Toward sustainable development of hydropower in Alaska: A briefing paper on approaches to avoid and minimize risks to Alaska's Pacific salmon populations

The Nature Conservancy

June 2016

Acknowledgements

This briefing paper was completed under the Conservancy's Coda Fellowship program as supported by the Alaska and Pennsylvania Chapters of The Nature Conservancy including generous support from the Gordon and Betty Moore Foundation. In particular we would like to thank the following organizations for their coordination and contributions to our understanding of Pacific salmon populations and related social and economic resources in the Susitna Basin as well as our understanding of the proposed Susitna-Watana hydropower project: National Oceanic and Atmospheric Administration, U.S. Fish and Wildlife Service, U.S. Environmental Protection Agency, Alaska Energy Authority, Alaska Department of Fish and Game, Susitna River Coalition, Aquatic Restoration and Research Institute, Trout Unlimited, Wild Salmon Center, Natural Resource Defense Council, Center for Water Advocacy, Talkeetna Air Taxi, Mahay's Jet Boat Adventures, Anchor QEA, LLC and Water and Power Law Group, PC. The author would also like to thank Jeff Opperman and Corinne Smith of The Nature Conservancy for providing review of the draft briefing paper.

Corresponding author:

Tara Moberg
The Nature Conservancy
2101 N. Front Street, Bldg 1, Suite 200
Harrisburg, PA 17102
tmoberg@tnc.org

Please cite as:

Moberg, T. 2016. Toward sustainable development of hydropower in Alaska: a briefing paper on approaches to avoid and minimize risk to Alaska's Pacific salmon populations. The Nature Conservancy. Harrisburg, PA.

Cover photo: © Cheryl Hughes -West Fork and Susitna Glaciers, headwaters of the Susitna River

Summary

Unlike the continental U.S., Alaska's major rivers are still free-flowing and support some of the most abundant Pacific salmon populations in the world - this includes the Susitna River. For the third time in six decades, a federal license for the construction and operation of a 600 MW hydropower dam is being considered on the Susitna's mainstem. This is the first time it is being considered as a renewable energy resource to meet the state's voluntary Renewable Energy Portfolio Goal of 50 percent by 2025.

Globally, we have decades of experience understanding the known and unintended consequences of large-scale hydropower development. It's from this experience that innovative governance, financing, planning, design and operational solutions have been born. Key to leveraging this experience to avoid unmitigable decisions is being forthright about what we still don't understand in those ecosystems we've been working to restore for decades. To date, despite significant investments in mitigating the impacts of large-scale hydropower in the continental U.S., affected Pacific salmon stocks have not yet recovered (NMFS 2015 & 2016).

The briefing paper builds on the Phase I Preliminary Framework for Ecological Risk Assessment of Large-scale Hydropower on Braided Rivers in Alaska (ERA), with a focus on risks to Pacific salmon populations (Anchor QEA 2015). The ERA methodology is based on a U.S. Environmental Protection Agency framework to define the problem, assess related impacts and characterize risks and uncertainty. Focusing on the proposed Susitna-Watana hydropower dam, the ERA identifies four 'first-order' effects of hydropower development on Pacific salmon – these include flow (and ice) regimes, sediment regimes, connectivity (instream barrier) and water quality – and serve as the hub of influence from which secondary and tertiary impacts are expected to radiate. This paper aims to contribute to a dialogue around hydropower development approaches and characteristics that may be compatible with supporting Alaska's robust Pacific salmon populations and the communities they support, by providing a summary of and references to:

- Contemporary approaches to sustainable hydropower development
- Supporting science, case studies and emerging technologies to avoid and minimize adverse first-order effects of hydropower development on flow, sediment, connectivity and water quality as they influence Pacific salmon populations; and
- A comparison between the proposed Susitna-Watana project and a range of first-order risk indicators, demonstrated best practices and mitigation technologies

Through this review we find incredible innovations in planning and design approaches and technologies available to meet energy and ecological objectives. Examples include, operational releases to support habitat and fish abundance, sediment bypass tunnels, regional fish migration plans, fishways safely passing more than 90% of migrating salmon and hydropower turbines and outlets that can both maintain water quality and increase electricity generation. Conversely, we find that the proposed siting, design and operation of the Susitna-Watana Project exceeds risk indicator thresholds and is outside of the range of reviewed mitigation technologies to avoid or mitigate significant impacts to stream flow, sediment transport, habitat connectivity and water quality.

Section 1. Introduction

With a changing climate, the need for low-carbon energy sources has renewed investment in hydroelectric power globally. The Nature Conservancy is currently engaged at all levels of the global hydropower development curve. In those regions planning significant hydropower development in the coming decades, like Latin America and Africa, we are working with governments and financial institutions to incentivize basin-scale planning and a decision process linked to a transparent sustainability framework. In places with a relatively mature hydropower network and evolved regulatory system, like the continental U.S., we are working with private and public dam owners to restore rivers by incorporating best practices into existing facility design and operations. Where those practices fall short of restoration goals, we are seeking and promoting opportunities to 're-think' our hydropower network, by concentrating investments and hydropower improvements in publically relevant infrastructure and removing those dams whose environmental and social costs outweigh their economic benefit.

Unlike the continental U.S., Alaska's major rivers are free-flowing and support some of the top remaining Pacific salmon populations in the world - this includes the Susitna River (Johnson and Daigneault 2013, ADFG 2013). For the third time in six decades, a federal license for the construction and operation of a 600 MW hydropower dam is being considered on the mainstem Susitna River. This is the first time it is being considered as a renewable energy resource to meet the state's voluntary Renewable Energy Portfolio Goal of 50 percent by 2025. While it is known that the Susitna River supports all five species of Pacific salmon (*Oncorhynchus spp*), including one of the top sockeye populations in the world, like much of Alaska's 365,000 miles of rivers and streams, the majority of the Basin's waters have not yet been surveyed (Johnson and Daigneault 2013). As proposed, the Susitna-Watana hydropower dam would disconnect migrating Chinook salmon from spawning habitat in the upper Susitna River, and its design and operation could affect flow, sediment and thermal regimes on the entire mainstem from the dam to Cook Inlet (Anchor QEA 2015).

Alaskans have a unique opportunity. Globally, we have decades of experience understanding the implications of known and unintended consequences of large-scale hydropower development. It's from this experience that innovative governance, financing, planning, design and operational solutions have been born. Key to leveraging this experience to avoid unmitigable decisions, is being forthright about what we still don't understand in those systems we've been working to restore for decades.

The objectives of this white paper are to provide a summary of, and references to:

- Section 2 (pg. 3). Contemporary approaches to sustainable hydropower development;
- Section 3 (pg.6). Supporting science, case studies and emerging technologies to avoid and minimize adverse effects of hydropower development on flow, sediment, connectivity and water quality; and
- Section 4 (pg. 27) A comparison between the proposed Susitna-Watana project and a range of risk indicators, demonstrated best practices and mitigation technologies.

Section 2. Contemporary approaches to sustainable hydropower development

- There are several converging global and domestic initiatives and supporting frameworks for sustainable hydropower development that include optimizing across social, environmental and economic objectives, at local and regional scales.
- In the U.S., not all hydropower is considered to be 'renewable' energy – with many states imposing limits to size, construction date, or requiring certification by the Low Impact Hydropower Institute.
- In the last couple of years, U.S. government agencies have placed a significant emphasis on sustainable hydropower development including the 2015 Sustainable Hydropower Action Plan (U.S. Department of Energy, U.S. Department of the Interior and the Department of the Army MOU) and the Department of Energy's Hydropower Vision.

Hydropower Sustainability Assessment Protocol (Protocol). The Protocol is an international sustainability assessment tool developed between 2008 and 2010 by a multi-stakeholder forum with representatives from social and environmental NGOs, governments, commercial and development banks and the hydropower sector (IHA 2010). The Protocol is not a certification rather it is an assessment and disclosure practice that was designed to be used at any stage of hydropower development including early stage, preparation, implementation and operation. The Protocol includes an assessment of sixteen indicators of sustainability, generally in the categories of social, economic and cultural sustainability (Table 1). The Protocol is overseen by the Hydropower Sustainability Assessment Council. The Conservancy generally supports use of the Protocol when developing new hydropower, but has identified areas for potential improvement including the future consideration of regional or basin-scale hydropower planning.[1]

The Nature Conservancy's Hydropower-by- Design Approach. Hydropower by Design is one of the Conservancy's approaches to identify development scenarios that allow for energy production while maintaining vital river functions. It involves the consideration of social and ecological resources when planning and developing hydropower resources. Principles of the approach include: (1) influencing the siting of hydropower, avoiding the most damaging sites and directing development toward sites with lower impacts; (2) minimizing impacts at a site, (3) effective basin-scale conservation and mitigation; and

---

[1] http://www.hydrosustainability.org/getattachment/82d03b4e-5feb-420b-9696-2d1341db7c90/The-Nature-Conservancy-Letter-of-Support.aspx

(4) seeking collaborative outcomes that provide benefits across stakeholder groups. At the 2015 World Hydropower Congress, the Conservancy (2015) launched a white-paper, "The Power of Rivers: Finding balance between energy and conservation in hydropower development." Using a Hydropower by Design approach, this work illustrates the opportunity to avoid impacts to ecological and cultural resources on more than 100,000 river kilometers while yielding the same energy benefits (Figure 1) (Hartmann et al. 2013, Opperman et al. 2015).

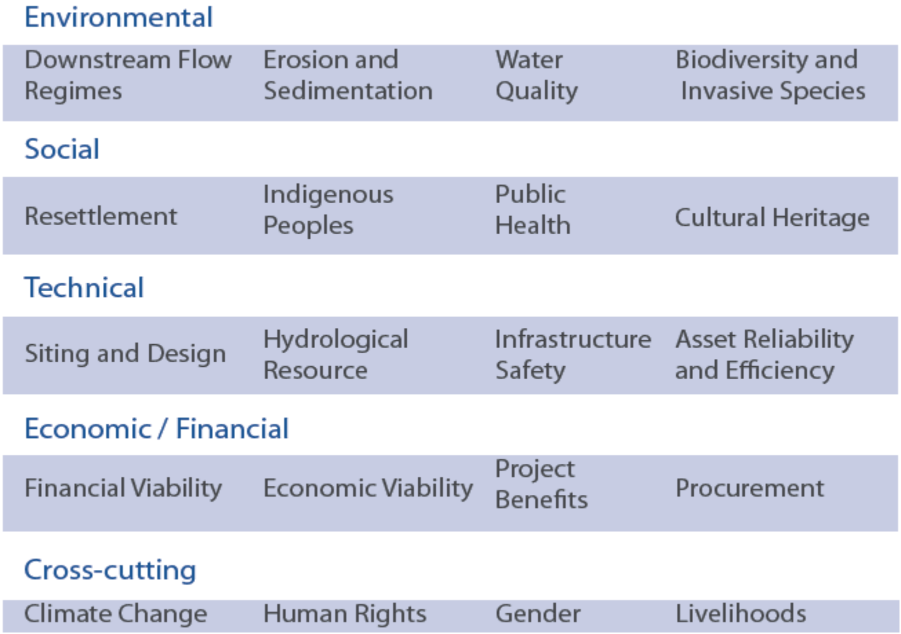
Low Impact Hydropower Institute *(LIHI).* LIHI is a U.S. based non-profit organization dedicated to reducing the impacts of hydropower generation through the certification of hydropower projects that have avoided or reduced their environmental impacts pursuant to LIHI's criteria. At this time, only existing projects generating electricity as of 1998 or existing dams that add new hydropower capacity are eligible for LIHI certification. New dams and facilities outside of the U.S. are not eligible. In the winter of 2016, LIHI adopted revised certification criteria related to eight social and environmental factors. The organization is currently considering expanding the program's eligibility requirements to include new projects in the U.S. and Canadian-based projects, and is considering additional criteria that could be used to assure these hydropower resources meet LIHI's program intent.

U.S. Department of Energy Hydropower Vision*.* The U.S. Department of Energy (DOE) Water Power Program is developing a long-range hydropower development vision and roadmap. The objectives of their Vision process include: leading the development of a cohesive long-term vision for the benefit of the broad U.S. hydropower community; analyzing a range of aggressive but attainable industry growth scenarios; providing best available information relative to stakeholder interests and providing objective and relevant information for use by policy and decision makers.

Parallel to this process, the Conservancy has worked with dozens of agencies, non-profits and research institutions to summarize existing approaches and drafted the following *working* definition for sustainable hydropower development in the U.S. (Richter 2009, IHA 2010, Kiesecker et al. 2010, Watts et al. 2011, USACE et al.2014, Hartman et al. 2013, McManamay and Bevelheimer 2013, Smart et al. 2013, , and LIHI 2016):

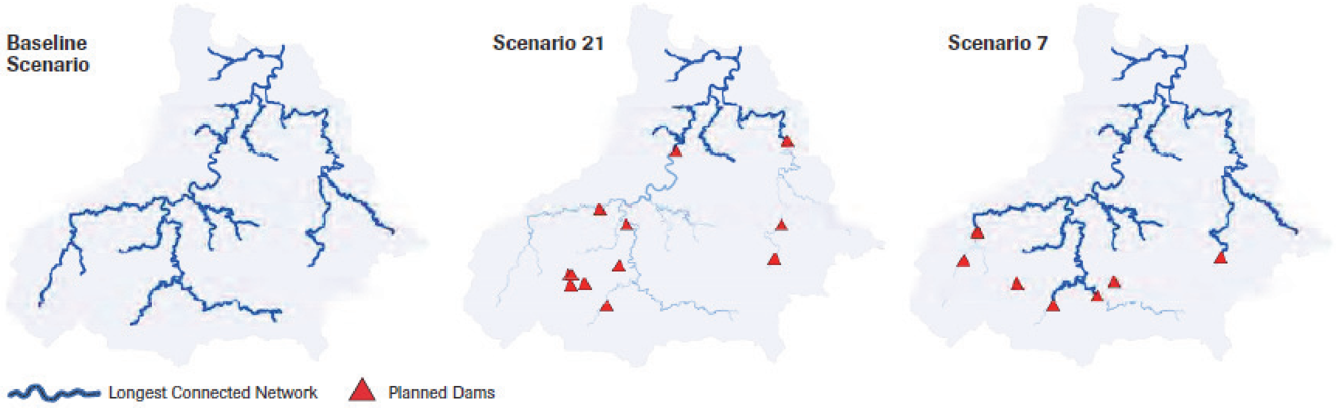
> *"Sustainable hydropower is hydropower that is sited, designed, constructed, operated, and decommissioned in a way that optimizes social, environmental, and economic objectives at local, basin, regional, and national scales. It is adaptable to changes in system state (e.g., changing climate and hydrologic regimes) and to accumulated scientific knowledge and new technologies that will improve the potential for meeting system objectives."*

Table 1. The 2010 International Hydropower Sustainability Assessment Protocol (HSAP) includes sixteen indicators of sustainability across the areas of environmental, social, technical, economic and cross-cutting (IHA 2010).



Environmental			
Downstream Flow Regimes	Erosion and Sedimentation	Water Quality	Biodiversity and Invasive Species
Social			
Resettlement	Indigenous Peoples	Public Health	Cultural Heritage
Technical			
Siting and Design	Hydrological Resource	Infrastructure Safety	Asset Reliability and Efficiency
Economic / Financial			
Financial Viability	Economic Viability	Project Benefits	Procurement
Cross-cutting			
Climate Change	Human Rights	Gender	Livelihoods

Figure 1. An illustration of basin scale hydropower planning comparing various scenarios of hydropower configurations for meeting economic, social, and environmental objectives (Opperman et al. 2015, Jager et al. 2015).



Section 3. Supporting science, case studies and emerging technologies to avoid and minimize 'first order impacts' of hydropower

How can we develop hydropower in a way that protects Alaska's Pacific salmon population, distribution and abundance for generations to come? This section focuses on approaches to hydropower planning, design and operation that may be compatible with sustaining Alaska's salmon resource. As mentioned in the previous section, an applied framework can be found in Hydropower by Design, the key steps of which are to (1) create a conservation blueprint, (2) map social values and (3) use the blueprint to provide an effective framework for avoidance, minimization and offset (Hartmann et al. 2013). Here we share more detail on developing a conservation blueprint and mitigation framework for Pacific salmon.

Conservation blueprint. In their Ecological Risk Assessment, Anchor QEA (2015) laid out a detailed plan to create a conservation blueprint. This includes involving key stakeholders in the development of population baselines, performance goals and collaborative governance– including local, state and federal regulatory agencies, indigenous groups, resource-based industries (fisheries cooperatives, eco-tourism groups), and non-governmental organizations with aligning missions. The blueprint should help to establish salmon population and habitat baselines for each life stage. Habitat baselines should include an understanding not only of the location and extent of habitat, but also its physical and chemical patterns including temperature, flow, water quality and nutrient and sediment regimes. In addition, population performance goals should be explicitly developed. These baselines and performance goals will serve as a reference point during planning, scenario modeling and adaptively managing any project (Anchor QEA 2015). For more detail about methods for salmon baseline habitat and population development and monitoring, see Anchor QEA 2015.

Avoiding, minimizing and mitigating 'first order impacts' to flow, sediment, connectivity and water quality (Figure 2). The blueprint can then be used to plan a hydropower approach that (a) avoids sites and designs that would incur significant impacts to flows, sediment, connectivity and water quality for those conservation areas identified in the blueprint, (b) minimizes direct impacts at a site through best practices in design and operation, and (c) provides an effective framework for offsetting those impacts that cannot be avoided – like protection and management of nearby rivers that provide similar benefits.
The remaining discussion focuses on the ecological risks of hydropower development, specifically those risks that pose a direct threat, or 'first order impacts,' to Pacific salmon populations. Here, we pair first order impacts identified in the Phase I: Ecological Risk Assessment (Anchor QEA 2015) with case studies, technologies and supporting science that demonstrate best practices for risk avoidance or mitigation. Best practices result from a combination of siting and planning, design, technology, operations and maintenance and decommissioning. For each first order impact, we discuss considerations at the basin scale, and at the development site, to avoid or minimize risks from hydropower to Pacific salmon populations. **These direct impacts must be avoided or mitigated in order to minimize the risk of cascading second and third order impacts on Pacific salmon abundance, productivity, spatial structure and diversity (Figure 2, Anchor QEA 2015).**

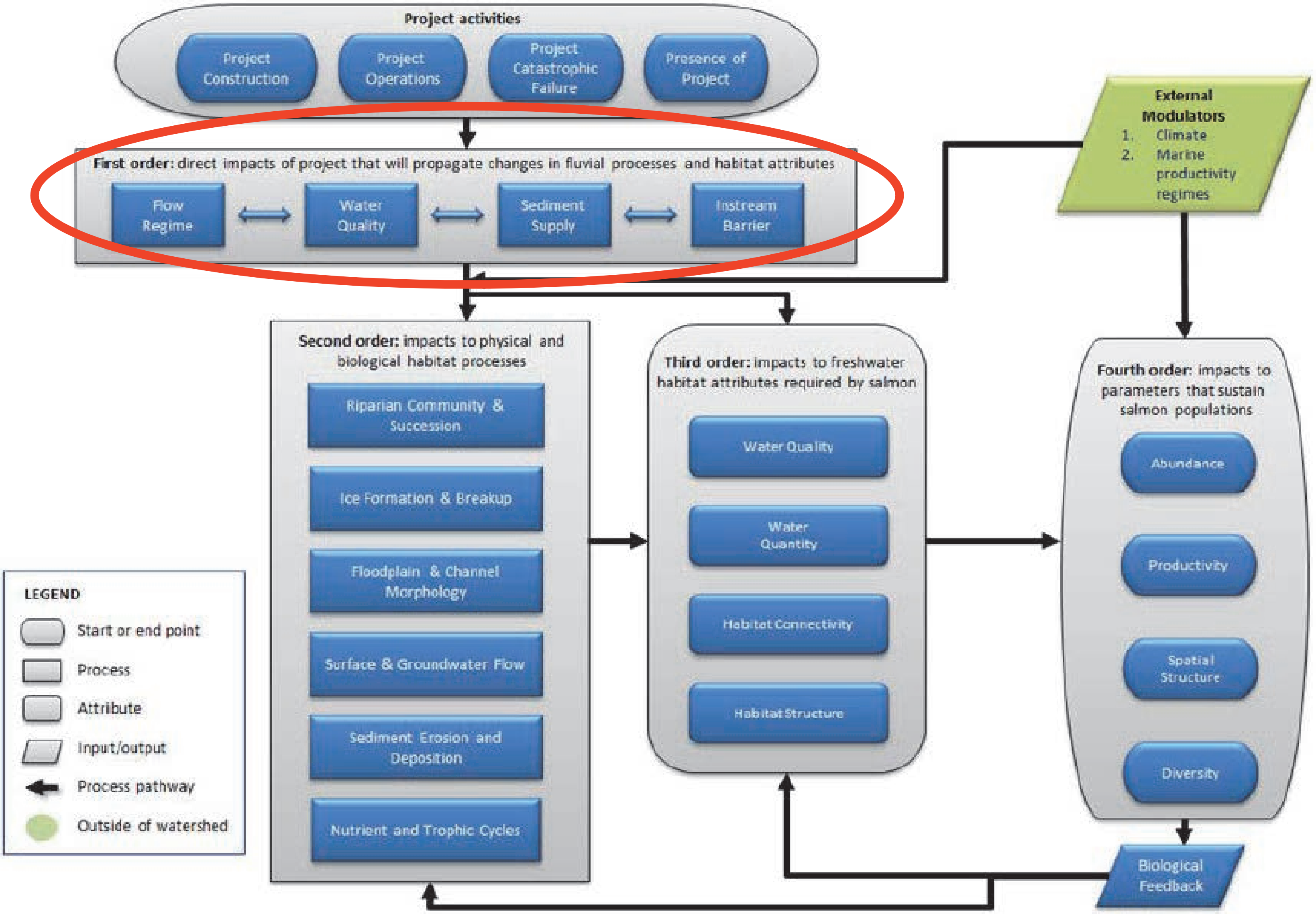


Figure 2. The Nature Conservancy's Ecological Risk Assessment identified four first order, or direct impacts (highlighted in the **red circle**) to salmon populations from hydropower development (Graphic Adapted from Anchor QEA 2015).

