PRELIMINARY FRAMEWORK FOR ECOLOGICAL RISK ASSESSMENT OF LARGE-SCALE HYDROPOWER ON BRAIDED RIVERS IN ALASKA: PHASE 1

Prepared for

The Nature Conservancy

Prepared by

Anchor QEA, LLC

June 2015

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LIST OF ACRONYMS AND ABBREVIATIONS

AEA	Alaska Energy Authority
ARLIS	Alaska Resources Library and Information Services
cfs	cubic feet per second
ERA	Ecological Risk Assessment
FERC	Federal Energy Regulatory Commission
FWMT	Fresh Water Management Tool
MWh	megawatt hours
NGO	non-governmental organization
PAD	Pre-Application Document
Project	Susitna-Watana Hydropower Project
RM	river mile
TNC	The Nature Conservancy
USEPA	U.S. Environmental Protection Agency

1 INTRODUCTION

This Phase 1 report establishes the Problem Formulation component of the Ecological Risk Assessment (ERA) and includes three primary components: 1) a literature review and summary of best available information; 2) key ecological attributes and preliminary characterization of risk factors; and 3) a preliminary characterization of ecological effects. The Problem Formulation is the foundation for subsequent Analyses and Risk Characterization steps of a final ERA. The analyses and risk characterization steps would be the focus of a Phase 2 report.

1.1 Purpose

The goal of this ERA is to characterize risks to wild salmon based on expected activities from large-scale hydropower projects and their effects on habitat attributes required by salmon. When completed, the analysis of specific risks can be used by The Nature Conservancy (TNC) to: 1) develop salmon-friendly criteria for avoidance, minimization, and mitigation of risks to wild salmon systems for large-scale hydropower; 2) comment on study plans and results of a large-scale hydropower project; and 3) contribute to the public discussion and decisions about how to balance the benefits of large-scale hydropower and the risks to wild salmon. The proposed Susitna-Watana Hydropower Project (Project) offers a specific example for characterizing ecological effects and analyzing risk.

The scale of a hydropower dam like the proposed Project and its potential risks reflect a complex interaction between physical, chemical, and biological processes that affect all life stages and life histories of the five anadromous salmon species. One of the challenges of this ERA is to depict individual risks in a manner that is straightforward but does not understate the potential complexity of a hydropower project or its potential effects. Balancing complexity with clarity is one of the key goals and, if successful, will set the stage for subsequent analyses in a context that remains useful and accessible to a potentially broad audience. More specifically, the choice of how risks are portrayed represents a prioritization of potential interactions and the desire to communicate them effectively.

The approach used in this document attempts to balance complexity and utility through the use of a conceptual model and "dashboard" illustrations of process pathways to generate specific risk profiles for each identified risk. In this sense, the risks are imbedded in the conceptual model and can be examined structurally on an individual basis to examine the integrity of their underlying logic. The treatment of each risk in the same profile template is also important for clearly explaining differences between each risk and the endpoint of subsequent risk analysis. More specifically, the risk profile for a specific risk should clearly identify what is at risk and the process pathway to the endpoint. Where the process and endpoints are clear, hypotheses can be developed for analyses of individual risks.

One of the other primary means to achieve this balance is to solicit input from highly qualified external reviewers. Their input will improve the structure and technical credibility of the ERA to ensure the veracity of its conclusions

1.2 Methodology

The ERA methodology are based on the general ERA framework and approach used by the U.S. Environmental Protection Agency (USEPA) and other recent ERAs conducted in the region. Using USEPA's template (USEPA 1998), the three primary ERA process steps are, sequentially: 1) problem formulation; 2) analysis; and 3) risk characterization. These steps will be conducted in a phased approach (Figure 1) and the reports generated at each phase will be subject to review by an external science panel. The ERA will use population endpoints (see Section 1.3) for considering risks to salmon.

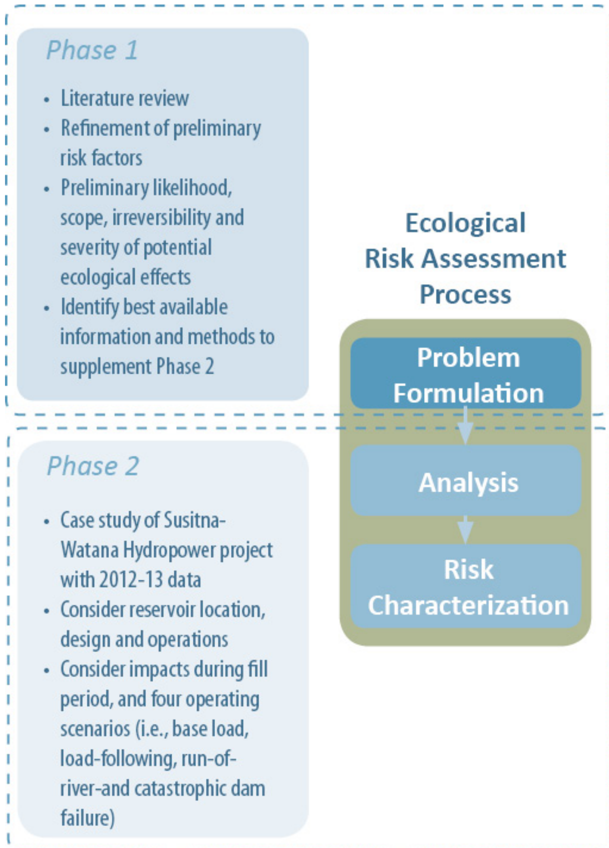


Figure 1
Phases 1 and 2 Contributions to the
Conceptual ERA Model for the Proposed Project

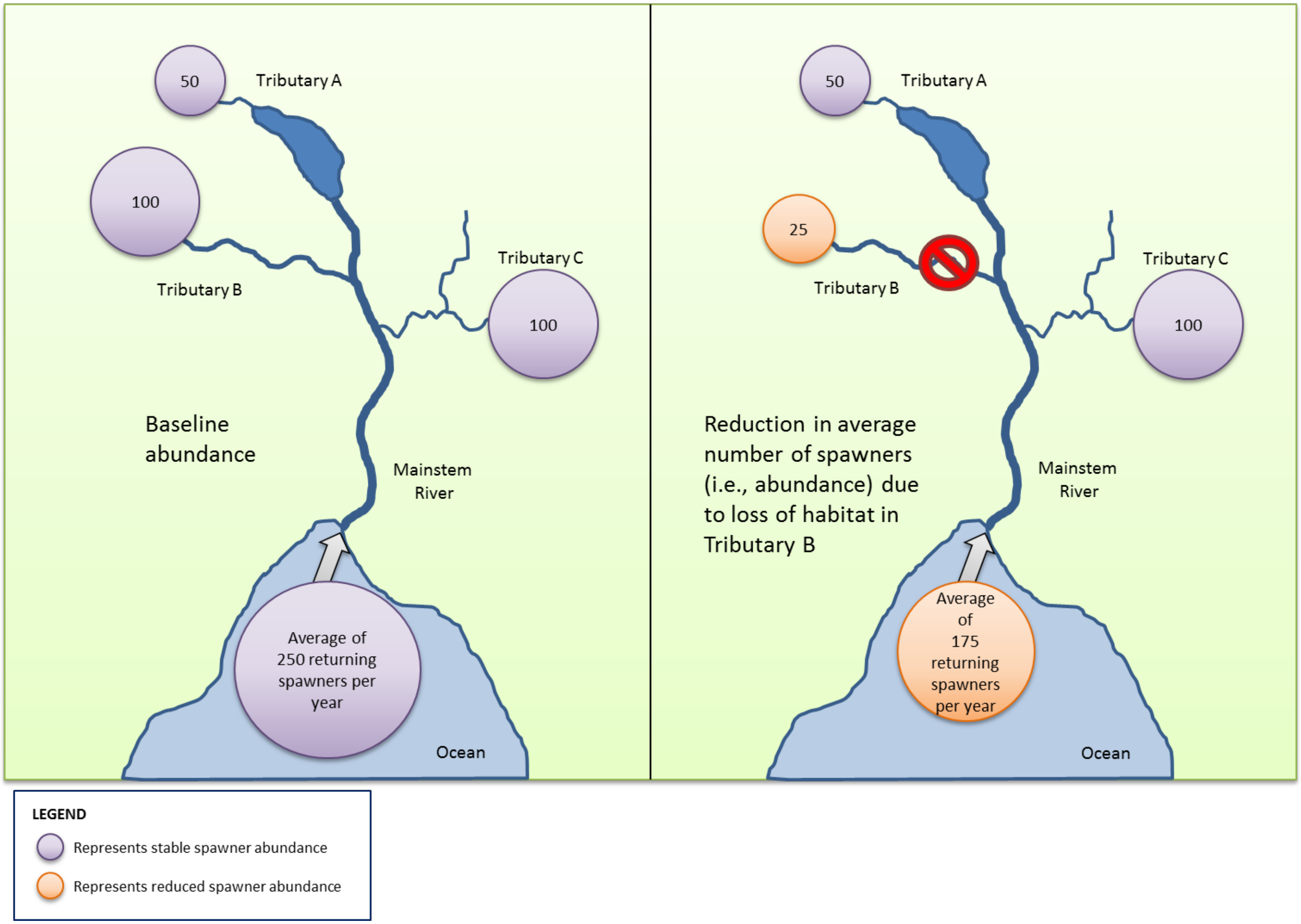
1.3 Importance of Population Endpoints

In evaluating large-scale project effects on salmon populations it is important to understand the population-level impact the project may have. The definition of a population is an important starting point for the ERA and we rely on information and concepts from *Viable Salmonid Populations and the Recovery of Evolutionarily Significant Units* (McElhany et al. 2000). Specifically, a population is defined as collection of one or more local breeding units whose population dynamics or extinction risk over a 100-year time period is not substantially altered by exchanges of individuals with other populations. McElhany et al. (2000) also note that independent populations are likely to inhabit geographic ranges on the scale of an entire river basin or major sub-basins, which suggests geographic congruence and relevancy with the scale of potential impacts contemplated for the Project. It is expected that specific population structures and boundaries for each species would be fully delineated with the completion of proposed Project-related studies.

The endpoint of a salmon-focused ERA should examine what impact, if any, a proposed action may have on the sustainability and resiliency of affected populations. In this ERA, we consider the population-level effects of the proposed Project on Pacific salmon through the use of four underlying population parameters that can be evaluated at different levels of resolution: 1) abundance; 2) productivity; 3) spatial structure; and 4) diversity (McElhany et al. 2000). These parameters also provide a logical endpoint for a risk analysis because they represent general attributes that are important to all populations and all species, they are measurable (McElhany et al. 2000), and they represent familiar metrics within the salmon conservation world and have recognized, yet flexible, utility as 'endpoints' for the evaluation of hydroproject impacts (Busch et al. 2008). In the context of our assessment, the parameters are defined as detailed in Sections 1.2.1 through 1.2.4 (based on McElhany et al. 2000).

1.3.1 Abundance

Abundance refers to the size of the population. A population should be large enough survive expected environmental variation, maintain genetic diversity, and continue to provide ecological feedback (McElhany et al. 2000). A key metric of abundance is the number of returning spawners, also known as "escapement." A hypothetical reduction in population abundance is presented in Figure 2.



Note: Reduction in average number of spawners (i.e., abundance), over a period of time, due to loss of habitat in Tributary B.

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Figure 2
Depiction of Hypothetical Change in the Abundance of a Population within a Watershed
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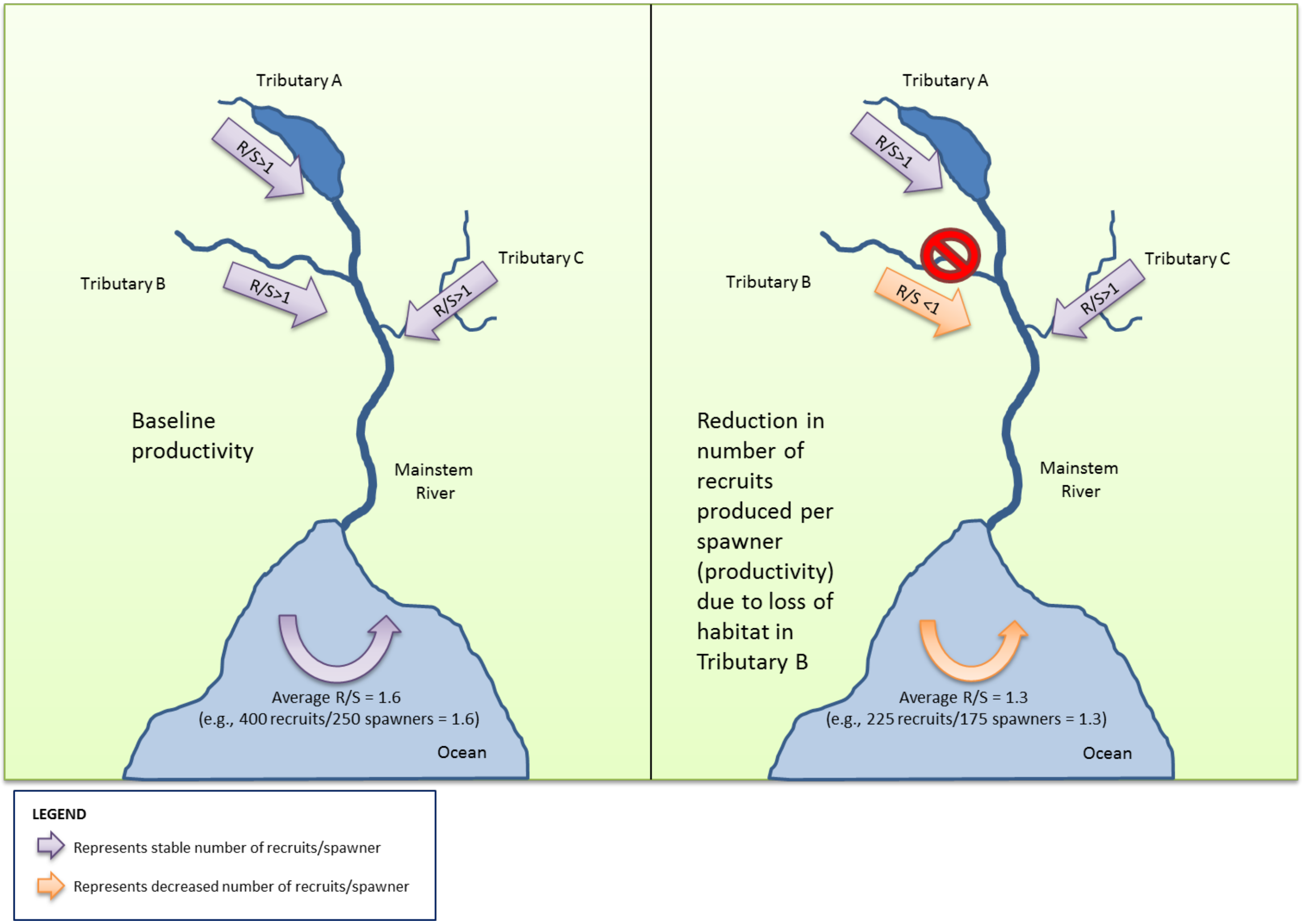
1.3.2 Productivity

Productivity refers to the growth of a population. This can be viewed simply as a population's ability to replace itself under normal conditions and potentially grow if abundance declines (McElhany et al. 2000). In the field of salmon management, a common metric for population growth is "recruits/spawner," which refers to the number of returning offspring (i.e., recruits) divided by the number of their parental spawners. For example, if ten spawners produced ten returning offspring, then replacement has occurred (i.e., 10 recruits/10 spawners =1). A hypothetical reduction in population productivity is presented in Figure 3.



Note: Individual straight arrows represent recruits/spawner (R/S) in individual tributaries, and the curved arrows represent the population-level cycle of R/S over time. Reduction in R/S (productivity) due to loss of habitat in Tributary B reduces the overall productivity of the population, which in this case still remains above replacement.

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Figure 3
Depiction of Hypothetical Change in the Productivity of a Population within a Watershed
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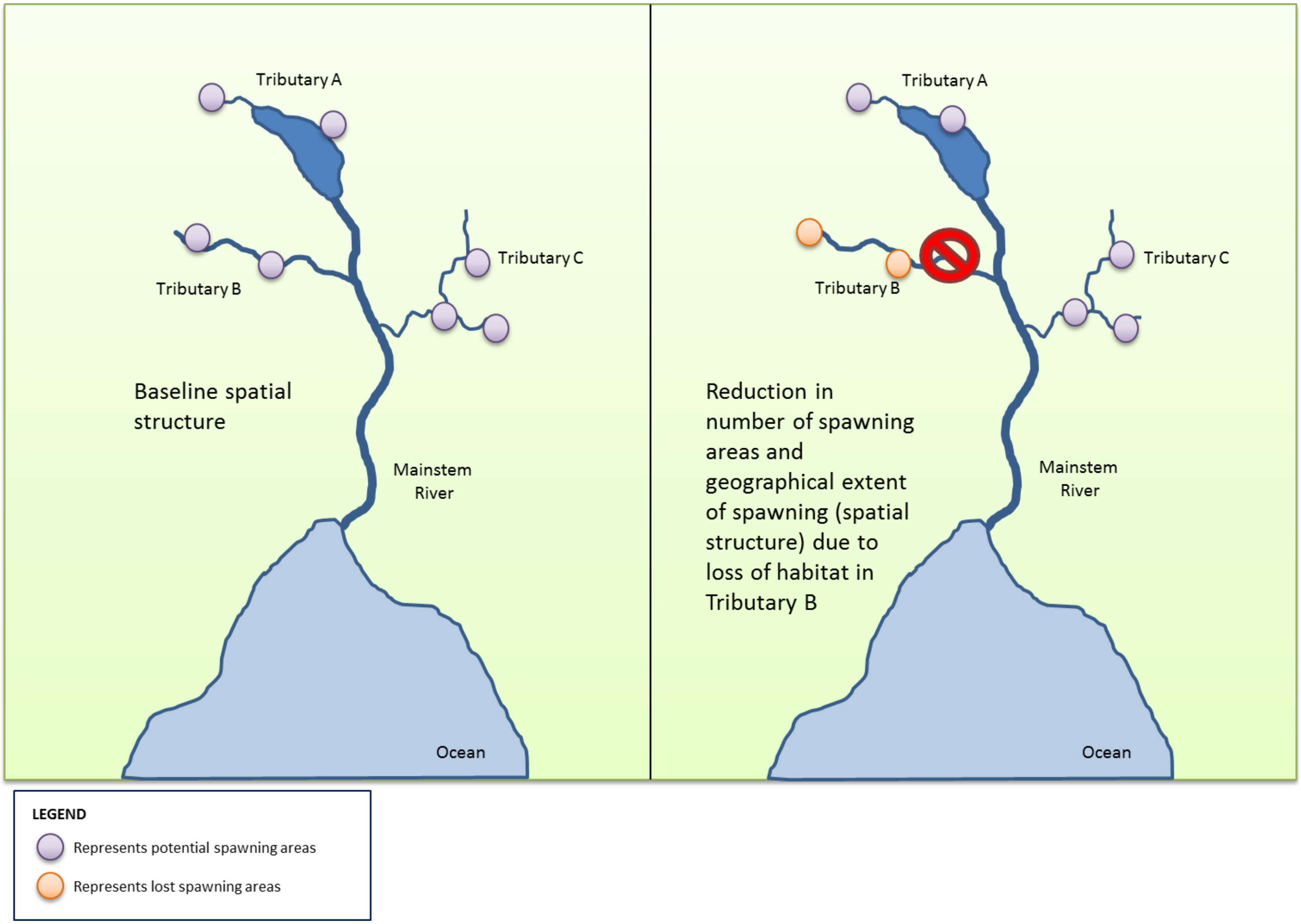
1.3.3 Spatial Structure

Spatial structure refers to the geographic distribution of a population and the factors that generate the distribution. Spatially structured populations are often generically referred to as "metapopulations." A population's spatial structure depends fundamentally on habitat quality, spatial configuration, and dynamics as well as the dispersal characteristics of individuals in the population (McElhany et al. 2000). Spatial structure is often measured in terms of stray rates between and among subpopulations (i.e., reproductive isolation) and the geographic distribution of spawners or spawning habitats that form discrete spawning areas. A hypothetical reduction in population spatial structure is presented in Figure 4.



Note: Reduction in number of spawning areas and geographical extent of spawning (spatial structure) due to loss of habitat in Tributary B. If these tributaries had equal sized populations, the reduction in spatial structure would represent about a third of the available habitat. To fully evaluate the significance of this loss it would be important to understand potential mechanisms of recolonization and interactions among tributaries (i.e., straying rates among tributaries and relative isolation of each population).

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Figure 4

Depiction of Hypothetical Change in the Spatial Structure of a Population within a Watershed
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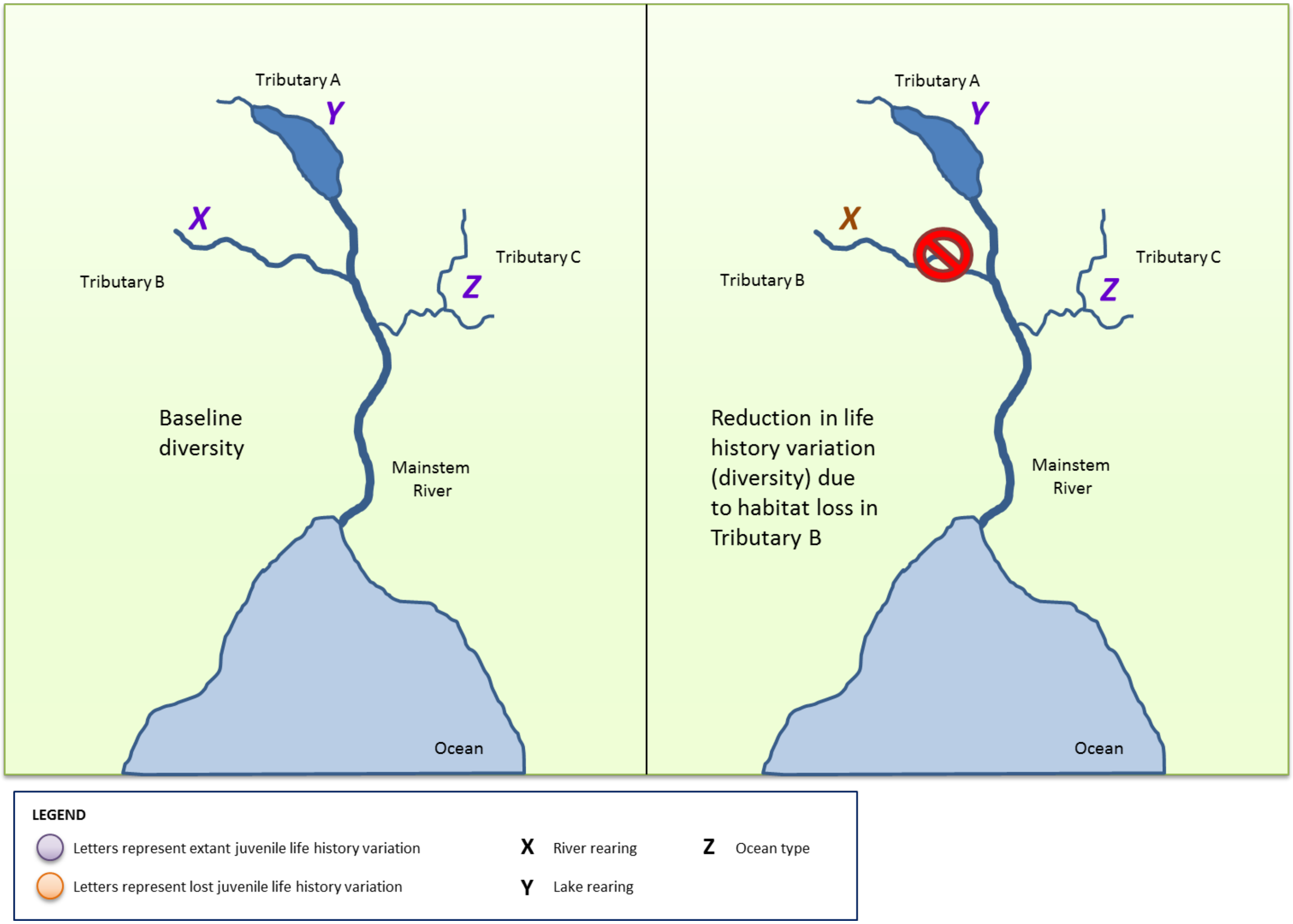
1.3.4 Diversity

Diversity refers to the genetic, morphological, and life history traits that exists within a population. These traits may include variation in anadromy, morphology, fecundity, run timing, spawn timing, juvenile behavior, age at smolting, age at maturity, egg size, developmental rate, ocean distribution patterns, male and female spawning behavior, physiology, and molecular genetic characteristics (McElhany et al. 2000). Measuring population diversity requires documenting variability in morphological and life history traits and ideally, examining the environmental or genetic basis for expression of the trait. A hypothetical reduction in population diversity is presented in Figure 5.



Note: Reduction in life history variation (diversity) due to habitat loss in Tributary B. This example reflects how the loss of abundance or spatial structure can be compounded if the lost habitat also supports unique life history attributes. Diversity interacts with the other parameters and reflects one of the primary sources of resiliency in a population, namely a source of portfolio diversification. If one tributary experiences a decline, the life history variation in the others provides a safety net.

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Figure 5
Depiction of Hypothetical Change in the Diversity of a Population within a Watershed
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1.3.5 Relevance of Population Parameters

These population parameters are important indicators of the health and sustainability of a population and provide a framework to interpret direct and indirect habitat effects. The examples in Figures 2 through 5 depict how these parameters could be affected by a generic habitat degradation event. Alternatively, each parameter could be enhanced by activities that increase habitat complexity or processes that improve habitat functionality. In short, the goal is not specifically to document population declines, but instead *changes*, either positive or negative.

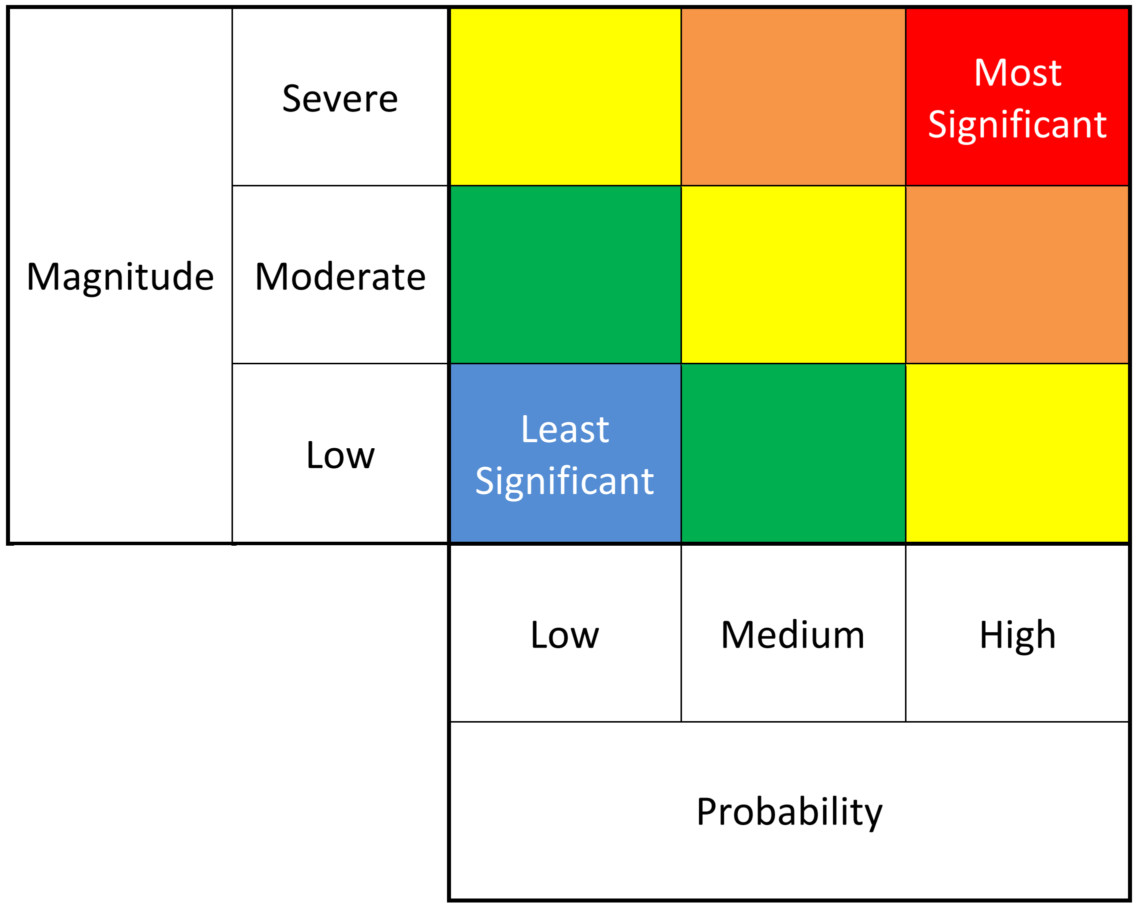
The evaluation of population-level effects complements the evaluation of specific habitat effects. The linkage between population parameters and specific habitat attributes is generally hierarchical where habitat processes can be viewed as governing the sustainability of populations by influencing each population parameter. This relationship is the basis for the evolution of locally adapted populations and explains both the success and inability of salmon to exist in habitats that have undergone significant changes (Waples et al. 2009, 2008a). Where population abundance is high, productivity is at or above replacement, populations are widely dispersed, and multiple life histories are prevalent, salmon are resilient to habitat alteration and have the requisite population-scale attributes to adapt, evolve, and colonize new habitats (Hilborn et al. 2003; Schindler et al. 2010). If these reinforcing parameters are diminished, the resiliency and adaptive capacity of a population is reduced and its response to habitat disturbance is limited. Salmon are extremely resilient to short-term perturbations in habitat quality, but have also declined substantially in areas where habitat loss is persistent or permanent (Healey 2009; Waples et al. 2008a). For these reasons, population-level endpoints (i.e., abundance, productivity, spatial structure, and diversity parameters) are useful in considering the risks posed by projects that cause large-scale, long-term habitat modification.

This leads to the central question of the risk of a large hydroproject: will the habitat changes caused by the development of a large-scale hydropower facility fundamentally alter the populations of salmon to the extent that their abundance, productivity, spatial structure, or diversity are negatively affected and reduce their long-term resiliency and sustainability?

1.4 Considerations of Risk and Uncertainty

Characterization of risk involves the examination of the possibility of loss or benefit to something of value that results from a definable action or activity. In this case, the valued items are salmon populations. This is not meant to discount any other financial or societal considerations that may accrue from a large hydroproject, but instead narrow the focus of this ERA to one specific resource.

The depiction of risk usually incorporates at least two components: 1) probability of occurrence; and 2) magnitude of loss or benefit. The definition of severity is contextual, but if an activity has a high probability of causing a major loss it would generally be considered to be a more significant risk than an activity with a low probability of causing a minor loss (Figure 6).



Note: Warmer colors represent more significant risks; cooler colors represent less significant risks.

Figure 6
Depiction of Interaction between the Magnitude and Probability of a Risk Using a “Heat Map”
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In our analysis of the Project as an example of a large-scale hydroproject, we have defined the focal resource (i.e., salmon) and the scale for evaluating the severity of a risk (i.e., population-level). A subsequent Phase 2 report would estimate the probability and magnitude of population-level effects that could result from the Project in order to predict the severity of risk to salmon populations.

The accuracy of a risk assessment is influenced by many factors including the availability of relevant data, quality of analytical tools, and temporal proximity of the occurrence of an event under consideration. These and other factors contribute to the "uncertainty" of a prediction and represent a third component of the risk probability-and-magnitude landscape: uncertainty increases the range of potential risk probabilities and range of magnitude of impacts.

The use of weather forecasting to evaluate the risk of storm damage provides some useful parallels to demonstrate how uncertainty enters the risk equation. In many locations, multiple forecast models are used to predict weather events. When a storm is distant (e.g., arbitrarily 5 days away), the forecasting models may suggest different interpretations of intensity and landfall location. As a result, the long-term forecast may provide high uncertainty in both the probability and magnitude of expected damage. As the storm nears, model resolution is improved as the forecasting algorithms are provided with additional data and the intensity and trajectory of the event are corrected. When the storm is very close (i.e., 24 hours from arrival), there is much less uncertainty about either the magnitude or probability of potential damage (Figure 7).

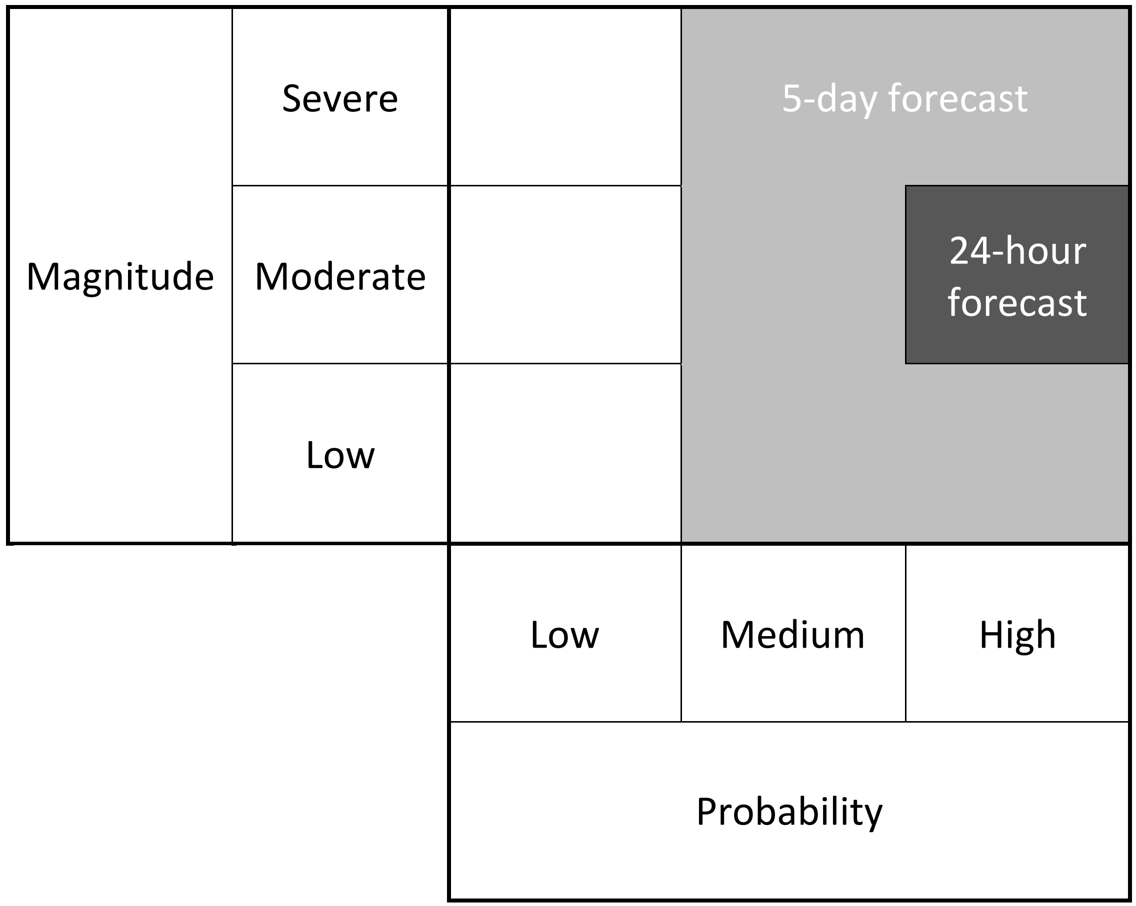

Figure 7
Hypothetical Forecasting Example Illustrating How Uncertainty Influences the Probability and Magnitude of Risk
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The interaction among probability, magnitude of impact, and uncertainty is an important consideration for risk management. Ultimately, these factors form the basis for accepting a risk or developing tactics to minimize risk exposure.

In the context of Phase 1 of the ERA, it is recognized that not all data are currently available to fully assess the probability or magnitude of risks to potentially affected salmon populations. It is expected that the Project proponent, in this case The Alaska Energy Authority (AEA), would conduct a number of studies (e.g., AEA 2013a) to generate data and results to improve the resolution of the final analysis and risk characterization for Phase 2 of the ERA. In order to effectively reduce this uncertainty and fully assess impacts, studies should be carried out on temporal and spatial scales that are relevant to salmon life cycles. A suggested approach is described in Section 6.

2 IDENTIFICATION OF PROJECT RISKS

In the context of Phase 1 of the ERA, we examined the risks posed by the Project to salmon populations by first identifying those specific proposed activities and processes that could affect salmon and their habitat. This initial step considered criteria provided by TNC as well as information contained in AEA project descriptions, studies associated with the Project, the Federal Energy Regulatory Commission (FERC) licensing process, and external literature. The intent is that the approach and results of this risk analysis would be applicable to proposed dams on other Alaskan rivers.

This section is organized sequentially to first provide an introduction to the proposed Project itself and then a description of the review process that was used to formulate individual risk profiles. The final portion of the section depicts the individual risks that will be considered in the ERA.

2.1 Project Description

The first step in identifying specific Project risks for the ERA was reviewing the Project description. The activities considered were primarily derived from the *Pre-Application Document* (PAD) provided by the AEA (2011) and *Scoping Document 2* provided by FERC (2012). These documents contain detailed information on the scope of the proposed Project as it pertains to FERC licensing. The descriptions below are intended to familiarize readers with the Project but are not intended to represent the entire depth or breadth of what is proposed. More comprehensive descriptions can be found in the documents cited above and from AEA directly (http://www.susitna-watanahydro.org/).

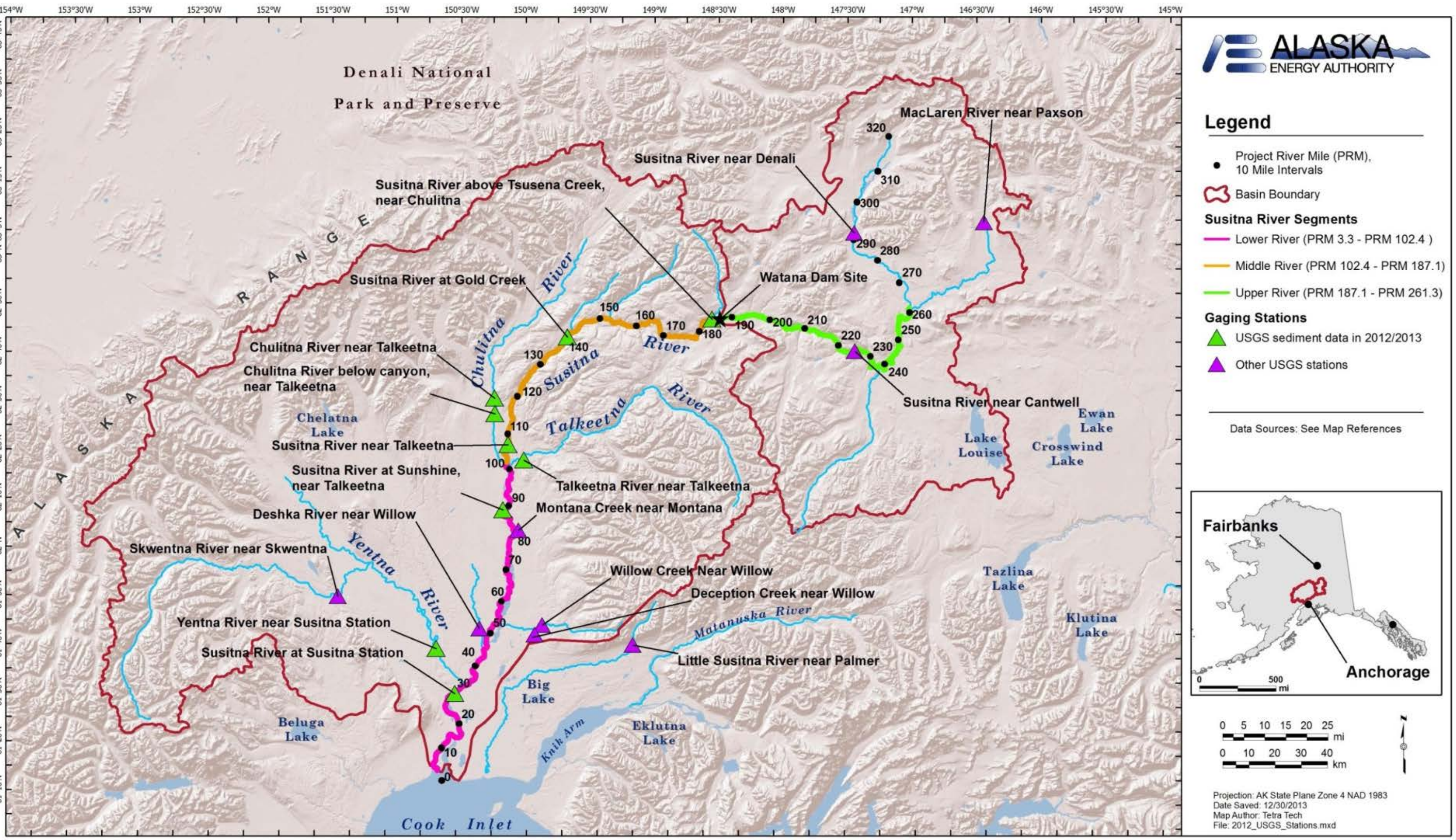
2.1.1 Overview

The general project summary below and map of the project area (Figure 8) are excerpted from *Scoping Document 2* (FERC 2012):

> *The proposed project is located in the Matanuska-Susitna Borough on the Susitna River at river mile 184 above the river mouth, approximately halfway between Anchorage and Fairbanks, Alaska. The small, unincorporated Native village of Cantwell, in the Denali Borough, is located about 45 air miles west of the proposed project dam, while Anchorage is approximately 180 air miles generally south of the*

project area. The project would occupy federal lands currently administered by the U.S. Bureau of Land Management (BLM) but selected by the State of Alaska under the Alaska Statehood Act, state lands administered by the Alaska Department of Natural Resources, and private lands owned by Alaska Native Corporations and others.

The proposed project would consist of a 700- to 800-foot-high by about 2,700 foot-long, concrete gravity or rock-filled dam that would create an approximately 39-mile-long reservoir with a surface area of 20,000 acres and 2,400,000 acre-feet of usable storage capacity. Optimization studies are ongoing, but the capacity of the project is expected to be between 600 and 800 megawatts (MW) depending on results of future updates to the Railbelt Integrated Resource Plan. An approximately 40- to 50-mile-long road and transmission line corridor would be constructed along one of three alternative routes (i.e., Chulitna, Gold Creek, or Denali). The project would be operated in a load following mode such that firm power is maximized during the critical winter months of November through April to meet the Railbelt utility load requirements. The estimated annual generation would be 2,500,000 gigawatt-hours (GWh). A detailed description of the project is provided in section 3.0.



Source: Tetra Tech and Watershed GeoDynamics 2014

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Figure 8
Susitna-Watana Project Area
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2.1.2 Project Schedule

The AEA proposed the following construction and development timeline for the Project, had sufficient state funding been made available for studies (AEA 2011):

- Total schedule – 12 years
- Pre-application studies and related activities – 3.5 years
- FERC and cooperating agencies post-filing activities – approximately 1.5 years
- Project construction – 6.5 years
- Reservoir filling – 1 to 2 years
- Site restoration – throughout construction

2.1.3 Proposed Operations

The AEA has provided a preliminary description of operations for the Project (AEA 2011):

> *During the preparation of this document computer modeling of several potential reservoir operation scenarios has been performed using the preliminary (Base Case) Project configuration as described above in Section 3.3. It is planned that the Project would be operated in a load following mode such that firm power is maximized during the critical winter months of November through April each year to meet Railbelt utility load requirements. To accomplish this, the reservoir would be drafted annually by an average of about 120 ft; the maximum annual drawdown would be approximately 150 ft, with a probability of occurring about once or twice in 50 years. Flow discharges through the powerhouse under this operating plan would range from a low of zero cfs* [cubic feet per second] *when the power plant is off line on rare occasions during emergency outages, to a high of about 14,500 cfs during times of maximum power generation. When the power plant is not discharging, instream flow releases would be made through a low-level outlet works in Watana dam.*
>
> *Daily power generation during the peak winter months would average about 6,000 MWh* [megawatt hours] *and powerhouse discharges would average approximately 6,700 cfs during that time. For load following, powerhouse discharges would vary over a 24-hour period in the winter months, typically ranging from a low of 3,000 cfs to a high of 10,000 cfs. For the Base Case operating plan, initial operation model runs have been made using the Case E-VI minimum instream flow criteria developed*

during the 1980s APA Susitna Hydroelectric Project studies. Those criteria specified a minimum wintertime flow release of 2,000 cfs and a minimum summertime flow release of about 9,000 cfs. Environmental studies will guide the daily range of flow variation permitted.

2.2 Project Assumptions and Uncertainties

At the time this report was written, there were a number of key Project attributes that were not fully described but would likely influence Pacific salmon directly or through habitat modifications. If the Project is pursued, AEA would conduct a number of studies that are anticipated to generate data and results that will reduce this uncertainty and improve the resolution of the final analysis and risk characterization for Phase 2 of the ERA. The Project attributes discussed in Sections 2.2.1 through 2.2.8 remain unclear or require significant assumptions in order to consider risks to salmon species.

2.2.1 Anticipated Project Operations

The entire suite of fluvial processes and potential risks to salmon downstream of the Project will be dependent on how the Project is expected to be operated. Operational descriptions contained in available FERC documents and AEA reports are portrayed as load-following, but the expected intensity of flow regulation is not specific enough to evaluate any scenario other than Maximum Load Following OS-1 (see Section 2.3). It is understood that the OS-1 scenario represents the maximum intensity of flow regulation, but it is not clear what the most likely level of flow regulation will be. It is assumed that AEA will model a number of operational scenarios that contemplate flow requirements for fish.

2.2.2 Upstream Passage

A passage feasibility study is underway but there is no existing proposal to provide upstream passage, so it is assumed that adult passage above the Project will not occur.

2.2.3 Downstream Passage

A study evaluating the future reservoir fish community and risk of entrainment is underway, but there are no proposed plans or measures that would provide downstream passage. It is assumed that juvenile passage or survival standards for out-migrating juveniles will not be provided at the Project location.

2.2.4 Lower River Effects

Project studies note that some habitat impacts associated with Project operations will attenuate across a downstream gradient and the most significant effects will occur in the middle river reach (Figure 2). Focusing on the most intense areas of habitat alteration is logical, but should not displace attention on the lower river. Changes to flow regimes and sediment supplies will cause a cascade of habitat effects that may take decades to reach a state of dynamic equilibrium following construction. It will be important to develop long-term predictions across the river continuum, including the lower river, to develop rigorous, comprehensive estimates of Project impacts to salmon.

2.2.5 Duration and Intensity of Construction and Initial Inundation

Similar to Project operations, the level of detail provided for interpreting effects of construction and initial inundation is low. A high resolution description addressing the stepwise progression of each activity is required to fully interpret the effects on salmon and interpret the risks posed. It has been assumed that the construction timeline will be followed. As such, effects of construction and initial inundation have been categorized as "temporary" because their duration would be less than 10 years, and the effect of these activities are considered independent of the existence of the Project (which is permanent). The assumption will be revisited when additional Project details are available.

2.2.6 Mitigation

There is currently no mitigation plan proposed for the Project. It is expected that as Project operations become more clear, so will the potential effects to habitat and the relevancy of, or necessity for, mitigation. In the absence of a mitigation proposal, the ERA assumes no beneficial effects from compensation for losses of fish or habitat availability, quality, or function.

2.2.7 *The Determination of Population Level Impacts to Affected Salmon Species*

The Project-related fisheries studies do not specifically address population-level impacts to affected salmon species. Given the large size of the watershed, abundance and diversity of salmon habitats, and the considerable modification of habitats that may result from the Project, multiple salmon population units will be affected for some or all species.

The current Project-related studies provide connections between habitat effects on individual species and different geographic study reaches but these are not nested for consideration within an explicit population-level framework for any salmon species. It remains unclear how the studies examining specific Project effects will be used to quantify impacts to salmon populations or if the ongoing analyses are being conducted at the correct resolution to predict effects to specific population units. This type of analysis would first require the delineation of existing population structure data and then consideration of how the Project affects each component. The designation of a population unit is typically performed by fisheries managers after consideration of genetic and other biological and ecological data. In other locations where salmon conservation drives analyses of project impacts (including hydroelectric dams), the affected population unit or "conservation unit" is defined, and specific population parameters are used as the endpoint of effect analyses (e.g., abundance, productivity, spatial structure, and diversity) and to provide a framework for interpreting effects and risks.

If different populations or contributing subpopulations are present within the basin, the diversity among these groups may be important to preserve in order to maintain sustainable productivity within the Susitna River. While the population structure data may exist (e.g., management studies conducted by state or federal agencies), or will be collected in the course of Project studies, they have not been discussed in relation to Project effects. In areas where salmon are abundant and resilient to large-scale declines (e.g., Bristol Bay sockeye salmon), their stability is supported by multiple population units, which provide the necessary diversity to maintain overall abundance and productivity when environmental changes or other perturbations decrease the contribution of any individual population component (e.g., Schindler et al. 2010). The understanding of a species population structure is a key component to the maintenance of its existence as well as understanding the significance of specific Project impacts.

2.2.8 Level of Precision

The Project-related fisheries studies do not articulate a standard for the level of precision expected or required for "valid" estimates of habitat effects or direct Project effects on fish populations. If there is no standard, it will be important to understand the observed precision of the studies that were conducted and develop appropriate confidence intervals for the results. In general, when a specific parameter is estimated using a very small sample size (e.g., using a small number of sample years to characterize the mean annual abundance of salmon), the estimate may be accompanied by a high standard error and low precision, which translates into an unreliable estimate. Predicting future effects using low precision estimates will not meaningfully reduce the uncertainty surrounding potential risks to Pacific salmon.

2.3 Categorization of Project Activities

Based upon criteria supplied by TNC and the review of the Project descriptions, we identified four broad Project activity categories: 1) construction, which includes staging for and building the Project as well as filling the reservoir, but is independent of operations or the presence of the Project; 2) operations, which includes flow control for generation and reservoir operations; 3) the presence of the Project itself, which considers the ongoing existence of the dam independent of operations; and 4) a hypothetical catastrophic failure scenario (e.g., resulting from a seismic event).

We also sorted each activity into subcategories based on the expected duration of the activity (i.e., short-term or long-term) and the persistence of its effects (transient, dynamic, and permanent). Short-term activities include those that will be completed in less than 10 years (e.g., 1 to 3 salmon generations) and long-term refers to those taking 10 years or longer to complete (multiple salmon generations). For persistence of impact, categories are defined as follows: 1) *transient* impacts attenuate after conclusion of activity; 2) *dynamic* impacts continue for the duration of an activity but fluctuate in intensity; and 3) *permanent* impacts are temporally stable.

Table 1

Categorization of Project Activities by the Duration of Activity and Persistence of Impact

Activity	Activity Duration/Persistence of Impact
Construction	Short-term/transient
Operations	Long-term/dynamic
Catastrophic Failure	Short-term/transient
Presence of Project	Long-term/permanent

The initial duration/persistence categorization is an important step in isolating the specific risks to salmon populations because the propagation of a risk from an activity to a salmon population parameter endpoint is dependent upon the number of generations that are affected. As described above, healthy populations are resilient to short-term disturbances (i.e., few generations affected) because there are abundant recruits and habitat to recolonize. On an annual basis, each spawning cohort produces a diversity of different age classes that serve as a hedge against risks that may appear in future years; that is, the loss of a single age class does not represent the loss of the entire population. However, long-term disturbances (e.g., multiple generations) or permanent habitat alterations reduce the resiliency of a population because the number of recruits and amount of habitat to recolonize is reduced. More specifically, the temporal scale of the disturbance exceeds the risk hedge conferred by multiple age classes of progeny, and the loss of available habitat may preclude rebounds in abundance, productivity, diversity, and spatial structure of the remaining population. In general, short-term activities with transient impacts represent a lesser risk than long-term activities with dynamic or permanent impacts. Overall, the most complicated risk scenarios are related to the operation of the Project as these are both long-term and dynamic. These operational scenarios represent the primary area of emphasis for the ERA.

Within the operations category, we will also examine three power generating scenarios: load following (i.e., Maximum Load Following OS-1; proposed scenario), base load (hypothetical), and run-of-the river (hypothetical). Load following provides the capacity of power generation to meet base and peak electrical demands. This requires the capability to store energy and release it based on a fluctuating demand curve. In this case, the energy is stored in the reservoir as potential energy and released through turbines, which turn generators and subsequently transform the potential energy to electricity. The amount of potential energy available at any given time is proportional to height of the dam (head), and the supply is based on the size of the reservoir.

Base load refers to a power generation scenario where electricity is supplied to meet the *minimum* day-to-day needs of customers, whereas load following has greater capacity to meet *peak* energy demands. Under base load conditions, power production above the base load would need to be provided by "peaking" facilities (at other locations), which would provide reserve power generation capacity. A base load facility would be designed to meet a specific desired power generation capacity, ostensibly lower than that of a load-following facility. Depending on the planned power production objectives, a base load facility could require less reservoir storage and a lower head dam than a load following facility.

Under run-of-the-river power generation, the amount of power produced is defined by the natural flow regime of the river. This scenario assumes a fundamentally different hydropower facility with a low-head dam and virtually no reservoir storage capacity. This alternative has the smallest footprint in terms of head and reservoir storage capacity.

In Phase 1 of this ERA we will focus primarily on the load following proposal, but all three alternatives will be discussed with respect to how their potential impacts may differ. In Phase 2, the alternatives' operations will be analyzed in more detail.

In summary, the Project activities included in this ERA are those that are likely to interact with salmon and their habitats. The categories of activities are also intended to help isolate and partition risk, so that alternative scenarios can be evaluated (e.g., multiple operational scenarios). It is important to note that while the categorical designations are intended to explicitly isolate activities for dissecting individual risks, there is a recognized interdependence among activities from a cumulative effects standpoint. For instance, the operations and presence of the Project are dependent on the construction of the Project; however, the impacts of construction, operations, and presence of the Project are individually potentially different from one another.

2.4 Review of Identified Project Effects and Determination of Habitat Controls and Response Categories

As a second step in the risk formulation process, we reviewed the AEA licensing documents, AEA directed studies, and other published literature to identify the range of anticipated direct and indirect effects to salmon and their habitats. This review was intended to help structure individual risks and connect linkages between Project activities, habitat processes, and salmon populations.

We specifically examined different ways of organizing the impacts into categories that could efficiently explain the propagation of risk within the criteria identified by TNC. We also considered different frameworks represented in peer-reviewed literature to provide a structural foundation for depicting relationships between impact categories. The approach we selected was based on *Application of a hierarchical framework for assessing environmental impacts of dam operation: Changes in streamflow, bed mobility and recruitment of riparian trees in a western North American river* (Burke et al. 2009), which effectively distilled complex habitat interactions within a hydropower context. Based on the categorization and framework review effort, we generated hierarchical groupings of activity-related impacts and an initial risk framework (Figure 9).

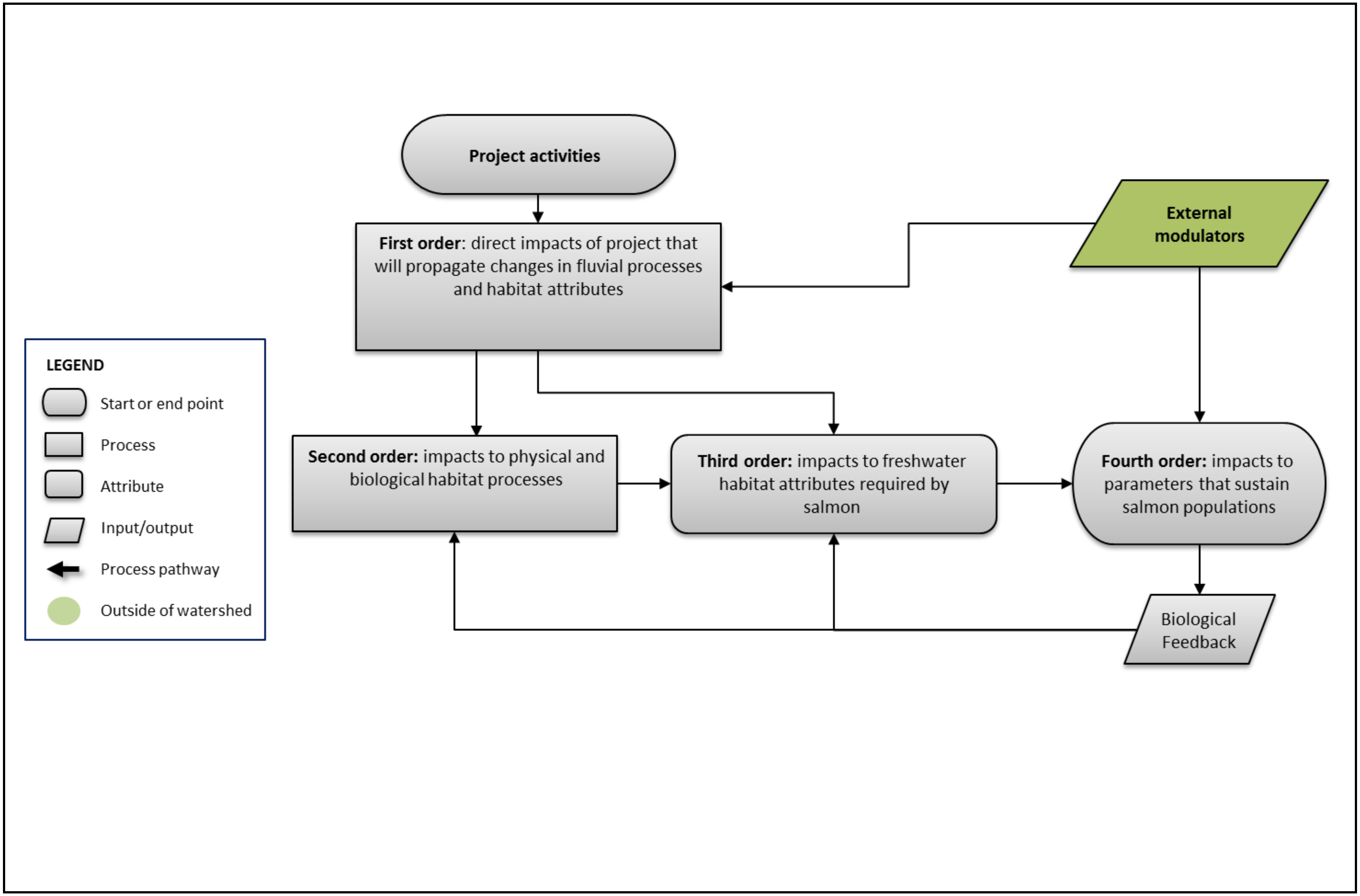

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Figure 9
Simplified Initial Risk Framework Depicting the Relationship among Project Activities and Impact Categories
Ecological Risk Assessment of Large-scale Hydropower on Braided Rivers in Alaska: Phase 1
The Nature Conservancy

First Order Impacts: This category encompasses the direct impacts to physical drivers of fluvial systems that would result from the Project. First order impacts are detectable in the immediate vicinity of the Project and are highly predictable in both scope and magnitude. Most importantly, they represent the precursors and causes of secondary ecological responses represented in subordinate impact levels, and therefore represent the "hub" of influence from which other impacts will radiate. The probability of first order impacts occurring is assumed to be 100 percent (upon construction and completion of Project). First order impacts affect: 1) flow regime; 2) water quality; 3) sediment supply; and 4) instream barrier.

Second Order Impacts: This category encompasses the habitat processes that result from first order impacts or feedback from third or fourth order impacts. Second order impacts are indirect (as opposed to first order impacts) and their intensity and propagation varies over spatial and temporal scales. Consequently, they are less predictable and understanding their probability of occurrence and magnitude requires significant analysis. Secondary impacts are highly interdependent and may not be apparent or reach a stable/dynamic equilibrium for years or decades after the Project is constructed. Second order impacts affect: 1) riparian and community succession; 2) ice formation and breakup; 3) floodplain and channel morphology; 4) surface and groundwater flow; 5) sediment erosion and deposition; and 6) nutrient and trophic cycles.

Third Order Impacts: This category encompasses the habitat attributes that are required by salmon and can be thought of as "what salmon need" while they are in freshwater. Third order impacts may be affected by first or second order impacts, as well as feedback from fourth order impacts. Each habitat attribute is potentially interdependent and each salmon species has specific requirements. Habitat attributes can be measured instantaneously and reflect "real time" habitat conditions. Over multiple generations the variability in habitat attributes is the foundation of local adaptation and governance of parameters that sustain salmon populations. Third order impacts affect: 1) water quality; 2) water quantity; 3) habitat connectivity; and 4) habitat structure.

Fourth Order Impacts: This category encompasses impacts to parameters that sustain salmon populations resulting from changes to habitat attributes. Whereas habitat attributes reflect instantaneous condition of the available habitat, the population parameters are typically lagged response metrics that reflect changes in long-term sustainability. More specifically, if a habitat attribute is not functioning or has been degraded, the detection of a response by a population may not be instantaneous. As an example, the establishment of a barrier to passage that limits access to spawning grounds may reduce the abundance of a population, but detecting this reduction requires the evaluation of recruits from the years of spawners that were affected by the barrier. In the case of Chinook salmon, this response may take more than 5 years to evaluate if spawner-to-spawner comparisons are used. For this reason, and to account for natural population variability, some population parameters are evaluated as they move along a decadal or longer scale (i.e., abundance and productivity). In other cases, the impact to a population parameter may be more immediately clear. Using the same example of a barrier to passage, the permanent truncation of available spawning habitat or elimination of a specific spawning area would immediately change the spatial structure of affected populations and could reduce life history diversity as well. Fourth order impacts affect: 1) abundance; 2) productivity; 3) spatial structure; and 4) diversity.

Biological Feedback: This pathway describes potential routes in which salmon populations themselves affect the habitat processes and attributes that create sustainable populations (i.e., influence second and third order impacts).

External Modulators: This category represents external processes or changes (i.e., not associated with the proposed Project) that have the effect of increasing or decreasing the amplitude of impacts associated with the Project or directly affect salmon populations independent of the Project. In the context of this ERA, climate change and marine productivity cycles (e.g., Pacific decadal oscillation) are primary external modulators. Other external modulators would include harvest and other sources of anthropogenic development.

2.5 Identified Risks

After evaluating Project descriptions, expected Project effects, and consulting with TNC, we developed a list of seven risk hypotheses and associated profiles to depict each risk within the initial framework. This approach attempts to balance complexity and utility through the use of "dashboard" diagrams that indicate process pathways in the profiles for each hypothesis. In this sense, each risk is imbedded in a diagram and can be examined structurally on an individual basis to examine the integrity of its underlying logic. The treatment of each risk in the same profile template is also important for clearly explaining differences between each risk and the endpoint of subsequent risk analysis. Finally, the isolation of specific risks helps to highlight important focal areas where alternative Project scenarios may exert different impacts.

2.6 Risk Hypotheses

The formulation of explicit hypotheses for each risk clarifies the relationships that are being examined between specific actions, habitat processes, and attributes. For each risk, an overarching hypothesis and nested sub-hypotheses are provided. The sub-hypotheses add more resolution to the expected route by which a risk may be propagated and are supported by related literature. All of these hypotheses should be considered as precursors to the analysis portion of the ERA, in Phase 2. More specifically, each hypothesis has yet to be rigorously evaluated within the context of the proposed Project and the literature cited does not reflect the full body of information that is expected to be available when the Project-related studies are completed.

The following hypotheses represent potential risks resulting from the Project:

1. **Presence of an Instream Barrier**
   Hypothesis: The presence of the proposed Project will create an instream barrier that will permanently affect habitat processes and attributes necessary to sustain wild salmon populations (long term/permanent; Figure 10).
   a. **Second order impacts to habitat processes:** The presence of an instream barrier will affect habitat-forming processes including riparian communities and succession (Collins et al. 2012; Jansson et al. 2000a, 2000b), ice formation and breakup (Ugedal et al. 2008), floodplain and channel morphology (Nilsson and Berggren 2000) and nutrient and trophic cycles (Freeman et al. 2003).
      i. **Third order impacts to habitat structure:** Presence of an instream barrier will alter habitat structure necessary to sustain wild salmon populations (e.g., Beechie et al. 1994; Dauble et al. 2003).
      ii. **Third order impacts to habitat connectivity**: Presence of an instream barrier will reduce habitat connectivity necessary to sustain wild salmon

populations (Beechie et al. 1994; Dauble et al. 2003; Evenden 2004; Gustafson et al. 2007; Hamilton et al. 2005; Isaak et al. 2007; Schick and Lindley 2007; Sheer and Steel 2006; Wofford et al. 2005).

