Instream Flow / Viable Salmonid Populations (VSP)

Workshop Summary

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1. INTRODUCTION

On May 22, 2008, the Washington State Department of Ecology convened a one-day workshop at the University of Washington to discuss the linkage between instream flow and viable salmonid populations (VSP). The topic is timely in that flow alteration has been identified as a factor that may limit the long-term viability of numerous populations of salmonids in the Pacific Northwest. The workshop was attended by invited technical experts from a variety of agencies and organizations engaged in salmon recovery activities and research (see Appendix A, Participant List). The goals of the workshop were to:

1. Provide an overview of the current state of instream flow/VSP science and flow assessment tools.
2. Develop a scientific research agenda for future instream flow/VSP work.

This report provides a synthesis of the workshop discussions. It also suggests next steps for filling important gaps in the 'toolbox' of models and analyses that will inform salmon recovery efforts in the future. While the report captures the major themes and points of discussion from the workshop, it also reflects the interpretations and perspectives of the author and workshop steering committee.

The audience for this report includes a variety of expert groups engaged in salmon recovery, such as the Puget Sound Salmon Recovery Implementation Technical Team (RITT), the Puget Sound Partnership's Science Panel and watershed-based salmon recovery groups. The report is also intended for academic researchers as well as federal, tribal, and state resource managers.

The body of this report is organized as follows:

- ***Section 2:*** Background and context for the workshop topic
- ***Section 3:*** Principal discussion themes; key points of agreement and unresolved issues
- ***Section 4:*** Synthesis of responses to the three questions that framed the workshop discussion
- ***Section 5:*** Recommendations for advancing the state of instream flow/VSP science, based on the content of the workshop and post-workshop questionnaires.

For more information:

To view or download background materials and workshop presentations, visit this site:

http://www.ecy.wa.gov/programs/wr/nwro/isf_vspw.html

To request a complete audio recording of the workshop, or attendee responses to a post-workshop questionnaire, contact the workshop coordinator, Jeff Bash, at jbas461@ecy.wa.gov.

2. BACKGROUND AND CONTEXT

The flow of water is a "master variable" that drives many critical physical processes in stream and river ecosystems, such as channel migration, sediment transport, and large-wood recruitment. These processes, in turn, have a profound influence on the ecological structure of the system.

Over time, the spatial and temporal flow variations within and between river systems have created a mosaic of habitat conditions in watersheds across the western U.S. and Canada. These habitats support a remarkable diversity of species and life-history types for both resident and anadromous salmonids. Recovery efforts have taken center stage following the listing of numerous salmonids under the Endangered Species Act (ESA). As a result, developing a scientifically credible linkage between flow and salmon population viability has emerged as a high priority.

The alteration of flow regimes is considered by many ecologists to pose one of the greatest threats to the ecological integrity of river and stream ecosystems. Landscape alterations, water withdrawal, and flow control (via dams) may all cause profound changes in the hydrology of a watershed.

To better understand the effects of flow alterations on salmon populations, the RITT has begun to develop a three-part analytical framework that integrates meta-population dynamics, the attributes of viable salmonid populations, and the dynamics of river ecosystems. The workshop explored these and other topics in an effort to assess the current state of the science and to identify promising avenues for developing new tools. The draft framework document prepared by the RITT served as one of several background resources for the workshop. You can view and download it at the following link:

> http://www.ecy.wa.gov/programs/wr/nwro/images/pdfs/framework_flowregime_salmonidpop.pdf

In January 2007, the National Marine Fisheries Service (NMFS) adopted the Puget Sound Salmon Recovery Plan. As described by Josh Baldi of the Washington State Department of Ecology, the Plan calls for a concurrent three-step program to ensure that instream flows are not a limiting factor in salmon recovery:

1) *Establish protective instream flows*. This refers to the establishment of regulatory Instream Flows, as described in the following section.

2) *Develop Instream Flow Protection and Enhancement Programs (PEPs) to improve streamflow in each watershed*. PEPs consist of watershed-specific scientific, behavioral, and regulatory programs and actions[1].

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[1] These include stormwater management (planning, facility retrofits, low-impact development); water conservation measure; compliance and monitoring programs; preservation of aquifer recharge areas through critical area regulations; and protection and enhancement of riparian areas.

3) *Advance our scientific understanding of the relationship between instream flow and salmon recovery.*

Step 3 was the focus of the workshop. From a policy perspective, current instream flow tools may be legally defensible, but they are inadequate to define the attributes of viable populations that are necessary for recovery. The scientific community must specify the target flow conditions that support viable populations. More simply, we must articulate how much water is needed, where, when, for how long, and why.

Instream Flow vs. instream flow

'Instream Flow'—with both words capitalized—is a term typically associated with the results of a formal process applied in Washington State to establish a water right to protect instream values. In most locations where Instream Flows have been set, they are expressed as minimum flows that must be met before new, additional water rights may be exercised. In this way, Instream Flows function very much like consumptive water rights. They define a threshold for further withdrawal by 'junior' water-right holders, but have no effect on 'senior' water rights, that is, those with an earlier priority date than that of the Instream Flow. Thus, 'Instream Flow' is really a management construct, even when the quantities of water associated with the right are based on scientific analysis.

In this discussion, 'Instream Flow' also includes flow prescriptions for hydroelectric projects or analogous sites where flow or discharge is specified and can be controlled to a substantial degree. Section 3 includes a brief discussion of the opportunities and limitations associated with flow-controlled rivers and flow management for addressing population viability.