Flow Regime

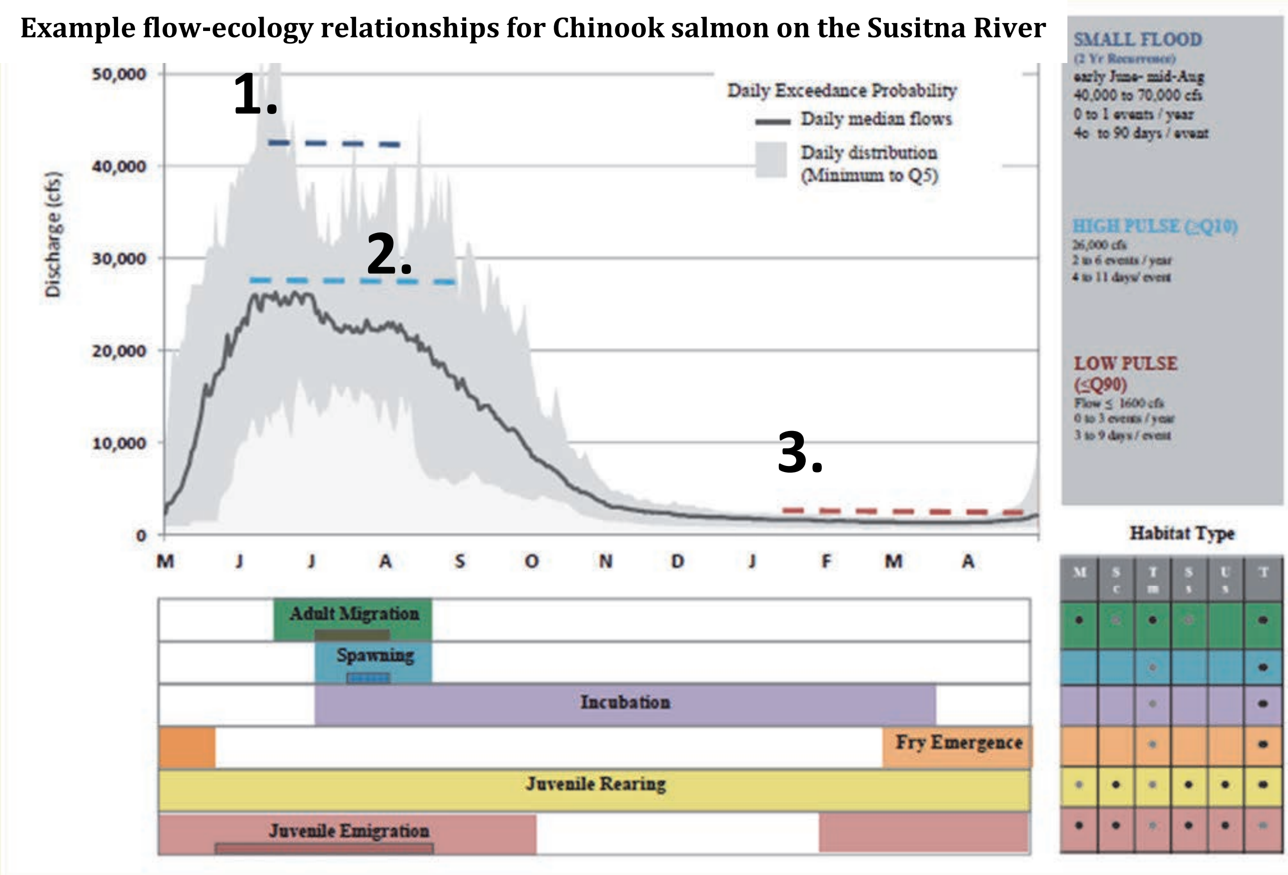
- Use a science-based framework, like the Ecological Limits of Hydrologic Alteration (ELOHA), to develop and protect instream flow reservations that support regionally-specific environmental flow goals or needs.
- Where environmental flow needs (flow-ecology relationships) are poorly understood, or resources are unavailable to develop instream flow reservations, a presumptive standard can be used to implement an interim low risk approach, at a minimum conserving daily, seasonal and inter-annual flow patterns.
- Screen the potential risks of water management scenarios using ecologically relevant statistics –for Alaska's streams this includes the *Cold-regions Indicators of Hydrologic Change (CHIC) for ecological flow needs assessments (Peters 2014).*
- Develop flow-habitat models to estimate the availability and connectedness of habitat under different water management scenarios for different life stages – over space, and time.
- Through off-stream siting, innovative design or operation, hydro-peaking facilities should avoid or mitigate habitat affected by extreme flow fluctuations –and use appropriate ramping rates for regional biota.

Flow alteration from reservoir storage and dam operations constitutes a global threat to river and estuarine function and diversity (Postel and Richter 2003, Nilsson et al. 2005, Poff et al. 2007, Poff and Zimmerman 2010, Carlisle et al. 2011). Specifically, dam operations have resulted in measured affects to daily, seasonal and annual time scales (Magilligan et al. 2003, Magilligan and Nislow 2005, Poff et al. 2007). The entire flow regime, including seasonal and inter-annual variability, is critical to maintain the diversity of biological communities in rivers (Power et al. 1995, Poff et al. 1997, Bunn and Arthington 2002). With this understanding, contemporary water resource planning includes water allocations to the environment, or 'environmental flows.' The following discussion provides an overview of approaches to maintain critical components of the flow regime at the basin and local scales, while considering hydropower development.

Basin scale planning

Risk from alteration to the flow regime should be assessed both for the direct influence of a proposed hydropower project on downstream hydrology and cumulatively, considering all upstream and downstream water uses. Recognizing the need to move beyond river-specific environmental flow prescriptions in order to protect streamflows, Poff et al. (2010) developed a framework - the Ecological

Limits of Hydrologic Alteration (ELOHA) - for the development of flow recommendations at the basin or regional scale. This framework has been successfully applied to several watersheds in the United States to establish regional instream flow policies and protection guidance (Kendy et al. 2012, DePhilip and Moberg 2013 a &b, Taylor et al. 2013, EPA and USGS 2016, *in draft*). It includes the development of regionally-specific flow-ecology relationships. In January of 2014, the Conservancy held a workshop in Anchorage to begin to characterize existing hydrology on the Susitna River and to hypothesize relationships between seasonal and interannual variability and the needs for all life stages of the five Pacific salmon species (Attachment 1). These conversations can serve as a foundation for the development of regional flow recommendations and appropriate instream flow reservations (under Alaska Statute 46.15.145) to support ecological needs including fish and wildlife habitat, migration, propagation and water quality.



Example flow-ecology relationships for Chinook salmon on the Susitna River

1. Spring high flow pulses cue upstream migration of spawning adults
2. High base flows in the spring provide quality of and connectivity between spawning habitats and directional cues for emigrating juveniles
3. Stable winter low flows maintain ice cover, dissolved oxygen and thermal buffering for incubation and juvenile rearing

Figure 3. Flow-ecology diagram and example relationships for Chinook salmon on the Susitna River. Please see Attachment 1 for flow-ecology diagrams for all five Pacific salmon.

This also includes identifying sites that may be suitable for off-stream generation. If considering on-stream dams, avoid proximity to species and habitats with particular flow-sensitivity. Additionally, siting higher in the watershed may provide the opportunity for tributary inflow to mitigate flow alteration to downstream salmon habitats or resources with high conservation value (Hartmann et al. 2013, Opperman et al. 2015, Jager et al. 2015).

Considerations at the development site

Avoid. One way to avoid risk to the flow regime downstream of a dam or diversion for hydropower can be operating under an instantaneous run-of-river mode. Under its proposed revised certification criteria, the Low Impact Hydropower Institute determines projects that operate in an instantaneous run-of-river mode to have deminimus risk to the flow regime (LIHI 2016). That is not to say that run-of-river projects avoid all risks. These projects may still pose a risk through the other first order impacts, including biological connectivity, water quality and sediment regimes (Anchor QEA 2015).

Minimize. In 2010, Zimmerman and Poff conducted one of the first meta-analyses of publications documenting ecological responses to flow alterations. They reviewed over 165 papers in an effort to develop quantitative relationships. While their analysis did not find one specific, globally transferable quantitative relationship, it does provide an important finding – flow alteration is associated with ecological change and the risk of ecological change increases with increasing magnitude of alteration. Several tools exist to assess hydrologic alteration, including the Conservancy's Indicators of Hydrologic Alteration. Specific to Alaska's rivers, where the salmon habitat template is defined by winter ice cover, scour, snowpack and a spring freshet, Peters et al. (2014) recently published a synthesis of flow-ecology relationships and ecologically relevant statistics to consider when assessing the implications of hydrologic alteration in cold regions. Additionally, Bevelheimer et al. (2013) cites ecologically-relevant sub-daily statistics that should be considered when reviewing the potential effects of hydro-peaking operations (Attachment 1). Another indicator that has been used to predict risk of hydrologic alteration is the storage ratio, or the ratio of reservoir storage to mean annual flow. When the ratio exceeds 2%, there may be a risk of hydrologic alteration; a storage ratio that exceeds 10% may risk impacts to ecosystem services (Nilsson et al. 2005, Vogel et al. 2007, Richter et al. 2012, Lehner et al. 2011).

River-specific and regional case studies led to the development of a 'presumptive standard' for environmental flow protection (Richter et al. 2012). This standard suggests that less than 10% alteration to daily flows should maintain ecosystem structure and function and result in minimal changes to the abundance and diversity of regional diversity. Between 10 and 20% alteration may maintain ecosystem function, but some changes to abundance and diversity are expected, and greater than 20% alteration is likely to result in moderate or greater changes to structure and function (Richter et al. 2012).

Mitigate. Typically triggered by the intensity of localized human water demands, prescriptions for ecosystem flows have been developed for a number of rivers systems globally (Annear et al. 2003, Tharme 2003, King and Brown 2006). In the U.S., the requirement for environmental flow releases related to privately owned and operated hydropower predominantly occurs through the FERC licensing and re-licensing processes. Despite relative consensus in the scientific community for the need to protect the entire flow regime including seasonality and inter-annual variability, unfortunately, the majority of prescriptions through the FERC process still focus on minimum flow releases (Jager et al. 2008). In the hydropower context the greatest barriers to implementation of site-specific ecological flow prescriptions include a lack of incentive for power producers and need for economic valuation of ecological benefits derived from various prescriptions (Jager et al. 2008). Further, instead of seeing ecological flows through a dual-objective, or multi-objective framework, most optimization approaches view environmental flows as a constraint (Jager et al. 2008). In a comprehensive ex-post analysis of a river re-licensing on the Manistee River, researchers found that the benefits from flow modifications to increase environmental flow releases were valued at more than twice the cost to power producers (Kotchen et al. 2006).

The hypothesized first, second and third-order impacts of hydrologic alteration on salmon populations in glacial rivers are discussed in detail in Anchor QEA 2015. In order to avoid these risks, water management scenarios should be vetted through flow-habitat models that consider seasonal and interannual variability and all salmon life stages and link to the population performance goals developed in the conservation blueprint. In addition, water management scenarios should be screened using ecologically relevant statistics (Attachment 1) including inter-annual, seasonal daily and sub-daily statistics – to predict the significance of alteration for glacial rivers (Richter et al. 1996, Mathews and Richter 2007, Peter et al. 2014). For on-stream dams, in order to provide mitigated flow releases that support key elements of annual and inter-annual variability, it is necessary to include flexible outlet works and a controlled spillway to allow the operator to adjust the volume of instream flow releases (ACOE 2013).

Sub-daily variability and rate of change

Some hydropower facilities, like the proposed Susitna project, are sited and designed to produce energy in order to meet peak-daily electricity demands. Often referred to as hydro-peaking dams, they release water to generate electricity during peak daily demands, and store water during periods of low daily or seasonal demand, often resulting in a marked 'yo-yo,' pattern in downstream hydrology. Specifically, for most on-stream reservoirs, this includes large fluctuations in water releases that may result in significant variations of downstream flow, depth, velocity and the wetted width of habitat, within a single day (Figure 4). This can be particularly detrimental to species and life stages with limited mobility that can be easily stranded by drastic changes in wetted channel margins, like larval fish and freshwater mussels (Maloney et al. 2012, Stalnaker 1995). For salmon habitats that support life stages with low mobility (like eggs, larvae and young-of-year), habitat persistence, or the availability of habitat over time and space (the connectivity of suitable habitat patches), should be modeled and can be used to compare the relative habitat availability between baseline and operational alternatives to find pathways to population goals (Maloney et al. 2012, Stalnaker 1995).

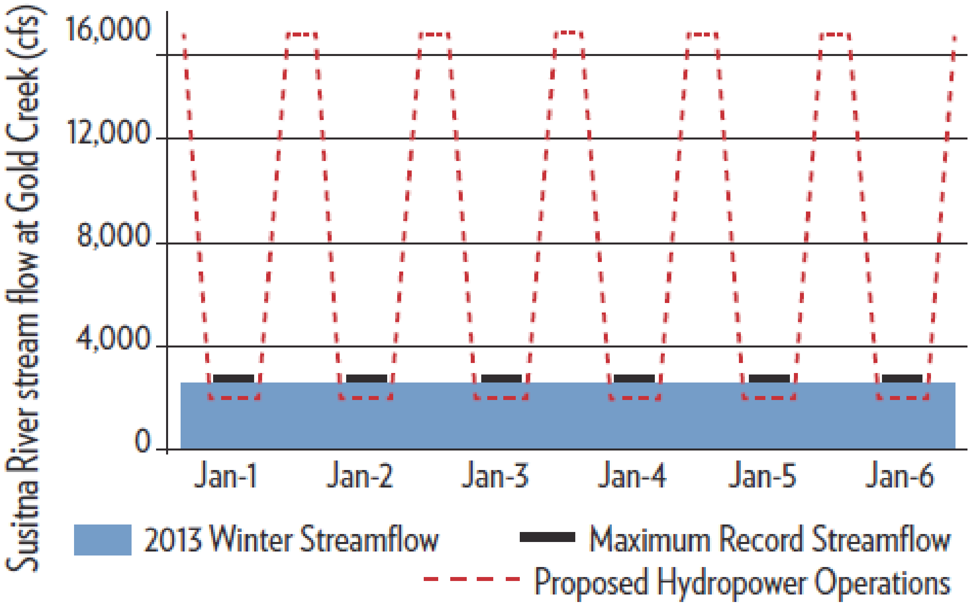


Figure 4. A comparison of winter streamflow on the Susitna River at Gold Creek under current conditions and proposed hydropower operations. Developed by T.Moberg for the Susitna River Coalition

The significance of hydro-peaking on downstream habitat and ecological processes will vary depending on stream order, hydrology and channel morphology (Stalnaker 1995). For river reaches below hydro-peaking facilities, it may not be possible to maintain flows within a natural range of variability, while achieving electricity generation goals (Jones 2014). On the Susitna, stable winter baseflows and ice cover support salmon egg incubation and juvenile rearing (Figure 3). During this sensitive life stage, proposed peaking operations may cause significant daily stage instability, increasing flows by 5 times the maximum recorded winter streamflow (Figure 4). In order to mitigate this impact, the original project (1960's) included a second dam for re-regulating peaking flows to mimic natural flows downstream. The current project design does not include a re-regulating dam.

As the ratio between generation flows (high) and minimum flows (low) increases, specialized species are often replaced by more generalist species (Poff et al. 1997, Jones et al. 2014). In a study of the effect of peaking magnitude on fish biomass in 5th to 7th order rivers in Austria, tailwaters with a ratio of generation flows (high flow releases) to minimum flows (low flow releases) of <=2:1 had a biomass of more than 400 kg ha. As the ratio transitioned to > 5:1, biomass for all sites was below 200 kg ha, and as the ratio increased above 10:1, fish biomass was less than 20 kg ha (Moog 1993). The ratio from proposed peaking operations of the Susitna-Watana project on the Susitna at Gold Creek is about 10:1 (Figure 4). On the Lower Susquehanna River below Conowingo Hydropower facility, peaking operations result in a ratio of > 10:1. As a result, an estimated 95% of persistent habitat has been lost for migratory fish like American shad, river herring and striped bass downstream of the dam (TNC MOI 2014).

Flow and Ice Regimes

While environmental flows science has developed considerably in the last three decades, the study of cold-regions, their river ice processes and resulting hydraulics is still an emerging area of science. For rivers like the Susitna, whose habitat template is defined by winter ice cover, scour, snowpack and a spring freshet, Peters et al. (2014) recently published a synthesis of flow-ecology relationships and ecologically relevant statistics to consider when assessing the implications of hydrologic alteration (See Table 3 below).

Right: Susitna River at Talkeetna, January 2014 © T.Moberg; Below: Global polar and snow driven climates (Peters et al. 2014).

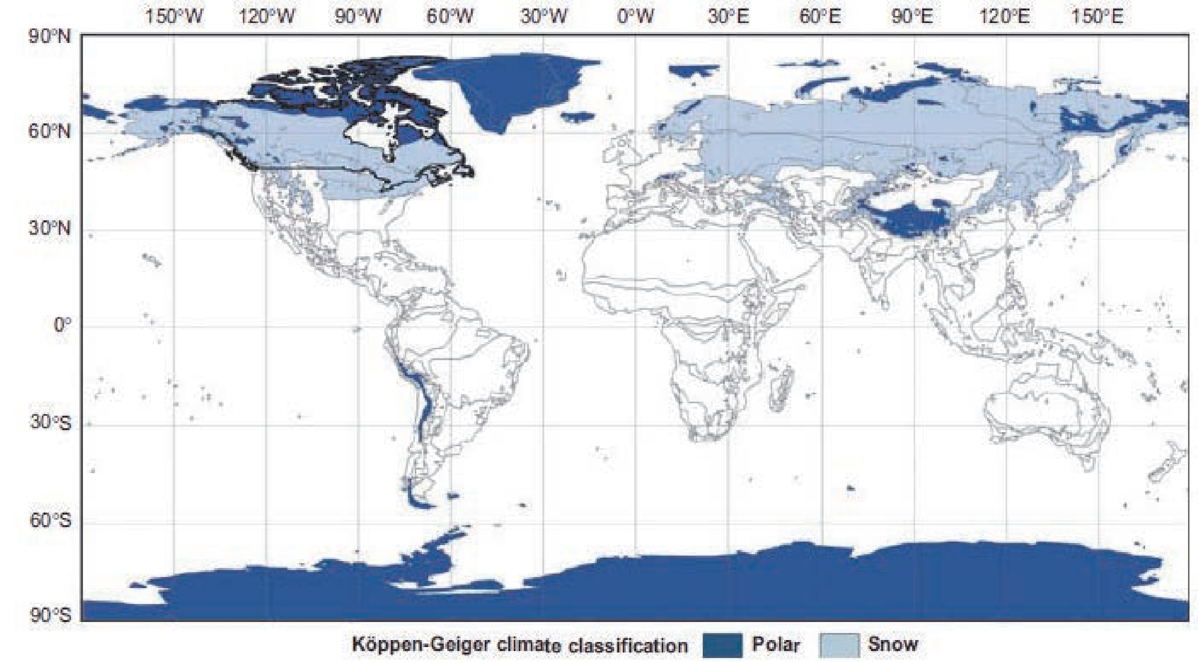
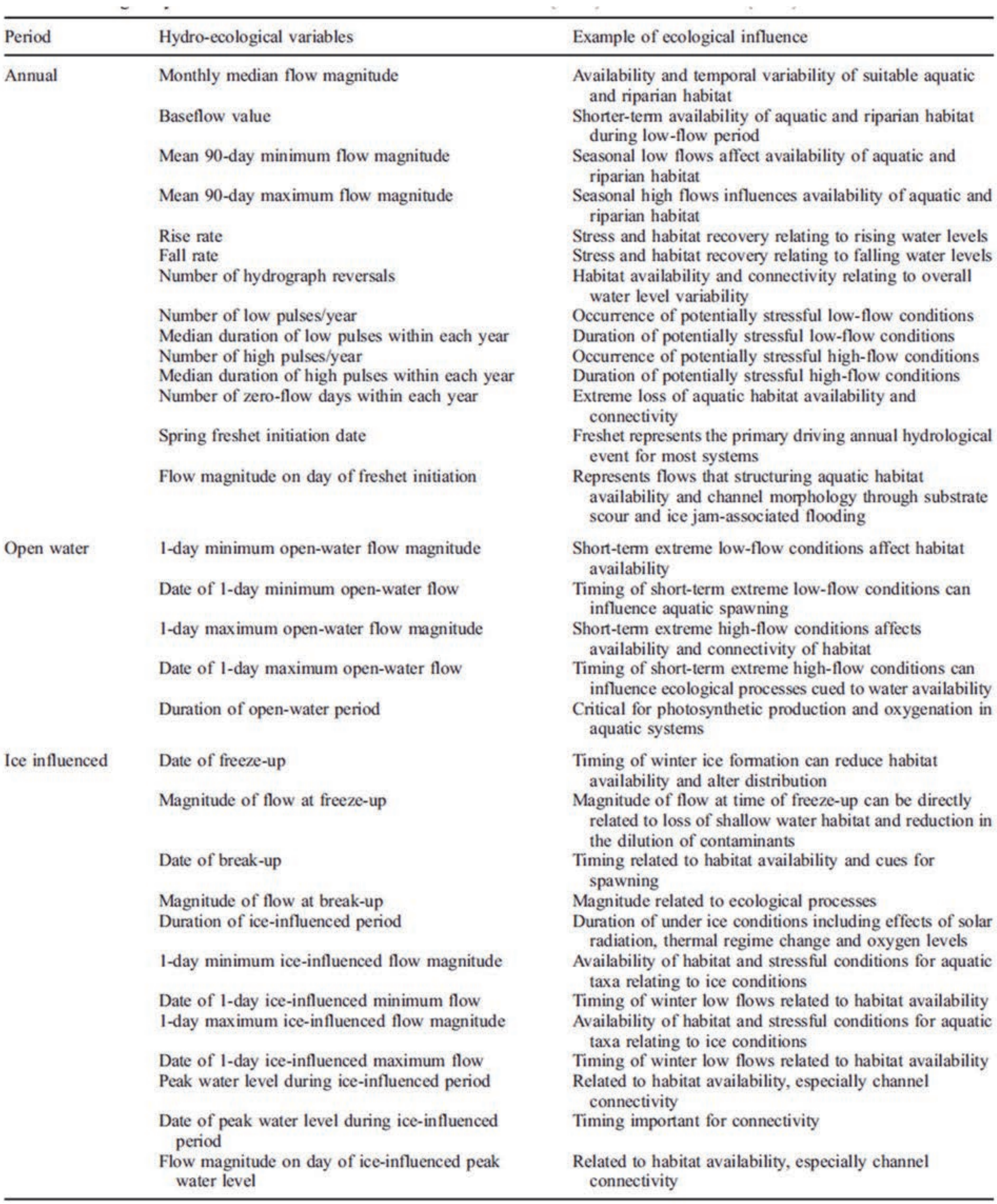


Figure 5. A summary of the importance of flows for supporting flow and ice regimes which define the river habitats of cold regions.