2. **Changes to Flow Regime**
   Hypothesis: Long-term Project operations will dynamically alter the flow regime of the Susitna River and affect habitat processes and attributes necessary to sustain wild salmon populations (long term/dynamic; Figure 11).
   a. **Second order impacts to habitat processes**: Alteration of the Susitna River flow regime will affect habitat-forming processes including riparian communities and succession (Andersson et al. 2000; Burke et al. 2009; Engström et al. 2011; Hill et al. 1998; Jansson et al. 2000a, 2000b; Ligon et al. 1995), ice formation and breakup (Engström et al. 2011; Ettema 2002; Healy and Hicks 2007; She et al. 2012; Stickler et al. 2010), floodplain and channel morphology (Collins et al. 2012; Ligon et al. 1995; Naiman et al. 2008; Nilsson and Berggren 2000; Poff et al. 1997), surface and groundwater flow (Arntzen et al. 2006; Cushman 1985; Nilsson and Berggren 2000; Poff et al. 1997), sediment erosion and deposition (Burke et al. 2009; Finger et al. 2006; Kondolf 1997; Poff et al. 1997), and nutrient and trophic cycles (Ben-David et al. 1998; Ellis and Jones 2013; Fisher and Lavoy 1972; Pinay et al. 2002).
      i. **Third order impacts to water quality:** Changes to the flow regime will alter water quality parameters necessary to sustain salmon populations (Horne et al. 2004; Jensen 2003; Naiman et al. 2008).
      ii. **Third order impacts to water quantity:** Changes to the flow regime will alter the quantity of water necessary to sustain salmon populations (Bell et al. 2008; Enders et al. 2012, 2008; Geist et al. 2008; Korman and Campana 2009; McMichael et al. 2005).
      iii. **Third order impacts to habitat structure:** Changes to the flow regime will alter habitat structure necessary to sustain salmon populations (Hedger et al. 2013; Korman et al. 2011; Ligon et al. 1995; Linnansaari and Cunjak 2010; Marchetti and Moyle 2001; Ugedal et al. 2008).
      iv. **Third order impacts to habitat connectivity:** Changes to the flow regime will alter habitat connectivity necessary to sustain salmon populations (Bell 1985; Bradford et al. 1995; Enders et al. 2008; Naiman et al. 2008, 1999).

3. **Changes to Water Quality**

   Hypothesis: Long-term Project operations will dynamically alter the water quality of the Susitna River and affect habitat processes and attributes necessary to sustain wild salmon populations (long term/dynamic; Figure 12).

   a. **Second order impacts to habitat processes:** Alteration of Susitna River water quality will affect habitat-forming processes including ice formation and breakup (Scrimgeour et al. 1994; She et al. 2012), floodplain and channel morphology (Kondolf 1997; Owens et al. 2005), sediment erosion and deposition (Finger et al. 2006; Kondolf 1997), and nutrient and trophic cycles (Naiman et al. 1999; Nilsson and Berggren 2000; Owens et al. 2005).

      i. **Third order impacts to water quality:** Changes in water quality will affect water quality parameters necessary to sustain salmon populations (AEA 2011; AEIDC 1984; Andrew and Geen 1960; Bunn and Arthington 2002; Crossin et al. 2008; Cushman 1985; Gregory and Levings 1998; Lloyd et al. 1987; Murphy et al. 2006; Quinn 2011; Ryan et al. 2000).

      ii. **Third order impacts to habitat structure:** Changes in water quality will alter habitat structure necessary to sustain salmon populations (AEA 2011; AEIDC 1984; Huusko et al. 2007; Kondolf 1997; Linnansaari et al. 2009; Ugedal et al. 2008).

4. **Changes to Sediment Supply**

   Hypothesis: Long-term Project operations will reduce the sediment supply of the Susitna River and affect habitat processes and attributes necessary to sustain wild salmon populations (long term/dynamic; Figure 13).

   a. **Second order impacts to habitat processes:** Reductions in sediment supply to the Susitna River will affect habitat-forming processes including riparian communities and succession (Karrenberg et al. 2002; Rood et al. 2007), floodplain and channel morphology (Grant et al. 2003; Kondolf 1997; Ligon et al. 1995; Poff et al. 1997), surface and groundwater flow (Ligon et al. 1995), sediment erosion and deposition (Finger et al. 2006; Grant et al. 2003; Kondolf 1997; Nilsson and Berggren 2000; Poff et al. 1997; Rood et al. 2003), and nutrient and trophic cycles (Naiman et al. 1999; Nilsson and Berggren 2000).

      i. **Third order impacts to water quality:** The reduction of sediment supply caused by the operation and presence of the Project will alter water quality parameters necessary to sustain salmon populations (Gregory and Levings 1998; Lloyd et al. 1987).

ii. **Third order impacts to habitat structure:** The reduction of sediment supply caused by the operation and presence of the Project will alter habitat structure necessary to sustain salmon populations (Beechie and Bolton 1999; Kondolf and Wolman 1993; Kondolf 1997; Montgomery et al. 1996; Quinn 2011).

iii. **Third order impacts to habitat connectivity:** The reduction of sediment supply caused by the operation and presence of the Project will alter habitat connectivity necessary to sustain salmon populations (Bjornn and Reiser 1991).

5. **Changes to Biological Feedback between Salmon Populations and Habitat Processes**
Hypothesis: Impacts to salmon populations resulting from first, second, and third order impacts will affect biological feedback to habitat processes and attributes necessary to sustain wild salmon populations (long term/dynamic; Figure 14).

a. **Second order impacts to habitat processes**: Impacts to salmon populations will provide feedback to habitat and habitat-forming processes including riparian community and succession (Ben-David et al. 1998; Bilby et al. 1996), floodplain and channel morphology (Helfield and Naiman 2001; Naiman et al. 1999), and nutrient and trophic cycles (Montgomery et al. 1996; Moore et al. 2004).

i. **Third order impacts to water quality**: Impacts to salmon populations will alter water quality parameters necessary to sustain wild salmon populations (Cederholm et al. 1999; Kline Jr. et al. 1993; Wipfli et al. 1998).

ii. **Third order impacts to habitat structure:** Impacts to salmon populations will alter habitat structure necessary to sustain wild salmon populations (Helfield and Naiman 2001; Montgomery et al. 1996; Moore et al. 2004).

6. **Modulation of Direct and Indirect Impacts Caused by External Factors**
Hypothesis: External factors will modulate the direct and indirect impacts associated with the operation and presence of the proposed Project and affect habitat processes and attributes necessary to sustain wild salmon populations (long term/dynamic; Figure 15).

a. **Second order impacts to habitat processes:** Climate change will alter habitat-forming processes within the watershed including riparian community and succession (Yarnell et al. 2010), ice formation and breakup (Brown and Mote 2009; Prowse et al. 2011; Prowse and Beltaos 2002), floodplain and channel morphology (Yarnell et al. 2010), surface and groundwater flow (Adam et al. 2009; Stone et al. 2002; Woo et al. 2008), sediment erosion and deposition (Yarnell et al. 2010), and nutrient and trophic cycles (Winder and Schindler 2004), and modulate the effects of the proposed Project.

i. **Third order impacts to water quality:** Climate change and variability will alter water quality parameters necessary to sustain salmon populations (Al-Chokhachy et al. 2013; Battin et al. 2007; Bryant 2009; Eliason et al. 2011; Kovach et al. 2013; Mantua et al. 2010).

ii. **Third order impacts to water quantity:** Climate change and variability will alter the quantity of water necessary to sustain salmon populations (Mantua et al. 2010; Neal et al. 2002; Woo et al. 2008).

iii. **Third order impacts to habitat structure:** Climate change and variability will alter habitat structure necessary to sustain salmon populations (Bryant 2009; Nielsen et al. 2013; Schindler et al. 2005).

iv. **Third order impacts to habitat connectivity:** Climate change and variability will alter habitat connectivity necessary to sustain salmon populations (Bryant 2009; Mantua et al. 2010).

b. **External modulation of fourth order impacts:** Climate change and marine production will affect Susitna River salmon abundance and productivity in marine habitats outside of the Project footprint (Beamish and Bouillon 1993; Beamish 1995; Hare et al. 1999; Mantua and Hare 2002; Mantua et al. 1997).

7. **Construction Activities and Catastrophic Failure**

Hypothesis: Construction activities or catastrophic failure of the Project will temporarily (i.e., less than 10 years) affect habitat processes and attributes necessary to sustain wild salmon populations (short-term/transient; Figure 16).

a. **Second order impacts to habitat processes related to construction:** The construction and reservoir inundation of the proposed Project will temporarily affect all habitat-forming processes within the watershed including riparian community and succession, ice formation and breakup, floodplain and channel morphology, surface and groundwater, sediment erosion and deposition, and nutrient and trophic cycles (AEA 2011).

b. **Second order impacts to habitat processes related to catastrophic failure[1]:** The catastrophic failure of the proposed Project will temporarily affect all habitat-forming processes within the watershed including riparian community and succession, ice formation and breakup, floodplain and channel morphology, surface and groundwater, sediment erosion and deposition, and nutrient and trophic cycles (Evenden 2004; Waples et al. 2009, 2008a).

   i. **Third order impacts to water quality:** High-intensity, short-term construction or failure related disturbances will alter water quality parameters necessary to sustain wild salmon populations (Jones et al. 2000; Trombulak and Frissell 2000; Waples et al. 2009, 2008a).

   ii. **Third order impacts to water quantity:** High-intensity, short-term construction or failure related disturbances will alter the quantity of water necessary to sustain wild salmon populations (Waples et al. 2009, 2008a).

   iii. **Third order impacts to habitat structure:** High-intensity, short-term construction or failure related disturbances will alter habitat structure necessary to sustain wild salmon populations (Jones et al. 2000; Waples et al. 2009, 2008a).

   iv. **Third order impacts to habitat connectivity:** High-intensity, short-term construction or failure related disturbances will alter habitat connectivity necessary to sustain wild salmon populations (Evenden 2004; Jones et al. 2000; O'Connor 2004; Waples et al. 2009, 2008a).

2.7 Risk Profiles

The diagrams used to profile each risk hypothesis use colors and symbols to represent active and inactive components. To interpret the figures below, the reader should consider the following:

1. Each figure represents an individual risk profile.
2. Red symbols identify the origin of the risk that is being considered.
3. Orange symbols represent activities and impacts that contribute to the identified risk.

[1] The catastrophic failure scenario is conceptual and does not reflect any proposed activity or analysis of activities provided by AEA.

4. Blue symbols represent impacts or activities that are not contributors or are not considered within the specific risk profile.
5. Any risk that is associated with a long-term activity also activates all four of the parameters that sustain salmon populations.
6. Short-term activities with transient effects are less likely to cause persistent changes to salmon populations, which explains why construction and catastrophic failure do not independently cause population-level impacts.
7. Some of the risks affect a similar group of habitat process and attributes at a coarse scale.

This is expected because of the interdependence between habitat processes, but does not imply that mechanisms are identical. For instance, changes in the sediment supply and flow regime both cause impacts to floodplain and channel morphology; however, the specific pathway for each is different.

As a final note, individual profiles are intended to simplify a multitude of very complex processes. There are many interactions between the components of each profile and we explicitly recognize that the models do not cover every possible combination of Project activities, habitat processes, and impacts to habitat attributes. Instead, they reflect a prioritization and summary of those most likely to influence salmon populations. The risk profiles and components will be improved and refined by peer review.

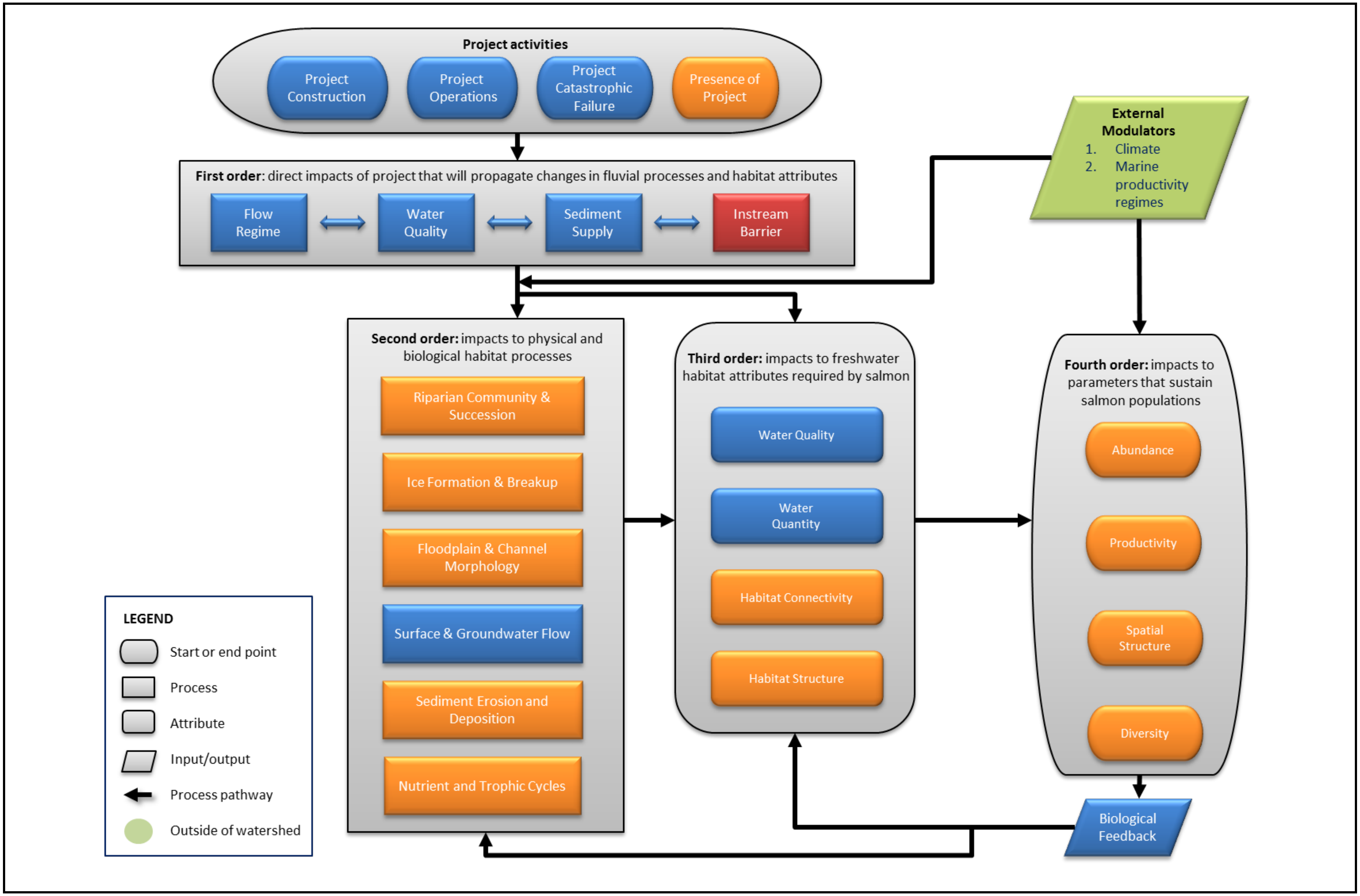

Figure 10
Risk Profile for Presence of an Instream Barrier
Ecological Risk Assessment of Large-scale Hydropower on Braided Rivers in Alaska: Phase 1
The Nature Conservancy

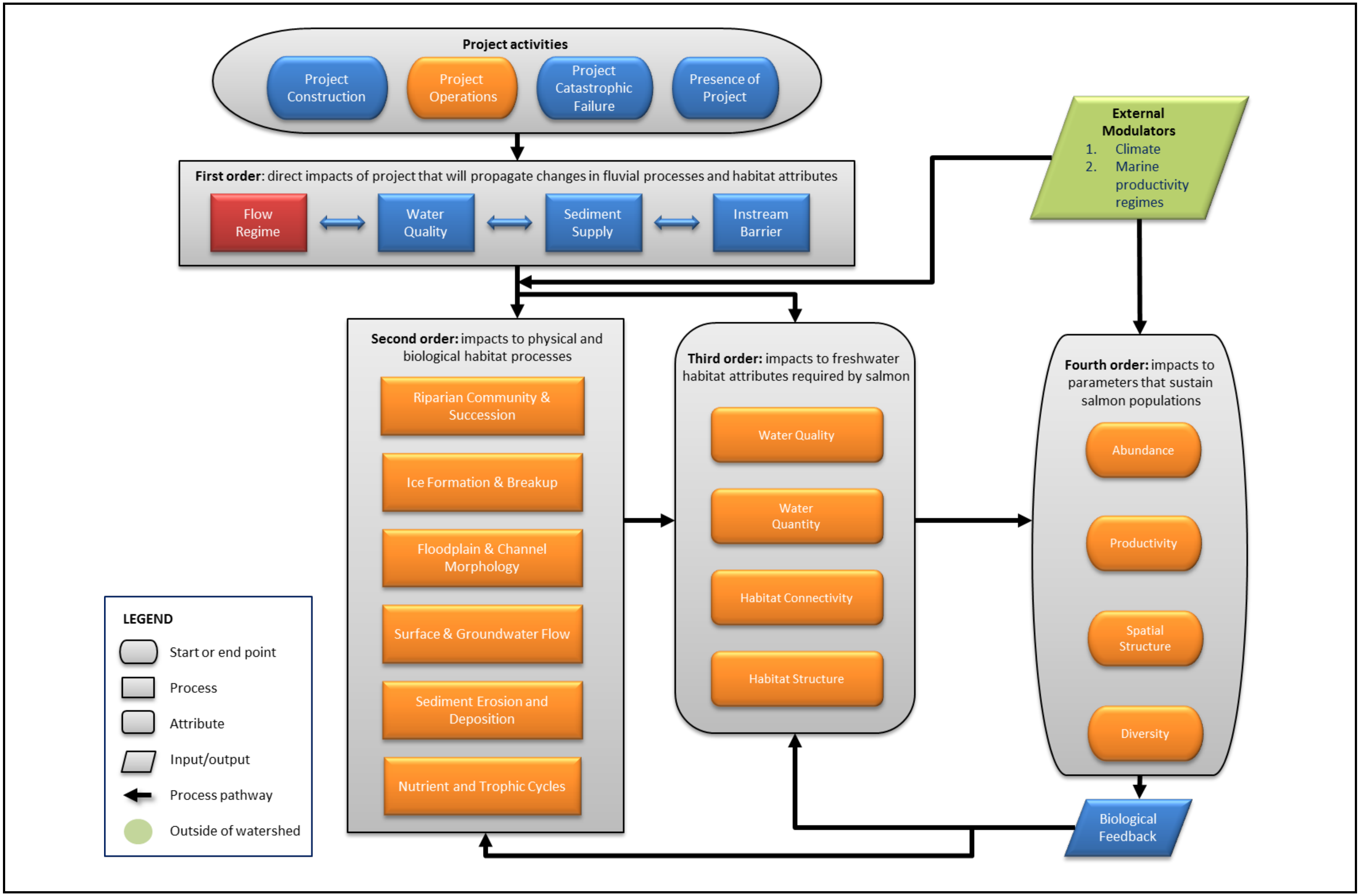

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Figure 11
Risk Profile for Changes to Flow Regime
Ecological Risk Assessment of Large-scale Hydropower on Braided Rivers in Alaska: Phase 1
The Nature Conservancy

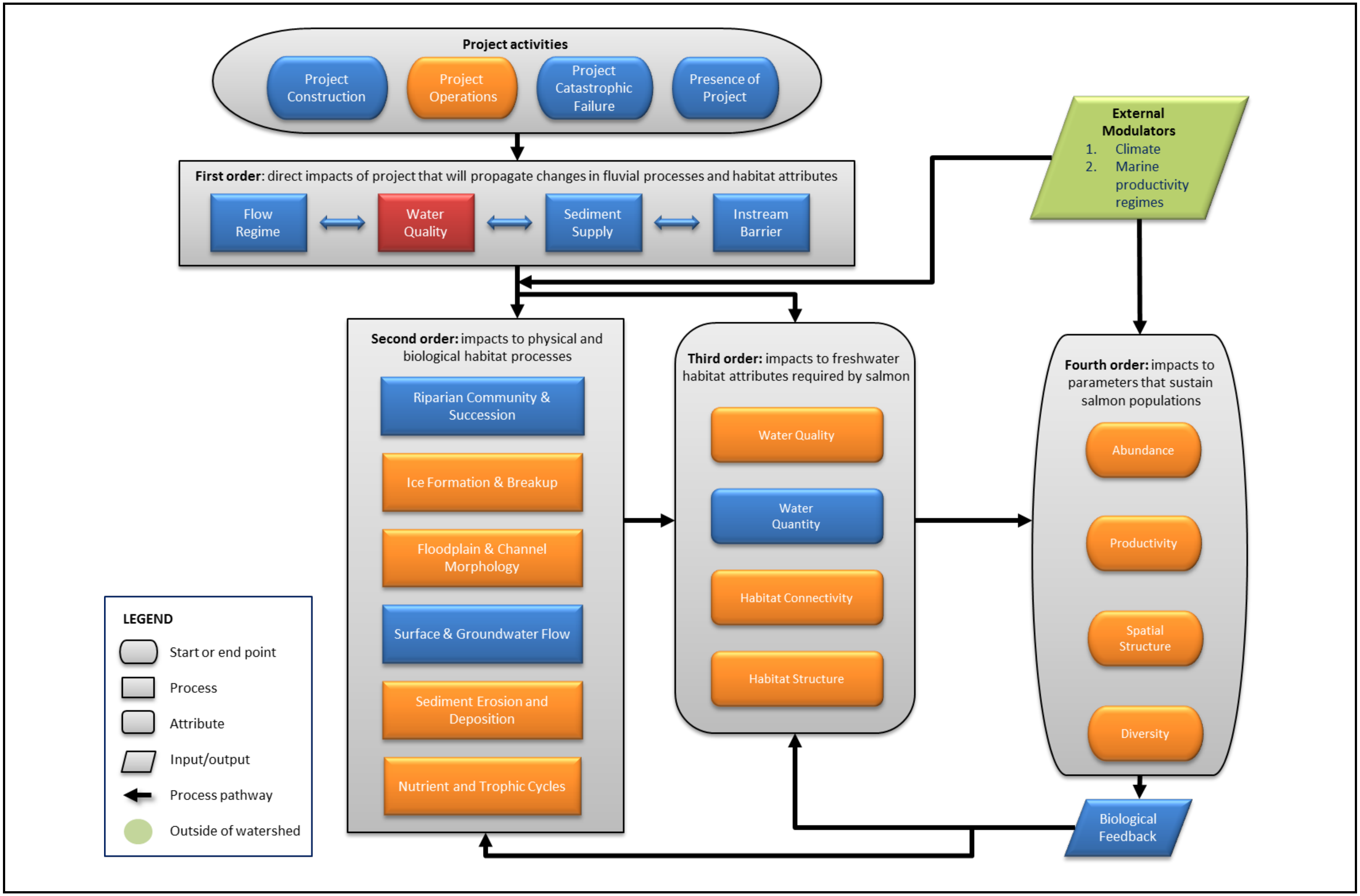

Figure 12
Risk Profile for Changes to Water Quality
Ecological Risk Assessment of Large-scale Hydropower on Braided Rivers in Alaska: Phase 1
The Nature Conservancy

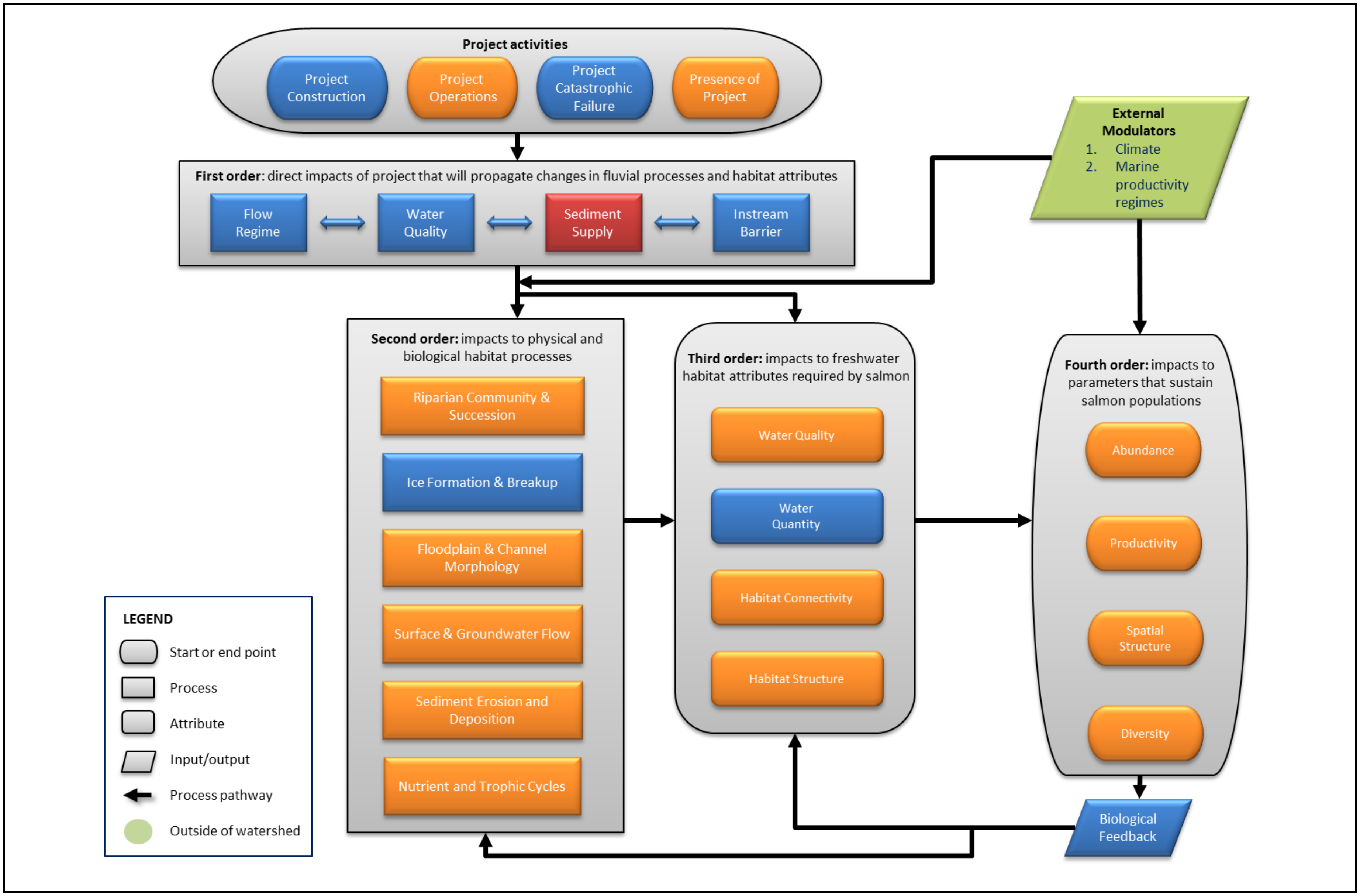

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Figure 13
Risk Profile for Changes to Sediment Supply
Ecological Risk Assessment of Large-scale Hydropower on Braided Rivers in Alaska: Phase 1
The Nature Conservancy

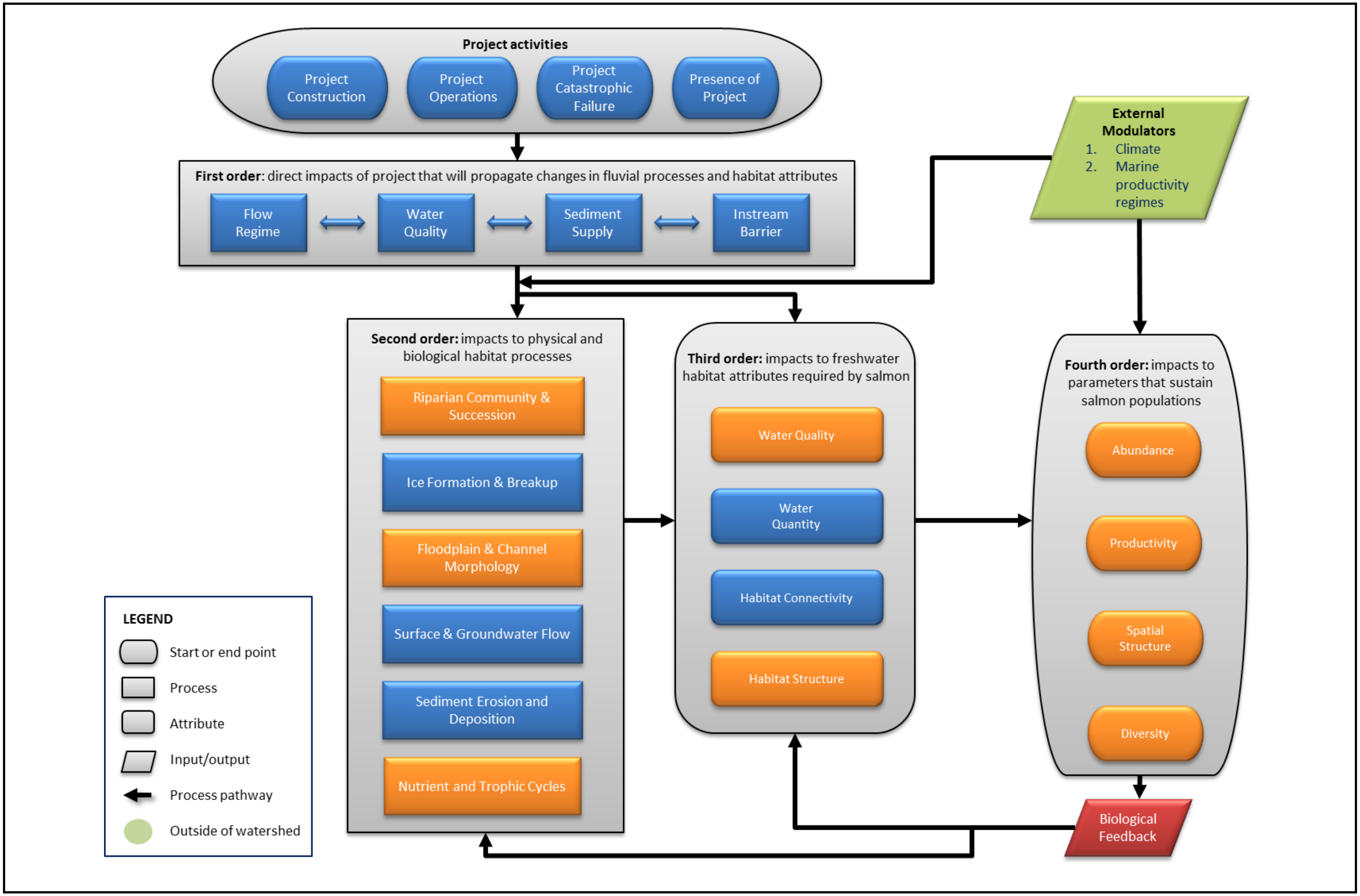

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Figure 14
Risk Profile for Changes to Biological Feedback between Salmon Populations and Habitat Processes
Ecological Risk Assessment of Large-scale Hydropower on Braided Rivers in Alaska: Phase 1
The Nature Conservancy

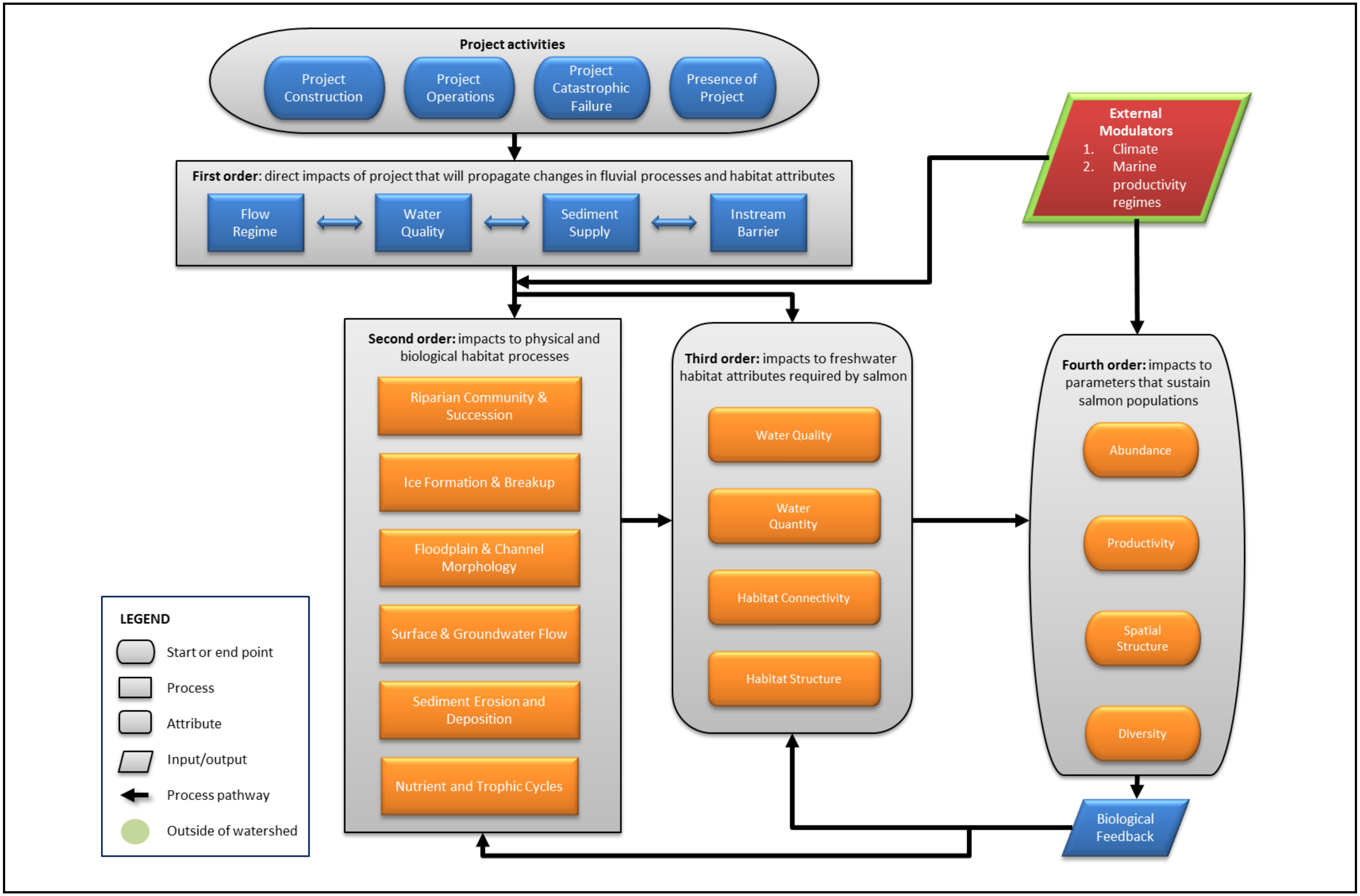

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Figure 15
Risk Profile for Modulation of Direct and Indirect Impacts Caused by External Factors
Ecological Risk Assessment of Large-scale Hydropower on Braided Rivers in Alaska: Phase 1
The Nature Conservancy

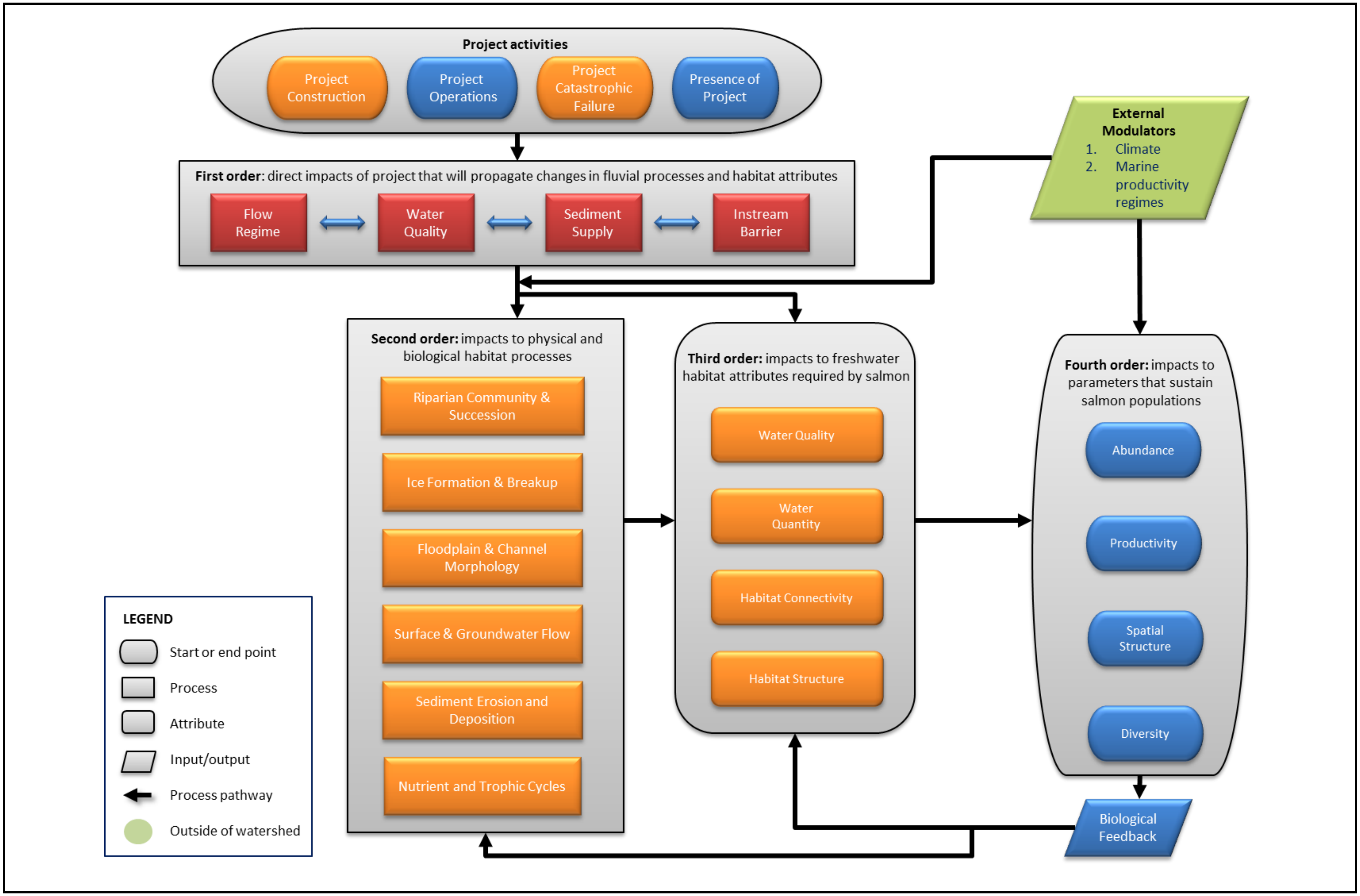

Figure 16
Risk Profile Caused by Construction Activities and Catastrophic Failure
Ecological Risk Assessment of Large-scale Hydropower on Braided Rivers in Alaska: Phase 1
The Nature Conservancy

3 DRAFT SUPPORTING INFORMATION

3.1 Introduction

The purpose of the literature review was to identify relevant information to evaluate the potential risks associated with the Project. A second objective was to develop a list of the best available information (i.e., regional datasets, models, gray and peer-reviewed literature, regional experts, and FERC studies) for reference in subsequent analyses and evaluations.

3.2 Methods

3.2.1 Search Criteria and Sources of Information Considered

There were two primary methods of obtaining literature for the review: 1) use of an online search engine, Google Scholar (http://scholar.google.com/) to search external literature; and 2) use of the AEA Project website (http://www.susitna-watanahydro.org/) and Alaska Resources Library and Information Services (i.e., ARLIS: http://www.arlis.org/docs/vol1/suhydro/) to search current and historic Project-related literature. Historic Project literature relates to a feasibility study and FERC license application undertaken but then halted in the 1980s. The final selection of literature included refinement using best professional judgment.

Because the scope of potential impacts covered virtually every fluvial process and all salmon life history stages, there was a considerable volume of information available. We attempted to narrow the search results by entering search terms that focused on the identified risks and their related actions and impacts. Example search criteria included permutations of coarse-scale criteria (e.g., *salmon, hydropower,* and *Alaska*) in conjunction with specific biological and fluvial, climate, and marine process terms (e.g., *flow regime, ice formation, erosion, sedimentation, channel morphology, floodplain, nutrients, water quality, marine derived nutrients, climate change, marine productivity,* and *catastrophic*). We relied on external sources exclusively to characterize marine productivity, climate change, and biological feedback in the context of salmon.

Searching the AEA site required systematically reviewing those reports and plans that had sections devoted to fluvial processes and aquatic species impacts. Citations from more recent

Project reports were used as starting points for focused queries within the ARLIS system for historic reports. For both recent and historic information, the most relevant of these were downloaded and included in the annotated bibliography. Under the FERC licensing process, many additional reports and studies would be carried out during the first 3.5 years of the proposed Project, and would provide the majority of the most relevant information for the Susitna River for the final risk analysis (e.g., ADF&G 2013).

3.2.2 Best Available Information

We ranked individual literature sources according to Best Available Information criteria (Table 2). Those sources with high scientific quality and value (i.e., peer-reviewed), geographic relevance (i.e., near the Project area), species relevance (i.e., salmon focused), temporal relevance (i.e., more recent), and congruence with the Project investigations (i.e., directly pertaining to the proposed Project) would represent the Best Available Information.

Table 2
Best Available Information Criteria

Category	Points
Scientific Quality and Value	
Peer-reviewed journal	3
Agency approved document	2
Other form of scientific review	1
Unknown	0
Geographic Relevance	
Within Susitna Watershed	3
Within Pacific Rim	2
Within North America	1
Elsewhere	0
Species Relevance	
Addresses Pacific salmon (*Oncorhynchus* spp.)	3
Addresses other salmonids	2
Addresses non-salmonids	1
Not related to fish	0
Temporal Relevance	
Published between 2000 and present	3

Category	Points
Published between 1990 and prior to 2000	2
Published between 1980 and prior to 1990	1
Published prior to 1980	0

3.3 Results

In total, more than 300 documents were reviewed and evaluated. A comprehensive annotated bibliography with individual scores is provided in Appendix A.

3.3.1 Presence of an Instream Barrier

3.3.1.1 External Literature Sources

The literature related to instream barriers covered a broad range of direct and indirect habitat effects. With respect to direct effects, fragmentation and truncation of existing habitats were identified as mechanisms by which habitat connectivity may be reduced (Fagan 2002; Gustafson et al. 2007; Hamilton et al. 2005; Isaak et al. 2007; Schick and Lindley 2007; Sheer and Steel 2006; Wofford et al. 2005). Similarly, instream barriers were identified as mechanisms for the reduction in quantity of physical habitat and productivity/abundance of salmon populations (Beechie et al. 1994; Dauble et al. 2003). Literature examples of natural and anthropogenic barriers are common with different levels of severity to salmon populations (Evenden 2004; Meixler et al. 2009; Quinn 2011; Sheer and Steel 2006; Steel et al. 2004). The AEA has focused specific studies on the evaluation of instream barriers and their direct impact to salmon at the mainstem and tributary levels (AEA 2013a; HDR 2013a, 2013b).

Literature addressing indirect effects of instream barriers (i.e., those effects that shape habitat processes that may lead to effects on salmon habitat attributes), covered riparian community processes, floodplain and channel morphology, and nutrient and trophic cycles. With respect to riparian communities, dams can interfere with plant dispersal and recruitment downstream of a project by fragmenting habitat (Jansson et al. 2000b) and reducing the magnitude of seasonal flooding events which normally distribute propagules and seeds long distances (Nilsson et al. 2010). Differences in plant communities above and below dams can develop (Merritt and Wohl 2006) with a reduction of riparian species richness downstream of the project (Andersson et al. 2000; Merritt and Wohl 2006). The impact of a dam as a barrier to plant dispersal is related to mode of dispersal and in some cases may not have significant impact (Jansson et al. 2005). Riparian species richness may improve with distance downstream of a dam due to inputs from tributary streams (Merritt and Wohl 2006). Effects to riparian communities interact with other habitat shaping processes (Collins et al. 2012). For channel and floodplain morphology, dams truncate the longitudinal lotic channel and inundate upstream river channels and floodplains (e.g., Nilsson and Berggren 2000; see flow risk). Dams may also act as a barrier to the distribution and abundance of migratory fauna that often provide trophic subsidies (Freeman et al. 2003; Nilsson and Berggren 2000) and shape the nutrient transport dynamic of a watershed (e.g., Ben-David et al. 1998; see biological feedback risk).

3.3.1.2 Project-specific Literature Sources

With respect to barriers to passage, the Project documents note that access to upstream habitats will be eliminated above the Project (AEA 2011; FERC 2012). Additionally, operations have the potential to alter connectivity between downstream macrohabitats and are the focus of historical and current Project studies (AEIDC 1984; HDR 2013a, 2013b; Riis and Friese 1977). The presence and significance of population structure or local adaptations of fish using habitat above Devils Canyon, a natural high-velocity impediment in the Middle River (river mile [RM] 150), are not known (ADF&G 2013).

3.3.2 Changes to Flow Regime

3.3.2.1 External Literature Sources

Literature related to changes in flow regime was abundant and covered a broad range of specific direct and indirect habitat effects. There were also many approaches to determining flow regimes meant to maintain elements of ecological integrity of rivers (Tharme 2003). For the purposes of the literature review, the search focused on "flow regulation" in general, as opposed to a specific hydropower operational scenario because the specific operations of the proposed Project are not yet known. In this instance, flow regulation included any situation where flow is managed to achieve goals, ranging from maintaining minimum flows for fish downstream of a reservoir to establishing environmental flows intended to mimic the natural hydrograph. The results included publications examining retrospective analyses of flow regulation, before-and-after comparisons, as well as the effects of modified flows for ecological purposes. Additionally, there were a number of broad syntheses that provided holistic overviews of potential effects of regulated flows (Bunn and Arthington 2002; Lytle and Poff 2004; Murchie et al. 2008; Naiman et al. 2008; Poff and Zimmerman 2010; Poff et al. 1997) and frameworks for planning environmental flows through proposed hydroprojects (Bradford et al. 2011; Richter et al. 2012; Poff et al. 2010).

With respect to direct effects on habitat attributes or salmonid populations, flow regulation impacts included consequences at multiple trophic levels through a range of abundance, diversity, and demographic responses (Poff and Zimmerman 2010). Flow regime may affect salmon habitat attributes through alteration of water quality (Naiman et al. 2008), water quantity (McMichael et al. 2005), habitat connectivity (Naiman et al. 2008), and habitat structure (see indirect effects). These impacts may decrease fish passage or delay adult salmon migrations (Bell 1985), strand juvenile salmonids (Bell et al. 2008; Bradford et al. 1995), redistribute salmon spawning areas (Dauble et al. 1999), affect the survival of incubating eggs (Korman et al. 2011), decrease availability of habitat for spawning (Ligon et al. 1995), reduce salmonid productivity through temperature increases (Horne et al. 2004), and cause specific behavioral and distributional responses to flow fluctuations (Enders et al. 2012; Korman and Campana 2009). The literature also contained examples of how flows were modified at existing hydroprojects to reduce impacts to fish caused by historical operations. For instance, adjustments to dam operations resulted in flows that reduced the risk of dewatering salmon fry and redds (Connor and Pflug 2004) and improved survival of outmigrating smolts (Connor et al. 2003) compared to historical modes of operation. Other studies identified theoretical approaches to flow regulation with the specific goal of improving salmon sustainability or diversity (Jager and Rose 2003) or broader optimization strategies that build upon existing operations (Jones 2013; Konrad et al. 2011).

Some literature sources indicated that regulated flows resulted in functionally similar or beneficial outcomes for affected species when compared to natural flow regimes. In a study of temperature changes before and after hydropower development, Jensen (2003) found that temperature regimes resulting from flow regulation may shift periods of salmonid growth to different periods, but not cause a major disparity between growth potential under regulated and unregulated conditions. Ligon et al. (1995) contrasts the results of regulation in the

McKenzie River, Oregon—an example of channel simplification and reduction of salmon productivity—with the Waitaki River, New Zealand—an extremely dynamic river where regulation reduced the mobilization of substrates by peak flows resulting in habitat-stabilization and increased salmon productivity. Hvidsten (1993) provides a case where smolt production was positively related to increased winter flows created by hydropower regulation in the River Orkla, Norway. Flows were naturally very low in winter when precipitation fell as snow. It was hypothesized that higher winter flows created more water-covered chambers in the substrate for fry to use for overwintering, thus improving winter survival rates.

The literature contained examples of interactions between flow and virtually all habitat shaping processes (i.e., indirect effect to habitat attributes).

With respect to riparian communities, flow regulation can impact plant dispersal by water and decrease species richness (Andersson et al. 2000; Jansson et al. 2000b), reduce species diversity at reservoirs (Hill et al. 1998; Nilsson et al. 1991), disrupt cottonwood recruitment (Burke et al. 2009; Rood et al. 2003), encourage encroachment by vegetation and stabilize riparian communities (Ligon et al. 1995), cause drought conditions and mortality resulting from groundwater depletion (Rood et al. 2003), and recruit large woody debris which, in turn, shapes channel morphology (Fetherston et al. 1995; Naiman et al. 2008). The type and intensity of flow regulation influences the level of impact to riparian vegetation communities (Jansson et al. 2000a) and interacts with other habitat processes (e.g., water temperature and geomorphological processes) to shape community structure (Engström et al. 2011). Additionally, regulation of flow regimes may cause broad declines in native, flow-adapted taxa and promote colonization by invasive species (Lytle and Poff 2004; Marchetti and Moyle 2001). Other riparian literature identified operational approaches to reduce flow regulation impacts (Burke et al. 2009).

With respect to floodplain and channel morphology, flow variation is a primary driver of floodplain and channel morphology (Naiman et al. 1999; Poff et al. 1997). Regulated flows typically reduce flooding and the functional extent of the active floodplain (Nilsson and Berggren 2000). Regulated flows, and the loss of bed mobilizing peak flows, may simplify channel morphology by discouraging the formation of within-channel bars and islands and eroding existing ones (Ligon et al. 1995). Similarly, loss of peak flows reduce the frequency and magnitude of disturbance regimes and encourage channel stabilizing vegetation encroachment (Ligon et al. 1995). If peak flows are reduced after placement of a dam, river conditions, such as stage fluctuations, mean stream power, and substrate mobility, may be greatly altered, though channel geometry (width and wetted perimeter) can be relatively unchanged if mean annual flows are similar to pre-dam periods (Burke et al. 2009).

Flow interacts with ice processes and channel morphology in that the effect of ice on river channel morphology is related to the length of time associated with dynamic anchor ice formation; ice-cover formation, presence, and breakup; and a channel's ability to respond to ice (Stickler et al. 2010; Ettema 2002). Regulated flows may produce minor changes in ice thickness and strength in comparison to the magnitude of the effect of climate variability (Prowse and Conly 1998). The thicknesses of ice jams formed under highly dynamic flow conditions (e.g., load-peaking) tend to be slightly thinner than those formed during steady carrier flows for comparable discharges (Healy and Hicks 2007). Ice jams interact with flow and can cause stage increases (Sui et al. 2005).

With respect to surface flow and groundwater flow, regulated flows reduce peak flooding and the frequency of high flows (Nilsson and Berggren 2000; Poff et al. 1997). Altered hydrology downstream of dams reduces groundwater recharge in the riparian zone and can result in a falling groundwater table (Nilsson and Berggren 2000). River discharge and sediment properties both control the water quality of the hyporheic zone (Arntzen et al. 2006). Peaking operations create large downstream flow fluctuations on a short temporal scale (i.e., daily load following) (Cushman 1985). The interaction between surface water and groundwater in the hyporheic zone has important implications for ecological processes and is influenced by the porosity of sediments (Boulton et al. 1998).

With respect to sediment erosion and deposition, flow drives sediment movement in fluvial systems (Poff et al. 1997). Flow regulation may change bed mobility so that it occurs at fewer locations but over a greater period of the year (Burke et al. 2009). Flow variability affects the recruitment of large woody debris, which in turn, affects local sediment erosion and deposition rates and creates habitat (Naiman et al. 2008). Hydropower operations can change the seasonality of particle inputs from summer to winter (Finger et al. 2006).

With respect to nutrient and trophic cycles, floods strongly influence nitrogen cycling (Pinay et al. 2002). In the floodplains of most large rivers, the main inputs of nutrients, sediment, and organic matter are mainly via surface flow from upstream (Pinay et al. 2002). Flooding distributes marine-derived nutrients from salmon carcasses and fertilizes terrestrial vegetation (Ben-David et al. 1998; Cederholm et al. 1989). Flow variation contributes nutrients and sediments to the floodplain, which, in turn, contribute to the productivity of soils and riparian communities (Nilsson and Svedmark 2002). Regulated flows can reduce benthic invertebrate diversity (Ellis and Jones 2013) and reduce benthic invertebrate and fish biomass long distances downstream (greater than 20 kilometers) of a hydroproject (Moog 1993). Hydropower operations and water level fluctuations may prevent the establishment of normal benthic invertebrate communities (Fisher and Lavoy 1972). Alternatively, a reduction in the amplitude and duration of power-peaking flow fluctuation may not reduce benthic invertebrate diversity below levels found in unregulated systems (Jones 2012), and can enhance aquatic insect standing crop (Gislason 1985). Flow regulation can be modified to improve the abundance and quality of invertebrate communities (compared to baseline regulated flow regimes [Morgan et al. 1991]).

3.3.2.2 Project-specific Literature Sources

The AEA contemplates the following direct salmon-related effects from operational flow alteration: restricted access to spawning sloughs, impediments to salmon migration upstream to tributary spawning habitat, loss of side channel and mainstem spawning habitat, changes in relative abundance of each species of salmon in the middle river, changes in overwinter survival, potential redd dewatering during winter, and reduced salmon productivity above Talkeetna. Alternatively, the AEA suggests that all five salmon species may increase their use of the Devils Canyon to Talkeetna reach, and reduced stranding of fry may occur because of flow stabilization (AEA 2011).

The AEA expects the proposed operational scenario to cause indirect effects to salmonid habitat attributes through regulated flows and discontinuity in sediment supplies that will alter channel morphology, aquatic habitats, channel erosion, and flooding. These conditions may reduce flow interactions between mainstem and side channel habitats and increase channel stability (AEA 2011). More specifically, the AEA expects flow to be increased during the typical low-flow season and decreased during the typical high-flow season (Tetra Tech 2013a), and peak discharges will be reduced in magnitude and probability of occurrence (Tetra Tech 2013a). Flow regulation will cause the winter stage cycle to fall and rise about 1.0 to 1.5 feet near Gold Creek and stage height during ice-free winter periods will be about 3.5 feet higher with the Project (HDR 2013c). During winter Project operations, the groundwater table could increase within the Susitna-Watana reach (AEA 2011). During normal summer Project operations, the groundwater table will be closer to the natural elevation than it will during the reservoir filling period (AEA 2011). During proposed load following operations, flows in the mainstem of Susitna River will be affected, but flows in tributaries above or below the dam, and in the mainstem above the reservoir are not expected to be affected (Tetra Tech 2013a). AEA expects that flow effects will attenuate downstream from the Project with the contribution of flow from other tributaries (AEA 2011).

With respect to riparian processes, Project literature indicated that operations may affect riparian communities through flow modulated changes in groundwater, ice processes, and fluvial geomorphology (ABR 2013; AEA 2011). Changes in riparian vegetation may cause subsequent changes in geomorphic features and aquatic habitats (Tetra Tech 2013b). Project operations may affect hydrochory (R2 Resource Consultants 2013a), plant community succession, and floodplain plant community development through effects on hydrologic and sediment regimes and groundwater and surface water regimes (R2 Resource Consultants 2013a). Project operations may have impacts on large woody debris recruitment, transport and function, and subsequent effects upon geomorphologic processes (AEA 2013b). The AEA expects that quantity and recruitment of woody debris above the Chulitna River will be reduced due to reduced peak flows (AEA 2011).

With respect to ice formation and breakup, Project literature indicated that the Project has the potential to affect ice processes, including the timing and extent of ice formation, severity of breakup, ice thickness, and winter water levels on the Susitna River downstream of the dam site (HDR 2013d). Project operations may affect ice jamming processes resulting in geomorphic habitat effects (AEA 2012; Tetra Tech 2013b). Changes in ice processes may also affect the establishment and recruitment of floodplain vegetation (R2 Resource

Consultants 2013a). Within the Project area, ice processes likely have an important role in the recruitment of large woody debris (AEA 2013b),

During Project operations, the AEA expects that the warmer water released from the Project will melt the cover between Devils Canyon and Talkeetna and that frazil ice formation will be reduced. The reduction in downstream ice-cover expected by the AEA between the proposed dam and Chulitna River is likely to reduce channel-shaping by ice forces in that reach. Higher discharge at freeze-up will lead to a higher stage than under natural conditions. Consequently, the AEA expects discharge could be increased through those sloughs that are currently overtopped and cause scour in the sloughs. Ice formation downstream from Talkeetna may be delayed about a month (AEA 2011).

The accuracy of hydrodynamic modeling during the ice-cover periods may or may not be sufficient to predict fish passage conditions or differences in hydraulic conditions (Tetra Tech 2013a).

With respect to changes in floodplain and channel morphology, Project literature indicated that Project operations, including regulated flows and discontinuity in sediment supplies will alter channel morphology, aquatic habitats, channel erosion, and flooding. During Project operations, river channel dynamics upstream of the Susitna-Chulitna confluence will change the morphology to a constrained channel with a narrower width. Reduced sediment transport will contribute to this effect and encourage vegetation encroachment. The change in channel morphology could cause some tributaries between the dam and Talkeetna to perch (AEA 2011). Channel change resulting from operations may extend to the lower Susitna River Segment (Tetra Tech 2013c).

3.3.3 Changes to Water Quality

3.3.3.1 External Literature Sources

The review of water quality literature included direct impacts to habitat attributes required by salmonids as well as indirect impacts to other habitat-forming processes.

Direct impacts included changes in turbidity (Finger et al. 2006), which can exert both positive (Gregory and Levings 1998) and negative (Lloyd et al. 1987) influences on salmonids. Dam operations, particularly spill, may also increase total dissolved gas levels and result in behavioral responses or gas bubble disease for exposed fish (Mesa et al. 2000; Ryan et al. 2000; Weitkamp et al. 2003). Direct effects also included changes in the thermal regime (Bunn and Arthington 2002). In cold climates, regulated winter discharges may be warmer than natural flow regimes because water is often drawn from the bottom of reservoirs at 4°C (She et al. 2012) and summer discharges may be cooler and oxygen deficient compared to unregulated rivers (Bunn and Arthington 2002). Temperature changes have wide ranging implications on the growth, development, and migration of salmonids (Quinn 2011). In particular, winters with more variable temperatures are more demanding on fish energetically than winters with consistently lower temperatures (Murphy et al. 2006). Ice processes directly affect fish physiology, movement, and distribution in winter (Prowse 2001). Surface ice may be an important overwinter habitat attribute for juvenile salmonids (Huusko et al. 2007; Linnansaari et al. 2009). Warm reservoir discharges can create open water conditions where ice coverage would normally exist (She et al. 2012). Under a regulated flow regime, increases in winter water temperatures change the period and spatial coverage of ice and reduce survival of overwintering fish (Ugedal et al. 2008). With respect to ice formation in regulated rivers, the period of ice development can be prolonged (She et al. 2012). Unstable frazil ice production can continue throughout the winter due to the persistent turbulent open water zone downstream of the dam, and dynamic hydrologic regulation (e.g., hydro-peaking) can destabilize developing ice cover, resulting in ice jams and flooding (She et al. 2012). Ice breakup is controlled by water temperature and interactions with other atmospheric and hydrologic variables (Scrimgeour et al. 1994). Ice cover promotes stable river water temperatures, and breakup can produce abrupt changes in water temperature (Scrimgeour et al. 1994).

With respect to sediment erosion and deposition, the primary water quality impact is the potential for sediment starved water originating from the reservoir to pick up sediment load through erosion at downstream locations (Kondolf 1997). Because organic and inorganic particles carrying nutrients may be liberated by erosion effects or sequestered in the deposition of upstream reservoir sediments, there is a feedback loop between water quality, sediment transport, and nutrient cycling (Naiman et al. 1999; Nilsson and Berggren 2000;

Owens et al. 2005). Erosion and deposition also shape channel and floodplain morphology (Kondolf 1997; Owens et al. 2005).

3.3.3.2 Project-specific Literature Sources

With respect to water quality, Project literature indicated that operations would primarily affect temperature, dissolved gasses, and turbidity. During Project operations, the seasonal variation in temperature within the Project reservoir and for a distance downstream of the dam would change after impoundment. The timing of high and low temperatures would also change. Water temperatures in the Watana-Talkeetna reach are expected to warm in June and July, whereas during August little heating or cooling is expected. In September, cooling of the outlet temperatures is expected. Reaches downstream of Talkeetna will have summer temperatures similar to existing temperatures but will have different fall, winter, and early spring temperatures compared to existing temperatures (AEA 2011).

The AEA expects that water temperatures in the sloughs will be similar to those under existing conditions for those times when the sloughs are not overtopped. Previous investigations indicated that groundwater temperatures in areas of upwelling in the sloughs reflected the long-term average water temperature of the Susitna River, which is approximately 3°C (AEA 2011). Previous analyses also suggested the most apparent Project-related change in Susitna River water temperature above Talkeetna will occur in the mainstem and side channels since these habitats will be directly affected by change in river discharge (AEIDC 1984). The AEA expects that downstream tributaries will buffer Project effects on mainstem temperatures downstream of the Project (AEIDC 1984). Additionally, the AEA suggests that the downstream effects of temperature may be influenced by the use of a multilevel intake at the Project (AEA 2011).

A number of potential salmon habitat impacts identified in Project literature were related to alterations to stream temperatures regimes. Potential increases in incubation rates due to warmer water temperatures in winter and autumn may occur and early-spawning pink and chum salmon (mid-July) may complete development to emergence stage by mid- to late October. This effect could be positive as it would potentially improve incubation habitats (AEIDC 1984), or it could be negative by advancing the timing of outmigration to a low survival window (AEA 2011). It was suggested in historical Project literature that cooler summer rearing temperatures could also reduce the growth rate of juvenile fish that are subject to the temperature changes, but the temperatures would not be outside of the thermal tolerances for any of salmon species (AEIDC 1984). Previous Project analyses suggested that temperatures during adult immigration could be cooler than natural conditions but well within the established temperature tolerances for Susitna adult salmon migrating to spawning habitats (AEIDC 1984).

During Project operations, decreased downstream flows during summer will cause a reduction in the levels and variation of dissolved gas concentrations below Devils Canyon. However, the AEA expects supersaturated dissolved gas levels to be managed by fixed cone valves and are not expected to be increased by the Project, except during flood releases through the spillway during highest floods. During Project operations, reservoir-derived, inorganic sediments are expected to settle in the reservoir and not cause significant downstream water quality impacts. With respect to turbidity, the AEA finds that winter silt load resulting from Project operations may reach levels detrimental for downstream redds, but stable flow and reductions in summertime turbidity may increase benthic productivity and food availability for juvenile salmon in the middle river (AEA 2011).

3.3.4 Changes to Sediment Supply

3.3.4.1 External Literature Sources

The review of sediment supply literature included direct impacts to habitat attributes required by salmonids as well as indirect impacts to other habitat-forming processes.

Direct impacts included loss of spawning substrates for adult salmonids from reduced sediment supplies (Kondolf 1997; Montgomery et al. 1996), and damaged rearing habitats (Beechie and Bolton 1999; Owens et al. 2005) and spawning habitats (Quinn 2011) from increasing sediment supplies, particularly fines (Owens et al. 2005). The availability of suitable spawning substrates may limit salmonid production (Kondolf and Wolman 1993).

The supply of sediment has a number of important potential effects on habitat processes. For riparian communities, the availability of sediments may shape the disturbance regime and influence the suitability of habitat for native vegetation (e.g., *Salix and Populus* spp.) (Karrenberg et al. 2002; Rood et al. 2003). Sediment supplies can also affect downstream erosion and deposition processes. Dams trap large quantities of sediments that would previously have been transported downstream (Nilsson and Berggren 2000; Poff et al. 1997); however, fine sediments may not settle out (Finger et al. 2006). Reduction of sediment supply can create sediment starved water that will propagate downstream erosion (Kondolf 1997). Without recruitment of new sediments, existing habitats are subject to erosion and coarsening of bed materials (Kondolf 1997; Ligon et al. 1995; Nilsson and Berggren 2000). Reductions in sediment supplies may also result in lateral channel adjustments, including both expansion and contraction of channel width (Grant et al. 2003), or channels may become prone to downcutting (Kondolf 1997; Ligon et al. 1995; Poff et al. 1997). Reduced sediment supply and smaller flow events (in magnitude and frequency) can limit the disturbance regime of floodplains and create more stable river channels that encourage vegetation encroachment processes (Karrenberg et al. 2002; Rood et al. 2003). The sediment supply also shapes the water chemistry and nutrient loads. Instream inorganic ion and nutrient concentrations often reflect the underlying geology of a watershed (Naiman et al. 1999) and are represented in sediments that are transported downstream (Nilsson and Berggren 2000) through erosion and disturbance events. Sediment delivery and storage effects are translated through multiple trophic levels in an ecosystem (Owens et al. 2005).

3.3.4.1 Project-specific Literature Sources

With respect to changes in sediment supply, Project literature indicated that Project operations and the existence of the Project and its reservoir would reduce the downstream sediment supply. More specifically, the reservoir would act as a sediment trap and larger diameter suspended sediment would settle out to form a delta at the upstream end of the reservoir (AEA 2011). Fine glacial sediments may pass through the reservoir (AEA 2011). The trapping effect and altered flow regime will reduce the recruitment of sediments to the middle river, but effects will attenuate downstream with sediment inputs from other tributaries (Tetra Tech 2013d). The annual bedload and suspended sediment load in the middle river are relatively low whereas the lower river has higher bed and suspended sediment loads owing to contributions from other tributaries (Tetra Tech 2013e).