This workshop focused on the lower-case 'instream flow'. This term captures the full suite of relationships among flow, channel form, habitat condition, and biota. Specifically, we focused on the linkage between instream flow and the VSP lens of salmonid viability.

While it is difficult to ignore the limitations of the current flow management framework, that discussion was outside the scope of this workshop. It may be true that current management tools are unable to address the full range of flow/VSP relationships, but the first step toward developing new tools is to understand what we need them to do.

Viable Salmon Populations

In the wake of numerous ESA listings of Pacific Northwest salmonids in the late 1990's, NOAA Fisheries prepared a memorandum (McElhany et al., 2000) to provide technical guidance on setting recovery goals for listed salmonids. ESA listings for salmonids are defined at the scale of an Evolutionarily Significant Unit (ESU). The criteria for an ESU are two-fold:

1) Must be a population or group of populations that is reproductively isolated to a substantial degree from other populations of the same species.

2) Must represent an important component of the evolutionary legacy of the species.

In many cases, such as with Puget Sound Chinook, the ESU encompasses a broad geographic area and numerous populations. By contrast, the Lake Ozette Sockeye ESU is far more limited in its spatial extent and consists of a single population.

The VSP memorandum describes a framework for defining an independent population as a component of an ESU and for assessing its viability[2]. The definitions of 'independent population' and of 'population viability' both incorporate an explicit consideration of extinction risk.

An independent population is:

> *"Any collection of one or more local breeding units whose population dynamics or extinction risk over a 100-year time period is not substantially altered by exchanges of individuals with other populations"*

A viable independent population is one that:

> *"… has a negligible risk of extinction due to threats from demographic variation, local environmental variation, and genetic diversity changes over a 100-year time frame"*

NOAA Fisheries' Technical Recovery Teams (TRTs) identified independent populations in each of the ESUs. Their evaluations considered several factors, including migration rates, geography, genetic markers, demographic patterns, life-history patterns, and environmental characteristics. For example, the Puget Sound TRT identified 22 independent Chinook populations within the Puget Sound ESU.

The VSP memorandum provides a framework for assessing the viability of a population based on four population parameters: abundance, productivity, diversity, and spatial structure. These parameters were chosen because they are measurable, are reasonable predictors of extinction risk, and reflect processes important to all populations.

- High abundance buffers a population against both normal and catastrophic variation in environmental conditions and other factors. All other factors being equal, a larger population is more resistant to extinction than a smaller one.

- The importance of high productivity is closely linked to density dependence and compensation. It is often assumed that during periods of low abundance, density dependence is largely absent, allowing the remaining population to produce at a rate that may be far higher than the 1:1 replacement rate.

- Diversity in morphology and life-history traits (such as spawn timing, juvenile life-history, and adult fish size) provides resilience against extinction risk. It does so through a basic premise of heterogeneity, whereby some traits are advantageous in some conditions but less so in others.

[2] The paper can be obtained through this link: http://www.ecy.wa.gov/programs/wr/nwro/images/pdfs/1NOAATechMemo.pdf

- Spatial structure is a geographic analogue to diversity, in that a population's extinction risk is lower if occupied habitat patches are widely distributed. This would ensure that a single catastrophic event would be unlikely to impact all occupied patches, and that normal patterns of environmental variability would favor different areas in different years. For example, if a population uses only one primary spawning area, the risk of catastrophic loss due to a natural landslide or unnatural toxic spill is much higher than for a population with multiple spawning areas. Considering spatial structure as a component of viability also accounts for the physical processes that make the spatial structure possible, such as flow conditions that connect habitat areas.

Instream flow can exert a strong influence on the expression of all four VSP parameters. For example, the spawning or rearing capacity of a particular watershed (and thus, potential population abundance) may dependent on critical flows, such as late summer flows for stream-rearing salmonids, or fall flows for fall-spawning species.

Population productivity is most often measured on an adult-to-adult basis (for example, recruits per spawner over time), but the net productivity rate is the result of sequential rates during the course of multiple life stages. From an extinction risk standpoint, it is important to understand the role of instream flow in regulating productivity when adult abundance is low (that is, conditions associated with compensation). If, for example, a flow regime has been impacted in such a way that early-juvenile rearing habitat is in short supply or inaccessible, then density-dependence (and reduced productivity) may be expressed during the juvenile life stage even if spawner densities are low. That is, the compensatory 'benefit' associated with low adult abundance may not occur.

Variation in the flow regime can be a major driver of life-history and morphological diversity. Yearly changes in rearing flows, for example, may lead species to favor certain types of off-channel habitats over others. Differences in rearing locations may also alter emigration timing. Morphologic diversity may be influenced by flows as well. For example, during lower spawning flows, certain spawning areas may not be used by the deepest-bodied individuals. This may lend a relative advantage to shallower-bodied or younger age-class spawners.

Similarly, the spatial structure of a population is affected when the connectivity of habitat varies according to flow level. For example, higher flows during the spawning period may make new spawning reaches available, which may also lead to a broader spatial distribution of juvenile rearing, particularly for extended stream-rearing salmonids like coho, steelhead, and stream-type Chinook.

The four attributes are, of course, interdependent. For instance, a population that is productive even when abundance is high is more likely to exhibit more complex spatial structure due to density pressure. Complex spatial structure, in turn, can promote the development of diverse life-history trajectories and the formation of sub-groups in areas where selective forces differ.

The effect of flow on each of the VSP parameters is closely linked to the associated channel and floodplain condition. This theme is discussed further in Section 3.

