coordinated with the NWIFC and USGS to conduct low-flow measurements in streams across western Washington during the late summer and early autumn in 2007, 2008, and 2009. The measurement sites were selected by tribal and agency staff on the basis of several criteria, including the importance of the resource, accessibility, whether a site had been monitored for other purposes (for example, assessment of 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 stream gage, sites influenced by meltwater from snowfields or glaciers, and sites at which the stream was likely to go dry for extended periods during the low-flow season ($Q_{7,10}$ = 0 ft^3/s) were avoided. Although most watersheds in the study area have been affected to some extent by land-use changes (deforestation, urban development), land use does not appear to have a significant effect on dry-season base flow in either urban streams of western Washington (Konrad and Booth, 2005) or forested coastal watersheds in the northwest (Harris, 1977). The sites at which flow was measured during the 2007–09 low-flow surveys have basin areas ranging from 0.06 to 48.9 mi^2 (fig. 4).

The overall strategy for the low-flow surveys was to make repeated measurements of flow 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 individual measurements made 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 analyses. The USGS conducted training prior to the surveys to ensure that hydrologic technicians were familiar with standard techniques for streamflow measurement (Rantz, 1982).

The measurements were made by technical staff from NWIFC-member tribes, the PNPTC, and NWIFC from late July through September in 2007, 2008, and 2009, and by USGS personnel in 2007 (fig. 5). Measurements were made at least 3 days after measurable rainfall that caused an increase in runoff. When possible, pairs of measurements separated by at least 7 days were made during a period of continuous base-flow recession to allow calculation of τ (eq. 1). Documentation of measurements included a listing of the meter type and an assessment of measurement quality. At about one-third of the sites, initial measurements were repeated for verification of results and consistency in measurement procedures.



Base from U.S. Geological Survey digital data, 1983, 1:100,000
Universal Transverse Mercator projection, Zone 10
Horizontal Datum: North American Datum of 1983 (NAD 83)

0 10 20 30 40 50 MILES
0 10 20 30 40 50 KILOMETERS

EXPLANATION

12035000 ▲ Index site with USGS gaging station No. defined in table 2

43 ▲ Partial-record site with stream No. defined in table 7

42 ▲ Miscellaneous site with stream No. defined in table 7

Figure 4. Locations of 63 partial-record and miscellaneous sites at which low-flow measurements were made by the Northwest Indian Fisheries Commission (NWIFC), NWIFC-member tribes, Point-No-Point Treaty Council, and the U.S. Geological Survey (USGS) from 2007 to 2009, and 43 USGS continuous streamflow-gaging stations (index sites) in western Washington.

Figure 5. 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 Streamflow-Measurement Sites

Low-flow characteristics such as the $Q_{7,10}$ at partial-record sites are commonly estimated by 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 Method

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). This method may be appropriate when there is a non-linear relation between base-flow measurements at the partial record site and concurrent daily mean flows at the index site (U.S. Geological Survey, 1985). Riggs (1972) recommended that the graphical method be used with at least 8 to 10 base-flow measurements made on different recessions during 2 or more years. To use the method, concurrent observations of base flow are plotted, and a best-fit line is drawn through the observations and extended as needed to estimate the low-flow statistic of interest at the partial-record site (fig. 6). When drawing the best-fit line, more weight should be given to lower base-flow observations (U.S. Geological Survey, 1985).

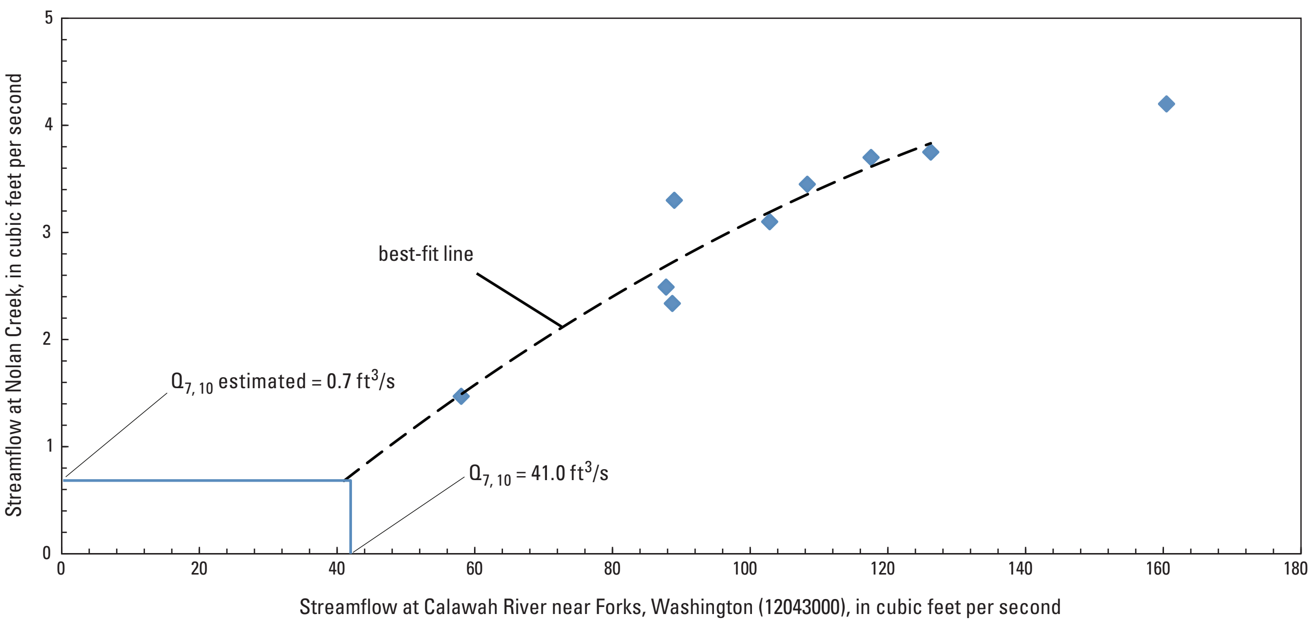


Figure 6. Example of graphical method used to estimate low-flow characteristics at a partial-record site (Nolan Creek, Jefferson County, Washington) from concurrent base flows at an index site (U.S. Geological Survey gaging station No.12043000, Calawah River near Forks, Washington) where the base-flow relation is non-linear.

Q-ratio Method

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 small (fewer than eight measurements). 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 multiplied by 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:

$$Q_p = Z(Q_i), \tag{2}$$

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_i is the low-flow statistic at the index site (in volume per time). The average flow ratio, Z, is calculated as

$$Z = \frac{1}{N}\sum_{k=1}^{N}\left(\frac{Q_{p,k}}{Q_{i,k}}\right), \tag{3}$$

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 to 2008 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 on the basis of basin similarity (in terms of basin area, mean annual precipitation, τ, and geographic proximity). Using equation 3, Z is calculated as the average ratio of the concurrent flow pairs (Z=2.99). Then using equation 2, the value of the $Q_{7,10}$ for Cabin Creek (9.93 ft^3/s) is estimated by multiplying the $Q_{7,10}$ for Huge Creek (3.32 ft^3/s) by Z.

Table 3. Example of the use of the Q-ratio method to estimate low-flow characteristics at a partial-record site (Cabin Creek, Jefferson County, Washington) on the basis of concurrent low-flow characteristics at an index site (U.S. Geological Survey gaging station No. 12073500, Huge Creek near Wauna, Washington).

[**$Q_{p,k}$**: The k^{th} streamflow measured at the partial-record site. **$Q_{i,k}$**: The k^{th} concurrent streamflow recorded at the index site. **Q-ratio**: The flow ratio equal to $Q_{p,k}/Q_{i,k}$. **Z**: The average ratio of concurrent flow pairs. **Q_i**: The value of the low-flow statistic ($Q_{7,10}$) at the index site. **Q_p**: The estimated value of the low-flow statistic ($Q_{7,10}$) at the partial-record site. **Abbreviations:** ft^3/s, cubic foot per second; –, does not apply]

Date	$Q_{p,k}$ (ft^3/s)	$Q_{i,k}$ (ft^3/s)	Q-ratio	Z	Q_i (ft^3/s)	Q_p (ft^3/s)
2007						
09-07	13.3	4.46	2.98	–	–	–
09-20	12.0	4.29	2.80	–	–	–
2008						
09-11	12.2	3.86	3.16	–	–	–
09-16	12.2	4.03	3.03	–	–	–
2007–08						
–	–	–	–	2.99	–	–
Period of record of index site						
–	–	–	–	–	3.32	9.93

MOVE.1 Method

The Maintenance of Variance Extension, Type 1 (MOVE.1) method (Hirsch, 1982) is commonly used for extending the length or filling missing periods of the flow record at a continuously recording streamflow-gaging station. However, the method also can 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 flow that is less biased. This method is recommended when eight or more base-flow measurements are available for a partial-record site and requires concurrent flows from a hydrologically similar index site. The MOVE.1 method follows the equation:

$$\hat{Y} = \overline{Y} + \frac{s_y}{s_x}\left(\hat{X} - \overline{X}\right), \tag{4}$$

where $\hat{Y}$ is the estimated low-flow statistic (transformed to log units) at the partial-record site, $\overline{Y}$ 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 $\overline{X}$ is the average of concurrent flows (log units) at the index site. Measurements of zero flow cannot be used as log transformations are required in this method.

As an example, MOVE.1 was used to estimate the $Q_{7,10}$ for a partial-record site on Winfield Creek in the Hoh River basin of Jefferson County, Washington. Ten low-flow measurements were made at this site from 2007 to 2009 (table 4) and are listed with concurrent flows at USGS streamflow-gaging station Calawah River (12043000), 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 Winfield Creek and Calawah River as 0.830 ($\bar{Y}$) and 2.02 ($\bar{X}$), respectively. Similarly, the standard deviations are calculated from the log-transformed streamflow values at each site as 0.129 (s_y) and 0.161 (s_x). The log-transformed $Q_{7,10}$ for the Calawah River ($\hat{X}$) is 1.61 ($Q_{7,10}$ is 41.0 ft^3/s) and, applying equation 4, the log-transformed $Q_{7,10}$ for Winfield Creek ($\hat{Y}$) is 0.502 ($Q_{7,10}$ is 3.18 ft^3/s).

Table 4. Example of the use of the MOVE.1 method to estimate the $Q_{7,10}$ at a partial-record site (Winfield Creek, Jefferson County, Washington) from concurrent low flows at an index site (U.S. Geological Survey gaging station No. 12043000, Calawah River near Forks, Washington).

[$\boldsymbol{Y_k}$: The k^{th} streamflow measured at the partial record site. $\boldsymbol{X_k}$: The k^{th} concurrent streamflow measured at the index site. $\boldsymbol{s_Y}$ and $\boldsymbol{s_X}$: The standard deviations of log-transformed flows at the partial-record site and index-site, respectively. $\boldsymbol{\bar{Y}}$ and $\boldsymbol{\bar{X}}$: The average of the log-transformed flows at the partial-record site and index site, respectively. $\boldsymbol{Q_i}$: The $Q_{7,10}$ at the index site. $\boldsymbol{\hat{X}}$: The log-transformed value of the $Q_{7,10}$ at the index site. $\boldsymbol{\hat{Y}}$: The log-transformed estimate of the $Q_{7,10}$ at the partial-record site; $\boldsymbol{Q_p}$: The estimate of $Q_{7,10}$ at the partial-record site. **Abbreviations:** ft^3/s, cubic foot per second; –, does not apply]

Date	Y_k (ft^3/s)	X_k (ft^3/s)	$\log_{10}Y_k$	$\log_{10}X_k$	s_Y	s_X	$\bar{Y}$	$\bar{X}$	Q_i (ft^3/s)	$\hat{X}$	$\hat{Y}$	Q_p (ft^3/s)
2007												
08-15	8.94	163	0.951	2.21	–	–	–	–	–	–	–	–
09-07	7.37	126	0.867	2.10	–	–	–	–	–	–	–	–
09-19	5.23	93.2	0.719	1.97	–	–	–	–	–	–	–	–
2008												
07-11	8.16	140	0.912	2.15	–	–	–	–	–	–	–	–
07-23	6.25	95.3	0.796	1.98	–	–	–	–	–	–	–	–
08-07	6.39	85.2	0.806	1.93	–	–	–	–	–	–	–	–
09-08	11.4	175	1.06	2.24	–	–	–	–	–	–	–	–
09-17	7.22	114	0.859	2.06	–	–	–	–	–	–	–	–
2009												
07-21	5.17	73.3	0.713	1.87	–	–	–	–	–	–	–	–
08-03	4.15	52.1	0.618	1.72	–	–	–	–	–	–	–	–
2007–09												
–	–	–	–	–	0.129	0.161	0.830	2.02	–	–	–	–
Period of record of index site												
–	–	–	–	–	–	–	–	–	41.0	1.61	0.502	3.18

Base-Flow Correlation Method

The Base-Flow Correlation method (Stedinger and Thomas, 1985) was developed as an un-biased 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 consecutive 7-day low flow, or Q_7) at 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). An estimate of the Q_7 with a recurrence interval of 10 years ($\hat{Q}_{7,10}$) is calculated for a partial-record site using the Base-Flow Correlation method

$$log_{10}\left(\hat{Q}_{7,10}\right) = \hat{\mu}_p + K_p\hat{\sigma}_p, \quad (5)$$

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 10 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 β_1 (slope) and β_0 (intercept). These coefficients are further used to estimate $\hat{\mu}_p$ and $\hat{\sigma}_p$ as follows:

$$\hat{\mu}_p = \beta_0 + \beta_1 m_i \quad (6)$$

and

$$\hat{\sigma}_p = \sqrt{\beta_1^2 s_i^2 + s_e^2\left[1 - \frac{s_i^2}{(n-1)s_c^2}\right]}, \quad (7)$$

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 concurrent base-flow measurement pairs, 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.

The standard deviate for the partial-record site, K_p, is assumed equal to the standard deviate for the index site, K_i, and, if not already known, is calculated as

$$K_i = \frac{log_{10}\left(Q_{7,10}\right) - m_i}{s_i}, \quad (8)$$

where $Q_{7,10}$ is known at the index site, m_i is described previously, and s_i is the standard deviation of the Q_7 time series at the index site.

As an example, the Base-Flow Correlation Method was used to estimate the $Q_{7,10}$ for a partial-record site on Dan Creek in Snohomish County, Washington, where 10 low-flow measurements were made from 2007 to 2009; data and derived coefficients are shown in table 5. Concurrent, daily mean flows were obtained from an index site with similar basin attributes, in this case, South Fork Sultan River near Sultan, Washington (USGS gaging station No. 12137290). A least-squares regression equation was developed with the log-transformed, concurrent flows at the partial-record and index sites, and the intercept and slope of the regression were computed. The time series of annual 7-day low flows (Q_7) was determined at the index site for the period of record, the values were log-transformed, and the mean was calculated. 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, and the estimated $Q_{7,10}$ for the partial-record site Dan Creek is calculated as 1.80 ft^3/s.

Table 5. Example of the Base-Flow 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 (U.S. Geological Survey gaging station No. 12137290, South Fork Sultan River near Sultan, Washington).