Table 3. Ecologically relevant hydrological indicators of change for cold-regions, including Alaska (Peters et al. 2014).



Period	Hydro-ecological variables	Example of ecological influence
Annual	Monthly median flow magnitude	Availability and temporal variability of suitable aquatic and riparian habitat
	Baseflow value	Shorter-term availability of aquatic and riparian habitat during low-flow period
	Mean 90-day minimum flow magnitude	Seasonal low flows affect availability of aquatic and riparian habitat
	Mean 90-day maximum flow magnitude	Seasonal high flows influences availability of aquatic and riparian habitat
	Rise rate	Stress and habitat recovery relating to rising water levels
	Fall rate	Stress and habitat recovery relating to falling water levels
	Number of hydrograph reversals	Habitat availability and connectivity relating to overall water level variability
	Number of low pulses/year	Occurrence of potentially stressful low-flow conditions
	Median duration of low pulses within each year	Duration of potentially stressful low-flow conditions
	Number of high pulses/year	Occurrence of potentially stressful high-flow conditions
	Median duration of high pulses within each year	Duration of potentially stressful high-flow conditions
	Number of zero-flow days within each year	Extreme loss of aquatic habitat availability and connectivity
	Spring freshet initiation date	Freshet represents the primary driving annual hydrological event for most systems
	Flow magnitude on day of freshet initiation	Represents flows that structuring aquatic habitat availability and channel morphology through substrate scour and ice jam-associated flooding
Open water	1-day minimum open-water flow magnitude	Short-term extreme low-flow conditions affect habitat availability
	Date of 1-day minimum open-water flow	Timing of short-term extreme low-flow conditions can influence aquatic spawning
	1-day maximum open-water flow magnitude	Short-term extreme high-flow conditions affects availability and connectivity of habitat
	Date of 1-day maximum open-water flow	Timing of short-term extreme high-flow conditions can influence ecological processes cued to water availability
	Duration of open-water period	Critical for photosynthetic production and oxygenation in aquatic systems
Ice influenced	Date of freeze-up	Timing of winter ice formation can reduce habitat availability and alter distribution
	Magnitude of flow at freeze-up	Magnitude of flow at time of freeze-up can be directly related to loss of shallow water habitat and reduction in the dilution of contaminants
	Date of break-up	Timing related to habitat availability and cues for spawning
	Magnitude of flow at break-up	Magnitude related to ecological processes
	Duration of ice-influenced period	Duration of under ice conditions including effects of solar radiation, thermal regime change and oxygen levels
	1-day minimum ice-influenced flow magnitude	Availability of habitat and stressful conditions for aquatic taxa relating to ice conditions
	Date of 1-day ice-influenced minimum flow	Timing of winter low flows related to habitat availability
	1-day maximum ice-influenced flow magnitude	Availability of habitat and stressful conditions for aquatic taxa relating to ice conditions
	Date of 1-day ice-influenced maximum flow	Timing of winter low flows related to habitat availability
	Peak water level during ice-influenced period	Related to habitat availability, especially channel connectivity
	Date of peak water level during ice-influenced period	Timing important for connectivity
	Flow magnitude on day of ice-influenced peak water level	Related to habitat availability, especially channel connectivity

Sediment Regime

- Dozens of case studies across five continents demonstrate the ability to site, size, design, retrofit and operate reservoirs to support system sediment regimes. Costs continue to deter widespread implementation.
- Siting and sizing are the most critical drivers determining a reservoir's influence on the local and regional sediment budget. Avoid streams with high sediment yields and avoid placing a barrier between major sediment sources and sinks. The risk of sediment trapping increases exponentially with increasing reservoir size and as you move further down into the watershed and can be mathematically estimated by the Brune Curve.
- Technologies like bypass tunnels have been used to successfully route sands, gravels and cobbles downstream of reservoirs with less than a 45,000 AF capacity and with a dam height of less than 300 ft.
- Hydraulic flushing has been demonstrated as a method that can be more cost-effective than dredging, but it must be done with careful planning to avoid significant downstream ecological effects.

Just as the development of hundreds of thousands of dams and reservoirs has had a global effect on flow regimes and dependent resources, these same structures have influenced the substrate size, distribution and timing of sediment transport processes in rivers, floodplains and estuaries. It is estimated that more than half of the global sediment flux is trapped in reservoirs (Vorosmarty et al. 2003). Dams tend to block bed load and coarse materials from moving downstream. Depending on the size of the reservoir and characteristics like length and slope, suspended sediments may also settle out of the water column and become trapped behind the dam (Kondolf et al. 2005, Walling 2006). The absence of sediment downstream of the dam results in 'sediment starvation,' or loss of sediments to maintain downstream geomorphic processes (Draut et al. 2011, Ma et al. 2012, Singer 2010).

Figure 6. Susitna River Mouth and Cook Inlet © USGS Landsat Image

Environmental implications include channel erosion, incision and loss of downstream habitat, including spawning gravels, as exampled below dams on the Elwha (recently decommissioned) and Colorado Rivers in the United States and the Yellow River in China (Kondolf 1995, Grams et al. 2007, Draut et al. 2011, Ma et al. 2012). Further downstream, the loss of sediment loads has implications including shrinking deltas, like the Mississippi (Syvitski et al. 2009). In cases where reservoirs have reached sediment equilibrium, large flood pulses can flush high loads of stored sediments resulting in a significant pulse of fine sediments to estuaries, like below Conowingo dam on the Chesapeake Bay (ACOE 2014). For more detail on the implications of sediment trapping and downstream starvation, Anchor QEA (2015) published the first, second and third-order implications of changes to the sediment regime on a glacial river.

Basin-scale planning

Avoid. Basin-scale planning can be used to both identify potential sites and appropriately size hydropower capacity that minimizes risks to basin sediment regimes. Hydropower technologies such as off-stream hydropower facilities and in-pipe turbines, also called conduit hydropower, avoid new on-stream storage reservoirs. If off-channel siting is not an alternative, identify development sites that maximize use of existing infrastructure, including non-powered dams and dams with the opportunity to increase efficiencies and to assess appropriate sites for intermittent infrastructure (e.g. inflatable dams).

Minimize. For on-stream barriers, Kondolf (et al. 2014) published an expert synthesis of experience across North America, Europe and Asia, in minimizing the impacts of reservoirs and dams on sediment regimes. They highlight several siting and sizing considerations (Figure 4):

- Avoid streams and rivers with high sediment yields, including streams in highly erodible areas;
- Size reservoirs and design bypasses and outlet works with an understanding of both the short- and long-term patterns of stream power sediment transport;
- Avoid placing an impermeable sediment barrier between major sediment sources and sinks.

Considerations at a development site

Mitigate. For those hydropower facilities that include an on-stream dam, there are three main areas of mitigation to reduce sediment storage in the reservoir: (1) methods to remove sediment load from upstream watershed, (2) methods to route sediment through or around reservoir and (3) methods, like hydraulic flushing, to remove sediment from the reservoir and replace it downstream. Here, we focus on the latter two, recognizing that methods to remove sediment load from the upstream watershed, like land management strategies, do not mitigate the downstream geomorphic impacts of sediment starvation.

Sediment bypass structures are considered to be sustainable remedial measures and their effectiveness has been best demonstrated in Japan and Switzerland (Sumi et al 2004, Visher et al. 1997, Schleiss et al. 2014). Bypass technologies can be either be incorporated into the design of proposed dams and reservoir, or they can be incorporated through retrofits.

Bypass tunnels. On the Tenryu River in Japan, Sumi (et al. 2004) documents the conditions under which retrofits to the Miwa, Koshibu and Matusukawa dams provide successful sediment bypass through construction tunnels. The catchments upstream from the dams contributed up to several thousand m^3/km/yr, with the highest volumes originating in the high mountain regions. Tunnel lengths range from 250 m to 4,300 m with cross-sectional areas between 10 and 60 m^2. Tunnel slopes varied between 1 and 4% with design discharges between 40 and 300 m^3 /s (Sumi et al. 2004). Studies found that two design considerations necessary to ensure structural integrity of the tunnel are the use of high strength concrete and a thicker top of the tunnel to compensate for the high rate of abrasion of the tunnel walls.

Also in Japan, the Asahi Dam resulted in sediment starvation and downstream scouring on the Asahi River. The Asahi is a cobble-bed river with a wide range of grain size distribution from boulders to sand. This resulted in the loss of channel habitat maintenance including sand bar development and migration (Fukuda et al. 2012). To restore channel-forming functions, a flushing bypass tunnel was installed and resulted in a shift in grain size distribution toward pre-dam conditions. Results include the recovery of geomorphic processes of to maintain sandbars, riffles and pools downstream of the dam. Sediments, including gravels, have been successfully transported downstream of the dam (Fukuda et al. 2012).

Bypass channels. In addition to bypass tunnels, small to medium reservoirs have been designed with the capacity to bypass bedload being transported during high flow events. Examples include the Robles diversion dam on the Ventura River (Lorang et al. 2013, Reclamation 2008). While these designs can be efficient in reducing the amount of sediment stored behind a dam during high flow events, as is the case with the Robles diversion dam, they often divert sediment to a side channel above the reservoir. Therefore, there often needs to be a complementary downstream sediment re-introduction plan to mitigate the impacts of downstream sediment starvation.

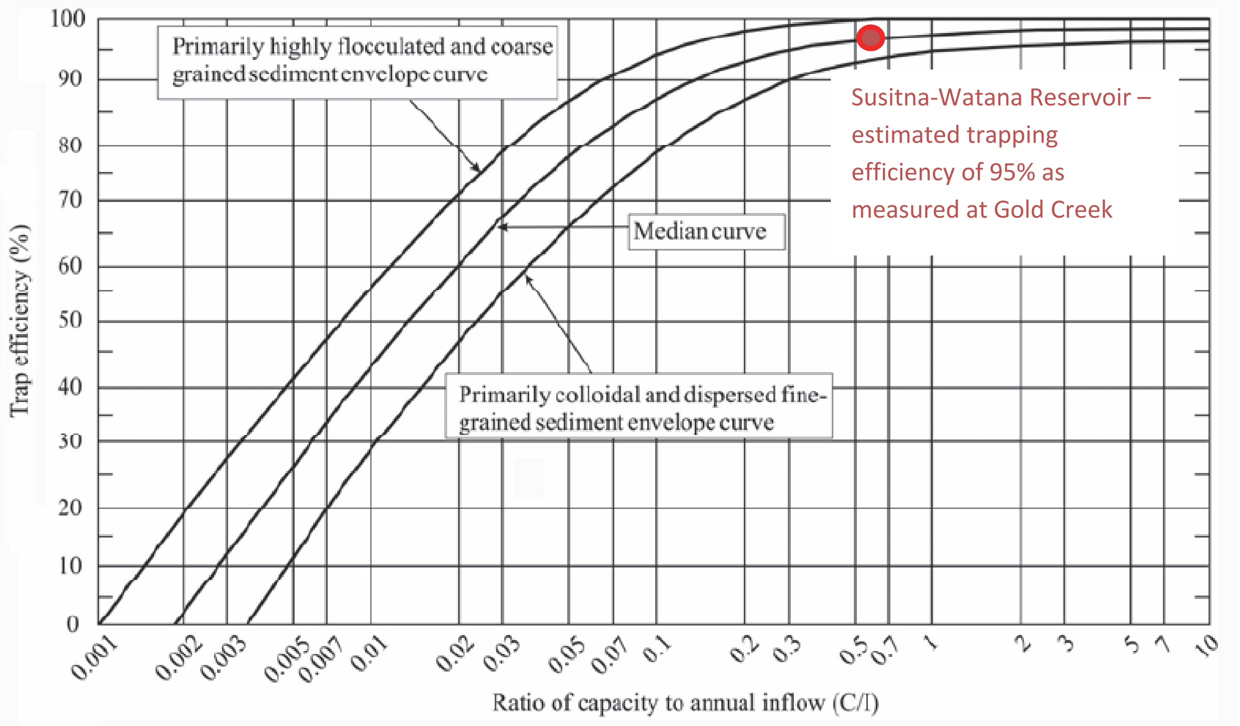


Figure 7. Reservoirs can be sized and sited to minimize the expected trap efficiency which is mathematically predicted by the ratio of reservoir capacity to average annual inflow**.** The proposed Susitna-Watana would have an estimated ratio of (**red dot**) .58, or 95% trapping efficiency as measured at Gold Creek (Brune 1953, Morris and Fan 1998).

A last method includes sediment removal by hydraulic flushing, because it operates by draining the reservoir, then scouring the sediment through a timed pulse, it changes the timing and distribution of transport downstream. This can have detrimental ecosystem effects downstream by burying habitats and immobile species in fine sediments (Lee and Foster 2013). An ‘environmentally friendly’ flushing approach has been pioneered at the Génissiat Dam in France. This approach syncs timing, and requires resources (hundreds of staff and millions of dollars), but in comparison, was found to be more cost-effective than dredging (Kandolf et al. 2014).

The Susitna River is a native Dena’ina name meaning ‘Sandy River.’ For hundreds of thousands of years, the river has moved glacial silt, sand and gravels from the mountains of the Alaska Range, including Denali, through the river beds, floodplains and ultimately the Cook Inlet delta and Pacific Ocean.

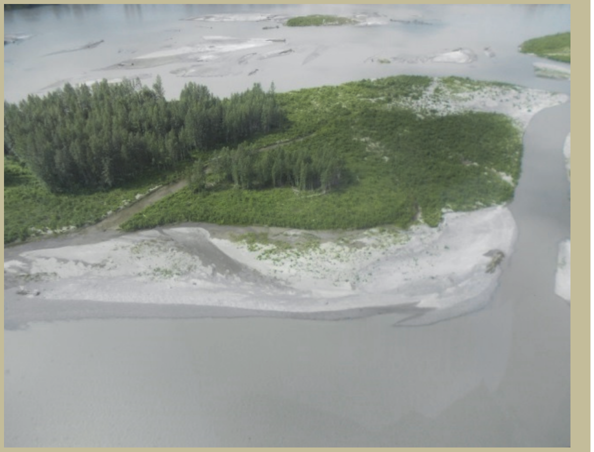


Figure 8. Susitna River Islands and gravel bars above the three rivers confluence, July 2014 © T.Moberg

Table 4. Summary table of successful sediment management case studies adapted from Sumi et al. (2004), Kondolf et al. (2014) and Structure Database (2015).

Strategy	Region	Facility Name	Dam Height	Reservoir Storage	Catchment Area	Design Discharge	Transport Mechanism
			feet (meters)	acre feet (thousand cubic meters)	square miles	cubic feet/s (cm/s)	
Sediment bypass tunnels	Asia, Japan	Miwa Dam	226 (69.1)	24,282 (29,952)	120	20,594 (300)	2.6 mile (4,300 m) Horseshoe shaped tunnel
	Asia, Japan	Koshibu Dam	335 (105)	47,021 (58,000)	111	13,066 (370)	2.4 mile (3,982 m) Horseshoe shaped tunnel
	Asia, Japan	Matusukawa Dam	272 (83)	6,039 (7,450)	23	7,062 (200)	.88 mile (1,417 m) archway tunnel
	Asia, Japan	Nunobuki Dam	109 (33)	338 (417)	4.1	1,377 (39)	.16 mile (258 m) Archway tunnel
	Asia, Japan	Asahi Dam	285 (87)	20,683 (25,513)	15.1	4,944 (140)	Retrofit to construct bypass 2,350 m long
	Switzerland	Egshi Dam	—	—	—	2,613 (74)	1,181 foot Circular tunnel
	Switzerland	Palagnedra Dam	236 (72)	3,453 (4,260)	53.2	3,885 (110)	5,905 ft Circular tunnel
	Switzerland	Pffaffensprung Dam	105 (32)	121 (150)	—	7,769 (220)	918 ft Horshoe shaped tunnel
	Switzerland	Rempen Dam	105 (32)	405 (500)	—	2,825 (80)	1,476 ft Horshoe shaped tunnel
	Switzerland	Runcahez Dam	108 (33)	389 (480)	—	3,885 (110)	1,876 ft Archway
	Switzerland	Solis Dam	200 (61)	3,299 (4,070)	—	6,003 (170)	3,175 ft Archway
Bypass spillways/sluicing	California	Robles Canal and Diversion Dam	—	—	—		Sluicing during high flow events
Ecological Hydraulic flushing	France	Génissiat dam	341 (104)	454 (560)	—	NA	Hydraulic flushing during high flow events

Biological Connectivity (Instream Barrier)

- Avoid new barriers by maximizing opportunities to use off-stream hydropower technologies and to add hydropower to existing non-powered water infrastructure.
- If an on-stream facility is used, avoid siting the facility within migratory corridors or key habitats for spawning and rearing. If migratory fish are present, the facility should be designed and operated to provide safe and timely up and downstream volitional fish passage consistent with performance-based passage standards (as opposed to technology-based prescriptions), monitoring and adaptive management that are linked to population goals.
- While fish passage science and engineering has developed considerably in the last two decades, there is still a lack of information to draw general conclusions about adequate design. Of the four groups of fishways (pool and weir, V-slot, Denil and nature-like), nature-like fishways had the highest passage efficiency for salmonids and are capable of passing multiple life stages up and downstream. In a recent review of pool and weir and vertical slot structures passing more than 80% of the upstream migrating spawning sockeye, all facilities had performance-based standards. Structurally the majority of the facilities had less than a 6% slope and were less than 85 feet in height.
- Recent technologies to prevent direct or indirect blade mortality during outmigration should be included in the design and operations, including vertical screens to prevent entrainment fish-friendly turbines and effective monitoring approaches.

Reproductive success of Pacific salmon depends in large part on completion of spawning migration from the Pacific Ocean to natal spawning grounds. In the Susitna River basin, each of the five species has preferential spawning habitats **–** including the mainstem river, side sloughs, tributary lakes and wetlands and the upper river (AEA 2014, Anchor QEA 2015, Attachment 1). Depending on their location, dams can and have impeded the connectivity between ocean and spawning habitats. This has contributed to significant declines in anadromous salmon in North America (Nehlsen et al. 1991, Slaney et al. 1996). Despite substantial investments in mitigation, including fishways, no Pacific salmon stock affected by large-scale hydropower has been fully recovered in the continental U.S (NMFS 2015, 2016). For more detail on specific hypotheses of the effects of an instream barrier on anadromous communities, Anchor QEA (2015) published the first, second and third-order implications of changes to biological connectivity on a glacial river.

Basin scale planning

Avoid. One of the most effective ways to protect the connectivity to and quality of spawning and rearing habitats is to avoid placement of on-stream barriers between those habitats (Hartmann et al. 2013, Jager et al. 2015). Additionally, as referenced previously, this approach is supported by several hydropower technologies and designs. In most of the U.S. and mature hydropower contexts, this concept is being applied through advanced spatial analysis to 're-design' the basin configuration of existing infrastructure. Governments and resource agencies in places like the Netherlands and the State of California have developed large-scale, regional fish migration plans to prioritize barrier mitigation and removal (Wannigen et al. 2010, State of California Department of Water Resources 2015, California Fish Passage Forum 2015).