Commonly applied instream flow tools

The most commonly applied tools are those that help to develop prescriptions for the capitalized 'Instream Flow' by linking hydraulics to fish habitat. These include the Physical Habitat Simulation (PHABSIM), Tennant, Wetted-width, and Toe-width methods. Variations of these general approaches include the 'percentage of Mean Annual Discharge' or MAD method described at the workshop by Ron Ptolemy of the British Columbia Ministry of Environment.

PHABSIM

PHABSIM is a data-intensive, microhabitat-scale approach to quantifying Weighted Usable Area (WUA) at a given site across a range of flows. The hydraulic portion of the model uses transect-based data collected at 3 to 5 calibration flows to compute water depth and velocity profiles across a range of discharges, including flow levels outside of the range of observed calibration flows[3]. The model combines the simulated hydraulic model with field data on substrate size-class at points along transects. (In the case of juvenile habitat, the distance to 'cover' habitat may be measured instead.) This results in a composite habitat description along each transect that combines depth, velocity, and substrate (or distance to cover).

By collecting data at several transects and assigning a 'weight' to each transect, the model characterizes the total wetted area in the study reach at a given discharge as a 'patchwork' of independent habitat cells. Each cell has its own depth, velocity and substrate class, and its own model-computed area in square feet or meters. Habitat Suitability Curves (HSCs) are then used to link the model-generated habitat patchwork to fish habitat. For each species and lifestage of interest, separate HSCs are used to describe the presumed suitability of depth, velocity, and substrate. Suitability is expressed as a value between zero and one[4].

To compute the WUA for the particular species and lifestage at a given discharge, the composite suitability of each model-generated habitat cell is multiplied by its area. In the model's most common application, the composite suitability is simply the product of the individual suitability values for depth, velocity, and substrate. Finally, the areas of all cells, weighted by their respective suitability values, are summed to produce the total WUA at the particular discharge of interest. The 'peak' WUA across a range of discharges represents the model-generated optimum flow.

While foregoing an in-depth discussion of the merits and shortcomings of PHABSIM, it is important to recognize that PHABSIM:

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[3] The extent to which it is appropriate to extrapolate the hydraulic model portions of PHABSIM outside of the calibration range is a source of disagreement. Inspection of model performance coupled with 'rules of thumb' have led to commonly applied ranges of extrapolation, but these are not universally accepted.

[4] For example, the Washington State Department of Fish & Wildlife default HSC for Chinook spawning velocity in large rivers has an 'optimum' (i.e., suitability = 1) between 1.5 and 3.7 feet-per-second, with lower suitability values outside this range, including zero for very low or very high velocities.

1) Assumes that habitat can be characterized simply as a function of the three factors (depth, velocity and substrate or distance to cover).

2) Assumes that the spatial distribution of suitable patches within a study reach is irrelevant.

3) Assumes that the stream or river is in dynamic equilibrium, so that even if the characteristics of the study site change over time as a result of river processes, the overall composition of habitat types will remain substantially unchanged over time[5].

4) Omits food availability, competition, water quality and other important factors that affect habitat suitability.

These limitations are acknowledged by practitioners. PHABSIM is intended to be used as one component of a much more comprehensive assessment, such as the Instream Flow Incremental Methodology (IFIM). However, in practice, the discharge optima modeled by PHABSIM for particular species and lifestages (such as Chinook spawning) often define the boundaries for discussion of desirable flow levels in a regulatory context.

Toe-Width Method

The other tools listed at the beginning of this section rely on simpler metrics as indices of available habitat. For example, the *toe-width method* uses a power function to predict the optimum flow to support a particular species and lifestage based on the toe-width of the channel. The function is based on extensive depth and velocity data collected in the 1970s at known salmon spawning locations over a range of discharges, coupled with depth and velocity preference curves for each species. The data were used to quantify a relationship between discharge and fish habitat. To find an alternative to extensive flow measurements, investigators tested the flow-habitat relationship for correlations with various watershed attributes. The toe-width of the stream proved to be the best predictor. Thus, the toe-width measurement can be used to calculate the ‘optimum’ flow level.

Tennant Method

The *Tennant method* (and the variant described by Ron Ptolemy), assumes a predictable relationship between the percentage of mean flow and the amount of habitat that supports a particular species and lifestage. For example, based on data collected in a large number of streams, the method may predict that 30% of mean annual discharge (MAD) is required to support adult salmon migration. In the work described by Ptolemy, the specific percentages vary by the size of the stream and its associated drainage. Generally, in smaller streams, a larger percentage of MAD is required to support a particular lifestage than in a larger stream or river. In the case of regulated flows, for example, calculating the ‘optimum’ flow regime to support a particular species requires an

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[5] The last assumption raises serious questions about the applicability of the model to reaches downstream of dams, since these areas are likely to experience long-term net export of large wood and of all but the largest substrate classes. However, these are precisely the locations where the model is often used.

understanding of the life-history of the species and an estimate of MAD. The percentage of MAD required for each month (or other time increment) is based on the life-history (e.g., spawn timing) of the species.

Hydrograph component analysis

An alternative approach to analyzing the effect of flow on habitat-forming processes and on other variables of interest was described by Bill Trush during the course of the workshop. In place of transect-based point measurements of hydraulic characteristics, the spatial unit of analysis (in alluvial systems) is a hydraulic unit bounded by the channel cross-over of the thalweg. The unit of analysis then contains several different habitat features in a spatially explicit, rather than disaggregated, context.

Instead of considering specific discharge levels and their translation into depth and velocity, each component of the annual hydrograph is examined for its effect on the functions of different pieces of the hydraulic unit, such as the mobilization of substrate on different portions of a point bar. By comparing hydrographs from dry, medium, and wet years, the analysis focuses on how different years influence ecological attributes of interest, such as colonization by riparian species, riffle inundation (supporting invertebrate production), and the temperature of back-eddies.