It is anticipated that the trapping of sediment behind the proposed Project may only affect sediment dynamics significantly between the dam site and the Susitna-Chulitna-Talkeetna confluence (AEA 2011). Project effects on gravel loads will derive primarily from the changes in flow regime (Tetra Tech 2013d). The AEA expects the loss of bed materials could lead to clear water-scour and local aggradation and flooding effects (AEA 2011). Decreased flooding frequency and reduction in silt/clay load is also expected to affect the floodplain sedimentation processes (Tetra Tech 2013d). However, the AEA suggests that coarse sediment deposition in the middle river could increase habitat for salmonids downstream of the canyon (AEA 2011).

3.3.5 Changes to Biological Feedback between Salmon Populations and Habitat Processes

3.3.5.1 External Literature Sources

The literature review identified numerous examples of direct and indirect habitat impacts that are shaped by biological feedback from salmon populations.

In terms of direct effects, salmon carcasses and eggs directly feed juvenile salmonids (Cederholm et al. 1999). In many northern oligotrophic systems, salmon contribute to multiple trophic levels and act as a keystone species (Willson and Halupka 1995) supplying both aquatic and terrestrial ecosystems with marine derived nutrients (Cederholm et al. 1999, 1989; Kline Jr. et al. 1993; Scheuerell et al. 2005; Schindler et al. 2003; Willson and Halupka 1995; Willson et al. 1998; Wipfli et al. 1998).

Through nutrient transport and spawning behavior, salmon have a substantial indirect effect on habitat shaping processes. Salmon contribute to riparian communities by providing nutrients to fertilize terrestrial vegetation (Ben-David et al. 1998; Bilby et al. 1996). These plants, in turn, provide essential habitat for spawning salmon by providing shade and cover, creating microhabitats (Naiman et al. 1999), and contributing to large woody debris inputs (Helfield and Naiman 2001). Riparian vegetation also provides food and habitat for beavers, which in turn, shape channel morphology by redistributing trees into the channel (Naiman et al. 1999). The act of spawning itself has a significant effect on channel morphology (Montgomery et al. 1996; Moore et al. 2004) and can redistribute benthic invertebrates and primary producers (Moore et al. 2004). Alternatively, reduced salmon abundance may increase freshwater density dependence and the productivity of aquatic ecosystems (Achord et al. 2003).

3.3.5.2 Project-specific Literature Sources

No Project-related literature was available on changes to biological feedback between salmon populations and habitat processes.

3.3.6 Modulation of Direct and Indirect Impacts Caused by External Factors

3.3.6.1 External Literature Sources

The literature reviewed for climate change suggests important fluvial habitat processes are already affected by increasing temperatures and will be to a greater extent in the future. Predicted instream temperature changes may reduce the quantity of suitable freshwater fish habitat (Al-Chokhachy et al. 2013; Battin et al. 2007; Bryant 2009; Eliason et al. 2011; Mantua et al. 2010) and diversity of life history phenotypes (Kovach et al. 2013). Climate change may also decouple important trophic interactions in aquatic habitats as the result of altered thermal regimes (Winder and Schindler 2004). In Washington State, changes in snow melt, stream flow and instream temperatures are expected to have a significant impact on the distribution and reproductive success of salmon by 2080 (Mantua et al. 2010). Alaska is expected to see more intense effects from climate change (Larsen et al. 2008). Previous episodes of climate change have caused significant variation in historical salmon abundance in the North Pacific and Alaska (Finney et al. 2000).

For some species, climate change may improve habitat functions for certain life history stages. Climate change has caused earlier spring ice breakup leading to improved productivity of sockeye rearing lakes in Alaska (Schindler et al. 2005) and may extend the northern distribution of salmon species (Nielsen et al. 2013). The effects will differ among salmon species in Alaska (Bryant 2009).

Aside from effects on distribution and productivity, temperature increases are expected to have comprehensive effects on habitat processes. Climate mediated changes in flow and vegetation communities may impact the structure of river channels (Yarnell et al. 2010). The effect of climate change in the boreal zone is likely to increase winter flow and cause earlier spring runoff dates, but peak flow will likely decline, as will summer flow, due to evaporation (Woo et al. 2008). Surface water and groundwater flows will be affected by changing snowmelt (Stone 2002), precipitation, snowpack (Mote 2006), and glacial runoff patterns (Adam et al. 2009; Barnett et al. 2008, 2005). These changes may be particularly important to the Susitna River, which receives significant glacial freshwater inputs (Clarke 1991; Harrison et al. 1983).

There are feedback loops between hydropower operations and climate change. Sediment trapping by dams may increase methane emissions and exacerbate anthropogenic climate change (Maeck et al. 2013). Conversely, hydropower may contribute to reductions in greenhouse gas emissions directly (compared to using other fuels) or by load balancing with renewable power sources (Prowse et al. 2011).

The literature on marine production suggests that salmon population dynamics are strongly influenced by the marine environment and regular patterns of climate variation (Beamish and Bouillon 1993; Kaeriyama et al. 2004). The Pacific Decadal Oscillation is a source of climatic variability that drives marine production and strongly influences salmon production (Hare et al. 1999; Mantua and Hare 2002; Mantua et al. 1997). Nearshore habitats (Greene and Beechie 2004) and estuarine habitats (Hoem Neher et al. 2013) represent an important interface between ocean and freshwater habitats and may also play a key role in explaining patterns of salmon abundance. The climate forces driving marine salmon productivity also impact freshwater habitats (Neal et al. 2002).

Marine productivity and climate change also interact. As an example, within the Gulf of Alaska, discharge from glaciers and icefields accounts for 47 percent of total freshwater discharge, with 10 percent coming from glacier volume loss associated with rapid thinning and retreat of glaciers. Climate mediated reductions in freshwater discharges could affect coastal circulation, which may affect both primary production and salmon production (Neal et al. 2010).

3.3.6.2 Project-specific Literature Sources

No Project-related literature was available on modulation of direct and indirect impacts caused by external factors.

3.3.7 Construction Activities and Catastrophic Failure

3.3.7.1 External Literature Sources

The literature review concerning impacts of construction and catastrophic failure is largely theoretical as the former is not well described for the proposed Project and the latter has not occurred on a scale comparable to the proposed Project. For these reasons, we greatly simplified what would actually be highly complex processes and relied extensively on surrogates (that may or may not be representative of what could or would occur).

For the consideration of catastrophic failure we looked at historical geological events that might represent a surrogate for dam failure. There are no examples of large-scale dam failures that would represent a reasonable comparison. Therefore, we created a general failure scenario based on simplifying assumptions: 1) the failure of the Project would be similar in scope to a natural catastrophic disturbance event (i.e., major landslide, volcanic eruption, or earthquake); 2) the actual failure process would transpire over a short period of time (e.g., days or weeks); and 3) natural habitat processes would be allowed to proceed thereafter. We also considered several examples of controlled dam removal to provide a surrogate means of examining potential recovery trajectories. Again, these may not be representative or appropriate because a catastrophic failure would not be planned.

Similar to a catastrophic failure, we also made some simplifying assumptions for the construction and reservoir filling processes, namely that they would occur at the intensity and within the schedules described in the AEA documents. Considering their effects independent of the existence of operations of the Project, construction and reservoir filling are assumed to be short-term but high intensity, transient impacts.

With these assumptions, the literature review found that catastrophic salmon population declines from natural and anthropogenic events are well documented (Evenden 2004; Good et al. 2008; Moser 1899; Nielsen et al. 2013; O'Connor 2004) and can become permanent if the causative agent is allowed to persist or transient if natural processes are allowed to act and management actions are taken to reduce the impact (Gustafson et al. 2007; Healey 2009; Waples et al. 2009, 2008b; Williams et al. 2008).

Pacific salmon have experienced massive amounts of geological upheaval and have persisted and adapted to new habitats that were created (Waples et al. 2008a). Within Alaska, geological activity is common and has led to spectacular, destructive events (Waythomas et al. 1996) in the middle of the most productive salmon habitats. In Washington State, Mount St. Helens' eruption in 1980 provided a contemporary example of geological upheaval and salmon response (O'Connor 2004; Waples et al. 2009). Similarly, the Fraser River Hells Gate landslides of 1912 to 1914 represented a different type of geological event that tested the resiliency of salmon populations (Evenden 2004; Waples et al. 2009, 2008b). In a dam removal scenario, the potential for recovery depends on the sensitivity of the organism, type of dam, and local geomorphology of the watershed (Doyle et al. 2005).

For construction impacts specifically, road building has the potential to cause widespread changes in the water quality and sediment supply of tributary habitats, as well as barriers to passage. The creation of access roads also promotes secondary development not associated with the Project (Jones et al. 2000; Trombulak and Frissell 2000). The external literature review for Project operations covers the additional habitat process and direct impacts that are expected from construction and reservoir filling.

3.3.7.2 Project-specific Literature Sources

Construction activities would temporarily dewater an approximately 1,800-foot-long segment of the Susitna River; however, AEA does not anticipate impacts to groundwater flow, and instream flow is not expected to be impacted significantly unless flows exceed the cofferdam's design criteria. Although the majority of construction material will come from borrow areas outside the river channel, some material may be excavated from the dewatered reach at the dam site. The AEA suggests construction impacts may result in increased concentrations of nutrients due to the disturbance of vegetation and soil cover and subsequent erosion of overburden and spoil materials. The AEA expects trace metal concentrations, water temperatures, and ice breakup are expected to be similar to pre-Project conditions. However, the AEA notes that petroleum products and construction materials could contaminate surface water and groundwater. The AEA expects suspended sediment and turbidity levels to increase because of construction activities (AEA 2011).

The AEA contemplates significant direct and indirect impacts to salmon and habitat processes during reservoir filling. The AEA expects direct impacts to salmon to be greatest during the second and third years of reservoir filling where large flow reductions are likely to cause large declines in salmon production (AEA 2011). During reservoir filling, most downstream side channels would not be inundated by overflow because high flows would be reduced to a maximum of about 30,000 cfs immediately downstream of the dam. The AEA also suggests that reservoir filling would also result in an altered relationship between mainstem and slough groundwater flows, disconnection between mainstem and other macrohabitats, and vegetation encroachment along the side channels and sloughs.

With respect to water quality, Project-related literature suggests that during reservoir filling well mixed waters should result in dissolved oxygen levels necessary to support aquatic fauna in the reservoir, and supersaturated dissolved gasses are not expected to occur downstream of the Project. During reservoir filling, the reservoir will take on the characteristics of a lentic habitat. The AEA expects river temperatures to initially be similar to but lower than existing river water temperatures. During November through April, the AEA expects average temperatures to be about 4°C (39°F), rather than the current average of 0°C (32°F). In general, the AEA expects discharges would be warmer than existing (pre-Project) temperatures in the winter and cooler than existing (pre-Project) temperatures in the summer. The AEA expects the disparity between predicted and existing temperatures would attenuate on a downstream gradient. The AEA expects thermal contributions of other tributaries to eliminate any Project-related temperature effects at the point of the confluence of the Yentna River (AEA 2011).

With respect to sediment erosion and deposition and nutrient loading, Project-related literature suggested that reservoir filling will trap bedload and reduce sediment transport downstream of the Project. Alluvial deposition is expected to occur at the confluence of the Susitna and Chulitna rivers, and reduced flows would decrease the frequency and amount of bed material transported downstream (AEA 2011). During reservoir filling, nutrient levels are expected to temporarily increase within the reservoir because of the initial inundation and leaching of materials from rocks and soils on the reservoir bottom (AEA 2011).

AEA did not identify impacts to salmon from catastrophic failure. Seismic activity is a recognized Project risk that is being studied (AEA 2013c).

4 KEY ECOLOGICAL ATTRIBUTES

4.1 Narrative Description of Key Ecological Attributes

All Pacific salmon require the same four essential habitat attributes during their freshwater life history: water quality, water quantity, habitat structure, and habitat connectivity (Figure 17). However, each species has unique requirements within each attribute that is related to its life history characteristics and associated spatial and temporal use of habitat within a watershed. Additionally, there may be variation within the same species across different watersheds.

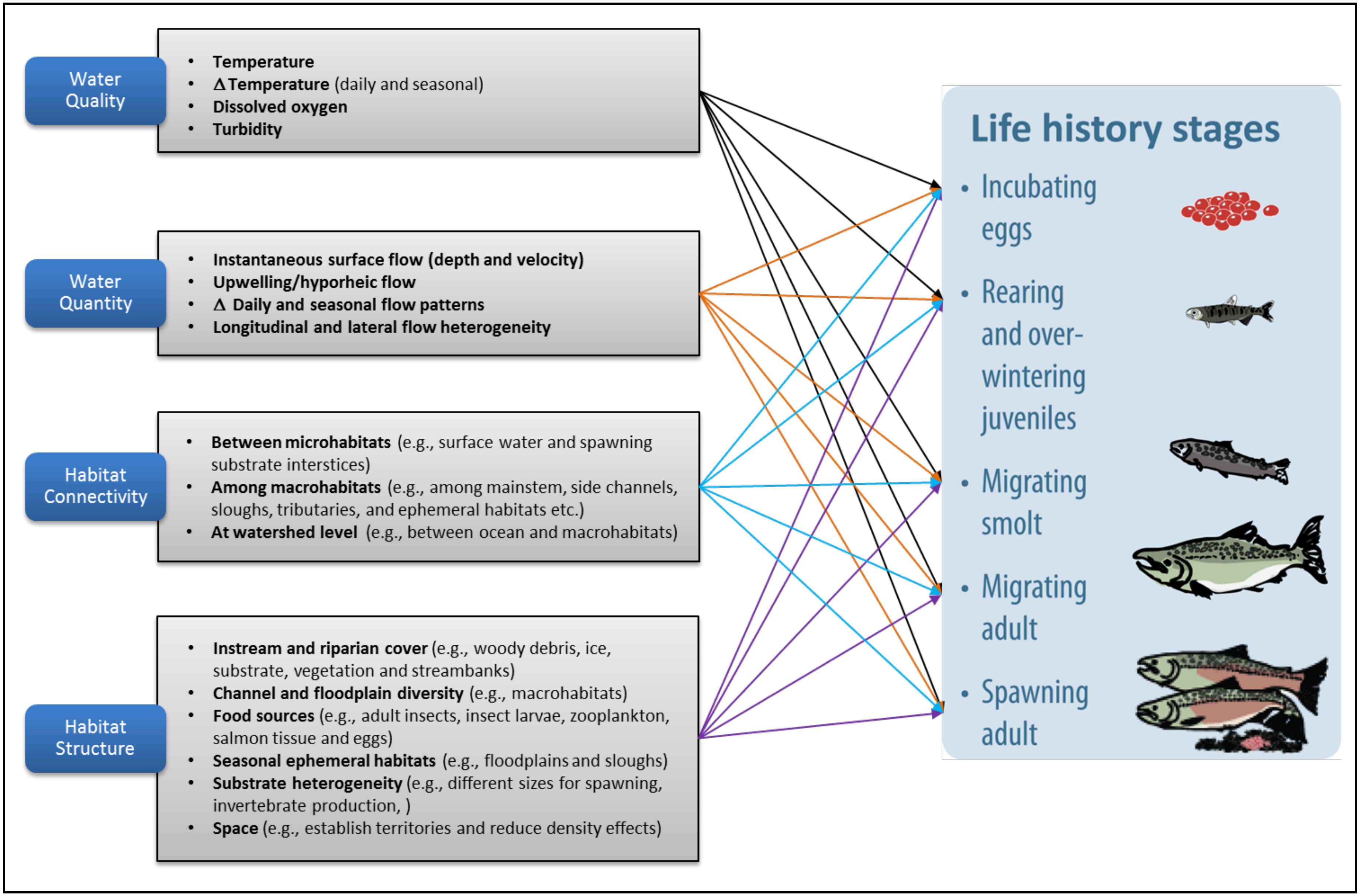

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Figure 17
Ecological Relationship between Salmon Habitat Attributes and Different Life History Stages
Ecological Risk Assessment of Large-scale Hydropower on Braided Rivers in Alaska: Phase 1
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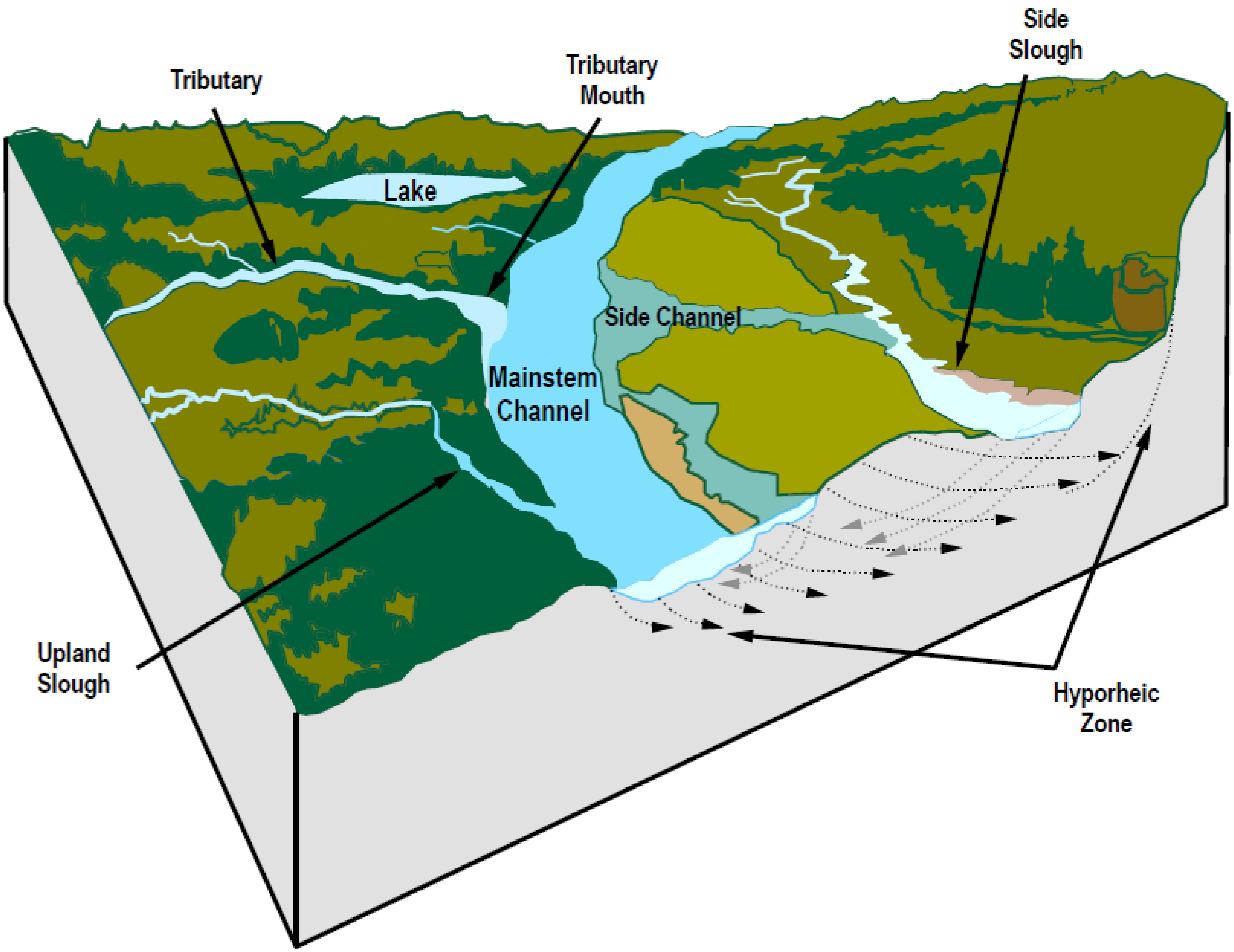
In this section we provide a brief overview of each species and summarize the ecological relationships between habitat attributes and different life history stages in the Susitna River. Much of the previous and current salmon-related Project data has been summarized and we report key findings from these sources as well as other external sources.

The text that follows uses a standard Project-wide delineation of river segments (see Figure 8 in Section 2.1.1):

- Upper river – above the proposed dam site (RM 184), including the MacLaren River, Tyone River, Susitna Lake, and the Oshetna River
- Middle river – north from the Three Rivers Confluence (Chulitna, Talkeenta, and Susitna rivers at RM 98) to the proposed dam site (RM 184), and major tributaries Portage Creek, Indian River, and Fourth of July Creek; Devils Canyon is located at RM 150 in the Middle River
- Lower river – Cook Inlet (RM 0) to the Three Rivers Confluence (RM 98), including the Chulitna River (RM 98), Talkeetna River (RM 97), Kashwitna River (RM 61), Willow Creek (RM 50), Deshka River (RM 41), and the Yentna River (RM 30)

Additionally, macrohabitats are described using the terminology in Figure 18.



Note: Figure adapted from ADF&G 1983 and Trihey 1982. Figure and caption from R2 Resource Consultants 2013b.

Figure 18
Habitat Types Identified in the Middle Reach of the Susitna River during the 1980s Studies
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4.2 Chinook Salmon

The narrative below provides a brief summary of the ecology of Chinook salmon in the Susitna River. Tables B-1 and B-2 in Appendix B provide specific summaries of the fine-scale habitat attributes required at each life history stage as well as the periodicity of life history residence and macrohabitat use in the Susitna River.

4.2.1 Spawning

Chinook salmon are the only anadromous species documented migrating in the tributaries within and above Devils Canyon, which contains three high-velocity impediments (RM 150 to 161; LGL 2013, 2011). Chinook in the lower and middle river generally do not spawn outside the tributaries (Barrett et al. 1985, 1984; Thompson et al. 1986). In the middle river, most Chinook spawn in the clear water tributaries of Portage Creek and Indian River, but a small proportion are understood to spawn in the mainstem Susitna (spawning could not be visually confirmed). In 2012, these fish may have spawned between approximately Deadhorse Creek and Portage Creeks (LGL 2013). In the lower river, 97 percent of lower river spawning Chinook went to the tributaries of Deshka, Chulitna, Talkeetna, and Yentna rivers and their tributaries, while most of the remainder are understood to have spawned between the Yentna and Deshka rivers on the Susitna. These results were consistent with the prior studies from the 1980s (Barrett et al. 1985, 1984; Thompson et al. 1986). Spawning tributaries are known to include Alexander Creek, Clear Creek, Goose Creek, Talachulitna River, and Willow Creek (ADF&G 1983).

Chinook salmon adults have been observed in upper Susitna river tributaries of Cheechako, Chinook, Devil, Fog, Tsusena, and Kosina creeks and in the Oshetna River (Buckwalter 2011; LGL 2013, 2011), but visual spawning evidence in some of these watercourses was not confirmed due to high water turbidity, turbulence, and steep terrain (LGL 2013). In 1984, Chinook salmon spawning was confirmed in Chinook and Fog creeks, the latter of which is just below the proposed dam site. The farthest upstream confirmed spawning location is Kosina Creek (Yanusz et al. 2013).

Proportionally, spawning Chinook lean heavily toward tributaries to the lower river such as Deshka River and Alexander Creek, which tend to account for 50 percent or more of

Chinook spawning. The Yentna River and the Talkeetna/Chulitna subbasins comprise 20 and 15 percent of spawning, while middle river tributaries include 5 percent of spawners (R2 Resource Consultants 2013b).

4.2.2 Juvenile Emergence, Rearing, and Smolt Migration

Incubation begins after spawning in late July and lasts through emergence in the following spring, typically late February to middle May. Chinook juveniles at age 0+ disperse downstream and use side channels for rearing (Delaney et al. 1981; Riis and Friese 1977; Suchanek et al. 1984). They are found more often in mainstem-associated microhabitats in later summer, starting in late July (Schmidt et al. 1984). In late August or early September, side channel use decreases and side sloughs become more important moving into the winter (Schmidt et al. 1984).

Throughout rearing, Chinook juveniles are widely distributed among Susitna tributary mouths and side channels, occurring more often in middle river versus lower river tributary mouths and in less turbid versus more turbid habitats (Suchanek et al. 1984). They prefer lower velocity waters and shallower depths in turbid conditions, and use object cover more in clear water. Rearing juvenile Chinook have also been found more often in warmer water areas within rearing zones, due to the conservation of energy in these conditions (Schmidt and Bingham 1983).

In 1983, Chinook juveniles were observed in mainstem sloughs and side channels, in addition to Chase Creek, Indian River, and Portage Creek; Portage Creek was the most upstream location where juveniles were sampled and (Schmidt et al. 1984). In 2003, juvenile Chinook salmon were found rearing in Fog Creek, Kosina Creek, and as far upstream as the mouth of the Oshetna River (Buckwalter 2011).

4.3 Chum Salmon

The narrative below provides a brief summary of the ecology of chum salmon in the Susitna River. Tables B-3 and B-4 in Appendix B provide specific summaries of the fine-scale habitat attributes required at each life history stage as well as the periodicity of life history residence and macrohabitat use in the Susitna River.

4.3.1 Spawning

River-wide, 62 percent of chum migrate to areas in the Susitna River upstream of the Yentna River confluence (Clearly et al. 2013). Mainstem rivers are important to chum; both the 2009 and 2010 studies by ADF&G reported that over half of all tagged chum salmon spawned in the Susitna, Yentna, or Skwentna river mainstems as opposed to other smaller tributaries (Merizon 2010). In the Yentna subbasin, the Yentna and Skwentna rivers may be particularly important, as a 1998 study found that most fish used the Yentna or Skwentna, and fewer fish used the Kichatna River (tributary to the Yentna) (Todd et al. 2011). Sloughs are especially important spawning habitat to chum salmon (Schmidt et al. 1984). Below is information about the lower and middle river portions of the escapement, respectively. Chum salmon do not migrate or spawn in the upper river above Devils Canyon.

Lower river spawning occurs in the mainstem Susitna River as well as in the Yentna, Chulitna, Talkeetna, and Deshka rivers. The trend of Yentna subbasin use seen in the above-described studies was observed in 2012 when most lower river spawners moving up the Susitna River migrated to the Yentna (LGL 2013). The small proportion of lower river spawners that did use the mainstem Susitna spawned between the Deshka and Kashwitna river mouths (LGL 2013).

In the middle river, most chum spawn in Portage Creek and in the Indian and Talkeetna rivers. They also spawn in Lane Creek, Fourth of July Creek, Little Portage Creek, Skull Creek, Fifth of July Creek, and Jack Long (Schmidt and Bingham 1983). In 2012, about a quarter of the middle river spawners went to the mainstem. These mainstem spawners spawned near sloughs and tributary deltas (LGL 2013). These results were similar to studies in the 1980s (Barrett et al. 1985, 1984; Thompson et al. 1986).

Chum salmon do not migrate past Devils Canyon in the upper Susitna River. The farthest upstream location of a tagged spawning chum was downstream of Jack Long Creek in 2009 and at the mouth of Indian Creek on the mainstem Susitna in 2010 (Clearly et al. 2013; Merizon 2010). In 2012, Portage Creek was the most upstream receiver location, and chum salmon were observed at this station as early as July 17. One chum approached the farthest downstream impediment in Devils Canyon but did not migrate above it (LGL 2013).

Proportional distributions of chum salmon among spawning areas vary by year, but lower river tributaries are consistently the key chum salmon production areas, with contributions from mainstem channels and sloughs. Significant production areas are also associated with mainstem channels, sloughs, and tributaries of the middle river (R2 Resource Consultants 2013b).

4.3.2 Juvenile Emergence, Rearing, and Migration

Chum salmon incubation spans from spawning in September to emergence in natal gravels in mid-April to June. Aside from pink salmon, which directly emigrate after emergence, chum have the shortest rearing period in freshwater compared to all other salmonids in the Susitna River (Schmidt and Bingham 1983). After spending about three months in freshwater, chum salmon fry outmigrate from the Susitna River system in early to mid-June to mid-July at age 0+ (Schmidt and Bingham 1983). They are found in high densities in natal side sloughs and tributaries early in the season (May to early June) and in upland sloughs and side channels in late June and July (Schmidt et al. 1984). They prefer shallow, lower velocity areas near the mouths of tributaries and sloughs during rearing (Dugan et al. 1984; Schmidt and Bingham 1983; Suchanek et al. 1984). Chum initially use substrate as cover and then school for protection from predators (Schmidt and Bingham 1983).

In 1983, chum juveniles were observed in mainstem sloughs and side channels, in addition to Chase Creek, Indian River, and Portage Creek; Portage Creek was the farthest upstream location where juveniles were sampled and found (Schmidt et al. 1984).

Mark-recapture studies from 1983 outmigration reported between 3,037,000 and 3,322,000 chum fry migrated down the Susitna River near the Chulitna confluence, with peak outmigration occurring in mid-June. Rates of outmigration showed higher correlations with discharge for chum than for other species (Schmidt et al. 1984).

4.4 Coho Salmon

The narrative below provides a brief summary of the ecology of coho salmon in the Susitna River. Tables B-5 and B-6 in Appendix B provide specific summaries of the fine-scale habitat attributes required at each life history stage as well as the periodicity of life history residence and macrohabitat use in the Susitna River.

4.4.1 Spawning

Coho salmon are the least numerous salmon in the Susitna basin and are documented from the mouth of the river to Devils Canyon at RM 151 (R2 Resource Consultants 2013b). River-wide, 59 percent of coho migrate to areas in the Susitna River upstream of the Yentna River confluence (Cleary et al. 2013). Tributaries are important to coho; both the 2009 and 2010 studies by ADF&G reported that less than half of all tagged coho spawned in the mainstem Susitna, Yentna, or Skwentna rivers as opposed to other smaller tributaries (Merizon et al. 2010). Below is information about the lower and middle river portions of the escapement, respectively. Coho salmon do not migrate or spawn in the upper river above Devils Canyon.

Lower river spawning is primarily in the Yentna, Chulitna, Talkeetna, and Deshka rivers, and a smaller proportion spawn in the mainstem Susitna (Merizon et al. 2010; LGL 2013). In the *Adult Salmon Distribution and Habitat Utilization Study* (LGL 2013), 7 percent of Lower Susitna River spawning fish went to the mainstem, and mainstem spawners were aggregated north of approximately Deadhorse Creek to the Whiskers Creek confluence.

Middle river coho typically spawn in the Indian River and in Portage and Jack Long creeks, and in 2012, 16 percent of middle river spawning fish migrated to the mainstem Susitna River. However, the actual locations of mainstem spawning could not be visually confirmed either in the 1980s or in 2012 (Barrett et al. 1985; Thompson et al. 1986; LGL 2013).

The farthest upstream location of a tagged spawning coho was in the mainstem Susitna near Jack Long Creek in 2009 and in lower Portage Creek in 2010 (Merizon et al. 2010). In 2012, Portage Creek was the farthest upstream receiver location, and coho were observed at this station as early as August 7 (LGL 2013).

Spawning coho salmon in the Susitna are proportionally more abundant in tributaries in the lower river, with contributing mainstem channels and sloughs. The middle river tributaries are only a small proportion of the river's chum production (R2 Resource Consultants 2013b).

4.4.2 Juvenile Emergence, Rearing, and Migration

Incubation lasts from spawning in August through late September, until juvenile coho emerge from natal gravels in clear water tributaries in March or April (Schmidt and Bingham 1983), spending the first 2 months after emergence in the vicinity of their natal areas (Morrow 1980). Age 0+ coho typically redistribute from natal streams to suitable rearing habitat in summer, mainly late July to early August (Suchanek et al. 1984). This suitable habitat is near clear water tributary mouths in the mainstem Susitna and in side sloughs and tributaries in close proximity to natal areas (Dugan et al. 1984; Suchanek et al. 1984; Schmidt and Bingham 1983). In the middle river, upland sloughs are also used, likely because these areas exhibit warmer groundwater influence, which helps conserve energy (Schmidt and Bingham 1983; Schmidt et al. 1984). Coho use side channels to a limited extent, favoring other, lower turbidity areas. They do not typically use turbid water or substrate as cover, preferring debris or undercut banks (Schmidt et al. 1984). They outmigrate as age 1+ or 2+ smolts in response to increased daylight, depths, and velocities experienced in the end of their overwinter period.

In 1983, coho juveniles were observed in mainstem sloughs, in addition to Chase Creek, Indian River, and Portage Creek; Portage Creek was the farthest upstream location where juveniles were sampled and found (Schmidt et al. 1984).

4.5 Pink Salmon

The narrative below provides a brief summary of the ecology of pink salmon in the Susitna River. Tables B-7 and B-8 in Appendix B provide specific summaries of the fine-scale habitat attributes required at each life history stage as well as the periodicity of life history residence and macrohabitat use in the Susitna River.

4.5.1 Spawning

Pink salmon have a strict 2-year life cycle, which results in distinct odd or even year runs. In the Susitna River, the even-year run is the strongest (Schmidt and Bingham 1983). They have been documented spawning in the Susitna basin from the mouth to Devils Canyon (RM 151); hence, the following information describes the lower and middle river portions of the run.

Lower river spawning for pinks is primarily in the Yentna, Chulitna, Talkeetna, and Deshka rivers, but a small proportion spawn in the mainstem Susitna. In the LGL study (2013), these mainstem spawners were located near tributary confluences (Willow Creek and Kashwitna River).

Middle river pink salmon typically spawn in the Indian and Talkeetna Rivers and in Portage and Fourth of July Creeks, while a small percentage spawn in the mainstem Susitna River. In 2012, the location of these mainstem spawners could not be confirmed, but holding behavior was observed at the mouths of Fourth of July Creek, Indian River, and Portage Creek (LGL 2013). Some spawning occurs in sloughs, but not as extensively as for chum or sockeye (Barrett et al. 1985, 1984; Thompson et al. 1986).

In 2012, Portage Creek was the farthest upstream receiver location, and pinks were observed at this station as early as July 30 (LGL 2013).

Proportionally, pink salmon spawn more often in the lower river tributaries of Deshka, Talkeetna, and Yentna rivers, as the middle river tributaries are only a small portion of total pink production (R2 Resource Consultants 2013b).

4.5.2 Juvenile Emergence, Rearing, and Migration

Incubation of eggs and emergence in pink salmon is poorly understood, but is currently believed to span from late March to May of the following year (R2 Resource Consultants 2013b; Schmidt and Bingham 1983). Pink salmon outmigrate immediately upon emerging from natal gravels (Morrow 1980), with peak outmigration occurring in early June and the migration concluding by mid-July (Schmidt et al. 1984)

There is currently no literature information on habitat use by pink salmon juveniles because of their rapid emigration from natal streams (R2 Resource Consultants 2013b).

4.6 Sockeye Salmon

The narrative below provides a brief summary of the ecology of sockeye salmon in the Susitna River. Tables B-9 and B-10 in Appendix B provide specific summaries of the fine-scale habitat attributes required at each life history stage as well as the periodicity of life history residence and macrohabitat use in the Susitna River.

4.6.1 Spawning

Considering the entire Susitna River, a large proportion of sockeye spawn in the Yentna River subbasin. The Yentna and other lower river tributaries are major sockeye spawning habitats because of the many associated lakes within those drainages (R2 Resource Consultants 2013b).

Lower river sockeye spawning is primarily in the Yentna River, but also occurs in the mainstem Susitna and in other spawning areas such as Fish Creek, Alexander Lake in the Alexander Creek drainage, Whitsol Lake in the Kroto slough drainage, Trapper and Neil lakes in the Deshka drainage, and Fish Lake in the Birch Creek drainage (R2 Resource Consultants 2013b).

Sockeye spawning occurs in the middle river above the Talkeetna River confluence. In 2012, middle river sockeye were observed spawning in varying proportions in tributaries (21 percent; Portage Creek, Chulitna River, Fourth of July Creek, Indian River, and Talkeetna River) and in the mainstem Susitna (37 percent). These mainstem spawners were confirmed in sloughs and side channels; use of these spawning habitat types was consistent with studies from the 1980s (Barrett et al. 1985, 1984; Schmidt and Bingham 1983; Thompson et al. 1986).

Sockeye salmon do not migrate or spawn in the upper river above Devils Canyon. In 2012, Portage Creek was the farthest upstream receiver location, and sockeye were observed at this station as early as July 5. One sockeye approached the farthest downstream impediment in Devils Canyon but did not migrate above it (LGL 2013).

Susitna River sockeye runs have ranged from 147, 000 to 773,000 spawners (Fair et al. 2009).

4.6.2 Juvenile Emergence, Rearing, and Migration

Incubation of sockeye eggs begins after spawning in July and August lasts until emergence in March through May of the following year (Schmidt and Bingham 1983). Sockeye juveniles generally redistribute into rearing habitat immediately after emergence. They are typically found in lakes and at tributary mouths associated with the lower river (Suchanek et al. 1984). The majority of Susitna sockeye juveniles rear in lake systems of the Yentna River drainage, mainly Chelatna, Shell, and Judd Lakes, as well as Larson Lake associated with the Talkeetna River (King et al. 1997). They have a limited distribution in middle basins, as most rearing is limited to side sloughs and sites along the mainstem that have lacustrine features (Dugan et al. 1984; Schmidt et al. 1984). Sockeye juveniles associate with low velocity and low turbidity waters (Schmidt and Bingham 1983), and use of side slough habitats is extensive, especially in close proximity to natal areas (Suchanek et al. 1984). As they rear, they use schooling as a means of predator avoidance and so are less dependent on cover than other salmonids (Schmidt et al. 1984). Age 0+ fry remain in shallow waters near shore while rearing and outmigrating and use deeper waters as growth increases. They begin redistributing from natal streams by mid-June, and peak outmigration occurs in late June. The majority of sockeye outmigrate as age 1+ smolts (Schmidt and Bingham 1983). In 1983, sockeye juveniles were observed in mainstem sloughs and side channels in addition to Portage Creek, which was the farthest upstream location where juveniles were sampled and found (Schmidt et al. 1984).

Mark-recapture studies from 1983 outmigration reported estimates of between 559,000 and 575,000 sockeye fry migrating down the Susitna River near the Chulitna confluence (Schmidt et al. 1984).

5 PRELIMINARY CHARACTERIZATION OF ECOLOGICAL EFFECTS

5.1 Interactions between the Risk Factors and Ecological Attributes

Based on the risk framework and literature review, we developed a conceptual model to depict the full translation of Project effects from Project activities to salmon population endpoints (Figure 19).

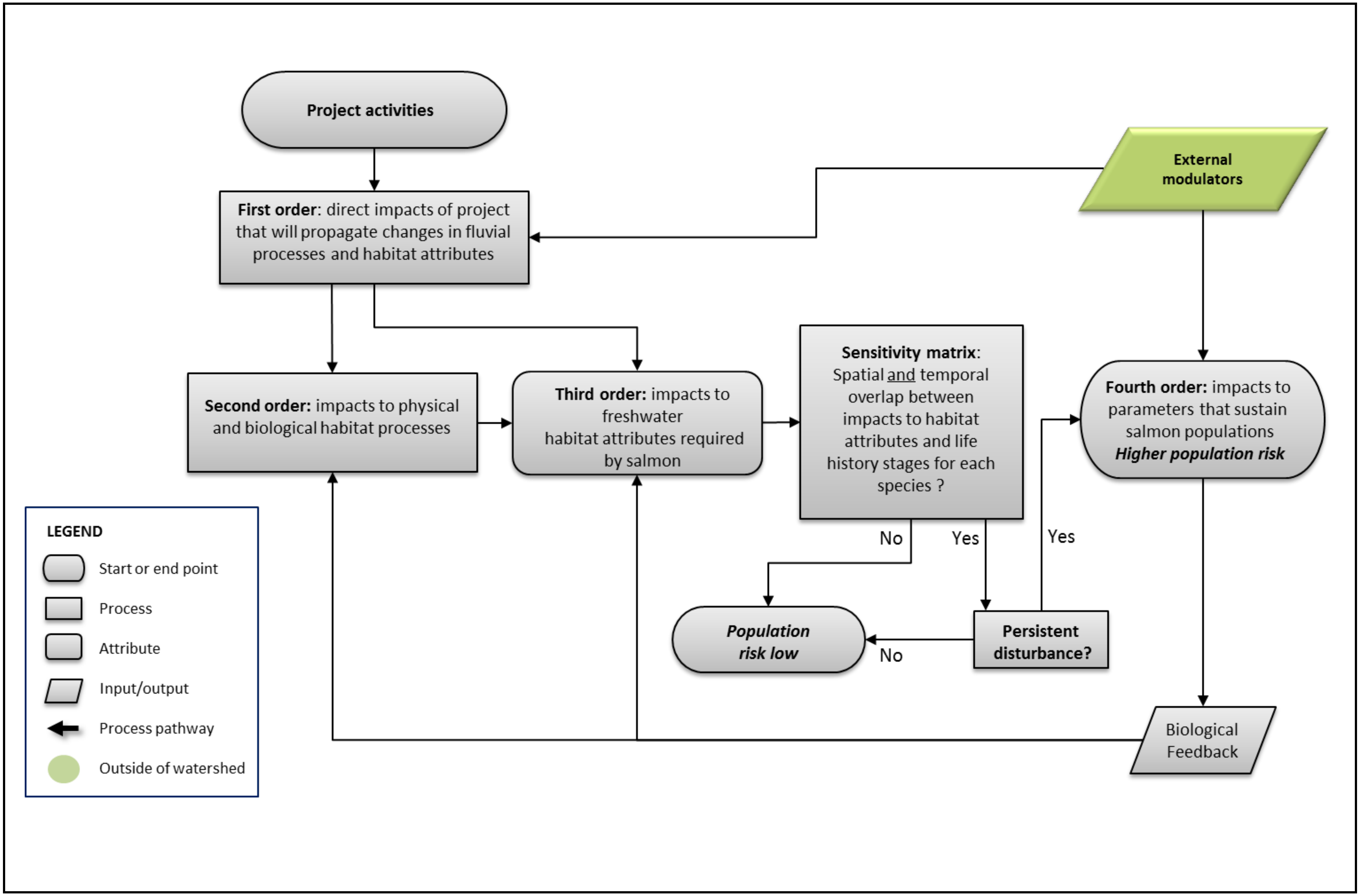

Figure 19
Conceptual Model Depicting the Relationships and Pathways among Project Activities, Habitat Processes, Habitat Attributes, and Salmon Populations
Ecological Risk Assessment of Large-scale Hydropower on Braided Rivers in Alaska: Phase 1
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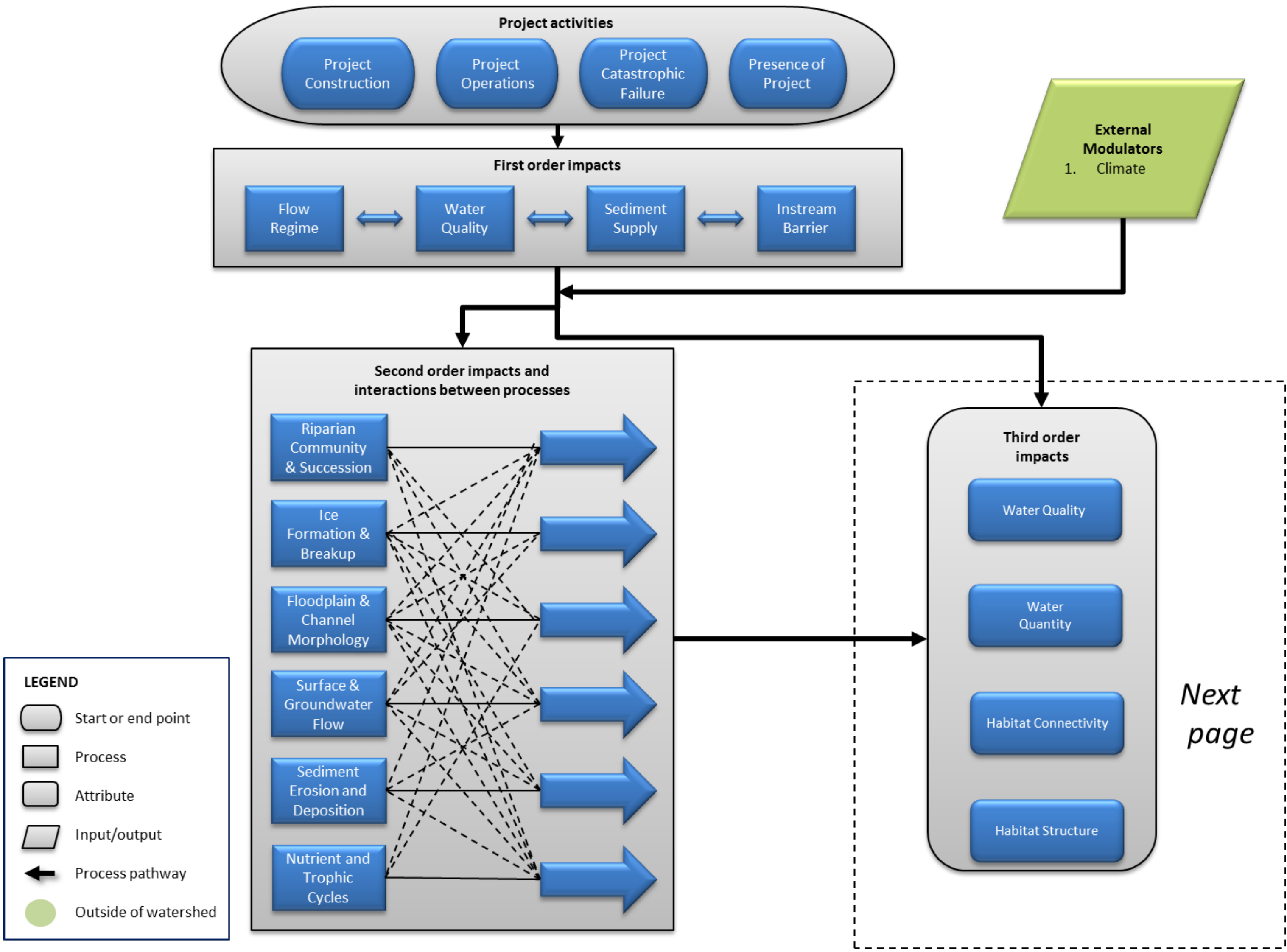
The model reflects an evolution of the risk framework that acknowledges the complexity of interactions between habitat processes and incorporates a sensitivity matrix to evaluate how changes to habitat attributes intersect with spatial and temporal characteristics of each species life history (Figures 20 and 21). When major alterations to habitat overlap with a species' life history usage of that habitat, there is potential for impacts to occur at the population level. Specifically, the habitat matrix includes a yes or no response (i.e., "Y/N?" boxes in Figure 21) for overlap between changes in each habitat attribute and each life history stage (and for each species). Where there is overlap, there is potential for impacts to occur at an individual or population levels. Population levels impacts would occur when the habitat attribute is changed for multiple generations. Therefore, the final determinant of population impact (within the conceptual model) is the persistence of the effect. If the multiple generations are affected (i.e., Figure 21), then there is a stronger potential for population level impacts (Healey 2009; Waples et al. 2009, 2008a). These situations are described as "higher risk" compared to non-persistent impacts (Figure 21).

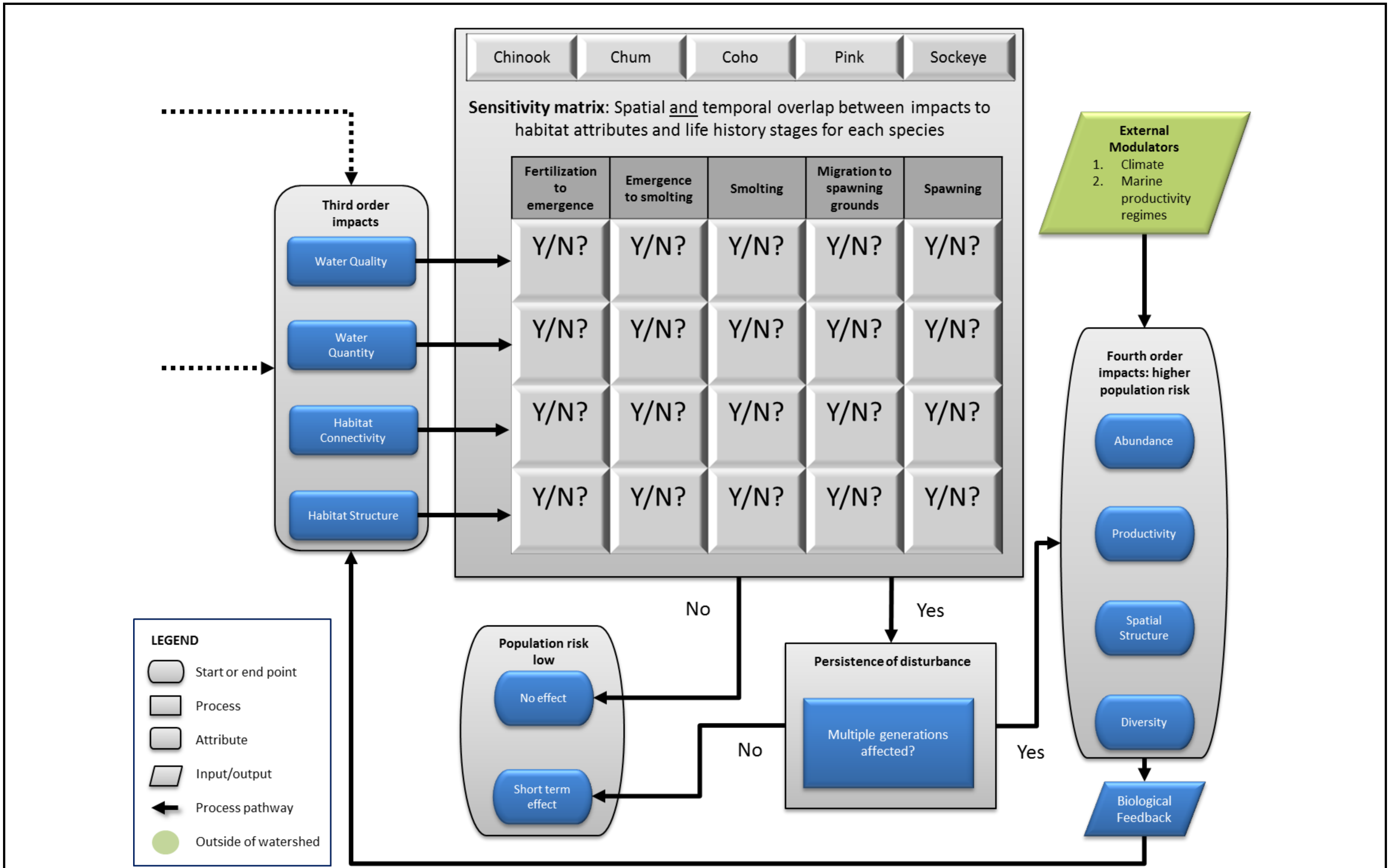
The direction and magnitude of a population impact is only detectable if measured against a baseline condition. For the population parameters that we've identified, there is a great deal of flexibility in choosing a specific metric. Because these parameters are important to all animal populations and have been used extensively in the salmon conservation and regulatory arenas, there are numerous examples of how they can be measured. The AEA Final Study Plan is essential for establishing a baseline. Specifically, examining the genetic relationships within and among salmon populations inhabiting the Susitna Watershed, quantifying the number of salmon within the watershed, and cataloging habitat use by life history stage will be important for defining the abundance, productivity, spatial structure, and diversity baselines.



Note: Panel 1 represents the focal area of Phase 1 of the ERA.

Figure 20

Panel 1 of Conceptual Model Illustrating the Pathways by which Project Activities are Translated to Habitat Attributes



Note: Panel 2 highlights the focal areas of the Analysis and Risk Characterization steps of the ERA.

Figure 21
Panel 2 of Conceptual Model Illustrating Changes to Habitat Attributes Translated to Low- and High-risk Population Outcomes
Ecological Risk Assessment of Large-scale Hydropower on Braided Rivers in Alaska: Phase 1
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5.2 Initial Consideration of Ecological Risk

The presence of the Project and proposed load following operations considered in this proposal are long-term in nature and have either permanent or dynamic impacts on flow regime, water quality, sediment supply, and the creation of an instream barrier. In both the external and Project-related literature review, there were strong indications that subordinate habitat processes and salmon habitat itself will be directly or indirectly altered through numerous pathways. Not all of the impacts are necessarily negative; there may be some improvements in habitat function, but the veracity of either beneficial or negative assessments requires comparison against a baseline that, in this case, is still forming. More specifically, there is a high degree of uncertainty about the magnitude or probability of these risks impacting salmon. In general, the most significant impacts appear to be located in the middle river and related to the following:

1. Changes in temperature that could affect the growth and development of eggs and rearing salmon
2. Loss of connectivity between macrohabitats (i.e., side channels and sloughs) that represent key sources of habitat complexity for juvenile and adult salmon
3. Disruption in timing and cues for juvenile and adult migrations
4. Poorly understood ice processes that appear to interact with virtually all habitat attributes/processes and will undergo substantial change
5. Loss of habitat above the Project (assuming a no passage scenario)
6. Flow fluctuations that have the potential to directly dewater redds or strand juveniles and indirectly cause habitat changes that alter the suitability of habitat for all life history stages (Figure 22)

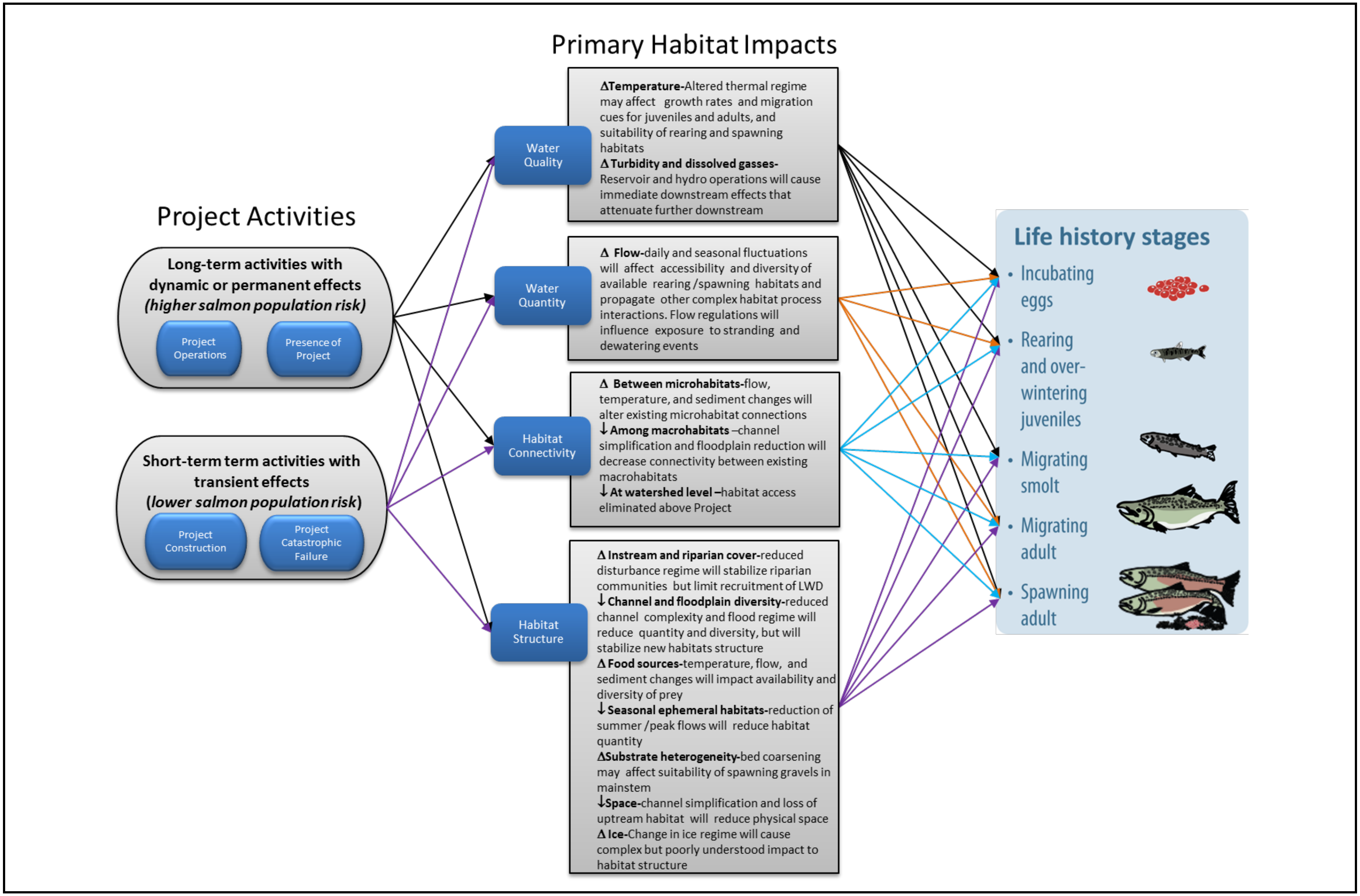

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Figure 22
Initial Summary of Ecological Interactions between Project Activities, Habitat Attributes, and Salmon Life Histories
Ecological Risk Assessment of Large-scale Hydropower on Braided Rivers in Alaska: Phase 1
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The effect of different facility type/power generation scenarios would likely change the severity of each risk. A run-of-the-river hydroproject would minimize operational disruptions to natural flow, water quality, and sediment supply considerably. It would not require a high head dam or major storage reservoir either. A base load facility would be intermediate to the run-of-the-river and load following configurations (both operationally and from a hydroproject footprint perspective). To maintain constant power generation capacity, a reservoir, albeit smaller, would be required and a dam that has enough head to meet the storage and generation capacity requirements. Either alternative would require major instream construction and would create short-term habitat degradation (i.e., independent of the operational effect of the Project). Of course, these alternatives may not be viable for a long list of reasons. One important consideration in the baseline environmental analysis of this Project is an evaluation of where power is likely to come from in the absence of the Project. It is outside of the scope of this ERA but is likely germane to the climate change risk.

Overlaid on long-term Project risks is the prospect of a rapidly changing climate that could modulate the Project impacts within the watershed and marine production outside of the watershed. Based on observations in Alaska and elsewhere, it appears that the effect of climate change will be significant and cause both the reduction of habitat through temperature thresholds and increase the suitability of other habitats that were formerly inaccessible or intolerable to salmon. In the absence of the Project proposal, there would likely be major impacts to some or all of the salmon species in the Susitna River based on the magnitude of climate change that is expected in Alaska and the glacial dynamics of the system.

The effects of construction, reservoir filling, and catastrophic failure are tentatively placed in a short-term transient impact category for the purpose of examining risks individually. The final assessment will include the cumulative sequential contributions of each and their potential interactions. That said, the combined construction and reservoir filling operations are on the outer edge of being considered "short-term" from a number-of-salmon-generations perspective and have considerable effects on habitat processes. In particular, the reduction of flow during reservoir filling appears to be one of the most intense Project effects and is anticipated to cause significant reductions in salmon productivity.

The risk of lost biological feedback starts and ends with the status of the population. If a population is healthy, the direct and indirect benefits of marine-derived nutrients will accrue. Because the biological feedback risk results as a consequence of all the other actions, it is more difficult to estimate how it will be affected by the Project, except that it will track the status of affected populations and perhaps buffer short-term impacts to them.

Based on our preliminary qualitative review of external and Project-related literature, it appears that Project operations would trigger a "Yes" in virtually every cell of the sensitivity matrix, for all species, life history stages, and habitat attributes. That is, all species will be affected by the proposed operational activities throughout their life histories. Additionally, because the operations will continue for decades into the foreseeable future, there is a strong element of persistence. The existence of overlap does not mean that all risks will translate to major declines in the populations, but it does suggest that the requisite components for population-level effects are in place. What remains largely unknown is the magnitude, and in some cases the direction, of the effect. Climate change and climate variability (i.e., marine productivity) are likely to amplify the effects either way.

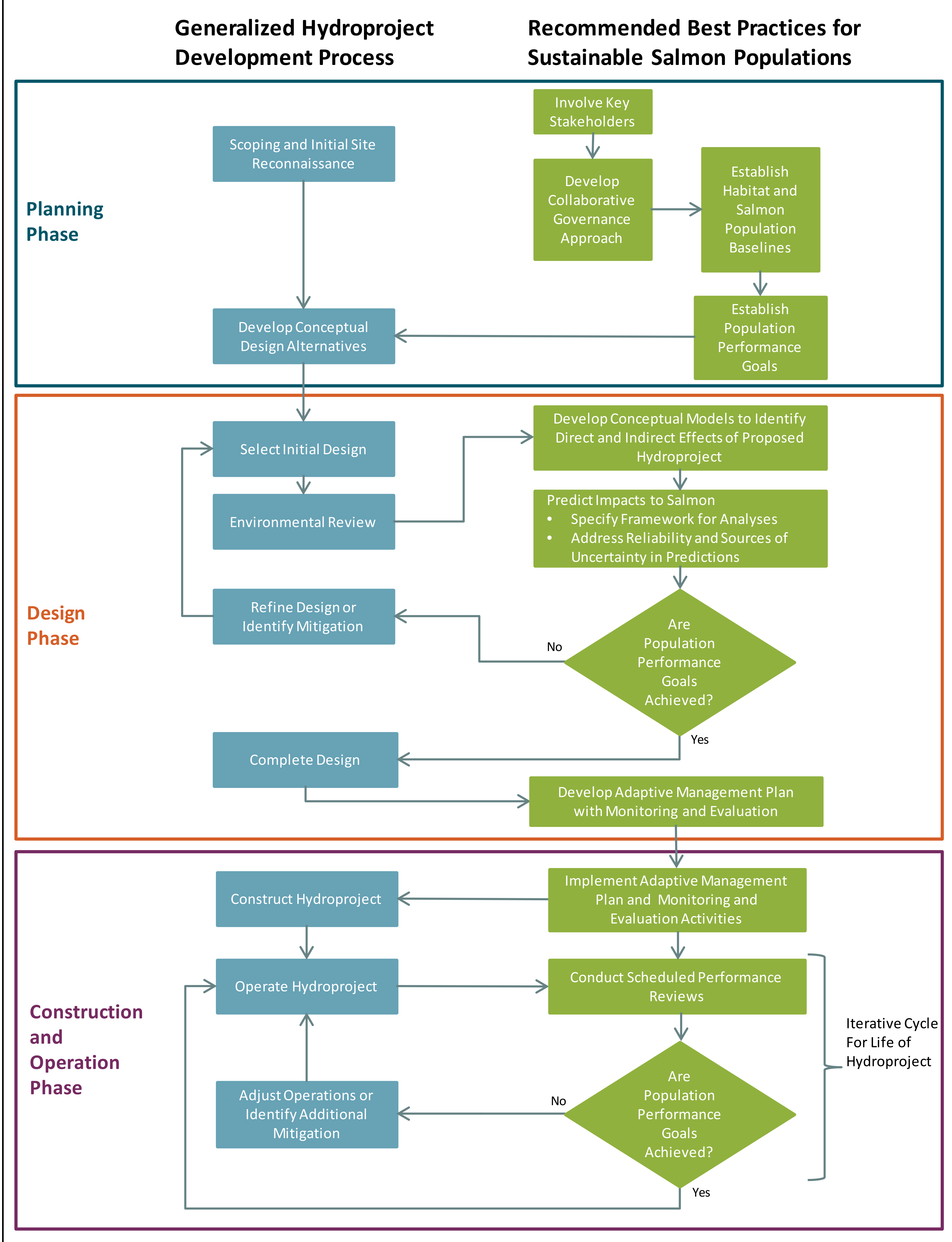
The formal analysis and risk characterization components of the ERA will include Project studies to establish baseline population parameters and will link potential habitat alterations to a measurable level of response by species and life history. Ultimately, these will be necessary to remove uncertainty from the risk equation and to inform the acceptance or mitigation of specific risks.

6 RECOMMENDED BEST PRACTICES

This section identifies recommended best practices for reducing risks to Pacific salmon during the planning, design, and implementation of large-scale hydropower projects in Alaska. These recommendations are based on information contained in other sections of this report as well as information and observations from other hydroprojects. The objective of these recommendations is to describe key process steps that will ensure that potential hydropower impacts are anticipated and ameliorated in order to maintain healthy, resilient salmon populations.

Sections 6.1 through 6.3 are organized to follow three generalized phases of hydroproject development: planning, design, and construction and operation. The planning phase represents the earliest part of the development process when scoping, site evaluations, and preliminary hydroproject design alternatives are considered. The design phase covers the period between the selection of a preferred conceptual design and the completion of the design process. During this period, licensing studies are implemented and environmental review processes are conducted. The construction and operation phase begins when the construction activities commence and continues through the operational life of the hydroproject. Because there are multiple licensing processes available (i.e., traditional, integrated, and alternative licensing processes) and the complexity of design will vary among potential project sites, we chose to use the generalized phases to represent and simplify a range of different development scenarios.

The recommendations provided for each phase are focused on establishing processes and broad goals that lead to sustainable populations rather than prescriptions for specific measures or actions. They are also intended to show how recommended best practices for maintaining sustainable salmon populations can be integrated into the development process (Figure 23). Again, this intentionally simplifies the expected process for any individual project to broaden the applicability of the recommendations.



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ANCHOR QEA

Figure 23
Recommended Steps and Integration between Best Practices for Salmon Populations and the Generalized Development Process for Large-scale Hydroproject
Ecological Risk Assessment of Large-scale Hydropower on Braided Rivers in Alaska: Phase 1
The Nature Conservancy

6.1 Planning Phase

The biggest opportunity for preserving sustainable salmon populations is early in the hydroproject development process, before design and permitting decisions have been made. During the planning period, recommendations include the following: 1) focusing on stakeholder involvement; 2) identifying collaborative decision-making processes; 3) establishing salmon and habitat population baselines; 4) identifying population performance goals for salmon that are affected by the proposed hydroproject; and, finally and most importantly, 5) incorporating performance goals into the hydroproject design (Figure 23). These recommendations are further detailed in Sections 6.1.1 through 6.1.5.