The Danube salmon restoration in Europe provides a similar case study to Pacific salmon restoration efforts in the Northwestern U.S. Hydropower development and river channelization have reduced the distribution of the Danube salmon to less than 10% of its former range. It is now one of the most endangered fish species in Europe. In response, the European Union has taken significant measures to restore connectivity between remaining population centers critical habitats. Connectivity is being restored using demonstrated methods of rock ramps and bypass channels (Schmitz et al. 2001). In addition, in order to restore flows in key stream reaches and through bypass channels, water rights have been partially or entirely assumed from the hydropower company after providing compensatory payments (Schmitz et al. 2001).

The Nature Conservancy has developed basin-scale tools to assist in mapping critical habitats and prioritizing habitat re-connection efforts through barrier removal. This includes mapping the configuration of new development in basins in Mexico and Gabón and re-design in places with a mature infrastructure and hydropower context, like the Chesapeake Bay, and the Northeastern and Southeastern United States (Martin and Apse 2011 & 2013, Opperman et al. 2015).

Considerations at a development site

Mitigate. If a hydropower facility is placed on-stream, resulting in disconnection of a migratory corridor, some volitional fish passage technologies have been demonstrated to support self-sustaining fish populations. Volitional means the fish are swimming through a fish lift or ladder to pass the barrier without being handled.

Fish passage mitigation strategies should consider both up and downstream migration for relevant species and life stages. The passage structures should be coupled with adequate stream flows to attract fish ('attraction flows') and provide timely passage. Like many mitigation approaches, our understanding of fish passage approaches is continuously evolving. It is now understood that even successful passage can have consequences to fitness of the spawning fish (Roscoe 2010). Depending on the sustained and burst swimming speeds of the migrating fish, passage can require high-levels of energy expenditure (Gowans et al. 2003; Brown et al. 2006). Fishways typically encourage migration by providing flows to attract fish to an entrance. This may result in high concentrations of fish in resting pools and at the base of the dam. High concentrations and delayed movement (while waiting for a lift or favorable conditions to enter the fishway) have resulted in increased predation and potential injury through fish interactions with the infrastructure (Bunt et al 2000, Keefer et al. 2004, Pelicice and Agostinho 2008 and Castro-Santos et al. 2009). Studies have also found differences in passage success between male and female fish. Crossin (et al. 2008) found female sockeye to be more susceptible to high temperatures and to have a higher passage failure and mortality than male sockeye.

When appropriately designed and situated, a fishway structure allows migratory fish to move both up and downstream (Jungwirth et al. 1998, Roscoe et al. 2010). In a recent meta-analysis (116 peer-review publications) reviewing the performance of fish passage structures at upstream barriers, Bunt (et al. 2012) found that the species of fish and structural design of the fishway have strong implications for passage efficiency, and in most cases, that there is insufficient data to support successful design recommendations. Related to this, there is a need for establishing systematic and broadly applied methods to document the relative contributions of fish attraction efficiency and passage efficiency to overall fish passage performance. Bunt (et al. 2012) found that the factors that most influenced passage performance include slope, width, length, depth and configuration (design and number of pools, traverses, baffles or roughness elements).

Fishways are generally categorized into four groups - pool and weir, vertical slot (or V-slot), Denil and nature-like. Bunt (et al. 2012) found that the pool and weir design had the highest attraction efficiency, but the lowest passage efficiency across fish taxa. This pattern held for the subset of samples that were measuring salmonid passage (Figure 9). Denil fishways tend to be deployed on small streams in the eastern part of the country and are not deployed in the Pacific Northwest. A cousin of the Denil fish ladder is the Alaska steepass – a prefabricated fish ladder for use in remote, steep streams. Because it is not hydraulically self-regulating (cannot function under a range of flows), this design is not used for passage at hydropower facilities (Katapodis 1992). Nature-like fishways had the highest passage efficiency for salmonids (up to 100%), with a median passage efficiency of 70% across all fish taxa. Nature-like fishways also had > 50% attraction efficiency for salmonids (Bunt et al. 2012). Vertical slots and nature- like fishways were the only technology that demonstrated > 70% passage efficiency for salmonids. Nature-like fishways are designed to provide both upstream and downstream passage, therefore we describe successful cases first, here.

Nature-like fishways are used commonly in Europe, Canada, Australia, Japan, and more recently in the United States. The definition for nature-like fishways can vary, but generally, the design takes on the philosophy of 'physiomimesis,' or the mimicking of natural systems (Katopodis 2001). Recognizing that species have evolved over millions of years to the physical and hydraulic conditions in the rivers systems

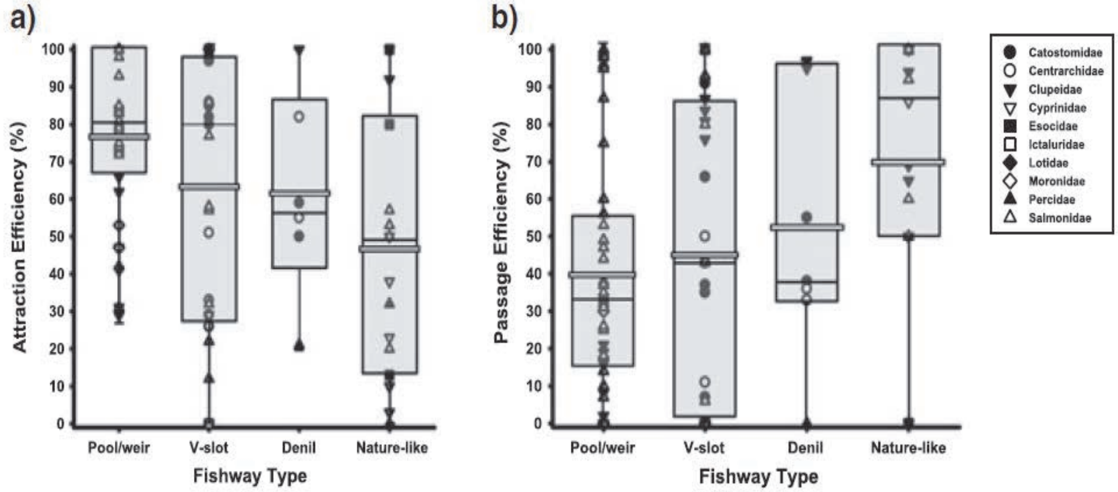


Figure 9. Attraction and passage efficiencies for fishway types (pool/weir, V-slot, Denil and nature-like) across ten fish families (Bunt et al. 2012).

they inhabit, this fishway design strives to pass the complement of fish species at varying life stages by simulating local stream characteristics and using native materials to provide suitable passage conditions for fish and other aquatic species over a range of flows (Katopodis 2001, Katapodis et al. 2004, Parasiewicz, et al. 1998, Wildman 2010). Wildman et al. 2010 refers to a collection of more than 85 case studies, documenting the river context and design approach for over 35 nature-like fishways. Case studies, like that on the Lima River in Portugal, demonstrate the ability of nature-like bypasses in facilitating volitional transport across species and life stages, including fish in the salmonid family (Santos et al. 2005).

Hydropower turbines can result in three types of mortality to outmigrating fish: (1) direct mortality, where lethal injuries are suffered during turbine passage, (2) indirect mortality, where sub-lethal injuries are suffered that lead to mortality from stress, predation or disease, and (3) delayed mortality, which occurs lower in the river, estuary or marine environment and is attributed to passage stress. It is estimated that 5 to 30% of fish passing through turbines are killed – with variation among fish length and turbine design and operation (Cada et al. 1997).

A couple of technologies for downstream passage include the use of fish friendly turbines to improve safe passage through the powerhouse, and vertical barrier screens to reduce entrainment and re-direct fish around the power house to a safe bypass facility. There are a couple of designs for 'fish friendly' turbines including the Alden turbine with fewer blades, larger diameter, lower rotational speed, and optimal hydraulics and the recent Voith hydro turbine (Biel 2014). Voith's turbine was recently commissioned by the U.S. Army Corps of Engineers at the Ice Harbor hydroelectric project (603 MW) to increase survival rates of out-migrating fish to up to 98% (Brown et al 2012, HydroWorld 2014).

From Cook Inlet to the Susitna Glacier. On the Susitna River, it was previously thought that the steep gradient and significant velocities kept Pacific salmon from migrating past Devil's Canyon, therefore the proposed dam would not preclude access to upstream habitat. However, during the 2014 AEA telemetry studies, Chinook were tracked migrating (green dots) not only past the proposed dam site (red line), but upstream to the base of the Susitna headwater glacier above the East Fork and Boulder Creek. While the study was not designed to determine whether they were spawning, this migration did coincide with the peak spawning period for Chinook throughout the month of July.

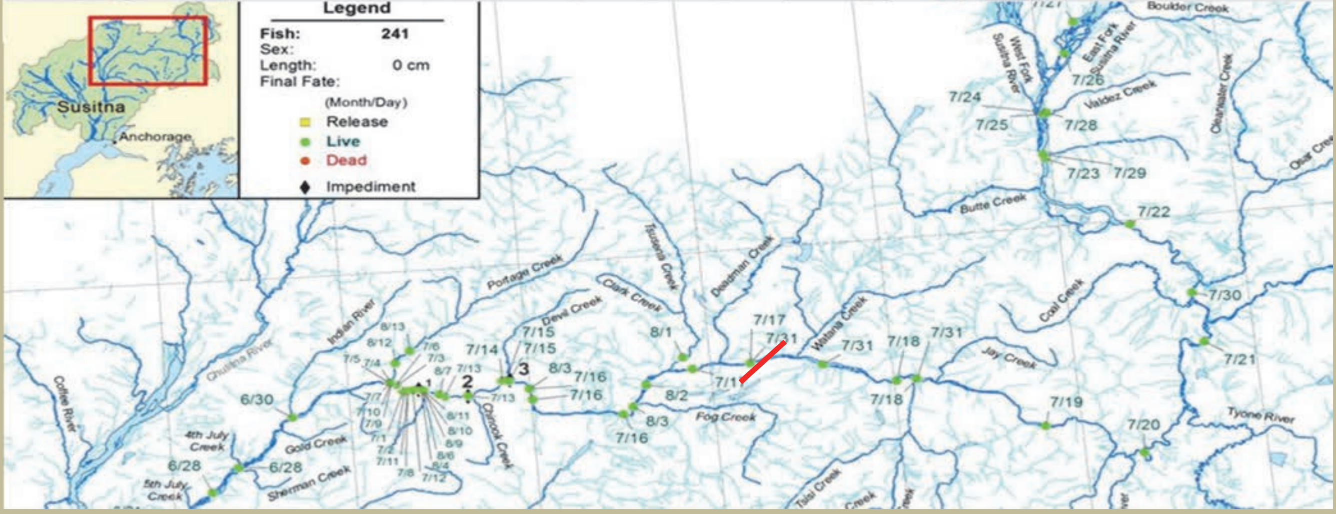


Figure 10. Extent of spawning migration for telemetered Chinook salmon documented to reach the Susitna glacier (AEA 2014).

Table 5. Summary table of upstream fish passage case studies summarizing structure characteristics and total passage efficiency (adapted from Bunt et al. 2012).

Strategy	Region	Facility Name	Structure Slope (%)	Height (m)	Elevation change (m)	Attraction (%)	Passage (%)	Total efficiency (%)	Species	Source
Pool-and-weir	Pacific Northwest, Lower Snake River 2002 - control	Granite Dam	6.6	77.4	11.9	100	0	0	Chinook	Naughton et al. 2007
	Pacific Northwest, Lower Snake River 2001 - control	Granite Dam	6.6	77.4	11.9	100	33	37	Chinook	Naughton et al. 2007
	Pacific Northwest, Lower Snake River - 2002 flow restricted	Granite Dam	6.6	77.4	11.9	100	25	25	Chinook	Naughton et al. 2007
	Pacific Northwest, Columbia River	John Day	4.7	32	32	85	95	81	Sockeye	Naughton et al. 2005
	Pacific Northwest, Columbia River	Dalles	4.4	79	24.1	98	97	85	Sockeye	Naughton et al. 2005
	Pacific Northwest, Columbia River	McNary	5	67	22.7	81	98	79	Sockeye	Naughton et al. 2005
	Pacific Northwest, Columbia River	Wells	5	21	21	42	96	40	Sockeye	Naughton et al. 2005
	Pacific Northwest, Columbia River	Right bank Rock Island	5.2	12.5	12.5	74	60	44	Sockeye	Naughton et al. 2005
	Pacific Northwest, Columbia River	Fishway, Rocky Reach	6.25	27.7	27.7	72	56	40	Sockeye	Naughton et al. 2005
	Pacific Northwest, Columbia River	Priest Rapids	6.25	25.6	25.6	79	95	75	Sockeye	Naughton et al. 2005
	Pacific Northwest, Columbia River	Left Bank Rock Island	6.2	12.5	12.5	74	31	23	Sockeye	Naughton et al. 2005
	Pacific Northwest, Columbia River	Bonneville	8.13	18.3	18.3	100	98	98	Sockeye	Naughton et al. 2005
	Pacific Northwest, Columbia River	Wanapum	10	25.1	25.2	75	99	74	Sockeye	Naughton et al. 2005
	Pacific Northwest, Columbia River	Middle Rock Island	10	12.5	12.5	74	7	5	Sockeye	Naughton et al. 2005
Vertical-slot	BC Canada, Seton River	Seton Dam	6.9	7.6	7.4	77	100	77	Sockeye	Pon et al. 2006
	BC Canada, Seton River	Seton Dam	6.9	7.6	7.4	86	93	80	Sockeye	Roscoe and Hinch 2008
	BC Canada, Seton River	Seton Dam	6.9	7.6	7.4	86	80	69	Sockeye	Roscoe et al. 2009

Water Quality

- Avoid new impoundments by maximizing opportunities to use off-stream hydropower technologies and to add hydropower to existing non-powered water infrastructure.
- Hydropower facilities likely to cause water quality impairments include reservoirs with depth greater than 15 m, power capacity greater than 10 MW, retention time greater than 10 days and reservoir volume greater than 50,000 acre feet
- Recent technologies should be included in the design of the turbines and outlet works to allow operators to match upstream water quality with the water quality of their releases. Aerating turbine technologies have recently demonstrated dual benefits to generating efficiency and water quality.

The construction and operation of a reservoir can impact the biogeochemistry above, within and downstream of the reservoir (Haxton et al. 2008). Historically, most reservoirs, particularly those designed to meet hydropower purposes, have constructed outlets at the base of the dam (in order to capitalize on the maximum hydraulic head). Reservoir stratification can cause hypoxic conditions in the water at the bottom of the reservoir. If the hydropower facility is diverting water from the bottom of the reservoir, it may release this poor quality water downstream. Similarly, reservoir stratification can significantly change the temperature of releases, often resulting in cooler than ambient releases during the summer months and warmer than ambient releases during the winter months (Straskraba et al. 2013). For more detail, Anchor QEA (2015) published a synthesis of the first, second and third-order implications of hydropower development and operation on water quality in a glacial river setting.

Basin-scale planning

Avoid. By using hydropower technologies and designs that take advantage of existing water infrastructure, like conduits and non-powered dams, cumulative basin-scale water quality impacts associated with new impoundments may be avoided. Further, the addition of new turbine technologies to non-powered dams may provide the opportunity for water quality improvements (see mechanical aeration below).

Minimize. Similar to the impacts associated with flow regimes and sediment, the scale of potential water quality impacts from hydropower is correlated with the site-specific river flow and, most importantly, with reservoir size. EPRI (1990) found that hydropower facilities associated with reservoirs greater than 15 m in depth, a power capacity greater than 10 MW, a reservoir volume of greater than 50,000 acre feet or a retention time of greater than 10 days, were likely to cause water quality problems. Depth, generation capacity, reservoir size and retention time are contributing factors of reservoir stratification and hypoxic hypolimnetic conditions. The larger the reservoir size, specifically the deeper the reservoir is, the more likely it is to seasonally stratify, resulting in a seasonally inverted thermal profile as compared to ambient river temperatures.

Considerations at a development site to minimize

Multi-level outlet works. Outlet works are the structures that allow water to pass through a dam. Conventional designs typically include one outlet or gate, near the bottom of the reservoir. This is called a hypolimnetic release. Multi-level outlet works can provide the necessary flexibility to meet downstream water quality performance standards by having multiple gates at different reservoir elevations to allow the operator to release water from the combination of reservoir elevations that most closely mimics the desired downstream water temperature and quality (Poore and Loftis 1983, Rheinheimer et al. 2014).

The spillway and outlet works should also be designed to avoid supersaturation of dissolved gases in the downstream river reach (Stewart et al. 2015). A recent study by Oakridge National Laboratory documented an approach to predicting total dissolved gas and optimizing operations using a readily-available model (Stewart et al. 2015). Supersaturation causes gas bubble disease in fish (Feng et al. 2014).

Mechanical aeration. The hydraulic and environmental performance of aerating turbines has made significant strides over the last decade. In addition to improving water quality conditions, aerating turbines have demonstrated the ability to provide higher generation efficiency and capacity (EPRI 2009). First pioneered at TVA's Norris Project by Voith Hydro, this technology demonstrated that up to 5.5 mg/L of dissolved oxygen could be obtained from a single unit when dissolved oxygen of the inflow water was 0 mg/L. This technology continues to be refined and adopted and is now supported by several manufacturers, including ALSTOM, American Hydro, Andritz and Voith Hydro (March 2012). While the advantages to environmental performance are a clear benefit, one of the barriers to wide-spread adoption of the technology is the high initial cost (March 2012, Liu et al. 2015).

Coupled with advances in aerating turbine technology, there have been innovations in real-time plant optimization to meet environmental performance standards. USACE's Thurmond project and Ameren Missouri's Osage Project have demonstrated that real-time optimization can improve environmental performance while increasing generation efficiencies and profitability (Smith et al. 2007). Similarly, with the exponential increase in big data computing technology, design models can predict the performance of these technologies before fabrication and installation (DOE 2004). In addition to turbine technologies, aeration technologies have also been applied directly in the tailrace.

Section 4. A comparison between the proposed Susitna-Watana project and a range of risk indicators, demonstrated best practices and mitigation technologies

Based on the referenced case studies and scientific research, this section summarizes indicators and thresholds of risk associated with development of hydropower to the first order impacts of flow, sediment, connectivity and water quality (Anchor QEA 2015). Here, we outline key characteristics of the proposed Susitna-Watana Project and its operations to compare to these indicators:

Siting:

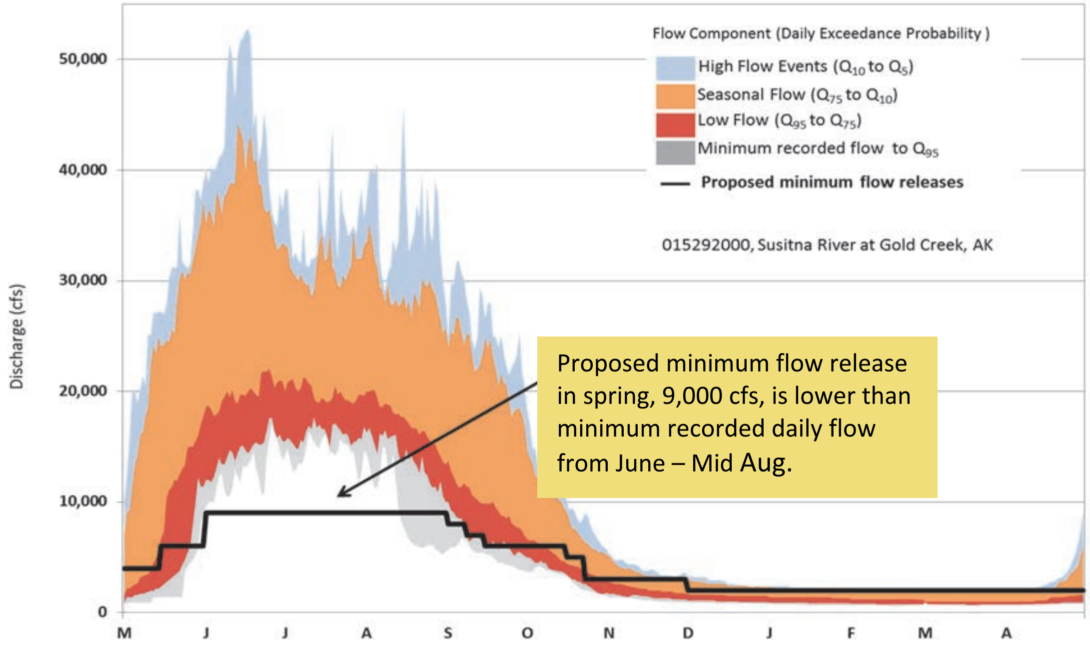
- **Sited on the mainstem Susitna River between Susitna Glacier and the Cook Inlet**, 184 miles upstream of the Cook Inlet

Design:

- **450 to 650 MW estimated generation capacity**
- **705 foot estimated dam height** (would be the second tallest dam in the U.S., if constructed)
- **42 mile long reservoir**
- **4,100,000 acre-foot (AF) capacity**

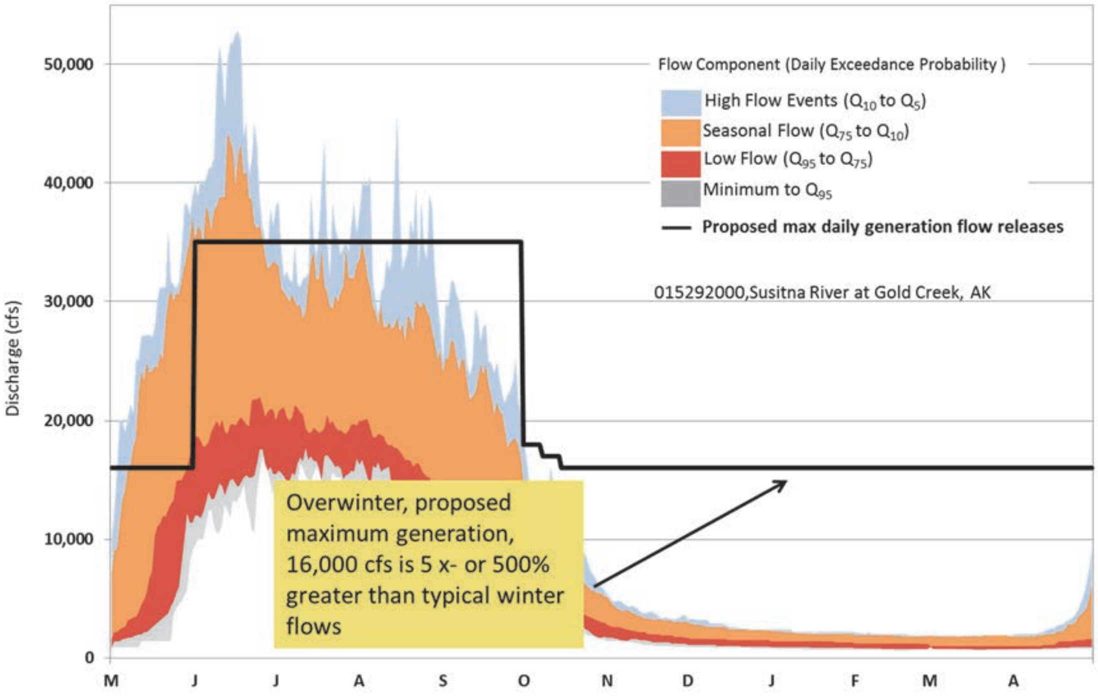
Operation:

- A water right that provides up **to 22,800 cfs diversion (median spring discharge) and 9,470,000 AF of annual storage**
- **Operating rules in pre-application document are illustrated in Figures 10 and 11.**
- Operated as a **hydro-peaking facility**, in particular to meet peak winter electricity demands



Proposed minimum flow release in spring, 9,000 cfs, is lower than minimum recorded daily flow from June – Mid Aug.