[Y_k: The k^{th} streamflow measured at the partial-record site. X_k: The k^{th} concurrent streamflow measured at the index site. Q_7: The annual minimum average low-flow for seven consecutive days at the index site; β_0 and β_1: The regression coefficients for intercept and slope, respectively. m_i: The mean of the annual Q_7 in log units. μ_p: The estimated mean of the annual Q_7 at the partial-record site. s_i^2: The variance of the Q_7 time series. s_e^2: The square of the standard error of regression among log-transformed concurrent flows at the partial-record and index sites. n_b: The number of base-flow measurements at the partial-record site. s_c^2: The variance of the concurrent flows at the index site. σ_p: The estimated standard deviation of the Q_7 time series at the partial-record site. Q_i: The $Q_{7,10}$ at the index site. K_p, log-Pearson Type III standard deviate for a recurrence interval of 10 years. Q_p: The estimate of $Q_{7,10}$ at the partial-record site. **Abbreviation:** ft^3/s, cubic foot per second]

Date	Y_k (ft^3/s)	X_k (ft^3/s)	$\log_{10}Y_k$	$\log_{10}X_k$	Year	Q_7 (ft^3/s)	$\log_{10}Q_7$	β_0	β_1	m_i	μ_p	s_i^2	s_e^2	n_b	s_c^2	σ_p	Q_i (ft^3/s)	$\log_{10}Q_i$	K_p	Q_p (ft^3/s)	$\log_{10}Q_p$
08-29-07	4.28	27.2	0.631	1.43																	
08-05-08	8.52	64.6	0.930	1.81																	
08-15-08	5.20	43.4	0.716	1.64																	
09-08-08	6.45	34.7	0.810	1.54																	
09-16-08	4.48	24.3	0.651	1.39																	
07-15-09	10.1	37.3	1.00	1.57																	
07-23-09	5.59	26.6	0.747	1.43																	
07-29-09	4.43	23.0	0.646	1.36																	
08-17-09	5.36	21.8	0.729	1.34																	
09-21-09	3.90	25.5	0.591	1.41																	
					1992	6.97	0.843														
					1993	7.47	0.873														
					1994	9.41	0.974														
					1995	9.13	0.960														
					1996	11.0	1.04														
					1997	11.6	1.06														
					1998	6.21	0.793														
					1999	13.0	1.11														
					2000	16.0	1.20														
					2001	12.6	1.10														
					2002	12.0	1.08														
					2003	5.10	0.708														
					2004	10.6	1.02														
					2005	10.0	1.00														
								-0.181	0.622	0.984	0.430	0.019	0.011	10	0.022	0.130	6.34	0.802	-1.33	1.80	0.255

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 data 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. 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 is 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) is repeated 500 times, and with each iteration an estimate of $Q_{7,10}$ is generated for each index site using the three correlation methods. Residual error is then determined for each correlation method by comparing the estimated $Q_{7,10}$ with the value determined from the streamflow record. The average error and bias associated with estimating the $Q_{7,10}$ at each synthetic partial-record site are computed for each correlation method under scenarios that differ in the number of observations and the combination of basin attributes used to select an index site.

In addition to evaluating correlation methods to estimate $Q_{7,10}$ values, the MATLAB program also calculated the base-flow recession time constant, τ, at each index site (Eng and Milly, 2007). The calculation of τ 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 τ. Because the value of τ is based on only a few observations, a more robust estimate, τ_{ideal}, was calculated for each index site based on 500 observation pairs from randomly selected recession segments. The values of τ calculated from 2 to 10 observation pairs for each index site were compared with τ_{ideal} to determine the optimum number of streamflow measurements required to reliably estimate τ at partial-record sites.

Basin-Attribute Selection

Fifteen 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. Basin attributes were selected to represent physical and climatic parameters in the region that might explain observed variations in base flow. Basin attributes are shown in table 6. The USGS Washington StreamStats program (U.S. Geological Survey, 2010) was used to delineate basin areas and determine 10 of the 15 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 (τ) was determined from the empirical Monte Carlo program, as previously described. Variables were screened for multi-collinearity, and where strong correlations were found between variables (for example, mean annual precipitation and mean basin elevation), only one variable was retained for further analysis. The five variables considered in the final empirical Monte Carlo analysis were: basin area (A), mean annual precipitation (P), geographic proximity (G), percentage of basin area covered with surficial geology classified as 'coarse-grained unconsolidated sediments' (S), and τ.

Index-Site Selection

An index site that would be used for correlating with each synthetic partial-record site was selected within the empirical Monte Carlo analysis on the basis of basin similarity. To quantify basin similarity, the Euclidean distance (measured in basin-attribute values) was calculated between the synthetic partial-record site and all index sites considered in the analysis. The index site with the minimum Euclidean distance relative to the synthetic partial-record site was considered closest in basin similarity and thus selected for use in further analysis.

The Euclidean distance was calculated as:

$$R_{ij} = \sum_{k=1}^{N}\left(\frac{\left(\log X_{1,i} - \log X_{1,j}\right)^2}{\sigma_k^2\left(\log X_1\right)} + \quad \ldots + \frac{\left(\log X_{k,i} - \log X_{k,j}\right)^2}{\sigma_k^2\left(\log X_k\right)}\right), \quad (9)$$

where R_{ij} is the Euclidean distance (dimensionless), i is the partial-record site, j is the index-site, N is the number of basin attributes, $X_{k,i}$ is the value of the k^{th} basin attribute for the partial-record site, $X_{k,j}$ is the value of the k^{th} basin attribute for the index site, and σ_k^2 is the variance of the log-transformed values of the k^{th} basin attribute for all potential index sites considered (Eng and others, 2009).

Table 6. Basin attributes and data sources used for index-site selection in the empirical Monte Carlo analysis and for developing preliminary regional low-flow regressions for western Washington.

[**Data source:** 1, U.S. Geological Survey, Washington StreamStats; 2, U.S. Weather Bureau, 1965; 3, Vaccaro and others, 1998; 4, National Elevation Dataset (NED) http://seamless.usgs.gov/ned1.php; 5, This report. **Abbreviation:** NAD 83, North American Datum of 1983]

Basin attribute	Description	Data source
Latitude	Latitude/Longitude, NAD 83	1
Basin area	Drainage area, in square miles	1
Precipitation	Mean annual precipitation (1930–57), in inches	1, 2
Relief	Relief (maximum minus minimum basin elevation), in feet	1, 4
Elevation	Mean basin elevation, in feet	1, 4
Elevation, maximum	Maximum basin elevation, in feet	1, 4
Elevation, minimum	Minimum basin elevation, in feet	1, 4
Slope	Mean basin slope, in percent	1, 4
Slope, greater than 30 percent	Percentage of basin area with slope greater than 30 percent	1, 4
Slope, greater than 30 percent facing north	Percentage of basin area with slope greater than 30 percent and facing north	1, 4
Bedrock	Percentage of basin area with surficial geology classified as bedrock	3
Fine grain	Percentage of basin area with surficial geology classified as fine-grained unconsolidated sediments	3
Coarse grain	Percentage of basin area with surficial geology classified as coarse-grained unconsolidated sediments	3
Alluvial	Percentage of basin area with surficial geology classified as alluvial sediments	3
Tau (τ)	Base-flow recession time constant, in days	5

Results of Analysis of Low Flow in Western Washington Streams

In western Washington, the mean monthly 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 base-flow recession associated with decreasing aquifer discharge to the stream in the late spring and early summer. Annual minimum streamflows are relatively stable from year to year, and range from about 70 to 130 percent of the median value at most gaging stations. On a unit-area basis, annual minimum streamflow ranges from 0.2 to 2 (ft^3/s)/mi^2 for the period of record at index sites, with a median of about 0.7 (ft^3/s)/mi^2. 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 $Q_{7,10}$.

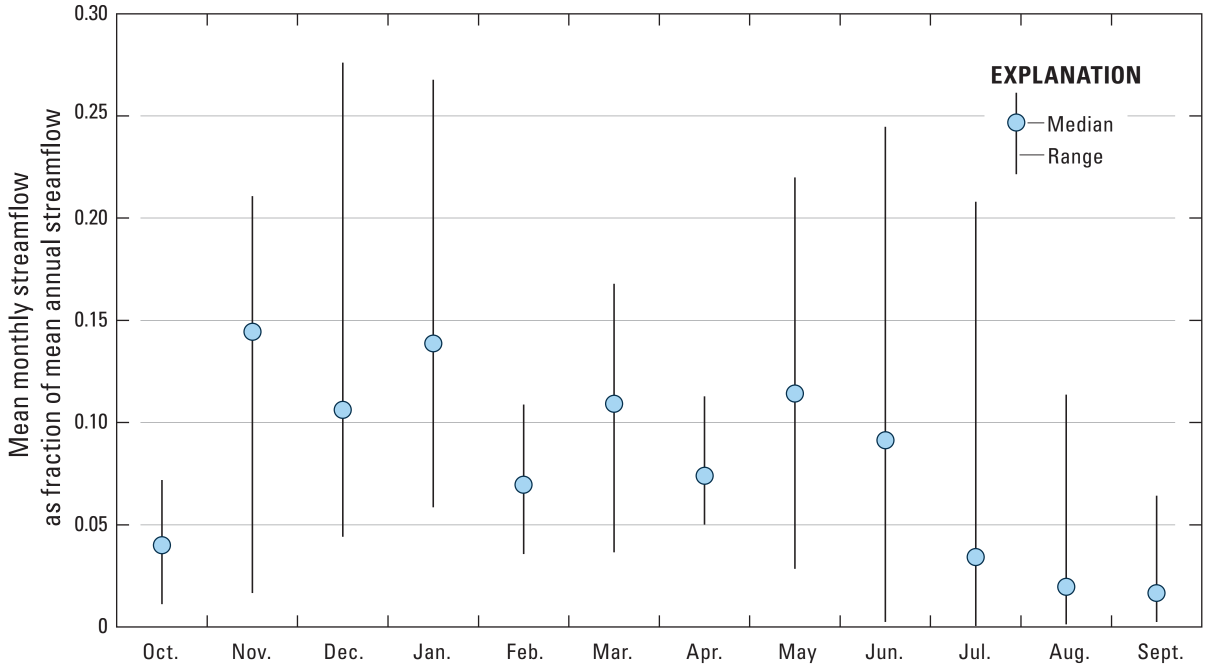


Figure 7. Range of mean monthly streamflow as a fraction of mean annual streamflow for the period of record at 43 index sites in western Washington.

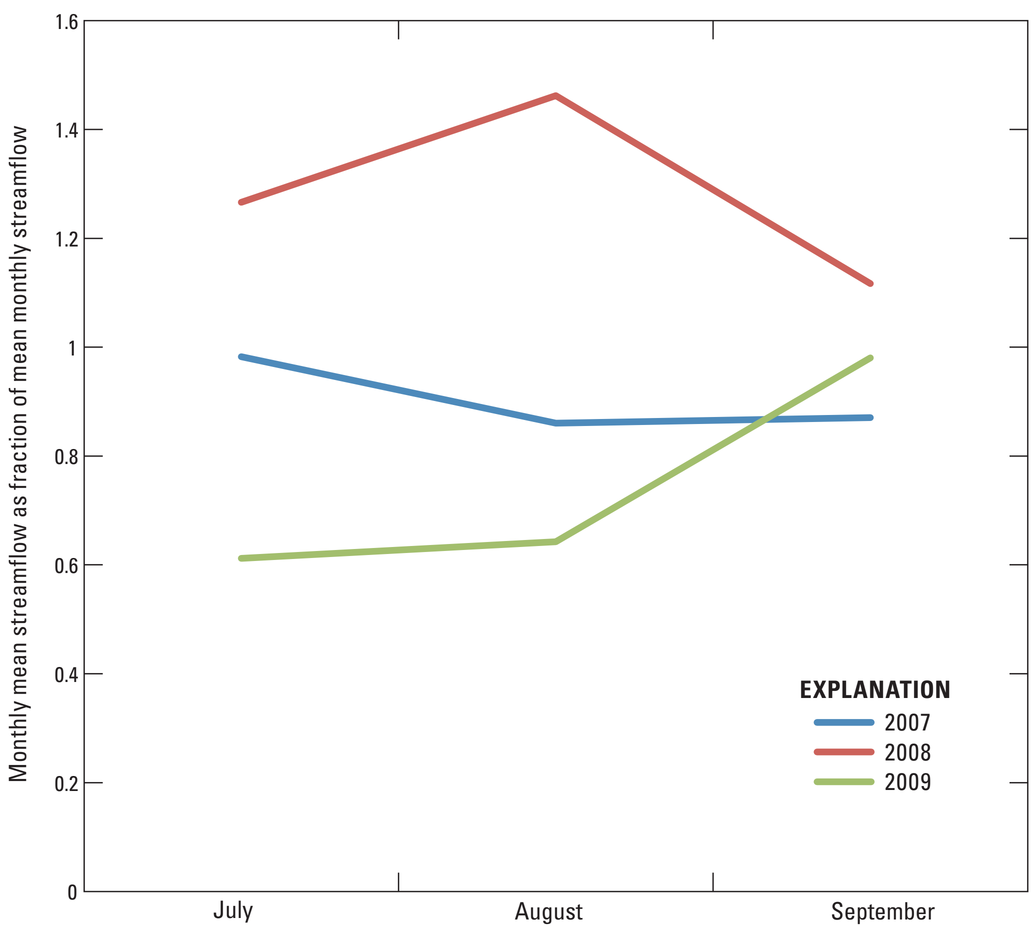


Figure 8. Monthly mean streamflow during July–September in 2007–09 as a fraction of mean monthly streamflow for the period of record at 43 index sites in western Washington.

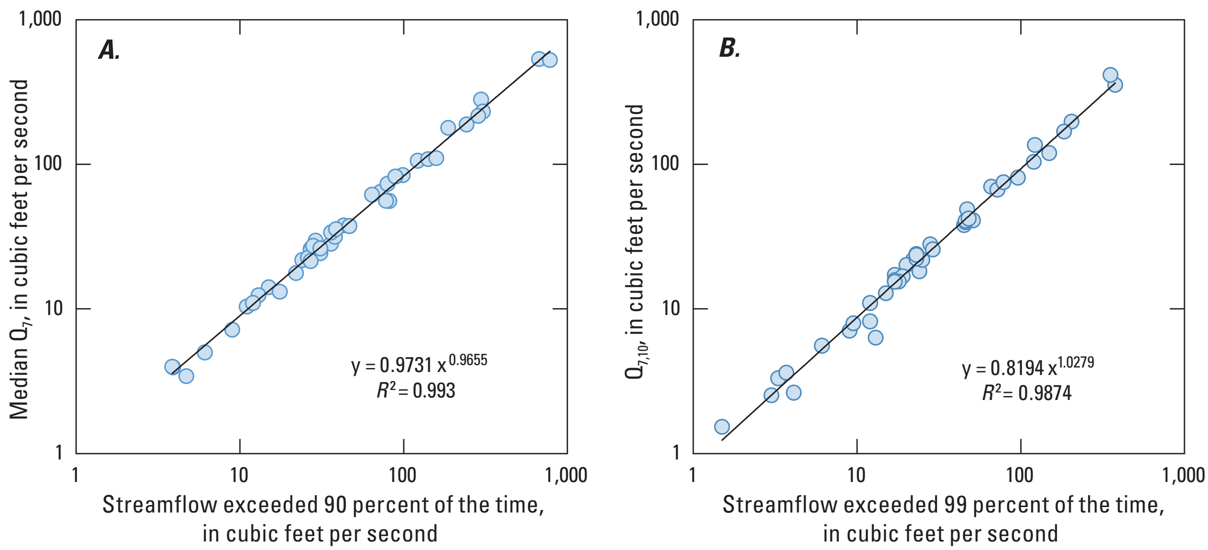


Figure 9. Streamflows at 43 index sites (*A*) median 7-day low flow (Q_7) versus streamflow exceeded 90 percent of the time, and (*B*) lowest average 7-day low flow that recurs on average every 10 years ($Q_{7,10}$) versus streamflow exceeded 99 percent of the time.