6.1.1 Involve Key Stakeholders

The participation of stakeholders in the planning process of a large-scale hydroproject is an important consideration for conserving ecological systems that support sustainable salmon populations. Early stakeholder involvement increases trust, understanding, and support for regional or ecosystem-based protection (Yaffee and Wondolleck 1997).

The roles of some stakeholders are established by regulations or management authority. For instance, state and federal agencies have managerial and regulatory responsibilities that ensure and delineate their involvement in hydropower planning processes. Other non-public entities may have discretionary or less direct involvement but can, nonetheless, change the trajectory of the development process. The breadth of stakeholders represented in the planning processes may be less important than the quality of contributions of a smaller set of "key stakeholders" (Brody 2003). The following groups represent non-public stakeholders that would be expected to play a significant role in the development of large-scale hydroproject development:

- Resource-based industries (e.g., commercial and sport fishing groups and tourism-based industries) bring additional data, resources, and innovation to planning processes. The groups may be particularly interested and effective because of the linkage between the economic viability of their operations and maintaining sustainable resources (Brody 2003).

- Non-governmental organizations (NGOs) whose missions are directly aligned with maintaining sustainable resources can significantly strengthen plans by bringing important environmental data and expertise to the planning process (Brody 2003)
- Native groups bring a depth of knowledge, data, and management involvement that has contributed to improved salmon conversation efforts (Kellert et al. 2000). In Alaska, native stakeholders also own large areas of land that may be affected by hydropower development and possesses strong cultural and economic links to sustainable salmon populations, factors which incentivize participation in planning processes.

The recommendation here is not to advocate for any specific entity as a stakeholder, but instead to note that the participation of key stakeholders matters in setting the trajectory of sustainability. Identifying and involving those key stakeholders that place a high priority on sustainable salmon will be important to ensuring that hydroproject design maintains this priority.

6.1.2 Incorporate Stakeholders in Collaborative Governance of Sustainable Salmon Populations

In addition to identifying key stakeholders, we also recommend adopting a "collaborative governance" approach to maximize the contributions of each towards achieving sustainable salmon populations. In this report, we include the general definition of collaborative governance provided by Ansell and Gash (2008) as the basis for our recommendation:

> *A governing arrangement where one or more public agencies directly engage non-state stakeholders in a collective decision-making process that is formal, consensus-oriented, and deliberative and that aims to make or implement public policy or manage public programs or assets.*

In this context, sustainable salmon populations would be the "public asset" and the "public agencies" and "non-state stakeholders" would be defined on a project-specific basis. Broadly, public agency representation would include state and federal fish managers, natural resource agencies, utilities, or other agencies. The non-state stakeholders would include native groups, NGOs, resource-based industries, or other interested parties.

The rationale for this approach is based on a number of different factors, including the complexity of balancing hydropower goals and sustainable salmon population goals. Complex resource management issues that require joint action of multiple parties are not well suited to traditional top-down, single-agency approaches (Berkes 2009). It is difficult for any single entity to possess all the information necessary for managing salmon and hydropower goals. Through a collaborative process, theoretically there is an opportunity to access and share the cumulative knowledge and data possessed by public agencies and non-state stakeholders (Armitage et al. 2008). The success of specific fish-friendly design efforts may in fact depend on bringing a wide range of expertise to the planning and design processes (Katopodis and Williams 2012). Including public agencies and non-state stakeholders in decision-making also provides an opportunity to distribute the responsibility for achieving population goals among stakeholders who possess a vested interest in sustainability. Ideally, this shared responsibility can build trust, promote more effective management (Brody 2003), and shift stakeholder interactions from adversarial to cooperative (Armitage et al. 2008).

Whether or not a collaborative governance approach would work in any setting is dependent on many factors such as prior history of conflict or cooperation, the incentives for stakeholders to participate, power and resources imbalances, leadership, and institutional design (Heikkila and Gerlak 2005; Ansell and Gash 2008). There are clear examples of collaborative processes that have achieved salmon conservation objectives (e.g., Kellert et al. 2000; Skalski and Bickford 2014) and examples where collaboration was less successful (e.g., Kellert et al. 2000; Waage 2003). The recommendation to address sustainable salmon populations through collaborative governance may be lofty, but also may represent the best possible outcome for salmon. Any recommendation to engage in collaborative governance would be incomplete without suggesting a thorough review of other case studies related to collaborative processes (e.g., Kellert et al. 2000; Brody 2003; Heikkila and Gerlak 2005; Armitage et al. 2008).

6.1.3 Establish Salmon Population and Habitat Baselines

Conducting a thorough inventory of the species that may be affected by hydropower development and establishing population baselines for each is a foundational step towards preserving healthy, sustainable salmon populations. The population baseline serves as a reference point from which impacts can be predicted, monitored, and evaluated.

Choosing appropriate population metrics is a key part of defining the baseline and sets the stage for future impact analyses. In this report, we identified four metrics or "population parameters"—abundance, productivity, diversity, and spatial structure—that are commonly used to characterize Pacific salmon populations and have been used extensively in conservation and recovery contexts. As noted in Section 1.3, these parameters represent general attributes that are important to all populations and all species, they are measurable, and they represent familiar metrics within the salmon conservation world and have recognized, yet flexible, utility as 'endpoints' for the evaluation of hydroproject impacts (McElhany et al. 2000; Busch et al. 2008). We recommend that these parameters should serve as general foundational components of any population baseline.

The baseline should also depict how the population parameters vary over time. Because salmon populations may exhibit significant fluctuations as a result of environmental drivers, the quality of the population baseline will be linked to the number of years of data that are available and the precision of monitoring efforts. Identifying meaningful changes in a population is complicated by natural variation and longer time series may improve the probability of detecting significant events (Fieberg and Ellner 2000; NOAA 2011).

It is worth noting that many of the strides made in conservation science, including formalized use of population parameters (McElhany et al. 2000), have occurred recently in the decades following construction of large hydroprojects in the Pacific Northwest. Many of these large-scale hydroprojects were constructed without a comprehensive population baseline or complete inventories of abundance, productivity, diversity, and spatial structure of affected species (ISAB 2015). As a result, many of the conservation, recovery, and mitigation efforts have been calibrated to an uncertain target or have been directed at estimating what the baseline was (ISAB 2015). It is difficult to identify what the recovery or conservation target should be in the absence of a reference baseline. In addition to the resources needed to attempt the forensic reconstruction of a population baseline, the lack of pre-project population data is also costly because it contributes to imprecise mitigation efforts that may further degrade the productivity of the remaining natural populations (Levin et al. 2001).

Similar to salmon population data, an understanding of baseline habitat function and processes is essential for predicting, monitoring, and evaluating how large-scale hydroprojects may influence the suitability and productivity of river habitats for salmon. More specifically, developing reliable quantitative relationships between habitat function and salmon population performance requires baseline data, for both habitat and salmon, of sufficient duration to account for variability and detection of change. Recognizing that large rivers are inherently dynamic, years of baseline data may be required to characterize habitat variability and predict or detect future changes associated with hydropower construction and operations. Long-term baseline study is necessary to assess the complete life cycles or multiple generations of salmonids, and may also reveal underlying biological feedback loops between salmon and habitats, as well as trends driven by external modulators such as climate change or marine productivity regimes.

The number of years and intensity of monitoring required for establishing an adequate habitat baseline would be case-specific and ideally aligned with the necessary inputs for models or other analyses used to link habitat change to salmon population responses (NOAA 2011).

The focal areas for a habitat baseline should be chosen on case-specific basis; however, in Section 2.4, some of the major habitat attributes and processes that may be impacted by large-scale hydroprojects in Alaska are presented and suggested as a starting point for establishing a habitat baseline. The impacts are defined and described in detail in Section 2.4 and include:

- First order impacts
  - Flow regime
  - Water quality
  - Sediment supply
  - Instream barriers to passage

- Second order impacts
  - Riparian community and succession
  - Ice formation and breakup
  - Floodplain and channel morphology
  - Surface and groundwater flow
  - Sediment erosion and deposition
  - Nutrient and trophic cycles
- Third order impacts
  - Water quality
  - Water quantity
  - Habitat connectivity
  - Habitat structure

For some watersheds, there may be existing monitoring data or ongoing research projects that can supply habitat baseline information (e.g., flow gages, water quality monitoring data, fisheries management data). However, for watersheds that are not well monitored, creating a robust baseline early in the planning stage will be challenging because the key variables that need to be monitored may not be fully apparent until the project is at a more complete design phase. Additionally, the commitment of resources necessary for intensive monitoring may not be available until there is adequate support for the hydroproject itself, which again requires significant design progress. If there is not clear agreement on the duration of baseline monitoring that is required for a large-scale hydroproject, design schedules may compress the window of time available for baseline monitoring. Therefore, one of the first and biggest planning challenges for establishing baselines may be identifying when monitoring needs to occur, for how long, and how it will be sequenced with the design.

6.1.4 Establish Population Performance Goals

Using habitat baselines and input from stakeholders, the most critical step in the planning process is to explicitly define the population performance goals that are necessary to maintain sustainable salmon populations. To the extent possible, we recommend that these goals are expressed using the population parameters that are congruent with population baseline data: abundance, productivity, spatial structure, and diversity. These parameters are used frequently in other population conservation contexts and therefore are supported by a foundation of scientific information from which each goal can be interpreted and evaluated (e.g., Good et al. 2007; Waples et al. 2009).

Selecting specific population performance goals serves several important purposes. First, the goals provide the foundation for defining sustainability and the currency for discussing and evaluating project impacts. With sufficient baseline data, the sensitivity and sustainability of a population can be modeled and specific goals evaluated before the project is implemented (e.g., Scheuerell et al. 2006). Additionally, if sustainability is defined by quantifiable goals—such as acceptable levels of change in abundance, productivity, spatial structure, and diversity parameters—the “sustainability target” can be scientifically evaluated and reviewed by stakeholders. Scientific review, in turn, provides an opportunity to reinforce the credibility and durability of sustainability goals that may require stakeholder approval and will be in place for multiple decades.

Population performance goals and metrics also establish endpoints for analytical frameworks that relate proposed project impacts and associated habitat changes to salmon populations. The existence of clear population goals also helps to illustrate the relationships between salmon and habitat related studies conducted under a FERC licensing process because the ultimate population endpoint is defined for both (i.e., population parameters are the endpoint).

6.1.5 Incorporating Population Performance Goals into the Basis of Design

A final benefit of defining explicit population performance goals during the planning process is their potential role in shaping the design of a hydroproject to minimize impacts to Pacific salmon. Establishing performance goals prior to completing the design, construction, and operation of a hydroproject provides an opportunity, if not a reason, to include the goals in the formal design process. Under this scenario, population performance goals become “design criteria” at a point where design modifications are still feasible. This option is preferable to identifying problems after the project is designed or operational, as fewer alternatives may exist to achieve performance goals at a later phase. For example, if connectivity between reaches upstream and downstream of a proposed dam is necessary to meet a population performance goal, design criteria such as the height of the project and development of fish passage alternatives could be considered to ensure that the performance goal is met. If performance goals are identified after design and construction are completed, the feasibility of providing fish passage may be reduced or very costly (Williams et al. 2012).

6.2 Design Phase

At the beginning of the design phase, it is assumed that a preferred conceptual design exists as the basis for environmental review and development of operational scenarios. Ideally, this early design is developed with salmon population performance goals as a portion of the design criteria (Figure 23) and with stakeholder involvement and collaborative governance continuing from the planning stage. As the design phase progresses; the information, processes, and goals established during the planning phase are used to interpret potential impacts from the proposed hydroproject and ideally to refine the design process until the final design is completed (Figure 23).

During the design phase, recommendations include: 1) using conceptual models to identify direct and indirect effect pathways between project activities and impacts to salmon; 2) predicting impacts to salmon; 3) evaluating whether predicted impacts allow achievement of salmon population performance goals; 4) developing adaptive management and monitoring and evaluation plans; and 5) identifying mitigation needs. These recommendations are further detailed in Sections 6.2.1 through 6.2.5.

6.2.1 Use Conceptual Models to Identify Direct and Indirect Effect Pathways between Project Activities and Impacts to Salmon

As a precursor to formally analyzing impacts from a large-scale hydroproject on salmon, we recommend developing conceptual models that illustrate the propagation of impacts from dam construction and operation through direct and indirect pathways to salmon populations.

Conceptual models serve several important functions including reducing complex systems or ecological interactions into manageable frameworks to support decision-making (DiGennaro et al. 2012), enhancing the communication of ideas among different disciplines (Heemskerk et al. 2003), establishing the framework for subsequent quantitative analyses (e.g., Guisan and Zimmermann 2000), and depicting or verifying the logic path for hypothesized ecological interactions (Geist and Dauble 1998; Thom 2000).

Within the context of sustainable salmon populations, developing conceptual models of direct and indirect effects before engaging in quantitative analyses of these effects is important. Specifically, conceptual models would provide the following opportunities:

- Allow stakeholders to evaluate the completeness of anticipated direct and indirect effects that will be studied
- Create a roadmap of the physical, biological, and ecological relationships that will be analyzed prior to allocating time and resources on specific in-depth licensing studies
- Ensure that project effect pathways lead to population performance metrics
- Enhance communication of anticipated project impacts among stakeholders

In Sections 2.4 and 2.7, we provide conceptual models and narratives that illustrate how different construction and operational scenarios may alter habitat processes, habitat attributes, and ultimately salmon populations through direct and indirect pathways. While these models may not be applicable to all large-scale hydroproject scenarios in Alaska, they illustrate a general framework by which project activities and their effects can be depicted. Again, any large-scale hydroproject would have unique direct and indirect effects on salmon that could vary considerably with the design and configuration of the hydroproject (Levin and Tolimieri 2001) as well as the environment in which it is constructed. The choice of a conceptual model should be tailored to these attributes and should consider the effectiveness of other models that have already been developed (e.g., Burke et al. 2009).

6.2.2 Predict Impacts to Salmon

In order to reasonably predict changes in population-level outcomes due to a large-scale hydroproject, project-related impacts should be formalized in a spatially-explicit, quantitative simulation model. The model is quantitative in that habitat attributes affecting salmon population persistence are represented numerically, and interactions between habitat attributes and population persistence are defined by mathematical relationships.

As background, it is useful to review some of the characteristics of quantitative models that may be used. There are two basic types: deterministic or stochastic. A deterministic model will always produce the same output when given the same inputs and starting conditions. A stochastic model incorporates randomness representing unpredictable natural variability (e.g., due to external modulators or unexpected biological feedback) and different runs of the model will produce different output when given the same inputs and starting conditions. A complete river simulation and life cycle model will incorporate both deterministic and stochastic components. For example, given a specified stream flow level, the water depth and the water velocity in a particular habitat unit are deterministic because of the physical properties of water when it fills a space. However, stream flow itself may be modelled stochastically to represent random variation due to weather fluctuations.

This rest of this section discusses the general use of quantitative models to predict how large-scale hydroprojects may impact salmon.

6.2.2.1 Specify Framework for Quantitative Analyses

The first step in predicting impacts to salmon is to establish the framework that will be used to conduct the analysis. This model framework should provide quantitative linkages that connect large-scale hydroproject activities to alterations in habitat processes, then to subsequent changes in population-level parameters. Thus, the model framework is a formalization of the risk framework discussed in Section 2.4 where impacts cascade from Project activities to first, second, third, and fourth order impacts.

Collectively, this framework represents the basis for a “simulation model.” Such a simulation model, if properly calibrated (matching model predictions for physical measurements such as water velocity to field measurement) and parameterized, can inform decision-making by providing estimates of the population-level outcomes associated with different hydroproject scenarios. A simulation model allows for tradeoffs between alternative hydroproject scenarios to be measured, providing the foundation for the development of management criteria that are mutually acceptable among stakeholders. Additionally, the process of developing a quantitative framework can reveal gaps in existing knowledge and expose critical areas of uncertainty. The results of a well-constructed quantitative simulation model can provide a reasonable basis for discussion of tradeoffs between various project scenarios.

The generalized framework that we suggest involves two stages. The first stage maps first order impacts to second and third order impacts in a physical river simulation model and the second stage maps second and third order impacts to fourth order impacts through a life cycle simulation model to population parameters.

For the first stage, a physical river simulation model would be used to represent the physical river system and would include key metrics such as stream flow; channel morphology; water depth, velocity, and temperature; and other aspects of physical habitat for salmonids. A river simulation model can be one- (e.g., PHABSIM, USGS; NetMap, Terrain Works), two- (e.g., River_2D, University of Alberta), or three-dimensional (e.g., UnTRIM); an increase in the number of dimensions represents a substantial increase in the complexity of the model but also an increase in the accuracy of the model at smaller scales. An example of a physical river simulation model is the River_2D model developed by the University of Alberta. This model begins with a representation of the physical features of the river channel bed as a collection of triangles that represent discrete areas of the river bed with associated topography. With a definition of the bed topography, and optionally ice topography, water depths and velocities are deterministically calculated for a given stream flow value. These values are then used to produce measurements of usable area for fish habitat. An example of a stochastic physical river model that incorporates disturbance is the Landscape Dynamics model of NetMap (Miller et al. 2002) that produces simulation of wood recruitment and changes in fish habitat.

For the second stage, the habitat characteristics of the physical river simulation model can be used as a template for a spatially explicit, life stage specific population dynamics model. A life stage specific population dynamics model uses habitat characteristics to stochastically predict fish population abundance, productivity, spatial structure, and diversity. The model is life stage specific in that the number of individuals of a fish population in a location at one stage of life (e.g., egg) is propagated to the next stage (e.g., fry) using a mathematic relationship. One common mathematical relationship is the Beverton-Holt function (Moussalli and Hilborn 1986), which determines the number of individuals at one stage based on the number of individuals at a previous stage and the expected survival of those individuals and the habitat capacity to support those individuals. Habitat characteristics, including water quality and physical habitat metrics, are related to survival and capacity based on empirical data. Examples of a spatially explicit, life stage specific population dynamics model include the SHIRAZ model (Scheuerell et al. 2006; Battin et al. 2007) and the Dam Impact Analysis model. The SHIRAZ model has been used to predict salmon responses to habitat change resulting from restoration or degradation in the Pacific Northwest (Scheurell et al. 2006; Honea et al. 2009). The Dam Impact Analysis model was developed to understand the impacts of multiple dams on the production of Atlantic salmon in the Penobscot River in the state of Maine (Nieland et al. 2013).

6.2.2.2 Address Reliability of Predictions and Identify Sources of Uncertainty

River simulation models are simplified representations of the physical river system, and as such, the predictions from a model are only approximations of the natural system. The quality of the predictions from a river simulation model is strongly dependent on the completeness of the model and the quality of the data used to parameterize the model. Here, parameterization means using empirical data to estimate the mathematical relationships between various components of the model. If the model is incomplete (for example, key characteristics like percent fines in sediment are missing), then the model predictions may not accurately reflect the real system because an important driver was left out of the model. If the data are of poor quality (for example, egg or fry survival data are insufficient to characterize the annual variability of egg-to-fry survival), then model predictions will also fail to be representative of the natural system.

The data necessary to parameterize the physical river simulation and fish life cycle components of the simulation model can come from a variety of sources. For the river simulation model, the data needed to specify the model are dependent on whether the model is one-, two-, or three-dimensional as well as the desired resolution, or smallest spatial unit of the model. A one-dimensional reach-based physical river simulation can be constructed using data acquired remotely in the form of digital elevation models to map the potential salmon habitat of a stream reach (Burnett et al. 2007). A two-dimensional river simulation model requires field-derived maps of bathymetry and dominant substrate type as well as in-field evaluation of water flow at various discharges to calibrate the model (Leclerc et al. 1995). Three-dimensional models are the most complicated, and include an extra term describing the physical properties of water at each depth (Casulli 2009). An example of a three-dimensional model is the UnTRIM model for the Sacramento-San Joaquin Delta (MacWilliams et al. 2007). Additional field data, such as water temperature measurements and transport of fine sediments, may be required for a more accurate model. For the fish life cycle components, the data needed to specify the model can come from field evaluations or from empirical relationships observed in similar systems (Honea et al. 2009). Examples of relationships between habitat characteristics and life-state-specific survival include the relationship between percent of fine sediment in a reach and egg survivorship (Tappel and Bjornn 1983) and the relationship between water temperature and the summer survivorship of juveniles (McHugh et al. 2004).

If only limited data are available to parameterize the simulation model, predictions may be unreliable because they will not fully capture the true range of variation in salmon populations. For example, the spatial distribution of both spawning adult and juvenile salmon are known to vary from year to year (Flitcroft et al. 2014). Similarly, overwinter survival and egg-to-smolt survival will vary spatially and among years and stocks (Ebersole et al. 2009, 2006). To obtain reasonable predictions, models should be parameterized using sufficient data to characterize this variability. This means multiple years of study may be needed to characterize variability of key parameters.

Lastly, any model will tend to make inaccurate predictions of unexpected or novel conditions. All models require assumptions of the inherent variability and expected range of outcomes, which are based on prior experience. However, there may exist conditions (e.g., catastrophic failure of the dam or large disturbances) that are well outside the range of prior experience. These events are metaphorically termed "black swan events"; they have a low probability of occurring, and large impacts (Taleb 2010). They are not well suited to study in a simulation model.

6.2.3 Evaluate Whether Predicted Impacts Allow Achievement of Salmon Population Performance Goals

From a sustainable population perspective, the key outcome of predicting project impacts on salmon is to assess whether or not the population performance goals are achievable based on the complete or near-complete design of the project (Figure 23). If the predicted impacts are within the range that allows population performance goals to be met, then the next step would be to develop an adaptive management plan with monitoring and evaluation steps (Figure 23). Alternatively, if population goals are unlikely to be met, design modifications or mitigation may be necessary (Figure 23).

6.2.4 Develop Adaptive Management and Monitoring and Evaluation Plans

When the construction and operation of the project are set to begin, having an adaptive management plan and monitoring and evaluation plan in place will be essential to ensure that the project actually meets the performance goals over the life of the project.

The development of an adaptive management plan should consider the specific attributes of a proposed hydroproject and population performance goals that have been identified. However, there are general components of adaptive management that are reiterated throughout the literature, summarized as follows. Adaptive management requires a clear statement of measurable management objectives and explicit predictions of expected outcomes. Alternative management actions that serve as alternative hypothesis should also be identified and be available for implementation if initial actions do not work as expected. Actions that are implemented should be treated as experiments in action and rigorously monitored; data from that monitoring should be acted upon to change (adapt) management actions if necessary. In summary, adaptive management is learning by doing and changing what is done based on what is learned (Walters and Holling 1990).

The management of river systems and salmon populations, with or without a hydropower project, often requires making difficult decisions. These decisions are usually made in the context of multiple objectives, constraints on authority and cost, and uncertainty about management outcomes. Because rivers and salmon populations are complex and interact dynamically, managers do not have perfect information from which to make decisions. In other words, uncertainty always accompanies management decisions. Adaptive management is a philosophy of natural resource management that provides a structure for making decisions under uncertainty while simultaneously reducing the uncertainty (Holling 1978; Williams and Johnson 1995). The central aim of adaptive management is to make decisions on the basis of clearly stated objectives that account for the current state of the system and anticipate the immediate and future impacts of decisions, and to learn from those decisions to inform future management (Williams et al. 2012). This attitude of management can be summarized as "policies are experiments: learn from them" (Lee 1993). Adaptive management is promoted by FERC as a method for reducing environmental impacts of existing hydroprojects. Recently, the U.S. Department of Energy has called for the use of adaptive management in monitoring and evaluating the environmental impacts of new hydrokinetic technologies in marine and river environments, the impacts of which are largely undetermined due to the novelty of such projects (DOE 2009).

Adaptive management is a structured and recurrent process. Adaptive management begins by recognizing that knowledge of ecological systems is incomplete and uncertain (Walters and Holling 1990). Thus, the first step to reducing this uncertainty it to define the problems and goals for management of the system through collaboration of scientists, managers, and stakeholders (Holling 1978; Walters 1986). Given a clear definition of problems and goals, the second step is to develop specific, measurable objectives, identify a suite of management actions and alternatives, and make predictions about the outcomes of those actions (Stankey et al. 2005). The third stage is to implement the management actions, treating implementation as an experiment by rigorously documenting and measuring the actions implemented (Lee 1999). The fourth stage is to monitor the systems after taking the management actions, again treating monitoring as a rigorous experiment (Williams et al. 2012). The fifth stage is to evaluate the system to determine if the management actions had the predicted effect, which leads back into a reassessment of the problem and renewal of the adaptive management process (Williams et al. 2009).

Monitoring is an essential component of the structured decision-making of adaptive management. A well-designed monitoring plan decreases uncertainty about key objectives and decisions and provides important information on the effectiveness of implemented actions. Monitoring fulfills three roles in adaptive management. First, baseline monitoring provides information on the current condition of the river system, which is used to inform the design of management alternatives. Second, implementation monitoring ensures that the actions taken are consistent with stated objectives. Third, effectiveness monitoring compares the changes in the system over time to predictions from competing hypothesis of the adaptive management process (Lyons et al. 2008; Nichols and Williams 2006). Thus, monitoring is used to reduce uncertainty and instigate change or adaptation of management strategies.

Monitoring under adaptive management is not simply gathering data in the hope of acquiring data that may prove useful. This type of surveillance monitoring is the monitoring of ecological systems without a specific objective and often focusing on multiple species of plant and animals, or over wide area (Yoccoz et al. 2001). Rather, monitoring as part of an adaptive management strategy should be designed to specifically address uncertainties identified in the design phase of adaptive management and to assess the stated objectives of the adaptive management program. The number of samples, frequency of monitoring, and level of precision of estimates should be guided by the specific objectives and hypothesis identified by adaptive management.

Targeted monitoring as part of an adaptive management program is a more efficient use of resources and provides more relevant data to meet management objectives. The monitoring of river systems and salmon populations is not an isolated activity, but rather an integrated component of an active and adaptive management strategy that reduces uncertainty and enhances the ability to make and implement decisions.

6.2.5 Identify Mitigation Needs

As the design phase progresses and the predicted impacts from a large-scale hydroproject become clearer, mitigation may be necessary to minimize negative impacts and help achieve population performance goals. Broad generalizations about the effectiveness of hydropower mitigation are difficult to make, as each project has a potentially different suite of impacts (Levin and Tolimieri 2001). However, some of the most commonly used mitigation approaches include the following:

- Improving fish passage for returning adults using fish ladders (Williams 2008)

- Improving downstream passage of juvenile salmon through the installation of bypass facilities or spilling water (Williams 2008)
- Modifying operations to create natural flow conditions or achieve specific life history survival objectives (Harnish et al. 2014)
- Using fish-friendly infrastructure to improve survival through turbines (Deng et al. 2011)
- Offsetting hydroproject mortality with hatchery produced salmon (Naish et al. 2007; Ferguson et al. 2010)
- Funding habitat improvements to address specific population goals (Hyatt et al. 2015)
- Minimizing gas supersaturation using different operational strategies (Politano et al. 2012)

Hydroproject mitigation that clearly addresses a population-limiting factor or a specific mechanism causing mortality may substantially improve the performance of an affected salmon population, but not all mitigation results in a clear benefit. Some of the most effective examples of mitigation include creating or improving adult and juvenile passage at dams (Kareiva et al. 2000) or modifying flow regimes to improve survival of targeted life history stages (Harnish et al. 2014). In other cases, the benefit of mitigation to wild salmon may be ambiguous. As an example, some hatcheries that produce salmon to mitigate for hydropower losses create additional conservation issues that can challenge the performance or recovery of the mitigated species (Levin et al. 2001; Naish et al. 2007). If the impacts of a large-scale hydroproject are substantial enough, there may not be an option that completely mitigates for habitat and population alterations (Williams 2008). Although each hydroproject is likely to create a unique set of impacts to salmon, it is worth considering previous case studies from the Pacific Northwest and elsewhere to fully evaluate the efficacy of mitigation approaches for a new project (Williams 2008; Ferguson et al. 2010)

6.3 Construction and Operation Phase

The construction and operation phase represents the culmination of planning and design efforts and the active on-the-ground portion of the project. Ideally, the population performance goals identified at the initial planning phase would be carried through the design process and fully realized upon construction and operation of the project. More specifically, the final design would be consistent with population sustainability and the implementation and adaptive management would be performed to verify achievement of specific performance goals. Similar to the previous phases, stakeholders and collaborative governance would remain important in the decision-making landscape as the project and adaptive management are actually implemented.

6.3.1 Implement Adaptive Management and Monitoring and Evaluation Plans

The implementation of the adaptive management plan would focus on monitoring population performance metrics after construction and during operations, and then evaluating the population performance (i.e., "performance review" in Figure 23) to determine if these actions had the predicted effect, which leads back into a reassessment of the problem and renewal of the adaptive management process (Williams et al. 2009). While we do not specify the frequency of performance evaluations, the simplified adaptive management process depicted in Figure 23 is iterative and would continue for the duration of the project. The adaptive management approach described in Figure 23 contemplates a simplified dichotomy: if performance goals are met, operations continue; if they are not met, operations are modified or additional mitigation is identified. The iterative process keeps performance goals and sustainability in focus over the life of the project. This approach relies on the existence of clear linkages between performance metrics and specific management actions identified during the development of the adaptive management plan (Section 6.2.4) and as informed by the accumulation of data and knowledge over multiple performance review cycles.

The following three examples represent success stories where new collaborative approaches and adaptive management during the operation phase have led to successful outcomes for salmon. In each example, salmon populations have rebounded following the major declines attributed in part to hydropower developments:

1. Upper Columbia River Juvenile Survival Standards (Skalski and Bickford 2014):
   - At Wells, Rocky Reach, and Rock Island dams, different combinations of operational and infrastructure improvements were used to reduce juvenile mortality

  - Collaborative effort between public utility districts, state and federal agencies, and native groups
  - Habitat conservation plans provided governance framework
  - Adaptive management provided flexibility for the development of different spill and bypass infrastructure options to meet survival goals
  - Survival standards were achieved for juvenile sockeye salmon, Chinook salmon, and steelhead

2. Improved Flow Regulation in Middle Columbia River (Harnish et al. 2014):

   - Hydroproject operations have been coordinated to improve the flow regime in the Hanford Reach to support fall Chinook salmon incubation and rearing objectives
   - Collaborative effort between public utility districts, state and federal agencies, and native groups
   - Hanford Reach Fall Chinook Protection Program provided framework for governance
   - Adaptive management provided flexibility to test different hydroproject operations to meet specific biological objectives during spawning, incubation, and emergence periods
   - Significant increases in fall Chinook salmon abundance coinciding with improved flow management

3. Okanogan River Fresh Water Management Tool (FWMT; Hyatt et al. 2015):

   - The FWMT was developed as an adaptive management option to compensate for hydroproject mortality (example of non-hatchery mitigation for hydropower impacts)
   - Increases survival of incubating sockeye salmon in the Okanogan River through improved flow management
   - Collaborative effort between a public utility district; state, federal, and provincial agencies; and native and private entities
   - Habitat conservation plans provided governance framework
   - Sockeye runs have increased significantly since the tool was developed

As noted above, there is a considerable body of knowledge related to the development and implementation of adaptive management plans and the use of collaborative processes (e.g., Walters and Holling 1990; Armitage et al. 2008). Our recommendation is to use both from the beginning of the project and to consider previous case studies to guide the development of specific plans for future large-scale hydroprojects in Alaska.

7 CONCLUSION

Large–scale hydroprojects can significantly alter the habitat processes and attributes, which wild salmon require. The risk posed by an individual hydroproject will be influenced to a great extent by the design and operation of the facility and the degree to which sustainable populations are prioritized in the planning and design process. In this ERA, we present information and conceptual models that are intended not only to show the linkages between impacts of a hydroproject to salmon habitat and the responses of salmon populations, but also to demonstrate the complexity of those relationships.

Clearly mapping impacts as they propagate from project activities through habitat pathways and ultimately to salmon populations is essential for interpreting the risk posed by any hydroproject. The framework used in this report provides one method of depicting impacts and evaluating risks of hydropower in Alaskan watersheds. One of the key conclusions of this report is the importance of defining clear endpoints for analyzing population risks. For wild salmon we recommend using population parameter endpoints that are quantifiable, recognized, and supported by a foundation of conservation science. Specifically, population abundance, productivity, diversity, and spatial structure meet these criteria and are useful endpoints for predicting and evaluating project impacts to wild salmon.

In the case of the proposed Susitna-Watana hydroproject, salmon habitat and populations would clearly be affected but there is a high degree of uncertainty about the magnitude or probability of the risks. Defining project operations and completing baseline studies will be necessary first steps to fully assess the impact or risk of the project to individual salmon populations. Because climate change, marine productivity, and biological feedback also play important roles in shaping salmon populations—and will interact with any hydroproject impacts—they should also be considered in future analyses. Moreover, once the results of baseline studies are available and an operational plan has been selected, this information needs to be incorporated into an analysis that provides an explicit prediction of population outcomes.

While each hydroproject presents a potentially unique risk profile, maintaining sustainable populations in any watershed requires clear goals for populations that may be affected.

Specifically, population performance goals must be made a priority in the planning, design, and operation of a hydroproject rather than an afterthought. The overall goal should be to protect salmon at the inception of a project rather than attempt to recover impaired populations in the future. To include salmon sustainability in plans for future large-scale hydroprojects in Alaska, we recommend the following:

- Implement collaborative processes and adaptive management from the initial planning phase through the life of the hydroproject
- Establish comprehensive baselines for affected habitat and populations
- Include climate change, marine productivity, and biological feedback in evaluations of hydroproject effects
- Establish salmon population performance goals that will be incorporated into the hydroproject design
- Use conceptual and analytical frameworks to illustrate how population impacts will be interpreted, and use stakeholder input to confirm and refine linkages among project activities, habitat processes, and population parameter endpoints
- Use stakeholder-reviewed conceptual and analytical frameworks as the foundation for developing baseline studies
- Explicitly predict hydroproject impacts to salmon populations and then compare results with population performance goals; if impacts are unacceptable, modify design or operation of the hydroproject
- Use monitoring plans and scheduled reviews to evaluate the achievement of population performance goals during construction and operation of the hydroproject
- When performance goals are not achieved, refine project operations or provide mitigation to meet goals

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APPENDIX A
ANNOTATED BIBLIOGRAPHY

ANNOTATED BIBLIOGRAPHY

PHASE 1 ANNOTATED BIBLIOGRAPHY
PRELIMINARY FRAMEWORK FOR ECOLOGICAL RISK ASSESSMENT OF LARGE-SCALE HYDROPOWER ON BRAIDED RIVERS IN ALASKA

Prepared for

The Nature Conservancy

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June 2015

1 SUMMARY OF CONTENTS

This document comprises the preliminary annotated bibliography for literature reviewed in the Ecological Risk Assessment (ERA) and Best Available Information scores for each item (Table A-1).

1.1 Annotated Bibliography

ABR, Inc., 2013. *Riparian Vegetation Study Downstream of the Proposed Susitna-Watana Dam. Susitna-Watana Hydroelectric Project (FERC No. 14241).* Alaska Energy Authority.

Abstract: The data collected for this study, in combination with the data collected for the Riparian Instream Flow Study, will provide the baseline information from which predictive models will be developed to assess likely changes in riparian ecosystems downstream of the proposed dam. A thorough understanding of how the proposed Project activities would affect hydrologic processes and riparian ecosystems downstream of the dam will be critical for developing best management practices, assessing potential impacts to wildlife, and preparing adequate Federal Energy Regulatory Commission (FERC) documentation of Project effects.

Achord, S., P.S. Levin, and R.W. Zabel, 2003. Density-dependent mortality in Pacific salmon: the ghost of impacts past? *Ecology Letters* 6, 335–342.

Abstract: Conservation biologists often ignore density dependence because at-risk populations are typically small relative to historical levels. However, if populations are reduced as a result of impacts that lower carrying capacity, then density-dependent mortality may exist at low population abundances. Here, we explore this issue in threatened populations of juvenile Chinook salmon (*Oncorhynchus tshawytscha*). We followed the fate of more than 50,000 juvenile Chinook in the Snake River Basin, USA to test the hypothesis that their survival was inversely associated with juvenile density. We also tested the hypotheses that non-indigenous brook trout and habitat quality affect the presence or strength of density dependence. Our results indicate that juvenile Chinook suffer density-dependent mortality and the strength of density dependence was greater in streams in which brook trout were absent. We were unable to detect an effect of habitat quality on the strength of density dependence. Historical impacts of humans have greatly reduced population sizes of salmon, and the density dependence we report may stem from a shortage of nutrients normally derived from decomposing salmon carcasses. Cohorts of juvenile salmon may experience density-dependent mortality at population sizes far below historical levels and recovery of imperiled populations may be much slower than currently expected.

Adam, J.C., A.F. Hamlet, and D.P. Lettenmaier, 2009. Implications of global climate change for snowmelt hydrology in the twenty-first century. *Hydrological Processes* 23, 962–972.

Abstract: For most of the global land area poleward of about 40° latitude, snow plays an important role in the water cycle. The (seasonal) timing of runoff in these areas is especially sensitive to projected losses of snowpack associated with warming trends, whereas projected (annual) runoff volume changes are primarily associated with precipitation changes, and to a lesser extent, with changes in evapotranspiration. Regional studies in the USA (and especially the western USA) suggest that hydrologic adjustments to a warming climate have been ongoing since the mid-twentieth century. We extend the insights extracted from the western USA to the global scale using a physically based hydrologic model to assess the effects of systematic changes in precipitation and temperature on snow-affected portions of the global land area as projected by a suite of global climate models. While annual (and in some cases seasonal) changes in precipitation are a key driver of projected changes in annual runoff, we find, as in the western USA, that projected warming produces strong decreases in winter snow accumulation and spring snowmelt over much of the affected area regardless of precipitation change. Decreased snowpack produces decreases in warm-season runoff in many mid- to high-latitude areas where precipitation changes are either moderately positive or negative in the future projections. Exceptions, however, occur in some high-latitude areas, particular in Eurasia, where changes in projected precipitation are large enough to result in increased, rather than decreased, snow accumulation. Overall, projected changes in snowpack and the timing of snowmelt-derived runoff are largest near the boundaries of the areas that currently experience substantial snowfall, and at least qualitatively, they mirror the character of observed changes in the western USA.

ADF&G (Alaska Department of Fish and Game), 1983a. *Aquatic Studies Procedures Manual: Phase II – Final Draft 1982-1983*. Alaska Department of Fish and Game. Su-Hydro Aquatic Studies Program. Anchorage, Alaska. 257 pp.

Abstract: Summary of historical study design information.

ADF&G, 1983b. *Susitna Hydro Aquatic Studies Phase II Report Volume I: Summarization of Volumes 2, 3, 4; Parts I and II, and 5*. Alaska Department of Fish and Game, Anchorage, Alaska. 146 pp.

Abstract: Summary of historical studies conducted by ADF&G to evaluate fish impacts.

ADF&G, 2013a. *Chinook Salmon Stock Assessment and Research Plan, 2013*. ADF&G Chinook Salmon Research Team. January 2013. Available from: http://www.adfg.alaska.gov/static/home/news/hottopics/pdfs/chinook_research_plan.pdf.

Abstract: Summary of Chinook salmon studies anticipated in response to recent regional declines.

ADF&G, 2013b. *Distribution of Spawning Susitna River Chinook Oncorhynchus tshawytscha and Pink Salmon O. gorbuscha, 2012*. Susitna-Watana Hydroelectric Project (FERC No. 14241). Alaska Energy Authority.

Abstract: This report provides the results of ADF&G's Chinook and pink salmon tasks of the 2012 Adult Salmon Distribution and Habitat Utilization Study (Chinook and pink salmon spawning distribution).

ADF&G, 2013c. *Implementation Plan for the Genetic Baseline Study for Selected Fish Species in the Susitna River, Alaska*. Susitna-Watana Hydroelectric Project (FERC No. 14241). Alaska Energy Authority.

Abstract: This operational plan describes the first study necessary for the application of genetic information and methods to evaluate Project effects on fish in the Susitna River. It will begin by developing a repository of fish tissues from anadromous (defined in this document as Chinook, chum, coho, pink, and sockeye salmon) and resident (defined in this document as all other species) fishes. These tissue repositories will be used for future studies necessary to characterize the genetic legacy and variation for species and populations of interest. It is important to collect tissue samples before the Project begins to examine possible changes in population structure associated with the Project.

ADF&G, 2013d. *Regional Operational Plan DF.#R.13-XX Implementation Plan for the Genetic Baseline Study for Selected Fish Species in the Susitna River, Alaska Susitna-Watana Hydroelectric Project (FERC No. 14241)*. Alaska Energy Authority.

Abstract: Submittal document for genetic study plan.

AEA (Alaska Energy Authority), 2011. *Pre-Application Document*.

Abstract: Summary of Project and anticipated impacts.

AEA, 2012. *Revised Study Plan*. Susitna-Watana Hydroelectric Project FERC Project No. 14241. Alaska Energy Authority, Anchorage, Alaska.

Abstract: Compilation of updated Project resource studies that have been proposed. Encompasses fish and aquatic resources.

AEA, 2013a. *Analysis of Fish Harvest in and Downstream of the Susitna-Watana Hydroelectric Project Area Study Plan Section 9.15 Final Study Plan*. Susitna-Watana Hydroelectric Project (FERC No. 14241). Alaska Energy Authority.

Abstract: Final study plan addressing harvest in the Project vicinity.

AEA, 2013b. *Aquatic Resources Study within the Access Alignment, Transmission Alignment, and Construction Area Study Plan Section 9.13 Final Study Plan*. Susitna-Watana Hydroelectric Project (FERC No. 14241). Alaska Energy Authority.

Abstract: Summary of construction-related non-hydro activities that will be associated with the Project.

AEA, 2013c. *Fish and Aquatic Resources Study Plan Section 9 Introduction Final Study Plan*. Susitna-Watana Hydroelectric Project (FERC No. 14241). Alaska Energy Authority.

Abstract: The final study plan focusing on fish and aquatic resources. One of several final resource study plans.

AEA, 2013d. *Probable Maximum Flood (PMF) Study Plan Section 16.5 Final Study Plan*. Susitna-Watana Hydroelectric Project (FERC No. 14241). Alaska Energy Authority.

Abstract: This study focuses on developing a site-specific Probable Maximum Precipitation and modeling the PMF.

AEA, 2013e. *Site-Specific Seismic Hazard Study Plan Section 16.6 Final Study Plan*. Susitna-Watana Hydroelectric Project (FERC No. 14241). Alaska Energy Authority.

Abstract: The goals of this study are to conduct deterministic and probabilistic seismic hazard evaluations to estimate earthquake ground motion parameters at the Project site, assess the risk at the site and the loads that the Project facilities would be subject to during and following seismic events, and propose design criteria for Project facilities and structures considering the risk level.

AEA, 2013f. *Susitna River Large Woody Debris Reconnaissance*. Technical Memorandum. Susitna- Watana Hydroelectric Project (FERC No. 14241). Alaska Energy Authority.

Abstract: This technical memorandum reports preliminary observations of the role and function of Susitna River large woody debris (LWD) made by the Riparian Vegetation Survey team over a 10-day period between June 23, 2012 and July 3, 2012.

AEA, 2013g. *The Future Watana Reservoir Fish Community and Risk of Entrainment Study Plan Section 9.10. Final Study Plan*. Susitna-Watana Hydroelectric Project (FERC No. 14241). Alaska Energy Authority.

Abstract: The nature of the fish community inhabiting the proposed Watana Reservoir will depend on a suite of interrelated factors affecting fish populations and their habitat. These factors may be influenced by the design and operation of the Project. This study plan describes the efforts that will be implemented to predict the fish community that will develop in the Project's reservoir and identify the effects of the Project on the future reservoir fish community.

AEIDC (Arctic Environmental Information and Data Center), 1984. *Assessment of the effects of the proposed Susitna Hydroelectric Project on instream temperature and fishery resources in the Watana to Talkeetna reach*. Submitted to Harza-Ebasco Susitna Joint Venture. The Alaska Power Authority.

Abstract: Historic evaluation of interactions between fish populations and the habitat modifications expected from the proposed Project.

Al-Chokhachy, R., S.J. Wenger, D.J. Isaak, and J.L. Kershner, 2013. Characterizing the Thermal Suitability of Instream Habitat for Salmonids: A Cautionary Example from the Rocky Mountains. *Transactions of the American Fisheries Society* 142, 793–801.

Abstract: Understanding a species' thermal niche is becoming increasingly important for management and conservation within the context of global climate change, yet there have been surprisingly few efforts to compare assessments of a species' thermal niche across methods. To address this uncertainty, we evaluated the differences in model performance and interpretations of a species' thermal niche when using different measures of stream temperature and surrogates for stream temperature. Specifically, we used a logistic regression modeling framework with three different indicators of stream thermal conditions (elevation, air temperature, and stream temperature) referenced to a common set of brook trout (*Salvelinus fontinalis*) distribution data from the Boise River basin, Idaho. We hypothesized that stream temperature predictions that were contemporaneous with fish distribution data would have stronger predictive performance than composite measures of stream temperature or any surrogates for stream temperature. Across the different indicators of thermal conditions, the highest measure of accuracy was found for the model based on stream temperature predictions that were contemporaneous with fish distribution data (percent correctly classified = 71%). We found considerable differences in inferences across models, with up to 43% disagreement in the amount of stream habitat that was predicted to be suitable. The differences in performance between models support the growing efforts in many areas to develop accurate stream temperature models for investigations of species' thermal niches.

Alderdice, D.F., W.P. Wickett, and J.R. Brett, 1958. Some Effects of Temporary Exposure to Low Dissolved Oxygen Levels on Pacific Salmon Eggs. *Journal of the Fisheries Research Board of Canada* 15, 229–250.

Abstract: Eggs of the chum salmon (*Oncorhynchus keta*) were exposed to various constant levels of dissolved oxygen for a period of seven days. The procedure was repeated with fresh egg samples at various developmental stages. Temperatures were constant at 10 °C from fertilization to hatching. Estimates of oxygen consumption uninhibited by low dissolved oxygen levels were obtained at various stages of egg development for whole eggs and also on the basis of the weight of larvae, excluding the yolk. Eggs were most sensitive to hypoxia between 100–200 Centigrade degree-days and compensated for reduced oxygen availability by reducing the oxygen demand and rate of development. Very low oxygen levels at early incubation stages resulted in the production of monstrosities. At about the time the circulatory system becomes functional the compensatory reduction in rate of growth under hypoxial conditions is reduced, but eggs no longer survive extreme hypoxial conditions. Eggs subjected to low dissolved oxygen levels just prior to hatching hatch prematurely at a rate dependent on the degree of hypoxia. The maximum premature hatching rate corresponded approximately with the median lethal oxygen level. Estimated median lethal levels rose slowly from fertilization to hatching. Oxygen consumption per egg rose from fertilization to hatching while the consumption per gram of larval tissue declined from a high to a low level at about the time of blastopore closure. Subsequently, a slight rise in the rate occurred up to a level which was more or less constant to hatching. "Critical" dissolved oxygen levels were calculated and they appear to define the oxygen level above which respiratory rate is unmodified by oxygen availability. Critical levels ranged from about 1 p.p.m. in early stages to over 7 p.p.m. shortly before hatching.

Andersson, E., C. Nilsson, and M.E. Johansson, 2000. Effects of river fragmentation on plant dispersal and riparian flora. *Regulated Rivers: Research & Management* 16, 83–89.

Abstract: We evaluated the effects of river fragmentation by dams on hydrochory (i.e., plant dispersal by water) and on plant distribution by comparing two adjacent rivers in northern Sweden, one free-flowing and the other regulated. We collected stranded drift material from both rivers in order to quantify the drift material and its species content. We also estimated the floristic continuity along the two rivers by comparing the drift flora with the riparian flora further upstream. The drift amount deposited on the riverbank, its species richness and its contribution to the species pool were higher in the free-flowing than in the regulated river. The floristic continuity was also higher in the free-flowing than in the regulated river.

Andrew, F.J., and G.H. Geen, 1960. *Sockeye and Pink Salmon Production in Relation to Proposed Dams in the Fraser River System (Bulletin XI)*. International Pacific Salmon Fisheries Commission, New Westminster, B.C., Canada.

Abstract: An analysis of salmon impacts expected from proposed hydro projects on the Fraser River.

Arntzen, E.V., D.R. Geist, and P.E. Dresel, 2006. Effects of fluctuating river flow on groundwater/surface water mixing in the hyporheic zone of a regulated, large cobble bed river. *River Research and Applications* 22, 937–946.

Abstract: Physicochemical relationships in the boundary zone between groundwater and surface water (i.e. the hyporheic zone) are controlled by surface water hydrology and the hydrogeologic properties of the riverbed. We studied how sediment permeability and river discharge altered the vertical hydraulic gradient (VHG) and water quality of the hyporheic zone within the Hanford Reach of the Columbia River. The Columbia River at Hanford is a large, cobble-bed river where water level fluctuates up to 2 m daily because of hydropower generation. Concomitant with river stage recordings, continuous readings were made of water temperature, specific conductance, dissolved oxygen and water level of the hyporheic zone. The water level data were used to calculate VHG between the river and hyporheic zone. Sediment permeability was estimated using slug tests conducted in piezometers installed into the river bed. The response of water quality measurements and VHG to surface water fluctuations varied widely among study sites, ranging from no apparent response to covariance with river discharge. At some sites, a hysteretic relationship between river discharge and VHG was indicated by a time lag in the response of VHG to changes in river stage. The magnitude, rate of change and hysteresis of the VHG response varied the most at the least permeable location (hydraulic conductivity (K) = 2.9 × 10−4 cms−1) and the least at the most permeable location (K = 8.0 × 10−3 cms−1). Our study provides empirical evidence that sediment properties and river discharge both control the water quality of the hyporheic zone. Regulated rivers, like the Columbia River at Hanford, that undergo large, frequent discharge fluctuations represent an ideal environment in which to study hydrogeologic processes over relatively short time periods (i.e. days to weeks) that would require much longer periods (i.e. months to years) to evaluate in unregulated systems.

Barnes, J.L., D.E. Peters, and J.W.A. Grant, 1985. Evaluation of a Velocity-Related Fish Passage Problem Downstream of the Upper Salmon Hydroelectric Development, Newfoundland. *Canadian Water Resources Journal* 10, 1–12.

Abstract: A potential velocity barrier which could preclude the migration of ouananiche (*Salmo salar*) and brook trout (*Salvelinus fontinalis*) to their spawning habitat in the upper West Salmon River was identified downstream of the Upper Salmon Hydroelectric Development. An HEC-2 backwater computer model was used to assess current velocities downstream of the project and to identify areas where fish passage might be prevented. Predicted velocities in three areas

appeared to be only marginally greater than that thought to be critical, indicating that fish passage might not be prevented. As a consequence, a post-development monitoring study was undertaken to determine the success of fish passage and the need for mitigation. The monitoring study found that fish passage was unimpeded under the post-development flow regime and that no mitigation was required. The interdisciplinary approach used to evaluate this velocity-related fish passage problem is discussed, and the interaction between regulator and proponent is examined in relation to the environmental impact assessment process.

Barnett, T.P., J.C. Adam, and D.P. Lettenmaier, 2005. Potential impacts of a warming climate on water availability in snow-dominated regions. *Nature* 438, 303–309.

Abstract: All currently available climate models predict a near-surface warming trend under the influence of rising levels of greenhouse gases in the atmosphere. In addition to the direct effects on climate—for example, on the frequency of heatwaves—this increase in surface temperatures has important consequences for the hydrological cycle, particularly in regions where water supply is currently dominated by melting snow or ice. In a warmer world, less winter precipitation falls as snow and the melting of winter snow occurs earlier in spring. Even without any changes in precipitation intensity, both of these effects lead to a shift in peak river runoff to winter and early spring, away from summer and autumn when demand is highest. Where storage capacities are not sufficient, much of the winter runoff will immediately be lost to the oceans. With more than one-sixth of the Earth's population relying on glaciers and seasonal snow packs for their water supply, the consequences of these hydrological changes for future water availability—predicted with high confidence and already diagnosed in some regions—are likely to be severe.

Barnett, T.P., D.W. Pierce, H.G. Hidalgo, C. Bonfils, B.D. Santer, T. Das, G. Bala, A.W. Wood, T. Nozawa, A.A. Mirin, D.R. Cayan, and M.D. Dettinger, 2008. Human-Induced Changes in the Hydrology of the Western United States. *Science* 319, 1080–1083.

Abstract: Observations have shown that the hydrological cycle of the western United States changed significantly over the last half of the 20th century. We present a regional, multivariable climate change detection and attribution study, using a high-resolution hydrologic model forced by global climate models, focusing on the changes that have already affected this primarily arid region with a large and growing population. The results show that up to 60% of the climate-related trends of river flow, winter air temperature, and snow pack between 1950 and 1999 are human-induced. These results are robust to perturbation of study variates and methods. They portend, in conjunction with previous work, a coming crisis in water supply for the western United States.

Barrett, B.M., F.M. Thompson, and S.N. Wick, 1984. *Adult anadromous fish investigations: May-October 1983. Report No. 1*. Alaska Department of Fish and Game, Susitna Hydro Aquatic Studies, Anchorage, Alaska.

Abstract: A study on seasonal distribution, relative abundance, and spawning areas of anadromous fish species--eulachon, Pacific salmon and Bering cisco--in the Susitna River and Yentna River with discussion on tributary creeks. Written as one of a series of reports used in feasibility studies of the Susitna Hydroelectric Project in Alaska.

Barrett, B.M., F.M. Thompson, and S.N. Wick, 1985. *Adult salmon investigations: May-October 1984*. Report No. 6. Alaska Department of Fish and Game, Susitna Hydro Aquatic Studies, Anchorage, Alaska.

Abstract: This (1984) ends the fourth consecutive year of study of the Susitna River adult anadromous fish populations by the ADF&G associated with APA proposed hydroelectric development at Watana and Devil canyons. The emphasis on the 1984 program was quantifying Susitna River salmon escapements and salmon spawning activity in the Susitna River main channel and directly associated streams, sloughs, and side channels.

Bartz, K.K., K.M. Lagueux, M.D. Scheuerell, T. Beechie, A.D. Haas, and M.H. Ruckelshaus, 2006. Translating restoration scenarios into habitat conditions : an initial step in evaluating recovery strategies for Chinook salmon (*Oncorhynchus tshawytscha*). *Canadian Journal of Fisheries and Aquatic Sciences* 63, 1578–1595.

Abstract: One of the challenges associated with recovering imperiled species, such as Chinook salmon (*Oncorhynchus tshawytscha*), is identifying a set of actions that will ensure species' persistence. Here we evaluate the effects of alternative land use scenarios on habitat conditions potentially important to Chinook salmon. We first summarize the alternative scenarios as target levels for certain land use characteristics. We then use the target levels to estimate changes in current habitat conditions. The scenarios we explore indicate considerable potential to improve both the quality and quantity of salmon habitat through protection and restoration. Results from this analysis constitute the habitat inputs to a population model linking changes in habitat to salmon population status. By transparently documenting the approach we use to translate land use actions into changes in salmon habitat conditions, we provide decision makers with a clear basis for choosing strategies to recover salmon.

Battin, J., M.W. Wiley, M.H. Ruckelshaus, R.N. Palmer, E. Korb, K.K. Bartz, and H. Imaki, 2007. Projected impacts of climate change on salmon habitat restoration. *Proceedings of the National Academy of Sciences* 104, 6720–6725.

Abstract: Throughout the world, efforts are under way to restore watersheds, but restoration planning rarely accounts for future climate change. Using a series of linked models of climate, land cover, hydrology, and salmon population dynamics, we investigated the impacts of climate change on the effectiveness of proposed habitat restoration efforts designed to recover depleted Chinook salmon populations in a Pacific Northwest river basin. Model results indicate a large negative impact of climate change on freshwater salmon habitat. Habitat restoration and protection can help to mitigate these effects and may allow populations to increase in the face of climate change. The habitat deterioration associated with climate change will, however, make salmon recovery targets much more difficult to attain. Because the negative impacts of climate change in this basin are projected to be most pronounced in relatively pristine, high-elevation streams where little restoration is possible, climate change and habitat restoration together are likely to cause a spatial shift in salmon abundance. River basins that span the current snow line appear especially vulnerable to climate change, and salmon recovery plans that enhance lower-elevation habitats are likely to be more successful over the next 50 years than those that target the higher-elevation basins likely to experience the greatest snow–rain transition.

Beacham, T.D., and C.B. Murray, 1989. Variation in developmental biology of sockeye salmon (*Oncorhynchus nerka*) and Chinook salmon (*O. tshawytscha*) in British Columbia. *Canadian Journal of Zoology* 67, 2081–2089.

Abstract: Embryos and alevins of coastal-spawning and interior-spawning sockeye (*Oncorhynchus nerka*) and Chinook (*O. tshawytscha*) salmon stocks in British Columbia were incubated under controlled water temperatures of 2,4, 8, 12, and 15 "C. At low incubation temperatures, interior-spawning stocks of both species had smaller eggs and higher embryo survival rates than did coastal-spawning stocks. Interior-spawning stocks had faster developmental rates to alevin hatching and fry emergence than did coastal-spawning stocks. Interior-spawning stocks had proportionately larger alevins or fry at 2°C (for sockeye salmon) or 4°C (for Chinook salmon) relative to their performance at 8°C than did coastal-spawning stocks. Red-fleshed Chinook salmon had higher embryo survival rates at 15°C than did white-fleshed Chinook salmon, as well as an indication of proportionately larger alevins or fry relative to the performance at lower incubation temperatures. Differences in developmental biology of interior- and coastal-spawning stocks may reflect adaptation to the thermal conditions experienced during development

Beamish, R., and C. Mahnken, 2001. A critical size and period hypothesis to explain natural regulation of salmon abundance and the linkage to climate and climate change. *Progress in Oceanography* 49, 423–437.

Abstract: We hypothesize that salmon year class strength is determined in two stages during the first year in the ocean. There is an early natural mortality that is mostly related to predation, which is followed by a physiologically-based mortality. Juvenile salmon that fail to reach a critical size by the end of their first marine summer do not survive the following winter. In this study we describe our initial tests of this critical size and critical period hypothesis using data from ocean surveys of juvenile salmon and from experimental feeding studies on coho. Conservative swept volume abundance estimates for juvenile coho, and possibly Chinook, indicate that there is high mortality in fall and winter during their first year in the sea. Studies of otolith weight show that the length and otolith-weight relationship for young coho changes in the early fall of their first ocean year. Studies of growth and associated hormone levels in feeding studies show that slow growing juvenile coho are stunted and deficient in an insulin-like growth factor-I (IGF-I). Juvenile coho sampled in September had low IGF-I values, indicative of poor growth. The results of these studies provide evidence for the general hypothesis that growth-related mortality occurs late in the first marine year and may be important in determining the strength of the year class (brood year). The link between total mortality and climate could be operating via the availability of nutrients regulating the food supply and hence competition for food (i.e. bottom–up regulation).

Beamish, R.J., 1995. *Climate Change and Northern Fish Populations*. NRC Research Press. 739 pp.

Abstract: A collection of studies related to climate change and management of northern fish populations from Symposium on Climate Change and Northern Fish Populations (1992: Victoria, B.C.)

Beamish, R.J., and D.R. Bouillon, 1993. Pacific Salmon Production Trends in Relation to Climate. *Canadian Journal of Fisheries and Aquatic Sciences* 50, 1002–1016.

Abstract: Pink (*Oncorhynchus gorbuscha*), chum (*O. keta*), and sockeye salmon (*O. nerka*) represent approximately 90% of the commercial catch of Pacific salmon taken each year by Canada, Japan, the United States, and Russia. Annual all-nation catches of the three species and of each species, from 1925 to 1989, exhibited long-term parallel trends. National catches, in most cases, exhibited similar but weaker trends. The strong similarity of the pattern of the all-nation pink, chum, and sockeye salmon catches suggests that common events over a vast area affect the production of salmon in the North Pacific Ocean. The climate over the northern North Pacific Ocean is dominated in the winter and spring by the Aleutian Low pressure system. The long-term pattern of the Aleutian Low pressure system corresponded to the trends in salmon

catch, to copepod production, and to other climate indices, indicating that climate and the marine environment may play an important role in salmon production.

Beechie, T., E. Beamer, and L. Wasserman, 1994. Estimating Coho Salmon Rearing Habitat and Smolt Production Losses in a Large River Basin, and Implications for Habitat Restoration. *North American Journal of Fisheries Management* 14, 797–811.

Abstract: To develop a habitat restoration strategy for the 8,270-km2 Skagit River basin, we estimated changes in smolt production of coho salmon *Oncorhynchus kisutch* since European settlement began in the basin, based on changes in summer and winter rearing habitat areas. We assessed changes in coho salmon smolt production by habitat type and by cause of habitat alteration. We estimated that the coho salmon smolt production capacity of summer habitats in the Skagit River basin has been reduced from 1.28 million smolts to 0.98 million smolts (–24%) and that the production capacity of winter habitats has been reduced from 1.77 million to 1.17 million smolts (–34%). The largest proportion of summer non-main-stem habitat losses has occurred in side-channel sloughs (41%), followed by losses in small tributaries (31%) and distributary sloughs (29%). The largest loss of winter habitats has occurred in side-channel sloughs (52%), followed by losses in distributary sloughs (37%) and small tributaries (11%). By type of impact, hydromodification (diking, ditching, dredging) associated with agricultural and urban lands accounts for 73% of summer habitat losses and 91% of winter habitat losses. Blocking culverts on small tributaries account for 13% of the decrease in summer habitat and 6% of the decrease in winter habitat. Forestry activities account for 9% of summer habitat losses and 3% of winter habitat losses. Limitations of the analysis and implications for developing a habitat restoration strategy are discussed.

Beechie, T., and S. Bolton, 1999. An Approach to Restoring Salmonid Habitat-forming Processes in Pacific Northwest Watersheds. *Fisheries* 24, 6–15.

Abstract: We present an approach to diagnosing salmonid habitat degradation and restoring habitat-forming processes that is focused on causes of habitat degradation rather than on effects of degradation. The approach is based on the understanding that salmonid stocks are adapted to local freshwater conditions and that their environments are naturally temporally dynamic. In this context, we define a goal of restoring the natural rates and magnitudes of habitat-forming processes, and we allow for locally defined restoration priorities. The goal requires that historical reconstruction focus on diagnosing disruptions to processes rather than conditions. Historical reconstruction defines the suite of restoration tasks, which then may be prioritized based on local biological objectives. We illustrate the use of this approach for two habitat-forming processes: sediment supply and stream shading. We also briefly contrast this approach to several others that may be used as components of a restoration strategy.

Bell, E., S. Kramer, D. Zajanc, and J. Aspittle, 2008. Salmonid Fry Stranding Mortality Associated with Daily Water Level Fluctuations in Trail Bridge Reservoir, Oregon. *North American Journal of Fisheries Management* 28, 1515–1528.

Abstract: Little information exists on how reservoir fluctuations affect stranding risk for early life stages of salmonids. This study focuses on the effects of hydroelectric-related water level fluctuations in Trail Bridge Reservoir, Oregon, where salmonids, including the bull trout *Salvelinus confluentus* and spring Chinook salmon *Oncorhynchus tshawytscha*, which are listed under the U.S. Endangered Species Act, commonly occur. A distance-from-line sampling design was employed using permanently established transects to estimate the magnitude of stranding of juvenile salmonids during 30 surveys over 3 months in spring 2006. All stranded fish observed during field surveys were mapped onto spatially rectified, low-elevation aerial photographs to assess the patterns in stranding. Most fish were stranded in habitats with a slope of less than 6%, typically in interstitial spaces among cobbles, and in "potholes." Fish were stranded in similar numbers following small or large fluctuations, and no relationship was apparent between the range in fluctuation and the number of stranded fish or between the average rate of water surface decline and the number of stranded fish. Based on extrapolation, we estimated that 808 spring Chinook salmon fry and 444 brook trout S. fontinalis fry were stranded in Trail Bridge Reservoir during spring 2006. One dead bull trout was observed, but based on the abrasions, open wounds, and signs of infection that we observed, it died prior to the decline in reservoir elevation. Our findings suggest that stranding in this reservoir could be reduced (while retaining the hydroelectric function of the reservoir) by restricting fluctuations to specific elevations during vulnerable fish migration periods, increasing the slope of areas identified as having a high stranding risk, or both.

Bell, L.M., 1985. A Fish Passage Problem at the Seton Hydroelectric Project in Southwestern British Columbia. *Canadian Water Resources Journal* 10, 32–39.

Abstract: The Seton hydroelectric project, completed in 1956, is located near the Village of Lillooet, 300 kilometres north of Vancouver. During July to November each year, two discrete runs of adult sockeye salmon must migrate past the powerhouse tailrace and through a fishway at a low head dam on Seton Creek, to successfully reach their spawning grounds at Gates Creek and Portage Creek. From 1956 to 1969, Cayoosh Creek (the only tributary of Seton Creek) was diverted into Seton Lake to provide additional water for power generation. In 1969, the diversion was discontinued and Cayoosh Creek once again discharged into Seton Creek. In 1972, a decrease in the numbers of salmon reaching the spawning grounds was observed by the International Pacific Salmon Fisheries Commission (IPSFC). Subsequent investigations resulted in a five-year study program to determine the cause of the fish passage problem. This paper describes the study, with emphasis on the hydrological aspects and the operating procedures recommended to control flows in Cayoosh and Seton Creeks, to alleviate the problem.

Bell, M.C., 1990. *Fisheries handbook of engineering requirements and biological criteria (Fisheries Handbook), Fish Passage Development and Evaluation Program*. US Army Corps of Engineers, Portland, Oregon.

Abstract: A summary of biological and physical habitat attributes required that contribute to fish passage design criteria.