Figure 10. Minimum daily flow release articulated in Pre-Application Document (AEA 2014).



Overwinter, proposed maximum generation, 16,000 cfs is 5 x- or 500% greater than typical winter flows

Figure 11. Maximum daily flow release articulated in Pre-Application Document (AEA 2014).

From the Ecological Risk Assessment (Anchor QEA 2015) we know that impacts to the flow and sediment regime, connectivity and water quality, must be avoided or mitigated in order to avoid cascading impacts on Pacific salmon abundance, productivity, spatial structure and diversity in Alaska's large braided rivers. Sub-daily, seasonal and interannual components of the flow regime are at risk as indicated by the reservoir storage ratio, presumptive flow standards and sub-daily alteration thresholds (Nilsson et al. 2005, Richter et al. 2010, Lehner et al. 2011, Richter et al. 2012, Moog 1993). The reservoir storage ratio indicates that risks to the flow regime may extend 184 miles from the proposed dam site through Cook Inlet. Regarding impacts to the sediment regime, as designed, the reservoir is expected to have a 95% or greater trapping efficiency and is outside of the range of demonstrated sediment bypass technologies (Table 4, Brune 1993, Morris and Fan 1998, Kondolfo et al. 2011). The proposed reservoir is also sited on a glacial river with high sediment yields and between a major source of sediment (Susitna glacier) and sink (Cook Inlet) (Kondolfo et al 2011). Similarly, the site would disconnect Chinook salmon spawning and rearing habitat and the reservoir design is outside of the range of demonstrated fish passage technologies (Figure 10, Table 6). Lastly, based on reservoir depth and size, the project exceeds indicators of impact to downstream water quality including thermal regime and dissolved oxygen, by more than ten-fold (EPRI 1990). **In summary, the proposed siting, design and operation of the Susitna-Watana Project exceeds risk indicator thresholds and is outside of the range of any demonstrated mitigation technologies to avoid significant impacts to stream flow, sediment transport, habitat connectivity and water quality (Table 6).**

Table 6. A comparison between the proposed Susitna-Watana project, risk indicators, demonstrated best practices and mitigation technologies.

First Order Impact	Summary Indicator	Proposed Susitna-Watana Hydropower Dam
Flow	**Storage Ratio:** Ratio of storage to mean annual flow**.** 2 to 10%: potential effects, > 10%: risk to ecosystem services (Nilsson et al. 2005, Richter et al. 2010, Lehner et al. 2011).	**Exceeds indicator threshold** from proposed dam site through Cook Inlet (58% at Gold Creek ; 24% at Sunshine; 12% at Susitna).
	Presumptive Flow Standard: Percent daily flow alteration. 10-20%: some changes to abundance and diversity; >20% to 50%: changes in ecosystem function and structure (Richter et al. 2012).	**Exceeds indicator threshold** (>100% percent daily flow alteration in all seasons at Gold Creek).
	Indicators of Hydrologic Alteration : Attachment 1 (Mathews 2007, Bevelheimer 2013, Peters 2014)	**Unknown at this time.** Daily and sub-daily operational releases have not yet been published, however base on the proposed operating rules, peaking, especially during the winter months, will likely result in unmitigable effects to overwintering eggs and juveniles (Figures 3,4 and 10).
	Sub-daily Alteration: Ratio of max flows to min releases. < 2:1: unmeasured impact; > 5:1, 50% loss in biomass; >10:1, 95% loss of biomass (Moog 1993).	**Exceeds indicator threshold** (10:1 during fall/winter and 5:1 during spring/summer at Gold Creek).
Sediment	**Reservoir Trapping efficiency:** Ratio of reservoir capacity to annual flow as an indicator of percent of sediment load that will be stored by the reservoir (Brune 1993, Morris and Fan 1998).	**Up to 95% trapping efficiency**. Estimated to trap 95% of upstream sediments at Gold Creek; 65% of upstream sediments at Sunshine; 40% of upstream sediments at Susitna. This is a coarse estimate based on basin area and not material contribution.
	Within demonstrated range of sediment bypass technology (Table 4).	**No.** Reservoir size and sediment capacity are outside of range.
	Avoids rivers with high sediment yields and maintains connections between major sediment sources and sinks (Kondolfo et al. 2011).	**No**. The proposed dam is sited on a glacial river and would disconnect the Susitna glacier from Cook Inlet.
Connectivity	**Maintains spawning and rearing migration corridors**	**No.** The proposed dam site would disconnect Chinook salmon from spawning habitat in the Upper River (Figure 10).
	Within range of successful volitional fish passage technology (Table 6).	**No.** The proposed dam height of 705 feet is outside of the range of successful volitional passage.
	Safe downstream migration	**Unknown.** It is not clear whether the final design will include fish screens or modified turbine designs to safely pass fish migrating downstream.
Water Quality	**Reservoir size and retention time:** Reservoirs with > 50 ft depth and capacity of >50, 000 AF had higher likelihood of downstream water quality impacts including changes to thermal regime and dissolved oxygen (EPRI 1990).	**Exceeds indicator threshold.** The proposed reservoir would be more than 500 ft deep and have a capacity of 4,100,000 AF.

Works Cited

(ADFG) Alaska Department of Fish and Game. (2013) 2013 Upper Cook Inlet commercial salmon fishery season summary. ADFG Division of Commercial Fisheries, Soldotna, AK.

Alden Research Laboratory. (2011) EPRI-DOE conference on environmentally-enhanced hydropower turbines: Technical papers. Prepared for the Electric Power Research Institute by Alden Research Laboratory, Holden, MA.

Anchor QEA, LLC. (2015) Phase 1: Preliminary Framework for Ecological Risk Assessment of Large-Scale Hydropower on Braided Rivers in Alaska. Report prepared for The Nature Conservancy. 326 pp.

Annear, T.C., Chisholm, I., Beecher, H., Locke, A, Aarrestad, P., Burkhart, N., Coomer, C., Estes, C., Hunt, H., Jacobson, R. (2002) Instream flows for riverine resource stewardship. The Instream Flow Council: Cheyenne, WY.

Bernhardt, E., Palmer, M., Allan, J., Alexander, G., Barnas, K., Brooks, S., Carr, J., Claton, S., Dahm, C., Follstad-Shah, J., Galat, D. (2005) Synthesizing U. S. river restoration efforts. Science, 308 (5722):636-637.

Bevelheimer, M., McManamay, R. and O'Connor, B. (2015) Characterizing sub-daily flow regimes: implications of hydrologic resolution on ecohydrology studies. River Research and Applications 31(7):867-879.

Boes, R.M, Auel, C, Hagmann, M. and Albayrak, I. (2014) Sediment bypass tunnels to mitigate reservoir sedimentation and restore sediment continuity. Reservoir Sedimentation. Taylor & Francis Group, London.

Bovee, K.D., Lamb, B.L., Bartholow, J.M., Stalnaker, C.B. and Taylor, J. (1998) Stream habitat analysis using the instream flow incremental methodology USGS Report No. USGS/BRD/ITR--1998-0004. Reston, VA.

Brown, R., Geist, D. and Mesa, M. (2006) Use of electromyogram telemetry to assess swimming activity of adult spring Chinook salmon migrating past a Columbia River dam. Transactions of the American Fisheries Society, 135:281-287.

Brown, R.S., Carlson, T., Gingerich, A., Stephenson, J., Pflugrath, B., Welch, A., Langeslay, M., Ahmann, M., Johnson, R., Skalski, J., Seaburg, A. and Townsend, G. (2012). Quantifying mortal injury of juvenile Chinook salmon exposed to simulated hydro-turbine passage. Transactions of the American Fisheries Society 14(1):147-157.

Brune, G.M. (1953) Trap efficiency of reservoir. Transactions American Geophysical Union 34(3):407-418.

Bunn, S.E. and Arthington, A.H. (2002) Basic principles and ecological consequences of altered flow regimes for aquatic biodiversity. Environmental management, 30(4):492-507.

Bunt, C.M., Castro-Santos, T. and Haro, A. (2012) Performance of fish passage structures at upstream barriers to migration. River Research and Applications, 28(4):457-478.

Cada, G.F., Coutant, C.C. and Whitney, R. (1997) Development of biological criteria for the design of advanced hydropower turbines. DOE/ID-10578. Prepared for the U.S. Department of Energy, Idaho Operations Office, Idaho Falls, Idaho.

California Fish Passage Forum. (2015) Fish passage barrier lists and recovery plans. http://www.cafishpassageforum.org/fish-passage-barrier-lists-and-recovery-plans

Carlisle, D.M., Wolock, D.M. and Meador, M.R. (2010) Alteration of streamflow magnitudes and potential ecological consequences: a multiregional assessment. Frontiers in Ecology and the Environment, 9(5):264-270.

Castro-Santos, T. (2006) Modeling the effect of varying swim speeds on fish passage through velocity barriers. Transactions of the American Fisheries Society 135:1230-1237.

Castro-Santos, T., Cotel, A.L.I.N.E. and Webb, P.W. (2009) Fishway evaluations for better bioengineering: an integrative approach. In Challenges for diadromous fishes in a dynamic global environment. American Fisheries Society, Symposium, 69: 557-575.

Crossin, G.T., Hinch, S.G., Cooke, S.J., Welch, D.W. Patterson, D.A., Jones, S.R., Lotto, A.G., Leggatt, R.A., Mathes, M.T., Shrimpton, J.M., Van der Kraak, G., Farrel, A., (2008) Exposure to high temperature influences the behavior, physiology and survival of sockeye salmon during spawning migration. Canadian Journal of Zoology 86:127-140.

(DOE) U.S. Department of Energy. (2004) Hydropower: setting a course for our energy future. Wind and Water Technologies Program. Washington, D.C. 24 pp.

Dynesius, M. and Nilsson, C. (1994) Fragmentation and regulation of river systems in the northern third of the world. Science, 266(5186):753-762.

DePhilip, M, and Moberg, T. (2010) Ecosystem flow recommendations for the Susquehanna River Basin. The Nature Conservancy, Harrisburg, PA.

DePhilip, M, and Moberg, T. (2013) Ecosystem flow recommendations for the Delaware River Basin. The Nature Conservancy, Harrisburg, PA.

Draut, A.E., Logan, J.B. and Mastin, M.C. (2011) Channel evolution of the dammed Elwha River, Washington, USA. Geomorphology 127:71-87.

(EPRI) Electric Power Research Institute. 1990 Maintaining and monitoring dissolved oxygen at hydroelectric projects: Status report, Report No. GS-7001. Palo Alto, California.

(EPA & USGS) Environmental Protection Agency and U.S. Geological Survey. 2016. Draft EPA-USGS Technical Report: Protecting Aquatic Life from Effects of Hydrologic Alteration. EPA Report 822-P-15-002 and USGS Scientific Investigations Report 2015-5160.

EWRI-AFS Fish Passage Reference Database. (2015) Warehouse of fish passage engineering, biology, design and disciplines. American Society of Civil Engineers and the American Fisheries Society http://scholarworks.umass.edu/fishpassage_database/

Feng, J., Li, R., and Shen, X. 2014. Eco-environmentally friendly operational regulation: an effective strategy to diminish the TDG supersaturation of reservoirs. Hydrology and Earth Systems Sciences 18:1213-1223.

Ferguson, J. W., Healey, M., Dugan, P., and Barlow, C. (2011) Potential effects of dams on migratory fish in the Mekong River: Lessons from salmon in the Fraser and Columbia Rivers. Environmental Management 47(1):141-159.

Fukuda, T., Yamashita, K., Osada, K., & Fukuoka, S. (2012). Study on Flushing Mechanism of Dam Reservoir Sedimentation and Recovery of Riffle-Pool in Downstream Reach by a Flushing Bypass Tunnel. In International Symposium on Dams for a Changing World-Need for Knowledge Transfer across the Generations & the World, Kyoto, Japan.

Gowans, A. R. D., Armstrong, J. D., Priede, I. G., & Mckelvey, S. (2003). Movements of Atlantic salmon migrating upstream through a fish-pass complex in Scotland. Ecology of Freshwater Fish, 12(3), 177-189.

Grams, P. E., J. C. Schmidt, and D. J. Topping. (2007) The rate and pattern of bed incision and bank adjustment on the Colorado River in Glen Canyon downstream from Glen Canyon Dam, 1956-2000, Geol. Soc. Am. Bull. 119(5-6): 556–575.

Gregory, R. S., and C. D. Levings. (1998) Turbidity reduces predation on migrating Pacific salmon, Transactions of the American Fisheries Society 127:275–285.

Hartmann, J., Harrison, D., Opperman, J. and Gill, R. (2013) The new frontier of hydropower sustainability: planning at the system scale. Prepared for the Inter-American Development Bank (IDB) by The Nature Conservancy. Washington, D.C.

Haxton, T.J., and Findlay, C.S. 2008. Meta-analysis of the impacts of water management on aquatic communities. Canadian Journal of Fisheries and Aquatic Science 65:437-447.

(IHA) International Hydropower Association. (2010) Hydropower Sustainability Assessment Protocol. http://www.hydrosustainability.org/Protocol/Protocol.aspx

Jager, H.I. and Rose, K.A. (2003) Designing optimal flow patterns for fall chinook salmon in a Central Valley, California, River. North American Journal of Fisheries Management, 23(1):1-21.

Jager, H.I. and Smith, B.T. (2008) Sustainable reservoir operation: can we generate hydropower and preserve ecosystem values. River research and Applications, 24(3):340-352.

Johnson, J. and Daigneault, M. (2013) Catalog of Waters Important for spawning, rearing or migration of anadromous fishes – western region. ADFG Divisions of Sport Fish and Habitat, Anchorage, AK.

Jones, N.E., Petreman, I.C. 2014. Environmental influences on fish migration in a hydropeaking river. River Research and Applications 31(9):1109-1118.

Jungwirth, M., Schmutz, S., & Weiss, S. (Eds.). (1998). Fish migration and fish bypasses (Vol. 4). Oxford: Fishing News Books.

Katapodis, C. (1992) “Introduction to Fishway Design.” Freshwater Institute, Central and Arctic Region Department of Fisheries and Oceans: R3T 2N6. Winnipeg, Manitoba, Canada.

Katopodis, C., Kells, J.A. and Acharya, M. (2001) Nature-like and conventional fishways: Alternative concepts. Canadian Water Resources Journal, 26(2):211-232.

Katopodis, C., Shepherd, D., Johnson, W., and Kemp, P. (2004) Hydraulic modelling of a nature-mimicking fishway design for the proposed Dunvegan Hydroelectric Project on the Peace River, northern Alberta, Canada. In Proceedings of the 5th International Symposium in Ecohydraulics, Aquatic Habitats: Analysis and Restoration (p. 1052).

Katopodis, C. (2005). Developing a toolkit for fish passage, ecological flow management and fish habitat works. Journal of Hydraulic Research, 43(5):451-467.

Katopodis, C. and Williams, J.G. (2012) The development of fish passage research in a historical context. Ecological Engineering, 48:8-18.

Keefer, M.L., Peery, C.A., Bjornn, T.C., Jepson, M.A. and Stuehrenberg, L.C. (2004) Hydrosystem, dam, and reservoir passage rates of adult Chinook salmon and steelhead in the Columbia and Snake rivers. Transactions of the American Fisheries Society, 133(6):1413-1439.

Kendy, E., Apse, C. and Blann, K. (2012) A practical guide to environmental flows for policy and planning. The Nature Conservancy, Arlington, VA.

Kiesecker, J.M., Copeland, H., Pocewicz, A., McKenney, B. (2010) Development by design: blending landscape-level planning with the mitigation hierarchy. Frontiers in Ecology and the Environment 8(5):261-266.

King, J. and Brown, C. (2006) Environmental flows: striking the balance between development and resource protection. Ecology and Society, 11(2):26.

Kondolf, G.M. (1995) Hungry water: Effects of dams and gravel mining on river channels. University of California, Berkeley, CA.

Kondolf, G. Mathias, Yongxuan Gao, George W. Annandale, Gregory L. Morris, Enhui Jiang, Junhua Zhang, Yongtao Cao, Hotchkiss, R. (2014) Sustainable sediment management in reservoirs and regulated rivers: Experiences from five continents. Earth's Future 2(5): 256-280.

Kotchen, M.J., Moore, M.R., Lupi, F. and Rutherford, E.S. (2006) Environmental constraints on hydropower: an ex post benefit-cost analysis of dam relicensing in Michigan. *Land Economics*, *82*(3), pp.384-403.

Lee, C. and Foster, G. (2013) Assessing the potential of reservoir outflow management to reduce sedimentation using continuous turbidity monitoring and reservoir modeling. Hydrologic Processes, 27:1426–1439.

Lehner, C., Liermann, C., Revenga, C., Vorosmarty, C., Fekete, B, Crouzet, P., Doll, P. (2011) High resolution mapping of the world's reservoirs and dams for sustainable river-flow management. Frontiers in Ecology and the Environment, 9:494-502.

(LIHI) Low Impact Hydropower Institute. (2016) 2nd Edition Low Impact Hydropower Institute Certification Handbook. 83 pp. http://lowimpacthydro.org/wp-content/uploads/2014/08/2nd-edition-handbook-20160307-FINAL-CLEAN.pdf

Ma, Y., H. Q. Huang, G. C. Nanson, Y. Li, and W. Yao. (2012) Channel adjustments in response to the operation of large dams: The upper reach of the lower Yellow River. Geomorphology, 147-148(0):35–48.

Magilligan, F.J., Nislow, K.H. and Graber, B.E. (2003) Scale-independent assessment of discharge reduction and riparian disconnectivity following flow regulation by dams. Geology, 31(7):569-572.

Magilligan, F. and Nislow, K.H. (2005) Changes in hydrologic regime by dams. Geomorphology 71:61-78.

Maloney, K.O., Lellis, W.A., Bennett, R.M. and Waddle, T.J. (2012) Habitat persistence for sedentary organisms in managed rivers: the case for the federally endangered dwarf wedgemussel (*Alasmidonta heterodon*) in the Delaware River. Freshwater Biology, 57(6):1315-1327.

March, P. 2012. Hydraulic and environmental performance of aerating turbine technologies. A supplement to the 2009 EPRI report, Technology Update on Aerating Turbines. Hydro Performance Processes Inc. 32 pp.

Martin, E.H. and Apse, C.D. (2011) Northeast Aquatic Connectivity: An assessment of dams on northeastern rivers. The Nature Conservancy, Eastern Freshwater Program.

Martin, E.H. and Apse, C.D. (2014) Southeastern Aquatic Connectivity: An assessment of dams on southeastern rivers. The Nature Conservancy, Eastern Freshwater Program.

Mathews, R. and Richter, B.D. (2007) Application of the indicators of hydrologic alteration software in environmental flow setting. Journal of the American Water Resources Association, J06030:1400-1407.

McManamay, R.A. and Bevelhimer, M.S. (2013) A Holistic Framework for Environmental Flows Determination in Hydropower Contexts. ORNL/TM-2013/159. Oak Ridge National Laboratory.

Monk, W.A., Peters, D.L. and Baird, D.J. (2012) Assessment of ecologically relevant hydrological variables influencing a cold-region river and its delta: the Athabasca River and the Peace–Athabasca Delta, northwestern Canada. Hydrological Processes, 26(12):1827-1839.