Indicators of Hydrologic Alteration (IHA) and associated tools

IHA is a descriptive tool developed by the Nature Conservancy (Richter et al., 1996; 1997; 1998[6]) to characterize the hydrology of a stream or river according to several dozen attributes. The tool ideally uses a long-term daily flow record, but simulated records are at times needed to fill gaps in the record. By comparing the hydrologic characterization between two time periods—for example, before and after a major alteration such as the construction of a dam—the tool enables quantitative analysis of the degree and nature of hydrologic alteration. One method for comparing the degree of change over two periods is the companion Range of Variability Analysis (RVA) developed by Richter.

Based on a daily flow record, IHA computes up to 67 flow statistics[7] that describe the magnitude, timing, duration, frequency, and rate of a variety of flow descriptors. These include standard statistics, such as monthly mean flow and the magnitude of the annual 1-day minimum flow, as well as the frequency of high flow 'pulses', the rate of change for rising and falling flow conditions, and a variety of other measurements.

IHA sometimes faces criticism for its lack of an explicit link to observable biological effects of a change in flow. However, a growing body of IHA applications is starting to build that bridge to ecological effects and management recommendations. It is easy to see how specific flow descriptors may have a direct relationship to one or more VSP attributes. For example, if the timing and duration of side-channel connectivity is flow-dependent, then an alteration (or natural variation) in the flow regime may increase or

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[6] http://www.nature.org/initiatives/freshwater/conservationtools/art17003.html

[7] Based on documentation for IHA version 7.

decrease the use of these areas by juveniles, with potential implications for abundance, productivity, and life-history diversity. The succession of riparian plant species is closely linked to the timing and duration of inundation over channel bars and banks relative to seed dispersal, germination timing, and other factors. Changes in the flow regime (coupled with other factors, such as sediment transport) may alter these ecological processes, which can have implications for the species diversity and health of the riparian area.

Of course, any of these flow statistics can be calculated without the use of IHA, and not all 67 flow statistics are needed to diagnose any single flow scenario. But the detailed hydrologic description provided by IHA offers a convenient, multi-faceted tool for understanding the hydrology of a system and changes in the hydrologic profile over time.

A team at the University of Washington (including workshop attendees Julian Olden and Cathy Reidy Liermann) is using the Ecological Limits of Hydrologic Alteration (ELOHA) approach (Poff et al., in review) to identify relationships between flow alteration and ecological responses for hydrologic classes of streams and rivers. In lieu of intensive, basin-specific instream flow studies, the approach attempts to link the hydrologic typology for rivers and streams to ecological changes that result from alteration. Studies have shown that different types of flow variability support different ecological communities and life-history strategies.

The ELOHA project aims to identify the specific and natural range of hydrologic and biologic variation for each stream class, and to develop a tool that would allow managers to predict ecological responses to various hydrologic alterations. Ecological response variables are not limited to salmonids, but also include invertebrates, riparian functions, and other biota and processes. A challenge for studies that attempt to link flow to fish or other ecological responses is the lack of contemporaneous data, that is, flow data collected at the same time and place as associated biological data. A goal of the study is to provide initial instream flow targets for watersheds across the region based on typology. These targets can be refined as necessary through basin-specific studies.

Key Questions

Before the workshop, attendees received a set of three questions to serve as discussion prompts. The intent was not to rigidly structure the workshop around these specific questions, but to highlight key areas of discussion that would be fruitful to address during the workshop.

1. *How well do current flow tools address each of the four VSP attributes?*
2. *Issue of scale: Can reach and sub-basin scale flow tools be "up-scaled" to match independent populations? Can VSP concepts be "down-scaled" to the reach and sub-basin level?*
3. *What are the highest-priority research questions for the next 5-10 years to address gaps in the tool box?*

After describing major themes discussed during the workshop (Section 3), we provide ‘composite’ answers to these questions from the sometimes differing perspectives of participants, and consider whether these were the right questions to ask in the first place (Section 4).

3. KEY THEMES

The following themes emerged from discussions around central topics during the workshop. While not all remarks, suggestions, and questions posed during the workshop could be included here, a sincere effort has been made to summarize principal topics.

Modified vs. unmodified channel and floodplain

The effect of a particular flow regime on the ecological processes, habitat features, and biota within a watershed is inextricably linked to the channel form and surrounding floodplain in which the flows occur. The point here is not that landscape alterations affect hydrology (which they do, profoundly), but that the same hydrology produces different effects depending on the type and degree of landscape alteration.

For example, in a river with natural banks and an intact floodplain, high flows behave very differently than in a levee-confined river. In the first case, flood flows overtop the banks and access the floodplain. The rougher, natural streambanks likely dissipate energy and reduce the velocity of flows within the channel with potentially direct reductions in the scour of salmon redds. At the same time, off-channel areas may become available as temporary refugia for adults and/or juveniles, with potential benefits to one or more year-classes of the same population.

In contrast, confinement by levees increases stream energy within the channel while denying access to important floodplain habitat. So, the flow itself may not have changed at all due to land use (assuming that the upper watershed is fully intact), but the effects of specific discharge rates on VSP may have changed dramatically.

This example could be expanded to discuss the many other benefits of natural river banks and intact floodplains, but the main point is that a change in hydrology must be considered in context with the channel and floodplain. This has important implications for the usefulness of generalizations linking flow to VSP. In an altered system, recapturing all attributes of the natural flow regime may be premature until the channel and floodplain conditions have been restored sufficiently to allow flows to function as they would in a natural channel context.