Ben-David, M., T.A. Hanley, and D.M. Schell, 1998. *Fertilization of Terrestrial Vegetation by Spawning Pacific Salmon: The Role of Flooding and Predator Activity*. Oikos 83, 47.

Abstract: Spawning Pacific salmon (*Onchorhynchus*) transport marine-derived nutrients into streams and rivers. Subsequently, these marine-derived nutrients are incorporated into freshwater and terrestrial food webs through decomposition and predation. In this study, we investigated the influence of spawning Pacific salmon on terrestrial vegetation using stable isotope analysis. We hypothesized that terrestrial vegetation near streams or in areas with activity of piscivorous predators will show higher δ^{15}SN values compared with the same species growing elsewhere. The influence of spawning Pacific salmon as observed in elevated δ^{15}SN in terrestrial consumers was also investigated. Data collected from five species of plants in 18 transects from the stream to the upland forest (0 to 1000 m) indicated that a significant decrease in δ^{15}SN values occurred with increase in distance and relative elevation from the stream in three of the five plant species sampled. Values of δ^{15}SN in plants at sites actively used by piscivorous predators were higher than those of the same plants growing elsewhere, and similar to values measured near the stream. A decrease in values of δ^{15}SN and increase in values of δ^{13}C in muscles of small mammals, with increase in distance from the stream, indicated that this signature was not a result of direct consumption of salmon carcasses but rather an indirect assimilation of marine-derived nitrogen through terrestrial vegetation. These results indicate that salmon carcasses contribute to the nitrogen pool available to riparian vegetation. The spatial distribution of the marine-derived nitrogen is apparently determined by flooding and the activity patterns of piscivorous predators. The importance of these nitrogen additions to the riparian zone, however, will depend on whether nitrogen is a limiting factor to plant growth in this system, and requires further investigation.

Berg, N.H., 1994. Ice in Stream Pools in California's Central Sierra Nevada: Spatial and Temporal Variability and Reduction in Trout Habitat Availability. *North American Journal of Fisheries Management* 14, 372–384.

Abstract: Ice in streams can be detrimental to fish in many ways, including physical exclusion of fish from habitat. Stream pools along an elevational gradient in California's central Sierra Nevada were monitored during winters 1990–1991 and 1991–1992 for ice thickness, coverage by ice, and below-ice water depth. Both ice thickness and duration in pools increased with site elevation. Because minimum water depths were below a 6-cm criterion for adult trout movement for only a 10-d period in only 1 of 30 pools monitored over the two winters, 1 concluded that physical exclusion of fish from habitat by ice was not a problem. Validated methods to predict the presence and thickness of ice in mountain streams are needed. Ice presence along the elevational gradient and ice thickness at the one pool evaluated were predicted moderately well from air temperature, There is a need for refined models that incorporate the effects of snow cover and stream velocity on ice formation.

Berggren, T.J., and M.J. Filardo, 1993. An Analysis of Variables Influencing the Migration of Juvenile Salmonids in the Columbia River Basin. *North American Journal of Fisheries Management* 13, 48–63.

Abstract: The amount of time that it takes juvenile Chinook salmon (*Oncorhynchus tshawytscha*) and steelhead (*O. mykiss*) to migrate (travel time) at different river flows through index reaches in the Snake and Columbia rivers was analyzed with bivariate- and multiple-regression models. Smolt travel time estimates for yearling Chinook salmon and steelhead in the Snake River, steelhead in the middle Columbia River, and subyearling Chinook salmon in the lower Columbia River were inversely related to average river flows. In the multiple-regression analyses, additional predictor variables that were related either to flow or to smoltification were used. These predictor variables were calculated over the same time period as the travel time estimates. Flow-related variables were referenced at a key hydroelectric site within each index reach, and included average river flow, minimum river flow, and absolute change in river flow. The smoltification-related variables provided indirect indices of smoltification. They included water temperature, date of entry into an index reach, Chinook salmon race, and travel time prior to entry into an index reach. The final models included those predictor variables explaining significant variation in smolt travel time, The variables in the final multiple-regression models explained 74% and 39% of the variation in the travel time for yearling Chinook salmon within the Snake and middle Columbia river index reaches, respectively; 90% and 62% for steelhead within the Snake and middle Columbia reaches; and 65% for subyearling Chinook salmon in the lower Columbia reach. Average river flow made the largest contribution to explaining variation in smolt travel time in the majority of the multiple-regression models. Additional variation in smolt travel time could be explained by including other flow- and smoltification-related variables in the models.

Bilby, R.E., B.R. Fransen, and P.A. Bisson, 1996. Incorporation of nitrogen and carbon from spawning coho salmon into the trophic system of small streams: evidence from stable isotopes. *Canadian Journal of Fisheries and Aquatic Sciences* 53, 164–173.

Abstract: Epilithic organic matter, all aquatic macroinvertebrates except shredders, and fish were significantly enriched with 15N and 13C in streams (western Washington state, U.S.A.) where spawning coho salmon (*Oncorhynchus kisutch*) were present. Riparian vegetation adjacent to salmon-bearing streams and shredding macroinvertebrates were enriched with 15N but not 13C. The highest levels of enrichment of the stream biota with the heavier isotopes occurred in the early spring, shortly after carcasses had decomposed. Following spawning, age-0 coho salmon exhibited a doubling in rate of growth. Age-0 cutthroat trout in a nearby stream without salmon exhibited no change in growth rate during the winter. Salmon-derived organic matter was incorporated into the stream biota through direct consumption of eggs, carcasses, and fry and by sorption onto the streambed substrate of dissolved organic matter released by decomposing carcasses. Autotrophic uptake was not an important avenue of incorporation. The proportion of nitrogen contributed by spawning salmon varied among trophic categories, ranging from about 17% in collector-gatherers to more than 30% in juvenile coho salmon. Carbon contributed by spawning salmon ranged from 0% in the foliage of riparian plants and shredders to 34% in juvenile coho salmon.

Bjornn, T.C., and D.W. Reiser, 1991. Habitat requirements of salmonids in streams. *American Fisheries Society Special Publication* 19, 83–138.

Abstract: An extensive summary of the habitat components required by salmonids in freshwater habitats.

Blair, G.R., D.E. Rogers, and T.P. Quinn, 1993. Variation in Life History Characteristics and Morphology of Sockeye Salmon in the Kvichak River System, Bristol Bay, Alaska. *Transactions of the American Fisheries Society* 122, 550–559.

Abstract: Sockeye salmon *Oncorhynchus nerka* spawn in many streams and along lake beaches of the Kvichak River system in Alaska, but fry from the distinct spawning areas reside in a common nursery habitat, Iliamna Lake. In addition, Kvichak River subpopulations have similar dates of adult entry into fresh water, similar migration distances, and similar spawning dates. These similarities in rearing environments and migratory timing enabled us to test the hypothesis that differences in spawning and incubation habitat alone can promote differentiation in traits associated with reproductive success. River-spawning sockeye salmon tended to be larger at age and older than those spawning along island beaches. Females from rivers were more fecund but had smaller eggs than the beach-spawning females. Males from beaches were deeper-bodied and (in one comparison) had relatively longer lower jaws than males from rivers. The tendency of river-spawning females to mature later than beach spawners may be related to a higher marine growth rate and greater increase in fecundity with length. Differences in male morphology may reflect the countervailing pressures of natural and sexual selection. We conclude that these patterns of variation reflect, in part, adaptations to spawning and incubation conditions of the populations.

Boulton, A.J., S. Findlay, P. Marmonier, E.H. Stanley, and H.M. Valett, 1998. The functional significance of the hyporheic zone in streams and rivers. *Annual Review of Ecology and Systematics* 59–81.

Abstract: The hyporheic zone is an active ecotone between the surface stream and groundwater. Exchanges of water, nutrients, and organic matter occur in response to variations in discharge and bed topography and porosity. Upwelling subsurface water supplies stream organisms with nutrients while downwelling stream water provides dissolved oxygen and organic matter to microbes and invertebrates in the hyporheic zone. Dynamic gradients exist at all scales and vary temporally. At the microscale, gradients in redox potential control chemical and microbially mediated nutrient transformations occurring on particle surfaces. At the stream-reachscale, hydrological exchange and water residence time are reflected in gradients in hyporheic faunal composition, uptake of dissolved organic carbon, and nitrification. The hyporheic corridor concept describes gradients at the catchment scale, extending to alluvial aquifers kilometers from the main channel. Across all scales, the functional significance of the hyporheic zone relates to its activity and connection with the surface stream

Bradford, M.J., J.A. Grout, and S. Moodie, 2001. Ecology of juvenile Chinook salmon in a small non-natal stream of the Yukon River drainage and the role of ice conditions on their distribution and survival. *Canadian Journal of Zoology* 79, 2043–2054.

Abstract: We investigated the ecology of juvenile stream-type Chinook salmon (*Oncorhynchus tshawytscha*) in Croucher Creek, a small non-natal tributary of the upper Yukon River, in 1998 and 1999. Underyearling (age 0+) salmon enter Croucher Creek from the Yukon River in June, and by midsummer reached an average density of >0.5/m2. Fish were most commonly found in small pools. Their mean size increased until the end of August, but growth virtually ceased after that, when water temperatures fell. Juveniles remained in the stream through winter, and their distribution and survival were strongly influenced by aufeis, a thick layer of ice that develops from the freezing of groundwater. Over-winter survival was not dependent on fish size. Those fish that survived the winter grew rapidly and doubled in body mass in the spring. About 900 yearling fish emigrated from Croucher Creek in late June and early July at a mean length of 89 mm and mass of 7.2 g. Most of the migrants overwintered in a 700 m long reach of the creek that was downstream from groundwater sources and did not experience severe icing conditions. We suggest that small streams may be important habitats for juvenile salmon in the Yukon drainage, especially if there is a year-round source of groundwater flow that creates conditions suitable for overwintering

Bradford, M.J., G.C. Taylor, J.A. Allan, and P.S. Higgins, 1995. An Experimental Study of the Stranding of Juvenile Coho Salmon and Rainbow Trout during Rapid Flow Decreases under Winter Conditions. *North American Journal of Fisheries Management* 15, 473–479.

Abstract: The stranding of juvenile coho salmon *Oncorhynchus kisutch* and rainbow trout *O. mykiss* on river bars caused by rapid decreases in river flow during the operation of hydroelectric facilities was investigated in an artificial stream channel. We conducted experiments with winter water temperatures (<4°C) and a gravel substrate, In daytime trials, many fish became stranded because they were concealed in the interstitial areas of the substrate and were reluctant to leave when water levels receded. Coho salmon were more likely to be stranded than rainbow trout. At night, instead of using the substrate as cover, fish were active in the water column and the incidence of stranding during flow reductions was greatly diminished. Stranding was less frequent at slow rates of dewatering. The addition of shallow, covered pools to the substrate did not alter the principal results. Our findings suggest that during winter months, fish losses from stranding will be minimized if flow reductions occur at night and at slow rates of change.

Brown, R.D., and P.W. Mote, 2009. The Response of Northern Hemisphere Snow Cover to a Changing Climate. *Journal of Climate* 22, 2124–2145.

Abstract: A snowpack model sensitivity study, observed changes of snow cover in the NOAA satellite dataset, and snow cover simulations from the Coupled Model Intercomparison Project phase 3 (CMIP3) multimodel dataset are used to provide new insights into the climate response of Northern Hemisphere (NH) snow cover. Under conditions of warming and increasing precipitation that characterizes both observed and projected climate change over much of the NH land area with seasonal snow cover, the sensitivity analysis indicated snow cover duration (SCD) was the snow cover variable exhibiting the strongest climate sensitivity, with sensitivity varying with climate regime and elevation. The highest snow cover–climate sensitivity was found in maritime climates with extensive winter snowfall—for example, the coastal mountains of western North America (NA). Analysis of trends in snow cover duration during the 1966–2007 period of NOAA data showed the largest decreases were concentrated in a zone where seasonal mean air temperatures were in the range of 258 to 158C that extended around the midlatitudinal coastal margins of the continents. These findings were echoed by the climate models that showed earlier and more widespread decreases in SCD than annual maximum snow water equivalent (SWEmax), with the zone of earliest significant decrease located over the maritime margins of NA and western Europe. The lowest SCD–climate sensitivity was observed in continental interior climates with relatively cold and dry winters, where precipitation plays a greater role in snow cover variability. The sensitivity analysis suggested a potentially complex elevation response of SCD and SWEmax to increasing temperature and precipitation in mountain regions as a result of nonlinear interactions between the duration of the snow season and snow accumulation rates.

Brown, R.S., S.S. Stanislawski, and W.C. Mackay, 1993. Effects of Frazil Ice on Fish. Presented at the Workshop on environ. aspects of river ice, Saskatoon, Canada, National Hydrology Research Institute. Canada, National Hydrology Research Institute., Saskatoon, Canada.

Abstract: Describes the interactions between fish and frazil ice in fluvial environments.

Bryant, M.D., 2009. Global climate change and potential effects on Pacific salmonids in freshwater ecosystems of southeast Alaska. *Climatic Change* 95, 169–193.

Abstract: General circulation models predict increases in air temperatures from 1°C to 5°C as atmospheric CO2 continues to rise during the next 100 years. Thermal regimes in freshwater ecosystems will change as air temperatures increase regionally. As air temperatures increase, the distribution and intensity of precipitation will change which will in turn alter freshwater hydrology. Low elevation floodplains and wetlands will flood as continental ice sheets melt, increasing sea-levels. Although anadromous salmonids exist over a wide range of climatic conditions along the Pacific coast, individual stocks have adapted life history strategies—time of emergence, run timing, and residence time in freshwater—that are often unique to regions and watersheds. The response of anadromous salmonids will differ among species depending on their life cycle in freshwater. For pink and chum salmon that migrate to the ocean shortly after they emerge from the gravel, higher temperatures during spawning and incubation may result in earlier entry into the ocean when food resources are low. Shifts in thermal regimes in lakes will change trophic conditions that will affect juvenile sockeye salmon growth and survival. Decreased summer stream flows and higher water temperatures will affect growth and survival of juvenile coho salmon. Rising sea-levels will inundate low elevation spawning areas for pink salmon and floodplain rearing habitats for juvenile coho salmon. Rapid changes in climatic conditions may not extirpate anadromous salmonids in the region, but they will impose greater stress on many stocks that are adapted to present climatic conditions. Survival of sustainable populations will depend on the existing genetic diversity within and among stocks, conservative harvest management, and habitat conservation.

Buckwalter, J.D., 2011. *Synopsis of Alaska Department of Fish and Game Upper Susitna Drainage Fish Inventory, August 2011.* Alaska Department of Fish and Game, Division of Sport Fish, Anchorage, Alaska. 27 pp.

Abstract: An inventory of all fish species observed in the upper reach of the Susitna River.

Bunn, S.E., and A.H. Arthington, 2002. Basic Principles and Ecological Consequences of Altered Flow Regimes for Aquatic Biodiversity. *Environmental Management* 30, 492–507.

Abstract: The flow regime is regarded by many aquatic ecologists to be the key driver of river and floodplain wetland ecosystems. We have focused this literature review around four key principles to highlight the important mechanisms that link hydrology and aquatic biodiversity and to illustrate the consequent impacts of altered flow regimes: Firstly, flow is a major determinant of physical habitat in streams, which in turn is a major determinant of biotic composition; Secondly, aquatic species have evolved life history strategies primarily in direct response to the natural flow regimes; Thirdly, maintenance of natural patterns of longitudinal and lateral connectivity is essential to the viability of populations of many riverine species;

Finally, the invasion and success of exotic and introduced species in rivers is facilitated by the alteration of flow regimes. The impacts of flow change are manifest across broad taxonomic groups including riverine plants, invertebrates, and fish. Despite growing recognition of these relationships, ecologists still struggle to predict and quantify biotic responses to altered flow regimes. One obvious difficulty is the ability to distinguish the direct effects of modified flow regimes from impacts associated with land-use change that often accompanies water resource development. Currently, evidence about how rivers function in relation to flow regime and the flows that aquatic organisms need exists largely as a series of untested hypotheses. To overcome these problems, aquatic science needs to move quickly into a manipulative or experimental phase, preferably with the aims of restoration and measuring ecosystem response.

Burgner, R.L., 1991. *Life History of Sockeye Salmon*. In: Pacific Salmon Life Histories. UBC Press, pp. 1–118.

Abstract: Comprehensive summary of sockeye salmon life history.

Burke, M., K. Jorde, and J.M. Buffington, 2009. Application of a hierarchical framework for assessing environmental impacts of dam operation: Changes in streamflow, bed mobility and recruitment of riparian trees in a western North American river. *Journal of Environmental Management* 90, S224–S236.

Abstract: River systems have been altered worldwide by dams and diversions, resulting in a broad array of environmental impacts. The use of a process-based, hierarchical framework for assessing environmental impacts of dams is explored here in terms of a case study of the Kootenai River, western North America. The goal of the case study is to isolate and quantify the relative effects of multiple dams and other river management activities within the study area and to inform potential restoration strategies. In our analysis, first-order impacts describe broad changes in hydrology (determined from local stream gages), second order impacts quantify resultant changes in channel hydraulics and bed mobility (predicted from a 1D flow model), and third-order impacts describe consequences for recruitment of riparian trees (recruitment box analysis). The study area is a 233 km reach bounded by two dams (Libby and Corra Linn). different times of dam emplacement (1974 and 1938, respectively) allow separation of their relative impacts. Results show significant changes in 1) the timing, magnitude, frequency, duration and rate of change of flows, 2) the spatial and temporal patterns of daily stage fluctuation, unit stream power, shear stress, and bed mobility, and 3) the potential for cottonwood recruitment (Populus spp.).We find that Libby Dam is responsible for the majority of first and second-order impacts, but that both dams diminish cottonwood recruitment; operation of Corra Linn adversely affects recruitment in the lower portion of the study reach by increasing stage recession rates during the seedling establishment period, while operation of Libby Dam affects recruitment in the middle and upper portions of the study reach by changing the timing, magnitude, and duration of flow. We also find that recent experimental flow releases initiated in the 1990s to stimulate recovery of endangered native fish may have fortuitous positive effects on cottonwood recruitment potential in the lower portion of the river. This case study demonstrates how a process-based, hierarchical framework can be used for quantifying environmental impacts of dam operation over space and time, and provides an approach for evaluating alternative management strategies.

Busch, S., P. McElhany, and M. Ruckelshaus, 2008. *A comparison of the viability criteria developed for management of ESA listed Pacific salmon and steelhead*. National Marine Fisheries Service Northwest Fisheries Science Center. 38pp.

Abstract: A comparison of how viable salmonid population parameters have been used across different recovery regions in the Pacific Northwest. Demonstration of the applicability and flexibility of the parameters in different scenarios.

Cederholm, C.J., D.B. Houston, D.L. Cole, and W.J. Scarlett, 1989. Fate of Coho Salmon (*Oncorhynchus kisutch*) Carcasses in Spawning Streams. *Canadian Journal of Fisheries and Aquatic Sciences* 46, 1347–1355.

Abstract: We examined the levels of retention and utilization of 945 coho salmon (*Oncorhynchus kisutch*) carcasses released experimentally into seven spawning streams on the Olympic Peninsula, Washington. Most carcasses were retained in the streams and in adjacent forests, few were flushed beyond 600 m. Organic debris caught and held many carcasses. Much of the fish mass was consumed by 22 species of mammals and birds. The distances that carcasses drifted appeared to be related directly to the occurrence of freshets and inversely to debris load and carnivore scavenging. The capacity of many streams and rivers to retain carcasses has probably been reduced by human activities. The importance of coho carcasses to populations of carnivores and to the dynamics of lotic food webs merits additional study.

Cederholm, C.J., M.D. Kunze, T. Murota, and A. Sibatani, 1999. Pacific salmon carcasses: essential contributions of nutrients and energy for aquatic and terrestrial ecosystems. *Fisheries* 24, 6–15.

Abstract: Pacific salmon and other anadromous salmonids represent a major vector for transporting marine nutrients across ecosystem boundaries (i.e., from marine to freshwater and terrestrial ecosystems). Salmon carcasses provide nutrients and energy to biota within aquatic and terrestrial ecosystems through various pathways. In this paper we review and synthesize the growing number of studies documenting this process in different localities. We also discuss the implications for maintaining the nutrient feedback system. Our findings show that future management will need to view spawning salmon and their carcasses as important habitat components for sustaining the production of fish as well as other salmon-dependent species within watersheds.

Clarke, T.S., 1991. Glacier dynamics in the Susitna River basin, Alaska, U.S.A. *Journal of Glaciology* 37, 97–106.

Abstract: The dynamics of the glaciers which form the headwaters of the Susitna River in central Alaska exhibit several interesting features, including a spectrum of surge-type behavior. A difference between balance flux and actual down-glacier transport, which is taken to be an indicator of surge behavior, shows West Fork Glacier and two tributaries of Susitna Glacier to be surge-type of varying strengths, while East Fork Glacier and one tributary of Susitna Glacier to be nonsurge-type. The main trunk of Susitna Glacier and its two unstable tributaries surge simultaneously with a period estimated to be 50-60 years. Having last surged in 1951-52, its next surge should be expected sometime in the first decade of the next century. West Fork Glacier last surged in about 1935 and again in 1987-88, indicating a similar surge period of about 50 years. Significant seasonal velocity variations were observed during the glacier's quiescent phases, with increases of 30-100% over background occurring early in the melt season. In some cases, the annual minimum occurred during late summer, implying that basal motion contributes measurably to winter velocity on at least some glaciers in the area. Events of rapid motion lasting a day or so also occur occasionally during the melt season and may account for brief velocity increases of up to 300%.

Cleary P., R.A. Merizon, R.J. Yanusz, and D.J. Reed, 2013. *Abundance and spawning distribution of Susitna River chum Oncorhynchus keta and coho O. kisutch salmon, 2010*. Alaska Fishery Data Series No. 13-05. Alaska Department of Fish and Game, Divisions of Sport Fish and Commercial Fisheries.

Abstract: A contemporary evaluation of the abundance and distribution of spawning Susitna River chum and coho salmon.

Collins, B.D., D.R. Montgomery, K.L. Fetherston, and T.B. Abbe, 2012. The floodplain large-wood cycle hypothesis: A mechanism for the physical and biotic structuring of temperate forested alluvial valleys in the North Pacific coastal ecoregion. *Geomorphology* 139-140, 460–470.

Abstract: A 'floodplain large-wood cycle' is hypothesized as a mechanism for generating landforms and influencing river dynamics in ways that structure and maintain riparian and aquatic ecosystems of forested alluvial river valleys of the Pacific coastal temperate rainforest of North America. In the cycle, pieces of wood large enough to resist fluvial transport and remain in river channels initiate and stabilize wood jams, which in turn create alluvial patches and protect them from erosion. These stable patches provide sites for trees to mature over hundreds of years in river valleys where the average cycle of floodplain turnover is much briefer, thus providing a future source of large wood and reinforcing the cycle. Different tree species can function in the floodplain large-wood cycle in different ecological regions, in different river valleys within regions, and within individual river valleys in which forest composition changes through time. The cycle promotes a physically complex, biodiverse, and self-reinforcing state. Conversely, loss of large trees from the system drives landforms and ecosystems toward an alternate stable state of diminished biogeomorphic complexity. Reestablishing large trees is thus necessary to restore such rivers. Although interactions and mechanisms may differ between biomes and in larger or smaller rivers, available evidence suggests that large riparian trees may have similarly fundamental roles in the physical and biotic structuring of river valleys elsewhere in the temperate zone.

Connor, E.J., and D.E. Pflug, 2004. Changes in the distribution and density of pink, chum, and Chinook salmon spawning in the upper Skagit River in response to flow management measures. *North American Journal of Fisheries Management* 24, 835–852.

Abstract: We analyzed the abundance and spatial distribution of spawning pink salmon *Oncorhynchus gorbuscha*, chum salmon *O. keta*, and Chinook salmon *O. tshawytscha* in a 27-mi section of the upper Skagit River, Washington, regulated by the Skagit Hydroelectric Project. Densities of spawning salmon were compared among three contiguous reaches of the upper Skagit River before and after the implementation of flow management measures in 1981. The measures were intended to minimize redd dewatering during the spawning and incubation periods and fry stranding during the emergence and outmigration periods. Field monitoring confirmed that increasing the minimum incubation flows created improvements in redd protection levels. Greater protection of fry from stranding was achieved by substantially reducing the annual number of downramping events and by reducing downramping during daytime, when fry are most vulnerable to stranding. Spawner abundance of all three species progressively increased in an upstream direction following implementation of flow measures; increases were greatest in the reach immediately below the hydroelectric project. The upstream shift in spawner abundance was highly significant based on factorial analyses of variance. The greatest increases in spawner abundance for Chinook salmon and chum salmon were observed during even years, when pink salmon did not spawn. Mean spawner abundance in the upstream-most study reach increased from 311 to 1,169 carcasses/mi (odd years) for pink salmon, from 6 to 115 fish/mi (odd years) or 58 to 462 fish/mi (even years) for chum salmon, and from 48 to 49 redds/mi (odd years) or 59 to 65 redds/ mi (even years) for Chinook salmon. The total number of pink salmon and chum salmon spawners significantly increased within the study area after 1981. These increases were substantially greater than those observed concurrently in other areas of the Skagit River basin and in other northern Puget Sound rivers. The average number of Chinook salmon spawners remained unchanged in the study area after 1981, while substantially declining in other unregulated Skagit River subbasins and most Puget Sound rivers. The study area now possesses the greatest percentage of pink, chum, and Chinook salmon spawners within the Skagit River basin. The Skagit River presently supports the largest run of native Chinook salmon in the Puget Sound region and the largest runs of pink and chum salmon in the coterminous United States.

Connor, W.P., H.L. Burge, J.R. Yearsley, and T.C. Bjornn, 2003. Influence of Flow and Temperature on Survival of Wild Subyearling Fall Chinook Salmon in the Snake River. *North American Journal of Fisheries Management* 23, 362–375.

Abstract: Summer flow augmentation to increase the survival of wild subyearling fall Chinook salmon *Oncorhynchus tshawytscha* is implemented annually to mitigate for the development of the hydropower system in the Snake River basin, but the efficacy of this practice has been disputed. We studied some of the factors affecting survival of wild subyearling fall Chinook salmon from capture, tagging, and release in the free-flowing Snake River to the tailrace of the first dam encountered by smolts en route to the sea. We then assessed the effects of summer flow augmentation on survival to the tailrace of this dam. We tagged and released 5,030 wild juvenile fall Chinook salmon in the free-flowing Snake River from 1998 to 2000. We separated these tagged fish into four sequential within-year release groups termed cohorts (N = 12). Survival probability estimates (mean ± SE) to the tailrace of the dam for the 12 cohorts when summer flow augmentation was implemented ranged from 36% ± 4% to 88% ± 5%. We fit an ordinary least-squares multiple regression model from indices of flow and temperature that explained 92% (N = 12; $P < 0.0001$) of the observed variability in cohort survival. Survival generally increased with increasing flow and decreased with increasing temperature. We used the regression model to predict cohort survival for flow and temperature conditions observed when summer flow augmentation was implemented and for approximated flow and temperature conditions had the summer flow augmentation not been implemented. Survival of all cohorts was predicted to be higher when flow was augmented than when flow was not augmented because summer flow augmentation increased the flow levels and decreased the temperatures fish were exposed to as they moved seaward. We conclude that summer flow augmentation increases the survival of young fall Chinook salmon.

Crossin, G.T., S.G. Hinch, S.J. Cooke, D.W. Welch, D.A. Patterson, S.R.M. Jones, A.G. Lotto, R.A. Leggatt, M.T. Mathes, J.M. Shrimpton, G. Van Der Kraak, and A.P. Farrell, 2008. Exposure to high temperature influences the behaviour, physiology, and survival of sockeye salmon during spawning migration. *Canadian Journal of Zoology* 86, 127–140.

Abstract: Since 1996, some populations of Fraser River sockeye salmon (*Oncorhynchus nerka* Walbaum in Artedi, 1792) have begun spawning migrations weeks earlier than normal, and most perish en route as a result. We suspect that a high midsummer river temperature is the principal cause of mortality. We intercepted 100 sockeye during normal migration near a spawning stream and measured somatic energy and aspects of plasma biochemistry. Fish were then held at either 10 or 18 °C for 24 days. Before release, fish were biopsied again and implanted with acoustic transmitters. A group of biopsied but untreated control salmon were released at the same time. Sixty-two percent (8 of 13) of control salmon and 68% (21 of 31) of 10 °C salmon reached spawning areas. The 18 °C-treated fish were half as successful (35%; 6 of 17). During the

holding period, mortality was 2 times higher and levels of Parvicapsula minibicornis (Kent, Whitaker and Dawe, 1997) infection were higher in the 18 °C-treated group than in the 10 °C-treated group. The only physiological difference between treatments was a change in gill Na+,K+-ATPase activity. This drop correlated negatively with travel times for the 18 °C-treated males. Reproductive-hormone levels and stress measures did not differ between treatments but showed significant correlations with individual travel times.

Cushman, R.M., 1985. Review of Ecological Effects of Rapidly Varying Flows Downstream from Hydroelectric Facilities. *North American Journal of Fisheries Management* 5, 330–339.

Abstract: Rapid changes in flow below hydroelectric facilities result from peaking operations, where water is typically stored in a reservoir at night and released through turbines to satisfy increased electrical demand during the day. Potential impacts of these short-term, recurring disturbances of aquatic systems below dams are important considerations in hydropower development. Reduced biotic productivity in tailwaters may be due directly to flow variations or indirectly to a variety of factors related to flow variations, such as changes in water depth or temperature, or scouring of sediments. Many riverine fish and invertebrate species have a limited range of conditions to which they are adapted. The relatively recent pattern of daily fluctuations in flow is not one to which most species are adapted; thus, such conditions can reduce the abundance, diversity, and productivity of these riverine organisms. Information needs for site-specific evaluations of potential impacts at hydroelectric peaking projects are outlined, along with management and mitigation options to reduce anticipated adverse effects.

Dauble, D.D., T.P. Hanrahan, D.R. Geist, and M.J. Parsley, 2003. Impacts of the Columbia River Hydroelectric System on Main-Stem Habitats of Fall Chinook Salmon. *North American Journal of Fisheries Management* 23, 641–659.

Abstract: Salmonid habitats in main-stem reaches of the Columbia and Snake rivers have changed dramatically during the past 60 years because of hydroelectric development and operation. Only about 13% and 58% of riverine habitats in the Columbia and Snake rivers, respectively, remain. Most riverine habitat is found in the upper Snake River; however, it is upstream of Hells Canyon Dam and not accessible to anadromous salmonids. We determined that approximately 661 and 805 km of the Columbia and Snake rivers, respectively, were once used by fall Chinook salmon *Oncorhynchus tshawytscha* for spawning. Fall Chinook salmon currently use only about 85 km of the main-stem Columbia River and 163 km of the main-stem Snake River for spawning. We used a geomorphic model to identify three river reaches downstream of present migration barriers with high potential for restoration of riverine processes: the Columbia River upstream of John Day Dam, the Columbia-Snake-Yakima River confluence, and the lower Snake River upstream of Little Goose Dam. Our analysis substantiated the assertion that historic spawning areas for fall Chinook salmon occurred primarily within wide alluvial floodplains, which were once common in the main-stem Columbia and Snake rivers.

These areas possessed more unconsolidated sediment and more bars and islands and had lower water surface slopes than did less extensively used areas. Because flows in the main stem are now highly regulated, the predevelopment alluvial river ecosystem is not expected to be restored simply by operational modification of one or more dams. Establishing more normative flow regimes—specifically, sustained peak flows for scouring—is essential to restoring the functional characteristics of existing, altered habitats. Restoring production of fall Chinook salmon to any of these reaches also requires that population genetics and viability of potential seed populations (i.e., from tributaries, tailrace spawning areas, and hatcheries) be considered.

Dauble, D.D., R.L. Johnson, and A.P. Garcia, 1999. Fall Chinook Salmon Spawning in the Tailraces of Lower Snake River Hydroelectric Projects. *Transactions of the American Fisheries Society* 128, 672–679.

Abstract: We conducted studies from 1993 to 1997 to identify and characterize potential spawning habitat of “endangered” fall Chinook salmon *Oncorhynchus tshawytscha* in areas downstream of four Snake River dams. This information was needed to provide guidelines for future operation of the lower Snake River hydroelectric system, including assessment of reservoir drawdown, and for site-specific construction planning. We used Geographic Information System mapping technology to direct our initial search efforts. Suitable spawning habitat was defined based on physical habitat characteristics of the tailrace areas. Redd surveys were conducted in primary search areas and planned construction sites from mid-November through December with an underwater video system. The survey path and redd locations were mapped by using a Global Positioning System. During the 4-year study, fall Chinook salmon redds were found in the tailrace downstream of Lower Granite (LGR), Little Goose (LGO), and Ice Harbor (IH) dams. The redds were the first verified sightings of salmon spawning at their locations since these dams were constructed in 1970, 1975, and 1972, respectively. The total area used for spawning was about 2,560 m2 for the LGR site and 580 m2 for the LGO site. Only one redd was found downstream of the IH project. Redds were in water from 4.0 to 8.1 m deep and on cobble substrate. All redds were adjacent to the outfall flow from juvenile fish bypass systems and on the powerhouse side of the river. Although temporal use was variable among individual projects, within-site fidelity was high. Tailrace spawning accounted for about 12% of the redds in the main stem of the Snake River during 1993 and 1994 but declined to less than 5% in 1996 and 1997.

Delaney, K.J., K. Hepler, and K. Roth, 1981. *Deshka River Chinook and coho salmon study.* ADF&G, Division of Sport Fish. Federal Aid in Fish Restoration, Project AFS-49-Vol 22.

Abstract: A historic examination of Chinook and coho salmon in a tributary of the Susitna River.

Delaney, K., D. Crawford, L. Dugan, S. Hale, K. Kuntz, B. Marshall, J. Mauney, J. Quinn, K. Roth, P. Suchanek, R. Sundet, and M. Stratton, 1981. *Juvenile Anadromous Fish*

Study on the Lower Susitna River. Alaska Department of Fish and Game, Susitna Hydro Aquatic Studies, Anchorage, Alaska 200 pp.

Abstract: Historic life history and habitat utilization study focused on salmonids in the lower Susitna River.

Dittman, A., and T. Quinn, 1996. Homing in Pacific salmon: mechanisms and ecological basis. *Journal of Experimental Biology* 199, 83–91.

Abstract: Pacific salmon (*Oncorhynchus* spp.) are famous for their homing migrations from oceanic feeding grounds to their natal river to spawn. During these migrations, salmon travel through diverse habitats (e.g. oceans, lakes, rivers), each offering distinct orientation clues and, perhaps, requiring distinct sensory capabilities for navigation. Despite these challenges, homing is generally precise and this philopatry has resulted in reproductively isolated spawning populations with specialized adaptations for their natal habitat. This paper reviews the mechanisms underlying all aspects of salmon homing but emphasizes the final, freshwater phase governed by olfactory recognition of homestream water. Prior to their seaward migration, juvenile salmon learn (imprint on) odors associated with their natal site and later, as adults, use these odor memories for homing. Our understanding of this imprinting process is derived primarily from studies using artificial odorants and hatchery-reared salmon. Recent findings suggest, however, that such studies may underestimate the complexity of the imprinting process in nature.

Doyle, M.W., E.H. Stanley, C.H. Orr, A.R. Selle, S.A. Sethi, and J.M. Harbor, 2005. Stream ecosystem response to small dam removal: Lessons from the Heartland. *Geomorphology* 71, 227–244.

Abstract: In this paper, we synthesize a series of small dam removal studies to examine how changes in channel form can affect riparian vegetation, fish, macroinvertebrates, mussels, and nutrient dynamics. Each of the ecosystem attributes responded to the disturbance of dam removal in different ways and recovered at very different rates, ranging from months to decades. Riparian vegetation appeared to require the greatest time for recovery, while macroinvertebrates had the least. Mussel communities were the most adversely affected group of species and showed no signs of recovery during the time period of the study. Based on these and other studies, we suggest that ecosystems may follow two trajectories of recovery following dam removal. First, ecosystems may fully recover to pre-dam conditions, although this may be unlikely in many cases. Even if full recovery occurs, the timescales over which different attributes recover will vary greatly and may be perceived by the public or management agencies as not recovering at all. Second, ecosystems may only partially recover to pre-dam conditions as the legacy of environmental damage of long-term dam presence may not be reversible or because other watershed changes inhibit full recovery. The potential for full or partial recovery is likely driven by the sensitivity of particular organisms, the characteristics of the dam removed, and the local geomorphic conditions of the watershed. Scientists and management agencies should assess the potential for full or partial recovery prior to dam removal and, in particular, should identify those species or groups of species that are likely to not recover to pre-dam conditions. Such information is critical in the decision of whether, or how, to remove a dam.

Dugan, L., D.A. Sterritt, and M.E. Stratton, 1984. The Distribution and Relative Abundance of Juvenile Salmon in the Susitna River Drainage above the Chulitna River Confluence. Page 59 in: *Part 2 of Resident and Juvenile Anadromous Fish Investigations (May - October 1983)*. D. Schmid, S.S. Hale, D.L. Crawford, and P.M. Suchanek (eds.). Alaska Department of Fish & Game Susitna Hydro Aquatic Studies. Report No.2. Anchorage, Alaska.

Abstract: Historic life history and habitat utilization study focused on salmonids in the upper Susitna River.

Eaton, J.G., and R.M. Scheller, 1996. Effects of climate warming on fish thermal habitat in streams of the United States. *Limnology and Oceanography* 41, 1109–1115.

Abstract: The effects of climate warming on the thermal habitat of 57 species of fish of the U.S. were estimated using results for a doubling of atmospheric carbon dioxide that were predicted by the Canadian Climate Center general circulation model. Baseline water temperature conditions were calculated from data collected at 1,700 U.S. Geological Survey stream monitoring stations across the U.S. Water temperatures after predicted climate change were obtained by multiplying air temperature changes by 0.9, a factor based on several field studies, and adding them to baseline water temperatures at stations in corresponding grid cells. Results indicated that habitat for cold and cool water fish would be reduced by ~50%, and that this effect would be distributed throughout the existing range of these species. Habitat losses were greater among species with smaller initial distributions and in geographic regions with the greatest warming (e.g. the central Midwest). Results for warm water fish habitat were less certain because of the poor state of knowledge regarding their high and low temperature tolerances ; however, the habitat of many species of this thermal guild likely will also be substantially reduced by climate warming, whereas the habitat of other species will be increased.

Edmundson, J.A., and A. Mazumder, 2001. Linking Growth of Juvenile Sockeye Salmon to Habitat Temperature in Alaskan Lakes. *Transactions of the American Fisheries Society* 130, 644–662.

Abstract: We examined the influence of temperature on the size of age-1 smolts of sockeye salmon *Oncorhynchus nerka* relative to that of food availability and density dependence across a variety of Alaskan lakes. We analyzed data from 36 lakes providing 134 lake years (annual means) of data. These lakes represent clear, organically stained, and glacially turbid lake types. They produce age-1 sockeye salmon smolts exhibiting a threefold variation in average length (52–145 mm) and a 30-fold variation in average weight (1–30 g). We used simple regression analysis to test for linkages between age-1 smolt size and the independent variables zooplankton biomass (mg/m2), smolt density (number/km2), length of the growing season, and mean water column temperature. Zooplankton biomass (ZB) was the strongest single predictor of smolt size, accounting for 52% of the variation in mean age-1 smolt fork length (FL) and weight (W). Individually, smolt density (SMD) accounted for only 10% of the variance in age-1 smolt size; however, mean water column temperature (Ts) explained 24% of the variation in FL and 19% of the variation in W. Smolt size was unrelated to the length of the growing season (S); however, growth rate indexed by length varied inversely with S while growth in terms of weight did not. Subsequently, we combined all factors into a multivariate model of age-1 smolt size and the population's biological and thermal environment. Taken together, the factors ZB, SMD, and Ts accounted for 70% of the variation in FL and W. The influence of temperature on smolt size appeared to be more direct (through its effect on metabolic rates) than indirect (through limiting food availability [plankton]). Our results may influence fishery management objectives and serve as a template to project future trends in juvenile sockeye salmon growth under different climatic conditions.

Eliason, E.J., T.D. Clark, M.J. Hague, L.M. Hanson, Z.S. Gallagher, K.M. Jeffries, M.K. Gale, D.A. Patterson, S.G. Hinch, and A.P. Farrell, 2011. Differences in Thermal Tolerance Among Sockeye Salmon Populations. *Science* 332, 109–112.

Abstract: Climate change–induced increases in summer water temperature have been associated with elevated mortality of adult sockeye salmon (*Oncorhynchus nerka*) during river migration. We show that cardiorespiratory physiology varies at the population level among Fraser River sockeye salmon and relates to historical environmental conditions encountered while migrating. Fish from populations with more challenging migratory environments have greater aerobic scope, larger hearts, and better coronary supply. Furthermore, thermal optima for aerobic, cardiac, and heart rate scopes are consistent with the historic river temperature ranges for each population. This study suggests that physiological adaptation occurs at a very local scale, with population-specific thermal limits being set by physiological limitations in aerobic performance, possibly due to cardiac collapse at high temperatures.

Ellis, L.E., and N.E. Jones, 2013. Longitudinal trends in regulated rivers: a review and synthesis within the context of the serial discontinuity concept. *Environmental Reviews* 21, 136–148.

Abstract: Dams alter the geomorphology, water quality, temperature regime, and flow regime of lotic systems influencing the resources and habitat of fish, benthic invertebrates, and lower trophic levels. Since the inception of the river continuum concept and the serial discontinuity concept (SDC), biotic and abiotic impacts below impoundments have been the focus of many

lotic studies. However, recovery gradients below dams are rarely examined in sufficient detail and no current synthesis of longitudinal impacts in regulated rivers exists. This understanding is needed to build ecological relationships in regulated rivers to inform environmental flows science and management. In this review, we provide evidence for SDC predictions on physical, chemical, and biological recovery in regulated rivers. Additionally, we determine how these changes are reflected in the benthic community. Our review suggests that two recovery gradients exist in regulated rivers: (1) a longer, thermal gradient taking up to hundreds of kilometres downstream; and (2) a shorter, resource subsidy gradient recovering within 1–4 km downstream of an impoundment. Total benthic invertebrate abundance varies considerably, with both increases and reductions observed at near-dam sites and varying in recovery downstream. Much of this variability stems from the degree of flow alteration and resource subsidies from the upstream reservoir. In contrast, benthic diversity is often reduced below dams irrespective of dam location and operation with little recovery observed downstream. The community at near-dam sites is largely composed of filter-feeding invertebrates which are quickly replaced downstream, while stoneflies are reduced below impoundments with limited downstream recovery. Despite a lack of formal testing, studies support SDC predictions. The SDC still provides a useful theoretical framework for hypothesis testing, and future studies should further expand the SDC to include empirical estimation within the context of the landscape.

Enders, E.C., M.H. Gessel, J.J. Anderson, and J.G. Williams, 2012. Effects of Decelerating and Accelerating Flows on Juvenile Salmonid Behavior. *Transactions of the American Fisheries Society* 141, 357–364.

Abstract: Migratory and resident fish species have evolved inherent flight responses to avoid potentially harmful situations. At many dams, fish screens or other structures have been installed to guide fish away from turbines or attract them to routes that will result in higher survival. Avoidance responses of fish to rapidly decelerating and accelerating flows at these structures have been repeatedly observed and can result in ineffective fish guidance. By using controlled flume experiments, we analyzed the avoidance behavior of actively migrating spring Chinook salmon *Oncorhynchus tshawytscha* smolts in relation to flow decelerations and accelerations. As smolts drifted into areas with decreasing velocities, they actively swam into the current; the larger was the change in water velocity with distance (spatial velocity gradient [SVG]), the faster was the swimming speed exhibited by smolts. Under accelerating flows, the response velocity varied significantly with flow conditions, but the median SVG at which smolts displayed an avoidance response was similar over all flows tested. For both decelerating and accelerating flows, the avoidance response occurred at an SVG of approximately 1 $cm \cdot s^{-1} \cdot cm^{-1}$. We suggest that this threshold is in part fixed by the energetically optimum swimming speed of the fish (1 body length/s).

Enders, E.C., M. Stickler, C.J. Pennell, D. Cote, K. Alfredsen, and D.A. Scruton, 2008. Variations in distribution and mobility of Atlantic salmon parr during winter in a small, steep river. *Hydrobiologia* 609, 37–44.

Abstract: In many rivers, natural variations in water discharge are affected by flow regulation related to hydropower production. Due to increased energy demand, there has been increased development of mini hydropower stations on small, steep rivers. As the majority of previous research has focused on experimental streams or larger river systems, knowledge on the effects of hydro regulation on small rivers, in particular during winter, are scarce. In order to increase our understanding on the winter ecology of Atlantic salmon parr (Salmo salar L.), we studied parr distribution and mobility in a small (average wetted width: 10.7 m), steep (average riverbed gradient: 1.3%) and unregulated river throughout winter. We tagged 145 parr using Passive Integrated Transponder (PIT) technology. During autumn, freeze-up, mid winter and late winter, parr were tracked using manual tracking devices. Each time an individual was found, its position was geo-referenced. Water discharge and water temperature were recorded continuously throughout the study period. Forty-eight parr were observed at least once during all four tracking surveys. Of these, only thirty-one were observed more than once during every survey. Our results indicate that (1) in comparison to autumn, parr moved closer to the shoreline during winter; (2) parr performed longer movements during autumn and freeze-up than during mid winter and late winter; and (3) within the range of naturally occurring fluctuations, no differences in the mobility pattern of parr was observed in relation to water discharge. However, parr moved less at low water temperatures. Further, we discuss the results on distribution and mobility of parr during winter in perspective to the potential effects of hydro regulation.

Engström, J., R. Jansson, C. Nilsson, and C. Weber, 2011. Effects of river ice on riparian vegetation. *Freshwater Biology* 56, 1095–1105.

Abstract: 1. Many rivers and streams experience pronounced ice dynamics caused by the formation of anchor and frazil ice, leading to flooding and disturbance of riparian and aquatic communities. However, the effects of dynamic ice conditions on riverine biota are little known.
2. We studied the formation of anchor ice in natural streams over 2 years and assessed the effects of anchor ice on riparian vegetation by comparing sites with frequent or abundant and little or no anchor ice formation. We also studied the direct impact of ice on riparian plants by experimentally creating ice in the riparian zone over three winters and by exposing plants of different life forms to −18 °C cold ice in the laboratory.
3. Riparian species richness per 1-m2 plot was higher at sites affected by anchor ice than at sites where anchor ice was absent or rare, whereas dominance was lower, suggesting that disturbance by ice enhances species richness. Species composition was more homogenous among plots at anchor ice sites. By experimentally creating riparian ice, we corroborated the comparative results, with species richness increasing in ice-treated plots compared to controls, irrespective of whether the sites showed natural anchor ice.

4. Because of human alterations of running waters, the natural effects of river ice on stream hydrology, geomorphology and ecology are little known. Global warming in northern streams is expected to lead to more dynamic ice conditions, offering new challenges for aquatic organisms and river management. Our results should stimulate new research, contributing to a better understanding of ecosystem function during winter.

Ettema, R., 2002. Review of Alluvial-channel Responses to River Ice. *Journal of Cold Regions Engineering* 16, 191–217.

Abstract: The extent to which alluvial channels respond to ice-cover formation, presence, and breakup is not well understood. Some responses are well known and observed, such as increased flow stage or localized scour beneath the toe of an ice jam. Other responses are known in concept, such as altered bedform geometry, but are not well documented. Some potential responses are barely recognized, such as channel-thalweg adjustment. Many responses are temporal, such as the channel readjusting itself once ice is gone. A few responses may have a more enduring impact, such as a meander-loop cutoff. Most responses have not been investigated rigorously. The responses affect the full gamut of relationships between flow discharge and stage, macroturbulence structures, sediment-transport and mixing processes, and alluvial-channel stability. Of importance are the relative scales of length and time associated with ice-cover formation, presence and breakup, and a channel's facility to respond to ice. This paper reviews alluvial-channel responses to ice formation, and raises practical engineering issues stemming from them.

Evans, S.G., and J.J. Clague, 1994. Recent climatic change and catastrophic geomorphic processes in mountain environments. *Geomorphology* 10, 107–128.

Abstract: Climatic warming during the last 100–150 years has resulted in a significant glacier ice loss from mountainous areas of the world. Certain natural processes which pose hazards to people and development in these areas have accelerated as a result of this recent deglaciation. These include glacier avalanches, landslides and slope instability caused by glacier debuttressing, and outburst floods from moraine- and glacier-dammed lakes. In addition, changes in sediment and water supply induced by climatic warming and glacier retreat have altered channel and floodplain patterns of rivers draining high mountain ranges.
The perturbation of natural processes operating in mountain environments, caused by recent climatic warming, ranges from tens of decades for moraine-dam failures to hundreds of years or more for landslides. The recognition that climatic change as modest as that of the last century can perturb natural alpine processes has important implications for hazard assessment and future development in mountains. Even so, these effects are probably at least an order of magnitude smaller than those associated with late Pleistocene deglaciation ca. 15,000 to 10,000 years ago.

Evenden, M., 2004. Social and environmental change at Hells Gate, British Columbia. *Journal of Historical Geography* 30, 130–153.

Abstract: This paper analyzes the contestation of a resource—salmon—and a site—Hells Gate, British Columbia, Canada—in a context of rapid environmental change. The focus is the Fraser River and its salmon fisheries during and following landslides at Hells Gate from 1912 to 1914. The landslides obstructed salmon migrations and affected salmon populations in future spawning cycles. Different social groups debated the causes and consequences of the landslides and vied for access to and control of Hells Gate and the salmon.

Fagan, W.F., 2002. Connectivity, fragmentation, and extinction risk in dendritic metapopulations. *Ecology* 83, 3243–3249.

Abstract: Neither linear nor two-dimensional frameworks may be the most appropriate for fish and other species constrained to disperse within river–creek systems. In particular, the hierarchical, dendritic structures of riverine networks are not well captured by existing spatial models. Here I use a simple geometric model and metapopulation modeling to make three points concerning the ecological consequences of dendritic landscapes. First, connectivity patterns of river–creek networks differ from linear landscapes, and these differences in connectivity can either enhance or reduce metapopulation persistence compared to linear systems, depending on the details of dispersal. Second, habitat fragmentation in dendritic landscapes has different (and arguably more severe) consequences on fragment size than in either linear or two-dimensional systems, resulting in both smaller fragments and higher variance in fragment size. Third, dendritic landscapes can induce striking mismatches between the geometry of dispersal and the geometry of disturbance, and as is the case for arid-lands fishes, such mismatches can be important for population persistence.

Fair, L.F., T.M. Willette, J.W. Erickson, R.J. Yanusz, and T.R. McKinley, 2010. *Review of salmon escapement goals in Upper Cook Inlet, Alaska, 2011*. Fishery Manuscript Series No 10-06. ADF&G, Anchorage, Alaska.

Abstract: A contemporary review of fishery escapement goals in Upper Cook Inlet for Chinook, chum, coho, and sockeye salmon stocks.

FERC (Federal Energy Regulatory Commission), 2012. *Scoping Document 2. Susitna-Watana Hydroelectric Project*. FERC Project No. P-14241-000.

Abstract: Scoping Document 2 is part of FERC's National Environmental Policy Act (NEPA) scoping effort for an anticipated environmental impact statement (EIS), which would be used by the Commission to determine whether, and under what conditions, to issue a license for the project. This scoping process will be used to support the preparation of the EIS, ensure that all pertinent issues are identified and analyzed, and ensure that the environmental document is thorough and balanced.

Fetherston, K.L., R.J. Naiman, and R.E. Bilby, 1995. Large woody debris, physical process, and riparian forest development in montane river networks of the Pacific Northwest. *Geomorphology* 13, 133–144.

Abstract: We present a conceptual biogeomorphic model of riparian forest development in montane river networks. The role of physical process in driving the structure, composition, and spatial distribution of riparian forests is examined. We classify the drainage network into disturbance process-based segments including: (1) debris-flow and avalanche channels, (2) fluvial and debris-flow channels, and (3) fluvial channels. Riparian forests are shown to be significant in the development of channel morphology through the stabilization of active floodplains and as sources of LWD. LWD is operationally defined as wood > 0.1 m diameter and > 1 m length. LWD plays a key role in the development of montane riparian forests. LWD deposited in the active channel and floodplain provides sites for vegetation colonization, forest island growth and coalescence, and forest floodplain development. Riparian forest patterns parallel the distribution of hillslope and fluvial processes through the network. Riparian forest structure:, composition, and spatial distribution through the network are driven by the major disturbance processes including: (1) avalanches, (2) debris-flows, and (3) flooding. Riparian forest patterns also reflect the action of LWD in the organization and development of forested floodplains in gravel bedded montane river networks. The focus of our examples are montane river networks of the Pacific Northwest, USA.

Finger, D., M. Schmid, and A. Wüest, 2006. Effects of upstream hydropower operation on riverine particle transport and turbidity in downstream lakes. *Water Resources Research* 42, W08429.

Abstract: Retention in upstream storage dams results in modified riverine water and particle discharge patterns. Particularly, suspended solids input and intrusion dynamics in downstream lakes are affected by dam operations. In a case study, size-dependent particle budgets for peri-alpine Lake Brienz (Switzerland), downstream of major hydropower installations, were determined for a recent 8-year period (1997–2004) and compared to hypothetical no-dam scenarios based on numerical simulations. For this purpose, current tributary particle loads, as well as lake-internal sedimentation and turbidity dynamics, were assessed with in situ measurements. The analysis shows that hydropower damming drastically diminishes particle fluxes and minimizes (short-term) peak discharges. Reductions of high-flow events substantially cut the number of deep intrusions increasing particle supply to the lake surface layer. Furthermore, these hydropower operations shift particle inputs from summer to winter. As a consequence, such peri-alpine lakes become more turbid during winter and less turbid during summer, influencing the seasonal light regime and subsequently the dynamics of phytoplankton growth.

Finney, B.P., I. Gregory-Eaves, J. Sweetman, M.S.V. Douglas, and J.P. Smol, 2000. Impacts of Climatic Change and Fishing on Pacific Salmon Abundance Over the Past 300 Years. *Science* 290, 795–799.

Abstract: The effects of climate variability on Pacific salmon abundance are uncertain because historical records are short and are complicated by commercial harvesting and habitat alteration. We use lake sediment records of δ15N and biological indicators to reconstruct sockeye salmon abundance in the Bristol Bay and Kodiak Island regions of Alaska over the past 300 years. Marked shifts in populations occurred over decades during this period, and some pronounced changes appear to be related to climatic change. Variations in salmon returns due to climate or harvesting can have strong impacts on sockeye nursery lake productivity in systems where adult salmon carcasses are important nutrient sources.

Finstad, A.G., T. Forseth, T.F. Næsje, and O. Ugedal, 2004. The importance of ice cover for energy turnover in juvenile Atlantic salmon. *Journal of Animal Ecology* 73, 959–966.

Abstract: 1 Under benign laboratory tank conditions we compared food consumption and metabolism of Atlantic salmon (Salmo salar) juveniles exposed to simulated ice cover (darkness) with fish in natural short, 6 h light, day length (without ice). Three different populations along an ice-cover gradient were tested (59°N−70°N).

2 Resting metabolism was on average 30% lower under simulated ice cover (6•6 J g−1 day−1) than under natural day length (9•4 J g−1 day−1), and the response was similar for all populations. Northern salmon grew equally well in dark and light conditions, whereas the southern grew significantly poorer in the dark. Fish from all populations fed more under natural day length than in the dark and the northern population had higher consumption than the southern. The relative high growth of fish from the northern population in the dark compared to the southern populations was due partly to higher consumption and partly to higher growth efficiency. Fish from the southern populations had negative growth efficiency in the dark.

3 We also studied the importance of ice cover under more hostile conditions in stream channels using the northern population only. Juveniles held in channels with simulated ice cover lost less energy (20 J g−1 day−1) than those held in channels with transparent cover (26 J g−1 day−1). This difference in energy loss was due partly (50%) to higher food consumption under simulated ice (4•5 and 1•6 J g−1, respectively) and partly (30%) to light-induced differences in resting metabolic rate.

4 In conclusion, both experiments showed lower metabolic costs in darkness under simulated ice cover than without ice. Under benign laboratory conditions the response to light (ice cover) varied among populations and only the northern population were able to attain positive growth in the dark. Under semi-natural conditions the lack of ice cover induced strong negative effects on the energy budget. Because energetic deficiencies are assumed to be an important cause of winter mortality, our study indicates that ice break-ups or removal following climatic change may affect winter survival significantly, particularly in northern populations.

Fisher, S.G., and A. Lavoy, 1972. Differences in Littoral Fauna Due to Fluctuating Water Levels Below a Hydroelectric Dam. *Journal of the Fisheries Research Board of Canada* 29, 1472–1476.

Abstract: Water level fluctuations below a hydroelectric dam on the Connecticut River produce a freshwater "intertidal" zone. Along a transect in this zone from high to low water mark benthic invertebrates increased markedly in density and taxonomic diversity. Community composition shifted from chironomid–oligochaete predominance on the most exposed sites to mollusc predominance on the least exposed sites.

Flory, E.A., and A.M. Milner, 1999. Influence of Riparian Vegetation on Invertebrate Assemblages in a Recently Formed Stream in Glacier Bay National Park, Alaska. *Journal of the North American Benthological Society* 18, 261-273.

Abstract: Influence of the development of riparian vegetation on benthic invertebrate assemblages was analyzed in a recently formed stream in southeast Alaska. Several features of riparian interaction were documented: 10 invertebrate use of willow catkins entering stream in summer, 2) invertebrate use of submerged alder roots as a substrate for attachment and as a source of building material for caddisfly cases, and 3) retention of leaf litter by salmon carcasses. The development of riparian vegetation markedly influenced colonization of the stream by certain invertebrate taxa and thereby played an important role in the successional sequence of macroinvertebrates and overall assemblage development in this stream.

Foerester, R.E., 1968. *The sockeye salmon, Oncorhynchus nerka*. Bulletin. Fisheries Research Board of Canada. 162.

Abstract: A comprehensive summary of biological and ecological information related to sockeye salmon.

Freeman, M.C., C.M. Pringle, E.A. Greathouse, and B.J. Freeman, 2003. Ecosystem-level consequences of migratory faunal depletion caused by dams, in: American Fisheries Society Symposium. pp. 255–266.

Abstract: Humans have been damming rivers for millennia, and our more ambitious efforts over the past century have arguably altered river ecosystems more extensively than any other anthropogenic activity. Effects of damming on river biota include decimation of migratory fauna (e.g., diadromous and potamodromous fishes and crustaceans), lost fisheries, and imperilment of obligate riverine taxa. Although effects of dams on biota have been widely documented, ecosystem-level consequences of faunal depletion caused by dams are only beginning to be appreciated. We discuss consequences to river ecosystems of altering distributions and abundances of migratory fauna, which often provide trophic subsidies and may strongly influence the structure of local habitats and communities. It is well documented that anadromous fishes can provide a major input of nutrients and energy to freshwater systems when spawning adults return from the sea. Other less-studied taxa that migrate between distinct portions of riverine systems (e.g., acipenserids, catostomids, and prochilodontids) may similarly provide trophic transfers within undammed river systems in addition to modifying local communities and habitats through feeding and spawning activities. Experimental faunal exclusions have demonstrated strong potential effects of some amphidromous shrimps and potamodromous fishes on benthic organic matter and algal and invertebrate communities. Depletion of these animals above dams is likely to significantly affect ecosystem processes such as primary production and detrital processing. The decline of freshwater mussels isolated by dams from their migratory fish hosts has likely lowered stream productivity, nutrient retention, and benthic stability. Greater focus on effects of dams on ecosystem processes, as mediated by faunal change, would improve our ability to assess the costs and benefits of future river management strategies.

Fukushima, M., and W.W. Smoker, 1997. Determinants of stream life, spawning efficiency, and spawning habitat in pink salmon in the Auke Lake system, Alaska. *Canadian Journal of Fisheries and Aquatic Sciences* 54, 96–104.

Abstract: Variation in stream life, spawning efficiency, and spawning habitat among adult pink salmon (*Oncorhynchus gorbuscha*) in the Auke Lake system, southeastern Alaska, was best explained by stream discharge, stream temperature, and a combination of stream temperature and discharge. We estimated these attributes of female pink salmon spawners in samples of daily cohorts tagged as they entered fresh water and used generalized linear models to analyze variation in the attributes with respect to environmental factors. Spawners varied in stream life (5–11 days), spawning efficiency (30–70% of females in daily entry cohorts retained less than 500 eggs at death), and spawning habitat (30–70% spawned in the lake outlet stream rather than the lake inlet stream). Observed variation of habitat (proportionately more use of the cooler inlet stream early in the spawning season when stream temperatures are warm and development is rapid) would contribute to synchronicity of fry emigration, which is known to be positively correlated with subsequent survival in Auke Lake pink salmon.

Fulton, L.A., 1968. *Spawning areas and abundance of Chinook salmon (Oncorhynchus tshawytscha) in the Columbia River Basin: past and present*. U.S. Department of the Interior, Bureau of Commercial Fisheries.

Abstract: Chinook salmon, the most abundant species of salmon in the Columbia Basin, formerly spawned in nearly all tributaries of the Columbia River and in many areas of the main river. Over the past 60 years, the construction of dams has inundated, impeded, or blocked access to spawning areas. Despite these heavy losses, large areas of spawning grounds in the middle and lower portions of the drainage are still available to Chinook salmon. Stream improvements by state and federal fishery agencies have rehabilitated some areas and have brought others into production for the first time. Important spawning areas are listed and charted in this report according to their past use (before 1965) and present use (1966). Estimates of recent spawning populations in major tributaries and in segments of the main stem are also given. Former and present levels of abundance are listed according to three major runs: spring, summer, and fall.

Geist, D.R., 2000. Hyporheic discharge of river water into fall Chinook salmon (*Oncorhynchus tshawytscha*) spawning areas in the Hanford Reach, Columbia River. *Canadian Journal of Fisheries and Aquatic Sciences* 57, 1647–1656.

Abstract: Fall Chinook salmon (*Oncorhynchus tshawytscha*) spawned predominantly in areas of the Hanford Reach of the Columbia River where hyporheic water discharged into the river channel. This upwelling water had a dissolved solids content (i.e., specific conductance) indicative of river water and was presumed to have entered highly permeable riverbed substrate at locations upstream of the spawning areas. Hyporheic discharge zones composed of undiluted ground water or areas with little or no upwelling were not used by spawning salmon. Rates of upwelling into spawning areas averaged 1200 L•m-2•day-1 (95% CI = 784-1665 L•m-2•day-1) as compared with approximately 500 L•m-2•day-1 (95% CI = 303-1159 L•m-2•day-1) in nonspawning areas. Dissolved oxygen content of the hyporheic discharge near salmon spawning areas was about 9 mg•L-1 (±0.4 mg•L-1) whereas in nonspawning areas, dissolved oxygen values were 7 mg•L-1 (±0.9 mg•L-1) or lower. In both cases, dissolved oxygen of the river water was higher (11.3 ± 0.3 mg•L-1). Physical and chemical gradients between the hyporheic zone and the river may provide cues for adult salmon to locate suitable spawning areas. This information will help fisheries managers to describe the suitability of salmon spawning habitat in large rivers.

Geist, D.R., and D.D. Dauble, 1998. Redd site selection and spawning habitat use by fall Chinook salmon: the importance of geomorphic features in large rivers. *Environmental Management* 22, 655–669.

Abstract: Knowledge of the three-dimensional connectivity between rivers and groundwater within the hyporheic zone can be used to improve the definition of fall Chinook salmon (*Oncorhynchus tshawytscha*) spawning habitat. Information exists on the microhabitat characteristics that define suitable salmon spawning habitat. However, traditional spawning habitat models that use these characteristics to predict available spawning habitat are restricted because they can not account for the heterogeneous nature of rivers. We present a conceptual spawning habitat model for fall Chinook salmon that describes how geomorphic features of river channels create hydraulic processes, including hyporheic flows, that influence where salmon spawn in unconstrained reaches of large mainstem alluvial rivers. Two case studies based on empirical data from fall Chinook salmon spawning areas in the Hanford Reach of the Columbia River are presented to illustrate important aspects of our conceptual model. We suggest that traditional habitat models and our conceptual model be combined to predict the limits of suitable fall Chinook salmon spawning habitat. This approach can incorporate quantitative measures of river channel morphology, including general descriptors of geomorphic features at different spatial scales, in order to understand the processes influencing redd site selection and spawning habitat use. This information is needed in order to protect existing salmon spawning habitat in large rivers, as well as to recover habitat already lost. The protection and restoration of spawning habitat within large mainstem rivers is included in most recovery plans for Pacific salmon

Geist, D.R., Z. Deng, R.P. Mueller, S.R. Brink, and J.A. Chandler, 2010. Survival and Growth of Juvenile Snake River Fall Chinook Salmon Exposed to Constant and Fluctuating Temperatures. *Transactions of the American Fisheries Society* 139, 92–107.