Low-Flow Surveys in 2007, 2008, and 2009

Flow was measured at 63 stream sites on 66 days in 2007, 2008, and 2009. Of the 283 measurements made, 42 were duplicate verification measurements. The number of measurements made at each stream ranged from 1 to 10. Pairs of measurements were made at 25 sites during the same base-flow recession period for estimating τ. Because rainfall varies across the region and is often of only local extent during summer, measurements were made on different days at different sites. The median unit-area flow of all measurements was 0.5 $(ft^3/s)/mi^2$, with a range from 0.06 to 16 $(ft^3/s)/mi^2$. The $Q_{7,10}$ was estimated using the Q-ratio method for miscellaneous sites and for partial-record sites with fewer than eight measurements. The MOVE.1 method was used for partial-record sites if eight or more measurements were made and concurrent flow pairs were reasonably well correlated (Pearson's r greater than or equal to 0.65); otherwise, the Q-ratio method was used. Index sites were selected on the basis of basin similarity, using the variables basin area (A), geographic proximity (G), mean annual precipitation (P), and τ (if known), and the minimum Euclidean distance determined from equation 9. All partial-record and miscellaneous sites where flow was measured during the low-flow surveys are listed in table 7, and the measurements and ancillary information are tabulated in appendix A. Basin attributes were determined for all partial-record and miscellaneous sites using the Washington StreamStats program (U.S. Geological Survey, 2010) and are listed in table 8.

The basin attributes for the partial-record and miscellaneous sites established during the low-flow surveys are not well represented in the existing streamflow-gaging-station network in western Washington. These sites are generally in smaller drainage areas (than sites in the existing network) that generate less runoff and have correspondingly lower values of $Q_{7,10}$ (fig. 10). The incorporation of these sites into the existing streamflow-gaging network will enable development of regional regression models that more accurately estimate low-flow characteristics at these types of ungaged stream sites.

Table 7. Location, number of measurements, and estimates of τ and $Q_{7,10}$ at partial-record and miscellaneous sites established by the Northwest Indian Fisheries Commission (NWIFC), NWIFC-member tribes, Point-No-Point Treaty Council, and U.S. Geological Survey as part of the low-flow surveys conducted in western Washington during 2007–09.

[Locations of sites are shown in figure 4. Shaded sites are miscellaneous sites and either had fewer than four measurements, or all measurements were made in the same year. **τ**: The base-flow recession time constant. **Correlation method used:** Q-ratio, a correlation method described by Potter (2001); MOVE.1, Maintenance of Variance Extension, Version 1, a correlation method described by Hirsch (1982). **$Q_{7,10}$**: The lowest average streamflow for a consecutive 7-day period that recurs on average once every 10 years. **r:** Pearson's correlation coefficient. **Abbreviations:** USGS, U.S. Geological Survey; ft^3/s, cubic foot per second; –, no data; na, does not apply]

Stream No.	Stream name	Latitude (decimal degrees)	Longitude (decimal degrees)	Number of low-flow measurements, 2007–09	Number of low-flow measurements made in each year			Number of measurement pairs used for estimating τ	Mean τ (days)	USGS station No. of index site used for correlating concurrent flows	Correlation method used	$Q_{7,10}$ (ft^3/s)	r
					2007	2008	2009						
1	Alder Creek	47.830	-124.226	8	3	3	2	3	19	12043300	Q-ratio	0.42	0.61
2	Ames Creek	47.661	-121.967	3	1	2	0	0	–	12120600	Q-ratio	1.08	na
3	Anderson Creek	47.772	-124.323	7	3	2	2	3	38	12043000	Q-ratio	0.67	na
4	Backman Creek	48.221	-121.579	9	0	4	5	3	38	12099600	MOVE.1	0.33	0.94
5	Bagley Creek	48.098	-123.330	1	1	0	0	0	–	12048000	Q-ratio	0.50	na
6	Barnes Creek	48.055	-123.794	2	1	1	0	0	–	12043300	Q-ratio	3.64	na
7	Boardman Creek	48.069	-121.681	1	1	0	0	0	–	12137290	Q-ratio	1.41	na
8	Cabin Creek	47.595	-123.128	4	2	2	0	1	126	12073500	Q-ratio	9.93	na
9	Campbell Creek	47.223	-123.013	6	2	2	2	2	60	12073500	Q-ratio	1.24	na
10	Canyon Creek	48.833	-122.137	1	1	0	0	0	–	12209490	Q-ratio	1.52	na
11	Cascade Creek	48.896	-121.859	2	1	1	0	0	–	12207750	Q-ratio	0.23	na
12	Cedar Creek	47.710	-124.412	8	3	3	2	3	42	12043000	Q-ratio	1.71	na
13	Clarks Creek	47.177	-122.317	1	1	0	0	0	–	12108500	Q-ratio	6.49	na
14	Clear Creek	48.219	-121.569	8	0	4	4	3	23	12137290	Q-ratio	9.61	na
15	Crescent Creek	47.356	-122.579	1	1	0	0	0	–	12073500	Q-ratio	1.56	na
16	Dan Creek	48.277	-121.556	10	1	4	5	3	20	12137290	MOVE.1	1.33	0.65
17	Deer Creek (Puget Sound)	47.265	-123.005	6	2	2	2	2	98	12073500	Q-ratio	15.3	na
18	Deer Creek (Puyallup River basin)	47.181	-122.262	2	0	2	0	0	–	12073500	Q-ratio	0.16	na
19	Deer Creek (Stillaguamish River basin)	48.091	-121.554	1	1	0	0	0	–	12137290	Q-ratio	1.29	na
20	Elk Creek	47.798	-124.197	8	3	3	2	3	73	12043000	MOVE.1	1.50	0.97
21	Ennis Creek	48.108	-123.398	1	1	0	0	0	–	12048000	Q-ratio	1.93	na
22	Field Creek	48.140	-123.785	1	0	1	0	0	–	12043300	Q-ratio	0.39	na
23	Gamble Creek	47.809	-122.581	5	0	0	5	0	–	12073500	Q-ratio	1.39	na
24	Goodman Creek	47.833	-124.461	7	3	2	2	2	43	12043000	Q-ratio	3.41	na
25	Gravel Creek	48.297	-121.525	1	1	0	0	0	–	12137290	Q-ratio	0.07	na
26	Harding Creek	47.585	-122.945	4	0	0	4	0	–	12073500	Q-ratio	3.13	na
27	Jefferson Creek	47.583	-123.107	2	2	0	0	0	–	12054000	Q-ratio	9.20	na
28	John Creek	47.539	-123.098	2	2	0	0	0	–	12073500	Q-ratio	0.09	na
29	Johnson Creek	48.993	-122.267	1	1	0	0	0	–	12209490	Q-ratio	5.97	na
30	Kalaloch Creek	47.614	-124.348	5	2	1	2	1	40	12043000	Q-ratio	3.75	na
31	Kennedy Creek	47.096	-123.090	6	2	2	2	1	111	12073500	Q-ratio	3.49	0.09
32	Little Boston Creek	47.855	-122.568	1	0	1	0	0	–	12073500	Q-ratio	0.24	na

Table 7. Location, number of measurements, and estimates of τ and $Q_{7,10}$ at partial-record and miscellaneous sites established by the Northwest Indian Fisheries Commission (NWIFC), NWIFC-member tribes, Point-No-Point Treaty Council, and U.S. Geological Survey as part of the low-flow surveys conducted in western Washington during 2007–09.—Continued

[Locations of sites are shown in figure 4. Shaded sites are miscellaneous sites and either had fewer than four measurements, or all measurements were made in the same year. **τ**: The base-flow recession time constant. **Correlation method used:** Q-ratio, a correlation method described by Potter (2001); MOVE.1, Maintenance of Variance Extension, Version 1, a correlation method described by Hirsch (1982). **$Q_{7,10}$:** The lowest average streamflow for a consecutive 7-day period that recurs on average once every 10 years. **r:** Pearson's correlation coefficient. **Abbreviations:** USGS, U.S. Geological Survey; ft^3/s, cubic foot per second; –, no data; na, does not apply]

Stream No.	Stream name	Latitude (decimal degrees)	Longitude (decimal degrees)	Number of low-flow measurements, 2007–09	Number of low-flow measurements made in each year			Number of measurement pairs used for estimating τ	Mean τ (days)	USGS station No. of index site used for correlating concurrent flows	Correlation method used	$Q_{7,10}$ (ft^3/s)	r
					2007	2008	2009						
33	Malaney Creek	47.249	-123.011	6	2	2	2	2	35	12073500	Q-ratio	0.84	na
34	Middle Creek	47.841	-122.566	1	1	0	0	0	–	12073500	Q-ratio	0.34	na
35	Middle Fork Woods Creek	47.882	-121.913	5	1	2	1	0	–	12155300	Q-ratio	3.92	na
36	Montague Creek	48.269	-121.881	1	1	0	0	0	–	12137290	Q-ratio	0.60	na
37	Mosquito Creek	47.809	-124.430	1	0	1	0	0	–	12043300	Q-ratio	3.41	na
38	North Fork Stillaguamish River	48.282	-121.641	1	1	0	0	0	–	12179900	Q-ratio	9.97	na
39	Nolan Creek	47.751	-124.324	9	3	4	2	3	31	12043000	MOVE.1	1.07	0.91
40	Olney Creek	47.873	-121.713	5	1	2	2	1	22	12137290	Q-ratio	4.09	na
41	Owl Creek	47.801	-124.079	8	3	3	2	3	58	12043000	MOVE.1	7.56	0.90
42	Percival Creek	47.022	-122.932	4	2	0	2	0	–	12073500	Q-ratio	2.00	na
43	Perry Creek	47.049	-123.007	6	2	2	2	2	33	12054000	Q-ratio	0.40	na
44	Purdy Creek	47.389	-122.625	4	2	0	2	0	–	12043300	Q-ratio	1.36	na
45	Rocky Creek	47.371	-122.781	6	2	2	2	1	35	12099600	Q-ratio	2.10	na
46	Schneider Creek	47.092	-123.071	6	2	2	2	2	129	12073500	Q-ratio	0.63	na
47	Segelson Creek	48.283	-121.716	1	1	0	0	0	–	12137290	Q-ratio	0.58	na
48	Shine Creek	47.874	-122.708	9	2	2	5	2	63	12073500	MOVE.1	1.58	0.77
49	Siebert Creek	48.094	-123.280	1	1	0	0	0	–	12048000	Q-ratio	1.64	na
50	Simons Creek	47.221	-122.306	2	0	2	0	0	–	12048000	Q-ratio	0.88	na
51	Sumas River	48.977	-122.254	1	1	0	0	0	–	12206900	Q-ratio	9.61	na
52	Thomas Creek	47.561	-122.973	6	0	2	4	1	41	12073500	Q-ratio	1.76	na
53	Tumwater Creek	48.107	-123.459	1	1	0	0	0	–	12048000	Q-ratio	0.60	na
54	Unknown tributary (Hamma Hamma River basin)	47.584	-123.087	2	2	0	0	0	–	12073500	Q-ratio	0.12	na
55	Unknown tributary (Puget Sound)	47.842	-122.591	1	1	0	0	0	–	12073500	Q-ratio	0.06	na
56	Unknown tributary (Nooksack River basin)	48.783	-122.219	1	1	0	0	0	–	12206900	Q-ratio	0.27	na
57	Unknown tributary (Woodard Creek basin)	47.084	-122.864	1	1	0	0	0	–	12073500	Q-ratio	0.00	na
58	Wacketickeh Creek	47.576	-123.059	4	2	2	0	2	26	12054000	Q-ratio	0.73	na
59	Wagley Creek	47.867	-121.790	5	1	2	2	0	–	12137290	Q-ratio	0.18	na
60	Wells Creek	48.867	-121.766	3	1	2	0	0	–	12207750	Q-ratio	8.89	na
61	Whiskey Creek	48.139	-123.765	1	0	1	0	0	–	12048000	Q-ratio	0.65	na
62	Willoughby Creek	47.822	-124.199	8	3	5	2	3	31	12054000	MOVE.1	0.78	0.98
63	Winfield Creek	47.798	-124.228	10	3	5	2	4	40	12043000	MOVE.1	3.18	0.96

Table 8. Location and basin attributes for partial-record and miscellaneous sites established by the Northwest Indian Fisheries Commission (NWIFC), NWIFC-member tribes, Point-No-Point Treaty Council, and U.S. Geological Survey as part of low-flow surveys conducted in western Washington during 2007–09.

[Location of partial-record sites are shown in figure 4. Basin characteristics were obtained from Washington StreamStats (http://water.usgs.gov/osw/streamstats/Washington.html). Shaded sites either have fewer than four measurements or all measurements were made in the same calendar year. **Relief**: Defined as maximum minus minimum basin elevations. **τ**: The base-flow recession time constant. **Abbreviations:** mi^2, square mile; ft, foot; in., inch; –, no data]

Stream No.	Stream name	Latitude (decimal degrees)	Longitude (decimal degrees)	Basin area (mi^2)	Mean basin elevation (ft)	Relief (ft)	Basin elevation (ft) Maximum	Basin elevation (ft) Minimum	Percentage of basin area covered by forest	Mean annual precipitation (in.)	Mean basin slope (percent)	Percentage of basin area with slope greater than 30 percent	Percentage of basin area with north-facing slope greater than 30 percent	Mean τ (days)
1	Alder Creek	47.830	-124.226	2.9	1,050	1,960	2,330	364	88.0	129	30.3	57.0	5.0	19
2	Ames Creek	47.661	-121.967	3.6	413	584	670	86	69.0	45.0	9.5	0.0	0.0	–
3	Anderson Creek	47.772	-124.323	3.0	622	1,300	1,430	132	81.0	116	22.7	26.0	1.0	38
4	Backman Creek	48.221	-121.579	0.7	2,620	5,080	5,710	629	77.0	95.3	63.1	84.0	44.0	38
5	Bagley Creek	48.098	-123.330	5.0	806	1,650	1,920	264	36.0	25.1	8.5	2.0	1.0	–
6	Barnes Creek	48.055	-123.794	15.7	3,240	4,900	5,540	644	87.0	89.7	61.8	94.0	26.0	–
7	Boardman Creek	48.069	-121.681	9.2	2,830	3,570	4,810	1,240	77.0	96.3	41.2	65.0	24.0	–
8	Cabin Creek	47.595	-123.128	7.1	2,910	4,290	4,860	564	76.0	85.8	62.8	96.0	13.0	126
9	Campbell Creek	47.223	-123.013	3.6	188	266	304	38	59.0	57.4	5.2	0.0	0.0	60
10	Canyon Creek	48.833	-122.137	9.0	2,940	4,660	5,010	354	72.0	91.5	43.2	77.0	22.0	–
11	Cascade Creek	48.896	-121.859	0.2	2,820	2,270	4,130	1,860	90.0	80.5	44.8	68.0	63.0	–
12	Cedar Creek	47.710	-124.412	10.4	418	1,350	1,370	22	81.0	106	12.4	5.0	1.0	42
13	Clarks Creek	47.177	-122.317	11.2	490	602	636	33	30.0	40.0	3.4	0.0	0.0	–
14	Clear Creek	48.219	-121.569	29.2	3,000	5,270	5,900	630	70.0	114	64.1	89.0	19.0	23
15	Crescent Creek	47.356	-122.579	4.9	269	350	406	56	74.0	50.0	6.1	0.0	0.0	–
16	Dan Creek	48.277	-121.556	16.5	2,860	6,440	6,890	457	83.0	110	39.7	74.0	13.0	20
17	Deer Creek (Puget Sound)	47.265	-123.005	14.5	196	368	396	28	72.0	60.8	6.7	0.0	0.0	98
18	Deer Creek (Puyallup River basin)	47.181	-122.262	0.9	409	502	582	80	25.0	40.0	6.6	0.0	0.0	–
19	Deer Creek (Stillaguamish River basin)	48.091	-121.554	4.5	3,390	3,680	5,320	1,640	73.0	124	63.5	91.0	23.0	–
20	Elk Creek	47.798	-124.197	3.7	652	1,400	1,810	406	76.0	127	12.2	14.0	9.0	73
21	Ennis Creek	48.108	-123.398	8.3	2,370	6,250	6,340	83	71.0	35.7	38.6	59.0	17.0	–
22	Field Creek	48.140	-123.785	0.6	1,420	1,340	2,210	869	78.0	64.4	25.6	30.0	1.0	–
23	Gamble Creek	47.809	-122.581	6.2	256	469	498	29	66.0	34.9	7.9	0.0	0.0	–
24	Goodman Creek	47.833	-124.461	23.0	633	1,370	1,460	82	84.0	112	17.5	11.0	3.0	43
25	Gravel Creek	48.297	-121.525	2.4	3,040	5,050	5,590	547	86.0	94.9	49.9	81.0	27.0	–
26	Harding Creek	47.585	-122.945	1.3	333	497	508	11	83.0	58.7	13.3	12.0	4.0	–
27	Jefferson Creek	47.583	-123.107	21.8	2,710	5,720	6,240	517	68.0	103	59.0	93.0	24.0	–
28	John Creek	47.539	-123.098	1.0	1,660	1,790	2,620	830	93.0	82.4	49.1	91.0	20.0	–
29	Johnson Creek	48.993	-122.267	19.2	91	185	220	35	7.0	44.2	1.3	0.0	0.0	–
30	Kalaloch Creek	47.614	-124.348	15.0	509	1,410	1,460	44	89.0	107	27.4	39.0	7.0	40

