State of Washington
CHRISTINE O. GREGOIRE, Governor

Department of Fish and Wildlife
Philip M. Anderson, Interim Director

SCIENCE DIVISION
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Report of Investigations in Instream Flow

HIGH FLOWS FOR FISH AND WILDLIFE IN WASHINGTON

by

Alan R. Wald, LHg.
Habitat Program. Olympia, WA.

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Acknowledgement. This study was proposed, developed, and guided by Dr. Hal Beecher, superviser of the Water Team in the Habitat Program. The author is deeply appreciative of his advice, encouragement, and thoughtful review. It is hoped this report may serve as an example of how the applied science of instream flows benefits from the collaboration of hydrologists and fisheries biologists.

Abstract

The Washington Department of Fish and Wildlife (WDFW) develops instream flow recommendations to protect and restore fish and wildlife habitat in streams. Recent advances in instream flow science document the importance of protecting and restoring high flows that create habitat. High flows provide desirable conditions for fish migration and spawning, flush organic matter from the channel, maintain channel geometry by transporting sediment, and form new channels by stream meandering, side-channel activation, and renewal of riparian and floodplain vegetation. Recommendations for protecting and restoring high flows include high flow pulses and flushing flows, channel maintenance flows, and channel forming flows. High flows are quantified by their magnitude, duration, frequency, timing (rate of change), and seasonality. Each of these characteristics may vary among different hydrologic regimes in the state. High flow pulses and flushing flows on unregulated streams are on the order of mean annual discharges. Channel maintenance flows on unregulated streams are on the order of 1.5 to 2-year recurrence interval peak flows. Channel forming flows on unregulated streams are on the order of 10 to 25-year recurrence interval peak flows. High flows on regulated streams may vary according to flow influences due to storage and diversion for agricultural irrigation, municipal water use, hydropower generation, flood control, or other purposes. This report presents proposed changes to high flow recommendations in the WDFW Instream Flow Guidelines.

1. Introduction

The Washington Department of Fish and Wildlife (WDFW) is responsible for preserving, protecting, and perpetuating the state's fish and wildlife resources in accordance with state law (Chapters 75 and 77 Revised Code of Washington, 2008). This responsibility includes preserving and protecting sufficient habitat to ensure the abundance, distribution, and diversity of fish and wildlife. WDFW resource managers recognize that the amount of water flowing in streams directly affects fish and wildlife habitat. WDFW recommends "instream flows" (flows needed to protect stream habitat) for watershed planning, water rights administration, mitigation of major project development and operations, and protection of endangered species. Instream flows include both relatively low chronic flows necessary for survival of fish and wildlife and shorter duration high flows necessary for preserving and creating their habitat.

WDFW provides technical assistance and instream flow recommendations based on its technical expertise in biology and ecology. Geomorphology has unfortunately not been extensively incorporated into instream flow science as practiced by instream flow biologists with fisheries backgrounds. That lack of knowledge has been widely noted and has limited the benefits of instream flow recommendations for protecting salmon and trout in the state.

Much of the following discussion addresses salmon and trout although flow also affects other wildlife. Instream flow directly affects riparian vegetation which is important habitat for a wide variety of birds, mammals, reptiles, and amphibians. Orca whales, harbor seals and sea lions, river otters, black bear, raccoons, bald eagles, osprey, mergansers, cormorants, and great blue herons all eat salmon that depend on stream habitat and flow.

High flows provide functions important for stream habitat such as channel flushing, sediment transport, wood recruitment, and maintenance of riparian and floodplain habitat. Instream flow recommendations for high flows include high flow pulses and flushing flows for in-channel functions, channel maintenance flows for in-channel and riparian functions, and channel forming flows for side-channel and floodplain functions. High flow recommendations for different hydrologic regimes are typically defined by empirical methods using stream gage records, frequency curves, and regional analysis.

WDFW has several policies for developing instream flow recommendations that include high flows but they are limited in practice. Revision of the WDFW Instream Flow Study Guidelines to include methods for defining high flow pulses and flushing flows, channel maintenance, and channel forming flows could improve this practice.

Note: all stream gages listed in the tables and figures of this report are in Washington.

2. High flow hydraulics

The hydraulic properties of high flow include the relationship of stream discharge to the stream power required for entrainment and transport of sediment and wood. Stream discharge (volume per unit time) is a product of flow velocity (distance water moves per unit time) multiplied by the cross-sectional area (depth times width) of a channel. Flow velocity derives primarily from channel slope and the energy grade line of a stream. Slope and velocity are directly proportional and an increase in slope increases flow velocity. An increase in velocity for a constant discharge requires a proportional decrease in flow area.

The Chezy equation, or:

$$\text{Velocity} = \text{a Constant (hydraulic radius x slope)}^{-2}$$

illustrates the relationship of flow velocity to flow area and channel slope where the hydraulic radius is the wetted perimeter of the channel cross-sectional area (Morisawa, 1964). Manning's equation introduces a channel roughness factor to the constant C to account for gravity and channel resistance at the hydraulic radius where;

$$\text{Velocity} = 1.49/n\ (\text{hydraulic radius})^{2/3}\ (\text{slope})^{1/2}$$

and n = a Manning's roughness coefficient.

Flow velocity increases with increased channel slope and decreases with greater channel roughness. The effect of roughness on flow velocity depends on depth of flow (submergence) and particle size of bed materials. Small-scale roughness occurs where the ratio of water depth to particle size is >15. Intermediate scale roughness occurs where the ratio is >4.0 and <15 which results in increased flow friction on bed sediments. Large scale roughness occurs where the ratio is <4 and velocity is reduced by tractive forces or drag on relatively large bed sediments.

Flow velocity, channel slope, and channel roughness influence channel form (Leopold, Wolman, and Miller,1964; Leopold, 1994). The fundamental relationships of velocity, slope, depth of flow, and roughness account for longitudinal change in alluvial channel forms from pools (low gradient, low velocity, greater depth, and small scale roughness) to runs (increased gradient, higher velocity, reduced depth, and intermediate scale roughness) to riffles (increased gradient, high velocity, shallow depth, and large scale roughness).

Stream discharge, sediment size, and stream power control the rate and volume of sediment and wood transport. Small particles of clay, silt, and find sand (up to .02 inches in diameter) move as suspended sediment in the water column. Medium to coarse sand (up to .08 inches in diameter) typically moves as wash load or suspended sediment near the bed surface. Bedload composed of larger sand, gravel, and cobbles (up to 10 inches in diameter) move by entrainment and saltation (skipping or bouncing). Wash load and bedload are difficult to mobilize and typically move in an episodic fashion, rather than by seasonal or continuous transport, when high velocity and tractive forces exceed boundary conditions for a mix of substrate sizes.

The DuBoys equation defines the critical tractive force F_t required for sediment mobilization, where:

F_t = the specific weight of water (lb) x depth (ft) x stream gradient (ft/mile)

The tractive force required for entrainment of various particle sizes ranges from .013 lbs/ft^2 for silts (.001 inch diameter) to .13 lbs/ft^2 for sands (.01 inch diameter) to 1.3 lb/ft^2 for small gravel (.1 inch diameter)

Table 1 presents the average discharge and theoretical tractive force for selected streams in Washington (WA). Tractive force ranges from .02 lbs/ft^2 for Crab Creek at Irby to 1.0 lbs/ft^2 for North Fork Quinault River near Amanda Park.