Morris, G. L., and J. Fan. (1998) Reservoir Sedimentation Handbook: Design and Management of Dams, Reservoirs and Watersheds for Sustainable Use, McGraw-Hill Book Co., New York.

Moog, O., 1993. Quantification of daily peak hydropower effects on aquatic fauna and management to minimize environmental impacts. Regulated Rivers: Research & Management, 8(1-2):5-14.

Nehlsen, W., Williams, J.E. and Lichatowich, J.A. (1991). Pacific salmon at the crossroads: stocks at risk from California, Oregon, Idaho, and Washington. Fisheries, 16(2):4-21.

Morris, G. and Fan, J. (1998) “Reservoir sedimentation handbook: Desing and management of dams, reservoirs and watershed for sustainable use,” McGraw-Hill, New York, NY.

(NMFS) National Marine Fisheries Service. (2008) Anadromous Salmonid passage facility design. NMFS, Northwest Region, Portland, OR.

NMFS. (2015) Status review update for Pacific salmon and steelhead listed under the Endangered Species Act: Pacific Northwest. Northwest Fisheries Science Center, Portland, OR.

NMFS. (2016) Viability assessment for Pacific salmon and steelhead listed under the Endangered Species Act: Southwest. Southwest Fisheries Science Center, Santa Cruz, CA.

Nilsson, C., Reldy, C., Dynesius, M. and Revenga, C. (2005) Fragmentaiton and flow regulation of the world’s large river systems. Science, 308:405-408.

Nilsson, C., Lepori, F., Malmqvist, B., Törnlund, E., Hjerdt, N., Helfield, J.M., Palm, D., Östergren, J., Jansson, R., Brännäs, E. and Lundqvist, H. (2005) Forecasting environmental responses to restoration of rivers used as log floatways: an interdisciplinary challenge. Ecosystems, 8(7):779-800.

Opperman, J.G., Grill, G., and Hartmann, J. (2015). The power of rivers: finding balance between energy and conservation in hydropower development. The Nature Conservancy: Washington, D.C.

Pelicice, F. and Agostinho, A.A. (2008) Fish-passage facilities as ecological traps in large neotropical rivers. Conservation biology, 22(1):180-188.

Peters, D.L., Monk, W. and Baird, D.J. (2015) Cold-regions hydrological indicators of change (chic) for ecological flow needs assessment. Hydrological Sciences Journal, 59 (3):502-516.

Poff, N.L., Allan, J.D., Bain, M.B., Karr, J.R., Prestegaard, K.L., Richter, B.D., Sparks, R.E. and Stromberg, J.C. (1997) The natural flow regime. BioScience, 47(11):769-784.

Poff, N.L., Olden, J.D., Merritt, D.M. and Pepin, D.M. (2007) Homogenization of regional river dynamics by dams and global biodiversity implications. Proceedings of the National Academy of Sciences, 104(14):5732-5737.

Poff, N.L., Richter, B.D., Arthington, A.H., Bunn, S.E., Naiman, R.J., Kendy, E., Acreman, M., Apse, C., Bledsoe, B.P., Freeman, M.C. and Henriksen, J. (2010) The ecological limits of hydrologic alteration (ELOHA): a new framework for developing regional environmental flow standards. Freshwater Biology, 55(1):147-170.

Poff, L. and Zimmerman, J.K.H. (2010) Ecological responses to altered flow regimes: a literature review to inform the science and management of environmental flows. Freshwater Biology 55(1):194-205.

Postel, S. and Richter, B. (2003) Rivers for life: managing water for people and nature. Island Press.

Power, M.E., Sun, A., Parker, G., Dietrich, W.E. and Wootton, J.T. (1995). Hydraulic food-chain models. BioScience, 45(3):159-167.

(Reclamation) U.S. Bureau of Reclamation. (2008) Robles diversion dam high flow and sediment bypass structure, Ventura California. Hydraulic Laboratory Report HL-2008-7. Denver, CO.

Rheinheimer, D.E. and Viers, J.H. (2014) Combined effects of reservoir operations and climate warming on the flow regime of hydropower bypass reaches of California's Sierra Nevada. River Research and Applications DOI: 10.1002/rra.2749.

Richter, B.D., Davis, M.M., Apse, C. and Konrad, C. (2012) A presumptive standard for environmental flow protection. River Research and Applications, 28(8):1312-1321.

Roscoe, D.W. and Hinch, S.G. (2010) Effectiveness monitoring of fish passage facilities: historical trends, geographic patterns and future directions. Fish and Fisheries, 11(1):12-33.

Schleiss, A.J., Cesare, G. and Althaus, J. (2014) Reservoir sedimentation and sustainable development. Workshop on Erosion, Transport and Deposition of Sediments

Singer, M. B. (2010), Transient response in longitudinal grain size to reduced gravel supply in a large river. Geophys. Res. Lett., 37(18):L18403.

Slaney, T.L., Hyatt, K.D., Northcote, T.G. and Fielden, R.J. (1996) Status of anadromous salmon and trout in British Columbia and Yukon. Fisheries, 21(10):20-35.

Smith, B.T., Jager, H.I., March, P.A. (2007). Prospects for combining energy and environmental objectives in hydropower optimization. Proceedings of Waterpower XV, Kansas City Missouri. HCI Publications.

Stalnaker, C., Lamb, B.L., Henriksen, J., Bovee, K. and Bartholow, J. (1995) The instream flow incremental methodology: a primer for IFIM. National Biological Service Center, Midcontinent Ecological Science Center, Fort Collins, CO.

State of California Department of Water Resources (2005). Fish Passage Improvement: An element of CALFED's Ecosystem restoration program. Bulleton 250 to support the Fish Passage Improvement Program (FPIP). http://www.water.ca.gov/fishpassage/#

Stewart, K.M., Witt, A. and Hadjerioua, B. (2015) Total dissolved gas prediction and optimization in RIVERWARE. Prepared for U.S. Department of Energy Wind and Water Program by Oakridge National Laboratory, Oak Ridge, TN.

Sumi, T., Okano, M., Takata, Y. (2004) Reservoir sedimentation management with bypass tunnels in Japan. Proceedings of the 9th International Symposium on river Sedimentation, ii, pp.1036-1043, Yichang, China.

Syvitski, J. P., Kettner, A. J., Overeem, I., Hutton, E. W., Hannon, M. T., Brakenridge, G. R., ... and Nicholls, R. J. (2009) Sinking deltas due to human activities. Nature Geoscience, 2(10):681-686.

Tharme, R.E., 2003. A global perspective on environmental flow assessment: emerging trends in the development and application of environmental flow methodologies for rivers. *River research and applications*,*19*(5-6), pp.397-441.

(USACE et al.) U.S. Army Corps of Engineers, U.S. Department of Energy and U.S. Department of Interior. (2012) Memorandum of Understanding for Sustainable Hydropower: Two-year progress report. Washington, D.C.

Vogel, R.M., Sieber, J., Archfield, S.A., Smith, M.P., Apse, C.D. and Huber-Lee, A., 2007. Relations among storage, yield, and instream flow. *Water Resources Research*, *43*(5).Poff, N.L. and

Vorosmarty, C.J., Meybeck, M., Fekete, B., Sharma, K., Green, P., and Syvitski, P.M. (2003) Anthropogenic sediment retention: major global impact from registered river impoundments, Global Planet Ghange 39:169-190.

Vischer, D., Hager, W.H., Casanova, C., Joos, B., Lier, P., and Martini, O. (1997) Bypass tunnels to prevent reservoir sedimentation Q74 R37, in Proceedings of 19th ICOLD Congress, Florence Italy.

Wannigan, H., Buijse, T., Breve, N., Kroes, M., Vriese, T. (2010) Breaking down barriers for fish migration in the Netherlands: Towards a streamlined approach to improve fish migration. http://www.sportvisserijnederland.nl/vis-water/vismigratie/

Wildman, L., Parasiewicz, P., Katopodis, C.K., Dumont, U. (2010). An illustrative handbook on nature-like fishways – Summarized Version. Marion, CT. 21 pp.

Zimmerman, J.K., 2010. Ecological responses to altered flow regimes: a literature review to inform the science and management of environmental flows. *Freshwater Biology*, *55*(1), pp.194-205.

Zhang, Z., Balay, J.W., Bertoldi, K.M. and MaCoy, P.O. (2015) Assessment of Water Capacity and Availability from Unregulated Stream Flows Based on Ecological Limits of Hydrologic Alteration (ELOHA) Environmental Flow Standards. River Research and Applications. DOI: 10.1002/rra.2979

Attachment 1.

Ecosystem Flows and Indicators of Hydrologic Alteration Workshop Agenda, Participant List and Supporting Materials

Mat-Su salmon
PARTNERSHIP

Ecosystem Flows and Indicators of Hydrologic Alteration Workshop Agenda

22 January 2014

Location: Room 107 Gorsuch Commons, University of Alaska Anchorage
OR webinar (information to be sent later)

Meeting objectives
- Overview of Ecosystem Flows including flow-ecology relationships in the Susitna basin
- Introduction to tools to characterize the flow regime and measure alteration, focusing on Indicators of Hydrologic Alteration (IHA)
- Introduce the preliminary framework of TNC's Ecological Risk Assessment (ERA)

Meeting materials to be provided:
- Flow-ecology diagrams for salmon
- Flow data for Susitna River and Willamette River case studies

What participants provide:
- If interested in hands-on IHA training, a laptop with IHA installed in advance (TNC will provide link and technical assistance)
- Flow data if interested in another river and/or effect other than hydropower (e.g. climate change or water withdrawals for mining)

9:00 a.m. Welcome, Introductions and Review of Agenda and meeting materials

9:30 a.m. Ecological Risk Assessment – Problem Formulation
- Approach and overview
- Present risk profile for changes to flow regime

10:00 a.m Ecosystem Flows
- Introduction to concept and supporting science
- Methods to define ecosystem flow needs and track change
- In practice – review large river case studies

11:00 a.m. Break

11:15 a.m. Flow-ecology relationships – Susitna case study
- Outline key flow-ecology relationships for the Susitna
- Review ecologically relevant statistics

12:15 p.m. Lunch (provided on site)

1:15 p.m. *Willamette River (Columbia River Basin) Case Study*
Assessing Hydrologic Alteration – Comparative Analysis and Outputs

- Overview of IHA
- Hydrologic data selection, sources and formatting
- Running IHA to compare unaltered and altered conditions
- Interpreting outputs
- Methods to assess sub-daily alteration with IHA and other tools

2:45 *Susitna River Case Study*
Characterizing a Baseline Flow Regime with IHA

- Application of a single-period analysis
- Analysis and interpreting outputs

3:45 Assessing Hydrologic Alteration - Defining the Question

Break-out session: Participants will be divided into two groups based on hydro-period. Each group will refine a few flow-ecology hypotheses about how changes to the *magnitude, duration, frequency or rate of change* of flows during a particular season may affect biota or processes in Susitna river reaches and macrohabitats

4:30 Exploration, Discussion and Questions

5:00 Meeting ends

Instructions for Downloading IHA

Link:
http://www.conservationgateway.org/ConservationPractices/Freshwater/EnvironmentalFlows/MethodsandTools/IndicatorsofHydrologicAlteration/Pages/indicators-hydrologic-alt.aspx/

- Click '[Downloads]'
- Click 'Download IHA Software [English],
- Read and decide whether you agree to legal disclosure and terms of use
- Download zip file
- Make a folder on your C: drive titled 'IHA'
- Extract the contexts of the zip file to C:/IHA
- Open IHA by clicking on the IHA7 application file

If you have any problems, we will also set up a help station during the lunch to install the program, so not to worry.

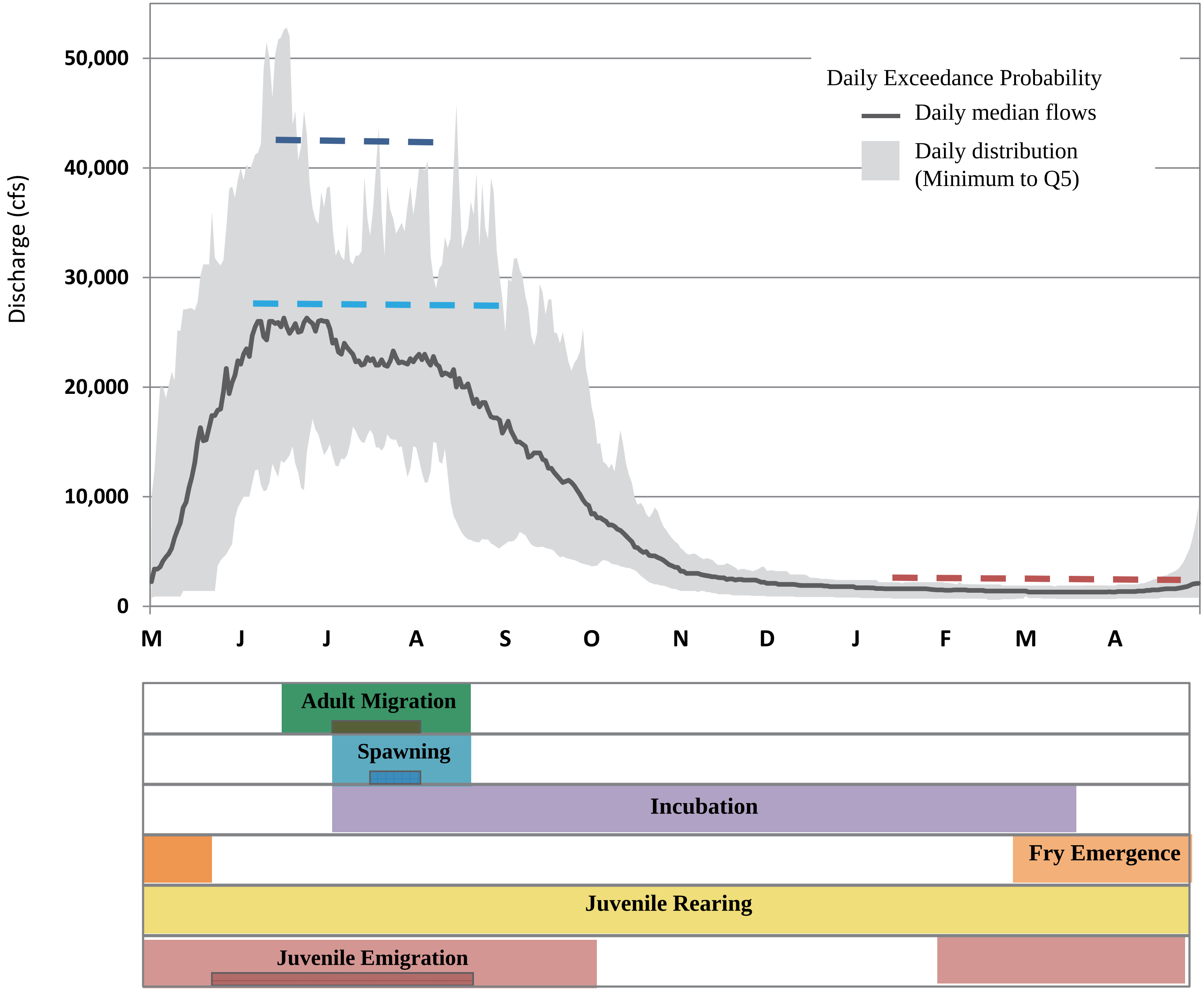
Flow-ecology Diagrams

We've included an example flow-ecology diagram for Chinook salmon and will provide additional diagrams at the workshop. Diagrams include:

- A hydrograph illustrating seasonal and among-year flow variability. Hydrographs are based on distribution of average daily flows at representative flow gages based on Water Years 1950-2013.
- Below each hydrograph, we indicate the timing of key life history stages. Darker bars indicate timing of peak use (R2 Resource Consultants 2013).
- Below each hydrograph, we also include a table of the macrohabitats used by each life stage. Black dots indicate peak use habitats and grey dots indicate general habitat use. The macrohabitats are main channel (M), side channel (Sc), tributary mouth (Tm), side slough (Ss), upland slough (Us) and tributary (T).

Flow-Ecology Diagram: Chinook Salmon

Upper River, Susitna River at Gold Creek, AK (USGS Gage 015292000)



SMALL FLOOD
(2 Yr Recurrence)
early June- mid-Aug
40,000 to 70,000 cfs
0 to 1 events / year
4o to 90 days / event

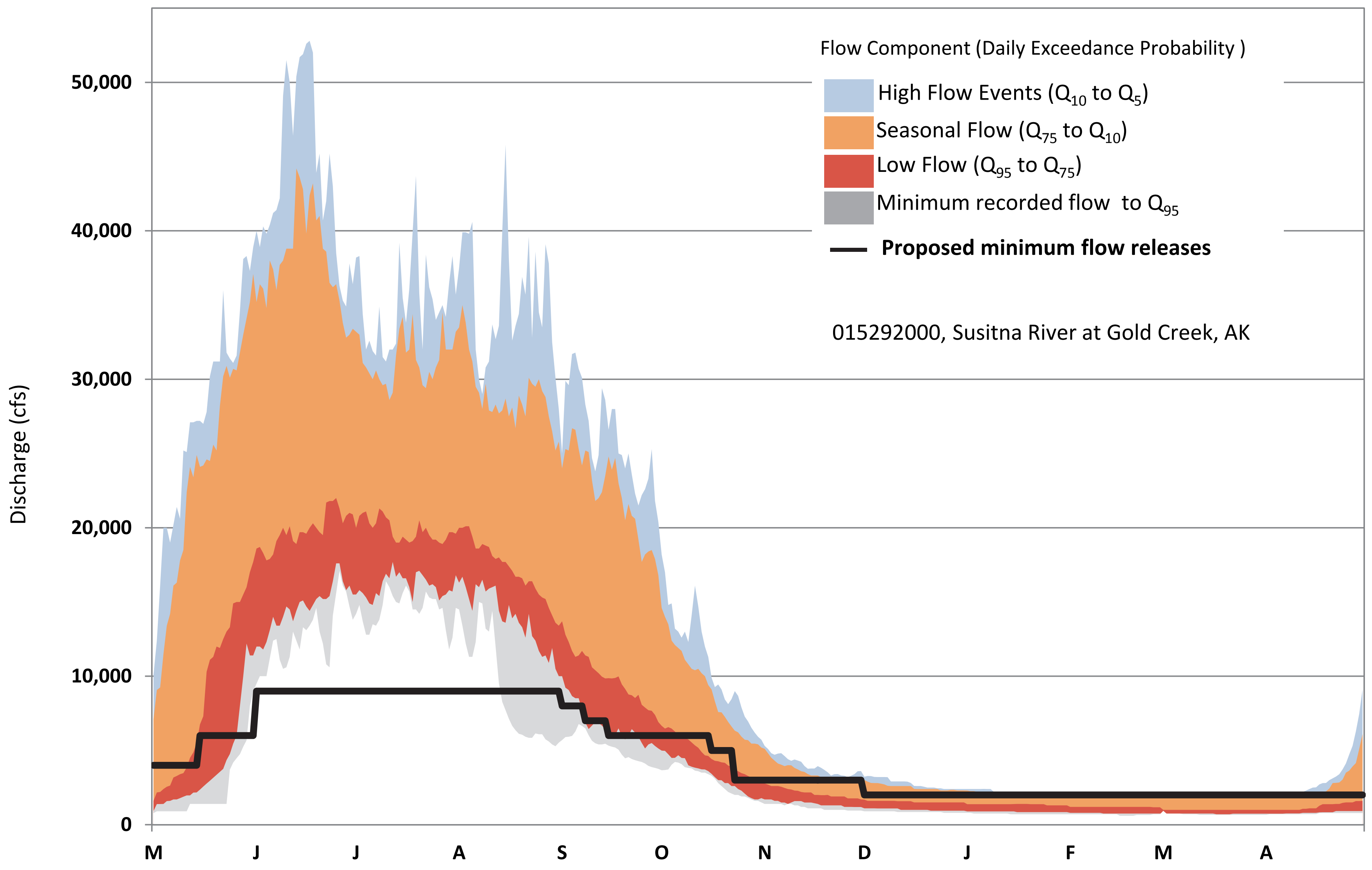
HIGH PULSE (≥Q10)
26,000 cfs
2 to 6 events / year
4 to 11 days/ event