Table 8. Location and basin attributes for partial-record and miscellaneous sites established by the Northwest Indian Fisheries Commission (NWIFC), NWIFC-member tribes, Point-No-Point Treaty Council, and U.S. Geological Survey as part of low-flow surveys conducted in western Washington during 2007–09.—Continued

[Location of partial-record sites are shown in figure 4. Basin characteristics were obtained from Washington StreamStats (http://water.usgs.gov/osw/streamstats/Washington.html). Shaded sites either have fewer than four measurements or all measurements were made in the same calendar year. **Relief**: Defined as maximum minus minimum basin elevations. **τ**: The base-flow recession time constant. **Abbreviations:** mi^2, square mile; ft, foot; in., inch; –, no data]

Stream No.	Stream name	Latitude (decimal degrees)	Longitude (decimal degrees)	Basin area (mi^2)	Mean basin elevation (ft)	Relief (ft)	Basin elevation (ft)		Percentage of basin area covered by forest	Mean annual precipitation (in.)	Mean basin slope (percent)	Percentage of basin area with slope greater than 30 percent	Percentage of basin area with north-facing slope greater than 30 percent	Mean τ (days)
							Maximum	Minimum						
31	Kennedy Creek	47.096	-123.090	19.4	668	2,320	2,350	29	69.0	58.5	22.8	27.0	12.0	111
32	Little Boston Creek	47.855	-122.568	0.7	266	330	405	74	84.0	31.8	8.9	0.0	0.0	–
33	Malaney Creek	47.249	-123.011	4.0	195	235	289	54	52.0	58.0	4.4	0.0	0.0	35
34	Middle Creek	47.841	-122.566	0.3	255	359	405	46	86.0	32.5	6.8	0.0	0.0	–
35	Middle Fork Woods Creek	47.882	-121.913	25.1	504	1,100	1,220	120	65.0	46.2	10.0	1.0	0.0	–
36	Montague Creek	48.269	-121.881	5.3	1,340	3,190	3,410	223	84.0	71.6	31.9	43.0	36.0	–
37	Mosquito Creek	47.809	-124.430	0.5	502	660	923	262	94.0	107	29.3	42.0	5.0	–
38	North Fork Stillaguamish River	48.282	-121.641	48.9	2,600	4,580	5,060	473	91.0	82.0	38.0	72.0	15.0	–
39	Nolan Creek	47.751	-124.324	9.7	577	1,670	1,790	118	76.0	115	13.6	13.0	5.0	31
40	Olney Creek	47.873	-121.713	19.8	1,790	4,650	4,810	159	82.0	71.3	31.4	47.0	12.0	22
41	Owl Creek	47.801	-124.079	9.3	1,820	2,990	3,380	389	84.0	143	50.6	89.0	31.0	58
42	Percival Creek	47.022	-122.932	4.7	195	357	500	143	38.0	52.7	4.0	0.0	0.0	–
43	Perry Creek	47.049	-123.007	6.4	650	1,570	1,580	6	72.0	59.6	24.1	31.0	11.0	33
44	Purdy Creek	47.389	-122.625	3.6	276	411	434	22	71.0	50.1	6.3	0.0	0.0	–
45	Rocky Creek	47.371	-122.781	18.4	333	515	531	16	71.0	54.9	5.5	0.0	0.0	35
46	Schneider Creek	47.092	-123.071	3.8	409	1,130	1,190	63	68.0	59.2	19.9	19.0	9.0	129
47	Segelson Creek	48.283	-121.716	3.8	2,870	4,120	4,530	413	73.0	82.9	37.9	68.0	3.0	–
48	Shine Creek	47.874	-122.708	3.9	295	484	528	44	76.0	31.4	10.6	1.0	0.0	63
49	Siebert Creek	48.094	-123.280	16.4	1,560	5,260	5,450	195	72.0	38.9	19.2	18.0	9.0	–
50	Simons Creek	47.221	-122.306	0.6	323	358	406	47	28.0	40.9	7.1	0.0	0.0	–
51	Sumas River	48.977	-122.254	31.0	682	3,370	3,410	42	51.0	51.7	17.7	25.0	8.0	–
52	Thomas Creek	47.561	-122.973	0.4	342	429	454	25	76.0	60.0	14.3	13.0	4.0	41
53	Tumwater Creek	48.107	-123.459	4.9	1,080	2,290	2,460	168	70.0	35.3	24.8	36.0	12.0	–
54	Unknown tributary (Hamma Hamma River basin)	47.584	-123.087	0.6	1,990	2,570	3,190	616	88.0	75.9	44.9	93.0	0.0	–
55	Unknown tributary (Puget Sound)	47.842	-122.591	0.1	301	337	404	67	65.0	34.0	12.4	11.0	0.0	–
56	Unknown tributary (Nooksack River basin)	48.783	-122.219	1.7	1,700	2,752	3,070	313	64.0	59.6	38.8	75.0	25.0	–
57	Unknown tributary (Woodard Creek basin)	47.084	-122.864	0.1	154	25	165	140	24.0	52.2	0.92	0.0	0.0	–

Table 8. Location and basin attributes for partial-record and miscellaneous sites established by the Northwest Indian Fisheries Commission (NWIFC), NWIFC-member tribes, Point-No-Point Treaty Council, and U.S. Geological Survey as part of low-flow surveys conducted in western Washington during 2007–09.—Continued

[Location of partial-record sites are shown in figure 4. Basin characteristics were obtained from Washington StreamStats (http://water.usgs.gov/osw/streamstats/Washington.html). Shaded sites either have fewer than four measurements or all measurements were made in the same calendar year. **Relief**: Defined as maximum minus minimum basin elevations. **τ**: The base-flow recession time constant. **Abbreviations:** mi^2, square mile; ft, foot; in., inch; –, no data]

Stream No.	Stream name	Latitude (decimal degrees)	Longitude (decimal degrees)	Basin area (mi^2)	Mean basin elevation (ft)	Relief (ft)	Basin elevation (ft)		Percentage of basin area covered by forest	Mean annual precipitation (in.)	Mean basin slope (percent)	Percentage of basin area with slope greater than 30 percent	Percentage of basin area with north-facing slope greater than 30 percent	Mean τ (days)
							Maximum	Minimum						
58	Wacketickeh Creek	47.576	-123.059	5.9	1,930	3,500	4,170	673	80.0	74.7	40.0	69.0	3.0	26
59	Wagley Creek	47.867	-121.790	2.9	422	992	1,180	184	36.0	57.4	10.3	6.0	0.0	–
60	Wells Creek	48.867	-121.766	5.1	4,570	4,010	6,490	2,480	48.0	117	48.8	81.0	27.0	–
61	Whiskey Creek	48.139	-123.765	1.5	1,470	2,190	2,520	332	87.0	57.2	32.4	61.0	25.0	–
62	Willoughby Creek	47.822	-124.199	3.2	1,320	2,340	2,600	263	84.0	134	41.9	75.0	7.0	31
63	Winfield Creek	47.798	-124.228	10.7	843	2,140	2,400	259	78.0	121	22.5	33.0	13.0	40

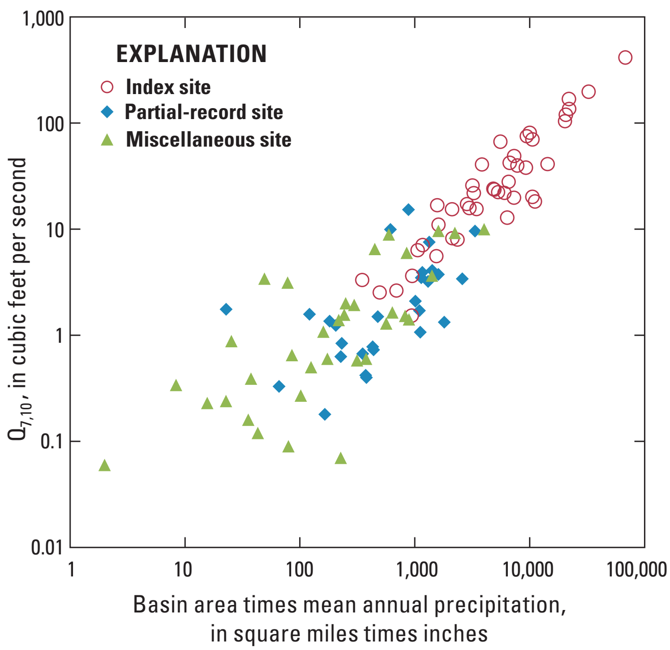


Figure 10. Relation between low-flow characteristics ($Q_{7,10}$) and selected basin attributes (basin area times mean annual precipitation) of index, partial-record, and miscellaneous sites in western Washington.

Empirical Monte Carlo Analysis

The $Q_{7,10}$ was estimated at 43 synthetic partial-record sites (defined in section Empirical Monte Carlo Technique for Evaluating Index-Site Correlation Methods) using each of the three correlation methods (Q-ratio, MOVE.1, and Base-Flow Correlation) in 170 scenarios. Each of these scenarios is defined by the number of streamflow observations (ranging from 4 to 20) or observation pairs (ranging from 2 to 10), and the combination of basin attributes used to select an index site. For example, in one scenario the $Q_{7,10}$ was estimated at each of the 43 synthetic partial-record sites on the basis of only four flow measurements, and the index site was selected based on similarity in the basin attributes of basin area (A), mean annual precipitation (P), and geographic proximity (G). For another scenario, three pairs of observations (each pair from the same base-flow recession segment) and only the basin attribute τ were used in the analysis. To allow the calculation of τ as a basin attribute, half of the scenarios contain streamflow observation pairs (Q_0 and Q_t, separated by t number of days; see equation 1) 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 $Q_{7,10}$ value (derived from the average of 500 repeated applications of the Q-ratio, MOVE.1, and Base-Flow Correlation methods) and the $Q_{7,10}$ value calculated from the continuous daily record at each of the 43 index sites. Generally, 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.

The overall bias (defined herein as the estimated value minus the true value) for each correlation method was calculated as the arithmetic average of the bias for all estimates of $Q_{7,10}$ in a given scenario (fig. 12). The correlation method with the largest absolute bias for each scenario generally was Base-Flow Correlation, whereas the method with the smallest absolute bias was Q-ratio. Additionally, the bias for the MOVE.1 and Base-Flow Correlation methods was consistently positive (estimates of $Q_{7,10}$ were greater than true values), whereas the Q-ratio method had a consistently negative bias (estimates of $Q_{7,10}$ were less than true values). In estimating low-flow statistics, methods that have smaller bias are 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.

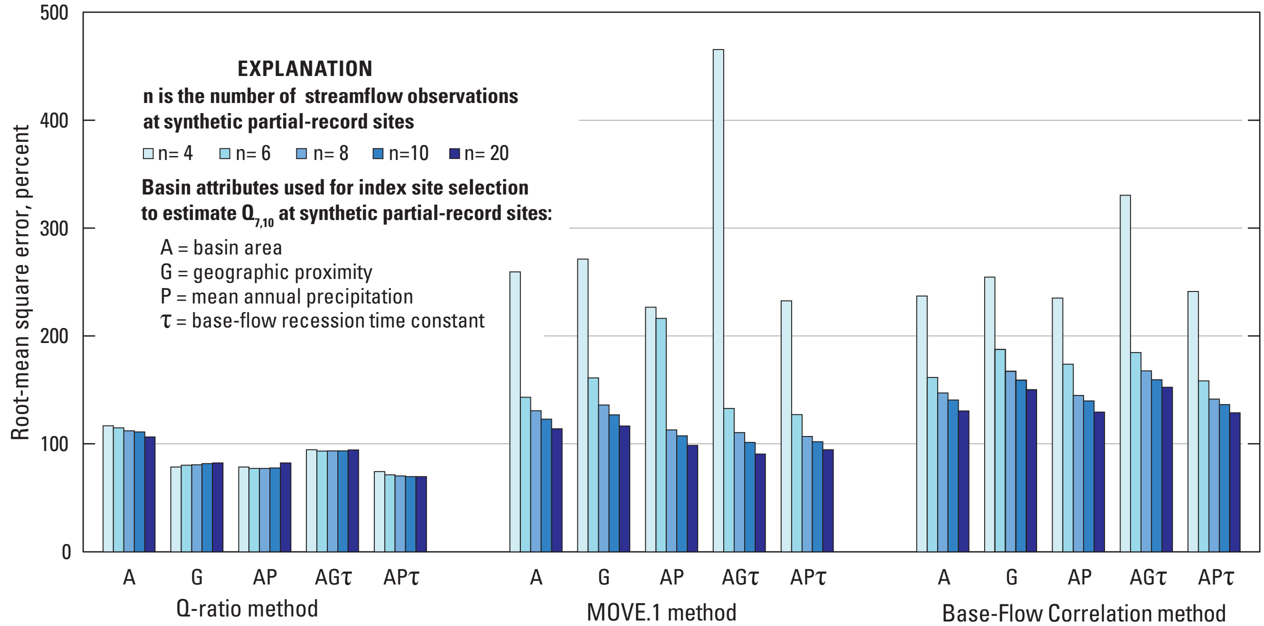


Figure 11. Root-mean square error of three correlation methods (Q-ratio, MOVE.1, and Base-Flow Correlation) in estimating the $Q_{7,10}$ at partial-record sites in western Washington, using scenarios defined by the number of streamflow observations (n) and the combination of basin attributes used to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

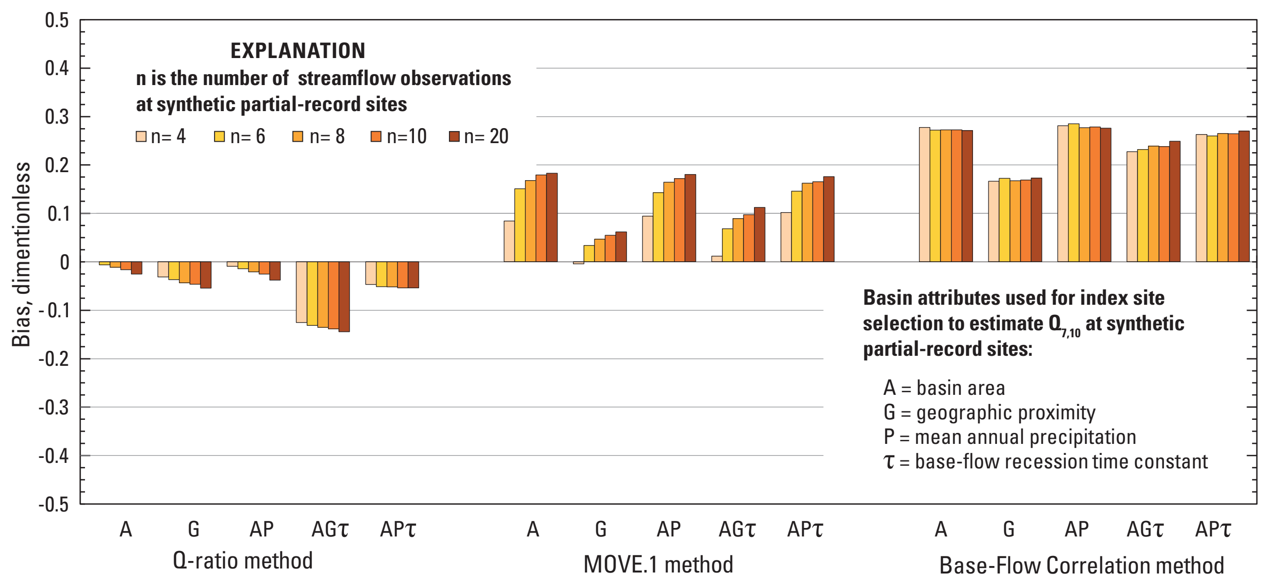


Figure 12. Overall bias associated with three index-site correlation methods (Q-ratio, MOVE.1, Base-Flow Correlation) in estimating the $Q_{7,10}$ at partial-record sites in western Washington, using scenarios defined by the number of streamflow observations and the combination of basin attributes used to select an index site.