An analogous case can be made for a low-flow scenario in a tributary that has become wider and shallower primarily due to landscape alteration and resulting erosion. In this case, the natural level of late-summer base flow may not be enough to support a healthy population. Flow augmentation may be a useful intervention until the shape of the channel and associated riparian condition can be restored to a more natural state.

These examples are not formal recommendations from the workshop. They simply illustrate the importance of understanding the specific channel and floodplain context in making a flow/VSP diagnosis.

Managed vs. unmanaged flow

Dams are prevalent in the river ecosystems of western North America. The adverse effects of dams on VSP are many and depend on multiple factors. In this discussion, we focus only on the flow effects to areas downstream of dams and the opportunities to reduce or mitigate adverse effects via flow control.

The effect of dams on downstream areas is a special case of channel modification. Dams not only affect the flow of water, but also the transport of sediment and large wood, both of which are often eliminated entirely. This means that the flows released from the dam are not acting on a natural channel or floodplain, even if the surrounding landscape itself is seemingly intact. Thus, the design of a model-generated 'optimal' flow regime must consider the physical context and its associated limitations.

Flow control may also provide opportunities to conduct experiments and to prescribe specific flow regimes to benefit priority resources, such as ESA-listed species or, in some cases, wholly different activities like whitewater rafting. Many hydroelectric dams in the U.S. and in Canada are required to provide specific flow levels during different times of year, often based on recommendations derived from instream flow studies. In most cases, required flows are expressed simply as a minimum flow for each month, week, or other increment of time, coupled with limitations on the rate of downward change in flow levels (i.e., down-ramping) to minimize fish stranding.

Flow requirements for fish are often balanced with other identified priorities, such as keeping reservoir levels high through the summer season for recreation, or providing flood control. In recent years, requirements for controlled higher flows have been implemented in a few cases to support 'channel maintenance' processes. However, these rarely exceed the maximum turbine capacity of the facility, that is, they are not equivalent to major floods. As one would expect, controlled flows that exceed bank-full levels are difficult to implement politically due to flood concerns.

The ability to tailor flows that pass through hydroelectric dams is often constrained by economic considerations. For most large-scale hydroelectric operations, profitability is directly linked to operational flexibility. In the diverse portfolio of a large power utility, hydroelectric plants can often respond quickly to changes in system demand, while fossil fuel plants are less flexible and are thus relied on more for base load. This means that most utilities have clear economic reasons to prefer maximum operational flexibility in the flow regime. If minimum flow levels are required, utilities prefer rules that remain the same year-to-year to allow efficient planning.

Moreover, in the U.S., the opportunity to negotiate changes in a flow regime typically arises only when a facility undergoes Federal Energy Regulatory Commission re-licensing (approximately every 30 to 50 years). As part of re-licensing, utilities often resist accepting an uncertain flow regime based on future results of monitoring and adaptive management, since this introduces unknown costs into the negotiation process. Still, many utilities have worked collaboratively with resource agencies and other parties to make voluntary improvements in flow releases based on results of technical studies.

The preceding discussion highlights both the opportunities and limitations of controlled flows in addressing VSP attributes. A flow regime that is designed to be 'optimum' based on studies such as PHABSIM may well provide a stable hydrologic environment, and the moderation of extremely high flows may increase species survival during incubation and thus increase abundance. But diversity is likely compromised by the homogenization of the flow regime. That homogenization may be evident on a number of biologically significant timescales, from daily flows up to decadal-scale patterns.

During the workshop, Ed Connor of Seattle City Light shared his observations of changes in salmon populations downstream of the utility's dam on the mainstem of the Skagit River. The changes he has observed following a change to more fish-friendly flows at the dam provided valuable insight into the effects of flow on VSP. Prior to the flow changes, Chinook, pink, and chum salmon redds in the spawning reach below the dam experienced periodic dewatering as flows decreased due to project operations. Spawners themselves were occasionally stranded by rapid flow fluctuations.

The 'new' flow regime is designed to be stable and to eliminate redd dewatering. The spawning populations below the dam have grown for all three of these species, though none are of a stream-rearing variety. Connor has not observed a similar change in coho or steelhead, both stream-rearing species. In addition, piscivorous bull trout seem to be attracted to this reach and tend to migrate less than their counterparts in other parts of the Skagit watershed. The Skagit watershed is home to no fewer than six independent Chinook populations. It does not appear that the other five populations in the basin are experiencing similar increases in abundance. Also, of all Chinook spawning in the basin, the percentage that spawn in the reach downstream of the dam has increased substantially under the new flow regime.

This example raises interesting questions about the unanticipated, indirect effects of flow modification. Are the benefits to one population coming at the expense of others? If the Chinook population below the dam continues to increase, will emigration rates increase and compromise the reproductive isolation of other independent populations? Even as abundance increases, is diversity decreasing? What about spatial structure? Is the homogenized flow regime harmful to stream-rearing species, some of which are also listed under the ESA (steelhead, for example)?

Flow → Habitat vs. Flow → Fish

Many of the current instream flow tools, such as PHABSIM, attempt to quantify the relationship between flow and fish habitat. They do this primarily by linking modeled hydraulics to functions that describe fish preferences, which are based on observations of fish behavior. However, few of these tools tell us anything about the effects of flow on observable VSP attributes. (The exception is abundance, which is assumed to increase with optimized habitat.)