Abstract: The incipient lethal temperature (ILT) and critical thermal maximum (CTM) methods are used to set temperature limits for fish. However, the standard application of these methods does not always match the temperature regimes that fish experience in the wild. We used alternative methods to determine the thermal tolerance thresholds of juvenile fall-run Chinook salmon *Oncorhynchus tshawytscha* exposed to the temperature regimes that are common in the entrapment pools that form along the shoreline of the Snake River when flows are altered to meet electric power demand. A modified CTM test with a steady temperature rise (1.5°C/h) showed that one-half the fish died when temperatures reached 27.4–27.9°C and that survival at 25°C was highly variable; the average time to the first death was 9.1 h, varying from 1.7 to 22.5 h. Over 30 d, 99.8% of the fish in the constant temperature regimes (14–22°C) survived. In the fluctuating temperature regimes (which varied from 10–14°C to 22–27.5°C), overall survival was 97.3%; however, only 83.0% and 88.9% survived in the groups that reached daily maximums of 27°C and 27.5°C, respectively. Growth over 30 d in the constant thermal regimes was nearly twice as high as that in the fluctuating regimes, even when daily average temperatures were similar. The maximum growth was 1.9%/d in terms of fork length [FL] and 11.2%/d in terms of weight (WT) at a constant 20°C. The lowest growth occurred in the two groups exposed to daily temperatures of 27°C or more, namely, 0.7–0.8% (FL) and 2.7–3.4% (WT). The results of this study suggest that thermal tolerance tests that expose juvenile fall Chinook salmon to thermal regimes that match the field conditions in entrapment pools along the shoreline of the Snake River provide higher temperature criteria than the standard ILT and CTM methods.

Geist, D.R., T.P. Hanrahan, E.V. Arntzen, G.A. McMichael, C.J. Murray, Y.J. Chien, 2002. Physicochemical Characteristics of the Hyporheic Zone Affect Redd Site Selection by Chum Salmon and Fall Chinook Salmon in the Columbia River. *North American Journal of Fisheries Management* 22, 1077–1085.

Abstract: Chum salmon *Oncorhynchus keta* and fall Chinook salmon *O. tshawytscha* spawned at separate locations in a side channel near Ives Island, Washington, in the Columbia River downstream of Bonneville Dam. We hypothesized that measurements of water depth, substrate size, and water velocity would not sufficiently explain the separation in spawning areas and began a 2-year investigation of physicochemical characteristics of the hyporheic zone. We found that chum salmon spawned in upwelling water that was significantly warmer than the

surrounding river water. In contrast, fall Chinook salmon constructed redds at downwelling sites, where there was no difference in temperature between the river and its bed. An understanding of the specific factors affecting chum salmon and fall Chinook salmon redd site selection at Ives Island will be useful to resource managers attempting to maximize available salmonid spawning habitat within the constraints imposed by other water resource needs.

Geist, D.R., C.J. Murray, T.P. Hanrahan, and Y. Xie, 2008. A Model of the Effects of Flow Fluctuations on Fall Chinook Salmon Spawning Habitat Availability in the Columbia River. *North American Journal of Fisheries Management* 28, 1894–1910.

Abstract: The logistic regression models that we previously used to predict where fall Chinook salmon *Oncorhynchus tshawytscha* would spawn in the Hanford Reach of the Columbia River were based on so-called static variables (i.e., the riverbed surface substrate, riverbed slope, and time-averaged velocity and depth [representing the velocity and depth in each cell associated with the 50% exceedance flow]). Not all habitat predicted to be used for spawning contained redds, and one explanation for the overprediction is that the models did not incorporate streamflow fluctuation. Streamflow fluctuation occurs daily in the Hanford Reach owing to load-following operations (power generation to meet short-term electrical demand) at Priest Rapids Dam, a hydroelectric dam located at the upper end of the reach. Daily flow fluctuations could change the hydraulic characteristics to which fall Chinook salmon respond in selecting redd sites. The purpose of this study was to determine whether incorporating metrics of flow variability would improve modeling of spawning habitat availability. Flow variability was represented by so-called dynamic variables (i.e., the standard deviations of velocity and depth for each habitat cell over a 60-d time segment during the fall spawning period in 1994, 1995, and 2001). Both the static and dynamic models were correct at least 85% of the time in predicting habitat as spawning or nonspawning. However, incorporation of the dynamic variables into the logistic regression models reduced the amount of overpredicted habitat by 42% in 1994, 32% in 1995, and 25% in 2001. For example, the area predicted to be suitable but not used in 1994 decreased from 20.8 ha for the static model to 12.1 ha for the dynamic model for all sites combined; similar results were found for 1995 and 2001. This represents an improvement in our ability to accurately predict suitable fall Chinook salmon spawning habitat in the Hanford Reach of the Columbia River.

Giorgi, A.E., T.W. Hillman, J.R. Stevenson, S.G. Hays, and C.M. Peven, 1997. Factors That Influence the Downstream Migration Rates of Juvenile Salmon and Steelhead through the Hydroelectric System in the Mid-Columbia River Basin. *North American Journal of Fisheries Management* 17, 268–282.

Abstract: We investigated the extent to which key factors influenced the migration rate of the smolts of Pacific salmon *Oncorhynchus* spp. through impounded portions of the mid-Columbia River, during the years 1989–1995. Actively migrating Chinook salmon O. tshawytscha (oceantype and stream-type forms), sockeye salmon O. nerka, and steelhead O. mykiss were

analyzed by bivariate and multiple-regression methods. The dependent variable was the rate (km/d) at which uniquely coded PIT-tagged (passive integrated transponder tags) smolts migrated between Rock Island Dam and McNary Dam. Predictor variables consisted of indices of river discharge volume (flow), water temperature, release date of tagged fish, and fish size. The variable of key interest was flow because water management strategies are in place to increase water velocity through flow augmentation, with the intention of increasing smolt migration rate to decrease smolt mortality. For spring-migrating sockeye salmon, hatchery steelhead, and wild steelhead, flow was the primary predictor variable entering the models, and the bivariate models explained 42, 36 and 31% of the observed variation in migration rate for those species, respectively. Yearling Chinook salmon migration rate was not correlated with any variable. Summer-migrating ocean-type Chinook salmon showed no response to flow over a broad range of discharge (1,500–5,000 m3/s). However, there was a positive relationship between migration rate and fish length at the time of tagging for oceantype Chinook salmon; r^2 in the bivariate model = 0.59. Implications of these findings to water management strategies are discussed.

Gislason, J.C., 1985. Aquatic Insect Abundance in a Regulated Stream under Fluctuating and Stable Diel Flow Patterns. *North American Journal of Fisheries Management* 5, 39–46.

Abstract: Aquatic insect abundance at water depths of 15-45 cm was examined in a fifth-order reach of the Skagit River, Washington from May to November in 1976 and 1977. The study site was subject to diel flow fluctuation in 1976 from hydroelectric power-peaking, and to a relatively stable flow pattern in 1977 while peaking was curtailed. Under fluctuating flow conditions, insect density increased from shallow to deep water and was negatively correlated (r = -0.76, P < 0.001) with hours of dewatering during the 2 weeks prior to sampling. Current fluctuation appeared to limit insect density at the 45-cm deep sampling locations that were not extensively dewatered during the daily peaking cycle. The highest density observed in 1976 was 1,788 insects/m 2 at 25 cm in July. Under stable flow conditions, the abundance of benthic insects was greatly enhanced and the densities at corresponding depths and months were 1.8-59 times higher in 1977 than in 1976. Insect densities increased steadily from May 1977 through September 1977 when they reached a maximum level of 16,763 insects/m 2 at 15 cm. Reduction in the amplitude and duration of power-peaking flow fluctuation can be a highly effective management strategy for enhancing aquatic insect standing crop, with a potential for increasing the survival and growth of fish dependent on insects for food.

Goniea, T.M., M.L. Keefer, T.C. Bjornn, C.A. Peery, D.H. Bennett, and L.C. Stuehrenberg, 2006. Behavioral Thermoregulation and Slowed Migration by Adult Fall Chinook Salmon in Response to High Columbia River Water Temperatures. *Transactions of the American Fisheries Society* 135, 408–419.

Abstract: The relationships between lower Columbia River water temperatures and migration rates, temporary tributary use, and run timing of adult fall Chinook salmon *Oncorhynchus*

tshawytscha were studied using historical counts at dams and recently collected radiotelemetry data. The results from more than 2,100 upriver bright fall Chinook salmon radio-tagged over 6 years (1998, 2000–2004) showed that mean and median migration rates through the lower Columbia River slowed significantly when water temperatures were above about 20 °C. Slowed migration was strongly associated with temporary use of tributaries, which averaged 2–7 °C cooler than the main stem. The proportion of radio-tagged salmon using tributaries increased exponentially as Columbia River temperatures rose within the year, and use was highest in the warmest years. The historical passage data showed significant shifts in fall Chinook salmon run timing distributions concomitant with Columbia River warming and consistent with increasing use of thermal refugia. Collectively, these observations suggest that Columbia River fall Chinook salmon predictably alter their migration behaviors in response to elevated temperatures. Coolwater tributaries appear to represent critical habitat areas in warm years, and we recommend that both main-stem thermal characteristics and areas of refuge be considered when establishing regulations to protect summer and fall migrants.

Good, T.P., J. Davies, B.J. Burke, and M.H. Ruckelshaus, 2008. Incorporating Catastrophic Risk Assessments Into Setting Conservation Goals for Threatened Pacific Salmon. *Ecological Applications* 18, 246–257.

Abstract: Catastrophic die-offs can have important consequences for vertebrate population growth and biodiversity, but catastrophic risks are not commonly incorporated into endangered-species recovery planning. Natural (e.g., landslides, floods) and anthropogenic (e.g., toxic leaks and spills) catastrophes pose a challenge for evolutionarily significant units (ESUs) of Pacific salmon listed under the Endangered Species Act and teetering at precariously low population levels. To spread risks among Puget Sound Chinook salmon populations, recovery strategies for ESU-wide viability recommend at least two viable populations of historical life-history types in each of five geographic regions. We explored the likelihood of Puget Sound Chinook salmon ESU persistence by examining spatial patterns of catastrophic risk and testing ESU viability recommendations for 22 populations of the threatened Puget Sound Chinook salmon ESU. We combined geospatial information about catastrophic risks and Chinook salmon distribution in Puget Sound watersheds to categorize relative catastrophic risks for each population. We then analyzed similarities in risk scores among regions and compared risk distributions among strategies: (1) population groups selected using the ESU viability recommendations of having populations spread out geographically and including historical life-history diversity, and (2) population groups selected at random. Risks from individual catastrophes varied among populations, but overall risk from catastrophes was similar within geographic regions. Recovery strategies that called for two viable populations in each of five geographic regions had lower risk than random strategies; strategies that included life-history diversity had even lower risks. Geographically distributed populations have varying catastrophic-risks profiles, thus identifying and reinforcing the spatial and life-history diversity critical for populations to respond to environmental change or needed to rescue severely depleted or extirpated populations.

Recovery planning can promote viability of Pacific salmon ESUs across the landscape by incorporating catastrophic risk assessments.

Grant, G.E., J.C. Schmidt, and S.L. Lewis, 2003. A geological framework for interpreting downstream effects of dams on rivers. *A Unique River, River Science and Application* 7 203–219.

Abstract: Despite decades of research and abundant case studies on downstream effects of dams on rivers, we have few general models predicting how any particular river is likely to adjust following impoundment. Here we present a conceptual and analytical framework for predicting geomorphic response of rivers to dams, emphasizing the role of geologic setting and history as first-order controls on the trajectory of change. Basin geology influences watershed and channel processes through a hierarchical set of linkages, extending from the drainage basin to the valley and channel, which determine the sediment transport and discharge regimes. Geology also directly shapes the suite of hillslope processes, landforms, and geomorphic disturbances impinging on the channel and valley floor. These factors, in turn, affect the "lability" or capacity for adjustment of the downstream channel, determining the type, direction, and extent of channel adjustments that occur, including incision, widening, and textural changes. We develop an analytical framework based on two dimensionless variables that predicts geomorphic responses to dams depending on the ratio of sediment supply below to that above the dam (S*) and the fractional change in frequency of sediment-transporting flows (T*). Drawing on examples from the Green, Colorado, and Deschutes Rivers, we explore how trajectories of geomorphic change, as defined by these two variables, are influenced by the geological setting and history of the river. This approach holds promise for predicting the magnitude and trend of downstream response to other dammed rivers, and can identify river systems where geological controls are likely to dominate.

Greene, C.M., and T.J. Beechie, 2004. Consequences of potential density-dependent mechanisms on recovery of ocean-type Chinook salmon (*Oncorhynchus tshawytscha*). *Canadian Journal of Fisheries and Aquatic Sciences* 61, 590–602.

Abstract: Restoring salmon populations depends on our ability to predict the consequences of improving aquatic habitats used by salmon. Using a Leslie matrix model for Chinook salmon (*Oncorhynchus tshawytscha*) that specifies transitions among spawning nests (redds), streams, tidal deltas, nearshore habitats, and the ocean, we compared the relative importance of different habitats under three density-dependent scenarios: juvenile density independence, density-dependent mortality within streams, delta, and nearshore, and density-dependent migration among streams, delta, and nearshore. Each scenario assumed density dependence during spawning. We examined how these scenarios influenced priorities for habitat restoration using a set of hypothetical watersheds whose habitat areas could be systematically varied, as well as the Duwamish and Skagit rivers. In all watersheds, the three scenarios shared high sensitivity to changes in in nearshore and ocean mortality and produced similar responses to changes in other parameters

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

Abstract: We field tested the hypothesis that predation by piscivorous fish is reduced in turbid compared with clear water. The Harrison River (1 nephelometric turbidity units, NTU) is a clear tributary of the naturally turbid Fraser River (27–108 NTU), in British Columbia, Canada. Age-0 juveniles of Harrison River stocks of Pacific salmon *Oncorhynchus* spp. migrating seaward in spring obligately pass through turbid and clear reaches of these rivers. To test the hypothesis, we compared predation on salmonids by potential predators caught by beach seine and by the rate of predator attack on tethered juvenile Chinook salmon O. tshawytscha in these two rivers. Of 491 predators examined, 30% of Harrison River piscivores had recently consumed fish compared with only 10% of Fraser River piscivores. Of those that ate fish, fish prey per predator was significantly lower in the Fraser River (mean = 1.1, N = 21) than in the Harrison River (mean = 1.7, N = 66). In a clear-water side channel of the Fraser River—Nicomen Slough (1–6 NTU)—both incidence of predation (37%) and number of fish prey per predator (mean = 2.4, N = 19) were similar to values for the Harrison River. Loss of prey from tethers was significantly higher in the Harrison River (23–61%) than in the Fraser River (10–24%). The loss of prey from tethers was highest at dusk and near the bottom in the Harrison River; no spatial or temporal difference occurred in the turbid Fraser River. Therefore, our data support the hypothesis. During their seaward migration in the Fraser River system, age-0 Pacific salmon were less likely to encounter and be consumed by fish piscivores in turbid water than in clear water.

Greig, S.M., D.A. Sear, and P.A. Carling, 2005. The impact of fine sediment accumulation on the survival of incubating salmon progeny: Implications for sediment management. *Science of The Total Environment* 344, 241–258.

Abstract: This paper draws on results from a recent research programme on the impact of fine sediment transport through catchments to present a case for the development of new approaches to improving the quality of salmonid spawning and incubation habitats. To aid the development of these programmes, this paper summarises the mechanisms by which fine sediment accumulation influences the availability of oxygen (O2) to incubating salmon embryos. The results of the investigation indicate that incubation success is inhibited by: (i) the impact of fine sediment accumulation on gravel permeability and, subsequently, the rate of passage of oxygenated water through the incubation environment; (ii) reduced intragravel O2 concentrations that occur when O2 consuming material infiltrates spawning and incubation gravels; and (iii) the impact of fine particles (clay) on the exchange of O2 across the egg membrane. It is concluded that current granular measures of spawning and incubation habitat quality do not satisfactorily describe the complexity of factors influencing incubation success. Furthermore, an assessment of the trends in fine sediment infiltration indicates that only a small proportion of the total suspended sediment load infiltrates spawning and incubation gravels. This casts doubt over the ability of current catchment-based land use management strategies to adequately reduce fine sediment inputs.

Groot, C., W.C. Clarke, and L. Margolis, 1995. *Physiological Ecology of Pacific Salmon*. UBC Press.

Abstract: A comprehensive summary of physiological attributes and habitat requirements for Pacific salmon species.

Gross, H.P., W.A. Wurtsbaugh, and C. Luecke, 1998. The Role of Anadromous Sockeye Salmon in the Nutrient Loading and Productivity of Redfish Lake, Idaho. *Transactions of the American Fisheries Society* 127, 1–18.

Abstract: We constructed a simulation model for Redfish Lake, Idaho, using water budget and nutrient loading measurements, to predict the dependence of lake production on nutrients from the watershed, precipitation, lake fertilization, and marine-derived nutrients from sockeye salmon *Oncorhynchus nerka* which historically have reared in the lake. We also used the model to simulate different management scenarios to help restore the endangered Snake River sockeye salmon. The model and other empirical evidence indicated that even before hydropower dams were present in the migration corridor, marine-derived nutrients were not of major importance to lake production, contributing only about 3% of the annual phosphorus load of the lake. This contribution was partially removed by the quick flushing rate (3 years) of the lake and phosphorus export by smolts. The model predicted annual adult sockeye salmon returns to be 3,800 fish under predam conditions, 370 fish under modern conditions, 780 fish when watershed nutrient loading was doubled (simulating lake fertilization), and 750 fish when smolt-to-adult survival was doubled. Although fertilization should stimulate sockeye salmon production, the effect would be transitory. The model predicted that 8 years after the end of a 3-year fertilization period, adult returns would be only 5% greater than those for unfertilized conditions. Our analysis suggests that to restore self-sustaining anadromous sockeye salmon populations to Redfish Lake, increased smolt-to-adult survival must be achieved; however, lake fertilization should be considered an important short-term tool for decreasing continued erosion of the stock.

Groves, P.A., and J.A. Chandler, 1999. Spawning Habitat Used by Fall Chinook Salmon in the Snake River. *North American Journal of Fisheries Management* 19, 912–922.

Abstract: Literature describing spawning habitat used by fall-run Chinook salmon *Oncorhynchus tshawytscha* is lacking for populations using large, main-stem rivers. A stable spawning flow regime in the Snake River below Hells Canyon Dam and enhanced survey capabilities using remote underwater videography allowed us to accurately describe spawning habitat used by fall Chinook salmon within this large river. Water depth measured at 205 fall Chinook salmon redds ranged from 0.2 to 6.5 m. Mean water column velocity at 145 redds ranged from 0.4 to 2.1 m/s, and substrate- level water velocity at 164 redds ranged from 0.1 to 2.0 m/s. Substrate size classifications from 112 redds indicated that areas having particle sizes that are relatively homogenous with diameters of 2.5–15.0 cm are used for spawning. During our study, spawning generally began as water temperatures dropped below 16.0°C, and concluded as temperatures approached 5.0°C. Our results corroborate earlier observations of fall Chinook salmon spawning in deep, fast-velocity water in the Hanford Reach of the Columbia River and significantly expand current criteria used to model spawning habitat availability for these fish within large rivers.

Groves, P.A., J.A. Chandler, and T.J. Richter, 2008. Comparison of Temperature Data Collected from Artificial Chinook Salmon Redds and Surface Water in the Snake River. *North American Journal of Fisheries Management* 28, 766–780.

Abstract: During three incubation periods, we collected temperature data from within artificial redds constructed in known spawning locations of Chinook salmon *Oncorhynchus tshawytscha* and from the surface water of the Snake River. Our objectives were to compare the data to determine (1) whether estimates of fry emergence timing differed between the two environments and (2) whether surface water data could be used to predict thermal conditions within redds. Statistical tests indicated that no differences could be detected between accumulated thermal units calculated from intraredd and surface water data (all $P \geq 0.06$). We observed very little diel thermal fluctuation or daily difference within and between environments. Regression of intraredd temperature on surface water temperature was significant ($r2 \geq 0.98$; all $P < 0.01$), indicating that surface water temperature data can be used to predict intraredd temperature. We conclude that it is feasible to use surface water temperature as a surrogate for intraredd temperature in estimating Chinook salmon embryo developmental timing within the Snake River and potentially in other large rivers.

Gustafson, R.G., R.S. Waples, J.M. Myers, L.A. Weitkamp, G.J. Bryant, O.W. Johnson, and J.J. Hard, 2007. Pacific Salmon Extinctions: Quantifying Lost and Remaining Diversity. *Conservation Biology* 21, 1009–1020.

Abstract: Widespread population extirpations and the consequent loss of ecological, genetic, and life-history diversity can lead to extinction of evolutionarily significant units (ESUs) and species. We attempted to systematically enumerate extinct Pacific salmon populations and characterize lost ecological, life history, and genetic diversity types among six species of Pacific salmon (Chinook [*Oncorhynchus tshawytscha*], sockeye [*O. nerka*], coho [*O. kisutch*], chum [*O. keta*], and pink salmon [*O. gorbuscha*] and steelhead trout [*O. mykiss*]) from the western contiguous United States. We estimated that, collectively, 29% of nearly 1400 historical populations of these six species have been lost from the Pacific Northwest and California since Euro-American contact. Across all species there was a highly significant difference in the proportion of population extinctions between coastal (0.14 extinct) and interior (0.55 extinct) regions. Sockeye salmon (which typically rely on lacustrine habitats for rearing) and stream-maturing Chinook salmon (which stay in freshwater for many months prior to spawning) had significantly higher proportional population losses than other species and maturation types. Aggregate losses of major ecological, life-history, and genetic biodiversity components across all species were estimated at 33%, 15%, and 27%, respectively. Collectively, we believe these population extirpations represent a loss of between 16% and 30% of all historical ESUs in the study area. On the other hand, over two-thirds of historical Pacific salmon populations in this area persist, and considerable diversity remains at all scales. Because over one-third of the remaining populations belong to threatened or endangered species listed under the U.S. Endangered Species Act, it is apparent that a critical juncture has been reached in efforts to preserve what remains of Pacific salmon diversity. It is also evident that persistence of existing, and evolution of future, diversity will depend on the ability of Pacific salmon to adapt to anthropogenically altered habitats.

Hamilton, J.B., G.L. Curtis, S.M. Snedaker, and D.K. White, 2005. Distribution of Anadromous Fishes in the Upper Klamath River Watershed Prior to Hydropower Dams—A Synthesis of the Historical Evidence. *Fisheries* 30, 10–20.

Abstract: Knowledge of the historical distribution of anadromous fish is important to guide management decisions regarding the Klamath River including ongoing restoration and regional recovery of coho salmon (*Oncorhynchus kisutch*). Using various sources, we determined the historical distribution of anadromous fish above Iron Gate Dam. Evidence for the largest, most utilized species, Chinook salmon (*Oncorhynchus tshawytscha*), was available from multiple sources and clearly showed that this species historically migrated upstream into tributaries of Upper Klamath Lake. Available information indicates that the distribution of steelhead (*Oncorhynchus mykiss*) extended to the Klamath Upper Basin as well. Coho salmon and anadromous lamprey (*Lampetra tridentata*) likely were distributed upstream at least to the vicinity of Spencer Creek. A population of anadromous sockeye salmon (*Oncorhynchus nerka*) may have occurred historically above Iron Gate Dam. Green sturgeon (*Acipenser medirostris*), chum salmon (*Oncorhynchus keta*), pink salmon (*Oncorhynchus gorbuscha*), coastal cutthroat trout (*Oncorhynchus clarki clarki*), and eulachon (*Thaleichthys pacificus*) were restricted to the Klamath River well below Iron Gate Dam. This synthesis of available sources regarding the historical extent of these species' upstream distribution provides key information necessary to guide management and habitat restoration efforts.

Hanrahan, T.P., D.D. Dauble, and D.R. Geist, 2004. An estimate of Chinook salmon (*Oncorhynchus tshawytscha*) spawning habitat and redd capacity upstream of a migration barrier in the upper Columbia River. *Canadian Journal of Fisheries and Aquatic Sciences* 61, 23–33.

Abstract: Chief Joseph Dam on the Columbia River is the upstream terminus for anadromous fish because of its lack of fish passage facilities. Management agencies are currently evaluating the feasibility of reintroducing anadromous fish upriver of Chief Joseph Dam. We evaluated the physical characteristics of potential fall Chinook salmon (*Oncorhynchus tshawytscha*) spawning habitat in the upper section of Chief Joseph Reservoir. The objectives were to estimate the location and quantity of potential spawning habitat and to determine the redd capacity of the area based on spawning habitat characteristics. The suitability of the study area was estimated through the use of geomorphic analysis, empirical physical data, and modeled hydraulic data. We estimated that 5% (48.7 ha) of the study area contains potentially suitable fall Chinook salmon spawning habitat. Potential spawning habitat is primarily limited by deep water and low water velocities, resulting in 20% (9.6 ha) of the potential spawning habitat being characterized as high quality. Estimates of redd capacity within potential spawning habitat range from 207 to 1599 redds. The results of our study provide fisheries managers with useful information for evaluating the complex issue of reintroducing anadromous fish to the Columbia River upstream of Chief Joseph Dam.

Hare, S.R., N.J. Mantua, and R.C. Francis, 1999. Inverse Production Regimes: Alaska and West Coast Pacific Salmon. *Fisheries* 24, 6–14.

Abstract: A principal component analysis reveals that Pacific salmon catches in Alaska have varied inversely with catches from the U.S. West Coast during the past 70 years. If variations in catch reflect variations in salmon production, then results of our analysis suggest that the spatial and temporal characteristics of this “inverse” catch/production pattern are related to climate forcing associated with the Pacific Decadal Oscillation, a recurring pattern of pan-Pacific atmosphere-ocean variability. Temporally, both the physical and biological variability are best characterized as alternating 20-to 30-year-long regimes punctuated by abrupt reversals. From 1977 to the early 1990s, ocean conditions have generally favored Alaska stocks and disfavored West Coast stocks. Unfavorable ocean conditions are likely confounding recent management efforts focused on increasing West Coast Pacific salmon production. Recovery of at-risk (threatened and endangered) stocks may await the next reversal of the Pacific Decadal Oscillation. Managers should continue to limit harvests, improve hatchery practices, and restore freshwater and estuarine habitats to protect these populations during periods of poor ocean productivity.

Harris, R.R., C.A. Fox, and R. Risser, 1987. Impacts of hydroelectric development on riparian vegetation in the Sierra Nevada region, California, USA. *Environmental Management* 11, 519–527.

Abstract: Fourteen streams in the Sierra Nevada in the USA were sampled to determine whether diversions of streamflow for hydroelectric development had caused significant changes in riparian vegetation. Several streams showed significant differences in vegetation cover, community composition, or community structure between pairs of diverted and undiverted reaches. On some streams, environmental conditions rather than streamflow diversions may have been responsible for vegetation differences. Streams in the Sierra Nevada respond individualistically to diversions. Prediction of vegetation responses must take into consideration environmental characteristics of specific stream reaches.

Harrison, W.D., B.T. Drage, S. Bredthauer, D. Johnson, C. Schoch, and A.B. Follett, 1983. Reconnaissance of the glaciers of the Susitna River basin in connection with proposed hydroelectric development. *Annals of Glaciology* 4, 99–104.

Abstract: A reconnaissance program has been carried out to identify problems caused by glaciers in a large proposed hydroelectric development in the Susitna River basin of Alaska. Balance measurements on the major glaciers have been initiated, and long-term balance between 1949 and 1980 has been estimated from existing photo sets. From the latter it appears that shrinking of the glaciers, which comprise 4% of the basin area, may have contributed appreciably to the measured basin runoff. A potential instability in the drainage of Eureka Glacier, on the edge of the basin, has been identified. The glaciers of the basin seem to be largely temperate, and most of them are surging or pulsing types. Velocity measurements show seasonal variations that suggest appreciable contribution to the motion from basal sliding. A study of the moraines of Susitna Glacier, which is a surging type, indicates that no surge is imminent. Glacier-dammed lakes exist in the basin; they are small but could be enlarged by surging or other mechanisms. Some general problems in the estimation of the transport of suspended sediment are noted.

Hasler, C.T., S.J. Cooke, S.G. Hinch, E. Guimond, M.R. Donaldson, B. Mossop, and D.A. Patterson, 2012. Thermal biology and bioenergetics of different upriver migration strategies in a stock of summer-run Chinook salmon. *Journal of Thermal Biology* 37, 265–272.

Abstract: By combining biotelemetry with animal-borne thermal loggers, we re-created the thermal histories of 21 summer-run Chinook salmon (*Oncorhynchus tshawytscha*) migrating in the Puntledge River, a hydropower impacted river system on Vancouver Island, British Columbia, Canada. Daily maximum water temperatures in the Puntledge River during the summer-run adult Chinook salmon migration and residency period frequently exceeded 21 °C, a value that has been observed to elicit behavioral thermoregulation in other Chinook salmon populations. We therefore compared river temperatures to body temperatures of 16 fish that migrated through the river to understand if cool-water refuge was available and being used by migrants. In addition, we used thermal histories from fish and thermal loggers distributed in the river to model the effect of thermal habitat on energy density using a bioenergetics model. In general, we found no evidence that cool-water refuge existed in the river, suggesting that there is no opportunity for fish to behaviorally thermoregulate during upriver migration through the regulated portion of the river. Of the thermal histories used in the bioenergetics model, fish that reached an upstream lake were able to access cooler, deeper waters, which would have reduced energy consumption compared to fish that only spent time in the warmer river. Consequently, the Puntledge River water temperatures are likely approaching and in some cases exceeding the thermal limits of the summer-run Chinook salmon during the spawning migration. Further warming may cause more declines in the stock.

HDR, Inc., 2013a. *Technical Memorandum: Characterization and Mapping of Aquatic Habitats, Susitna-Watana Hydroelectric Project (FERC No. 14241)*. Alaska Energy Authority.

Abstract: The methodology used for selection of tributaries within the inundation zone that will be habitat mapped incorporates three independent steps. Step 1 describes tributaries selected as proposed in the RSP Section 9.9. These tributaries represent primarily larger primary and secondary tributaries. Steps 2 and 3 described below are in response to Item 3 of FERC's recommendations for the selection of additional small and additional low-order tributaries within the proposed inundation zone.

HDR, 2013b. *Susitna River Ice Processes Study Report*. Susitna-Watana Hydroelectric Project (FERC No. 14241). Alaska Energy Authority.

Abstract: The purpose of the 2012 Ice Processes Study was to document baseline winter ice conditions on the Susitna River between Cook Inlet and the Oshetna River confluence near river mile (RM) 234. The specific information sought included the location of open leads in the ice cover in late winter, the progression of breakup, including the locations and effects of ice jams, the progression of freeze-up, and the interaction between river ice processes and riparian vegetation and fish habitat. This baseline data will help identify the river reaches most likely to experience changes in river ice formation as a result of Project construction and operation.

HDR, 2013c. *Study of Fish Passage Barriers in the Middle and Upper Susitna River and Susitna Tributarie*s. Implementation Plan. Susitna-Watana Hydroelectric Project (FERC No. 14241). Alaska Energy Authority.

Abstract: This study focuses on locating, describing, and assessing potential fish passage barriers in the Middle and Upper Susitna River that could be created or eliminated as a result of Project construction and operation.

HDR, 2013d. *Study of Fish Passage Barriers Implementation Plan.* Susitna-Watana Hydroelectric Project (FERC No. 14241). Alaska Energy Authority.

Abstract: Submittal to FERC. The goal of this study is to evaluate the potential effects of Project-induced changes in flow and water surface elevation on free access of fish into, within, and out of suitable habitats in the Upper Susitna River (inundation zone above the Watana Dam site) and the Middle Susitna River (Watana Dam site to the confluence of Chulitna and Talkeetna rivers).

HDR, 2013e. *Characterization and Mapping of Aquatic Habitats*. Technical Memorandum. Susitna-Watana Hydroelectric Project (FERC No. 14241) Upper Middle River. Alaska Energy Authority.

Abstract: This study focuses on the characterization and mapping of aquatic habitats in the upper and Middle Susitna River with the potential to be altered and/or lost as the result construction and operation of the proposed Susitna-Watana Hydroelectric Project.

HDR, 2013f. *Characterization and Mapping of Aquatic Habitats*. Technical Memorandum. Susitna-Watana Hydroelectric Project (FERC No. 14241) Reservoir Inundation Zone. Alaska Energy Authority.

Abstract: In this technical memorandum AEA has described a proposed method that will result in the selection of 25 tributaries within the reservoir inundation zone for habitat mapping. Ten of these tributaries are large primary and secondary tributaries known to support fish populations and are targeted for fish sampling under RSP Section 9.5. In addition, AEA provides a systematic approach to grouping smaller primary, secondary, and tertiary tributaries based on physical characteristics and random selection of tributaries within categories. This will result in selection of an additional 10 primary tributaries and at least 5 lower-order tributaries for habitat mapping.

HDR, 2013g. *Characterization and Mapping of Aquatic Habitats*. Technical Memorandum. Susitna-Watana Hydroelectric Project (FERC No. 14241). Alaska Energy Authority.

Abstract: Submittal to FERC. In this technical memorandum AEA has described a proposed method that will result in the selection of 25 tributaries within the proposed reservoir inundation zone for habitat mapping. Ten of these tributaries are large primary and secondary tributaries known to support fish populations and are targeted for fish sampling under RSP Section 9.5. In addition, AEA provides a systematic approach to grouping smaller primary, secondary, and tertiary tributaries based on physical characteristics and random selection of tributaries within categories. This will result in selection of an additional 10 primary tributaries and at least 5 secondary or tertiary tributaries for habitat mapping.

HDR, 2013h. *Attachment B. Middle Susitna River Segment Remote Line Habitat Mapping Technical Memorandum*. Susitna-Watana Hydroelectric Project (FERC No. 14241). Alaska Energy Authority.

Abstract: The goal of this study was to determine the composition and frequency of mainstem aquatic habitats and delineate the proportion of habitat in the Middle Susitna River from aerial imagery or videography.

HDR, 2013i. *Appendix-A. Description of 31 Primary and Secondary Tributaries above Devils Canyon from which 20 Tributaries were Selected for Habitat Mapping*. Characterization and Mapping of Aquatic Habitats. Technical Memo. Susitna-Watana Hydroelectric Project (FERC No. 14241). Alaska Energy Authority.

Abstract: Description and GIS figures of the tributaries above Devils Canyon.

HDR, 2013j. *Appendix B. Map of Tributaries in the Middle and Upper Susitna River above Devils Canyon*. Characterization and Mapping of Aquatic Habitats. Technical Memorandum. Susitna-Watana Hydroelectric Project (FERC No. 14241). Alaska Energy Authority.

Abstract: GIS figures of the tributaries in the middle and upper Susitna River.

HDR, 2013k. *2012 Upper Susitna River Fish Distribution and Habitat Study*. Habitat Report. Susitna-Watana Hydroelectric Project (FERC No. 14241). Alaska Energy Authority.

Abstract: The 2012 Upper River Habitat study has two major components: a fish barrier assessment and habitat mapping study. The Fish Passage Barriers Assessment identified the locations of potential fish passage barriers in tributary streams upstream of Devils Canyon. Information regarding fish passage barriers, and specifically barriers to adult salmon migration, is important to define the extent of potential Project effects to fish and aquatic habitat. These data will also inform the planning and design of other Upper Susitna River studies related to fish distribution, particularly juvenile and adult salmon surveys. The study area included all tributary streams beginning at river mile (RM) 150 upstream to and including the Oshetna River at RM 233.5. Named tributaries in the study area include Cheechako Creek, Chinook Creek, Devil Creek, Fog Creek, Tsusena Creek, Deadman Creek, Watana Creek, Kosina Creek, Goose Creek and the Oshetna River.

HDR, 2013l. *2012 Upper Susitna River Fish Distribution and Habitat Study*. Fish Distribution Report. Susitna-Watana Hydroelectric Project (FERC No. 14241). Alaska Energy Authority.

Abstract: Two study components were conducted to document distribution and relative abundance of adult Chinook salmon and provide information on the distribution of all fish species and aquatic habitats upstream of Devils Canyon.

Healey, M.C., 1991. Life History of Chinook Salmon, in: *Pacific Salmon Life Histories* pp. 311-394.

Abstract: A comprehensive summary of the life history and habitat attributes of sockeye salmon.

Healey, M.C., 2009. Resilient salmon, resilient fisheries for British Columbia, Canada. *Ecology and Society* 14, 2.

Abstract: Salmon are inherently resilient species. However, this resiliency has been undermined in British Columbia by a century of centralized, command-and-control management focused initially on maximizing yield and, more recently, on economic efficiency. Community and cultural resiliency have also been undermined, especially by the recent emphasis on economic efficiency, which has concentrated access in the hands of a few and has disenfranchised fishery-dependent communities. Recent declines in both salmon stocks and salmon prices have revealed the systemic failure of the current management system. If salmon and their fisheries are to become viable again, radically new management policies are needed. For the salmon species, the emphasis must shift from maximizing yield to restoring resilience; for salmon fisheries, the emphasis must shift from maximizing economic efficiency to maximizing community and cultural resilience. For the species, an approach is needed that integrates harvest management, habitat management, and habitat enhancement to sustain and enhance resilience. This is best achieved by giving fishing and aboriginal communities greater responsibility and authority to manage the fisheries on which they depend. Co-management arrangements that involve cooperative ownership of major multistock resources like the Fraser River and Skeena River fisheries and community-based quota management of smaller fisheries provide ways to put species conservation much more directly in the hands of the communities most dependent on the well-being and resilience of these fisheries

Healy, D., and F.E. Hicks, 2007. Experimental study of ice jam thickening under dynamic flow conditions. *Journal of Cold Regions Engineering* 21, 72–91.

Abstract: River ice jams are a common occurrence on northern rivers, and their formation can present a severe flood risk to nearby communities. As more and more river regulation projects are developed to provide an alternative to fossil fuels for electrical power-generating capacity, our need to understand the mechanisms associated with ice jam formation under variable flow conditions becomes more vital. This is because, at present, hydropeaking operations are often severely curtailed during the ice-affected seasons due to concerns that sudden flow fluctuations might instigate ice jams and associated flooding. Here, an experimental investigation explores the effects of rapid increases in discharge on ice jam formation and evolution. It is found that the thickness of ice jams formed under highly dynamic flow conditions tend to be slightly thinner than those formed during steady carrier flows for comparable discharges. Also, despite the highly dynamic nature of these consolidation events, the resulting ice thicknesses appear reasonably well approximated by steady flow theory.

Heard, W.L., 1991. Life History of Pink Salmon, in: *Pacific Salmon Life Histories*. UBC Press, pp. 110–230.

Abstract: A comprehensive summary of the life history and habitat attributes of pink salmon.

Hedger, R.D., T.F. Næsje, P. Fiske, O. Ugedal, A.G., Finstad, and E.B. Thorstad, 2013. Ice-dependent winter survival of juvenile Atlantic salmon. *Ecology and Evolution* 3, 523–535.

Abstract: Changes in snow and ice conditions are some of the most distinctive impacts of global warming in cold temperate and Arctic regions, altering the environment during a critical period for survival for most animals. Laboratories studies have suggested that reduced ice cover may reduce the survival of stream dwelling fishes in Northern environments. This, however, has not been empirically investigated in natural populations in large rivers. Here, we examine how the winter survival of juvenile Atlantic salmon in a large natural river, the River Alta (Norway, 70°N), is affected by the presence or absence of surface ice. Apparent survival rates for size classes corresponding to parr and presmolts were estimated using capture-mark-recapture and Cormack-Jolly-Seber models for an ice-covered and an ice-free site. Apparent survival (Φ) in the ice-covered site was greater than in the ice-free site, but did not depend on size class (0.64 for both parr and presmolt). In contrast, apparent survival in the ice-free site was lower for larger individuals (0.33) than smaller individuals (0.45). The over-winter decline in storage energy was greater for the ice-free site than the ice-covered site, suggesting that environmental conditions in the ice-free site caused a strong depletion in energy reserves likely affecting survival. Our findings highlight the importance of surface ice for the winter survival of juvenile fish, thus, underpinning that climate change, by reducing ice cover, may have a negative effect on the survival of fish adapted to ice-covered habitats during winter.

Helfield, J.M., and R.J. Naiman, 2001. Effects of Salmon-Derived Nitrogen on Riparian Forest Growth and Implications for Stream Productivity. *Ecology* 82, 2403–2409.

Abstract: Anadromous Pacific salmon (*Oncorhynchus* spp.) transport marine-derived nitrogen (MDN) to the rivers in which they reproduce. Isotopic analyses indicate that trees and shrubs near spawning streams derive 22–24% of their foliar nitrogen (N) from spawning salmon. As a consequence of this nutrient subsidy, growth rates are significantly increased in Sitka spruce (*Picea sitchensis*) near spawning streams. As riparian forests affect the quality of instream habitat through shading, sediment and nutrient filtration, and production of LWD, this fertilization process serves not only to enhance riparian production, but may also act as a positive feedback mechanism by which salmon-borne nutrients improve spawning and rearing habitat for subsequent salmon generations and maintain the long-term productivity of river corridors along the Pacific coast of North America.

Higgs, D.A., J.S. Macdonald, C.D. Levings, and B.S. Dosanjh, 1995. Nutrition and feeding habits in relation to life history stage, in: *Physiological Ecology of Pacific Salmon*. pp. 159–315.

Abstract: A review of information regarding Pacific Salmon nutrition and feeding at different life history stages.

High, B., C.A. Peery, and D.H. Bennett, 2006. Temporary Staging of Columbia River Summer Steelhead in Coolwater Areas and Its Effect on Migration Rates. *Transactions of the American Fisheries Society* 135, 519–528.

Abstract: We used radiotelemetry to evaluate the temporary staging of adult migrating steelhead *Oncorhynchus mykiss* into nonnatal tributary rivers of the Columbia River and to determine the effects of staging behavior on migration rate. By monitoring the movement patterns of 2,900 individual steelhead over 3 years (1996, 1997, and 2000), we determined that an average of 61% of the steelhead destined for upstream areas temporarily staged in one or more tributaries in the lower Columbia River for durations from less than 1 h to 237 d. Median residence time varied significantly by tributary used and year and, based on canonical correlation analysis, was correlated with main-stem Columbia River water temperature. Steelhead that temporarily staged in tributary rivers migrated through the lower Columbia River significantly more slowly than steelhead that did not use tributaries. Use of coolwater tributaries as thermal refugia during warm summertime conditions significantly influences the migratory behavior of Columbia River adult steelhead. Our results highlight the need to preserve the water quality parameters of existing cooler-water Columbia River tributaries and to rehabilitate watersheds that historically maintained cooler-water tributaries as sources of thermal refugia for adult summer steelhead returning to the basin.

Hilborn, R., T.P. Quinn, D.E. Schindler, and D.E. Rogers, 2003. Biocomplexity and fisheries sustainability. *Proceedings of the National Academy of Sciences* 100(11), 6564-6568.

Abstract: A classic example of a sustainable fishery is that targeting sockeye salmon in Bristol Bay, Alaska, where record catches have occurred during the last 20 years. The stock complex is an amalgamation of several hundred discrete spawning populations. Structured within lake systems, individual populations display diverse life history characteristics and local adaptations to the variation in spawning and rearing habitats. This biocomplexity has enabled the aggregate of populations to sustain its productivity despite major changes in climatic conditions affecting the freshwater and marine environments during the last century. Different geographic and life history components that were minor producers during one climatic regime have dominated during others, emphasizing that the biocomplexity of fish stocks is critical for maintaining their resilience to environmental change.

Hill, N.M., P.A. Keddy, and I.C. Wisheu, 1998. A Hydrological Model for Predicting the Effects of Dams on the Shoreline Vegetation of Lakes and Reservoirs. *Environmental Management* 22, 723–736.

Abstract: The species richness of shoreline vegetation of unregulated lakes in Nova Scotia, Canada, is known to increase as a function of catchment area, a topographic variable governing water level fluctuations. Predictions based on catchment area however, fail to account for richness patterns at the margins of lakes enlarged by dams. Here, we compare the vegetation

and hydrological regimes of regulated and unregulated systems. Hydrological regimes of regulated systems deviated from natural systems of similar catchment area by being either hypovariable or hypervariable for both within-year and among-year fluctuations in water level. Plant communities of dammed systems were less diverse, contained more exotic species, and were, with one exception, devoid of rare shoreline herbs. Data from ''recovering,'' or previously dammed systems indicated that shoreline communities can be restored upon return of the appropriate hydrological regime. Using observed within-year and among-year water level fluctuation data, we propose a general model for the maintenance or restoration of diverse herbaceous wetlands on shorelines of temperate lakes or reservoirs. Managers can manipulate the within-year water level variation within prescribed limits (1–2 m), while ensuring that among-year variation (SD of summer levels) is less than 25% of within-year variation. This preliminary model is based on data from low-fertility, temperate lakes in river systems. To calibrate the model, plant community data from other regions are needed, as are long-term water-level data for unregulated lakes, data which are essential but largely lacking in many areas.

Hinch, S.G., and P.S. Rand, 1998. Swim speeds and energy use of upriver-migrating sockeye salmon (*Oncorhynchus nerka*): role of local environment and fish characteristics. *Canadian Journal of Fisheries and Aquatic Sciences* 55, 1821–1831.

Abstract: We used electromyogram (EMG) radiotelemetry to assess swimming activity (e.g., swim speeds), behaviour, and migration speeds (e.g., ground speeds) of individual adult sockeye salmon (*Oncorhynchus nerka*) migrating through several reaches of the Fraser and Nechako rivers in British Columbia. Using a laboratory swim flume and volitionally swimming adult fish carrying EMG transmitters, we developed relationships between EMG pulse intervals and swim speeds. A bioenergetics model was used to estimate reach-specific energy use per metre for each individual based on the average swim speed, migration time, body size, and river temperature. Migration was most energetically efficient (i.e., migration costs per unit distance traveled were relatively low) for females compared with males, large males compared with small males, and 1995 males compared with 1993 males. In all three cases, differences in swim speed patterns were primarily responsible for differences in energy use. For both sexes and in both years, migrations through reaches that contained a constriction (caused by an island, gravel bar, or large rock outcropping) were energetically inefficient compared with that through reaches with no constrictions. The high energetic costs at constrictions seem to result from long travel times probably caused by turbulent flow patterns that may generate confusing migrational cues.

Hoar, W.S., 1958. The Evolution of Migratory Behaviour among Juvenile Salmon of the Genus *Oncorhynchus*. *Journal of the Fisheries Research Board of Canada* 15, 391–428.

Abstract: The discussion is based on a detailed etiological comparison of four species of juvenile *Oncorhynchus*—coho, chum, sockeye and pink salmon. Their behaviour is described in terms of

five fixed behaviour patterns—hiding under stones, occupying territories, schooling, feeding and escaping predators. These are performed in relation to five directive factors—light, temperature, current, salinity and objects in the environment. Behaviour patterns and directing factors are associated with characteristic appetitive behaviour. The internal motivation seems to have an endocrinological basis. The coho fry, because of its river habitat, territorial behaviour, low nocturnal activity and smolt transformation, is considered to show behaviour nearest to that of the parental type of the genus. The pink fry has the most highly specialized sea-going behaviour. Three major developments are evident in the evolution of obligatory pelagic and ocean dwelling species (a) early smolt transformation (b) increased nocturnal activity.

Hodgson, S., and T.P. Quinn, 2002. The timing of adult sockeye salmon migration into fresh water: adaptations by populations to prevailing thermal regimes. *Canadian Journal of Zoology* 80, 542–555.

Abstract: Anadromous fishes migrate to sea, apparently to take advantage of growing conditions, and return to fresh water to spawn. Despite favorable growing conditions at sea in summer, some populations leave the ocean in spring, many months prior to spawning. We hypothesized that this premature migration is a consequence of the fish having to avoid stressful summer temperatures in order to access certain suitable areas for spawning in the fall. We tested this idea in sockeye salmon, *Oncorhynchus nerka*, by compiling data on the timing of migration and spawning and the freshwater temperature regime along the migration route in populations throughout the species' North American range. The timing of migration varied among populations and was primarily related to temperature regime during migration and the timing of spawning. When temperatures were moderate (<19°C), sockeye salmon tended to migrate to the vicinity of the spawning grounds about 1 month prior to spawning, regardless of the length of the freshwater migration. However, populations on whose migration route the average temperature exceeded 19°C displayed two basic patterns. Some populations entered fresh water prior to the warmest period, months before spawning, whereas others migrated after the period of highest temperatures had occurred.

Hoem Neher, T.D., A.E. Rosenberger, C.E. Zimmerman, C.M. Walker, and S.J. Baird, 2013. Estuarine Environments as Rearing Habitats for Juvenile Coho Salmon in Contrasting South-Central Alaska Watersheds. *Transactions of the American Fisheries Society* 142, 1481–1494.

Abstract: For Pacific salmon, estuaries are typically considered transitional staging areas between freshwater and marine environments, but their potential as rearing habitat has only recently been recognized. The objectives of this study were two-fold: (1) to determine if Coho Salmon *Oncorhynchus kisutch* were rearing in estuarine habitats, and (2) to characterize and compare the body length, age, condition, and duration and timing of estuarine occupancy of juvenile Coho Salmon between the two contrasting estuaries. We examined use of estuary habitats with analysis of microchemistry and microstructure of sagittal otoliths in two

watersheds of south-central Alaska. Juvenile Coho Salmon were classified as estuary residents or nonresidents (recent estuary immigrants) based on otolith Sr : Ca ratios and counts of daily growth increments on otoliths. The estuaries differed in water source (glacial versus snowmelt hydrographs) and in relative estuarine and watershed area. Juvenile Coho Salmon with evidence of estuary rearing were greater in body length and condition than individuals lacking evidence of estuarine rearing. Coho Salmon captured in the glacial estuary had greater variability in body length and condition, and younger age-classes predominated the catch compared with the nearby snowmelt-fed, smaller estuary. Estuary-rearing fish in the glacial estuary arrived later and remained longer (39 versus 24 d of summer growth) during the summer than did fish using the snowmelt estuary. Finally, we observed definitive patterns of overwintering in estuarine and near shore environments in both estuaries. Evidence of estuary rearing and overwintering with differences in fish traits among contrasting estuary types refute the notion that estuaries function as only staging or transitional habitats in the early life history of Coho Salmon.

Holbrook, C.M., J. Zydlewski, D. Gorsky, S.L. Shepard, and M.T. Kinnison, 2009. Movements of Prespawn Adult Atlantic Salmon Near Hydroelectric Dams in the Lower Penobscot River, Maine. *North American Journal of Fisheries Management* 29, 495–505.

Abstract: Acoustic telemetry was used to assess riverine behavior and passage success for prespawn male adult Atlantic salmon Salmo salar in the lower Penobscot River, Maine, in 2005 (n = 10) and 2006 (n = 25). Only 3 of 10 (30%) and 2 of 25 (8%) tagged Atlantic salmon successfully passed all three dams between the head of tide and presumed spawning habitat in 2005 and 2006, respectively. Migrants that failed to pass the second upstream dam frequently fell back into the estuary (3 of 4 in 2005; 17 of 23 in 2006), and few successfully reascended Veazie Dam at the head of tide. Fallback behavior was associated with temperatures exceeding 22°C and may reflect a strategy for coping with thermal stress and migratory delays. Atlantic salmon were also observed to actively seek out thermal refuge near one of the dams. Passage data were compared with results from previous telemetry studies that used Carlin tags and radio telemetry from 1987–1990 and 1992, and passive integrated transponder tags from 2002–2004. For all 10 years of study combined, median passage success was 64, 72, and 93% for the three dams. While 2006 may represent an uncommonly poor year for upstream passage at these dams, median cumulative passage past two of these dams was only 71% and ranged from 8% to 87% among years. Study results indicate that poor upstream passage severely limits migratory success in this system, particularly during periods of high discharge. Planned removal of two of these lower river dams is expected to improve migratory success for adult Atlantic salmon in the Penobscot River system.

Honea, J.M., J.C. Jorgensen, M.M. McClure, T.D. Cooney, K. Engie, D.M. Holzer, and R. Hilborn, 2009. Evaluating habitat effects on population status: influence of habitat restoration on spring-run Chinook salmon. *Freshwater Biology* 54, 1576–1592.

Abstract: 1. A key element of conservation planning is the extremely challenging task of estimating the likely effect of restoration actions on population status. To compare the relative benefits of typical habitat restoration actions on Pacific salmon (*Oncorhynchus* spp.), we modeled the response of an endangered Columbia River Chinook salmon (*O. tshawytscha*) population to changes in habitat characteristics either targeted for restoration or with the potential to be degraded.

2. We applied a spatially explicit, multiple life stage, Beverton-Holt model to evaluate how a set of habitat variables with an empirical influence on spring-run Chinook salmon survivorship influenced fish population abundance, productivity, spatial structure and diversity. Using habitat condition scenarios – historical conditions and future conditions with restoration, no restoration, and degradation – we asked the following questions: (i) how is population status affected by alternative scenarios of habitat change, (ii) which individual habitat characteristics have the potential to substantially influence population status and (iii) which life stages have the largest impact on population status?

3. The difference in population abundance and productivities resulting from changes in modeled habitat variables from the 'historical' to 'current' scenarios suggests that there is substantial potential for improving population status. Planned restoration actions directed toward modeled variables, however, produced only modest improvements.

4. The model predicted that population status could be improved by additional restoration efforts directed toward further reductions in the percentage of fine sediments in the streambed, a factor that has a large influence on egg survival. Actions reducing fines were predicted to be especially effective outside the national forest that covers most of the basin.

Scenarios that increased capacity by opening access to habitat in good condition also had a positive but smaller effect on spawner numbers.

5. Degradation in habitat quality, particularly in percent fine sediments, within stream reaches located in the national forest had great potential to further reduce this population's viability. This finding supports current forest planning efforts to minimize road density and clear-cut harvests and to return forest stand structure in dry regions to the historical condition that promoted frequent low-intensity fires rather than catastrophic standreplacing fires, as these landscape factors have been shown to influence percent fine sediment in streams.

Horne, B.D., E.S. Rutherford, and K.E. Wehrly, 2004. Simulating effects of hydro-dam alteration on thermal regime and wild steelhead recruitment in a stable-flow Lake Michigan tributary. *River Research and Applications* 20, 185–203.

Abstract: Hydroelectric dams may affect anadromous fish survival and recruitment by limiting access to upstream habitats and adversely affecting quality of downstream habitats. In the Manistee River, a tributary to Lake Michigan, two hydroelectric dams potentially limit

recruitment of anadromous rainbow trout (steelhead) by increasing tailrace water temperatures to levels that significantly reduce survival of young-of-year (YOY) fish. The objectives of this study were to determine whether proposed restoration scenarios (dam removals or a bottom withdrawal retrofit) would alter the Manistee River thermal regime and, consequently, improve wild steelhead survival and recruitment. Physical process models were used to predict Manistee River thermal regimes following each dam alteration scenario. Empirical relationships were derived from historical field surveys to quantify the effect of temperature on YOY production and potential recruitment of Manistee River steelhead. Both dam alteration scenarios lowered summer temperatures and increased steelhead recruitment by between 59% and 129%, but total recruitments were still low compared to other Great Lakes tributaries. Considering only temperature effects, bottom withdrawal provides the greatest promise for increasing natural steelhead recruitment by decreasing the likelihood of year-class failures in the warmest summers. Results of this study may allow managers to evaluate mitigation alternatives for Manistee River dams during future relicensing negotiations, and illustrate the utility of physical process temperature models in groundwater-fed rivers.

Hughes, F.R.M., J. Brasington, and K.S. Richards, 2008. Geomorphic dynamics of floodplains: ecological implications and a potential modelling strategy. *Freshwater Biology* 21, 559-579.

Abstract: The dynamics of channel migration and floodplain renewal constitute an important control of the ecological diversity of river corridors. Restoration initiatives should therefore assess whether these dynamics must be reinstated in order to address the cause rather than the symptoms of floodplain biodiversity decline. 2. Restoration of reach-scale dynamism in rivers where this is a natural behavioural process will restore smaller-scale geomorphological and sedimentological processes that encourage vegetation regeneration, but may require catchment-scale management of material flows. 3. Channel dynamics depend on the style of river–floodplain interaction, and this may be summarized in qualitative, classificatory, sedimentological models of floodplain architecture that have been somewhat neglected in the ecological literature. 4. One approach to the assessment of floodplain biodiversity and its restoration would be through the development of simulation models based on specified channel styles, and involving simplified hydrodynamics and successional changes. Such models, currently the subject of research as a spin-off from modelling studies of landscape evolution, would permit evaluation of the consequences for ecological diversity of implementing various management options that may affect the dynamics of channel migration.

Huusko, A., L. Greenberg, M. Stickler, T. Linnansaari, M. Nykänen, T. Vehanen, S. Koljonen, P. Louhi, and K. Alfredsen, 2007. Life in the ice lane: the winter ecology of stream salmonids. *River Research and Applications* 23, 469–491.

Abstract: Despite the common view that conditions in winter strongly influence survival and population size of fish, the ecology of salmonids has not been as extensively studied in winter as

in other seasons. In this paper, we review the latest studies on salmonid winter survival, habitat use, movement and biotic interactions as they relate to the prevailing physical and habitat conditions in rivers and streams. The majority of research conducted on the winter ecology of salmonids has been carried out in small rivers and streams, where temperatures are above zero and where there is no ice. Investigations in large rivers, regulated and dredged rivers, and under conditions of different ice formations are almost totally lacking, presumably related to sampling difficulties with these systems. The studies-at-hand indicate that a multitude of physical and biological factors affect the survival, behavior, and habitat use of salmonids in winter. The general concept that winter functions as a critical period for the survival of young salmonids is not well supported by the literature. Instead, overwinter survival of juvenile fish appears to be context-dependent, related to specific habitat characteristics and ice regimes of streams. In general, over wintering salmonids prefer sheltered, low velocity microhabitats, are mainly nocturnal, and interact relatively little with conspecifics or interspecifics. Specific descriptions of microhabitat preferences of salmonids are difficult to make due to highly disparate results from the literature. We suggest that future research should be directed towards (1) being able to predict the dynamics of freezing and ice processes at different scales, especially at the local scale, (2) studying fish behavior, habitat use and preference under partial and full ice cover, (3) evaluating the impacts of man-induced environmental modifications (e. g. flow regulation, land-use activities) on the ecology of salmonids in winter, and (4) identifying methods to model and assess winter habitat conditions for salmonids.

Hvidsten, N.A., 1993. High winter discharges after regulation increases production of Atlantic Salmon (*Salmo salar*) smolts in the River Orkla, Norway. In: *Production of Juvenile Atlantic Salmon, Salmo Salar, in Natural Waters*. Can. J. Spec. Publ. Fish. Aquat. Sci. NRC Research Press, 118, pp. 175–178.

Estimated smolt production has increased considerably in the period after hydro-power development in the River Orkla. The low winter discharges increased about five-fold after storage regulation. Smolt production during and after regulations is positively influenced by high winter discharges. The smolt production has probably increased due to reduced mortality during the ice-covered period, and as a result of increased food items at elevated minimum water levels.

Isaak, D.J., R.F. Thurow, B.E. Rieman, and J.B. Dunham, 2007. Chinook Salmon use of Spawning Patches: Relative Roles of Habitat Quality, Size, and Connectivity. *Ecological Applications* 17, 352–364.

Abstract: Declines in many native fish populations have led to reassessments of management goals and shifted priorities from consumptive uses to species preservation. As management has shifted, relevant environmental characteristics have evolved from traditional metrics that described local habitat quality to characterizations of habitat size and connectivity. Despite the implications this shift has for how habitats may be prioritized for conservation, it has been rare to assess the relative importance of these habitat components. We used an information–theoretic approach to select the best models from sets of logistic regressions that linked habitat quality, size, and connectivity to the occurrence of Chinook salmon (*Oncorhynchus tshawytscha*) nests. Spawning distributions were censused annually from 1995 to 2004, and data were complemented with field measurements that described habitat quality in 43 suitable spawning patches across a stream network that drained 1150 km2 in central Idaho. Results indicated that the most plausible models were dominated by measures of habitat size and connectivity, whereas habitat quality was of minor importance. Connectivity was the strongest predictor of nest occurrence, but connectivity interacted with habitat size, which became relatively more important when populations were reduced. Comparison of observed nest distributions to null model predictions confirmed that the habitat size association was driven by a biological mechanism when populations were small, but this association may have been an area-related sampling artifact at higher abundances. The implications for habitat management are that the size and connectivity of existing habitat networks should be maintained whenever possible. In situations where habitat restoration is occurring, expansion of existing areas or creation of new habitats in key areas that increase connectivity may be beneficial. Information about habitat size and connectivity also could be used to strategically prioritize areas for improvement of local habitat quality, with areas not meeting minimum thresholds being deemed inappropriate for pursuit of restoration activities.

Jager, H.I., and K.A. Rose, 2003. *Designing Optimal Flow Patterns for Fall Chinook Salmon in a Central Valley, California, River*.

Abstract: Widespread declines in stocks of Pacific salmon in the genus *Oncorhynchus* highlight the need for research to find new and effective management strategies for recovery. Two recovery objectives are (1) to ensure that recruitment is adequate to rebuild self-sustaining populations and (2) to maintain phenotypic diversity. This study seeks to understand how seasonal flow patterns in a flow-regulated California river might be managed to attain each of these recovery objectives, specifically for the fall and late-fall runs of Chinook salmon *O. tshawytscha*. We ask two questions: (1) Does the optimal pattern of seasonal flows change as the amount of water available is constrained by droughts or diversions of flows? and (2) How do optimal flow regimes designed for the two conservation objectives differ? We coupled simulated annealing with a recruitment model to find flow regimes that maximize either the number of smolt out-migrant “recruits” (MR) or the variation in spawning times among recruits (MV). Optimal flow regimes identified for both the MR and MV objectives changed as we increased the annual quantity of water available, allocating higher flows during the spring and fall seasons. Flow regimes that optimized the MR and MV objectives were different. For example, the MV flow regime with unlimited annual flow provided a pulse of high flow 2 weeks before the peak spawning date of the minority late-fall run. Simulated recruits produced by MV flow regimes were fewer in number—and had parents that spawned later and over a wider range of dates—than recruits produced by MR flow regimes. Although these results have not been verified by empirical studies, they demonstrate the potential for managing species with

special conservation status by combining state-of-the-art numerical optimization methods with mechanistic ecological models.

Jakober, M.J., T.E. McMahon, R.F. Thurow, and C.G. Clancy, 1998. Role of Stream Ice on Fall and Winter Movements and Habitat Use by Bull Trout and Cutthroat Trout in Montana Headwater Streams. *Transactions of the American Fisheries Society* 127, 223–235.

Abstract: We used radiotelemetry and underwater observation to assess fall and winter movements and habitat use by bull trout Salvelinus confluentus and westslope cutthroat trout *Oncorhynchus clarki lewisi* in two headwater streams in the Bitterroot River drainage, Montana, that varied markedly in habitat availability and stream ice conditions. Bull trout and cutthroat trout made extensive (>1 km) downstream overwintering movements with declining temperature in the fall. Most fish remained stationary for the remainder of the study (until late February), but some fish made additional downstream movements (1.1–1.7 km) in winter during a low-temperature (1°C) period marked by anchor ice formation. Winter movement was more extensive in the mid-elevation stream where frequent freezing and thawing led to variable surface ice cover and frequent supercooling (<0°C). Habitat use of both species varied with availability; beaver ponds and pools with LWD were preferred in one stream, and pools with boulders were preferred in the other. Trout overwintered in beaver ponds in large (N = 80–120), mixed aggregations. In both streams, both species decreased use of submerged cover following the formation of surface ice. Our results indicate that (1) continued activity by trout during winter is common in streams with dynamic ice conditions and (2) complex mixes of habitat are needed to provide suitable fall and winter habitat for these species.

Jansson, R., C. Nilsson, M. Dynesius, and E. Andersson, 2000a. Effects of river regulation on river-margin vegetation: a comparison of eight boreal rivers. *Ecological Applications* 10, 203–224.

Abstract: Regulation and fragmentation by dams belong to the most widespread deliberate impacts of humans on the world's rivers, especially in the Northern Hemisphere. We evaluated the effects of hydroelectric development by comparing the flora of vascular plants in 200-m-long reaches of river margin distributed along eight entire rivers in northern Sweden. Four of these rivers were free-flowing, and four were strongly regulated for hydroelectric purposes. First, we compared species diversity per site between entire free-flowing and regulated rivers. To reduce the effects of natural, between-river variation, we compared adjacent rivers. One regulated river had lower plant species richness and cover than two adjacent free-flowing ones, whereas two other parallel rivers, one regulated and another free-flowing, did not differ significantly. Second, river-margin vegetation responded differently to different types of regulated water-level regimes. Both along run-of-river impoundments, with small but daily water-level fluctuations, and along storage reservoirs, with large fluctuations between low water levels in spring and high levels in late summer and fall, the number of species and their

cover per site were lower than along the free-flowing rivers. Regulated but unimpounded reaches were most similar to free-flowing rivers, having lower plant cover per site, but similar numbers of species. For reaches with reduced discharge, evidence was mixed; some variables were lower compared to free-flowing rivers whereas others were not. However, for the last two types of regulation, statistical power was low due to small sample sizes. Third, we classified all plant species according to their dispersal mechanisms and tested whether they respond differently to different types of regulated water-level regimes. Three out of four types of regulation had higher proportions of wind-dispersed species, and two out of four had lower proportions of species without specific mechanisms for dispersal, compared to free-flowing rivers, suggesting that dispersal ability is critical for persistence following regulation. Run-of-river impoundments had higher proportions of long-floating species and species with mechanisms for vegetative dispersal, suggesting that water dispersal may still be important despite fragmentation by dams. Fourth, plant species richness and cover varied with both local factors, such as water-level regime, and regional factors, such as length of the growing season. Presence of clay and silt in the river-margin soil, preregulation position of the contemporary river margin, non-reservoir sites, low altitudes, and long growing seasons were associated with high plant species richness and cover.

Jansson, R., C. Nilsson, and B. Renöfält, 2000b. Fragmentation of Riparian Floras in Rivers with Multiple Dams. *Ecology* 81, 899–903.