Incorporation of τ and Partial-Record Streamflow-Measurement Sites into Regional Low-Flow Regression Models

Previous studies have demonstrated the value of including τ as an explanatory variable in regional regression models 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 recording gaging stations, a reliable estimate of τ is readily calculated from the daily streamflow record. Where the continuous streamflow-gaging network is not represented, either geographically or outside the range of explanatory variables, estimates of τ can be calculated at partial-record sites to extend network coverage. For partial-record sites, τ can be estimated using equation 1, with measurement pairs made on the receding limb of the hydrograph during base-flow conditions. In establishing partial-record sites, however, questions arise as to where sites should be located, what types of basins to include, and, once a site is established, the number of measurements needed to reliably estimate τ.

To answer these questions, a series of regional low-flow regression models were developed for the sole purpose of evaluating the benefits of including τ 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 τ at partial-record sites. Regression models for estimating the $Q_{7,10}$ at ungaged sites were developed using basin area (*A*), mean annual precipitation (*P*) and τ as explanatory variables and the $Q_{7,10}$ derived from 65 continuous streamflow-gaging stations (the 43 index sites and 22 discontinued gaging stations) in western Washington with 7 or more years of daily streamflow record. Three regression models developed using an ordinary least-squares (OLS) method (which is considered sufficient for purposes of the analysis) were evaluated using the performance metric of RMSE expressed as a percentage (fig. 13). The three regression models estimate $Q_{7,10}$ as a function of *A*, *P*, and τ as:

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

$$Q_{7,10} = 8.48 \times 10^{-4}(A^{1.17}\,P^{1.23}), \qquad R^2 = 0.79, \qquad (11)$$

and

$$Q_{7,10} = 6.47 \times 10^{-6}(A^{0.968}\,P^{1.16}\,\tau^{1.68}), \qquad R^2 = 0.90, \qquad (12)$$

where $Q_{7,10}$ is the low-flow characteristic (the lowest average streamflow for a consecutive 7-day period that recurs on average once every 10 years) in cubic feet per second, *A* is basin area in square miles, *P* is mean annual precipitation in inches, τ is the base-flow recession time constant in days, and R^2 is the coefficient of determination. In the empirical Monte Carlo analysis, τ was calculated from 500 randomly sampled observation pairs to obtain the best estimate (τ_{ideal}), and from a much smaller number of observation pairs ranging from 1 to 10 to represent the estimate at a partial-record site.

The RMSE of the regression models generally decreases as the number of explanatory variables increases, and the fraction of variation explained by the regressions (R^2) increases with the incorporation of additional variables. For example, the regression model that uses only A as an explanatory variable has an RMSE of 133 percent, and the regression model that uses A and P as explanatory variables has an RMSE of 114 percent. By incorporating τ 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 τ. Eight measurement pairs are optimal for estimating τ at partial-record sites, after which additional measurements yield diminishing effects in lowering the RMSE.

Although the OLS regression method was adequate for evaluating explanatory variables and optimizing the number of measurement pairs for estimating τ (at partial-record sites), this method assumes that the $Q_{7,10}$ determined at continuous gaging stations and partial-record sites is equally accurate. This is not usually the case, however, as sites with long streamflow records (for example, long-term continuous gaging stations) will generally provide more reliable estimates of $Q_{7,10}$ than sites with only a few years of record or several low-flow measurements (such as partial-record sites). For this reason, use of the weighted least-squares (WLS) method is preferable for developing regional low-flow regressions that include partial-record sites because WLS allows sites with more reliable estimates of the $Q_{7,10}$ to have more influence in determining the regression model. Software tools such as the Weighted-Multiple-Linear Regression (WREG) Program (Eng and others, 2009; U.S. Geological Survey, 2011b) have been developed by the USGS to assist users in generating WLS regressions and could be used for determining future low-flow regressions for western Washington as the number of fully developed partial-record sites (sites with eight or more measurement pairs to reliably estimate τ) increases.

The ability of regional regression models to accurately estimate low-flow characteristics at ungaged sites over a large range of stream types and geography depends on the extent of the regional streamflow-gaging-station network. Regression models generally provide better estimates of low-flow characteristics at ungaged sites when basin attributes are well represented in the data set from which the regressions were developed. Results from this study indicate that partial-record sites can be used to efficiently fill gaps and expand the coverage of the streamflow-gaging network for specific basin attributes such as τ, thereby extending the applicable range of regression models for estimating low-flow characteristics at ungaged sites in western Washington (fig. 14).

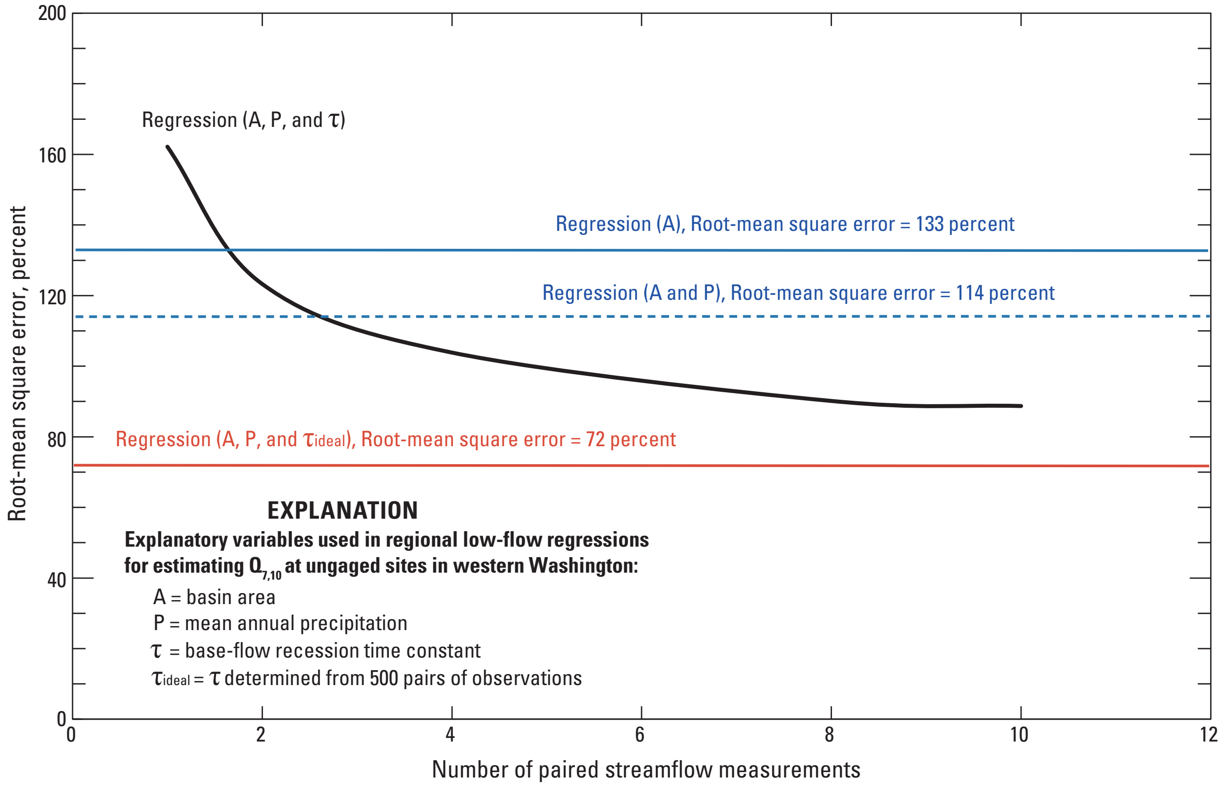


Figure 13. Root-mean square error of regression models for estimating the $Q_{7,10}$ at ungaged sites in western Washington, using different combinations of explanatory variables and numbers of paired streamflow measurements.

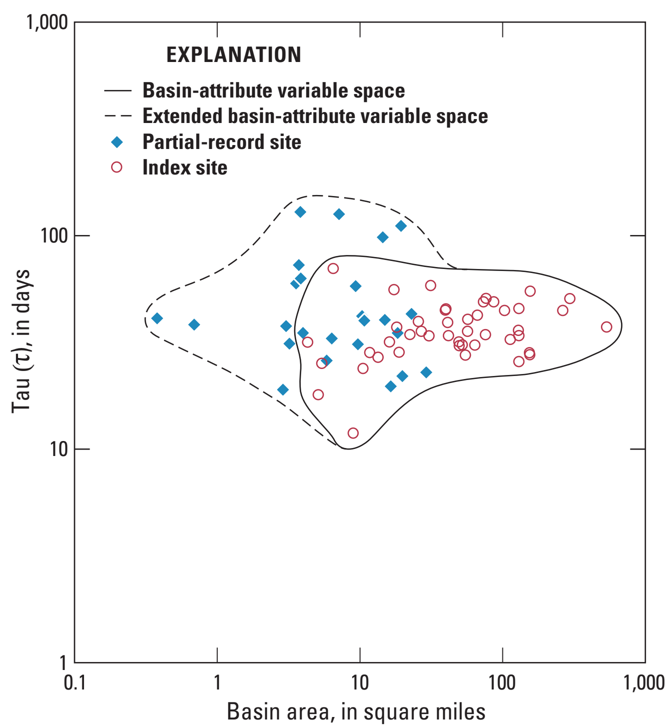


Figure 14. Coverage of basin-attribute variable space defined by basin area and τ for index sites and partial-record sites established during 2007–09 low-flow surveys in western Washington.

A low-flow survey strategy that includes measurements of τ at partial-record sites requires additional effort and planning, but has the potential to reduce the error of regional regression models for estimating low-flow characteristics at ungaged sites. As Vogel and Kroll (1992) point out, however, regression models that include τ as an explanatory variable present a problem in that an estimate of τ first must be made for the ungaged site. To accomplish this, previous researchers have mapped τ 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, the Northwest Indian Fisheries Commission (NWIFC) and its member tribes identified documentation of low-flow conditions in western Washington streams as a high priority. To document the low flows, a regional low-flow survey of small streams was initiated by the NWIFC, NWIFC-member tribes, and Point-No-Point Treaty Council in cooperation with the U.S. Geological Survey (USGS) in 2007, and repeated by the tribes during the low-flow seasons (July–September) of 2008 and 2009. As part of the survey, flow was measured at 63 stream sites; the number of measurements made at each site ranged from 1 to 10. A strategy of making paired measurements during receding base flows was used to compute the base-flow recession time constant, or τ, at 25 sites. The $Q_{7,10}$, defined as the lowest average streamflow for a consecutive 7-day period that recurs on average once every 10 years, was estimated at stream sites using either the Q-ratio or MOVE.1 correlation method, and required concurrent daily mean streamflows from index sites that were selected from the USGS streamflow-gaging-station network on the basis of basin similarity. Generally, partial-record and miscellaneous sites established during the low-flow surveys are in smaller drainage areas, generate less runoff, and have correspondingly lower values of $Q_{7,10}$ than do most continuous streamflow-gaging stations in the network.

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 evaluated using an empirical Monte Carlo technique for different scenarios, each defined by the number of streamflow measurements and the combination of basin attributes used to select an index site. Of the three correlation methods, Q-ratio had the smallest root-mean square error (RMSE), which ranged from 70 to 118 percent for all scenarios, and the optimum number of streamflow measurements for estimating the $Q_{7,10}$ at partial-record sites was four, with only slight reductions in the RMSE gained by additional measurements.

By incorporating τ as an explanatory variable in regional low-flow regressions, the regression RMSE for estimating the $Q_{7,10}$ at ungaged sites can be reduced to as low as 72 percent, 42 percent lower than if only basin area and mean annual precipitation are used as explanatory variables. In practice, if partial-record sites are included in the regression data set, τ must be estimated from pairs of base-flow recession measurements. The Monte Carlo analysis also determined that eight is the optimum number of measurement pairs for estimating τ at partial-record sites, after which additional measurements yield diminishing effects in lowering the RMSE.

Partial-record sites offer an affordable way to expand the geographic coverage of low-flow information in a region and include combinations of basin attributes (for example, small, low-elevation streams) that are underrepresented in the streamflow-gaging-station network. A low-flow survey strategy that includes measurements of τ at partial-record sites requires additional effort and planning, but has the potential to significantly reduce the error of regional regression models for estimating low-flow characteristics at ungaged sites in western Washington.

Acknowledgments

The authors gratefully acknowledge the efforts of the following individuals (and their respective tribal governments or agencies), who collected and provided streamflow data as part of the low-flow surveys in western Washington (2007–09): Warren Scarlett (Hoh Indian Tribe), Ann Savery (Tulalip Tribes), John Konovsky (Squaxin Island Tribe), Steve Todd (Point-No-Point Treaty Council), Sarah Burlingame (Port Gamble S'Klallam Tribe), Lynn Doremus (Nooksack Indian Tribe), Jody Brown (Stillaguamish Tribe of Indians), Scott Morris (Sauk-Suiattle Indian Tribe), Elsie Wescott (Puyallup Tribe of Indians), and Tyson Waldo (Northwest Indian Fisheries Commission).

References Cited

Bent, G.C., and Steeves, P.A., 2006, A revised logistic regression equation and an automated procedure for mapping the probability of a stream flowing perennially in Massachusetts: U.S. Geological Survey Scientific Investigations Report 2006-5031, 107 p.

Bingham, R.H., 1986, Regionalization of low-flow characteristics of Tennessee streams: U.S. Geological Survey Water-Resources Investigations Report 85-4191, 63 p.

Brutsaert, Wilfried, and Nieber, J.L., 1977, Regionalized drought flow hydrographs from a mature glaciated plateau: Water Resources Research, v. 13, p. 637– 643.

Collings, M.R., and Hidaka, F.T., 1974, Low-flow characteristics of streams in the Willapa Bay drainages, Washington: U.S. Geological Survey Water Resources Investigation Report 74-8, 16 p.

Cummans, J.E., 1977, Low-flow characteristics of streams on the Kitsap Peninsula and adjacent islands, Washington: U.S. Geological Survey Open-File Report 76-704, 19 p.

Curran, C.A., and Olsen, T.D., 2009, Estimating low-flow frequency statistics and hydrological analysis of selected streamflow-gaging stations, Nooksack River basin, northwestern Washington and Canada: U.S. Geological Survey Scientific Investigations Report 2009-5170, 44 p.