USGS gage	Stream or River	Average Discharge (cfs)	Mean Slope (ft/mi)	Depth (ft)	Tractive Force F_t (lbs/ft^2)
12035000	Satsop River nr Satsop	2009	14	5.6	.08
12039300	NF Quinault River nr Amanda P.	874	238	4.3	1.0
12449500	Methow River at Twisp	1324	72	2.2	.31
12040500	Queets River nr Clearwater	4224	31	4.8	.15
12465000	Crab Creek at Irby	67.8	13	1.6	.02
12113000	Green River nr Auburn	1343	33	3.6	.12
12093500	Puyallup River near Orting	718	214	2.8	.59
12148500	Tolt River nr Carnation	609	115	3.5	.40
12424000	Hangman Creek at Spokane	229	12.5	2.7	.03

Table 1. Average discharge and theoretical tractive force for selected streams in WA.

All nine stations have a theoretical tractive force at average discharge sufficient for entrainment of medium to coarse sand particles (.01 - .02 lbs/sq ft). Six stations have a theoretical tractive force at average discharge sufficient for entrainment of fine gravel particles (.1 - .2 lbs/sq ft). The North Fork Quinault River has sufficient theoretical tractive force at average discharge for entrainment of gravel (1-2 lbs/sq ft).

The Reynolds Number defines the depth-velocity criteria for turbulent flow (Reynolds Number >500) where viscosity is the resistance to flow:

Reynolds Number = the density of flow (velocity x hydraulic radius) (viscosity of flow)$^{1/2}$

Flow in natural rivers is nearly always fully turbulent (Leopold, Wolman, and Miller, 1964). Streams in Washington typically have a Reynolds Number that is orders of magnitude greater than 500. The

Reynolds Number for an average discharge of 2009 cfs on the Satsop River at Satsop is 9.27×10^5.

The Froude Number defines the depth-velocity threshold (Froude Number > 1) for supercritical flow (which is laminar and of high velocity, typically greater than 10 feet/sec) where:

Froude Number = velocity (force of gravity x depth of flow)$^{1/2}$

The Froude Number provides an index to shear forces and the erosion potential of high velocities acting on bed sediments. Higher flows may entrain loose, fine sediments when the Froude Number is > 0.1. High flow pulses and channel flushing flows would require a Froude Number > 0.1. Channel maintenance flows with active bedload entrainment would require a considerably higher Froude Number (>0.1 but <1.0). A Froude Number >1.0 is associated with smooth, confined channels and supercritical velocities.

Table 2 compares Froude Numbers for a range of flows for selected streams in Washington. The flows are average discharge, 2 times average discharge, and 10-year recurrence interval peak flow. The Froude Number ranges from .02 for average discharge on the Satsop River at Satsop to .64 for a 10-year recurrence interval peak flow on the Methow River at Twisp.

USGS gage	Stream or River	Fr_{avg*}	Fr_{2x**}	$Fr_{10\text{-}yr***}$
12035000	Satsop River nr Satsop	.02	.24	.57
12039300	NF Quinault River nr Amanda	.14	.17	
12449500	Methow River at Twisp	.49	.48	.64
12081000	Woodland Creek nr Olympia	.20	.15	
12040500	Queets River nr Clearwater	.18	.24	.4

*avg = average discharge
**2x = 2 times average discharge
***10-yr = 10- year recurrence interval discharge

Table 2. Froude number for a range of flows for selected streams in WA.

The Froude Numbers (based on mean depth and velocity criteria) presented in Table 2 suggest that average discharge on these streams could entrain fine sediment and organic material for channel flushing functions. The ratio of minimum mean depth (1.3 feet) to particle size for high flow pulses is >15 for particle sizes of less than 1 inch. High flow pulses (2 times average discharge) have sufficient submergence and Froude Numbers to flush fine to medium sands from the channel. A 10-year recurrence interval peak flow would mobilize coarse gravel and cobbles.

Depth-velocity criteria and submergence determine the size of entrained sediment but flow magnitude determines the volume of sediment in transport. The duration of high flows with sustained tractive forces determine the distance coarse sediment travels. Rainfall dominated hydrologic regimes with numerous high flow events of fairly short duration (typically a few days at a time) may move suspended sediments a considerable distance downstream but are less likely to move coarse bedload appreciable distances. Several studies have documented snowmelt derived high flows with durations of 22 days or longer and bedload travel distances of greater than 900 feet per year (Leopold and Emmett, 1984). The frequency of occurrence of high flow of sufficient magnitude and duration to mobilize coarse sediment determines the total load and sediment yield.

3. High flow functions.

Early analyses of the minimum flow needed for salmon and steelhead in the Pacific Northwest focused on spawning habitat, fish passage in shallows, and food production for young fish. There was early recognition that maintaining gravel quality for spawning and incubation required flushing by higher flows. Stream biologists have long recognized the role of high flows or freshets for migration of adult and juvenile fish. High flows are also known to have adverse effects on fish and fish habitat. Large floods that provide habitat benefits for fish populations on the whole may also scour redds, dislodge or smother eggs, and strand juvenile and adult fish as the water recedes.

Instream flow science has evolved in recent years to recognize the role of high flows and the functions they provide in a more holistic consideration of stream ecology (Poff et al, 1997). High flow functions combine dynamic elements of physical habitat, flow factors, and life stages of fish. Using flow as a common denominator for these physical-biological interactions is a simplification of the web of ecological processes in a stream that includes plant, invertebrate and vertebrate species interactions, water quality factors, and a host of other variables.

A “three rivers concept” considers the dynamic interaction of water, sediment, and wood in natural channels. A river transports sediment entrained from headwater, tributary, and riverbank sources down the channel with temporary deposition and storage in gravel bars, bedload deposits, and overbank areas to eventually discharge at the mouth. A river transports wood entrained from riparian and floodplain sources down the channel with temporary deposition and storage in logjams, gravel bars, and pools to eventually discharge at the mouth. High flows provide much of the energy needed for entrainment and transport of these river loads. The dynamic interaction of the three elements accounts for recruitment and entrainment of large woody debris by bank erosion and channel changes during high flows, degradation of bedload size and roughness (smoothing and alignment of bed material) during transport, storage of sediment deposits behind wood accumulations, and deposition of fine sediment and organic matter in deltas at the mouths of rivers. A river observer standing on a bridge or high bank should be able to distinguish elements of these three rivers of water, sediment, and wood. Figure 1 shows elements of water, sediment, and wood in stages of entrainment and temporary storage in the Deschutes River, near Olympia.

Figure 1. Elements of water, sediment and wood in the Deschutes River near Olympia

High flow functions associated with sediment and wood transport vary with the hydrologic regime or pattern of streamflow. For example, channelmaintenance flows on natural streams may occur during prolonged rains in the Fall or snowmelt in the Spring. The Nature Conservancy has developed an Indicators of Hydrologic Alteration (IHA) program for quantifying flow components in a regulated hydrologic regime (Richter, 1999). The program extracts the occurrence of high flow pulses, small floods, and large floods from stream gage records.

Flushing flows are high flow pulses that provide sufficient flow depth and velocity for fish migration and flushing organic matter and fine sediment from the channel. Flushing flows renew spawning habitat and maintain juvenile rearing areas. Restoration of flushing flows is an important component of managing sediment accumulation in salmon spawning and juvenile rearing habitat (Higgins, 2008). The magnitude and seasonality of flushing flows are an important element of freshwater inflows that provide nutrients, sediment loading, and tidal mixing in bay and estuarine systems (Tolan, 2008). The mean annual or average discharge on unregulated streams in Washington typically has sufficient depth and velocity to provide both fish passage functions and tractive forces necessary for flushing organic matter and fine-grained sediment from the channel.