Abstract: Rivers are increasingly fragmented by dams, resulting in disruption of natural dispersal pathways and subsequent changes of riverine communities. We assessed the effect of dams as barriers to plant dispersal along rivers by comparing the flora of vascular plants between pairs of run-of-river impoundments in northern Sweden. Adjacent impoundments in similar environmental settings develop different riparian floras because species with poor floating capacity become unevenly distributed among impoundments. Such discontinuities were not found along a free-flowing river, suggesting effective dispersal of riparian plants in the absence of dams. Given that dams regulate most of the world's rivers, floristic disruptions of riparian corridors may be a global phenomenon. The extensive fragmentation of other ecosystems may have caused similar obstructions to organism dispersal, with subsequent changes in species composition.

Jansson, R., U. Zinko, D.M. Merritt, and C. Nilsson, 2005. Hydrochory increases riparian plant species richness: a comparison between a free-flowing and a regulated river: Hydrochory and plant species richness. *Journal of Ecology* 93, 1094–1103.

Abstract: 1. The importance of dispersal for plant community structure is poorly understood. Previous studies have hypothesized that patterns in the distribution and genetic structure of riparian plant communities were caused by hydrochory, i.e. plant dispersal by water. We separated the relative contributions of propagules from hydrochory and other dispersal vectors

by comparing colonization in pairs of plots, one subject to flooding and deposition of hydrochores and the other unflooded.
2. The number of colonizing individuals and the mortality rate of individuals per year did not differ significantly with flooding, but hydrochory increased the number of colonizing species per year and plot by 40–200%. The pool of colonizing species was 36–58% larger per year for flooded than for unflooded plots, indicating that hydrochory increased the diversity by facilitating long-distance dispersal. Hydrochory resulted in more diverse plant communities after 3 years of succession at both plot and reach scales, despite the fact that flooding caused plant mortality.
3. We found no evidence that dams reduce the abundance and diversity of water-dispersed propagules by acting as barriers for plant dispersal. The role of hydrochory for plant colonization was similar between a free-flowing and a regulated river, although in fragmented rivers propagule sources are likely to be more local (within-impoundment).
4. We conclude that plant dispersal by water, as well as fluvial disturbance, is important for enhancing species richness in riparian plant communities. As flowing water may carry buoyant seeds long distances, riparian plant communities may receive a comparatively large proportion of their seeds by long-distance dispersal.

Jeffres, C.A., J.J. Opperman, and P.B. Moyle, 2008. Ephemeral floodplain habitats provide best growth conditions for juvenile Chinook salmon in a California river. *Environmental Biology of Fishes* 83, 449–458.

Abstract: We reared juvenile Chinook salmon for two consecutive flood seasons within various habitats of the Cosumnes River and its floodplain to compare fish growth in river and floodplain habitats. Fish were placed in enclosures during times when wild salmon would naturally be rearing in floodplain habitats. We found significant differences in growth rates between salmon reared in floodplain and river enclosures. Salmon reared in seasonally inundated habitats with annual terrestrial vegetation experienced higher growth rates than those reared in a perennial pond on the floodplain. Growth of fish in the non-tidal river upstream of the floodplain varied with flow in the river. When flows were high, there was little growth and high mortality, but when the flows were low and clear, the fish grew rapidly. Fish displayed very poor growth in tidally influenced river habitat below the floodplain, a habitat type to which juveniles are commonly displaced during high flow events due to a lack of channel complexity in the main-stem river. Overall, ephemeral floodplain habitats supported higher growth rates for juvenile Chinook salmon than more permanent habitats in either the floodplain or river. Variable responses in both growth and mortality, however, indicate the importance of providing habitat complexity for juvenile salmon in floodplain reaches of streams, so fish can find optimal places for rearing under different flow conditions.

Jennings, T.R., 1985. *Fish Resources and Habitats in the Middle Susitna River*. Woodward-Clyde Consultants and Entrix. Final Report to Alaska Power Authority. 175 pp.

Abstract: A description of historic fish and habitat associations within the middle Susitna River.

Jensen, A.J., 2003. Atlantic salmon (*Salmo salar*) in the regulated River Alta: effects of altered water temperature on parr growth. *River Research and Applications* 19, 733–747.

Abstract: The chief objective of this study was to analyse the effects of altered water temperature, due to the hydropower regulation of the River Alta, on growth of Atlantic salmon parr. The river was developed for hydroelectric purposes in 1987. A 110 m high concrete dam was built in the main river 49 km upstream from the outlet to the sea. The outlet of the power station is located 2.5 km downstream from the dam. The annual regime of water temperature has been altered downstream from the power station because of the regulation. It has decreased 1–2° C during June, July and the first half of August, while it has increased up to 3° C during late summer. During winter, water temperature has increased from 0° C to about 0.3–0.4° C. Atlantic salmon is the predominant fish species in the river. They can penetrate 46 km from the sea, up to the outlet of the power station.

In this paper I have studied the relationship between growth of juvenile Atlantic salmon and water temperature in the upper part of the river. At similar temperatures, the growth rate of salmon parr in the River Alta is higher in early summer than later in the growing season. In early summer the salmon grew faster than the maximum rate predicted by a recently published model. Therefore, I adjusted the model to describe growth rates of salmon in early summer (ice break to mid-August), using data derived prior to the hydropower development (1981–1986). The new model proved effective at describing growth rates of fish in early summer following the hydropower development (1987–1996). After development, growth rates decreased during early summer, but increased correspondingly later in the season. There was close agreement between these growth changes and the altered annual regime of river temperature. Overall, only minor changes in annual growth rates have been observed after the hydropower development.

Jones, J.A., F.J. Swanson, B.C. Wemple, and K.U. Snyder, 2000. Effects of roads on hydrology, geomorphology, and disturbance patches in stream networks : Ecological effects of roads. *Conservation Biology* 14, 76–85.

Abstract: We outline a view of how road networks interact with stream networks at the landscape scale and, based on examples from recent and current research, illustrate how these interactions might affect biological and ecological processes in stream and riparian systems. At the landscape scale, certain definable geometric interactions involving peak flows (floods) and debris flows (rapid movements of soil, sediment, and large wood down steep stream channels) are influenced by the arrangement of the road network relative to the stream network. Although disturbance patches are created by peak-flow and debris-flow disturbances in

mountain landscapes without roads, roads can alter the landscape distributions of the starting and stopping points of debris flows, and they can alter the balance between the intensity of flood peaks and the stream network's resistance to change. We examined this conceptual model of interactions between road networks and stream networks based on observations from a number of studies in the H. J. Andrews Experimental Forest, Oregon (U.S.A.). Road networks appear to affect floods and debris flows and thus modify disturbance patch dynamics in stream and riparian networks in mountain landscapes. We speculate that these changes may influence the rates and patterns of survival and recovery of disturbed patches in stream networks, affecting ecosystem resilience, and we outline an approach for detecting such effects based on a patch dynamics perspective. A field sampling scheme for detecting the magnitude of various road effects on stream and riparian ecology could involve (1) landscape stratification of inherent stream network susceptibility to floods or debris flows, (2) overlay of road and stream networks and creation of areas with various densities of road-stream crossings, emphasizing midslope road-stream crossings, and (3) designations of expected high- and low-impact stream segments based on numbers of upstream road-stream crossings where sampling of selected biological variables would be conducted.

Jones, N.E., 2012. Patterns of Benthic Invertebrate Richness and Diversity in the Regulated Magpie River and Neighbouring Natural Rivers. *River Research and Applications* 9, 1090–1099.

Abstract: Fluctuating flows common in hydropeaking operations present biota with contrasting and challenging environments. Taxa that require a narrow range of water velocity or are not adapted to withstand sudden changes in discharge will likely be eliminated or competitively disadvantaged under such circumstances, perhaps leading to reduced biodiversity. I investigated the whole river, longitudinal and lateral patterns of benthic invertebrate abundance, Shannon–Wiener diversity, and rarefied taxa density and richness in the hydropeaking Magpie River and 16 neighbouring natural rivers. The Magpie River had greater abundances of benthic invertebrates than natural rivers, particularly near the dam. General differences in benthic community characteristics were largely based on the near absence of Odonata and Plecoptera and an abundance of snails and worms in the Magpie River. Family density, richness and diversity were greater in the regulated Magpie River and unregulated upper Magpie River than found in natural rivers. Longitudinally, family density, diversity and particularly richness increased downstream in the Magpie River. Laterally, diversity did not show any trends with increasing depth along transects, except at near the dam where it decreased sharply with depth, velocity, and an abundance of filter feeding invertebrates. Taxa density did not show any lateral trends in natural rivers, whereas in the Magpie River, it increased with water velocity and depth. The results of this study are contradictory to the general findings of others implying reduced biodiversity below hydropower facilities. Possible explanations are examined and contrasted with other examinations of benthic invertebrate response below hydropeaking dams.

Jones, N.E., 2014. The Dual Nature of Hydropeaking Rivers: Is Ecopeaking Possible? *River Research and Applications* 30, 521–526.

Abstract: Philosophically, the natural flow regime concept is tremendously appealing; however, its application can be challenging for many biologists without the expertise or resources to handle such approaches on their own. This is particularly true on hydropeaking rivers, where incorporating natural flow is sometimes challenging. Additional challenges include our limited understanding of how individual flow components relate to geomorphic and ecological processes. Supplementary to environmental flow approaches is understanding that many hydropeaking rivers are ecologically two different rivers in one: the low flow and high peaking flow. Taxa that require a narrow range of water velocities or cannot withstand rapid changes in discharge would likely be eliminated or competitively disadvantaged under such harsh environmental conditions. As the low and peak flows diverge, the two rivers become increasingly different ecologically, and there will likely be fewer taxa that can withstand such abiotic variability. Deviations from a natural flow regime may result in new constraints on certain fishes and invertebrates, but this does not necessarily mean a loss of productive fish habitat. Viewing hydropeaking rivers as two rivers in one and the risks associated with high to low flow ratios may serve as a more practical and useful perspective towards maintaining altered yet productive rivers while representing a step towards improving the management river ecosystems.

Kaeriyama, M., M. Nakamura, R. Edpalina, J.R. Bower, H. Yamaguchi, R.V. Walker, and K.W. Myers, 2004. Change in feeding ecology and trophic dynamics of Pacific salmon (*Oncorhynchus* spp.) in the central Gulf of Alaska in relation to climate events. *Fisheries Oceanography* 13, 197–207.

Abstract: The effects of climate events on the feeding ecology and trophic dynamics of Pacific salmon (*Oncorhynchus* spp.) in offshore waters of the central Gulf of Alaska were investigated during early summers (1994–2000), based on analyses of stomach contents, and carbon and nitrogen stable isotopes (δ13C and δ15N). Gonatid squids (mainly *Berryteuthis anonychus*) were the dominant prey of all salmon species except for chum salmon (*O. keta*). During the 1997 El Niño event and the 1999 La Niña event, squids decreased sharply in the diets of all Pacific salmon except coho salmon (*O. kisutch*) in the Subarctic Current, and chum salmon diets changed from gelatinous zooplankton (1995–97) to a more diverse array of zooplankton species. A δ13C and δ15N analysis indicated that all salmon species occupied the same branch of the food web in 1999–2000. We hypothesize that high-seas salmon adapt to climate-induced changes in their prey resources by switching their diets either within or between trophic levels. To understand the effects of climate change on Pacific salmon in the Gulf of Alaska, biological oceanographic research on B. *anonychus* and other important prey resources is needed.

Karrenberg, S., P.J. Edwards, and J. Kollmann, 2002. The life history of Salicaceae living in the active zone of floodplains. *Freshwater Biology* 47, 733–748.

Abstract: 1. Exposed riverine sediments are difficult substrata for seedling establishment because of extremes in the microclimate, poor soil conditions and frequent habitat turnover. Various species of willows and poplars (Salicaceae) appear to be particularly successful in colonising such sediments and are often dominant in floodplain habitats throughout the northern temperate zone. 2. In many Salicaceae regeneration seems to be adapted to regular disturbance by flooding. Efficient seed dispersal is achieved by the production of abundant seed in spring and early summer, which are dispersed by air and water. Seeds are short-lived and germinate immediately on moist surfaces. Seedling establishment is only possible if these surfaces stay moist and undisturbed for a sufficient period of time. 3. Larger plants of Salicaceae have exceptional mechanical properties, such as high bending stability, which enable them to withstand moderate floods. If uprooted, washed away or fragmented by more powerful floods these plants re-sprout vigorously. 4. While these life characteristics can be interpreted as adaptations to the floodplain environment, they may also cause a high genetic variability in populations of Salicaceae and predispose Salicaceae to hybridization. Thus, a feed back between adaptive life history characteristics and the evolutionary process is proposed.

Keefer, M.L., C.T. Boggs, C.A. Peery, and C.C. Caudill, 2008. Overwintering Distribution, Behavior, and Survival of Adult Summer Steelhead: Variability among Columbia River Populations. *North American Journal of Fisheries Management* 28, 81–96.

Abstract: Unlike most anadromous salmonids, summer steelhead *Oncorhynchus mykiss* overwinter in rivers rather than the ocean for 6–10 months prior to spring spawning. Overwintering in rivers may make summer steelhead more vulnerable to harvest and other mortality sources than are other anadromous populations, but there has been little systematic study of this life history strategy. Here, we used a large-scale radiotelemetry study to examine the overwintering behaviors and distributions of 26 summer steelhead stocks within the regulated lower Columbia–Snake River hydrosystem. Over 6 years, we monitored 5,939 fish, of which 3,399 successfully reached spawning tributaries or the upper Columbia River basin and were assigned to specific populations. An estimated 12.4% of fish that reached spawning areas overwintered at least partially within the hydrosystem (annual estimates = 6.8–19.6%), while the remainder overwintered in tributaries. Across all populations, later-arriving fish were more likely to overwinter in the hydrosystem; overwintering percentages ranged from less than 1% for fish tagged in June to over 40% for those tagged in October. Proportionately more interior-basin steelhead (Clearwater, Salmon, and Snake River metapopulations) overwintered in the hydrosystem than did fish from lower-river populations. Steelhead were distributed in mixed-stock assemblages throughout the hydrosystem during winter, usually in reservoirs closest to their home rivers but also in nonnatal tributaries. Overwintering fish moved upstream and downstream between reaches in all months; a nadir occurred in early January and peak egress into spawning tributaries was in March. The estimated survival to tributaries was higher for fish that overwintered in the hydrosystem (82%) than for fish that did not (62%); this difference was largely attributable to low winter harvest rates. Our results suggest that large main-stem habitats, including reservoirs, may be widely used by overwintering summer steelhead. The complex migration behaviors of steelhead indicate both the potential for adaptation and possible susceptibility to future river environment changes.

Kiell, D.J., 1982. Development of a Reservoir Preparation Strategy. *Canadian Water Resources Journal* 7, 112–131.

Abstract: An exercise to determine an effective reservoir preparation strategy was undertaken during the environmental assessment of the Upper Salmon Project, a proposed hydroelectric development in Newfoundland. The study examined forestry resources and wildlife habitat and use in the flood zone. Also considered was the predicted littoral zone development, water quality changes and fisheries impacts. The recommended action was to completely clear selected areas of the reservoir (approximately 57%) mainly in response to requirements of migrating caribou and in order to enhance recreation potential. This paper discusses the value of the reservoir preparation study approach in light of actual clearing costs incurred during construction, the reaction of regulatory agencies, and similar studies completed on other proposed reservoirs in the Province.

Kimmerer, W.J., 2002. Physical, biological, and management responses to variable freshwater flow into the San Francisco Estuary. *Estuaries* 25, 1275–1290.

Abstract: Freshwater flow is the principal cause of physical variability in estuaries and a focus of conflict in estuaries where a substantial fraction of the freshwater is diverted. Variation in freshwater flow can have many effects: inundation of flood plains, increase loading and advective transport of materials and organisms, dilution or mobilization of contaminants, compression of the estuarine salinity field and density gradient, increase in stratification, and decrease in residence time for water while increasing it for some particles and biota. In the San Francisco Estuary, freshwater flow is highly variable, and has been altered by shifts in seasonal patterns of river flow and increases in diversions from tidal and nontidal regions, entraining fish of several species of concern. Abundance or survival of several estuarine-dependent species also increases with freshwater outflow. These relationships to flow may be due to several potential mechanisms, each with its own locus and period of effectiveness, but no mechanism has been conclusively shown to underlie the flow relationship of any species. Several flow-based management actions were established in the mid-1990s, including a salinity standard based on these flow effects, as well as reductions in diversion pumping during critical periods for listed species of fish. The effectiveness of these actions has not been established. To make the salinity standard more effective and more applicable to future estuarine conditions will require investigation to determine the underlying mechanisms. Effects of entrainment at diversion facilities are more straightforward conceptually but difficult to quantify, and resolving these may require experimental manipulations of diversion flow.

Kline Jr., T.C., J.J. Goering, O.A. Mathisen, P.H. Poe, P.L. Parker, and R.S. Scalan, 1993. Recycling of Elements Transported Upstream by Runs of Pacific Salmon: II. δ15N and δ13C Evidence in the Kvichak River Watershed, Bristol Bay, Southwestern Alaska. *Canadian Journal of Fisheries and Aquatic Sciences* 50, 2350–2365.

Abstract: Many Alaskan freshwaters provide important spawning and nursery habitat for salmonid fishes. Pacific salmon are well known for their anadromous and semelparous natural history of rearing in the marine environment and returning to freshwater as adults to spawn once before dying in their natal habitat. Five species of anadromous Pacific salmon, *Oncorhynchus nerka* (sockeye or red salmon), *O. kisutch* (coho or silver salmon), *O. gorbuscha* (pink or humpback salmon), *O. keta* (chum or dog salmon), and *O. tshawytscha* (Chinook or king salmon) spawn in Alaskan freshwaters. The time juvenile salmon reside in freshwater following emergence from the gravel as fry until smoltification (physiological preparation for migration to saltwater) depends on species and location. Because freshwater residence can range from virtually no time to several years, considerable variation in dependence on the freshwater habitat as a nursery environment exists. The sockeye salmon is the only Pacific salmon to have a juvenile stage that is usually dependent on a lacustrine habitat and a forage base of Zooplankton. Because lakes used for rearing by juvenile salmon are typically oligotrophic, the productivity of sockeye lakes has been studied as a factor limiting sizes of salmon runs (see Chapter 8; and Burgner et al., 1969; Hyatt and Stockner, 1985; Stockner, 1981, 1987).

Kondolf, G.M., 1997. Profile: Hungry Water: Effects of Dams and Gravel Mining on River Channels. *Environmental Management* 21, 533–551.

Abstract: Rivers transport sediment from eroding uplands to depositional areas near sea level. If the continuity of sediment transport is interrupted by dams or removal of sediment from the channel by gravel mining, the flow may become sediment-starved (hungry water) and prone to erode the channel bed and banks, producing channel incision (downcutting), coarsening of bed material, and loss of spawning gravels for salmon and trout (as smaller gravels are transported without replacement from upstream). Gravel is artificially added to the River Rhine to prevent further incision and to many other rivers in attempts to restore spawning habitat. It is possible to pass incoming sediment through some small reservoirs, thereby maintaining the continuity of sediment transport through the system. Damming and mining have reduced sediment delivery from rivers to many coastal areas, leading to accelerated beach erosion. Sand and gravel are mined for construction aggregate from river channel and floodplains. In-channel mining commonly causes incision, which may propagate up- and downstream of the mine, undermining bridges, inducing channel instability, and lowering alluvial water tables. Floodplain gravel pits have the potential to become wildlife habitat upon reclamation, but may be captured by the active channel and thereby become instream pits. Management of sand and gravel in rivers must be done on a regional basis, restoring the continuity of sediment transport where possible and encouraging alternatives to river-derived aggregate sources

Kondolf, G.M., and M.G. Wolman, 1993. The sizes of salmonid spawning gravels. *Water Resources Research* 29, 2275–2285.

Abstract: The availability of suitably sized spawning gravels limits salmonid (salmon and trout) populations in many streams. We compiled published and original size distribution data to determine distinguishing characteristics of spawning gravels and how gravel size varies with size of the spawning fish. Median diameters of 135 size distributions ranged from 5.4 to 78 mm, with 50% falling between 14.5 and 35 mm. All but three spawning gravel size distributions were negatively skewed (on a log-transformed basis), with 50% of the skewness coefficients falling between −0.24 and −0.39. Fewer than 20% of the distributions were bimodal. Although tending to be coarser, spawning gravels had sorting and skewness values similar to other fluvial gravels reported in the literature. The range of gravel sizes used by fish of a given species or length is great, but the relation between fish size and size of gravel can be described by an envelope curve. In general, fish can spawn in gravels with a median diameter up to about 10% of their body length.

Konecki, J.T., C.A. Woody, and T.P. Quinn, 1995. Critical thermal maxima of coho salmon (*Oncorhynchus kisutch*) fry under field and laboratory acclimation regimes. *Canadian Journal of Zoology* 73, 993–996.

Abstract: Juvenile coho salmon (*Oncorhynchus kisutch*) from three populations in Washington State were captured in the field and tested for critical thermal maximum (CTM). Tolerances varied among the populations (mean CTMs were 28.21, 29.13, and 29.23 °C) and exceeded published data from some laboratory tests. The population from a relatively cool stream had a lower CTM than the two populations from warmer streams. However, after the salmon had been in the laboratory for 3 months under constant, common temperature regimes, the CTMs no longer differed, indicating that the population-specific differences resulted from different acclimation regimes rather than from genetic adaptation.

Konrad, C.P., J.D. Olden, D.A. Lytle, T.S. Melis, J.C. Schmidt, E.N. Bray, M.C. Freeman, K.B. Gido, N.P. Hemphill, M.J. Kennard, L.E. McMullen, M.C. Mims, M. Pyron, C.T. Robinson, and J.G. Williams, 2011. Large-scale Flow Experiments for Managing River Systems. *BioScience* 61, 948–959.

Abstract: Experimental manipulations of streamflow have been used globally in recent decades to mitigate the impacts of dam operations on river systems. Rivers are challenging subjects for experimentation, because they are open systems that cannot be isolated from their social context. We identify principles to address the challenges of conducting effective large-scale flow experiments. Flow experiments have both scientific and social value when they help to resolve specific questions about the ecological action of flow with a clear nexus to water policies and decisions. Water managers must integrate new information into operating policies for large-scale experiments to be effective. Modeling and monitoring can be integrated with experiments to analyze long-term ecological responses. Experimental design should include spatially extensive observations and well-defined, repeated treatments. Large-scale flow manipulations are only a part of dam operations that affect river systems. Scientists can ensure that experimental manipulations continue to be a valuable approach for the scientifically based management of river systems.

Korman, J., and S.E. Campana, 2009. Effects of Hydropeaking on Nearshore Habitat Use and Growth of Age-0 Rainbow Trout in a Large Regulated River. *Transactions of the American Fisheries Society* 138, 76–87.

Abstract: Hourly fluctuations in flow from Glen Canyon Dam were increased in an attempt to limit the population of nonnative rainbow trout *Oncorhynchus mykiss* in the Colorado River, Arizona, due to concerns about negative effects of nonnative trout on endangered native fishes. Controlled floods have also been conducted to enhance native fish habitat. We estimated that rainbow trout incubation mortality rates resulting from greater fluctuations in flow were 23–49% (2003 and 2004) compared with 5–11% under normal flow fluctuations (2006–2010). Effects of this mortality were apparent in redd excavations but were not seen in hatch date distributions or in the abundance of the age-0 population. Multiple lines of evidence indicated that a controlled flood in March 2008, which was intended to enhance native fish habitat, resulted in a large increase in early survival rates of age-0 rainbow trout. Age-0 abundance in July 2008 was over fourfold higher than expected given the number of viable eggs that produced these fish. A hatch date analysis indicated that early survival rates were much higher for cohorts that hatched about 1 month after the controlled flood (April 15) relative to those that hatched before this date. The cohorts that were fertilized after the flood were not exposed to high flows and emerged into better-quality habitat with elevated food availability. Interannual differences in age-0 rainbow trout growth based on otolith microstructure supported this hypothesis. It is likely that strong compensation in survival rates shortly after emergence mitigated the impact of incubation losses caused by increases in flow fluctuations. Control of nonnative fish populations will be most effective when additional mortality is applied to older life stages after the majority of density-dependent mortality has occurred. Our study highlights the need to rigorously assess instream flow decisions through the evaluation of population-level responses.

Korman, J., M. Kaplinski, and T.S. Melis, 2011. Effects of Fluctuating Flows and a Controlled Flood on Incubation Success and Early Survival Rates and Growth of Age-0 Rainbow Trout in a Large Regulated River. *Transactions of the American Fisheries Society* 140, 487–505.

Abstract: Hourly fluctuations in flow from Glen Canyon Dam were increased in an attempt to limit the population of nonnative rainbow trout *Oncorhynchus mykiss* in the Colorado River, Arizona, due to concerns about negative effects of nonnative trout on endangered native fishes. Controlled floods have also been conducted to enhance native fish habitat. We estimated that rainbow trout incubation mortality rates resulting from greater fluctuations in flow were 23–

49% (2003 and 2004) compared with 5–11% under normal flow fluctuations (2006–2010). Effects of this mortality were apparent in redd excavations but were not seen in hatch date distributions or in the abundance of the age-0 population. Multiple lines of evidence indicated that a controlled flood in March 2008, which was intended to enhance native fish habitat, resulted in a large increase in early survival rates of age-0 rainbow trout. Age-0 abundance in July 2008 was over fourfold higher than expected given the number of viable eggs that produced these fish. A hatch date analysis indicated that early survival rates were much higher for cohorts that hatched about 1 month after the controlled flood (~April 15) relative to those that hatched before this date. The cohorts that were fertilized after the flood were not exposed to high flows and emerged into better-quality habitat with elevated food availability. Interannual differences in age-0 rainbow trout growth based on otolith microstructure supported this hypothesis. It is likely that strong compensation in survival rates shortly after emergence mitigated the impact of incubation losses caused by increases in flow fluctuations. Control of nonnative fish populations will be most effective when additional mortality is applied to older life stages after the majority of density-dependent mortality has occurred. Our study highlights the need to rigorously assess instream flow decisions through the evaluation of population-level responses. Received March 30, 2010; accepted October 28, 2010

Kovach, R.P., J.E. Joyce, J.D. Echave, M.S. Lindberg, and D.A. Tallmon, 2013. Earlier Migration Timing, Decreasing Phenotypic Variation, and Biocomplexity in Multiple Salmonid Species. *PLoS ONE* 8, e53807.

Abstract: Climate-induced phenological shifts can influence population, evolutionary, and ecological dynamics, but our understanding of these phenomena is hampered by a lack of long-term demographic data. We use a multi-decade census of 5 salmonid species representing 14 life histories in a warming Alaskan stream to address the following key questions about climate change and phenology: How consistent are temporal patterns and drivers of phenology for similar species and alternative life histories? Are shifts in phenology associated with changes in phenotypic variation? How do phenological changes influence the availability of resource subsidies? For most salmonid species, life stages, and life histories, freshwater temperature influences migration timing – migration events are occurring earlier in time (mean = 1.7 days earlier per decade over the 3–5 decades), and the number of days over which migration events occur is decreasing (mean = 1.5 days per decade). Temporal trends in migration timing were not correlated with changes in intra-annual phenotypic variation, suggesting that these components of the phenotypic distribution have responded to environmental change independently. Despite commonalities across species and life histories, there was important biocomplexity in the form of disparate shifts in migration timing and variation in the environmental factors influencing migration timing for alternative life history strategies in the same population. Overall, adult populations have been stable during these phenotypic and environmental changes ($\lambda \approx 1.0$), but the temporal availability of salmon as a resource in freshwater has decreased by nearly 30 days since 1971 due to changes in the median date of migration timing and decreases in intra-annual variation in migration timing. These novel observations advance our understanding of

phenological change in response to climate warming, and indicate that climate change has influenced the ecology of salmon populations, which will have important consequences for the numerous species that depend on this resource.

Larsen, P.H., S. Goldsmith, O. Smith, M.L. Wilson, K. Strzepek, P. Chinowsky, and B. Saylor, 2008. Estimating future costs for Alaska public infrastructure at risk from climate change. *Global Environmental Change* 18, 442–457.

Abstract: This analysis reports on the projected cost of Alaska's public infrastructure at risk from rapid climate change. Specifically, we coupled projections of future climate with engineering rules of thumb to estimate how thawing permafrost, increased flooding, and increased coastal erosion affect annualized replacement costs for nearly 16,000 structures. We conclude that climate change could add \$3.6–\$6.1 billion (+10% to +20% above normal wear and tear) to future costs for public infrastructure from now to 2030 and \$5.6–\$7.6 billion (+10% to +12%) from now to 2080. These estimates take into account different possible levels of climate change and assume agencies strategically adapt infrastructure to changing conditions. In addition to implementing a risk-based economic analysis of climate change impacts, this research effort demonstrates that implementing plausible adaptation strategies could offset impacts by up to 45% over the long-run.

Lehner, B., G. Czisch, and S. Vassolo, 2005. The impact of global change on the hydropower potential of Europe: a model-based analysis. *Energy Policy* 33, 839–855.

Abstract: This study presents a model-based approach for analyzing the possible effects of global change on Europe's hydropower potential at a country scale. By comparing current conditions of climate and water use with future scenarios, an overview is provided of today's potential for hydroelectricity generation and its mid- and long-term prospects. The application of the global water model WaterGAP for discharge calculations allows for an integrated assessment, taking both climate and socioeconomic changes into account. This study comprises two key parts: First, the 'gross' hydropower potential is analyzed, in order to outline the general distribution and trends in hydropower capabilities across Europe. Then, the assessment focuses on the 'developed' hydropower potential of existing hydropower plants, in order to allow for a more realistic picture of present and future electricity production. For the second part, a new data set has been developed which geo-references 5991 European hydropower stations and distinguishes them into run-of-river and reservoir stations. The results of this study present strong indications that, following moderate climate and global change scenario assumptions, severe future alterations in discharge regimes have to be expected, leading to unstable regional trends in hydropower potentials with reductions of 25% and more for southern and southeastern European countries.

LGL, 2011. *Aquatic Resources Data Gap Analysis*. Draft. Prepared by LGL Alaska Research Associates, Inc. for Alaska Energy Authority. July 2011.

Abstract: An analysis of information needed for evaluating project impacts on aquatic resources.

LGL, 2013. *Adult Salmon Distribution and Habitat Utilization Study*. Draft. Susitna-Watana Hydroelectric Project (FERC No. 14241). Alaska Energy Authority.

Abstract: Summary of field activities and data collected during recent fish sampling efforts. Includes mark-recapture and radio telemetry distribution data.

Ligon, F.K., W.E. Dietrich, and W.J. Trush, 1995. Downstream Ecological Effects of Dams. *BioScience* 45, 183–192.

Abstract: A comprehensive evaluation of the effects of dams on ecological processes.

Linnansaari, T., K. Alfredsen, M. Stickler, J.V. Arnekleiv, A. Harby, and R.A. Cunjak, 2009. Does ice matter? Site fidelity and movements by Atlantic salmon (*Salmo salar L.*) parr during winter in a substrate enhanced river reach. *River Research and Applications* 25, 773–787.

Abstract: In-stream habitat enhancement is a common remedial action in rivers where degradation/lack of suitable fish habitat can be diagnosed. However, post-project monitoring to assess the response of the biota to modification is rare particularly during winter. We conducted in situ monitoring during the winters of 2004–2006 in the regulated Dalåa River, central Norway, in order to determine if winter habitat requirements of Atlantic salmon (Salmo salar L.) parr were realized in an enhanced (substrate and mesohabitat modification) reach. In total, 140 parr were marked with passive integrated transponder (PIT) tags and the fish were followed by carrying out active tracking surveys under variable ice conditions throughout the winter. Highest emigration (44%) occurred before ice formation started. Emigration was reduced after ice formed and was largely offset by parr re-entering the enhanced area. Dispersal into the non-enhanced, small substrate control area was observed only when the study reach was ice covered, and no parr were subsequently encountered in the control section after ice had melted. In the enhanced area, declining water temperature and surface ice conditions did not affect the spatial distribution of the resident salmon parr at the studied scale. Areas with 'solid' anchor ice precluded access for salmon parr whilst areas with 'patchy' anchor were used throughout the winter. Our results indicate that surface ice creates conditions that allow salmon parr to use stream habitats that otherwise provide only a limited amount of in-stream cover. Ice processes should be taken into consideration when habitat enhancement projects are carried out and subsequently assessed for effectiveness.

Linnansaari, T., and R.A. Cunjak, 2010. Patterns in apparent survival of Atlantic salmon (*Salmo salar*) parr in relation to variable ice conditions throughout winter. *Canadian Journal of Fisheries and Aquatic Sciences* 67, 1744–1754.

Abstract: Apparent within-site survival of Atlantic salmon (Salmo salar) parr, individually tagged with passive integrated transponders, was not constant throughout the winter period in a 3-year study (2003–2006) in Catamaran Brook, New Brunswick, Canada. Highest decline in apparent survival (19.4%–33.3% of the study population) occurred prior to any ice formation and coincided with early winter acclimatization period (dynamic temperature and discharge regime). Stream discharge and parr maturity were identified to be relevant factors explaining emigration prior to ice formation. Apparent survival was improved during the period affected by subsurface ice and considerably better when surface ice was prevailing, with a decline in population size between 0% and 15.4%. Overall, observed within-site winter mortality was low (4.4%), and the majority of the loss of tagged salmon parr occurred because of emigration. On average, the within-site population of tagged salmon parr declined by 31.7% over the whole winter (November–April). Our data suggest that anthropogenic impacts, like climate change or river regulation, are likely to affect the apparent survival rate and distribution of juvenile Atlantic salmon because of their effects on natural ice regime in streams.

Lloyd, D.S., J.P. Koenings, and J.D. Laperriere, 1987. Effects of Turbidity in Fresh Waters of Alaska. *North American Journal of Fisheries Management* 7, 18–33.

Abstract: Turbidity results from the scattering of light in water by organic and inorganic particles; however, high turbidities usually are caused by suspended inorganic particles, particularly sediment. For several Alaskan lakes, we found that the depth to which 1% of subsurface light penetrated had a strong inverse correlation with sediment-induced turbidity. We also developed a model that describes the decrease in primary production in shallow interior Alaskan streams caused by sediment-induced turbidity. Euphotic volume in lakes correlated strongly with production of juvenile sockeye salmon (*Oncorhynchus nerka*). We also observed reduced abundance of zooplankton, macroinvertebrates, and Arctic grayling (*Thymallus arcticus*) in naturally and artificially turbid aquatic systems. Turbidity measurements correlated less consistently with measures of suspended sediment concentration (total nonfilterable residue), but provided an adequate estimator for use as a water quality standard to protect aquatic habitats.

Lorenz, J.M., and J.H. Filer, 1989. Spawning habitat and redd characteristics of sockeye salmon in the glacial Taku River, British Columbia and Alaska. *Transactions of the American Fisheries Society* 118, 495–502.

Abstract: Spawning habitats of sockeye salmon *Oncorhynchus nerka* in the Taku River and its tributaries in British Columbia and Alaska were studied to determine habitat use and redd characteristics in a glacial river system. We used radiotelemetry to track adult sockeye salmon to 26 spawning reaches, and 63 spawning sites were sampled for habitat characteristics. Over 40% of the sockeye salmon in the sampling area had a freshwater age of zero, and most of these spawned in main channels or off channel areas. The availability of upwelling groundwater influenced habitat use in the main stem of the river; upwelling groundwater was detected in nearly 60% of the sites sampled in main-stem areas. Spawning sites with upwelling groundwater had lower water velocities and more variable substrate compositions than sites without upwelling groundwater. Redds had two to four times more fine sediment than previously reported. The probability of use was greatest when substrate had less than 15% fine sediment, water velocity was between 10 and 15 cm/s, and intragravel temperature was between 4.5 and 6.0°C.

Lytle, D.A., and N.L. Poff, 2004. Adaptation to natural flow regimes. *Trends in Ecology & Evolution* 19, 94–100.

Abstract: Floods and droughts are important features of most running water ecosystems, but the alteration of natural flow regimes by recent human activities, such as dam building, raises questions related to both evolution and conservation. Among organisms inhabiting running waters, what adaptations exist for surviving floods and droughts? How will the alteration of the frequency, timing and duration of flow extremes affect flood- and drought-adapted organisms? How rapidly can populations evolve in response to altered flow regimes? Here, we identify three modes of adaptation (life history, behavioral and morphological) that plants and animals use to survive floods and/or droughts. The mode of adaptation that an organism has determines its vulnerability to different kinds of flow regime alteration. The rate of evolution in response to flow regime alteration remains an open question. Because humans have now altered the flow regimes of most rivers and many streams, understanding the link between fitness and flow regime is crucial for the effective management and restoration of running water ecosystems.

Maeck, A., T. DelSontro, D.F. McGinnis, H. Fischer, S. Flury, M. Schmidt, P. Fietzek, and A. Lorke, 2013. Sediment Trapping by Dams Creates Methane Emission Hot Spots. *Environmental Science & Technology* 130715152553007.

Abstract: Inland waters transport and transform substantial amounts of carbon and account for 18% of global methane emissions. Large reservoirs with higher areal methane release rates than natural waters contribute significantly to freshwater emissions. However, there are millions of small dams worldwide that receive and trap high loads of organic carbon and can therefore potentially emit significant amounts of methane to the atmosphere. We evaluated the effect of damming on methane emissions in a central European impounded river. Direct comparison of riverine and reservoir reaches, where sedimentation in the latter is increased due to trapping by dams, revealed that the reservoir reaches are the major source of methane emissions (0.23 mmol CH4 m–2 d–1 vs 19.7 mmol CH4 m–2 d–1, respectively) and that areal emission rates far exceed previous estimates for temperate reservoirs or rivers. We show that sediment accumulation correlates with methane production and subsequent ebullitive release rates and may therefore be an excellent proxy for estimating methane emissions from small reservoirs. Our results suggest that sedimentation-driven methane emissions from dammed river hot spot sites can potentially increase global freshwater emissions by up to 7%.

Mantua, N., I. Tohver, and A. Hamlet, 2010. Climate change impacts on streamflow extremes and summertime stream temperature and their possible consequences for freshwater salmon habitat in Washington State. *Climatic Change* 102, 187–223.

Abstract: This study evaluates the sensitivity of Washington State's freshwater habitat of Pacific Salmon (*Oncorhynchus* spp.) to climate change. Our analysis focuses on summertime stream temperatures, seasonal low flows, and changes in peak and base flows because these physical factors are likely to be key pressure points for many of Washington's salmon populations. Weekly summertime water temperatures and extreme daily high and low streamflows are evaluated under multimodel composites for A1B and B1 greenhouse gas emissions scenarios. Simulations predict rising water temperatures will thermally stress salmon throughout Washington's watersheds, becoming increasingly severe later in the twenty-first century. Streamflow simulations predict that basins strongly influenced by transient runoff (a mix of direct runoff from cool-season rainfall and springtime snowmelt) are most sensitive to climate change. By the 2080s, hydrologic simulations predict a complete loss of Washington's snowmelt dominant basins, and only about ten transient basins remaining in the north Cascades. Historically transient runoff watersheds will shift towards rainfall dominant behavior, undergoing more severe summer low flow periods and more frequent days with intense winter flooding. While cool-season stream temperature changes and impacts on salmon are not assessed in this study, it is possible that climate-induced warming in winter and spring will benefit parts of the freshwater life-cycle of some salmon populations enough to increase their reproductive success (or overall fitness). However, the combined effects of warming summertime stream temperatures and altered streamflows will likely reduce the reproductive success for many Washington salmon populations, with impacts varying for different life history-types and watershed-types. Diminishing streamflows and higher stream temperatures in summer will be stressful for stream-type salmon populations that have freshwater rearing periods in summer. Increased winter flooding in transient runoff watersheds will likely reduce the egg-to-fry survival rates for ocean-type and stream-type salmon.

Mantua, N.J., and S.R. Hare, 2002. The Pacific Decadal Oscillation. *Journal of Oceanography* 58, 35–44.

Abstract: The Pacific Decadal Oscillation (PDO) has been described by some as a long-lived El Niño-like pattern of Pacific climate variability, and by others as a blend of two sometimes independent modes having distinct spatial and temporal characteristics of North Pacific sea surface temperature (SST) variability. A growing body of evidence highlights a strong tendency for PDO impacts in the Southern Hemisphere, with important surface climate anomalies over the mid-latitude South Pacific Ocean, Australia and South America. Several independent studies find evidence for just two full PDO cycles in the past century: “cool” PDO regimes prevailed from 1890–1924 and again from 1947–1976, while “warm” PDO regimes dominated from 1925–1946 and from 1977 through (at least) the mid-1990s. Interdecadal changes in Pacific climate have widespread impacts on natural systems, including water resources in the Americas and many marine fisheries in the North Pacific. Tree-ring and Pacific coral based climate reconstructions suggest that PDO variations—at a range of varying time scales—can be traced back to at least 1600, although there are important differences between different proxy reconstructions. While 20th Century PDO fluctuations were most energetic in two general periodicities—one from 15-to-25 years, and the other from 50-to-70 years—the mechanisms causing PDO variability remain unclear. To date, there is little in the way of observational evidence to support a mid-latitude coupled air-sea interaction for PDO, though there are several well-understood mechanisms that promote multi-year persistence in North Pacific upper ocean temperature anomalies.

Mantua, N.J., S.R. Hare, Y. Zhang, J.M. Wallace, and R.C. Francis, 1997. A Pacific Interdecadal Climate Oscillation with Impacts on Salmon Production. *Bulletin of the American Meteorological Society* 78, 1069–1079.

Abstract: Evidence gleaned from the instrumental record of climate data identifies a robust, recurring pattern of ocean–atmosphere climate variability centered over the midlatitude North Pacific basin. Over the past century, the amplitude of this climate pattern has varied irregularly at interannual-to-interdecadal timescales. There is evidence of reversals in the prevailing polarity of the oscillation occurring around 1925, 1947, and 1977; the last two reversals correspond to dramatic shifts in salmon production regimes in the North Pacific Ocean. This climate pattern also affects coastal sea and continental surface air temperatures, as well as streamflow in major west coast river systems, from Alaska to California.

Marchetti, M.P., and P.B. Moyle, 2001. Effects of Flow Regime on Fish Assemblages in a regulated California Stream. *Ecological Applications* 11, 530–539.

Abstract: The fishes in Lower Putah Creek, a regulated stream in the Central Valley of California, were sampled over a 5-year period, 1994–1998. Distinct fish assemblages were observed in the lower 37 km of stream using two-way indicator species analysis (TWINSPAN) and canonical correspondence analysis (CCA). The assemblages segregated in an upstream-to-downstream manner. Distinct differences were found between assemblages of native and nonnative fishes and their association with environmental variables and habitat use. Native fishes tended to cluster in areas with colder temperatures, lower conductivity, less pool habitat, faster streamflow, and more shaded stream surface. Numbers of nonnative fish were negatively correlated with increased streamflow, and numbers of native fish were positively correlated with increased flow. Hydrologic variability between years and seasons indicated that flow regime had a large effect on the fish assemblages. This study provides a clear demonstration of how native fishes in streams of the western United States exhibit different habitat requirements and respond to temporal variation in flow in a different manner than nonnative fishes. It supports the concept that restoration of natural flow regimes, in company with other restoration measures, is necessary if the continued downward decline of native fish populations in the western United States is to be reversed.

McElhany, P., M. Ruckelshaus, M. Ford, T. Wainwright, and E. Bjorkstedt, 2000. *Viable Salmonid Populations and the Recovery of Evolutionarily Significant Units*. NOAA Technical Memorandum NMFS-NWFSC-42.

Abstract: A description of viable salmonid population parameters and their use in recovery planning.

McGlauflin, M.T., D.E. Schindler, L.W. Seeb, C.T. Smith, C. Habicht, and J.E. Seeb, 2011. Spawning Habitat and Geography Influence Population Structure and Juvenile Migration Timing of Sockeye Salmon in the Wood River Lakes, Alaska. *Transactions of the American Fisheries Society* 140, 763–782.

Abstract: The strict homing of sockeye salmon *Oncorhynchus nerka* results in reproductively isolated populations that often spawn in close proximity and share rearing habitat. High spawning fidelity enables these populations to adapt to local conditions, resulting in a wide range of life history characteristics and genetic variation within individual watersheds. The Wood River system in southwestern Alaska provides a pristine, well-studied system in which to examine fine-scale population structure and its influences on juvenile life histories. Adult sockeye salmon spawn in lake beaches, rivers, and small tributaries throughout this watershed, and juveniles rear in five nursery lakes. We genotyped 30 spawning populations and 6,066 migrating smolts at 45 single nucleotide polymorphism loci, two of which are candidates for positive selection in the study system. We show that there is significant genetic structure (FST = 0.032) in the Wood River lakes and that divergence is generally related to spawning rather than nursery habitat (hierarchical analysis of molecular variance; $P < 0.05$). Four groups of populations were identified based on genetic structure and used to determine the composition of unknown mixtures of migrating smolts using a Bayesian modeling framework. We demonstrate that smolt migration timing is related to genetic structure; stream and river populations dominate catches in early June, while beach spawners and the populations in Lake Kulik are more prevalent from mid-June to early September. Age-2 smolts are primarily produced by the Lake Kulik and beach spawning populations, showing that genetic differences may reflect divergent freshwater and migration life history strategies. These results indicate that local adaptation to spawning habitat influences genetic divergence in the Wood River lakes, affecting both adult and juvenile life stages of sockeye salmon.

McMichael, G.A., C.A. McKinstry, J.A. Vucelick, and J.A. Lukas, 2005a. Fall Chinook Salmon Spawning Activity versus Daylight and Flow in the Tailrace of a Large Hydroelectric Dam. *North American Journal of Fisheries Management* 25, 573–580.

Abstract: We deployed an acoustic system during the spawning season for fall Chinook salmon *Oncorhynchus tshawytscha* in 2001 to determine whether fall Chinook salmon spawning activity in a hydroelectric dam tailrace area was affected by daylight or river flow. Our study design allocated sampling effort nearly equally between hours of darkness and hours of daylight throughout each 24-h period. The acoustic system recorded sounds of fall Chinook salmon spawning activity in two index areas downstream of Wanapum Dam on the Columbia River in Washington State. One index area was a deepwater spawning site located in 9–11 m of water. The other index area was a moderate-depth midchannel bar, where water depths ranged from 2.5 to 6 m. We defined the rate of spawning activity in digs per minute. Fall Chinook salmon spawning activity rates in the Wanapum Dam tailrace were influenced by both daylight and river discharge, which had a pronounced nonlinear effect on spawning activity rates. To account for nonlinearity, a generalized additive model was used to characterize the combined effects of river flow and daylight. The final model also suggested that both flow and daylight influenced spawning activity. Spawning activity occurred during both daylight and darkness, significantly more activity occurring during daylight in both index areas. Spawning activity was generally highest at project discharges between 1,700 and 2,266 m3/s in both spawning areas; spawning activity diminished as discharge increased from 3,400 to 4,250 m3/s. We concluded that fall Chinook salmon spawning activity in this regulated discharge environment was affected more by flow (and velocity) than by daylight.

McMichael, G.A., C.L. Rakowski, B.B. James, and J.A. Lukas, 2005b. Estimated Fall Chinook Salmon Survival to Emergence in Dewatered Redds in a Shallow Side Channel of the Columbia River. *North American Journal of Fisheries Management* 25, 876–884.

Abstract: Fall Chinook salmon *Oncorhynchus tshawytscha* often spawn in the tailraces of large hydroelectric dams on the Columbia River. Redds built in shallow habitats downstream of these dams may be periodically dewatered as a result of load-following operations and subsequent changes in water surface elevation before the fry emerge. To determine whether fall Chinook salmon redds in a shallow area subjected to periodic dewatering downstream of Wanapum Dam on the Columbia River produced live fry, we installed seven redd caps and monitored emergence. Large numbers of live fry were captured from the redds between March 9 and May 18, 2003. Estimated survival from egg to fry for these redds, which were dewatered approximately 3.1% of the time during the posthatch intragravel rearing period, ranged from 16.9% to 66.6% and averaged 29.2% (assuming 4,272 viable eggs/redd). The peak emergence date ranged from April 1 to April 29 (average, about April 14). Peak emergence dates corresponded well with predicted emergence dates based on 1,000 accumulated temperature units. For fall Chinook salmon emerging from individual redds the mean fork length for each

redd ranged from 38.3 to 41.2 mm, and lengths of fish emerging from individual redds increased throughout the emergence period.

Meixler, M.S., M.B. Bain, M. Todd Walter, 2009. Predicting barrier passage and habitat suitability for migratory fish species. *Ecological Modelling* 220, 2782–2791.

Abstract: Fish migrate to spawn, feed, seek refuge from predators, and escape harmful environmental conditions. The success of upstream migration is limited by the presence of barriers that can impede the passage of fish. We used a spatially explicit modeling strategy to examine the effects of barriers on passage for 21 native and non-native migratory fish species and the amount of suitable habitat blocked for each species. Spatially derived physical parameter estimates and literature based fish capabilities and tolerances were used to predict fish passage success and habitat suitability. Both the fish passage and the habitat suitability models accurately predicted fish presence above barriers for most common, non-stocked species. The fish passage model predicted that barriers greater than or equal to 6 m block all migratory species. Chinook salmon (*Oncorhynchus tshawytscha*) was expected to be blocked the least. The habitat suitability model predicted that low gradient streams with intact habitat quality were likely to support the highest number of fish species. The fish passage and habitat suitability models were intended to be used by environmental managers as strategy development tools to prioritize candidate dams for field assessment and make decisions regarding the management of migratory fish populations.

Merizon, R.A.J., 2010. *Distribution of spawning Susitna River chum Oncorhynchus keta and coho O. kisutch salmon, 2009*. Alaska Dept. of Fish and Game, Division of Sport Fish, Research and Technical Services, Anchorage, Alaska.

Abstract: Recent evaluation of chum and coho spawning areas in the Susitna River.

Mesa, M.G., L.K. Weiland, and A.G. Maule, 2000. Progression and Severity of Gas Bubble Trauma in Juvenile Salmonids. *Transactions of the American Fisheries Society* 129, 174–185.

Abstract: We conducted laboratory experiments to assess the progression and to quantify the severity of signs of gas bubble trauma (GBT) in juvenile Chinook salmon *Oncorhynchus tshawytscha* and steelhead *Oncorhynchus mykiss* exposed to different levels of total dissolved gas (TDG), and we attempted to relate these signs to the likelihood of mortality. When fish were exposed to 110% TDG for up to 22 d, no fish died, and there were few signs of GBT in the lateral line or gills. Bubbles in the fins, however, were relatively common, and they progressively worsened over the experimental period. When fish were exposed to 120% TDG for up to 140 h, Chinook salmon had an LT20 (time necessary to kill 20% of the fish) ranging from 40 to 120 h, whereas steelhead had LT20s ranging from 20 to 35 h. In steelhead, bubbles in the lateral line, fins, and gills displayed poor trends of worsening over time, showed substantial interindividual

variability, and were poorly related to mortality. In Chinook salmon, only bubbles in the lateral line showed a distinct worsening over time, and the severity of bubbles in the lateral line was highly correlated with mortality. When fish were exposed to 130% TDG for up to 11 h, LT20s for Chinook salmon ranged from 3 to 6 h, whereas those for steelhead ranged from 5 to 7 h. In Chinook salmon, bubbles in the lateral line and fins, but not those in the gills, showed distinct trends of worsening over time. In steelhead, bubbles in the lateral line displayed the most significant trend of progressive severity. In both species at 130% TDG, the severity of all GBT signs was highly correlated with mortality. The progressive nature of GBT and the methods we developed to examine fish for GBT may be useful for monitoring programs that aim to assess the severity of dissolved gas supersaturation exposures experienced by fish in the wild. However, the efficacy of such programs seems substantially hindered by problems associated with (1) the variable persistence of GBT signs; (2) the inconsistent relation of GBT signs to mortality; (3) the insufficient knowledge of the relation between exposure history and GBT sign development for fish in the wild; and (4) an extreme amount of interindividual variation in terms of susceptibility to GBT.

Milner, A.M., and G.E. Petts, 1994. Glacial rivers: physical habitat and ecology. *Freshwater Biology* 32, 295–307.

Abstract: 1. This review examines the physical habitat and ecology of glacial rivers which have been relatively unstudied compared with rivers originating from other sources.
2. Typical glacial rivers have summer temperatures below 10°C, a single seasonal peak in discharge, which in the Northern Hemisphere typically occurs in July, a diel fluctuation in flow which usually peaks in late afternoon, and turbidity levels in summer that exceed 30 NTU. These variables contrast with those in snowmelt/rainfall streams, particularly in summer, and make conditions more extreme for the biota.
3. Where maximum temperatures are 2°C benthic invertebrate communities are dominated by Diamcsa (Chironomidae). Downstream, temperatures increase, channels become more stable and valley floors become older. Orthocladiinae (Chironomidae), Simuliidae, Baetidae, Nemouridae and Chloroperlidae become characteristic members of the invertebrate community.
4. Fauna may be displaced, or at least colonization delayed, by channel instability; the variable age structure of the valley floor will influence the faunal gradient, which may also be reset by the effects of tributaries, lakes and valley confinement.
5. We propose a qualitative model that outlines zoobenthic community gradients determined by two principal variables, water temperature and channel stability, as a function of distance downstream, or time since deglaciation.

Molnia, B.F., 2007. Late nineteenth to early twenty-first century behavior of Alaskan glaciers as indicators of changing regional climate. *Global and Planetary Change* 56, 23–56.

Abstract: Alaska's climate is changing and one of the most significant indications of this change has been the late 19th to early 21st century behavior of Alaskan glaciers. Weather station

temperature data document that air temperatures throughout Alaska have been increasing for many decades. Since the mid-20th century, the average change is an increase of ~ 2.0 °C. In order to determine the magnitude and pattern of response of glaciers to this regional climate change, a comprehensive analysis was made of the recent behavior of hundreds of glaciers located in the eleven Alaskan mountain ranges and three island areas that currently support glaciers. Data analyzed included maps, historical observations, thousands of ground-and-aerial photographs and satellite images, and vegetation proxy data. Results were synthesized to determine changes in length and area of individual glaciers. Alaskan ground photography dates from 1883, aerial photography dates from 1926, and satellite photography and imagery dates from the early 1960s. Unfortunately, very few Alaskan glaciers have any mass balance observations.

In most areas analyzed, every glacier that descends below an elevation of ~ 1500 m is currently thinning and/or retreating. Many glaciers have an uninterrupted history of continuous post-Little-Ice-Age retreat that spans more than 250 years. Others are characterized by multiple late 19th to early 21st century fluctuations. Today, retreating and/or thinning glaciers represent more than 98% of the glaciers examined. However, in the Coast Mountains, St. Elias Mountains, Chugach Mountains, and the Aleutian Range more than a dozen glaciers are currently advancing and thickening. Many currently advancing glaciers are or were formerly tidewater glaciers. Some of these glaciers have been expanding for more than two centuries. This presentation documents the post-Little-Ice-Age behavior and variability of the response of many Alaskan glaciers to changing regional climate.

Montgomery, D.R., J.M. Buffington, N.P. Peterson, D. Schuett-Hames, and T.P. Quinn, 1996. Stream-bed scour, egg burial depths, and the influence of salmonid spawning on bed surface mobility and embryo survival. *Canadian Journal of Fisheries and Aquatic Sciences* 53, 1061–1070.

Abstract: Bed scour, egg pocket depths, and alteration of stream-bed surfaces by spawning chum salmon (Onchorhynchus keta) were measured in two Pacific Northwest gravel-bedded streams. Close correspondence between egg burial depths and scour depths during the incubation period suggests an adaptation to typical depths of bed scour and indicates that even minor increases in the depth of scour could significantly reduce embryo survival. Where egg burial depths are known, expressing scour depth in terms of bed-load transport rate provides a means for predicting embryo mortality resulting from changes in watershed processes that alter shear stress or sediment supply. Stream-bed alteration caused by mass spawning also may influence embryo survival. Theoretical calculations indicate that spawning-related bed surface coarsening, sorting, and form drag reduce grain mobility and lessen the probability of stream-bed scour and excavation of buried salmon embryos. This potential feedback between salmon spawning and bed mobility implies that it could become increasingly difficult to reverse declines in mass-spawning populations because decreased spawning activity would increase the potential for bed scour, favoring higher embryo mortality. Further analysis of this effect is warranted, however, as the degree to which spawning-related bed loosening counteracts

reduced grain mobility caused by surface coarsening, sorting, and redd form drag remains uncertain

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

Abstract: The effects of intermittent power generation on the fish fauna and benthic invertebrates of several Austrian rivers have been investigated quantitatively. In contrast to the more or less local adverse effects of impoundments or stream channelization, artificial flow fluctuations generally disturb a long section of a given river. Within all the river sections investigated, a breakdown of the benthic invertebrate biomass of between 75 and 95% was observed within the first few kilometres of river length. A reduction of between 40 and 60% of biomass compared with undisturbed areas could be detected within the following 20–40 km. The reduction of the fish fauna is within the same order of magnitude and correlates well with the amplitude of the flow fluctuations. Several reasons for the breakdown are summarized and proposals for the minimization of these detrimental effects of artificial short-term fluctuations are given.

Moore, J.W., M. McClure, L.A. Rogers, and D.E. Schindler, 2010. Synchronization and portfolio performance of threatened salmon. *Conservation Letters* 3, 340–348.

Abstract: Interpopulation variation in dynamics can buffer species against environmental change. We compared population synchrony in a group of threatened Chinook salmon in the highly impacted Snake River basin (Oregon, Washington, Idaho) to that in the sockeye salmon stock complex of less impact Bristol Bay (Alaska). Over the last 40 years, >90% of populations in the Snake River basin became more synchronized with one another. However, over that period, sockeye populations from Alaska did not exhibit systemic changes in synchrony. Coincident with increasing Snake River population synchrony, there was an increase in hatchery propagation and the number of large dams, potentially homogenizing habitats and populations. A simulation using economic portfolio theory revealed that synchronization of Snake River salmon decreased risk-adjusted portfolio performance (the ratio of portfolio productivity to variance) and decreased benefits of population richness. Improving portfolio performance for exploited species, especially given future environmental change, requires protecting a diverse range of populations and the varied habitats upon which they depend.

Moore, J.W., D.E. Schindler, and M.D. Scheuerell, 2004. Disturbance of freshwater habitats by anadromous salmon in Alaska. *Oecologia* 139, 298–308.

Abstract: High densities of habitat modifiers can dramatically alter the structure of ecosystems. Whereas spawning sockeye salmon (*Oncorhynchus nerka*) dig nests that cover over 2 m2 and are at least 20 cm deep, and can spawn at high densities, relatively little attention has been devoted to investigating the impacts of this disturbance. We hypothesized that this temporally and spatially predictable bioturbation has large impacts on the coastal aquatic habitats used by sockeye. We experimentally investigated the impacts of disturbance caused by spawning sockeye in two streams and two lakes in Alaska by excluding salmon from 2.25 m2 plots where they traditionally spawn. We sampled exclusions and control plots before, during, and after spawning. During sockeye spawning, fine sediment accumulated in areas where sockeye were excluded from spawning. In addition, sockeye spawning significantly decreased algal biomass by 80% compared to exclusion plots. We found mixed effects of spawning on the invertebrate assemblage. Tricladida and Chironomidae densities increased by 3x in exclusion plots relative to control plots in one creek site. However, for most taxa and sites, invertebrate densities declined substantially as spawning progressed, regardless of experimental treatment. Habitat modification by spawning salmon alters both community organization and ecosystem processes.

Morgan, R.P., R.E. Jacobsen, S.B. Weisberg, L.A. McDowell, and H.T. Wilson, 1991. Effects of Flow Alteration on Benthic Macroinvertebrate Communities below the Brighton Hydroelectric Dam. *Journal of Freshwater Ecology* 6, 419–429.

Abstract: Installation of hydroelectric power at Brighton Dam on the Patuxent River (near Olney, Maryland) in December 1985 was accompanied by a revised (versus preoperational) flow release schedule intended to reduce the amount of time downstream macroinvertebrates were exposed to extreme high and low flows and to eliminate rapid changes in flow between these extremes. To assess whether the flow regime was effective at protecting downstream biota, benthic macroinvertebrate populations were monitored for 20 months before and 23 months after the revised flow regime was implemented. Changes in invertebrate abundance below the dam were tested using an analysis of covariance, employing abundance above the dam as a covariate to account for seasonal and among-year variation.
The revised flow regime resulted in a 35% reduction in low flows (defined as flows less than half the average annual flow) and a 25% reduction in high flows (defined as greater than twice the average annual flow). Benthic macroinvertebrates responded to this improvement in the flow pattern with a doubling in total density at the downstream sites. The altered flow regime also resulted in increased abundance at below dam stations for six of the 11 taxa that were analyzed individually as well as a higher quality invertebrate community at the downstream station nearest the dam (measured by the Hilsenhoff index). Careful planning of flow modification associated with hydroelectric operations was effective not only at protecting, but also enhancing the downstream biota.

Morrow, J.E., 1980. *The freshwater fishes of Alaska*. Alaska Northwest Publishing Company, Anchorage, Alaska. 248 pp.

Abstract: A review of the biology and distribution of freshwater fishes in Alaska.

Moser, J.F., 1899. *The Salmon and Salmon Fisheries of Alaska: Report of the Operations of the United States Fish Commission Steamer Albatross for the Year Ending June 30, 1898*. U.S. Government Printing Office.

Abstract: Historic document that identifies major impacts from over fishing prior to contemporary salmon management,

Mote, P.W., 2006. Climate-Driven Variability and Trends in Mountain Snowpack in Western North America. *Journal of Climate* 19, 6209–6220.

Abstract: Records of 1 April snow water equivalent (SWE) are examined here using multiple linear regression against reference time series of temperature and precipitation. This method permits 1) an examination of the separate roles of temperature and precipitation in determining the trends in SWE; 2) an estimation of the sensitivity of SWE to warming trends, and its distribution across western North America and as a function of elevation; and 3) inferences about responses of SWE to future warming. These results emphasize the sensitivity to warming of the mountains of northern California and the Cascades of Oregon and Washington. In addition, the contribution of modes of Pacific climate variability is examined and found to be responsible for about 10%–60% of the trends in SWE, depending on the period of record and climate index.

Mundie, J.H., and R. Bell-Irving, 1986. Predictability of the Consequences of the Kemano Hydroelectric Proposal for Natural Salmon Populations. *Canadian Water Resources Journal* 11, 14–25.

Abstract: The Aluminum Company of Canada, Limited (Alcan) has proposed completion of its hydroelectric developments to increase aluminum smelting capacity in north-central B.C. The project was started in 1950 and included the Kenney Dam on the Nechako River in the Fraser catchment area, the creation of the Nechako Reservoir, and the construction of facilities for generating power at the Kemano River on the west coast. Completion of development (Kemano Completion Proposal), at a cost of over $2 billion, would divert 84 percent of the initial mean annual discharge of the Nechako River, and 62 percent of the mean annual discharge of the Nanika River in the Skeena catchment area, to the Kemano River. The proposal offers discharges that are intended to protect Pacific salmon stocks, or, where this is not possible, mitigation of losses. This paper identifies the more obvious effects of abstraction and regulation on salmon populations and their habitat. These include interference with migration of adults, changes in the quality of spawning gravel, imposition of stress on all stages of the fish from high total gas pressures and from alterations in ambient temperature, changes in the composition of the total fish community, changes in the production and availability of food, stranding of fish, weakening or loss of cues for homing, and increased exposure to predation from fish and birds. A major difficulty in trying to relate effects to salmon populations lies in distinguishing fish numbers as determined by habitat effects, from numbers determined by the level of recruitment to the

rivers as a result of exploitation by the fishery. Three approaches to the problem are: experimental design of impact assessment, modelling changes of discharge and salmon habitat, and analysis of case histories of regulated discharge. The last seems to be the most instructive per unit of effort required. As an approximation to obtaining replication of treatment effects, and to judge the reliability of prediction of effects of flow regulation, case histories of regulated salmonid rivers were examined. It was found that negative effects outnumbered positive ones, that prediction was usually incorrect, and that, even where flow regulation was implemented with the express intention of increasing numbers of salmonids the results fell short of

Murchie, K.J., K.P.E. Hair, C.E. Pullen, T.D. Redpath, H.R. Stephens, and S.J. Cooke, 2008. Fish response to modified flow regimes in regulated rivers: research methods, effects and opportunities. *River Research and Applications* 24, 197–217.

Abstract: Globally, rivers are increasingly being subjected to various levels of physical alteration and river regulation to provide humans with services such as hydropower, freshwater, flood control, irrigation and recreation. Although river regulation plays an important role in modern society, there are potential consequences which may negatively affect fish and fish habitat. While much effort has been expended examining the response of fish to fluctuating flow regimes in different systems, there has been little in the way of a comprehensive synthesis. In an effort to better understand the effects of river regulation on fish and fish habitat, we conducted a systematic review of available literature with three goals: (1) summarize the various research methodologies used by regulated river researchers, (2) summarize the effects found on fish and fish habitat and (3) identify opportunities for future research. The results of the synthesis indicate that a wide variety of methodologies are being employed to study regulated river science, yet there is a gap in incorporating methodologies that examine effects on fish at a cellular level or those techniques that are interdisciplinary (e.g. behaviour and physiology). There is a clear consensus that modified flow regimes in regulated rivers are affecting fish and fish habitat, but the severity and direction of the response varies widely. Future study designs should include methods that target all biological levels of fish response, and in which detailed statistical analyses can be performed. There is also a need for more rigorous study designs including the use of appropriate controls and replicates. Data on physical variables that co-vary with flow should be collected and examined to add explanatory power to the results. Increased multi-stakeholder collaborations provide the greatest promise of balancing ecological concerns with economic needs.