Dragovich, J.D., Dunn, A.B., Parkinson, K.T., Kahle, S.C., and Pringle, P.T., 1997, Quaternary stratigraphy and cross-sections, Nooksack, Columbia, and Saar Creek Valleys, Kendall and Deming 7.5-minute quadrangles, Western Whatcom County, Washington: Washington Division of Geology and Earth Resources Open-File Report 97-4, 13 p.

Eng, Ken, Chen, Yin-Yu, and Kiang, Julie, 2009, User's guide to the weighted-multiple-linear regression program (WREG version 1.0): U.S. Geological Survey Techniques and Methods, book 4, chap. A8, 21 p.

Eng, Ken, and Milly, P.C.D., 2007, Relating low-flow characteristics to the base-flow recession time constant at partial record stream gauges: Water Resources Research, v. 43, 8 p., W01201, doi:10.1029/2006WR005293.

Funkhouser, J.E., Eng, Ken, and Moix, M.W., 2008, Low-flow characteristics and regionalization of low-flow characteristics for selected streams in Arkansas: U.S. Geological Survey Scientific Investigations Report 2008-5065, 161 p.

Hamilton, D.A., Sorrell, R.C., and Holtschlag, D.J., 2008, A regression model for computing index flows describing the median flow for the summer month of lowest flow in Michigan: U.S. Geological Survey Scientific Investigations Report 2008-5096, 43 p.

Harris, D.D., 1977, Hydrologic changes after logging in two small Oregon coastal watersheds: U.S. Geological Survey Water-Supply Paper 2037, 31 p.

Haushild, W.L., and LaFrance, D.E., 1977, Low-flow characteristics of streams on the Olympic Peninsula, Washington: U.S. Geological Survey Open-File Report 77-812, 29 p.

Hidaka, F.T., 1973, Low-flow characteristics of streams in the Puget Sound region, Washington: U.S. Geological Survey Open-File Report 72-163, 56 p.

Hirsch, R.M., 1982, A comparison of four streamflow record extension techniques: Water Resources Research, v. 18, no. 4, p. 1081-1088.

Hortness, J.E., 2006, Estimating low-flow frequency statistics for unregulated streams in Idaho: U.S. Geological Survey Scientific Investigations Report 2006-5035, 40 p.

Jones, M.A., 1999, Geologic framework of the Puget Sound aquifer system, Washington and British Columbia: U.S. Geological Survey Professional Paper 1424-C, 31 p.

Konrad, C.P., 2005, Scientific framework for a comprehensive assessment of tribal water resources in western Washington: U.S. Geological Survey Open-File Report 2005-1390, 16 p.

Konrad, C.P., and Booth, D.B., 2005, Hydrologic changes in urban streams and their ecological significance, *in* Brown, L.R., Gray, R.H., Hughes, R.M., and Meador, M.R., eds., Effects of urbanization on stream ecosystems: American Fisheries Society Symposium 47, Bethesda, Md., p. 157-177.

Konrad, C.P., Brasher, A.M.D., and May, J.T., 2008, Assessing streamflow characteristics as limiting factors on benthic invertebrate assemblages in streams across the western United States: Freshwater Biology v. 53, doi: 10.1111/j.1365-2427.2008.02024.x, p. 1983-1998.

Lane, R.C., 2009, Estimated water use in Washington, 2005: U.S. Geological Survey Scientific Investigations Report 2009-5128, 30 p.

Linneman, Scott, Pittman, Paul, and Vaugeois, Laura, 2007, Lively landscapes—Major Holocene geomorphic events in the Nooksack–Sumas Valley, *in* Stelling P., and Tucker, D.S., eds., Floods, Faults and Fire—Geological field trips in Washington State and southwest British Columbia: Geological Society of America Field Guide 9, p. 99-119.

Milly, P.C.D., Betancourt, Julio, Falkenmark, Malin, Hirsch, R.M., Kundzewicz, Z.W., Lettenmaier, D.P., and Stouffer, R.J., 2008, Climate change—Stationarity is dead—Whither Water management?: Science, v. 319, no. 5863, p. 573-574.

Potter, K.W., 2001, A simple method for estimating base-flow at ungaged locations: Journal of the American Water Resources Association, v. 37, no. 1, p. 177-184.

Rantz, S.E., 1982, Measurement and computation of streamflow: U.S. Geological Survey Water Supply Paper 2175, v.1, 284 p.

Ries, K.G., III, and Friesz, P.J., 2000, Methods for estimating low-flow statistics for Massachusetts streams: U.S. Geological Survey Water-Resources Investigation Report 00-4135, 81 p.

Riggs, H.C., 1972, Low-flow investigations: U.S. Geological Survey Techniques of Water Resources Investigations, book 4, chap. B1, 18 p.

Risley, John, Stonewall, Adam, and Haluska, Tana, 2008, Estimating flow-duration and low-flow frequency statistics for unregulated streams in Oregon: U.S. Geological Survey Scientific Investigations Report 2008-5126, 22 p.

Searcy, J.K., 1959, Flow-duration curves—Manual of hydrology—Part 2, low-flow techniques: U.S. Geological Survey Water Supply Paper 1542-A, 33 p.

Sinclair, K.A., and Pitz, C.F., 1999, Estimated base-flow characteristics of selected Washington rivers and streams: Washington State Department of Ecology Water Supply Bulletin No. 60 (pub. No. 99-327), 24 p., accessed April 2, 2008, at http://www.ecy.wa.gov/biblio/99327data.html.

Stedinger, J.R., and Thomas, W.O., Jr., 1985, Low-flow frequency estimation using base-flow measurements: U.S. Geological Survey Open-File Report 85-95, 22 p.

Tasker, G.D., 1987, Comparison of methods for estimating low flow characteristics of streams: Water Resources Bulletin, 23, no. 6, p. 1077-1083.

The MathWorks Inc., 2008, MATLAB Version 7.6.0.324 (R2008a).

U.S. Census Bureau, 2000, Census 2000, Washington by county: U.S. Census Bureau database accessed May 5, 2010, at 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.

U.S. Environmental Protection Agency, 2011, Water—BASINS 4.0: U.S. Environmental Protection Agency database, accessed February 29, 2012, at http://water.epa.gov/scitech/datait/models/basins/b3webdwn.cfm.

U.S. Geological Survey, 1985, Low-flow frequency estimation at partial-record sites: Office of Surface Water Technical Memorandum No. 86-02, accessed May 15, 2009, at http://water.usgs.gov/admin/memo/SW/sw86.02.html and http://water.usgs.gov/osw/pubs/sw86.02.attachment.pdf.

U.S. Geological Survey, 2010, StreamStats: U.S. Geological Survey database, accessed February 29, 2012, at http://water.usgs.gov/osw/streamstats/Washington.html.

U.S. Geological Survey, 2011a, National Water Information System: U.S. Geological Survey database, accessed February 29, 2012, at http://waterdata.usgs.gov/nwis.

U.S. Geological Survey, 2011b, Weighted-Multiple-Linear Regression (WREG) Program, ver. 1.02: U.S. Geological Survey software, accessed February 29, 2012, at http://water.usgs.gov/software/WREG/.

U.S. Weather Bureau, 1965, State of Washington, mean annual precipitation, 1930–1957: Portland, Oreg., Soil Conservation Service, map M-4430, 1 sheet [no scale].

Vaccaro, J.J., Hansen, A.J., and Jones, M.A., 1998, Hydrogeologic framework of the Puget Sound aquifer system, Washington and British Columbia: U.S. Geological Survey Professional Paper 1424-D, 77 p.

Vogel, R.M., and Kroll, C.N., 1992, Regional geohydrologic-geomorphic relationships for the estimation of low-flow statistics: Water Resources Research, v. 28, no. 9, p. 2451-2458.

Williams, J.R., Pearson, H.E., and Wilson, J.D., 1985a, Streamflow statistics and drainage basin characteristics for the Puget Sound region, Washington, volume 1: U.S. Geological Survey Open-File Report 84-144A, 420 p.

Williams, J.R., Pearson, H.E., and Wilson, J.D., 1985b, Streamflow statistics and drainage basin characteristics for the Puget Sound region, Washington, Volume 2: U.S. Geological Survey Open-File Report 84-144B, 320 p.

Appendix A. Measurements At Partial-Record And Miscellaneous Streamflow-Measurement Sites For Low-Flow Surveys In 2007, 2008, And 2009

During the 2007–09 low-flow surveys, 283 streamflow measurements were made by the Northwest Indian Fisheries Commission (NWIFC), NWIFC-member tribes, Point-No-Point Treaty Council, and U.S. Geological Survey (USGS) (2007 only). Measurements were made in perennial streams that are not part of the USGS streamflow-gaging-station network, using various types of current meters, and following streamflow-measurement methods outlined by Rantz (1982). All measurements are listed in table A1.

Reference Cited

Rantz, S.E., 1982, Measurement and computation of streamflow: U.S. Geological Survey Water Supply Paper 2175, v. 1, 284 p. (Also available at http://pubs.er.usgs.gov/publication/wsp2175_vol1.)

Table A1. Streamflow measurements made during the 2007–09 low-flow survey conducted by the Northwest Indian Fisheries Commission (NWIFC), NWIFC-member tribes, Point-No-Point Treaty Council, and U.S. Geological Survey in western Washington.

[**Tribe, organization, or agency that made the measurement:** NWIFC, Northwest Indian Fisheries Commission; PNPTC, Point-No-Point Treaty Council; USGS, U.S. Geological Survey. **Q:** streamflow. **Measurement rating:** E, excellent, less than 2 percent error; F, fair, less than 8 percent error; G, good, less than 5 percent error; P, poor, greater than or equal to 8 percent error. **Abbreviations**: ft^3/s, cubic foot per second; ft^2, square foot; ft; foot; ft/s; foot per second; –, information not provided]

Stream name	Latitude (decimal degrees)	Longitude (decimal degrees)	Tribe, organization, or agency that made the measurement	Date	Q (ft^3/s)	Area (ft^2)	Width (ft)	Number of sections per measurement	Maximum stream depth (ft)	Mean velocity (ft/s)	Current meter type	Measurement rating
Alder Creek	47.830	-124.226	Hoh Indian Tribe	08-16-07	1.55	3.6	11.0	22	0.540	0.43	Marsh-McBirney	F
				08-16-07	1.63	3.8	11.0	22	0.540	0.43		F
				09-06-07	1.75	4.0	11.0	22	0.570	0.44		F
				09-06-07	1.73	4.0	11.0	22	0.580	0.44		F
				09-19-07	0.75	2.9	10.5	20	0.500	0.26		F
				08-07-08	1.06	6.0	13.0	–	0.750	0.18		G
				09-09-08	2.70	7.4	14.0	–	0.800	0.37		G
				09-18-08	1.39	6.3	13.0	–	0.730	0.22		G
				07-21-09	0.43	5.7	9.6	18	0.930	0.08		G
				08-04-09	0.26	3.8	8.3	16	0.680	0.07		G
Ames Creek	47.661	-121.967	Tulalip Tribes	09-07-07	1.84	1.6	6.5	24	0.440	1.15	Price Pygmy	G
				09-09-08	1.48	2.4	6.8	29	0.700	0.61		G
				10-02-08	1.54	2.6	6.6	27	0.710	0.60		E
Anderson Creek	47.772	-124.323	Hoh Indian Tribe	08-17-07	3.26	8.4	12.6	26	0.920	0.39	Marsh-McBirney	F
				09-07-07	2.59	8.5	12.5	25	0.930	0.31		F
				09-07-07	2.58	8.4	12.5	25	0.950	0.31		F
				09-21-07	1.41	7.9	12.5	25	0.900	0.18		F
				07-11-08	2.04	10.2	13.0	–	1.130	0.20		F
				07-23-08	1.25	9.3	13.0	–	0.950	0.14		F
				07-22-09	0.89	5.5	12.0	23	0.640	0.16		G
				08-04-09	0.73	5.4	11.5	24	0.650	0.14		G
Backman Creek	48.221	-121.579	Sauk-Suaittle Indian Tribe	08-05-08	2.79	7.8	7.2	–	1.440	0.36	Sontek Flowtracker	F
				08-15-08	2.04	7.5	7.6	–	1.410	0.27		F
				09-08-08	1.30	6.6	7.5	–	1.260	0.20		G
				09-16-08	1.03	6.5	7.4	–	1.250	0.16		G
				07-15-09	2.24	7.1	7.8	20	1.290	0.31	Marsh-McBirney	G
				07-23-09	1.62	6.8	7.9	20	1.250	0.24		G
				07-29-09	1.68	6.7	7.9	19	1.240	0.25	Sontek Flowtracker	G
				08-17-09	0.94	6.2	7.8	19	1.170	0.15		G
				09-21-09	0.97	6.2	7.9	19	1.200	0.16		P
Bagley Creek	48.098	-123.330	USGS	09-09-07	0.76	1.6	6.7	24	0.440	0.48	Price Pygmy	G
Barnes Creek	48.055	-123.794	USGS	08-28-07	11.60	11.7	19.0	26	1.200	0.99	Price Pygmy	G
			PNPTC	09-15-08	10.48	10.9	16.0	–	1.120	0.96	Price Pygmy	G

Table A1. Streamflow measurements made during the 2007–09 low-flow survey conducted by the Northwest Indian Fisheries Commission (NWIFC), NWIFC-member tribes, Point-No-Point Treaty Council, and U.S. Geological Survey in western Washington.—Continued

[**Tribe, organization, or agency that made the measurement:** NWIFC, Northwest Indian Fisheries Commission; PNPTC, Point-No-Point Treaty Council; USGS, U.S. Geological Survey. **Q:** streamflow. **Measurement rating:** E, excellent, less than 2 percent error; F, fair, less than 8 percent error; G, good, less than 5 percent error; P, poor, greater than or equal to 8 percent error. **Abbreviations**: ft^3/s, cubic foot per second; ft^2, square foot; ft; foot; ft/s; foot per second; –, information not provided]