Table 3 presents average discharge and mean velocity for selected stations in WA. Mean depth of flow ranges from 0.96 feet for Woodland Creek near Olympia to 5.6 feet for Satsop River near Satsop. Mean depth is taken from a cross-section of the channel and would vary in other locations according to actual channel dimensions. Mean velocity ranges from 1.12 ft/second for Woodland Creek near Olympia to 4.08 ft/second for Methow River at Twisp. Mean velocity is from one cross-section of the channel and would vary in other locations across the channel. These velocities are sufficient to initiate flushing of loose silt and fine sands in the channel (Hjulstrom, 1935).

USGS gage	Stream or River	Average Discharge (cfs)	Stream Flow * (cfs)	Mean Depth (ft)	Mean Velocity (ft/sec)
12035000	Satsop River nr Satsop	2009	2000	5.6	2.02
12039300	NF Quinault River nr Amanda	874	882	4.3	1.58
12449500	Methow River at Twisp	1324	1380	2.2	4.08
12081000	Woodland Creek nr Olympia	21.4	21.1	.96	1.12
12040500	Queets River nr Clearwater	4224	4080	4.0	2.53
12465000	Crab Creek at Irby	67.8	72.8	1.6	1.53
12093500	Puyallup River near Orting	714	716	2.8	2.82
12479500	Yakima River at Cle Elum	2044	1710	2.0	3.79
12120000	Mercer Creek nr Bellevue	22.7	23.1	1.1	1.04

*measured stream flow

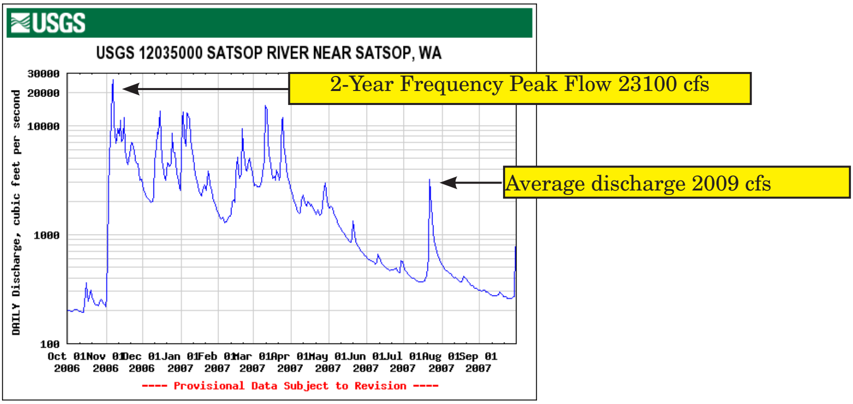
Table 3. Average discharge and mean velocity for selected streams in WA

Channel maintenance flows are small floods that provide geomorphic and ecological functions, such as sediment transport and maintenance of streamside vegetation, necessary for “securing favorable conditions of water flows” (Potyondy and Merritt, 2008). They scour the channel bed to reshape alluvial features, provide lateral migration and periodic inundation of the floodplain, and protect and sustain channel banks and the floodplain by maintaining healthy streamside vegetation (Schmidt and Potyondy, 2004). Channel maintenance flows mobilize sand and larger sediments, scour streambeds and undercut banks, relocate in-channel wood, and prevent riparian encroachment in the channel. They provide floodplain connectivity and access to important rearing areas for juvenile salmon (Opperman, 2006). Floodplain inundation can increase the surface area of submerged wood by 20 to 50% of the river bed surface with commensurate increases in biomass and annual productivity of aquatic invertebrates (Benke, 2008). High flows for channel maintenance and floodplain connectivity are necessary for recruitment of cottonwood seedlings (Mahoney and Rood, 1998) and are key components of ecosystem-based analysis of instream flow needs (Locke, 2008).

Channel maintenance flows are estimated by empirical methods using field measurement and calculation of dominant discharge, effective discharge, or bankfull discharge. Dominant discharge is flow that produces the greatest morphological effect in a stream over an extended period of time. It is derived from Lane’s Equation of Dynamic Equilibrium in which a channel is maintained by balancing changes in sediment load and sediment size with compensating changes in discharge and energy gradient. Effective discharge is defined as the flow that transports the most bedload over time. It is considered an approximation of dominant discharge and may be determined by sediment transport measurements relative to water discharge during high flows. It assumes the largest proportion of bedload is transported by flows at the peak of a total bedload transport curve (Schmidt and Potyondy, 2004). Bankfull flow fills the channel to the top of its banks to a point where it begins to overflow onto a floodplain. Wolman and Leopold (1957) define bankfull flow as a discharge which just begins to inundate the floodplain. They define “bankfull stage” as the stage at which a stream first begins to overflow its natural banks onto its active floodplain.

The 2-year recurrence interval peak flow on unregulated streams in Washington has sufficient depth, velocity, and stream power to transport bedload and large wood, scour riparian and stream bank areas, and connect the channel to the floodplain. It likely exceeds these empirical discharge calculations and is readily available from published studies and internet programs (http://water.usgs.gov/osw/streamstats.Washington.html).

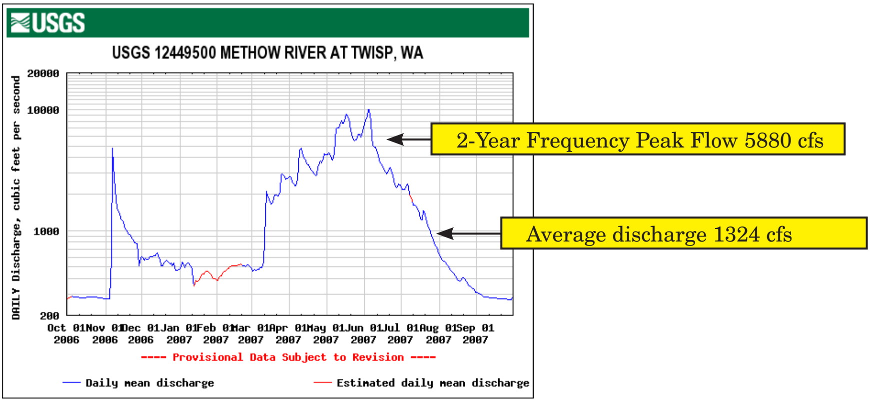
Figures 2-5 present average discharge and 2-year recurrence interval peak flows for selected streams in WA. The frequency of high flows exceeding mean annual discharge range from greater than 100 events/year on Mercer Creek near Bellevue to one event/year on Crab Creek at Irby.



2-Year Frequency Peak Flow 23100 cfs

Average discharge 2009 cfs

Figure 2. Average discharge and 2-year frequency peak flow for the Satsop River near Satsop.



2-Year Frequency Peak Flow 5880 cfs

Average discharge 1324 cfs

Figure 3. Average discharge and 2-year frequency peak flow for the Methow River at Twisp.