Direct inferences (without an intervening habitat model) of the **Flow → Fish** relationship have been made by analyzing flow records coupled with outmigration estimates based on smolt trap data. In some cases, adult escapement estimates have been combined with flow data from the spawning period of the parent generation to make similar inferences. The best-known examples of this type of analysis are credited to Dave Seiler and colleagues at the Washington State Department of Fish and Wildlife, but examples are also available from several other sources. Across a range of studies—in most cases confined to single basins with contemporaneous flow and fish data—quantitative relationships have been observed between a variety of flow indices and subsequent survival. Examples include the following:

- The magnitude of persistent summer low flows has been positively correlated with coho smolt production.
- High flows during spawning have correlated with higher coho adult returns two years later. (Seiler hypothesized that this was due to greater access to spawning grounds and associated rearing habitat.)
- Peak flows during incubation have been negatively correlated with Chinook egg-to-fry survival in certain locations, presumably due to redd scour.
- Higher spring emigration flows have been positively correlated with higher subsequent Chinook survival in the flow-controlled Lewis River.

These data and associated analyses have greatly enhanced our understanding of the relationship between flow and abundance. They also provide signposts for further research into the mechanisms that govern these relationships. Workshop participants provided several suggestions for novel ways to approach retrospective analysis of data from these studies. These suggestions are discussed in Section 5.

But knowledge of these types of **Flow → Fish** relationships still does not provide a straightforward bridge from flow to VSP, even if the relationships themselves are confirmed at other locations. If, for example, higher late-summer rearing flows produce more juveniles in a given year, does it mean that higher late-summer flows are desirable every year? What is the effect of one or more years of very low late-summer flows on VSP? While short-term fish abundance may suffer, might the dry years enable specific riparian species to colonize mid-channel bars, thus creating the habitat conditions that will later boost the abundance or productivity of a subsequent year-class of fish? Is the richness of invertebrate species tied to flow variation? Moreover, population persistence through variable conditions is presumed to depend in part on life-history and genetic diversity. The analysis of hydrograph components (as described by Bill Trush) may be a viable way to explore the importance of flow variation at a site-specific level, but generalizations at the population level will require new approaches.

Scale

One of the key challenges in linking existing instream flow tools to VSP attributes is the mismatch in scale—both temporally and spatially—among the tools, the populations, and the physical processes of interest.

Spatially, most instream flow tools are applied at the scale of reaches or independent drainages. The thoughtful selection of transects or other hydraulic units of analysis can ensure that the study sites are physically representative (at least at one point in time) of the reach or drainage of interest, but independent populations of salmonids tend to operate within a broader stream network or watershed.

Descriptive hydrologic tools like IHA can be applied at any scale, provided a long-term daily discharge record is available. However, analysis of a mainstem gage at the mouth of a major river may not be sufficiently informative about specific conditions in sub-basins within the larger drainage. Hence, the linkage between flow and the biological organization of the population may not be evident.

One possible approach discussed at the workshop is the use of a combination of existing tools through spatial nesting and replication to provide a more detailed, multi-scale view of a particular watershed. However, replication of field studies across more locations is expensive, as is the installation and long-term maintenance of gages. And even with expanded spatial coverage and replication, the availability of instream flow data and analyses does not enable a VSP 'diagnosis' of the system. This issue is discussed further in the following section.

The temporal scales associated with flow tools, flow effects on populations, and VSP attributes was also discussed. One inherent challenge is quantifying the role, significance, and duration of antecedent hydrologic conditions in shaping a population's trajectory. The observed habitat condition at a place and point in time is the product of previous conditions that may extend backward in time for weeks, months, or years, or to the last channel-resetting flow event. Thus, the time lags between flow observations and population responses can confound the analysis.

The RITT framework document attempts to reconcile 1) the temporal and spatial scales of the physical processes (including flow) that shape ecosystems, and 2) the scale of demographic processes and structures. A challenge to doing so is that both operate simultaneously at multiple scales. For instance, the temporal persistence of specific habitat patches is likely much shorter than the persistence of the broader habitat mosaic that supports the population. This suggests that to evaluate flow effects on VSP, the scale of tools must span the full scale of physical processes—both temporally and spatially—that support a population, including micro-habitat, meso-habitat, reaches, and stream networks. Thus, the unit of analysis in this case might reasonably be based on the population distribution rather than on any arbitrary reach length. This would immediately link one important hydrologic scale with the population scale, which would be an improvement over current methods.

Diagnosis – What does it look like when flow supports viability?

From an ecological perspective, there is no 'extra' flow in a watershed. All components of a hydrograph—including its annual and decadal variations—play a role in shaping the ecological characteristics and biological organization of the system. But from a practical perspective, water must be made available to support other beneficial uses at certain times and locations. How do we know whether the instream flow in a particular watershed supports VSP? How do we know whether there is 'water to spare'?

To understand the role of flow in VSP in the context of a watershed or stream network that constitutes the freshwater geographic 'space' of the population, we must understand the relationship and role of different spatial units to the biological organization of the population. An independent salmon population may contain several levels of organization, including local aggregations and even smaller units. As explained in the RITT framework document, VSP attributes may look very different depending on the level of organization. Productivity and diversity in particular may vary when measured at different levels of organization.

For the sake of example, assume that an independent population has three core spawning locations and several secondary spawning locations that are used less frequently as a function of variable spawner density, hydraulic connectivity, or other factors. The locations may also differ in the relative availability and types of proximate rearing habitat. The most important flow attributes to support viability may differ between locations, and different thresholds for 'acceptable' alteration may also come into play. Of course, in the context of a stream network, flows in one area may affect flows in another, so the analysis must account for hydrologic interdependence between areas.