Stream name	Latitude (decimal degrees)	Longitude (decimal degrees)	Tribe, organization, or agency that made the measurement	Date	Q (ft^3/s)	Area (ft^2)	Width (ft)	Number of sections per measurement	Maximum stream depth (ft)	Mean velocity (ft/s)	Current meter type	Measurement rating
Boardman Creek	48.069	-121.681	NWIFC	09-06-07	4.71	6.1	15.5	32	0.700	0.78	Price, Price Pygmy	F
Cabin Creek	47.595	-123.128	USGS	09-07-07	13.30	16.3	19.5	29	1.340	0.82	Price Pygmy	G
				09-20-07	12.00	15.4	19.3	26	1.400	0.78	Sontek Flowtracker	G
			PNPTC	09-11-08	12.23	17.5	29.2	–	1.000	0.70	Price Pygmy	G
				09-16-08	12.24	19.1	28.8	–	1.450	0.64		G
Campbell Creek	47.223	-123.013	Squaxin Island Tribe	08-28-07	3.34	7.9	6.8	14	2.200	0.42	Price Pygmy	F
				08-28-07	3.61	7.9	6.8	14	2.200	0.46		P
				09-10-07	1.33	4.2	9.4	20	0.650	0.32		F
				09-09-08	1.01	3.4	7.5	–	0.790	0.30		E
				09-17-08	0.87	3.3	7.6	–	0.780	0.26		E
				08-20-09	1.09	3.8	7.0	21	0.000	0.28		G
				08-27-09	0.98	4.0	7.5	21	0.000	0.25		G
Canyon Lake Creek	48.833	-122.137	NWIFC	09-11-07	2.34	4.6	13.6	37	0.720	0.51	Price Pygmy	F
Cascade Creek	48.896	-121.859	USGS	08-30-07	0.82	1.3	0.0	27	0.460	0.64	Price Pygmy	G
			Nooksack Indian Tribe	09-16-08	0.24	0.0	0.0	–	0.000	0.00	Price Pygmy	F
Cedar Creek	47.710	-124.412	Hoh Indian Tribe	08-23-07	5.90	7.6	17.0	17	0.650	0.78	Marsh-McBirney	G
				08-23-07	5.60	7.3	17.0	17	0.650	0.77		G
				09-07-07	4.77	7.1	17.0	17	0.640	0.68		G
				09-07-07	4.84	7.1	17.0	17	0.630	0.68		G
				09-20-07	4.18	6.2	16.5	30	0.630	0.67		G
				09-06-08	5.14	8.5	19.0	–	0.720	0.60		E
				09-08-08	8.44	10.5	18.5	–	0.900	0.80		E
				09-17-08	4.80	8.5	18.0	–	0.760	0.57		E
				07-16-09	3.01	5.6	11.1	24	0.730	0.50		F
				07-30-09	1.62	4.8	10.7	28	0.640	0.34		F
Clarks Creek	47.177	-122.317	USGS	09-12-07	8.00	9.5	28.5	30	0.800	0.83	Sontek Flowtracker	F
Clear Creek	48.219	-121.569	Sauk-Suiattle Indian Tribe	08-05-08	86.61	87.1	37.3	–	3.500	0.99	Sontek Flowtracker	F
				08-15-08	59.14	75.2	36.5	–	2.910	0.79		G
				09-08-08	50.42	69.3	36.4	–	2.920	0.73		E
				09-16-08	31.24	58.4	36.3	–	2.680	0.54		G
				07-14-09	58.88	79.0	36.9	31	3.400	0.75		G
				07-23-09	41.48	70.3	36.9	29	2.930	0.59		G
				08-17-09	39.29	65.4	36.8	32	2.930	0.60		E
				09-21-09	46.46	75.6	36.9	34	2.980	0.61		E

Table A1. Streamflow measurements made during the 2007–09 low-flow survey conducted by the Northwest Indian Fisheries Commission (NWIFC), NWIFC-member tribes, Point-No-Point Treaty Council, and U.S. Geological Survey in western Washington.—Continued

[**Tribe, organization, or agency that made the measurement:** NWIFC, Northwest Indian Fisheries Commission; PNPTC, Point-No-Point Treaty Council; USGS, U.S. Geological Survey. **Q:** streamflow. **Measurement rating:** E, excellent, less than 2 percent error; F, fair, less than 8 percent error; G, good, less than 5 percent error; P, poor, greater than or equal to 8 percent error. **Abbreviations**: ft^3/s, cubic foot per second; ft^2, square foot; ft; foot; ft/s; foot per second; –, information not provided]

Stream name	Latitude (decimal degrees)	Longitude (decimal degrees)	Tribe, organization, or agency that made the measurement	Date	Q (ft^3/s)	Area (ft^2)	Width (ft)	Number of sections per measurement	Maximum stream depth (ft)	Mean velocity (ft/s)	Current meter type	Measurement rating
Crescent Creek	47.356	-122.579	USGS	09-07-07	2.09	4.9	16.0	30	0.780	0.43	Sontek Flowtracker	F
Dan Creek	48.277	-121.556	Sauk-Suiattle Indian Tribe	08-29-07	4.28	16.3	0.0	27	1.100	0.26	Price Pygmy	F
				08-05-08	8.52	9.1	19.6	–	0.800	0.94	Sontek Flowtracker	P
				08-15-08	5.20	7.2	19.4	–	0.690	0.72		P
				09-08-08	6.45	8.0	19.3	–	0.760	0.81		P
				09-16-08	4.48	6.8	16.9	–	0.730	0.65		P
				07-15-09	10.11	11.0	22.6	28	1.060	0.92		F
				07-23-09	5.59	8.3	21.9	28	0.930	0.67		P
				07-29-09	4.43	7.7	19.1	26	0.850	0.57		P
				08-17-09	5.36	8.8	21.9	27	0.920	0.61		P
				09-21-09	3.90	7.5	19.6	23	0.840	0.52		P
Deer Creek (Puget Sound tributary)	47.265	-123.005	Squaxin Island Tribe	08-29-07	19.01	13.5	20.4	26	1.000	1.41	Price Pygmy	E
				08-29-07	19.21	13.5	20.4	21	1.000	1.42		G
				09-10-07	17.91	14.3	20.0	21	1.130	1.25		G
				09-10-07	18.34	14.7	20.0	25	1.150	1.24		G
				09-09-08	16.81	7.8	12.2	–	0.880	2.15		E
				09-17-08	15.44	7.8	12.0	–	0.840	1.98		G
				08-20-09	17.38	12.6	21.0	22	0.000	1.38		G
				08-27-09	16.23	11.7	20.5	21	0.000	1.39		G
Deer Creek (Stillaguamish River basin)	48.091	-121.554	NWIFC	09-06-07	4.34	7.7	17.2	25	1.100	0.56	Price, Price Pygmy	F
Deer Creek (Puyallup River basin)	47.181	-122.262	Puyallup Tribe of Indians	09-10-08	0.19	1.5	4.0	–	0.500	0.12	Sontek Flowtracker	E
				09-10-08	0.18	1.4	3.8	–	0.500	0.13		E
				09-15-08	0.19	1.5	4.0	–	0.500	0.13		E
				09-15-08	0.19	1.5	4.0	–	0.500	0.13		E
Elk Creek	47.798	-124.197	Hoh Indian Tribe	08-15-07	2.61	12.1	17.0	17	1.080	0.22	Marsh-McBirney	F
				08-15-07	2.68	12.3	17.0	17	1.050	0.22		F
				09-06-07	2.54	11.8	17.0	17	1.000	0.22		F
				09-06-07	2.58	11.9	17.0	17	1.000	0.22		F
				09-20-07	1.90	11.2	17.0	28	0.920	0.17		F
				08-06-08	2.11	8.2	14.0	–	0.900	0.26		G
				09-08-08	2.72	9.0	15.0	–	0.960	0.30		G
				09-17-08	2.39	8.2	14.5	–	0.930	0.29		G
				07-20-09	1.95	9.3	16.3	30	0.970	0.21		F
				08-03-09	1.70	8.4	15.5	31	0.840	0.20		F

Table A1. Streamflow measurements made during the 2007–09 low-flow survey conducted by the Northwest Indian Fisheries Commission (NWIFC), NWIFC-member tribes, Point-No-Point Treaty Council, and U.S. Geological Survey in western Washington.—Continued

[**Tribe, organization, or agency that made the measurement:** NWIFC, Northwest Indian Fisheries Commission; PNPTC, Point-No-Point Treaty Council; USGS, U.S. Geological Survey. **Q:** streamflow. **Measurement rating:** E, excellent, less than 2 percent error; F, fair, less than 8 percent error; G, good, less than 5 percent error; P, poor, greater than or equal to 8 percent error. **Abbreviations**: ft^3/s, cubic foot per second; ft^2, square foot; ft; foot; ft/s; foot per second; –, information not provided]

Stream name	Latitude (decimal degrees)	Longitude (decimal degrees)	Tribe, organization, or agency that made the measurement	Date	Q (ft^3/s)	Area (ft^2)	Width (ft)	Number of sections per measurement	Maximum stream depth (ft)	Mean velocity (ft/s)	Current meter type	Measurement rating
Ennis Creek	48.108	-123.398	USGS	09-09-07	2.92	4.4	10.6	27	0.900	0.66	Price Pygmy	G
Field Creek	48.140	-123.785	Port Gamble S'Klallam Tribe	09-15-08	1.00	1.0	1.0		1.000	1.00	Other	P
Gamble Creek	47.809	-122.581	Port Gamble S'Klallam Tribe	08-24-09	1.39	1.2	5.2	21	0.340	1.19	Price Pygmy	G
				09-11-09	1.46	1.3	5.0	21	0.360	1.13		G
				09-18-09	1.32	1.4	4.9	21	0.380	0.96		G
				09-21-09	1.42	1.5	5.3	22	0.380	0.92		G
				09-28-09	1.40	1.5	5.3	21	0.390	0.91		G
Goodman Creek	47.833	-124.461	Hoh Indian Tribe	08-17-07	15.25	21.1	29.0	29	1.260	0.72	Marsh-McBirney	P
				08-17-07	15.32	21.5	29.0	29	1.300	0.71		P
				09-11-07	9.76	17.3	27.0	27	1.040	0.57		P
				09-11-07	9.54	17.0	27.0	27	1.050	0.56		P
				09-21-07	7.21	16.2	26.5	43	1.020	0.44		P
				08-05-08	15.23	24.2	32.0	–	1.170	0.63		F
				09-19-08	9.33	20.0	32.0	–	1.170	0.47		F
				07-22-09	2.61	19.6	34.0	39	0.930	0.13		P
				07-30-09	2.23	19.0	34.0	38	0.900	0.12		P
Gravel Creek	48.297	-121.525	USGS	08-29-07	0.32	0.6	0.0	22	0.340	0.50	Price Pygmy #8009583	F
Harding Creek	47.585	-122.945	Port Gamble S'Klallam Tribe	07-30-09	2.88	2.1	7.5	27	0.480	1.36	Price Pygmy	G
				08-06-09	3.62	2.6	7.5	34	0.460	1.37	Swoffer 2100	F
				08-25-09	3.43	2.5	7.6	33	0.430	1.40		F
				08-26-09	3.09	2.5	7.7	33	0.450	1.23	Price Pygmy	G
Jefferson Creek	47.583	-123.107	USGS	09-07-07	16.10	26.6	22.5	26	2.200	0.60	Price, Price Pygmy S/N P97402	G
				09-20-07	12.00	26.5	23.0	21	2.350	0.45	ADV	G
John Creek	47.539	-123.098	USGS	09-07-07	0.23	0.6	2.7	12	0.380	0.36	Price, Price Pygmy S/N P97402, and bucket	F
				09-20-07	0.21	0.0	0.0	–	0.000	0.00	Calibrated bucket	F
Johnson Creek	48.993	-122.267	NWIFC	09-07-07	10.07	18.2	16.8	29	1.360	0.55	Price, Price Pygmy	G
				09-07-07	9.95	18.4	16.8	31	1.360	0.54		G

Table A1. Streamflow measurements made during the 2007–09 low-flow survey conducted by the Northwest Indian Fisheries Commission (NWIFC), NWIFC-member tribes, Point-No-Point Treaty Council, and U.S. Geological Survey in western Washington.—Continued

[**Tribe, organization, or agency that made the measurement:** NWIFC, Northwest Indian Fisheries Commission; PNPTC, Point-No-Point Treaty Council; USGS, U.S. Geological Survey. **Q:** streamflow. **Measurement rating:** E, excellent, less than 2 percent error; F, fair, less than 8 percent error; G, good, less than 5 percent error; P, poor, greater than or equal to 8 percent error. **Abbreviations**: ft^3/s, cubic foot per second; ft^2, square foot; ft; foot; ft/s; foot per second; –, information not provided]

Stream name	Latitude (decimal degrees)	Longitude (decimal degrees)	Tribe, organization, or agency that made the measurement	Date	Q (ft^3/s)	Area (ft^2)	Width (ft)	Number of sections per measurement	Maximum stream depth (ft)	Mean velocity (ft/s)	Current meter type	Measurement rating
Kalaloch Creek	47.614	-124.348	Hoh Indian Tribe	09-11-07	6.94	14.0	17.0	24	1.270	0.50	Marsh-McBirney	F
				09-11-07	7.04	13.9	17.0	24	1.280	0.51		F
				09-21-07	7.17	14.4	16.5	33	1.360	0.50		F
				08-06-08	13.42	47.1	34.0	–	2.170	0.28		F
				07-16-09	6.85	14.5	16.0	31	1.370	0.47		F
				07-29-09	4.96	12.8	15.0	34	1.250	0.36		F
Kennedy Creek	47.096	-123.090	Squaxin Island Tribe	08-28-07	4.17	4.8	17.3	25	0.490	0.86	Price Pygmy	E
				08-28-07	4.25	5.0	17.3	19	0.490	0.86		G
				09-11-07	3.94	4.2	16.4	18	0.400	0.94		G
				09-11-07	4.01	4.1	16.4	24	0.400	0.97		E
				09-10-08	3.85	8.8	21.0	–	0.620	0.44		E
				09-19-08	3.78	8.4	21.5	–	0.600	0.45		E
				08-20-09	4.26	12.2	18.5	22	0.000	0.35		G
				08-27-09	4.00	12.2	18.5	20	0.000	0.33		G
Little Boston Creek	47.855	-122.568	Port Gamble S'Klallam Tribe	09-04-08	0.28	0.7	2.7	–	0.300	0.40	Price Pygmy	P
Malaney Creek	47.249	-123.011	Squaxin Island Tribe	08-28-07	1.99	3.9	8.5	17	0.800	0.52	Price Pygmy	F
				08-28-07	2.04	4.2	8.5	16	0.900	0.48		F
				09-10-07	0.88	2.0	6.5	14	0.420	0.45		F
				09-09-08	0.82	2.4	9.2	–	0.500	0.35		E
				09-17-08	0.65	2.2	9.2	–	0.520	0.29		E
				08-20-09	0.82	3.8	9.5	31	0.000	0.22		G
				08-27-09	0.67	4.0	10.2	19	0.000	0.17		G
Middle Creek	47.841	-122.566	PNPTC	08-23-07	0.47	0.7	2.7	16	0.400	0.69	Swoffer 3000	G
Middle Fork Woods Creek	47.882	-121.913	Tulalip Tribes	09-06-07	5.84	12.6	18.1	27	0.880	0.46	Price Pygmy	F
				09-06-07	6.25	11.9	0.0	28	0.870	0.53		G
				09-08-08	7.05	8.9	18.1	22	0.770	0.79		G
				10-02-08	7.66	9.1	17.8	29	0.800	0.84		E
				09-28-09	5.16	9.3	19.9	24	0.900	0.56		G
Montague Creek at Highway 530 Bridge	48.269	-121.881	Stillaguamish Tribe of Indians	09-04-07	2.09	0.0	14.8	25	0.300	0.64	Swoffer 2100	G
Mosquito Creek	47.809	-124.430	Hoh Indian Tribe	08-05-08	7.22	11.4	19.0	–	0.980	0.63	Marsh-McBirney	F

Table A1. Streamflow measurements made during the 2007–09 low-flow survey conducted by the Northwest Indian Fisheries Commission (NWIFC), NWIFC-member tribes, Point-No-Point Treaty Council, and U.S. Geological Survey in western Washington.—Continued

[**Tribe, organization, or agency that made the measurement:** NWIFC, Northwest Indian Fisheries Commission; PNPTC, Point-No-Point Treaty Council; USGS, U.S. Geological Survey. **Q:** streamflow. **Measurement rating:** E, excellent, less than 2 percent error; F, fair, less than 8 percent error; G, good, less than 5 percent error; P, poor, greater than or equal to 8 percent error. **Abbreviations**: ft^3/s, cubic foot per second; ft^2, square foot; ft; foot; ft/s; foot per second; –, information not provided]