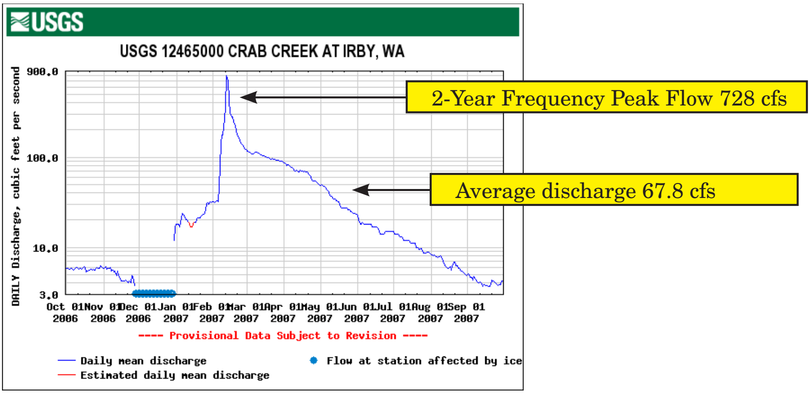


Figure 4. Average discharge and 2-year frequency peak flow for Crab Creek at Irby,

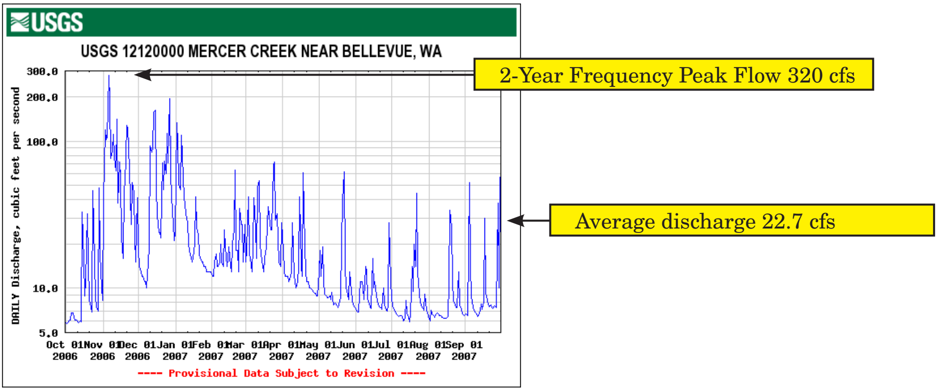


Figure 5. Average discharge and 2-year frequency peak flow for Mercer Creek near Bellevue.

Channel forming flows are large floods that create and sustain channel patterns and floodplain morphology. They form and maintain side channels, scour floodplain surfaces, refill off-channel wetlands and oxbow lakes, and recharge groundwater storage in hyporheic and floodplain aquifers (Trush et al, 2000). Large floods transport significant amounts of bedload sediment, recruit large woody debris from the floodplain, and maintain floodplain habitat.

The 10-year recurrence interval peak flow typically has sufficient depth, velocity, and stream power to cause rapid channel meandering, channel avulsions, and activation of most floodplain processes. They are assumed to provide channel flushing and channel maintenance functions. Channel forming flows may also be determined by assessment of historic channel changes, identification of the causes of channel change, and replication of specific flows. Table 4 presents

2-year and 10-year recurrence interval peak discharges on three streams in Washington (USGS, 2008).

USGS Station	2-year peak flow (cfs)	10-year peak flow (cfs)
12035000 Satsop River at Satsop	23100	36000
12449500 Methow River at Twisp	5880	11000
12465000 Crab Creek at Irby	728	3050

Table 4. 2-year and 10-year peak flow for three streams in WA.

4. Hydrologic regimes

A hydrologic regime is the annual pattern of flow or discharge in a river (Poff et al, 1997; Annear et al, 2004). The pattern of flow reflects the relative magnitude, duration, frequency, timing (rate of change), and seasonality of different flows (Richter at al, 1997). Figure 6 shows examples of these flow characteristics in a sample hydrograph.

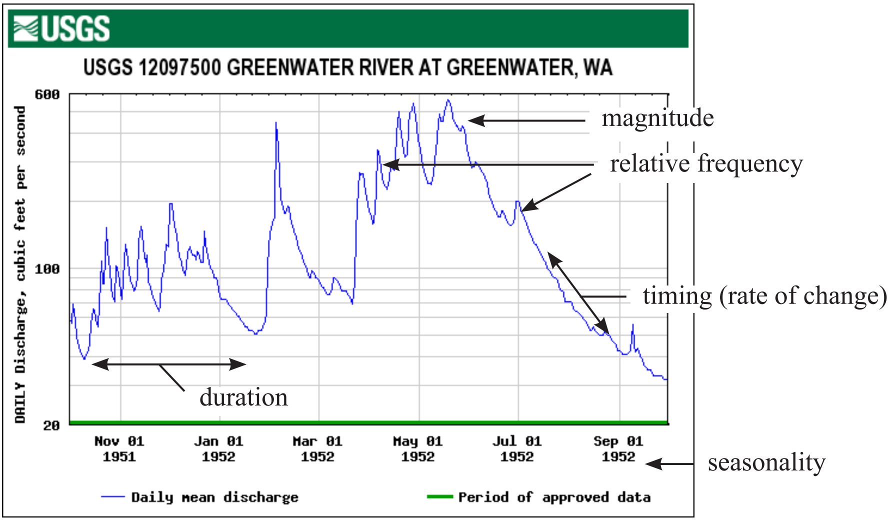


Figure 6. Characteristics of a hydrologic regime: magnitude, duration, relative frequency, timing (rate of change) and seasonality.

Protection and restoration of natural hydrologic regimes is a goal of environmental flow requirements to protect fish and wildlife resources (Annear et al, 2004). Hydrologic regimes on streams in Washington may be natural or unregulated, regulated by storage dams or diversions, or combinations of natural and regulated regimes on different tributaries in a single watershed. Poff et al (1997) notes other distinctions between natural and regulated regimes affected by hydropower, irrigation, municipal storage, urbanization, and flood control developments.

A large river basin or watershed with a wide range in elevation and climatic factors may include one or more hydrologic regimes. The Nooksack River in Northwestern Washington has snowmelt dominant peak flows in its headwaters, rain-on-snow dominant peak flows in mid-elevations, and rainfall dominant peak flows in the lowlands. Some watersheds may also have groundwater dominant flows in lower elevation streams.

Table 5 presents the hydrologic regime and mean basin elevation for selected streams in Washington. They range in elevation from 71 feet, or slightly above sea level, to 5180 feet in the North Cascades Mountains. Annual streamflow above 2,000 feet in elevation generally has snowmelt influences

USGS gage	Streams and Rivers	Hydrologic Regime	Mean Basin Elevation
12035000	Satsop River near Satsop	rainfall	500 ft
12039300	NF Quinault River nr Amanda Park	rain-on-snow	3410
12449500	Methow River at Twisp	snowmelt	5180
12081000	Woodland Creek near Olympia	groundwater	71
12040500	Queets River near Clearwater	glacial melt	1700
12465000	Crab Creek at Irby	semi-arid	2200
12113000	Green River near Auburn	regulated, flood control	2400
12479500	Yakima River at Cle Elum	regulated, irrigation	no data
12120000	Mercer Creek near Bellevue	urbanized watershed	no data

Table 5. Hydrologic regime and mean basin elevation for selected streams in WA

Tables 6 and 7 present the drainage area and flow characteristics for these streams. Drainage area varies from 12 square miles for Mercer Creek near Bellevue to 1301 square miles for the Methow River at Twisp. Average flow varies from .065 cubic feet per square mile (cfsm) for Crab Creek at Irby to 11.7 cfsm for North Fork Quinault River near Amanda Park. High flows with a 2-year recurrence interval vary from .7 cfsm for Crab Creek at Irby to 4.5 cfsm for the Methow River at Twisp to 192 cfsm for the North Fork Quinault River near Amanda Park.