LOW PULSE
(≤Q90)
Flow ≤ 1600 cfs
0 to 3 events / year
3 to 9 days / event

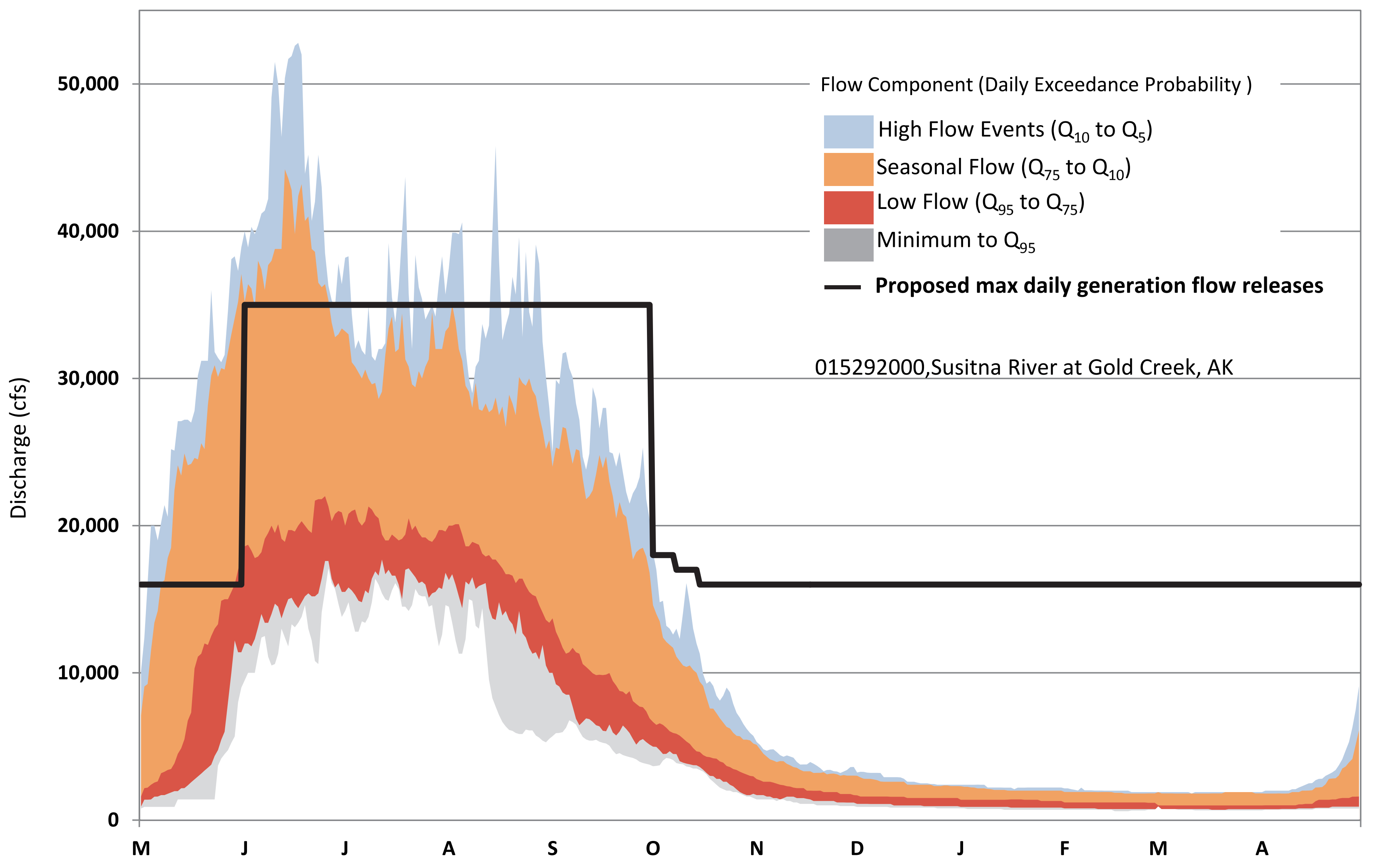
Habitat Type

M	S c	T m	S s	U s	T
●	•	●	•		●
		•			●
		•			●
		•			●
•	●	•	●	●	●
●	●	•	●	●	•

Proposed Operating Rules for Susitna-Watana Hydroelectric Project, Base Case Scenario as Submitted in the Pre-Application Document



Proposed Operating Rules for Susitna-Watana Hydroelectric Project, Base Case Scenario as Submitted in the Pre-Application Document



Workshop Participant List

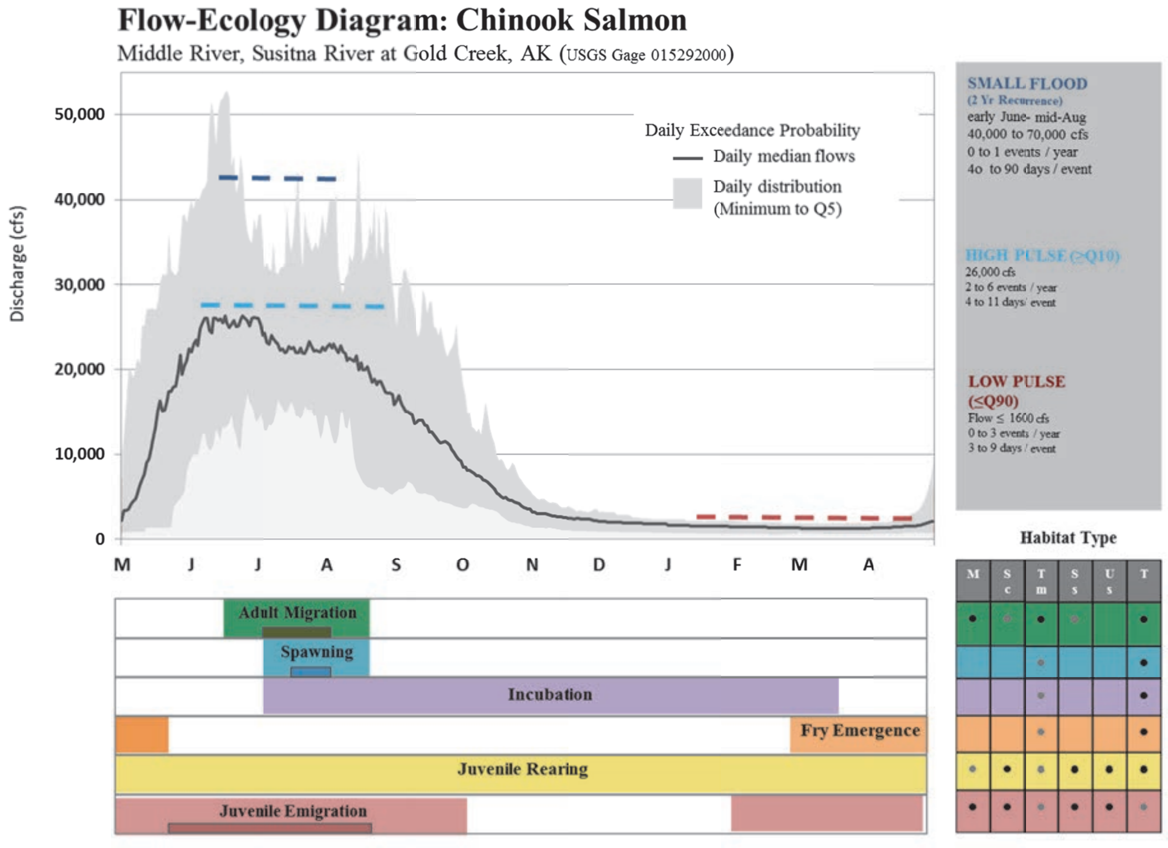
	Name	Organization
1	Adams, Jeff	US Fish and Wildlife Service
2	Angela Hunt	Alaska Department of Transportation
3	Becky Long	Susitna River Coalition
4	Benjamin Meyer	University of Alaska Fairbanks
5	Betsy McCracken	US Fish and Wildlife Service
6	Bill Rice	US Fish and Wildlife Service
7	Cassie Thomas	US National Park Service
8	Chuck Kaucic	Wasilla Soil and Water Conservation District
9	Corinne Smith	The Nature Conservancy
10	Dave Albert	The Nature Conservancy
11	Dave Ianson	Palmer Soil and Water Conservation District
12	Eric Rothwell	US National Oceanic and Atmospheric Administration
13	Gay Davis	Aquatic Restoration and Research Institute
14	Gayle Martin	US Environmental Protection Agency
15	Gene Agnew	Chickaloon Village Native Tribe
16	Hal Shepherd	Center for Water Advocacy
17	Jake Greuey	Alaska Department of Environmental Conservation
18	James Rypkema	Alaska Department of Environmental Conservation
19	Jan Konigsberg	Alaska Hydro Project
20	Jasper Hardison	US Fish and Wildlife Service
21	Jeanette Alas	Alaska Department of Fish and Game
22	Jeff Adams	US Fish and Wildlife Service
23	Jeff Davis	Aquatic Restoration and Research Institute
24	Jeff Smeenk	Palmer Soil and Water Conservation District
25	Jennie Spegon	US Fish and Wildlife Service
26	Jessica Speed	The Nature Conservancy
27	Jill Weitz	Trout Unlimited
28	Jim DePasquale	The Nature Conservancy
29	Joe Miller	Anchor QEA
30	Jonathan Kirsch	HDR
31	Josh Brekken	Alaska Department of Fish and Game
32	Justin Miner	Three Parameters Plus, Inc.
33	Kelly Strawn	Palmer Soil and Water Conservation District
34	Kendra Zamzow	Center for Science in Public Participation (CSP2)
35	Lori Verbrugge	US Fish and Wildlife Service
36	Mark Eisman	Alaska Department of Fish and Game
37	Matt LaCroix	US Environmental Protection Agency
38	Melissa Hill	Alaska Department of Natural Resources
39	Merlyn Schelske	US Bureau of Land Management

40	Michael Daigneault	Alaska Department of Fish and Game
41	Monty Miller	Alaska Department of Fish and Game
42	Phil Brna	US Fish and Wildlife Service
43	Polly Bass	University of Alaska Anchorage
44	Raymond O'Neil	Project Engineer
45	Ronald Benkert	Alaska Department of Fish and Game
46	Sarah O'Neal	Trout Unlimited
47	Shannon Dewandel	Alaska Department of Transportation
48	Stormy Haught	Alaska Department of Fish and Game
49	Sue Mauger	Cook Inletkeeper
50	Susan Walker	National Oceanic and Atmospheric Administration
51	Tara Moberg	The Nature Conservancy
52	Tom Cappiello	Alaska Department of Fish and Game
53	Warren Keogh	Retired
54	Whitney Wolf	Susitna River Coalition
55	William Ashton	Alaska Department of Environmental Conservation
56	William Bechtol	Bechtol Research

Flow-ecology hypotheses are relationships derived from data, literature and expert input about the expected influence of change to an environmental flow component on physical, chemical and particularly biological processes within a river or habitat type. The hypotheses should be as specific as existing information allows, with the goal of creating hypotheses that can be tested through subsequent quantitative analysis. Hypotheses should be expressed so they address the following:

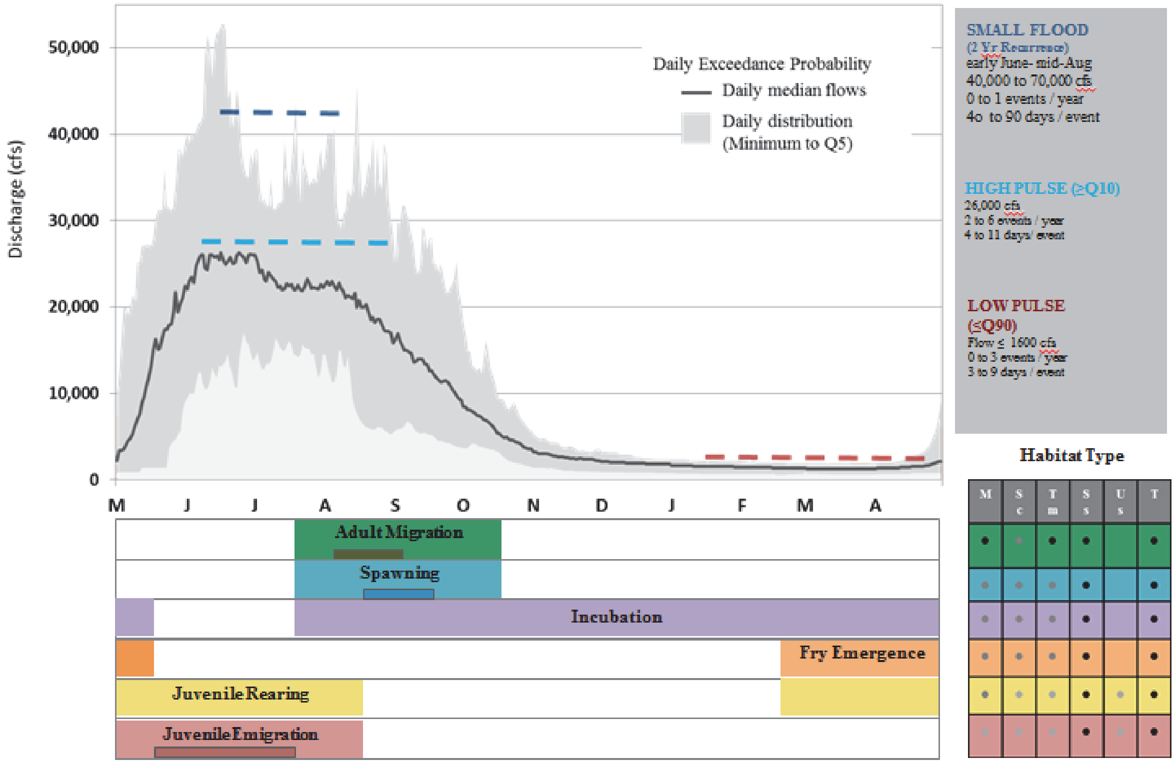
- Who (species, group of species, physical or chemical process)
- What (flow component and)
- When (month or season)
- Where (river type, reach, habitat)
- Why/how (expected ecological response)

Example: "From mid-June through mid-August (*when*) if monthly median flows decrease (*what*), access to tributary mouths and tributaries (*where*) for adult migrating Chinook (*who*) may be reduced or eliminated, resulting in reduced extent of upstream migration and reduced year class strength (*why/how*)."



Flow-Ecology Diagram: Chum Salmon

Middle River, Susitna River at Sunshine, AK (USGS Gage 015292780)



SMALL FLOOD
(2 Yr Recurrence)
early June- mid-Aug
40,000 to 70,000 cfs
0 to 1 events / year
4o to 90 days / event

HIGH PULSE (≥Q10)
26,000 cfs
2 to 6 events / year
4 to 11 days/ event

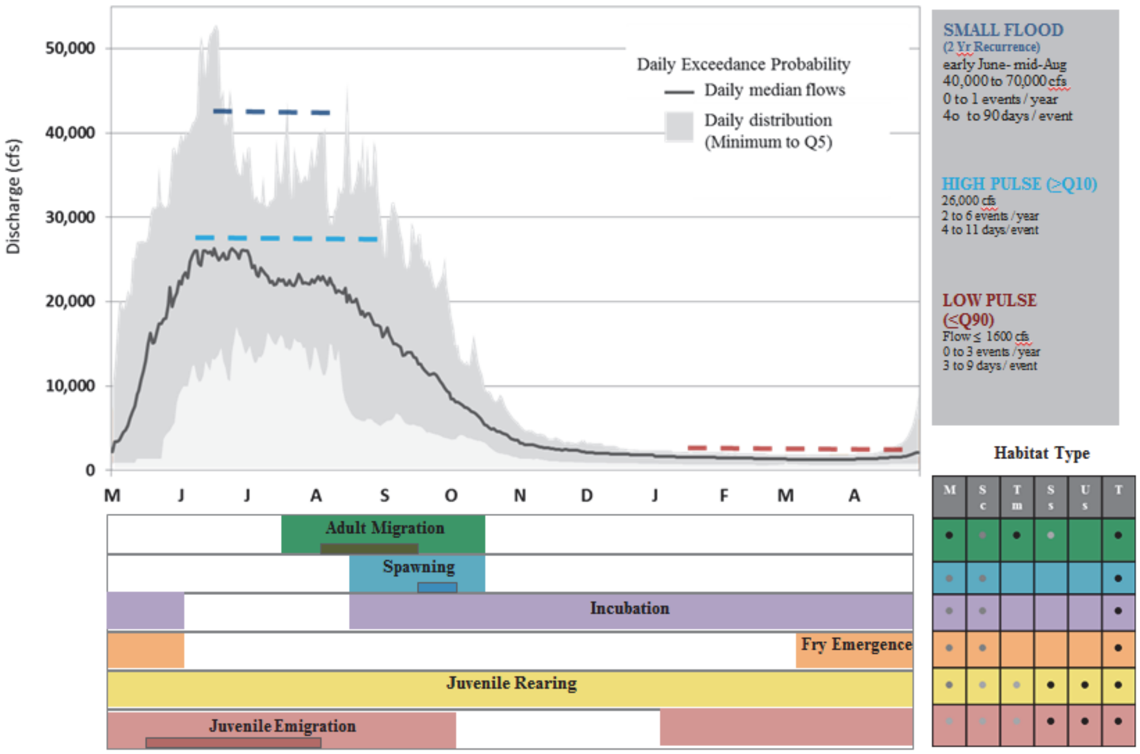
LOW PULSE
(≤Q90)
Flow ≤ 1600 cfs
0 to 3 events / year
3 to 9 days / event

Habitat Type

M	Sc	Tm	Ss	Us	T
●	•	●	●		●
•	•	•	●		●
•	•	•	●		●
•	•	•	●		●
•	•	•	●	•	●
•	•	•	●	•	●

Flow-Ecology Diagram: Coho Salmon

Middle River, Susitna River at Sunshine, AK (USGS Gage 015292780)



SMALL FLOOD
(2 Yr Recurrence)
early June- mid-Aug
40,000 to 70,000 cfs
0 to 1 events / year
4o to 90 days / event

HIGH PULSE (≥Q10)
26,000 cfs
2 to 6 events / year
4 to 11 days/event

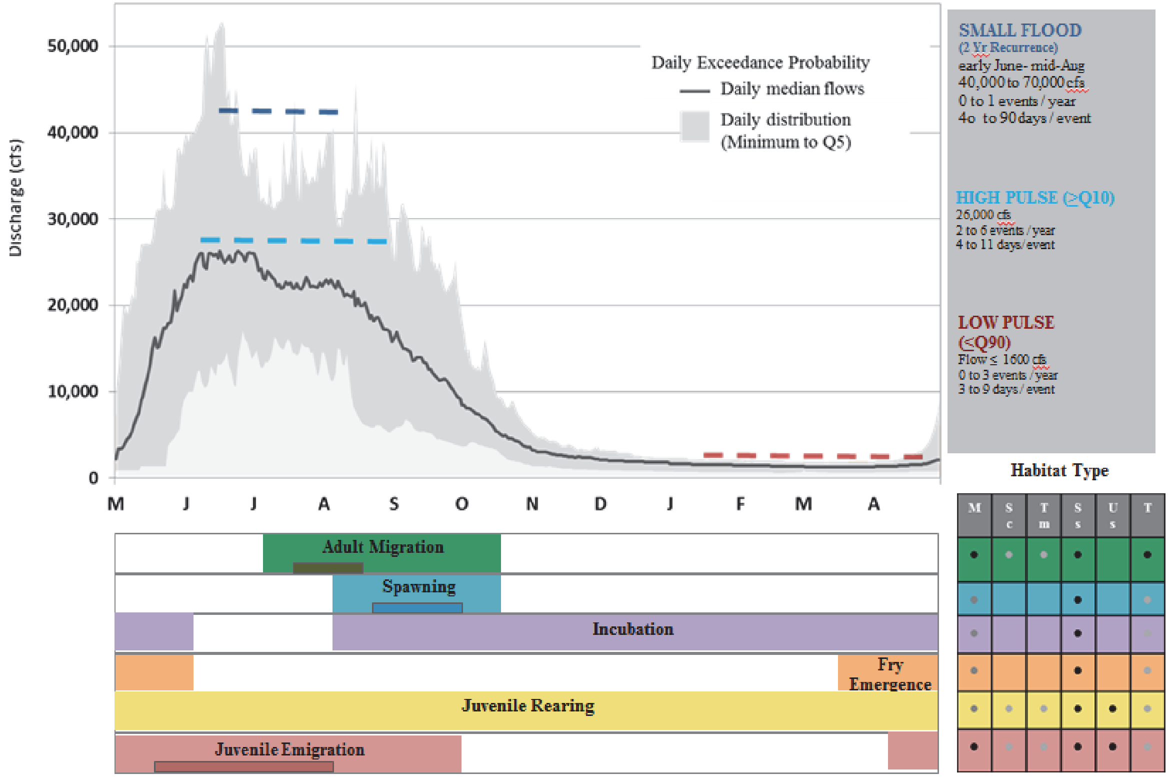
LOW PULSE
(≤Q90)
Flow ≤ 1600 cfs
0 to 3 events / year
3 to 9 days / event

Habitat Type

M	Sc	Tm	Ss	Us	T
●	•	●	•		●
•	•				●
•	•				●
•	•				●
•	•	•	●	●	●
•	•	•	●	●	●

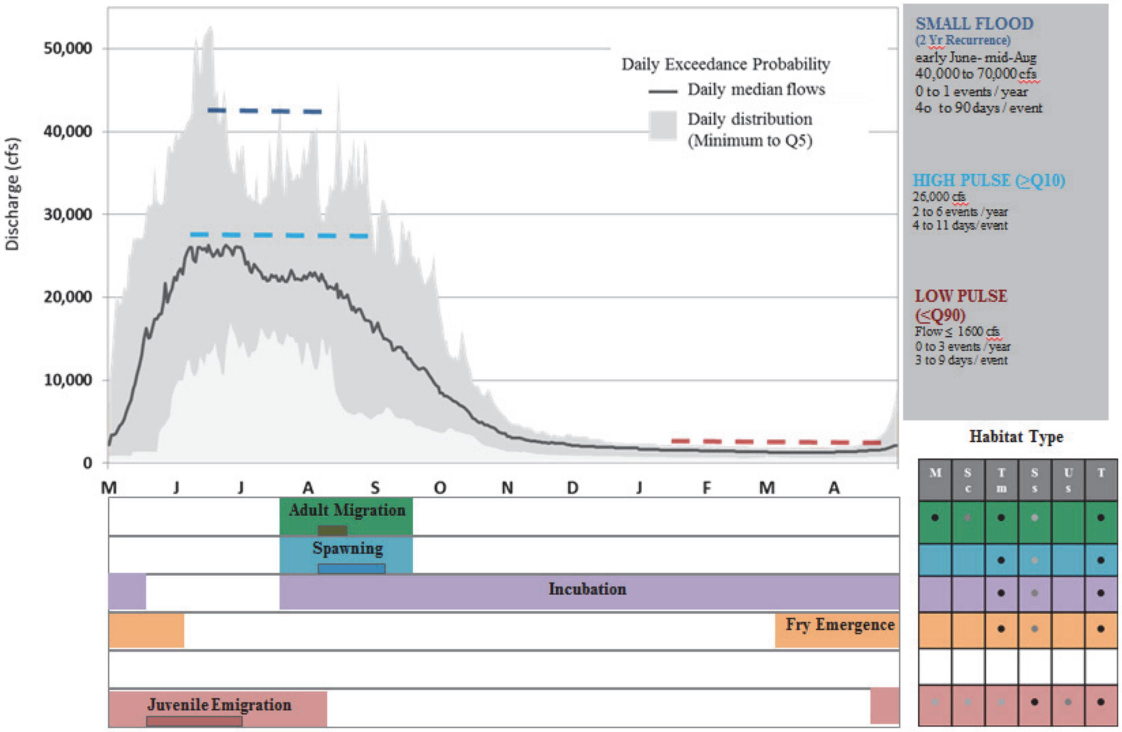
Flow-Ecology Diagram: Sockeye Salmon

Middle River, Susitna River at Sunshine, AK (USGS Gage 015292780)