As a contrasting example, consider the VSP role of a headwater tributary that is naturally inaccessible to anadromous fish. Flows in the tributary may play a very different but critical role in the biological organization of the population; accordingly, the conceptual model of the system and the analytical tools applied to it must reflect that unique role.

Thus, absent a coherent framework for linking spatially explicit flow information at several scales to the biological organization of the population, even a large stockpile of data and studies does not add up to a VSP evaluation.

For both practical and ecological reasons, the identification of important thresholds of alteration was recognized as a key topic. For example, the percentage of impervious area in a basin has been linked to not only changes in flow but to biological integrity. Different thresholds may apply in different contexts. Developing typological tools for the classification of streams is an important effort.

By combining several of these concepts, a list of components contributing to VSP diagnosis begins to take shape:

1. A clear understanding of the biological organization of the population across multiple spatial and temporal scales.

2. A conceptual framework that identifies the role of specific locations (tributaries, reaches, confluences) in supporting the biological organization.

3. Analytical flow tools at multiple temporal and spatial scales that can be applied selectively to assess the ability of particular locations to perform the roles identified in #2.,

4. Identification of key thresholds of alteration that, over time, are likely to compromise one or more VSP attributes and increase the risk of extinction.

This list is not meant to be comprehensive, but rather reflective of the tools and analytical methods that need to be developed and integrated over time. Some existing tools will likely play an important role. The missing link is the framework that ties them together.

4. KEY QUESTIONS

The three questions introduced in Section 2 were used to frame the workshop discussions. While no attempt was made to reach consensus, the following is a summary of key points raised during the workshop and in follow-up questionnaires.

1. How well do current flow tools address each of the four VSP attributes?

- Current tools can help to quantify some relationships, such as the effect of flow magnitude on the survival of juvenile salmon during emigration; the effect of peak-flow magnitude on the survival of incubating salmonids; and the relationship between the flow at which salmonid redds are created and the flow at which they become dewatered.
- IHA may provide a way to link flow diversity to population diversity, but we need a tool that will link specific hydrologic alterations, habitat functions, and population responses.
- In scenarios where spatial structure is primarily a function of fish-passage flows, existing tools can quantify how well flows support passage at a specific location. However, we cannot know whether a particular frequency or degree of connectivity supports VSP without understanding the biological organization of the population.
- Current tools generally fail to address VSP attributes, with the partial exception of abundance. However, some combination of current tools and new tools may hold promise.
- Current tools are not intended to generate population numbers or dynamics. If that is the intent, we need tools that are linked to spatially-explicit population models if possible.
- The spatial scales of most current tools are far too small for populations, and the tools do not account for the heterogeneity and turnover in habitat patches over time.
- Existing tools do not adequately address ecosystem processes that shape and maintain the environment of target biota.
- Existing tools do not reflect the assumptions of salmonid population dynamics. How might development of flow analyses from the standpoint of biological and ecological assumptions differ from current methods?

2. Issue of scale: Can reach and sub-basin scale flow tools be “up-scaled” to match independent populations? Can VSP concepts be “down-scaled” to the reach and sub-basin level?

- Applying a tool at a different scale than the one for which it is designed can be problematic. Without explicit assumptions and model elements for the broader spatial scale, errors associated with local assumptions may be propagated across the landscape.

- Some tools can be up-scaled to match the scales of interest for populations, but that will require better definition and resolution of VSP attributes and metrics.
- Some approaches can be up-scaled by replication across a population's range. The challenge lies in integrating what is learned from such an exercise into sound population-scale management.
- Some up-scaling to match spatial scale can be accomplished, but capturing the temporal aspects of VSP will require wholly different frameworks for analysis.

3. What are the highest-priority research questions for the next 5–10 years to address gaps in the tool box?

- Develop a better understanding of VSP attributes within populations in order to develop appropriate instream flow tools. Currently, VSP is too theoretical to allow direct linkage of flow to VSP attributes.
- Reconstruct the historical ecology of the rivers and populations in question. This may involve the use of hydrologic models to reconstruct the spatial and temporal distributions of various VSP-related flow parameters.
- Study salmon distributions relative to river morphology and valley geology in both undisturbed (i.e., reference) and modified systems.
- Investigate flow effects on rates of habitat patch turnover and on population dynamics.
- Identify key thresholds of hydrologic alteration that trigger serious consequences for population viability.
- Develop clear explanations of the connections between human actions (such as landscape alteration and water withdrawal), ecological processes, and living resources.
- Define realistic, desired bio-geophysical stream channel and floodplain conditions that will support viable salmonid populations, and the flow regimes that make them possible.
- Evaluate the role of peak flows in driving habitat formation and maintenance processes where high flows contribute to redd scour and mortality, and the trade-offs on multiple timescales with impacts to populations.
- Develop tools to link land management and stream-flow management to restore the bio-geophysical structure of salmon-bearing rivers and streams.
- Develop and test regionally applicable flow management approaches based on typological characterization to enable setting of flow targets in basins where none exist.

Do we need to link flow to VSP in the first place?

The workshop and the guiding questions were framed under the basic assumption that instream flow needs to be linked to salmon population viability. In general, that charge was interpreted as a need for a general framework for assessing the role of flow in each of the four VSP attributes. Workshop participant Matt Longenbaugh (NMFS Habitat Conservation Division) questioned whether such a generalized linkage is needed in the first place.