USGS gage	Stream or River	Drainage Area	Ave Q	2-Year* Q	Ratio
12035000	Satsop River nr Satsop	299 sq mi	2009 cfs	23100 cfs	11.5
12039300	NF Quinault River	74.4	874	14300	16.4
12449500	Methow River at Twisp	1301	1324	5880	4.4
12081000	Woodland Creek nr Olympia	24.6	21.4	419	19.6
12040500	Queets River nr Clearwater	445	4224	49300	11.7
12465000	Crab Creek at Irby	1042	67.8	728	0.7
12113000	Green River nr Auburn	399	1343	11500	8.6
12479500	Yakima River at Cle Elum	495	2044	2310	1.1
12120000	Mercer Creek nr Bellevue	12	22.7	320	14.1

*2-year recurrence interval discharge in cfs

Table 6. Drainage area and flow characteristics for selected streams in WA.

USGS gage	Stream or River	Average** Q	2-Year** Q
12035000	Satsop River nr Satsop	6.7 cfsm	77.3 cfsm
12039300	NF Quinault River nr Amanda Park	11.7	192
12449500	Methow River at Twisp	1.0	4.5
12081000	Woodland Creek nr Olympia	87	17
12040500	Queets River nr Clearwater	9.5	110.8
12465000	Crab Creek at Irby	.065	.7
12113000	Green River nr Auburn	3.4	28.8
12479500	Yakima River at Cle Elum	4.1	4.7
12120000	Mercer Creek nr Bellevue	1.9	26.7

**Discharge per unit drainage area

Table 7. Average and 2-year peak discharge per unit drainage area for selected streams in WA.

Figure 7 presents monthly discharge as a fraction of annual discharge for these streams. High flows on Crab Creek near Irby occur in the winter while high flows for the Methow River at Twisp occur in the spring. The figure includes a key to gaging station locations.

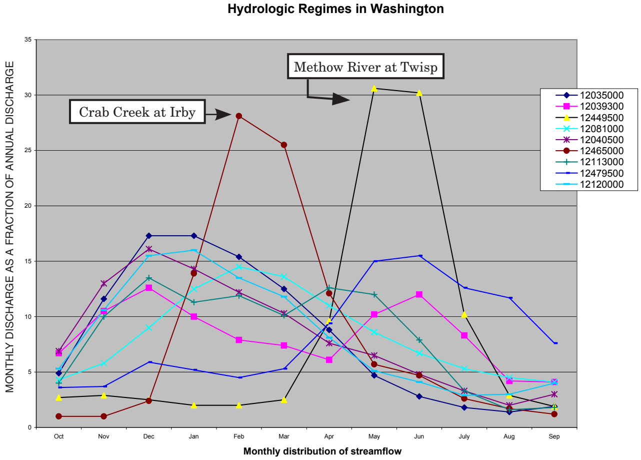


Figure 7. Monthly discharge as a fraction of annual discharge on selected streams in WA.

key: 12035000, Satsop River near Satsop. 12039300, NF Quinault River near Amanda Park. 12449500, Methow River at Twisp. 12081000, Woodland Creek near Olympia. 12040500, Queets River near Clearwater. 12465000, Crab Creek near Irby. 12113000, Green River near Auburn. 12479500, Yakima River at Cle Elum. 12120000, Mercer Creek near Bellevue.

There are different types of regulated hydrologic regimes in Washington depending on the size and purpose of dams and reservoirs in the basin. There are about 1025 dams in Washington with greater than 10 acre-feet of storage. These dams regulate flows for recreation, flood control, hydropower, irrigation, water supply, water quality, and other purposes (Ecology, 2005). There are currently 165 water supply and irrigation reservoirs with greater than 50 acre-feet of storage in Washington. These reservoirs hold a combined storage of about 16.25 million acre-feet.

Hydrologic regimes regulated for flood control typically have only a few small floods, greatly reduced or no large floods and extended durations of high flow pulses. Figure 8 shows annual peak flows from 1940-2006 on the Green River, before and after Howard Hanson dam was built in 1962. It shows large floods were eliminated by flood control storage at the dam.

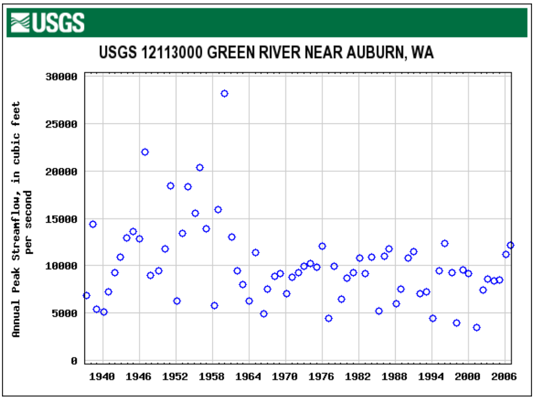


Figure 8. 1940-2006 annual peak flow on the Green River near Auburn.

Run-of-the-river hydropower projects usually have little storage and only minor alteration of medium to large floods. Hydropower projects with large storage dams often store small floods for power generation at later times. Power generation may cause rapid changes in flow when “downramping” or reducing flows through the turbines. Water supply dams that store inflows for release during the dry season frequently capture small floods, greatly reduce large floods, and later release flows in a “reverse hydrology” for long-durations during the summer months (Richter and Thomas, 2007).

Figures 9-17 show the seasonal patterns of high flows over two water years for nine different hydrologic regimes in Washington. They show the variability in high flow magnitudes, duration, frequency, and seasonality for natural and regulated hydrologic regimes in different areas of the state. Flows in unregulated streams reflect the dominant runoff processes in the basin. Flows in regulated streams generally reflect the man-made storage of high flows for use during low flow months.

The Satsop River near Satsop is a rainfall regime with high flows occurring most of the year. The North Fork Quinault River near Amanda Park is a rain-on-snow regime with fall and spring high flows due to snowmelt. The Methow River at Twisp is a snowmelt regime with high flows from rainstorms in early Fall and snowmelt in Spring. McAllister Springs near Olympia is a groundwater regime with flows due to aquifer discharge. The Queets River near Clearwater is a glacial meltwater regime with high flow from rainfall most of the year and sustained flow in summer due to meltwater from snowfields and glaciers. Crab Creek at Irby is a semi-arid regime with high flow due to snowmelt in the early spring. The Green River near Auburn is a rainfall regime with regulated high flows of less than 12,000 cfs to prevent overbank flooding downstream. Flow releases to reduce storage in the flood control reservoir keep downstream flows high long after a storm. The Yakima River at Cle Elum is regulated for irrigation with spring and summer flows released for irrigation. Mercer Creek near Bellevue is a rainfall regime altered by urbanization with high flows due to increased impervious area and channelization in the watershed.