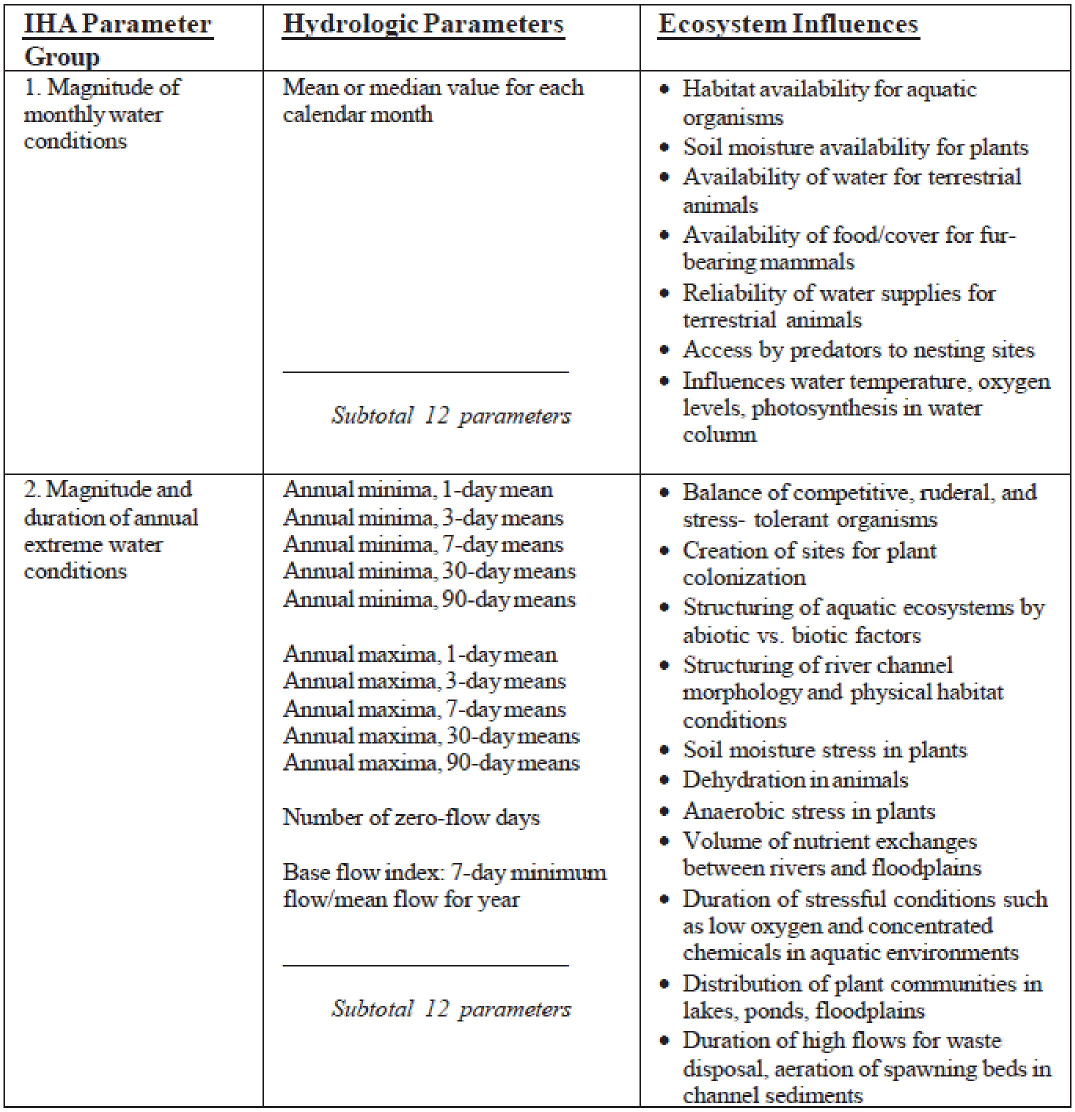
Flow-Ecology Diagram: Pink Salmon

Middle River, Susitna River at Sunshine, AK (USGS Gage 015292780)



Ecologically-relevant flow statistics are statistics that represent environmental flow components and (Mathews and Richter 2007), when altered, have been linked to a published ecological response.

Table 1. A subset of statistics calculated by the Indicators of Hydrologic Alteration and their Ecosystem Influences

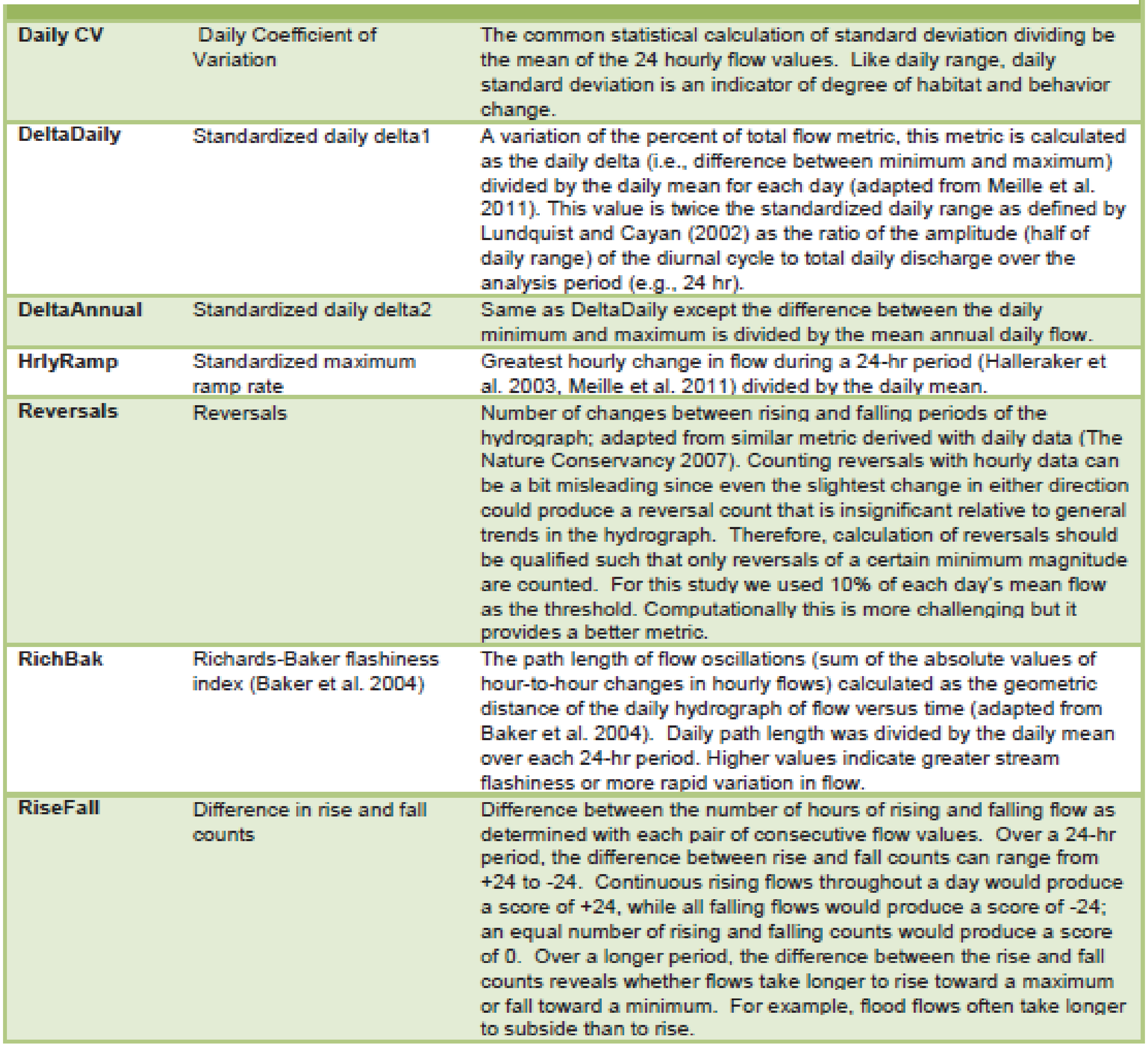


IHA Parameter Group	Hydrologic Parameters	Ecosystem Influences
1. Magnitude of monthly water conditions	Mean or median value for each calendar month *Subtotal 12 parameters*	• Habitat availability for aquatic organisms • Soil moisture availability for plants • Availability of water for terrestrial animals • Availability of food/cover for fur-bearing mammals • Reliability of water supplies for terrestrial animals • Access by predators to nesting sites • Influences water temperature, oxygen levels, photosynthesis in water column
2. Magnitude and duration of annual extreme water conditions	Annual minima, 1-day mean Annual minima, 3-day means Annual minima, 7-day means Annual minima, 30-day means Annual minima, 90-day means Annual maxima, 1-day mean Annual maxima, 3-day means Annual maxima, 7-day means Annual maxima, 30-day means Annual maxima, 90-day means Number of zero-flow days Base flow index: 7-day minimum flow/mean flow for year *Subtotal 12 parameters*	• Balance of competitive, ruderal, and stress- tolerant organisms • Creation of sites for plant colonization • Structuring of aquatic ecosystems by abiotic vs. biotic factors • Structuring of river channel morphology and physical habitat conditions • Soil moisture stress in plants • Dehydration in animals • Anaerobic stress in plants • Volume of nutrient exchanges between rivers and floodplains • Duration of stressful conditions such as low oxygen and concentrated chemicals in aquatic environments • Distribution of plant communities in lakes, ponds, floodplains • Duration of high flows for waste disposal, aeration of spawning beds in channel sediments

Table 1, Continued

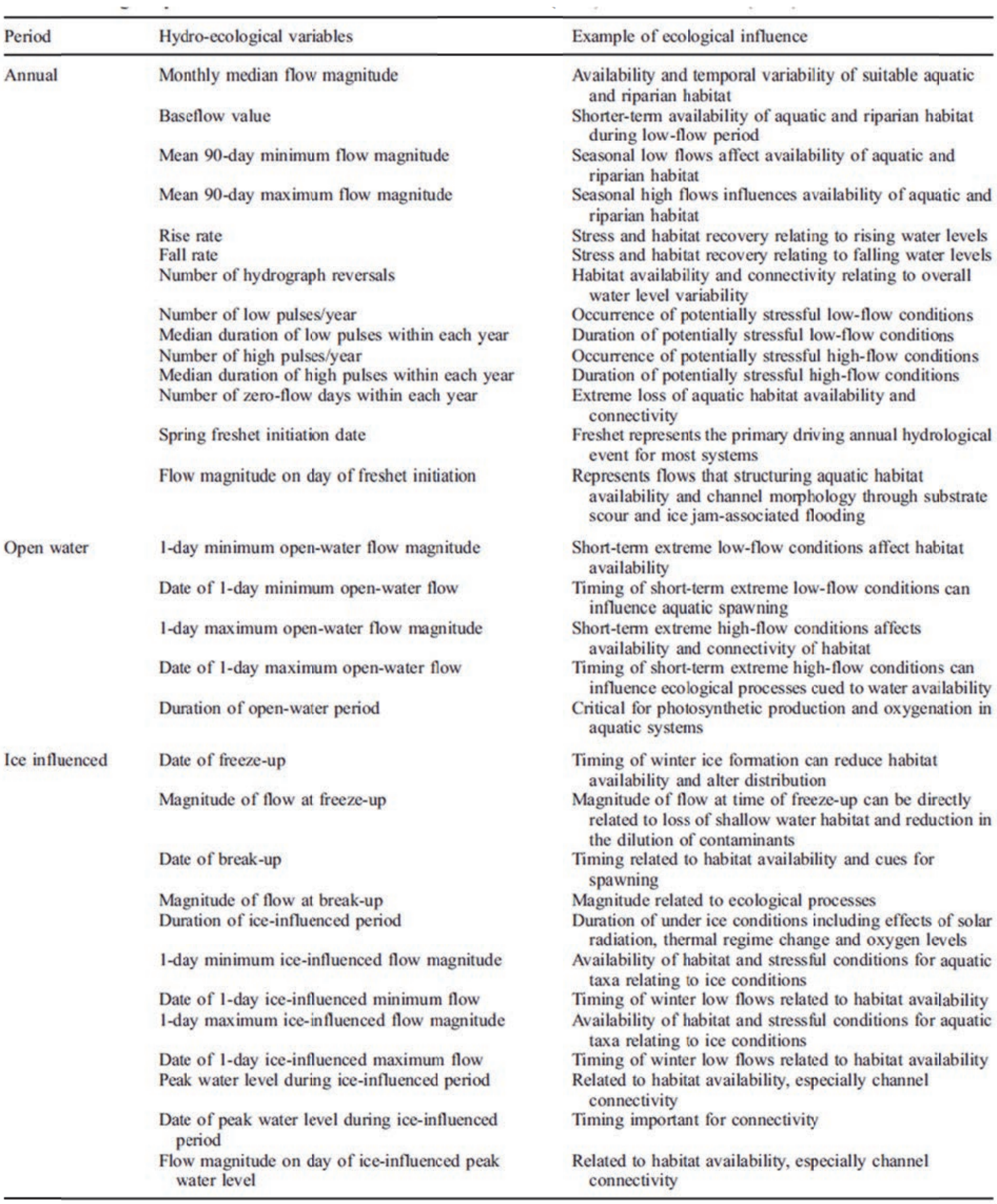
3. Timing of annual extreme water conditions	Julian date of each annual 1-day maximum Julian date of each annual 1-day minimum *Subtotal 2 parameters*	• Compatibility with life cycles of organisms • Predictability/avoidability of stress for organisms • Access to special habitats during reproduction or to avoid predation • Spawning cues for migratory fish • Evolution of life history strategies, behavioral mechanisms
4. Frequency and duration of high and low pulses	Number of low pulses within each water year Mean or median duration of low pulses (days) Number of high pulses within each water year Mean or median duration of high pulses (days) *Subtotal 4 parameters*	• Frequency and magnitude of soil moisture stress for plants • Frequency and duration of anaerobic stress for plants • Availability of floodplain habitats for aquatic organisms • Nutrient and organic matter exchanges between river and floodplain • Soil mineral availability • Access for waterbirds to feeding, resting, reproduction sites • Influences bedload transport, channel sediment textures, and duration of substrate disturbance (high pulses)
5. Rate and frequency of water condition changes	Rise rates: Mean or median of all positive differences between consecutive daily values Fall rates: Mean or median of all negative differences between consecutive daily values Number of hydrologic reversals *Subtotal 3 parameters* **Grand total 33 parameters**	• Drought stress on plants (falling levels) • Entrapment of organisms on islands, floodplains (rising levels) • Desiccation stress on low-mobility streamedge (varial zone) organisms

Table 2. Seven sub-daily flow statistics and their description (Bevelhimer et al. 2013)



Daily CV	Daily Coefficient of Variation	The common statistical calculation of standard deviation dividing be the mean of the 24 hourly flow values. Like daily range, daily standard deviation is an indicator of degree of habitat and behavior change.
DeltaDaily	Standardized daily delta1	A variation of the percent of total flow metric, this metric is calculated as the daily delta (i.e., difference between minimum and maximum) divided by the daily mean for each day (adapted from Meille et al. 2011). This value is twice the standardized daily range as defined by Lundquist and Cayan (2002) as the ratio of the amplitude (half of daily range) of the diurnal cycle to total daily discharge over the analysis period (e.g., 24 hr).
DeltaAnnual	Standardized daily delta2	Same as DeltaDaily except the difference between the daily minimum and maximum is divided by the mean annual daily flow.
HrlyRamp	Standardized maximum ramp rate	Greatest hourly change in flow during a 24-hr period (Halleraker et al. 2003, Meille et al. 2011) divided by the daily mean.
Reversals	Reversals	Number of changes between rising and falling periods of the hydrograph; adapted from similar metric derived with daily data (The Nature Conservancy 2007). Counting reversals with hourly data can be a bit misleading since even the slightest change in either direction could produce a reversal count that is insignificant relative to general trends in the hydrograph. Therefore, calculation of reversals should be qualified such that only reversals of a certain minimum magnitude are counted. For this study we used 10% of each day's mean flow as the threshold. Computationally this is more challenging but it provides a better metric.
RichBak	Richards-Baker flashiness index (Baker et al. 2004)	The path length of flow oscillations (sum of the absolute values of hour-to-hour changes in hourly flows) calculated as the geometric distance of the daily hydrograph of flow versus time (adapted from Baker et al. 2004). Daily path length was divided by the daily mean over each 24-hr period. Higher values indicate greater stream flashiness or more rapid variation in flow.
RiseFall	Difference in rise and fall counts	Difference between the number of hours of rising and falling flow as determined with each pair of consecutive flow values. Over a 24-hr period, the difference between rise and fall counts can range from +24 to -24. Continuous rising flows throughout a day would produce a score of +24, while all falling flows would produce a score of -24; an equal number of rising and falling counts would produce a score of 0. Over a longer period, the difference between the rise and fall counts reveals whether flows take longer to rise toward a maximum or fall toward a minimum. For example, flood flows often take longer to subside than to rise.

Table 3. Ecologically relevant hydrological indicators of change for cold-regions, including Alaska (Peters et al. 2014).



Period	Hydro-ecological variables	Example of ecological influence
Annual	Monthly median flow magnitude	Availability and temporal variability of suitable aquatic and riparian habitat
	Baseflow value	Shorter-term availability of aquatic and riparian habitat during low-flow period
	Mean 90-day minimum flow magnitude	Seasonal low flows affect availability of aquatic and riparian habitat
	Mean 90-day maximum flow magnitude	Seasonal high flows influences availability of aquatic and riparian habitat
	Rise rate	Stress and habitat recovery relating to rising water levels
	Fall rate	Stress and habitat recovery relating to falling water levels
	Number of hydrograph reversals	Habitat availability and connectivity relating to overall water level variability
	Number of low pulses/year	Occurrence of potentially stressful low-flow conditions
	Median duration of low pulses within each year	Duration of potentially stressful low-flow conditions
	Number of high pulses/year	Occurrence of potentially stressful high-flow conditions
	Median duration of high pulses within each year	Duration of potentially stressful high-flow conditions
	Number of zero-flow days within each year	Extreme loss of aquatic habitat availability and connectivity
	Spring freshet initiation date	Freshet represents the primary driving annual hydrological event for most systems
	Flow magnitude on day of freshet initiation	Represents flows that structuring aquatic habitat availability and channel morphology through substrate scour and ice jam-associated flooding
Open water	1-day minimum open-water flow magnitude	Short-term extreme low-flow conditions affect habitat availability
	Date of 1-day minimum open-water flow	Timing of short-term extreme low-flow conditions can influence aquatic spawning
	1-day maximum open-water flow magnitude	Short-term extreme high-flow conditions affects availability and connectivity of habitat
	Date of 1-day maximum open-water flow	Timing of short-term extreme high-flow conditions can influence ecological processes cued to water availability
	Duration of open-water period	Critical for photosynthetic production and oxygenation in aquatic systems
Ice influenced	Date of freeze-up	Timing of winter ice formation can reduce habitat availability and alter distribution
	Magnitude of flow at freeze-up	Magnitude of flow at time of freeze-up can be directly related to loss of shallow water habitat and reduction in the dilution of contaminants
	Date of break-up	Timing related to habitat availability and cues for spawning
	Magnitude of flow at break-up	Magnitude related to ecological processes
	Duration of ice-influenced period	Duration of under ice conditions including effects of solar radiation, thermal regime change and oxygen levels
	1-day minimum ice-influenced flow magnitude	Availability of habitat and stressful conditions for aquatic taxa relating to ice conditions
	Date of 1-day ice-influenced minimum flow	Timing of winter low flows related to habitat availability
	1-day maximum ice-influenced flow magnitude	Availability of habitat and stressful conditions for aquatic taxa relating to ice conditions
	Date of 1-day ice-influenced maximum flow	Timing of winter low flows related to habitat availability
	Peak water level during ice-influenced period	Related to habitat availability, especially channel connectivity
	Date of peak water level during ice-influenced period	Timing important for connectivity
	Flow magnitude on day of ice-influenced peak water level	Related to habitat availability, especially channel connectivity