While Longenbaugh agrees that current flow tools do not specifically address VSP attributes, he does not believe that they need to. In his view, the mismatch between the scales of flow tools and populations does not need to be reconciled in order for NMFS to determine whether an ESU or Distinct Population Segment is recovered to the point of ESA-delisting. Instream flow conditions are only one of the eleven categories of habitat threats (see Appendix B) that must be addressed by NMFS to determine delisting (although the condition of other habitat attributes—such as channel function—are directly linked to flow). He does not believe that each of the eleven habitat threats needs an explicit link to VSP to determine delisting conditions.

Finally, Longenbaugh notes that the extent to which instream flows limit the viability of any particular salmon population will vary by watershed and by population characteristics. He argues that because each watershed will present a separate set of research needs, it is not necessary to build a general link of instream flows with VSP.

This perspective poses an interesting set of questions about future directions. Will any general framework to link flow to VSP lack the specificity required at the level of an independent population? Should the flow/VSP relationship be further explored only in places where flow is obviously a major problem? If so, who should make that determination, and how?

5. RESEARCH PRIORITIES AND NEXT STEPS

To provide management guidance for the protection and restoration of instream flow to support salmon populations, the science will need to couple measurable changes in the flow regime with measurable changes in VSP. To that end, the following suggestions identify important areas for future development, in addition to the specific items listed under Key Question 3, above.

- Develop a conceptual framework that links flow to VSP in a way that addresses the many challenges identified in the workshop, such as linking population organization to flow and other physical processes in a spatially and temporally explicit way. The RITT framework document suggests a set of principles to guide such an effort.

- Conduct retrospective analysis of the **Flow → Fish** relationship using existing data. One option is to gather all available datasets that link specific flow metrics to abundance and analyze the information differently. For example, rather than associating outmigrants or adult returns with the specific discharge, the flow levels could be normalized as a percentage of MAD. Stratification by basin size, location, or type could yield further insight into key relationships between flow and subsequent production.

- Improve understanding of how different flow components contribute to specific processes, functions, and population attributes at multiple spatial and temporal scales. At certain scales (such as the hydraulic units used by Bill Trush), the tools may already exist. Other tools remain to be developed.

- Identify the types of biological, physical, and hydrologic information needed to support analyses in the context of a flow/VSP conceptual framework. Leverage existing efforts, such as the Intensively Monitored Watersheds program[8].

- Identify existing locations with contemporaneous flow and fish data, and expand coverage of the data network across core populations.

- Adapt monitoring programs to detect change in VSP attributes. Conventional population monitoring efforts are likely insufficient to detect changes in VSP attributes. For example, spawner surveys typically focus on reaches that feature the highest observed concentrations of spawners. This may make sense for the purposes of abundance estimation, but how do we discern whether the spatial structure is expanding or contracting? To do so, secondary or potential spawning areas should be integrated into the monitoring program.

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[8] The Intensively Monitored Watershed project is a joint effort of the Washington Departments of Fish and Wildlife and Ecology, NOAA Fisheries, U.S. Environmental Protection Agency, Lower Elwha Klallam Tribe and Weyerhaeuser Company and is financially supported by the Washington Salmon Recovery Funding Board.

- Develop models that combine hydrology, land-use, and riparian condition in a way that helps to identify and communicate the consequences of different land- and water-management alternatives.

APPENDIX A: PARTICIPANT LIST

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APPENDIX B: NOAA FISHERIES LIST OF HABITAT THREATS

Excerpted from Final Supplement to the Shared Strategy's Puget Sound Salmon Recovery Plan, November, 2006:

To determine that the ESU is recovered, threats to habitat should be addressed as outlined below:

1. Channel function, including vegetated riparian areas, instream wood, streambank stability, off-channel and side-channel habitats, natural substrate and sediment processes, and channel complexity is restored to provide rearing, migration, and spawning habitat to meet the Recovery Plan's recovery goals.

2. Instream flow conditions and programs that support salmon rearing, spawning, and migration needs and meet the Chinook population targets are achieved.

3. Floodplain function and the availability of floodplain habitats for salmon is restored to a degree sufficient to support a viable ESU, including tidal swamp and marsh habitat in estuaries and the tidal freshwater portion of the lower rivers. This restoration should include connectedness between river and floodplain and the restoration of impaired sediment delivery processes and conditions affecting both estuaries and lower mainstem rivers.

4. Deleterious effects of stormwater runoff are eliminated or controlled so as not to impair water quality and quantity in salmonid streams or the riparian habitats supporting them.

5. Agricultural practices are implemented and programs are in place to protect and restore riparian areas, floodplains, and stream channels, and to protect water quality from sediment, pesticide, herbicide, and fertilizer runoff.

6. Urban and rural development, including land use conversion from agriculture and forest land to developed areas, does not impair water quality or result in dysfunctional stream conditions.

7. As appropriate or necessary to support region-wide recovery goals, passage obstructions (e.g. dams, tidegates, and/or culverts) are removed or modified to restore fish access to historically accessible habitat.

8. Nearshore processes are protected and restored so that ecological inputs (of sediment, insects, leaves and wood) to drift cells and mudflats function properly to support Chinook salmon and the species they prey upon. Programs are in place to ensure continued protection and restoration of water quality.

9. The effects of toxic contaminants on salmonid fitness and survival in the Puget Sound estuaries, lower mainstem rivers, and nearshore ocean are sufficiently limited and programs are in place to ensure continued limiting so as not to affect recovery.

10. Activities that dredge or fill in nearshore and river beds or harden stream banks are sufficiently mitigated.

11. Forest management practices that protect and restore watershed and stream functions are implemented on Federal, state, Tribal, and private lands and programs are in place to ensure continued mitigation.