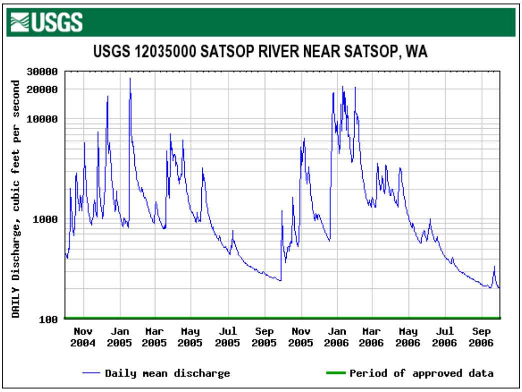


Figure 9. 2-Year hydrograph for the Satsop River near Satsop

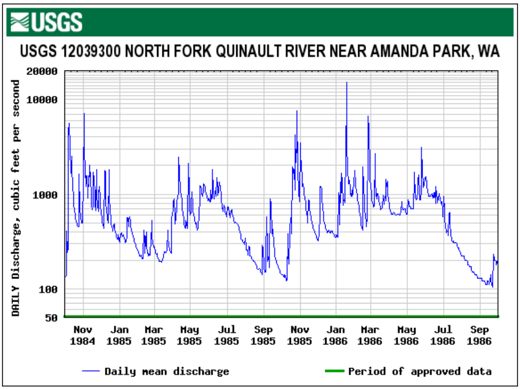


Figure 10. 2-Year hydrograph for the North Fork Quinault River near Amanda Park

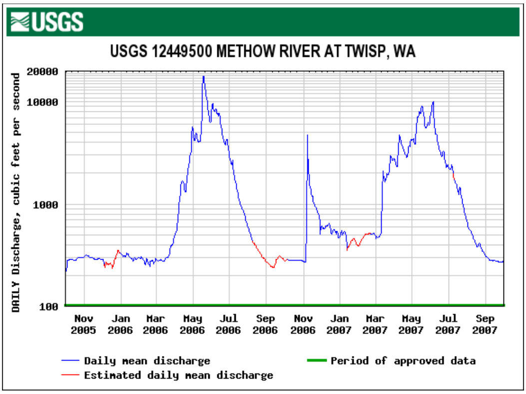


Figure 11. 2-Year hydrograph for the Methow River at Twisp

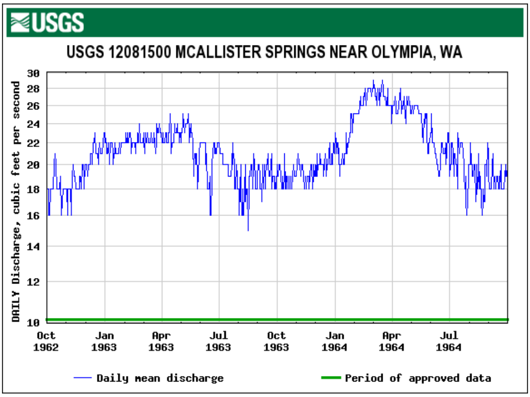


Figure 12. 2-Year hydrograph for McAllister Springs near Olympia

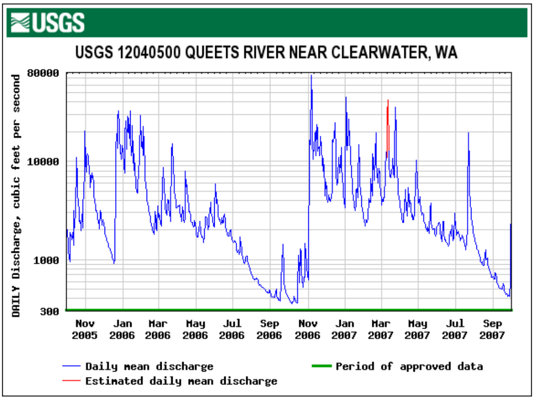


Figure 13. 2-Year hydrograph for the Queets River near Clearwater

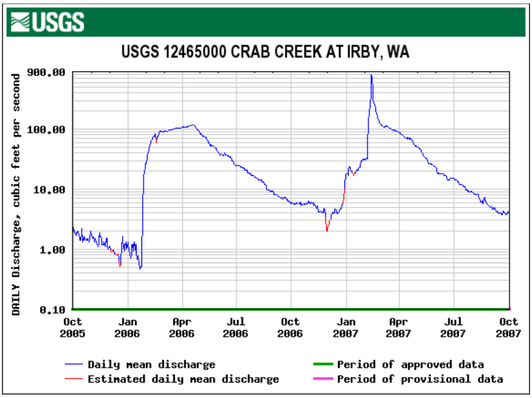


Figure 14. 2-Year hydrograph for Crab Creek at Irby

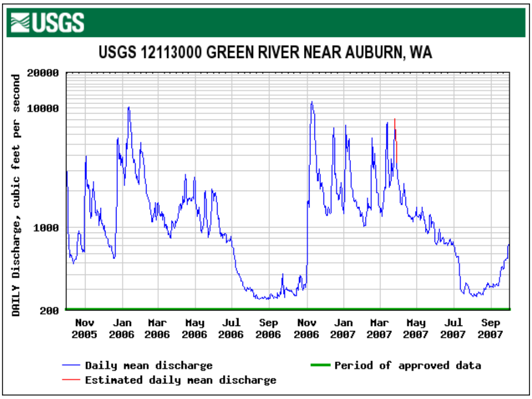


Figure 15. 2-Year hydrograph for the Green River near Auburn

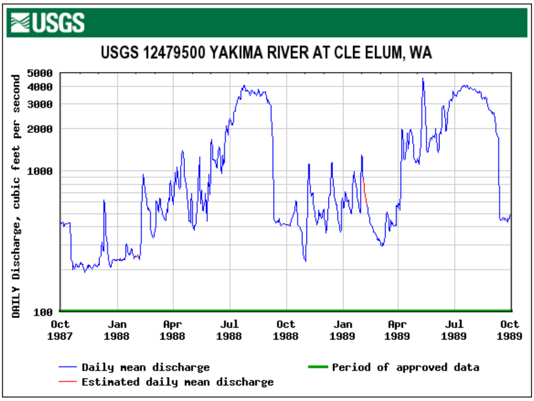


Figure 16. 2-Year hydrograph for the Yakima River at Cle Elum

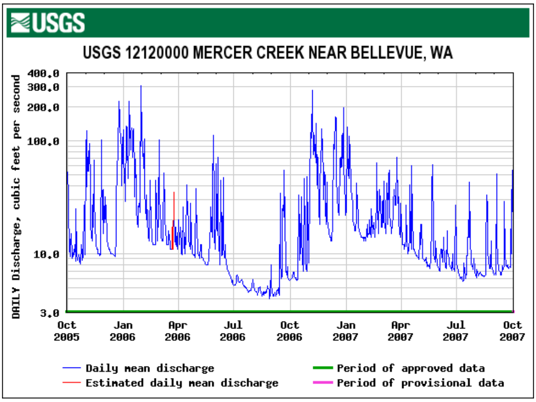


Figure 17. 2-Year hydrograph for Mercer Creek near Bellevue

5. High flow recommendations

Researchers in other states have developed instream flow and flow release recommendations for high flows and high flow functions. Stillwater Sciences (2003) developed recommendations for ten classes of high flows for streams in California. Recommendations included in-channel flows to maintain flow depths for pool-scouring, riffle cleaning, and riffle mobilization as well as over-bank flows for margin accretion, channel migration, floodplain deposition, and floodplain mobilization. The Oregon Department of Fish and Wildlife (ODFW) developed recommendations for two classes of high flows in Oregon (Robison, 2007). Recommendations included ecological flows (high flow pulses) for migration of adult fish, outmigration of juvenile fish, and habitat for macroinvertebrates and channel maintenance flows for flushing fines, scouring riparian vegetation, recruiting large woody debris, and maintaining bed form. ODFW considered channel maintenance flows equivalent to bankfull flow on sand-bed streams, 80% of bankfull to the 2-year recurrence interval peak flow on gravel bed streams, and greater than 2-year recurrence interval peak flow on cobble and bedrock streams.

This report presents instream flow and flow release recommendations for three classes of high flows on streams in Washington. Recommendations include high flow pulses for fish migration and channel flushing, channel maintenance flow for creating and maintaining physical habitat in the channel, and channel forming flows for changing channel patterns and activating riparian and floodplain processes.

WDFW considers mean annual discharge an approximation of high flow pulses and flushing flows. Mean annual discharge typically has sufficient depth and velocity to provide fish passage functions and sufficient tractive force to flush organic matter and fine-grained particulates from the channel. The 1.5 to 2-year recurrence interval peak flow is an approximation of channel maintenance flows. The 1.5 to 2-year frequency peak flow on most streams has sufficient depth, velocity, and stream power to transport bedload and large wood, scour riparian and stream bank areas, and connect the channel to the floodplain. The 2 to 10-year recurrence interval peak flow is an approximation of channel forming flows. The 10-year frequency peak flow typically has sufficient depth, velocity, and stream power to cause rapid channel meandering, channel avulsions, and activation of various floodplain processes.