Stream name	Latitude (decimal degrees)	Longitude (decimal degrees)	Tribe, organization, or agency that made the measurement	Date	Q (ft^3/s)	Area (ft^2)	Width (ft)	Number of sections per measurement	Maximum stream depth (ft)	Mean velocity (ft/s)	Current meter type	Measurement rating
Nolan Creek	47.751	-124.324	Hoh Indian Tribe	08-16-07	4.18	7.0	12.5	25	0.930	0.60	Marsh-McBirney	F
				08-16-07	4.21	7.0	12.5	25	0.930	0.60		F
				09-07-07	3.75	6.7	12.5	22	0.880	0.56		F
				09-07-07	3.74	6.7	12.5	22	0.850	0.56		F
				09-20-07	2.34	5.8	12.5	23	0.800	0.40		F
				08-06-08	3.30	6.2	12.0	–	0.800	0.53		G
				09-16-08	3.70	7.1	12.5	–	0.800	0.52		G
				09-19-08	3.45	7.1	12.5	–	0.770	0.49		G
				09-23-08	3.10	6.8	12.5	–	0.720	0.45		G
				07-16-09	2.49	4.3	10.5	20	0.600	0.59		G
				07-30-09	1.47	3.3	10.0	23	0.490	0.44		G
North Fork Stilllaguamish River	48.282	-121.641	Stillaguamish Tribe of Indians	09-04-07	24.23	0.0	66.5	26	1.600	0.44	Swoffer 2100	F
				09-04-07	22.26	0.0	61.0	25	1.870	0.25		F
Olney Creek	47.873	-121.713	Tulalip Tribes	09-06-07	10.31	12.9	24.5	25	1.200	0.81	Price Pygmy	E
				09-06-07	10.10	13.5	65.0	26	1.020	0.75	Sontek Flowtracker	F
				09-09-08	20.48	16.1	26.2	27	1.130	1.28	Price Pygmy	G
				10-02-08	21.31	16.7	26.2	30	1.120	1.28		E
				09-24-09	12.39	10.2	17.0	25	1.000	1.21		G
				09-28-09	10.30	9.0	16.5	22	1.000	1.14		G
Owl Creek	47.801	-124.079	Hoh Indian Tribe	08-15-07	18.98	15.8	24.0	23	1.050	1.20	Marsh-McBirney	F
				08-15-07	18.60	15.9	24.0	23	1.050	1.17		F
				09-06-07	14.74	13.7	23.0	23	0.950	1.07		F
				09-06-07	14.42	13.8	23.0	23	0.950	1.05		F
				09-20-07	11.82	12.8	23.0	35	0.880	0.92		F
				08-05-08	14.54	17.5	23.5	–	1.280	0.83		F
				09-09-08	22.41	22.1	26.0	–	1.450	1.01		F
				09-18-08	16.66	19.2	26.0	–	1.240	0.87		F
				07-20-09	11.47	24.5	23.0	28	1.640	0.47		F
				08-03-09	9.58	23.7	21.7	33	1.640	0.41		F
Percival Creek	47.022	-122.932	Squaxin Island Tribe	08-28-07	2.50	3.7	11.8	12	0.500	0.68	Swoffer	G
				08-28-07	2.20	3.7	11.8	12	0.500	0.60	Swoffer	G
				09-21-09	2.41	2.8	9.4	20	0.000	0.86	Price Pygmy	G
				09-28-09	2.01	2.9	9.4	19	0.000	0.69	Price Pygmy	G

Table A1. Streamflow measurements made during the 2007–09 low-flow survey conducted by the Northwest Indian Fisheries Commission (NWIFC), NWIFC-member tribes, Point-No-Point Treaty Council, and U.S. Geological Survey in western Washington.—Continued

[**Tribe, organization, or agency that made the measurement:** NWIFC, Northwest Indian Fisheries Commission; PNPTC, Point-No-Point Treaty Council; USGS, U.S. Geological Survey. **Q:** streamflow. **Measurement rating:** E, excellent, less than 2 percent error; F, fair, less than 8 percent error; G, good, less than 5 percent error; P, poor, greater than or equal to 8 percent error. **Abbreviations**: ft^3/s, cubic foot per second; ft^2, square foot; ft; foot; ft/s; foot per second; –, information not provided]

Stream name	Latitude (decimal degrees)	Longitude (decimal degrees)	Tribe, organization, or agency that made the measurement	Date	Q (ft^3/s)	Area (ft^2)	Width (ft)	Number of sections per measurement	Maximum stream depth (ft)	Mean velocity (ft/s)	Current meter type	Measurement rating
Perry Creek	47.049	-123.007	Squaxin Island Tribe	08-28-07	0.61	3.5	8.8	24	0.700	0.17	Price Pygmy	G
				08-28-07	0.59	3.6	8.8	23	0.690	0.17		G
				09-11-07	0.48	3.4	8.9	18	0.680	0.14		F
				09-10-08	0.52	2.8	7.8	–	0.510	0.19		E
				09-19-08	0.44	2.2	8.0	–	0.420	0.20		E
				09-21-09	0.68	3.3	16.0	19	0.000	0.21		G
				09-28-09	0.39	4.0	17.8	26	0.000	0.10		G
Purdy Creek	47.389	-122.625	Squaxin Island Tribe	08-29-07	1.60	1.6	7.3	21	0.380	1.03	Price Pygmy	G
				08-29-07	1.56	1.6	7.3	21	0.400	1.00		G
				09-10-07	1.57	1.7	7.5	16	0.380	0.95		F
				08-20-09	1.43	2.9	8.5	23	0.000	0.50		G
				08-27-09	1.43	2.8	8.5	20	0.000	0.50		G
Rocky Creek	47.371	-122.781	Squaxin Island Tribe	08-29-07	3.60	6.1	16.0	27	0.750	0.59	Price Pygmy	G
				08-29-07	3.51	6.0	16.0	18	0.740	0.59		G
				09-10-07	3.74	6.1	15.8	21	0.730	0.61		G
				09-09-08	3.33	9.4	17.0	–	0.830	0.36		E
				09-17-08	2.65	9.7	17.5	–	0.950	0.27		E
				08-20-09	2.84	9.1	22.0	25	0.000	0.31		G
				08-27-09	2.75	8.8	21.8	24	0.000	0.31		G
Schneider Creek	47.092	-123.071	Squaxin Island Tribe	08-28-07	0.89	1.3	4.0	14	0.590	0.68	Price Pygmy	G
				08-28-07	0.91	1.2	4.0	14	0.580	0.73		F
				09-11-07	0.86	1.2	4.1	9	0.500	0.70		F
				09-10-08	0.67	1.9	9.3	–	0.370	0.35		E
				09-19-08	0.63	2.6	10.0	–	0.530	0.24		E
				09-21-09	0.66	3.1	10.0	17	0.000	0.21		G
				09-28-09	0.62	2.3	9.4	18	0.000	0.27		G
Segelson Creek	48.283	-121.716	Stillaguamish Tribe of Indians	09-04-07	2.01	0.0	19.0	24	1.320	0.14	Swoffer 2100	E
				09-04-07	2.04	0.0	19.0	24	1.220	0.14		E

Table A1. Streamflow measurements made during the 2007–09 low-flow survey conducted by the Northwest Indian Fisheries Commission (NWIFC), NWIFC-member tribes, Point-No-Point Treaty Council, and U.S. Geological Survey in western Washington.—Continued

[**Tribe, organization, or agency that made the measurement:** NWIFC, Northwest Indian Fisheries Commission; PNPTC, Point-No-Point Treaty Council; USGS, U.S. Geological Survey. **Q:** streamflow. **Measurement rating:** E, excellent, less than 2 percent error; F, fair, less than 8 percent error; G, good, less than 5 percent error; P, poor, greater than or equal to 8 percent error. **Abbreviations**: ft^3/s, cubic foot per second; ft^2, square foot; ft; foot; ft/s; foot per second; –, information not provided]

Stream name	Latitude (decimal degrees)	Longitude (decimal degrees)	Tribe, organization, or agency that made the measurement	Date	Q (ft^3/s)	Area (ft^2)	Width (ft)	Number of sections per measurement	Maximum stream depth (ft)	Mean velocity (ft/s)	Current meter type	Measurement rating
Shine Creek	47.874	-122.708	PNPTC	08-29-07	1.92	4.0	11.5	28	0.720	0.48	Swoffer 3000	F
				09-13-07	2.07	3.7	11.5	24	0.810	0.56		F
				09-05-08	2.12	2.8	7.5	–	0.630	0.75	Price Pygmy	G
				09-16-08	1.75	3.1	7.3	–	0.640	0.57		G
			Port Gamble S'Klallam Tribe	08-24-09	1.64	2.9	6.8	30	0.680	0.57	Price Pygmy	G
				08-24-09	1.64	3.0	6.8	30	0.710	0.54	Swoffer 2100	G
				09-11-09	1.65	3.3	7.1	32	0.730	0.50	Price Pygmy	G
				09-18-09	1.49	3.2	7.2	31	0.730	0.46		G
				09-21-09	1.59	3.4	7.1	28	0.710	0.47		G
				09-28-09	1.67	3.5	7.5	31	0.710	0.48		G
Siebert Creek	48.094	-123.280	USGS	09-09-07	2.48	4.2	16.0	26	0.500	0.59	Price Pygmy	F
Simons Creek	47.221	-122.306	Puyallup Tribe of Indians	09-09-08	1.37	2.3	4.8	–	0.700	0.59	Marsh-McBirney	E
				09-09-08	1.45	2.4	4.8	–	0.700	0.61		E
				09-15-08	1.44	2.2	4.6	–	0.700	0.66		E
				09-15-08	1.44	2.2	4.6	–	0.700	0.65	Sontek Flowtracker	E
South Fork Nooksack River	48.783	-122.219	NWIFC	09-07-07	0.24	1.0	3.4	12	0.440	0.24	Price, Price Pygmy	F
				09-07-07	0.27	0.9	3.4	11	0.420	0.30		F
Sumas River	48.977	-122.254	NWIFC	09-07-07	8.92	15.3	11.9	19	1.900	0.58	Price, Price Pygmy	G
Thomas Creek	47.561	-122.973	Port Gamble S'Klallam Tribe	09-02-08	2.61	1.2	3.7	–	0.400	2.23	Price Pygmy	P
				09-12-08	2.04	1.3	4.6	–	0.430	1.62		F
				07-30-09	1.64	0.9	5.0	25	0.330	1.88		G
				08-06-09	2.10	1.2	4.9	22	0.380	1.72	Swoffer 2100	F
				08-25-09	1.58	1.2	5.0	22	0.370	1.35	Price Pygmy	G
				09-23-09	1.63	1.2	5.3	22	0.380	1.35		G
Tumwater Creek	48.107	-123.459	USGS	09-09-07	0.90	1.5	7.1	24	0.320	0.62	Price Pygmy	G
Unknown Tributary	47.842	-122.591	PNPTC	08-23-07	0.09	0.0	1.3	–	0.000	0.00	Bucket and Watch	F
Unknown Tributary	47.584	-123.087	USGS	09-07-07	0.17	0.0	0.0	–	0.000	0.00	Calibrated bucket	F
				09-20-07	0.14	0.0	0.0	–	0.000	0.00		F
Wacketickeh Creek	47.576	-123.059	USGS	09-07-07	1.55	5.5	12.0	26	0.900	0.28	Price Pygmy	P
				09-20-07	0.98	5.6	13.8	33	0.700	0.18	Sontek Flowtracker	F
			Port Gamble S'Klallam Tribe	09-11-08	1.05	4.0	5.3	–	1.040	0.26	Price Pygmy	F
				09-16-08	0.85	4.0	5.5	–	1.000	0.21	Marsh-McBirney	F

Table A1. Streamflow measurements made during the 2007–09 low-flow survey conducted by the Northwest Indian Fisheries Commission (NWIFC), NWIFC-member tribes, Point-No-Point Treaty Council, and U.S. Geological Survey in western Washington.—Continued

[**Tribe, organization, or agency that made the measurement:** NWIFC, Northwest Indian Fisheries Commission; PNPTC, Point-No-Point Treaty Council; USGS, U.S. Geological Survey. **Q:** streamflow. **Measurement rating:** E, excellent, less than 2 percent error; F, fair, less than 8 percent error; G, good, less than 5 percent error; P, poor, greater than or equal to 8 percent error. **Abbreviations**: ft^3/s, cubic foot per second; ft^2, square foot; ft; foot; ft/s; foot per second; –, information not provided]

Stream name	Latitude (decimal degrees)	Longitude (decimal degrees)	Tribe, organization, or agency that made the measurement	Date	Q (ft^3/s)	Area (ft^2)	Width (ft)	Number of sections per measurement	Maximum stream depth (ft)	Mean velocity (ft/s)	Current meter type	Measurement rating
Wagley Creek	47.867	-121.790	Tulalip Tribes	09-06-07	0.55	1.3	3.1	27	0.510	0.42	Price Pygmy	G
				09-06-07	0.57	1.2	27.0	27	0.490	0.48		F
				09-09-08	0.83	2.2	9.8	26	0.800	0.37		G
				10-02-08	0.80	1.4	9.1	31	0.230	0.56		E
				09-24-09	0.50	1.0	9.5	23	0.320	0.50		G
				09-28-09	0.48	1.1	9.8	24	0.350	0.43		G
Wells Creek	48.867	-121.766	USGS	08-30-07	33.60	18.3	0.0	32	1.040	1.83	Price Pygmy	F
			Nooksack Indian Tribe	09-17-08	21.60	0.0	0.0	–	0.000	0.00	Price Pygmy	F
				10-28-08	18.65	0.0	0.0	–	0.000	0.00		F
Whiskey Creek	48.139	-123.765	Port Gamble S'Klallam Tribe	09-15-08	1.00	1.0	1.0	–	1.000	1.00	–	P
Willoughby Creek	47.822	-124.199	Hoh Indian Tribe	08-16-07	3.06	11.9	20.0	20	0.970	0.26	Marsh-McBirney	F
				08-16-07	2.92	11.7	20.0	20	0.980	0.25		F
				09-06-07	2.89	12.6	19.0	21	0.950	0.23		F
				09-06-07	3.07	12.8	19.0	21	0.980	0.24		F
				09-19-07	1.91	11.9	19.0	23	0.920	0.16		F
				07-11-08	2.70	12.7	18.5	–	1.140	0.21		F
				07-24-08	1.98	12.1	18.2	–	1.100	0.16		F
				08-07-08	2.04	12.9	18.5	–	1.020	0.16		F
				09-09-08	4.54	14.2	18.0	–	1.050	0.32		F
				09-18-08	2.91	12.9	18.0	–	0.950	0.23		F
				07-21-09	1.70	5.1	12.0	22	0.640	0.34		G
				08-04-09	1.21	4.6	11.0	27	0.610	0.26		G
Winfield Creek	47.798	-124.228	Hoh Indian Tribe	08-15-07	8.88	21.7	38.0	19	1.000	0.41	Marsh-McBirney	G
				08-15-07	9.00	21.8	38.0	19	1.000	0.41		G
				09-07-07	7.51	21.6	37.0	19	0.950	0.35		G
				09-07-07	7.23	21.4	37.0	19	0.960	0.34		G
				09-19-07	5.23	19.1	36.0	30	0.940	0.27		G
				07-11-08	8.16	20.8	37.5	–	1.130	0.39		G
				07-23-08	6.25	19.9	35.0	–	1.180	0.31		G
				08-07-08	6.39	19.9	34.5	–	1.170	0.32		G
				09-08-08	11.40	24.5	40.0	–	1.270	0.47		G
				09-17-08	7.22	21.2	37.0	–	1.140	0.34		G
				07-21-09	5.17	14.2	20.0	39	1.030	0.36		G
				08-03-09	4.15	13.9	20.0	38	1.050	0.30		G
Woodard Creek	47.084	-122.864	Squaxin Island Tribe	08-28-07	0.00	1.6	4.0	9	0.300	0.00	Swoffer	–

Publishing support provided by the U.S. Geological Survey
Publishing Network, Tacoma Publishing Service Center

For more information concerning the research in this report, contact the
Director, Washington Water Science Center
U.S. Geological Survey
934 Broadway, Suite 300
Tacoma, Washington 98402
http://wa.water.usgs.gov

USGS

Curran and others— **Analysis of Low Flows and Methods for Estimating Low-Flow Characteristics at Stream Sites in Western Washington**—Scientific Investigations Report 2012-5078