Duration and frequency of these high flow recommendations are based on the natural hydrologic regime. They are expected to vary seasonally from wet to dry years based on runoff characteristics and climatic conditions in different areas of the state. Timing is based on the shape of naturally occurring hydrographs for the stream. Seasonality is tied to the life stages of fish and wildlife historically common to each stream.

These recommendations are first estimates for unregulated streams in the state. Detailed recommendations for instream flows and high flow releases on regulated streams may require additional assessment of watershed conditions, runoff processes and flow regulation, channel conditions, hydrologic regime, and life stages and seasonal occurrence of fish and wildlife using the stream.

The life stages of resident and anadromous fish include adult spawners, fish eggs, intra-gravel emergents, fry, juveniles, smolts, and migratory or holding adults that could occupy that stream. Life stages of salmonids in the Pacific Northwest are very much tied to physical habitat conditions and seasonal flow factors. Different life stages require different flow conditions for rearing, migration, and survival ranging from summer base flows to flushing flows and high flow pulses for migration with high flow pulses and channel maintenance flows for access to upper reaches and tributaries in winter. Juvenile outmigration typically requires additional high flow pulses in the spring.

Figure 18 shows the range in daily gage heights and high flow functions for 2006 on the Methow River at Twisp. The range in gage heights shows different flow depths important for high flow functions. Figure 19 shows the range in daily gage heights and habitat components for this station (relative elevations are approximate and have not been surveyed). It shows the range in gage heights and potential connectivity with different fish habitats. Figure 20 shows the seasonal characteristics of different life stages of salmonids for this reach of the Methow River (WDFW, 2007).

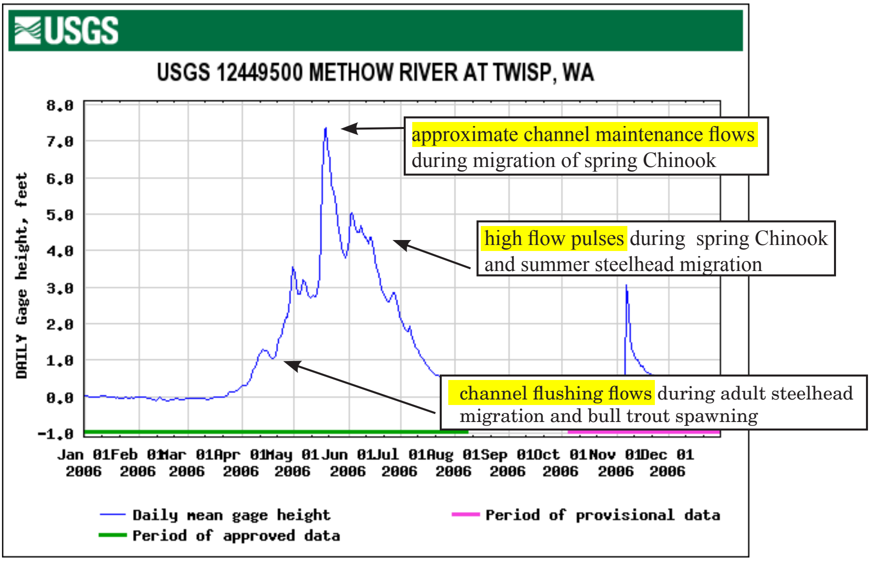


Figure 18. Daily gage heights and high flows for the Methow River at Twisp

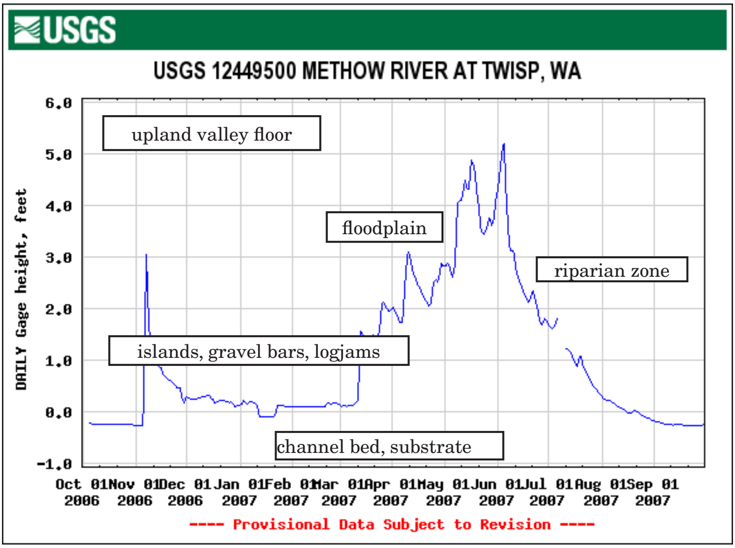
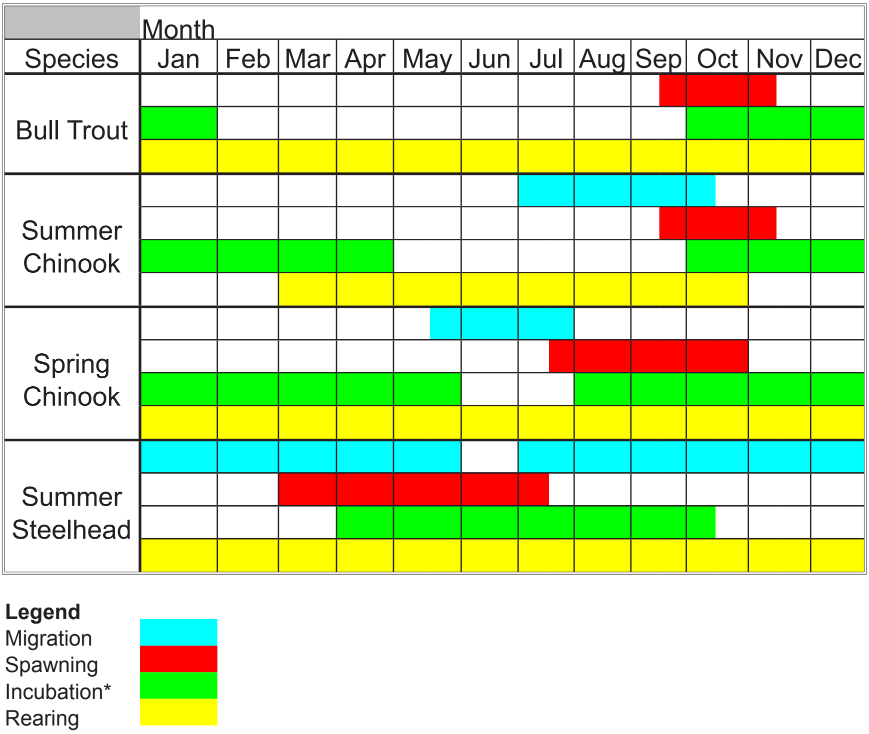


Figure 19. Daily gage heights and habitat components for the Methow River at Twisp



	Month											
Species	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Bull Trout									🟥	🟥	🟥	
	🟩									🟩	🟩	🟩
	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
Summer Chinook							🟦	🟦	🟦	🟦		
									🟥	🟥	🟥	
	🟩	🟩	🟩	🟩						🟩	🟩	🟩
			🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨		
Spring Chinook					🟦	🟦	🟦					
							🟥	🟥	🟥	🟥		
	🟩	🟩	🟩	🟩	🟩			🟩	🟩	🟩	🟩	🟩
	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
Summer Steelhead	🟦	🟦	🟦	🟦	🟦		🟦	🟦	🟦	🟦	🟦	🟦
			🟥	🟥	🟥	🟥	🟥					
				🟩	🟩	🟩	🟩	🟩	🟩	🟩		
	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨

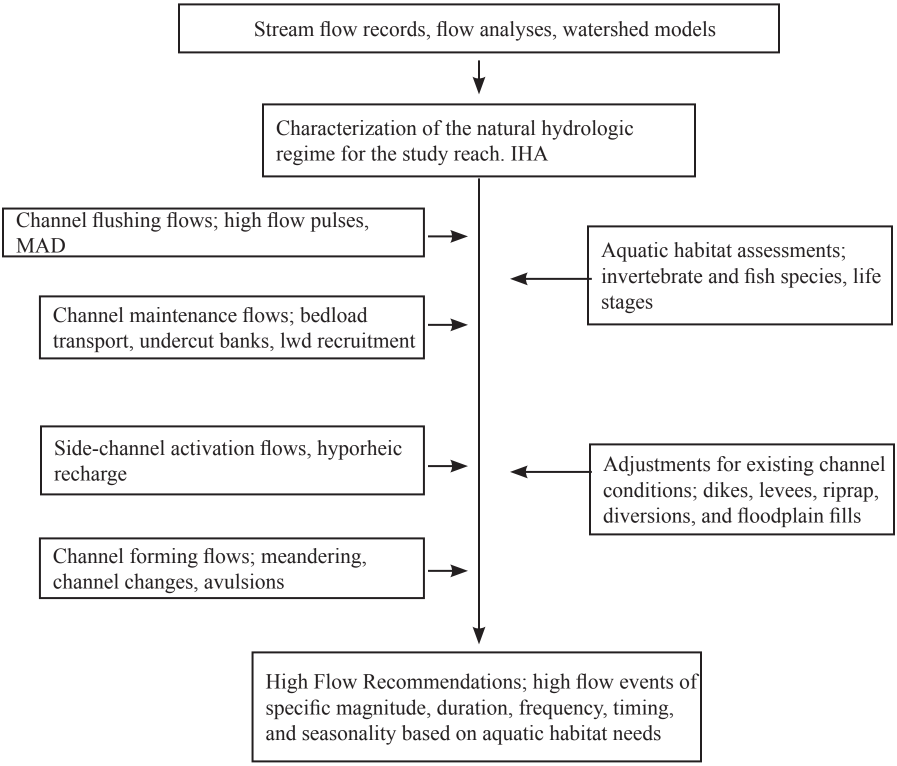
Legend
Migration 🟦
Spawning 🟥
Incubation* 🟩
Rearing 🟨

Figure 20. Life stages of fish species in the Methow River

A comparison of Figures 18-20 shows how channel flushing flows inundate the channel bed and portions of islands, gravel bars, and logjams during migration of summer steelhead and late spawning by bull trout and summer Chinook in the Methow River. High flow pulses inundate the undercut banks, the upper stream bank, and riparian vegetation during migration of spring Chinook and summer steelhead. Channel maintenance flows activate side channels and flood the floodplain during migration of spring Chinook. Channel flushing flows, high flow pulses, and channel maintenance flows also occur during rearing stages of all four species.

Figure 21 presents a flow chart for developing high flow recommendations by characterizing the natural hydrologic regime, assessing high flows and high flow functions, assessing aquatic habitat needs, and adjusting for existing channel conditions. WDFW high flow recommendations include discharges of specific magnitude, duration, frequency, timing, and seasonality based on aquatic habitat needs.

Figure 21. Flow chart for developing high flow recommendations



6. High Flow Policies.

WDFW has policies for developing instream flow recommendations to protect high flow functions in Washington streams. These policies provide procedures and standards for recommending mitigation (POL-M5002), reviewing water projects (POL-5204) and water rights applications (POL-5205), and applying Instream Flow Study Guidelines (WDFW, 2007).

Policy M5002 applies to issuing or commenting on environmental permits. Its goal is to achieve "no loss of habitat functions and values" when recommending mitigation. It could require mitigation for loss of habitat functions due to diversion of high flows for water storage projects, Policy M5002 requires habitat mitigation measures based on best available science. Best available science is defined as "analysis and research conducted by qualified individuals using documented methodologies with information reviewed by qualified scientific experts and criticism addressed by the proponents" (DCD, 2000). Best available science for instream flows includes high flow functions identified in current scientific literature as important to preserving fish and wildlife habitat. Policy 5204 applies to WDFW instream flow recommendations for watershed planning. It requires setting minimum instream flows based on a quantitative analysis of the relationship between stream discharge and stream habitat. The instream flow is based on specified methods and data collected from site-specific field studies. WDFW recommends instream flows based on this policy to protect fish and wildlife production potential, maintain riparian habitat, and provide channel forming and maintenance flows. It also recommends minimum instream flows necessary to protect hyporheic flows, maintain fish passage and migration, avoid adverse impacts on estuarine and marine habitats, and provide connectivity of channel processes such as movement of sediment and wood (WDFW, 2004b).

Policy 5205 applies to WDFW review of applications for water rights and projects submitted pursuant to RCW 77.57.020. It provides a framework for recommendations to protect fish and wildlife when issuing or conditioning water rights.

The Instream Flow Study Guidelines include methods for developing recommendations for instream flows as conditions of water rights, Clean Water Act (Section 401) certifications, and hydroelectric power project licenses. The guidelines note that instream flow study plans need to include channel maintenance flows to maintain macrohabitat features of the stream channel. Requirements are based on the relative occurrence of high flows and the functions they perform on a particular stream. The guidelines include controlling ramping rates or changes in flow associated with flow releases, flow diversions, or other flow influences.

WDFW uses the Instream Flow Study Guidelines to fulfill its mandate to preserve, protect, and perpetuate fish and wildlife and the habitat needed to support them. Based on this study, the author recommends they include the following flows:

Fish migration and spawning flows – High flow pulses to facilitate salmon spawning and migration should provide adequate water temperature, sufficient flow depth, appropriate seasonality and diurnal conditions, and sufficient flow duration for adult fish to migrate upstream to suitable spawning or holding areas and for juvenile fish to migrate downstream when necessary.

Flushing flows – Flushing flows to improve gravel quality for spawning and incubation habitat provide the greatest benefit when they occur at the beginning of spawning seasons. Flushing flows in the fall remove organic matter and fines that accumulate during the summer. Flushing flows in the spring provide migration flows while they reduce the amount of fines in spawning gravels. The author recommends preserving or providing the mean annual discharge as a flushing flow for 6 to 12 hours duration during specified seasons and at intervals of at least 2 per year if not provided naturally.

Channel maintenance flows - Channel maintenance flows for activating geomorphic processes are greater in magnitude and duration than flows necessary for initiation of bedload movement. The author recommends preserving or providing the 2-year frequency peak flow or 200% of mean annual discharge for at least 24 hours duration at specified seasons as a channel maintenance flow at intervals of 2 years if not provided naturally. Release rates should be controlled according to specified ramping rates (Hunter,1999).

Channel forming flows –The author recommends preserving or providing the 10-year frequency peak flow for at least 24 hours duration at specified seasons as a channel forming flow at intervals of 10 years if not provided naturally. Release rates should be controlled according to specified ramping rates (Hunter,1999)

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