Murphy, M.H., M.J. Connerton, and D.J. Stewart, 2006. Evaluation of Winter Severity on Growth of Young-of-the-Year Atlantic Salmon. *Transactions of the American Fisheries Society* 135, 420–430.

Abstract: Overwinter growth of young-of-the-year (age-0) Atlantic salmon Salmo salar was studied during two winters in central New York streams. We hypothesized that longer and colder winters would negatively influence the growth of age-0 Atlantic salmon. Further, we predicted that Atlantic salmon growth and survival would be positively correlated with their size before the winter period. Four cages were placed in streams at three sites in the winters of 2000 and 2001, with six individually marked Atlantic salmon per cage. One cage was retrieved monthly at each site and the weight, length, and energy density of each fish were measured to calculate growth rate and condition factor. All fish survived the winter experiment irrespective of starting size. Mean energy density of fish at the conclusion of each experiment was positively related to fish weight at the start. Winter conditions were different between years, stream temperatures being colder in 2000 than in 2001 (overall winter mean [SD], 0.71°C [2.487°C] versus 1.93°C [2.87°C]), accompanied by less variable temperatures, lower discharge, and more ice cover. Growth rates were negative during both winters, weight loss being significantly greater in the year with warmer, more variable temperatures. Growth rates were also significantly different between months, weight loss being greater in December and January and less (or replaced by positive growth) by the end of the winters (March). Mean energy density of salmon increased during the colder winter of 2000 but declined in 2001. Based on the observations in the current study, lower threshold temperatures for feeding activity may be even lower than previously reported, possibly near 0°C. We discuss the energetic implications of variable winter conditions on age-0 Atlantic salmon.

Murphy, M.L., J. Heifetz, J.F. Thedinga, S.W. Johnson, and K.V. Koski, 1989. Habitat Utilization by Juvenile Pacific Salmon (*Onchorynchus*) in the Glacial Taku River, Southeast Alaska. *Canadian Journal of Fisheries and Aquatic Sciences* 46, 1677–1685.

Abstract: Habitat utilization was determined in summer 1986 by sampling 54 sites of nine habitat types: main channels, backwaters, braids, channel edges, and sloughs in the river; and beaver ponds, terrace tributaries, tributary mouths, and upland sloughs on the valley floor. Physical characteristics were measured at all sites, and all habitats except main channels (current too swift for rearing salmon) were seined to determine fish density. Sockeye (*Oncorhynchus nerka*) averaged 23 fish/100 m2, nearly twice the density of coho (*O. kisutch*) and four times that of Chinook (O. tshawytscha), 14 and 6 fish/100 m2, respectively. Sockeye were age 0, 27–84 mm fork length (FL), and most abundant in upland sloughs, beaver ponds, and tributary mouths. Coho were ages 0 and 1, 33–132 mm FL, and most abundant in beaver ponds and upland sloughs. Chinook were age 0, 40–93 mm FL, and more abundant than the other species in habitats with faster currents (1–20 cm/s), particularly channel edges. Each species was absent from about one-quarter of the seining sites of each habitat type. Thus, the lower Taku River provides important summer habitat for juvenile salmon, but many suitable areas were unoccupied, possibly because of their distance from spawning areas and poor access for colonizing fish.

Murphy, M.L., K.V. Koski, J.M. Lorenz, and J.F. Thedinga, 1997. Downstream migrations of juvenile Pacific salmon (*Oncorhynchus* spp.) in a glacial transboundary river. *Canadian Journal of Fisheries and Aquatic Sciences* 54, 2837–2846.

Abstract: Migrations of juvenile Pacific salmon (*Oncorhynchus* spp.) in the glacial Taku River (seventh order) were studied to assess movement from upriver spawning areas (in British Columbia) into lower-river rearing areas (in Alaska). Differences between fyke-net catches in the river and seine catches in the river's estuary indicated that many downstream migrants remained in the lower river instead of migrating to sea. In particular, age-0 coho salmon (*O. kisutch*) and Chinook salmon (*O. tshawytscha*) moved downriver from May to November but were not caught in the estuary. Age-0 sockeye salmon (*O. nerka*), coho presmolts, and other groups delayed entry into the estuary after moving downriver. We tagged groups of juvenile coho (ages 0–2) from the fyke net with coded-wire to determine when they left the river. One-third of all tags recovered from sport and commercial fisheries occurred 2–3 years later, showing that many coho remained in fresh water for 1–2 years after moving to the lower river. Lower-river areas of large glacial rivers like the Taku River can provide essential rearing habitat for juvenile salmon spawned upriver and are important to consider in integrated whole-river management of transboundary rivers.

Murray, C.B., and J.D. McPhail, 1988. Effect of incubation temperature on the development of five species of Pacific salmon (*Oncorhynchus*) embryos and alevins. *Canadian Journal of Zoology* 66, 266–273.

Abstract: Embryo and alevin survival, time to hatching and emergence, and alevin and fry size of five species of Pacific salmon (*Oncorhynchus*) were observed at five incubation temperatures (2, 5, 8, 11, and 14 °C). No pink (*Oncorhynchus gorbuscha*) or chum (*O. keta*) salmon embryos survived to hatching at 2 °C. Coho (*O. kisutch*) and sockeye (*O. nerka*) salmon had higher embryo survival at 2 °C than Chinook (*O. tschawytscha*) salmon. At 14 °C, chum, pink, and Chinook salmon had higher embryo survival than coho or sockeye salmon. In all species, peaks of embryo mortality occurred at specific developmental stages (completion of epiboly, eye pigmentation, and hatching). Alevin survival to emergence was high for all species, except for coho and pink salmon at 14 °C. Hatching and emergence time varied inversely with incubation temperature, but coho salmon hatched and emerged sooner at all temperatures than the other species. Coho and sockeye salmon alevins were larger at 2 °C, pink, chum, and Chinook salmon alevins were larger at 5° and 8°C. Coho salmon fry were larger at 2°C, Chinook and chum salmon fry were larger at 5°C, and sockeye and pink salmon fry were larger at 8°C. High incubation temperatures reduced fry size in all species. Each species of Pacific salmon appears to be adapted to different spawning times and temperatures, and thus indirectly to specific incubation temperatures, to ensure maximum survival and size and to maintain emergence at the most favorable time each year.

Naiman, R.J., S.R. Elliott, J.M. Helfield, and T.C. O'Keefe, 1999. Biophysical interactions and the structure and dynamics of riverine ecosystems: the importance of biotic feedbacks. *Hydrobiologia* 410, 79–86.

Abstract: Characteristics of streams and rivers reflect variations in local geomorphology, climate, natural disturbance regimes and the dynamic features of the riparian forest. Hierarchical interactions between these components result in a rich variety of distinct stream communities which, when considered in combination with strong biotic feedbacks to the physical environment, present formidable challenges in discovering and understanding fundamental, system- level characteristics of natural rivers. The objectives of this article are to briefly review the traditional view of hierarchical physical controls on stream structure and dynamics and to show how this viewpoint is changing as recognition of strong biological influences on physical structure are emerging. In combination, identifying natural stream characteristics and the interactions among individual components, as well as recognizing the importance of biotic feedbacks on physical structure, form the basis for establishing effective conservation strategies.

Naiman, R.J., J.J. Latterell, N.E. Pettit, and J.D. Olden, 2008. Flow variability and the biophysical vitality of river systems. *Comptes Rendus Geoscience* 340, 629–643.

Abstract: We illustrate the fundamental importance of fluctuations in natural water flows to the long-term sustainability and productivity of riverine ecosystems and their riparian areas. Natural flows are characterized by temporal and spatial heterogeneity in the magnitude, frequency, duration, timing, rate of change, and predictability of discharge. These characteristics, for a specific river or a collection of rivers within a defined region, shape species life histories over evolutionary (millennial) time scales as well as structure the ecological processes and productivity of aquatic and riparian communities. Extreme events – uncommon floods or droughts – are especially important in that they either reset or alter physical and chemical conditions underpinning the long-term development of biotic communities. We present the theoretical rationale for maintaining flow variability to sustain ecological communities and processes, and illustrate the importance of flow variability in two case studies – one from a semi-arid savanna river in South Africa and the other from a temperate rainforest river in North America. We then discuss the scientific challenges of determining the discharge patterns needed for environmental sustainability in a world where rivers, increasingly harnessed for human uses, are experiencing substantially altered flow characteristics relative to their natural states.

Neal, E.G., E. Hood, and K. Smikrud, 2010. Contribution of glacier runoff to freshwater discharge into the Gulf of Alaska. *Geophysical Research Letters* 37, L06404.

Abstract: Watersheds along the Gulf of Alaska (GOA) are undergoing climate warming, glacier volume loss, and shifts in the timing and volume of freshwater delivered to the eastern North Pacific Ocean. We estimate recent mean annual freshwater discharge to the GOA at 870 km3 yr−1. Small distributed coastal drainages contribute 78% of the freshwater discharge with the

remainder delivered by larger rivers penetrating coastal ranges. Discharge from glaciers and icefields accounts for 47% of total freshwater discharge, with 10% coming from glacier volume loss associated with rapid thinning and retreat of glaciers along the GOA. Our results indicate the region of the GOA from Prince William Sound to the east, where glacier runoff contributes 371 km3 yr−1, is vulnerable to future changes in freshwater discharge as a result of glacier thinning and recession. Changes in timing and magnitude of freshwater delivery to the GOA could impact coastal circulation as well as biogeochemical fluxes to near-shore marine ecosystems and the eastern North Pacific Ocean.

Neal, E.G., M. Todd Walter, and C. Coffeen, 2002. Linking the pacific decadal oscillation to seasonal stream discharge patterns in Southeast Alaska. *Journal of Hydrology* 263, 188–197.

Abstract: This study identified and examined differences in Southeast Alaskan streamflow patterns between the two most recent modes of the Pacific decadal oscillation (PDO). Identifying relationships between the PDO and specific regional phenomena is important for understanding climate variability, interpreting historical hydrological variability, and improving water-resources forecasting. Stream discharge data from six watersheds in Southeast Alaska were divided into cold-PDO (1947–1976) and warm-PDO (1977–1998) subsets. For all watersheds, the average annual streamflows during cold-PDO years were not significantly different from warm-PDO years. Monthly and seasonal discharges, however, did differ significantly between the two subsets, with the warm-PDO winter flows being typically higher than the cold-PDO winter flows and the warm-PDO summer flows being typically lower than the cold-PDO flows. These results were consistent with and driven by observed temperature and snowfall patterns for the region. During warm-PDO winters, precipitation fell as rain and ran-off immediately, causing higher than normal winter streamflow. During cold-PDO winters, precipitation was stored as snow and ran off during the summer snowmelt, creating greater summer streamflows. The Mendenhall River was unique in that it experienced higher flows for all seasons during the warm-PDO relative to the cold-PDO. The large amount of Mendenhall River discharge caused by glacial melt during warm-PDO summers offset any flow reduction caused by lack of snow accumulation during warm-PDO winters. The effect of the PDO on Southeast Alaskan watersheds differs from other regions of the Pacific Coast of North America in that monthly/seasonal discharge patterns changed dramatically with the switch in PDO modes but annual discharge did not.

Nickelson, T.E., and P.W. Lawson, 1998. Population viability of coho salmon, *Oncorhynchus kisutch*, in Oregon coastal basins: application of a habitat-based life cycle model. *Canadian Journal of Fisheries and Aquatic Sciences* 55, 2383–2392.

Abstract: To assess extinction risk for Oregon coastal coho salmon, *Oncorhynchus kisutch*, we developed a life cycle model based on habitat quality of individual stream reaches estimated from survey data. Reach-specific smolt output was a function of spawner abundance, demographic stochasticity, genetic effects, and density- and habitat-driven survival rates. After natural mortality and ocean harvest, spawners returned to their natal reaches. Populations in reaches with poor habitat became extinct during periods of low marine survival. With favorable marine survival, high productivity reaches served as sources for recolonization of lower quality reaches through straying of spawners. Consequently, both population size and distribution expanded and contracted through time. Within a reach, populations lost resilience at low numbers when demographic risk factors became more important than density-dependent compensation. Population viability was modeled for three coastal basins having good, moderate, and poor habitat. Reductions in habitat quality up to 60% in 99 years resulted in reduced coho salmon populations in all basins and significantly increased extinction risk in the basin with poor habitat.

Nielsen, J.L., G.T. Ruggerone, and C.E. Zimmerman, 2013. Adaptive strategies and life history characteristics in a warming climate: Salmon in the Arctic? *Environmental Biology of Fishes* 96, 1187–1226.

Abstract: In the warming Arctic, aquatic habitats are in flux and salmon are exploring their options. Adult Pacific salmon, including sockeye (*Oncorhynchus nerka*), coho (*O. kisutch*), Chinook (*O. tshawytscha*), pink (*O. gorbuscha*) and chum (*O. keta*) have been captured throughout the Arctic. Pink and chum salmon are the most common species found in the Arctic today. These species are less dependent on freshwater habitats as juveniles and grow quickly in marine habitats. Putative spawning populations are rare in the North American Arctic and limited to pink salmon in drainages north of Point Hope, Alaska, chum salmon spawning rivers draining to the northwestern Beaufort Sea, and small populations of chum and pink salmon in Canada's Mackenzie River. Pacific salmon have colonized several large river basins draining to the Kara, Laptev and East Siberian seas in the Russian Arctic. These populations probably developed from hatchery supplementation efforts in the 1960s. Hundreds of populations of Arctic Atlantic salmon (Salmo salar) are found in Russia, Norway and Finland. Atlantic salmon have extended their range eastward as far as the Kara Sea in central Russian. A small native population of Atlantic salmon is found in Canada's Ungava Bay. The northern tip of Quebec seems to be an Atlantic salmon migration barrier for other North American stocks. Compatibility between life history requirements and ecological conditions are prerequisite for salmon colonizing Arctic habitats. Broad-scale predictive models of climate change in the Arctic give little information about feedback processes contributing to local conditions, especially in freshwater systems. This paper reviews the recent history of salmon in the Arctic and explores various patterns of climate change that may influence range expansions and future sustainability of salmon in Arctic habitats. A summary of the research needs that will allow informed expectation of further Arctic colonization by salmon is given.

Nilsson, C., and K. Berggren, 2000. Alterations of Riparian Ecosystems Caused by River Regulation. *BioScience* 50, 783–792.

Abstract: A comprehensive review of how riparian ecosystems are influenced by regulated flows.

Nilsson, C., A. Ekblad, M. Gardfjell, and B. Carlberg, 1991. Long-Term Effects of River Regulation on River Margin Vegetation. *The Journal of Applied Ecology* 28, 963–987.

Abstract: (1) The effects of river regulation on river margin vegetation were evaluated by comparing two parallel seventh order rivers, one natural and the other strongly regulated, in northern Sweden. Prior to regulation, both rivers had similar vegetation. (2) No difference between the natural and the regulated river was found in width and height (relative to the summer low-water level) of the river margin, number of substrates, and mean annual discharge. (3) Frequency distributions of species differed in that the regulated river had fewer frequent and more infrequent species. Species-richness and the percentage cover of vegetation were both lower per site in the regulated river. The proportion of annual plus biennial species-richness was higher and that of perennial species-richness lower along the regulated river. (4) Reservoirs retaining pre-regulation river margins and remnants of their former vegetation, and stretches with a modest flow regulation, were most floristically similar to the natural river. (5) Regression equations including eight independent variables explained 10-77% of the variation in species-richness in thirteen groups of plants and in plant cover for two vegetation layers. Presence of pre-regulation river margin vegetation, water-level regime, height of the river margin, and mean annual discharge were the most important variables for species-richness, while water-level regime, mean annual discharge and substrate fineness were most important for plant cover. (6) In most cases, values of species-richness were higher in natural sites and in regulated sites with remnants of pre-regulation river margin vegetation, whereas they decreased with increasing height of the river margin. Percentage cover of ground vegetation was highest in natural sites with a fine-grade substrate.

Nilsson, C., and M. Svedmark, 2002. Basic Principles and Ecological Consequences of Changing Water Regimes: Riparian Plant Communities. *Environmental Management* 30, 468–480.

Abstract: Recent research has emphasized the importance of riparian ecosystems as centers of biodiversity and links between terrestrial and aquatic systems. Riparian ecosystems also belong among the environments that are most disturbed by humans and are in need of restoration to maintain biodiversity and ecological integrity. To facilitate the completion of this task, researchers have an important function to communicate their knowledge to policy-makers and managers. This article presents some fundamental qualities of riparian systems, articulated as three basic principles. The basic principles proposed are: (1) The flow regime determines the successional evolution of riparian plant communities and ecological processes. (2) The riparian corridor serves as a pathway for redistribution of organic and inorganic material that influences plant communities along rivers. (3) The riparian system is a transition zone between land and water ecosystems and is disproportionately plant species-rich when compared to surrounding ecosystems. Translating these principles into management directives requires more information about how much water a river needs and when and how, i.e., flow variables described by magnitude, frequency, timing, duration, and rate of change. It also requires information about how various groups of organisms are affected by habitat fragmentation, especially in terms of their dispersal. Finally, it requires information about how effects of hydrologic alterations vary between different types of riparian systems and with the location within the watershed.

O'Connor, J.E., 2004. The evolving landscape of the Columbia River Gorge. Lewis and Clark and cataclysms on the Columbia. *Oregon Historical Quarterly* 105, 390–421.

Abstract: Travelers retracing Lewis and Clark's journey to the Pacific over the past two hundred years have witnessed tremendous change to the Columbia River Gorge and its primary feature, the Columbia River. Dams, reservoirs, timber harvest, altered fisheries, transportation infrastructure, and growth and shrinkage of communities have transformed the river and valley. This radically different geography of human use and habitation is commonly contrasted with the sometimes romantic view of a prior time provided both by early nineteenth-century chroniclers and present-day critics of the modern condition — an ecotopia of plentiful and perpetual resources sustaining a stable culture from time immemorial. Reality is more complicated. Certainly the human-caused changes to the Columbia River and the gorge since Lewis and Clark have been profound; but the geologic history of immense floods, landslides, and volcanic eruptions that occurred before their journey had equally, if not more, acute effects on landscapes and societies of the gorge. In many ways, the Lewis and Clark Expedition can be viewed as a hinge point for the Columbia River, the changes engineered to the river and its valley in the two hundred years since their visit mirrored by tremendous changes geologically engendered in the thousands of years before.

Owens, P.N., R.J. Batalla, A.J. Collins, B. Gomez, D.M. Hicks, A.J. Horowitz, G.M. Kondolf, M. Marden, M.J. Page, D.H. Peacock, E.L. Petticrew, W. Salomons, and N.A. Trustrum, 2005. Fine-grained sediment in river systems: environmental significance and management issues. *River Research and Applications* 21, 693–717.

Abstract: Fine-grained sediment is a natural and essential component of river systems and plays a major role in the hydrological, geomorphological and ecological functioning of rivers. In many areas of the world, the level of anthropogenic activity is such that fine-grained sediment fluxes have been, or are being, modified at a magnitude and rate that cause profound, and sometimes irreversible, changes in the way that river systems function. This paper examines how anthropogenic activity has caused significant changes in the quantity and quality of fine-grained sediment within river systems, using examples of: land use change in New Zealand; the effects of reservoir construction and management in different countries; the interaction between sediment dynamics and fish habitats in British Columbia, Canada; and the management of contaminated sediment in USA rivers. The paper also evaluates present programmes and

initiatives for the management of fine sediment in river systems and suggests changes that are needed if management strategies are to be effective and sustainable.

Paragamian, V.L., 2002. Changes in the species composition of the fish community in a reach of the Kootenai River, Idaho, after construction of Libby Dam. *Journal of Freshwater Ecology* 17, 375–383.

Abstract: I evaluated fish community structure and the density and growth of mountain whitefish (*Prosopium williamsoni*) downstream of Libby Dam in a 1.0-km reach of the Kootenai River, Idaho, in 1994 and compared the results with those of a similar study in 1980, after closure of the dam. In 1980 seven species of fish were collected; mountain whitefish comprised 70% of the sample (42% by weight), and largescale sucker (*Catostomus macrocheilus*) represented 19% of the sample (49% by weight). In 1994 of the eight species caught, mountain whitefish represented only 40% by number (19% by weight), and the largescale sucker was 65% of the sample (70% by weight). Growth of mountain whitefish was also slower in the early 1990s compared to the later 1970s. Reduced productivity because of the nutrient sink effect of Lake Koocanusa, river regulation, the lack of flushing flows, power peaking, and changes in river temperature may have led to the changes in the fish community structure.

Pinay, G., J.C. Clement, and R.J. Naiman, 2002. Basic Principles and Ecological Consequences of Changing Water Regimes on Nitrogen Cycling in Fluvial Systems. *Environmental Management* 30, 481–491.

Abstract: Understanding the environmental consequences of changing water regimes is a daunting challenge for both resource managers and ecologists. Balancing human demands for fresh water with the needs of the environment for water in appropriate amounts and at the appropriate times are shaping the ways by which this natural resource will be used in the future. Based on past decisions that have rendered many freshwater resources unsuitable for use, we argue that river systems have a fundamental need for appropriate amounts and timing of water to maintain their biophysical integrity. Biophysical integrity is fundamental for the formulation of future sustainable management strategies. This article addresses three basic ecological principles driving the biogeochemical cycle of nitrogen in river systems. These are (1) how the mode of nitrogen delivery affects river ecosystem functioning,(2) how increasing contact between water and soil or sediment increases nitrogen retention and processing, and (3) the role of floods and droughts as important natural events that strongly influence pathways of nitrogen cycling in fluvial systems. New challenges related to the cumulative impact of water regime change, the scale of appraisal of these impacts, and the determination of the impacts due to natural and human changes are discussed. It is suggested that cost of longterm and long-distance cumulative impacts of hydrological changes should be evaluated against short-term economic benefits to determine the real environmental costs.

Poff, N.L., J.D. Allan, M.B. Bain, J.R. Karr, K.L. Prestegaard, B.D. Richter, R.E. Sparks, and J.C. Stromberg, 1997. The Natural Flow Regime. *BioScience* 47, 769–784.

Abstract: A foundational synthesis describing the importance of natural flow regimes for habitat and ecological processes.

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

Abstract: In an effort to develop quantitative relationships between various kinds of flow alteration and ecological responses, we reviewed 165 papers published over the last four decades, with a focus on more recent papers. Our aim was to determine if general relationships could be drawn from disparate case studies in the literature that might inform environmental flows science and management.
2. For all 165 papers we characterised flow alteration in terms of magnitude, frequency, duration, timing and rate of change as reported by the individual studies. Ecological responses were characterised according to taxonomic identity (macroinvertebrates, fish, riparian vegetation) and type of response (abundance, diversity, demographic parameters). A 'qualitative' or narrative summary of the reported results strongly corroborated previous, less comprehensive, reviews by documenting strong and variable ecological responses to all types of flow alteration. Of the 165 papers, 152 (92%) reported decreased values for recorded ecological metrics in response to a variety of types of flow alteration, whereas 21 papers (13%) reported increased values.
3. Fifty-five papers had information suitable for quantitative analysis of ecological response to flow alteration. Seventy per cent of these papers reported on alteration in flow magnitude, yielding a total of 65 data points suitable for analysis. The quantitative analysis provided some insight into the relative sensitivities of different ecological groups to alteration in flow magnitudes, but robust statistical relationships were not supported. Macroinvertebrates showed mixed responses to changes in flow magnitude, with abundance and diversity both increasing and decreasing in response to elevated flows and to reduced flows. Fish abundance, diversity and demographic rates consistently declined in response to both elevated and reduced flow magnitude. Riparian vegetation metrics both increased and decreased in response to reduced peak flows, with increases reflecting mostly enhanced non-woody vegetative cover or encroachment into the stream channel.
4. Our analyses do not support the use of the existing global literature to develop general, transferable quantitative relationships between flow alteration and ecological response; however, they do support the inference that flow alteration is associated with ecological change and that the risk of ecological change increases with increasing magnitude of flow alteration.
5. New sampling programs and analyses that target sites across well-defined gradients of flow alteration are needed to quantify ecological response and develop robust and general flow alteration–ecological response relationships. Similarly, the collection of pre- and post-alteration

data for new water development programs would significantly add to our basic understanding of ecological responses to flow alteration.

Power, M.E., 2006. Environmental controls on food web regimes: A fluvial perspective. *Progress in Oceanography* 68, 125–133.

Abstract: Because food web regimes control the biomass of primary producers (e.g., plants or algae), intermediate consumers (e.g., invertebrates), and large top predators (tuna, killer whales), they are of societal as well as academic interest. Some controls over food web regimes may be internal, but many are mediated by conditions or fluxes over large spatial scales. To understand locally observed changes in food webs, we must learn more about how environmental gradients and boundaries affect the fluxes of energy, materials, or organisms through landscapes or seascapes that influence local species interactions. Marine biologists and oceanographers have overcome formidable challenges of fieldwork on the high seas to make remarkable progress towards this goal. In river drainage networks, we have opportunities to address similar questions at smaller spatial scales, in ecosystems with clear physical structure and organization. Despite these advantages, we still have much to learn about linkages between fluxes from watershed landscapes and local food webs in river networks. Longitudinal (downstream) gradients in productivity, disturbance regimes, and habitat structure exert strong effects on the organisms and energy sources of river food webs, but their effects on species interactions are just beginning to be explored. In fluid ecosystems with less obvious physical structure, like the open ocean, discerning features that control the movement of organisms and affect food web dynamics is even more challenging. In both habitats, new sensing, tracing and mapping technologies have revealed how landscape or seascape features (e.g., watershed divides, ocean fronts or circulation cells) channel, contain or concentrate organisms, energy and materials. Field experiments and direct in situ observations of basic natural history, however, remain as vital as ever in interpreting the responses of biota to these features. We need field data that quantify the many spatial and temporal scales of functional relationships that link environments, fluxes and food web interactions to understand how they will respond to intensifying anthropogenic forcing over the coming decades.

Power, M.E., W.E. Dietrich, and J.C. Finlay, 1996. Dams and downstream aquatic biodiversity: Potential food web consequences of hydrologic and geomorphic change. *Environmental Management* 20, 887–895.

Abstract: Responses of rivers and river ecosystems to dams are complex and varied, as they depend on local sediment supplies, geomorphic constraints, climate, dam structure and operation, and key attributes of the biota. Therefore, "one-size-fits-all" prescriptions cannot substitute for local knowledge in developing prescriptions for dam structure and operation to protect local biodiversity. One general principle is self-evident: that biodiversity is best protected in rivers where physical regimes are the most natural. A sufficiently natural regime of flow variation is particularly crucial for river biota and food webs. We review our research and

that of others to illustrate the ecological importance of alternating periods of low and high flow, of periodic bed scour, and of floodplain inundation and dewatering. These fluctuations regulate both the life cycles of river biota and species interactions in the food webs that sustain them. Even if the focus of biodiversity conservation efforts is on a target species rather than whole ecosystems, a food web perspective is necessary, because populations of any species depend critically on how their resources, prey, and potential predators also respond to environmental change. In regulated rivers, managers must determine how the frequency, magnitude, and timing of hydrologic events interact to constrain or support species and food webs. Simple ecological modeling, tailored to local systems, may provide a framework and some insight into explaining ecosystem response to dams and should give direction to mitigation efforts.

Prowse, T., K. Alfredsen, S. Beltaos, B.R. Bonsal, W.B. Bowden, C.R. Duguay, A. Korhola, J. McNamara, W.F. Vincent, V. Vuglinsky, K.M.W. Anthony, and G.A. Weyhenmeyer, 2011. Effects of Changes in Arctic Lake and River Ice. *AMBIO* 40, 63–74.

Abstract: Climatic changes to freshwater ice in the Arctic are projected to produce a variety of effects on hydrologic, ecological, and socio-economic systems. Key hydrologic impacts include changes to low flows, lake evaporation regimes and water levels, and river-ice break-up severity and timing. The latter are of particular concern because of their effect on river geomorphology, vegetation, sediment and nutrient fluxes, and sustainment of riparian aquatic habitats. Changes in ice phenology will affect a wide range of related biological aspects of seasonality. Some changes are likely to be gradual, but others could be more abrupt as systems cross critical ecological thresholds. Transportation and hydroelectric production are two of the socio-economic sectors most vulnerable to change in freshwater-ice regimes. Ice roads will require expensive on-land replacements while hydroelectric operations will both benefit and be challenged. The ability to undertake some traditional harvesting methods will also be affected.

Prowse, T.D., and S. Beltaos, 2002. Climatic control of river-ice hydrology: a review. *Hydrological Processes* 16, 805–822.

Abstract: Ice is present during a part of the year on many rivers of cold, and even temperate, regions of the globe. Though largely ignored in hydrological literature, river ice has serious hydrologic impacts, including extreme flood events caused by ice jams, interference with transportation and energy production, low winter flows and associated ecological and water quality consequences. It is also a major factor in the life cycle of many aquatic and other species, being both beneficial and destructive, depending on location and time of year. A brief review of the hydrologic aspects of river ice shows strong climatic links and illustrates the sensitivity of the entire ice regime to changes in climatic conditions. To date, this sensitivity has only partly been documented: the vast majority of related studies have focused on the timing of freeze-up and break-up over the past century, and indicate trends that are consistent with concomitant changes in air temperature. It is only in the past few years that attention has been paid to the more complex, and practically more important, question of what climatic change may do to the frequency and severity of extreme ice jams, floods and low flows. The probable changes to the ice regime of rivers, and associated hydrological processes and impacts, are discussed in the light of current understanding.

Prowse, T.D., and F.M. Conly, 1998. Effects of climatic variability and flow regulation on ice-jam flooding of a northern delta. *Hydrological Processes* 12, 1589–1610.

Abstract: Ice-induced backwater has been shown to be the only method by which flooding has supplied water to perched basins within the Peace-Athabasca Delta, one of the world's largest freshwater deltas. The frequency of such events, however, markedly declined in the mid-1970s. To explain this shift, various hydrometeorological conditions that control the severity of river ice break-up were analysed. Specific emphasis was placed on the roles of flow regulation and climate variability. Flow regulation seems to have produced only minor changes in factors such as ice thickness and strength, and not to have reduced the flow at the time of break-up. Moreover, regulation has actually led to an increase in spring flow originating from the headwater region. Since the mid-1970s, however, spring runoff has declined in the downstream portions of the basin unaffected by regulation. This has been linked to a decrease in the magnitude of the winter snowpack. Elevated ice levels and winter flows resulting from regulation have further reduced the potential of tributary runoff to produce severe break-up floods. Thus the absence of a high-order event between 1974 and 1992 seems to be related to a combined effect of flow regulation and the vagaries of climate.

Prowse, T.D., and J.M. Culp, 2003. Ice breakup: a neglected factor in river ecology : River ice engineering. *Canadian Journal of Civil Engineering* 30, 128–144.

Abstract: To minimize environmental impacts that may result from any engineered modifications of stream or river systems, a basic understanding of river ecology is required. Most fundamental theories of river ecology have developed largely from studies of warm-temperate and tropical streams and rivers. As these theories evolved over the last few decades, floods were recognized increasingly as dominant hydrologic events that control numerous abiotic and biotic forms and processes, both within the channel and on the adjacent riparian floodplains. Over approximately the same time frame, river-ice breakup was shown to be a major, if not predominant, source of floods on cold-regions rivers. Despite this, rarely has the role of ice-induced flooding been considered by subsequent modifications to the original theories or in the extensive studies and literature that they spawned. This manuscript reviews the broad, although frequently anecdotal, information about the abiotic and biotic effects of breakup processes and flooding. Based on this, it argues for breakup to be incorporated in future advancements of river ecological theory. The extensive list of cited studies provides a valuable reference source for scientists and engineers assessing development-related impacts on cold-regions streams and rivers, or further researching ecological aspects of river-ice breakup.

Quinn, T.P., 2011. *The Behavior and Ecology of Pacific Salmon and Trout*. UBC Press. 378pp.

Abstract: A contemporary review of salmon behavior and ecology with focus on Alaskan populations.

Quinn, T.P., and A.H., Dittman, 1990. Pacific salmon migrations and homing: mechanisms and adaptive significance. *Trends in Ecology & Evolution* 5, 174–177.

Abstract: Pacific salmon are noted for their lengthy foraging migrations and for their precise homing ability. Extensive sampling has documented the general migratory patterns of the major populations, but many basic aspects of their marine ecology are still poorly understood. Their life history pattern has been interpreted as an adaptation to exploit the higher productivity of the marine environment over that in fresh water. The adaptive significance of homing is implied by the specializations of populations for their natal habitat and the competitive superiority of locally adapted populations over transplants from other rivers. However, the establishment of new populations by strays and the levels of gene flow between natural populations have only recently received much attention. Research on salmon migrations has also focused on the mechanisms that guide homing at sea and in fresh water. While salmon have highly developed sensory systems, the ways in which inputs are integrated to guide migration through diverse and complex habitats are still being investigated.

R2 Resource Consultants, 2013a. *Instream Flow Planning Study Summary Review of Susitna River Aquatic and Instream Flow Studies Conducted in the 1980s with Relevance to Proposed Susitna – Watana Dam Project – 2012: A Compendium of Technical Memoranda*. Susitna-Watana Hydroelectric Project (FERC No. 14241). Alaska Energy Authority.

Abstract: A summary of previous work related to instream flow planning. Includes six technical memoranda: Technical Memorandum 1 – River Stratification and Study Site Selection Process: 1980s Studies and 2013-2014 Studies – discusses the study site selection process applied during the 1980s studies that allows for a comparison with the process proposed for the 2013-2014 studies. Technical Memorandum 2 – Summary of Fish Distribution and Abundance Studies Conducted during the 1980s Su-Hydro Project – summarizes the methods used and study sites sampled for evaluating fish distributions in the Susitna River in the 1980s. This TM does not have a corollary section for the 2013-2014 studies since there are 12 separate fish related studies proposed for 2013-2014 (see RSP Sections 9.5 through 9.16). Technical Memorandum 3 – Selection of Target Species and Development of Species Periodicity Information: 1980s Studies and 2013-2014 Studies – summarizes the data and information that was collected in the 1980s that was used in identifying target species and developing species periodicities, and provides a general overview of the approach for developing this information in the 2013-2014 studies. Technical Memorandum 4– Development of Habitat Suitability Curves and Habitat Utilization Information: 1980s Studies and 2013-2014 Studies – describes methods used for collecting HSC data in the 1980s and provides a listing of HSC curves that were developed; the TM also provides an overview of the approach for developing this information in the 2013-2014 studies. Technical Memorandum 5 – Review of Habitat Modeling Methods: 1980s Studies and 2013-2014 Studies – describes the different instream flow related methods that were applied during the 1980s studies and provides an overview of the approaches that will be applied in the 2013-2014 studies. Technical Memorandum 6 – Biologically Relevant and Flow Dependent Physical Processes: 1980s Studies and 2013-2014 Studies – discusses various physical processes that were considered biologically relevant during the 1980s studies and that are linked to surface flow conditions; these processes are also briefly discussed relative to the 2013- 2014 studies.

R2 Resource Consultants, 2013b. *Riparian Physical Process Modeling*. Technical Memorandum. Susitna-Watana Hydroelectric Project (FERC No. 14241). Alaska Energy Authority.

Abstract: This technical memorandum provides a summary overview of the various climatic, seed dispersal, ice process, geomorphologic, and groundwater physical process modeling studies conducted in support of the Riparian Instream Flow Study.

R2 Resource Consultants, 2013c. S*ynthesis of Existing Fish Population Data*. Susitna-Watana Hydroelectric Project (FERC No. 14241). Alaska Energy Authority.

Abstract: The objective of this technical memorandum (TM) is to summarize the available contemporary and historical fish and aquatic studies to support the development and implementation of studies needed to understand the potential effects of the proposed Susitna-Watana Hydroelectric Project. The summary is focused on the studies conducted by the Alaska Department of Fish and Game and Trihey and Associates during the 1980s as part of the Susitna-Hydroelectric Aquatics Studies Program.

R2 Resource Consultants, GW Scientific, Brailey Hydrologic, and Geovera, 2013. *Attachment A. Open Water HEC-RAS Flow Routing Model*. Susitna-Watana Hydroelectric Project (FERC No. 14241). Alaska Energy Authority.

Abstract: In an effort to meet multiple resource interests, available resources under existing conditions will be analyzed in comparison to alternative operational scenarios. To analyze the impacts of alternative Project operational scenarios on habitats downstream of the Watana Dam site, an open-water flow routing model will be used to translate the effects of changes in flow associated with Project operations to downstream Susitna River locations.

Ramstad, K.M., C.A. Woody, and F.W. Allendorf, F.W., 2009. Recent local adaptation of sockeye salmon to glacial spawning habitats. *Evolutionary Ecology* 24, 391–411.

Abstract: Salmonids spawn in highly diverse habitats, exhibit strong genetic population structuring, and can quickly colonize newly created habitats with few founders. Spawning traits

often differ among populations, but it is largely unknown if these differences are adaptive or due to genetic drift. To test if sockeye salmon (*Oncorhynchus nerka*) populations are adapted to glacial, beach, and tributary spawning habitats, we examined variation in heritable phenotypic traits associated with spawning in 13 populations of wild sockeye salmon in Lake Clark, Alaska. These populations were commonly founded between 100 and 400 hundred sockeye salmon generations ago and exhibit low genetic divergence at 11 microsatellite loci (FST < 0.024) that is uncorrelated with spawning habitat type. We found that mean PST (phenotypic divergence among populations) exceeded neutral FST for most phenotypic traits measured, indicating that phenotypic differences among populations could not be explained by genetic drift alone. Phenotypic divergence among populations was associated with spawning habitat differences, but not with neutral genetic divergence. For example, female body color was lighter and egg color was darker in glacial than non-glacial habitats. This may be due to reduced sexual selection for red spawning color in glacial habitats and an apparent trade-off in carotenoid allocation to body and egg color in females. Phenotypic plasticity is an unlikely source of phenotypic differences because Lake Clark sockeye salmon spend nearly all their lives in a common environment. Our data suggest that Lake Clark sockeye salmon populations are adapted to spawning in glacial, beach and tributary habitats and provide the first evidence of a glacial spawning ecotype in salmonids. Glacial spawning habitats are often young (i.e., <200 years old) and ephemeral. Thus, local adaptation of sockeye salmon to glacial habitats appears to have occurred recently.

Regetz, J., 2003. Landscape-level constraints on recruitment of Chinook salmon (*Oncorhynchus tshawytscha*) in the Columbia River basin, USA. *Aquatic Conservation: Marine and Freshwater Ecosystems* 13, 35–49.

Abstract: 1. The decline of salmonid populations in the Pacific Northwest has been well-documented. It is unclear, however, which threats to salmonid persistence are the most serious, and how best to prioritize recovery efforts intended to ameliorate these threats. 2. It has been argued previously that one possible cause of salmon endangerment is degradation of spawning grounds. In order to explore this hypothesis, this study examines the relationships between Chinook salmon (*Oncorhynchus tshawytscha*) productivity and landscape-level characteristics of spawning grounds in the interior Columbia River Basin. 3. Population productivity is expressed as the mean and maximum recruitment rates for different stocks, measured from 1980 to 1990; habitat conditions are calculated using sub-watershed scale data on land cover, land use, water quality and watershed hydrology. 4. Significant linear regression results were obtained for three environmental variables: percentage of land classified as urban, proportion of stream length failing to meet water quality standards, and an index of the ability of streams to recover from sediment flow events. A multiple regression with all three variables accounts for over 60% of the variation in mean salmon recruitment. 5. It further appears that these landscape attributes may limit the maximum recruitment rates of salmon, with a magnitude of difference in productivity large enough to be relevant to recovery planners. Additional study will be necessary to identify cause-and-effect linkages between habitat quality and salmon recruitment success, and to

determine the ultimate impact of changes in recruitment rates on short- and long-term salmon population trajectories.

Richter, A., and S. Kolmes, 2005. Maximum Temperature Limits for Chinook, Coho, and Chum Salmon, and Steelhead Trout in the Pacific Northwest. *Reviews in Fisheries Science* 13, 23–49.

Abstract: Wild salmon stocks in the Pacific Northwest are imperiled by a variety of anthropogenic environmental modifications, not the least of which is increasing maximum water temperatures. While many reports have been written on physiological or population-level influences of temperature in terms of the decline of wild salmon, synthesis of these diverse sources is needed for evaluation of numeric temperature criteria and their potential in salmon recovery planning. Various sensitive life stages and biological processes are impacted differently for different salmon species. This article reviews the literature for Chinook, coho, chum, and steelhead, which are currently listed in the Columbia River Basin under the Endangered Species Act. Spawning, incubation and early fry development, juvenile rearing and growth, smoltification, and migration are considered. Swimming speed, disease susceptibility, chemical considerations, and lethality are also reviewed. Regional population growth and climate change will exacerbate the difficulties of recovering Northwestern salmon beyond remnant runs. Ethical analysis of the assumptions underlying recovery policy decisions, proposals for regime-based water quality standards, and a systems level vulnerability analysis are components of the recovery planning discussions. Specific numeric maximum temperature criteria that can be integrated into a broader recovery planning process are described for sensitive life stages of three species of Pacific Northwest salmon and steelhead.

Riis, J.C., and N.V. Friese, 1977. *Fisheries and Habitat Investigations of the Susitna River - A Preliminary Study of Potential Impacts of the Devils Canyon and Watana Hydroelectric Projects*. Alaska Department of Fish and Game, Divisions of Sport and Commercial Fish, Anchorage, AK.

Abstract: A preliminary analysis of the anticipated impact of the historic Project proposal on fish populations.

Rogers, L.A., D.E. Schindler, P.J. Lisi, G.W. Holtgrieve, P.R. Leavitt, L. Bunting, B.P. Finney, D.T. Selbie, G. Chen, I. Gregory-Eaves, M.J. Lisac, and P.B. Walsh, 2013. Centennial-scale fluctuations and regional complexity characterize Pacific salmon population dynamics over the past five centuries. *PNAS* 110, 1750–1755.

Abstract: Observational data from the past century have highlighted the importance of interdecadal modes of variability in fish population dynamics, but how these patterns of variation fit into a broader temporal and spatial context remains largely unknown. We analyzed

time series of stable nitrogen isotopes from the sediments of 20 sockeye salmon nursery lakes across western Alaska to characterize temporal and spatial patterns in salmon abundance over the past ~500 y. Although some stocks varied on interdecadal time scales (30- to 80-y cycles), centennial-scale variation, undetectable in modern-day catch records and survey data, has dominated salmon population dynamics over the past 500 y. Before 1900, variation in abundance was clearly not synchronous among stocks, and the only temporal signal common to lake sediment records from this region was the onset of commercial fishing in the late 1800s. Thus, historical changes in climate did not synchronize stock dynamics over centennial time scales, emphasizing that ecosystem complexity can produce a diversity of ecological responses to regional climate forcing. Our results show that marine fish populations may alternate between naturally driven periods of high and low abundance over time scales of decades to centuries and suggest that management models that assume time-invariant productivity or carrying capacity parameters may be poor representations of the biological reality in these systems

Rood, S.B., J.H. Braatne, and F.M. Hughes, 2003. Ecophysiology of riparian cottonwoods: stream flow dependency, water relations and restoration. *Tree Physiology* 23, 1113–1124.

Abstract: Cottonwoods (Populus spp.) are adapted to riparian or floodplain zones throughout the Northern Hemisphere; they are also used as parents for fast-growing hybrid poplars. We review recent ecophysiological studies of the native cottonwoods Populus angustifolia James, P. balsamifera L., P. deltoides Marsh., P. fremontii S. Watson and P. trichocarpa T. & G. in North America, and P. nigra L. in Europe. Variation exists within and across species and hybrids; however, all riparian cottonwoods are dependent on shallow alluvial groundwater that is linked to stream water, particularly in semi-arid regions. This conclusion is based on studies of their natural occurrence, decline following river damming and dewatering (water removal), water relations, isotopic composition of xylem water, and by the establishment of cottonwoods along formerly barren natural channels after flow augmentation in response to the conveyance of irrigation water. When alluvial groundwater is depleted as a result of river dewatering or groundwater pumping, riparian cottonwoods exhibit drought-stress responses including stomatal closure and reduced transpiration and photosynthesis, altered 13C composition, reduced predawn and midday water potentials, and xylem cavitation. These physiological responses are accompanied by morphological responses including reduced shoot growth, altered root growth, branch sacrifice and crown die-back. In severe cases, mortality occurs. For example, severe dewatering of channels of the braided Big Lost River in Idaho led to mortality of the narrow-leaf cottonwood, P. angustifolia, and adjacent sandbar willows, Salix exigua Nutt., within 5 years, whereas riparian woodlands thrived along flowing channels nearby. The conservation and restoration of cottonwoods will rely on the provision of river flow regimes that satisfy these ecophysiological requirements for survival, growth and reproduction.

Rood, S.B., L.A. Goater, J.M. Mahoney, C.M. Pearce, and D.G. Smith, 2007. Floods, fire, and ice: disturbance ecology of riparian cottonwoods. Special Issue on Poplar Research in Canada. *Canadian Journal of Botany* 85, 1019–1032.

Abstract: Cottonwoods are poplar trees that are well adapted to dynamic riparian, or streamside, zones throughout the Northern Hemisphere. Here we assess the influences of three prominent physical disturbances, floods, fire, and ice, on cottonwood population ecology. We emphasize cottonwoods along rivers from the "Crown of the Continent", the central Rocky Mountain zone around the Canada – United States border, where five Populus species overlap and four hybridize. Moderate to major floods scour banks and deposit bars, creating barren and moist colonization sites that are essential for cottonwood seedling recruitment. Floods also scarify shallow roots, thus promoting clonal suckering, especially for the section Tacamahaca species: narrowleaf cottonwood (Populus angustifolia James), balsam poplar (Populus balsamifera L.), and black cottonwood (Populus trichocarpa Torr. & A. Gray). Fire would naturally be less frequent in some riparian zones because of the moist conditions and firebreaks provided by the streams.

Rørslett, B., M. Mjelde, and S.W. Johansen, 1989. Effects of hydropower development on aquatic macrophytes in norwegian rivers: Present state of knowledge and some case studies. *Regulated Rivers: Research & Management* 3, 19–28.

Abstract: A multitude of Norwegian rivers are managed for generating hydroelectric power (HEP). The hydrology of these hydrorivers changes in various ways which reflect the implemented HEP schemes. Increased winter flows and a concomitant lack of ice-cover are features found downstream of power installations on many Norwegian hydrorivers.
Our study objectives were (1) to assess the changes in aquatic macrophyte abundance subsequent to HEP development; and (2) to evaluate the environmental conditions under which nuisance growths of macrophytes are likely to occur. Towards these ends, Norwegian literature data were compiled and assessed. Some case studies are outlined showing the variety of situations under which prolific growths of macrophytes might result. Unfortunately, available data on macrophyte-associated problems proved deficient in many respects. This occurred chiefly because most macrophyte studies are conducted either before, or after, an HEP scheme is completed. Evidently, no concerted efforts are made for assessing the likelihood of macrophyte-dominated nuisance growth in the planning stage of a Norwegian HEP scheme.

Rosenfeld, J.S., and S. Boss, 2001. Fitness consequences of habitat use for juvenile cutthroat trout: energetic costs and benefits in pools and riffles. *Canadian Journal of Fisheries and Aquatic Sciences* 58, 585–593.

Abstract: To assess freshwater habitat requirements of juvenile anadromous cutthroat trout, *Oncorhynchus clarki*, we measured habitat preference and growth rates of young-of-the-year (YOY) and 1- to 2-year-old fish confined to either pools or riffles in Husdon Creek, British

Columbia, during 1999. YOY preferred pools to riffles in habitat-preference experiments, despite normally occurring at lower densities in pools. YOY grew in both pools and riffles when experimentally confined to either habitat, but growth rates were higher in pools. Larger juvenile cutthroat trout, on average, grew in pools, but consistently lost weight in riffles, indicating that pools are a habitat preference for YOY but a requirement for larger fish. A bioenergetic cost–benefit analysis (based on swimming costs and energy intake from invertebrate drift) indicates that energetics alone are sufficient to account for avoidance of riffles by larger cutthroat trout, without having to invoke greater predation risk in shallow habitats. Energetics modeling demonstrates that the smaller size and energetic needs of YOY allow exploitation of habitats (e.g., pocket pools in riffles) that are unavailable to larger fish.

Roth, K.J., D.C. Gray, J.W. Anderson, A.C. Blaney, and J.P. McDonnell, 1986. *The Migration and Growth of Juvenile Salmon in the Susitna River, 1985*. Prepared by Alaska Department of Fish and Game, Susitna Hydro Aquatics Studies. Prepared for Alaska Power Authority Anchorage, Alaska. 130 pp.

Abstract: An examination of early life history behavior and growth of salmonids in the Susitna River.

Roussel, J.M., R.A. Cunjak, R. Newbury, D. Caissie, and A. Haro, 2004. Movements and habitat use by PIT-tagged Atlantic salmon parr in early winter: the influence of anchor ice. *Freshwater Biology* 49, 1026–1035.

Abstract: 1. Movements and habitat use by Atlantic salmon parr in Catamaran Brook, New Brunswick, were studied using Passive Integrated Transponder technology. The fish were tagged in the summer of 1999, and a portable reading system was used to collect data on individual positions within a riffle-pool sequence in the early winter of 1999. Two major freezing events occurred on November 11–12 (Ice 1) and November 18–19 (Ice 2) that generated significant accumulations of anchor ice in the riffle.
2. Individually tagged parr (fork length 8.4–12.6 cm, n = 15) were tracked from 8 to 24 November 1999. Over this period, emigration (40%) was higher from the pool than from the riffle. Of the nine parr that were consistently located, seven parr moved <5 m up- or downstream, and two parr moved more than 10 m (maximum 23 m). Parr moved significantly more by night than by day, and diel habitat shifts were more pronounced in the pool with some of the fish moving closer to the bank at night.
3. During Ice 2, there was relatively little movement by most of the parr in the riffle beneath anchor ice up to 10 cm in thickness. Water temperature was 0.16 °C above the freezing point beneath anchor ice, suggesting the existence of suitable habitats where salmon parr can avoid supercooling conditions and where they can have access to low velocity shelters. To our knowledge, these are the first data on habitat use by Atlantic salmon parr under anchor ice.

Ryan, B.A., E.M. Dawley, and R.A. Nelson, 2000. Modeling the Effects of Supersaturated Dissolved Gas on Resident Aquatic Biota in the Main-Stem Snake and Columbia Rivers. *North American Journal of Fisheries Management* 20, 192–204.

Abstract: Dissolved-gas levels in the Columbia and Snake rivers during the spring freshet often exceed 110% of saturation, the maximum level permitted by the U.S. Environmental Protection Agency. The highest levels of supersaturation result from high springtime river flows and turbine outages, conditions over which there is little control and that cause high volumes of water passing over the dams and through spillways instead of through turbines. During the spring freshets of 1994–1997, we surveyed nonsalmonid fishes and invertebrates for signs of gas bubble disease (GBD) and conducted holding experiments in three river reaches where gas saturation commonly exceeds 120%. We developed a dissolved-gas exposure index for nonsalmonid fishes sampled at specific times and locations; mean daily total dissolved-gas saturation (TDGS) was ranked and then summed over a 7-d period. We analyzed observations of 39,924 nonsalmonid fishes in an iterative process, which led to development of a mathematical equivalence model for TDGS duration and level of exposure that was strongly correlated with prevalence of GBD signs (R2 5 0.79). We believe this simple model is a reliable predictor of external GBD signs resulting from prolonged exposure to supersaturated dissolved gas in the Columbia and Snake rivers. When TDGS levels were below 120%, GBD signs in fish were rare; when TDGS levels exceeded 120%, the model reliably predicted the extent to which fish displayed external GBD signs. In addition, we attempted to evaluate GBD-related mortality over the 4 years of net-pen holding experiments. However, due to the high variability we observed in these evaluations and the paucity of dead fish recovered from these rivers, we concluded that an accurate model relating TDGS to mortality could not be developed using these methods.

Salo, E.O., 1991. Life History of Chum Salmon. In: *Pacific Salmon Life Histories*. UBC Press, pp. 231–310.

Abstract: A comprehensive review of the life history and habitat attributes of chum salmon.

Sandercock, F.K., 1991. Life History of Coho Salmon. In: *Pacific Salmon Life Histories*. UBC Press, pp. 395–446.

Abstract: A comprehensive review of the life history and habitat attributes of coho salmon.

Scheuerell, M.D., R. Hilborn, M.H. Ruckelshaus, K.K. Bartz, K.M. Lagueux, A.D. Haas, and K. Rawson, 2006. The Shiraz model : a tool for incorporating anthropogenic effects and fish-habitat relationships in conservation planning. *Canadian Journal of Fisheries and Aquatic Sciences* 63, 1596–1607.

Abstract: Current efforts to conserve Pacific salmon (*Oncorhynchus* spp.) rely on a variety of information sources, including empirical observations, expert opinion, and models. Here we

outline a framework for incorporating detailed information on density-dependent population growth, habitat attributes, hatchery operations, and harvest management into conservation planning in a time-varying, spatially explicit manner. We rely on a multistage Beverton–Holt model to describe the production of salmon from one life stage to the next. We use information from the literature to construct relationships between the physical environment and the necessary productivity and capacity parameters for the model. As an example of how policy makers can use the model in recovery planning, we applied the model to a threatened population of Chinook salmon (*Oncorhynchus tshawytscha*) in the Snohomish River basin in Puget Sound, Washington, USA. By incorporating additional data on hatchery operations and harvest management for Snohomish River basin stocks, we show how proposed actions to improve physical habitat throughout the basin translate into projected improvements in four important population attributes: abundance, productivity, spatial structure, and life-history diversity. We also describe how to adapt the model to a variety of other management applications.

Scheuerell, M.D., P.S. Levin, R.W. Zabel, J.G. Williams, and B.L. Sanderson, 2005. A new perspective on the importance of marine-derived nutrients to threatened stocks of Pacific salmon (*Oncorhynchus* spp.). *Canadian Journal of Fisheries and Aquatic Sciences* 62, 961–964.

Abstract: Considerable research has highlighted the important role of anadromous salmon in importing marine-derived nutrients to freshwater and riparian ecosystems. These subsidies are thought to support diverse food webs and increase the growth and survival of juvenile salmon during their freshwater residency. Quite recently, however, salmon smolts have been identified as important exporters of nutrients from freshwater ecosystems. Using a mass-balance approach, we examined the phosphorus-transport dynamics by spring/summer Chinook salmon (*Oncorhynchus tshawytscha*) in the Snake River basin and estimated that net phosphorus transport into the basin over the past 40 years was <2% of historical levels. Furthermore, a nonlinear relationship existed between nutrient import by adults and subsequent export by smolts, such that smolts exported proportionally more phosphorus as spawner abundance decreased. In 12% of years, smolts exported more than adults imported, resulting in a net loss of phosphorus from the ecosystem. This loss of marine subsidies may have caused a state shift in the productivity of the freshwater ecosystem, resulting in strong density-dependent survival observed in juvenile salmon. These results suggest that conserving this threatened stock of salmon requires the need to explicitly address the important role of marine-derived nutrients and energy in sustaining salmon populations.

Schick, R.S., and S.T. Lindley, 2007. Directed connectivity among fish populations in a riverine network. *Journal of Applied Ecology* 44, 1116–1126.

Abstract: 1. The addition of large water storage dams to rivers in California's Central Valley blocked access to spawning habitat and has resulted in a dramatic decline in the distribution and

abundance of spring-run Chinook salmon *Oncorhynchus tshawytscha* (Walbaum 1792). Successful recovery efforts depend on an understanding of the historical spatial structure of these populations, which heretofore has been lacking.
2. Graph theory was used to examine the spatial structure and demographic connectivity of riverine populations of spring-run Chinook salmon. Standard graph theoretic measures, including degree, edge weight and node strength, were used to uncover the role of individual populations in this network, i.e. which populations were sources and which were pseudo-sinks.
3. Larger spatially proximate populations, most notably the Pit River, served as sources in the historic graph. These source populations in the graph were marked by an increased number of stronger outbound connections (edges), and on average had few inbound connections. Of the edges in the current graph, seven of them were outbound from a population supported by a hatchery in the Feather River, which suggests a strong influence of the hatchery on the structure of the current extant populations.
4. We tested how the addition of water storage dams fragmented the graph over time by examining changing patterns in connectivity and demographic isolation of individual populations. Dams constructed in larger spatially proximate populations had a strong impact on the independence of remaining populations. Specifically, the addition of dams resulted in lost connections, weaker remaining connections and an increase in demographic isolation.
5. A simulation exercise that removed populations from the graph under different removal scenarios – random removal, removal by decreasing habitat size and removal by decreasing node strength – revealed a potential approach for restoration of these depleted populations.
6. Synthesis and applications. Spatial graphs are drawing the attention of ecologists and managers. Here we have used a directed graph to uncover the historical spatial structure of a threatened species, estimate the connectivity of the current populations, examine how the historical network of populations was fragmented over time and provide a plausible mechanism for ecologically successful restoration. The methods employed here can be applied broadly across taxa and systems, and afford scientists and managers a better understanding of the structure and function of impaired ecosystems.

Schindler, D.E., R. Hilborn, B. Chasco, C.P. Boatright, T.P. Quinn, L.A. Rogers, and M.S. Webster, 2010. Population diversity and the portfolio effect in an exploited species. *Nature* 465, 609–612.

Abstract: One of the most pervasive themes in ecology is that biological diversity stabilizes ecosystem processes and the services they provide to society, a concept that has become a common argument for biodiversity conservation. Species-rich communities are thought to produce more temporally stable ecosystem services because of the complementary or independent dynamics among species that perform similar ecosystem functions. Such variance dampening within communities is referred to as a portfolio effect and is analogous to the effects of asset diversity on the stability of financial portfolios. In ecology, these arguments have focused on the effects of species diversity on ecosystem stability but have not considered the importance of biologically relevant diversity within individual species. Current rates of

population extirpation are probably at least three orders of magnitude higher than species extinction rates, so there is a pressing need to clarify how population and life history diversity affect the performance of individual species in providing important ecosystem services. Here we use five decades of data from *Oncorhynchus nerka* (sockeye salmon) in Bristol Bay, Alaska, to provide the first quantification of portfolio effects that derive from population and life history diversity in an important and heavily exploited species. Variability in annual Bristol Bay salmon returns is 2.2 times lower than it would be if the system consisted of a single homogenous population rather than the several hundred discrete populations it currently consists of. Furthermore, if it were a single homogeneous population, such increased variability would lead to ten times more frequent fisheries closures. Portfolio effects are also evident in watershed food webs, where they stabilize and extend predator access to salmon resources. Our results demonstrate the critical importance of maintaining population diversity for stabilizing ecosystem services and securing the economies and livelihoods that depend on them. The reliability of ecosystem services will erode faster than indicated by species loss alone.

Schindler, D.E., D.E. Rogers, M.D. Scheuerell, and C.A. Abrey, 2005. Effects of Changing Climate on Zooplankton and Juvenile Sockeye Salmon Growth in Southwestern Alaska. *Ecology* 86, 198–209.

Abstract: Detecting and forecasting the effects of changing climate on natural and exploited populations represent a major challenge to ecologists and resource managers. These efforts are complicated by underlying density-dependent processes and the differential responses of predators and their prey to changing climate. We explored the effects of density-dependence and changing climate on growth of juvenile sockeye salmon and the densities of their zooplankton prey in the Wood River system of southwestern Alaska. We fit dynamic time-series models to data collected between 1962 and 2002 describing growth of juvenile sockeye, timing of spring ice breakup, and summer zooplankton densities. The timing of spring breakup has moved about seven days earlier now than it was in the early 1960s. Our analyses suggest that most of this shift has been a response to the warm phase of the Pacific Decadal Oscillation that persisted from the mid-1970s to the late 1990s. This progression toward earlier spring breakup dates was associated with warmer summer water temperatures and increased zooplankton (especially Daphnia) densities, which translated into increased sockeye growth during their first year of life. The number of spawning adults that produced each year class of sockeye had a strong negative effect on juvenile sockeye growth rates, so that the size of the density-dependent effect was, on average, twice as large as the effect of spring breakup date. These results highlight the complexity of ecological responses to changing climate and suggest that climate warming may enhance growing conditions for juvenile salmonids in large lakes of Alaska.

Schindler, D.E., M.D. Scheuerell, J.W. Moore, S.M. Gende, T.B. Francis, and W.J. Palen, 2003. Pacific salmon and the ecology of coastal ecosystems. Frontiers in Ecology and the Environment 1, 31–37.

Abstract: One of the most spectacular phenomena in nature is the annual return of millions of salmon to spawn in their natal streams and lakes along the Pacific coast of North America. The salmon die after spawning, and the nutrients and energy in their bodies, derived almost entirely from marine sources, are deposited in the freshwater ecosystems. This represents a vital input to the ecosystems used as spawning grounds. Salmon-derived nutrients make up a substantial fraction of the plants and animals in aquatic and terrestrial habitats associated with healthy salmon populations. The decline of salmon numbers throughout much of their southern range in North America has prompted concern that the elimination of this "conveyor belt" of nutrients and energy may fundamentally change the productivity of these coastal freshwater and terrestrial ecosystems, and consequently their ability to support wildlife, including salmon. If progress is to be made towards understanding and conserving the connection between migratory salmon and coastal ecosystems, scientists and decision-makers must explore and understand the vast temporal and spatial scales that characterize this relationship.

Schindler, D.W., 2001. The cumulative effects of climate warming and other human stresses on Canadian freshwaters in the new millennium. *Canadian Journal of Fisheries and Aquatic Sciences* 58, 18–29.

Abstract: Climate warming will adversely affect Canadian water quality and water quantity. The magnitude and timing of river flows and lake levels and water renewal times will change. In many regions, wetlands will disappear and water tables will decline. Habitats for cold stenothermic organisms will be reduced in small lakes. Warmer temperatures will affect fish migrations in some regions. Climate will interact with overexploitation, dams and diversions, habitat destruction, non-native species, and pollution to destroy native freshwater fisheries. Acute water problems in the United States and other parts of the world will threaten Canadian water security. Aquatic communities will be restructured as the result of changes to competition, changing life cycles of many organisms, and the invasions of many non-native species. Decreased water renewal will increase eutrophication and enhance many biogeochemical processes. In poorly buffered lakes and streams, climate warming will exacerbate the effects of acid precipitation. Decreases in dissolved organic carbon caused by climate warming and acidification will cause increased penetration of ultraviolet radiation in freshwaters. Increasing industrial agriculture and human populations will require more sophisticated and costly water and sewage treatment. Increased research and a national water strategy offer the only hope for preventing a freshwater crisis in Canada.

Schmidt, D., and A. Bingham, 1983. *Synopsis of the 1982 Aquatic Studies and Analysis of Fish and Habitat Relationships*. Alaska Department of Fish and Game, Susitna Hydro Aquatic Studies, Anchorage, Alaska. 185 pp.

Abstract: A summary of historic sampling efforts conducted in the 1980s by ADF&G to support the evaluation of the proposed project.

Schmidt, D., S.S. Hale, D.L. Crawford, and P.M. Suchanek, 1984. *Resident and juvenile anadromous fish investigations (May - October 1983)*. Prepared for the Alaska Power Authority. Alaska Department of Fish and Game Susitna Hydro Aquatic Studies Anchorage, Alaska. 458 pp.

Abstract: Includes seven chapters covering: 1) The Outmigration of Juvenile Salmon from the Susitna River above the Chulitna River Confluence; 2) The Distribution and Relative Abundance of Juvenile Salmon in the Susitna River Drainage Above the Chulitna River Confluence; 3) Juvenile Salmon Rearing Suitability Criteria; 4) Juvenile Salmon Rearing Habitat Model; 5) Resident Fish Distribution and Population Dynamics in the Susitna River Below Devil Canyon; 6) Resident Fish Habitat Studies; and 7) Modelling of Juvenile Salmon and Resident Fish Habitat.

Scott, M.L., J.M. Friedman, and G.T. Auble, 1996. Fluvial process and the establishment of bottomland trees. *Geomorphology* 14, 327–339.

Abstract: The effects of river regulation on bottomland tree communities in western North America have generated substantial concern because of the important habitat and aesthetic values of these communities. Consideration of such effects in water management decisions has been hampered by the apparent variability of responses of bottomland tree communities to flow alteration. When the relation between streamflow and tree establishment is placed in a geomorphic context, however, much of that variability is explained, and prediction of changes in the tree community is improved.
The relation between streamflow and establishment of bottomland trees is conditioned by the dominant fluvial process or processes acting along a stream. For successful establishment, cottonwoods, poplars, and willows require bare, moist surfaces protected from disturbance. Channel narrowing, channel meandering, and flood deposition promote different spatial and temporal patterns of establishment. During channel narrowing, the site requirements are met on portions of the bed abandoned by the stream, and establishment is associated with a period of low flow lasting one to several years. During channel meandering, the requirements are met on point bars following moderate or higher peak flows. Following flood deposition, the requirements are met on flood deposits ;high above the channel bed. Flood deposition can occur along most streams, but where a channel is constrained by a narrow valley, this process may be the only mechanism that can produce a bare, moist surface high enough to be safe from future disturbance. Because of differences in local bedrock, tributary influence, or geologic history, two nearby reaches of the same stream may be dominated by different fluvial processes

and have different spatial and temporal patterns of trees. We illustrate this phenomenon with examples from forests of plains cottonwood (Populus deltoides ssp. monilifera) along meandering and constrained reaches of the Missouri River in Montana.

Scrimgeour, G.J., T.D. Prowse, J.M. Culp, and P.A. Chambers, 1994. Ecological effects of river ice break-up: a review and perspective. *Freshwater Biology* 32, 261–275.

Abstract: 1. Abiotic disturbances strongly modify spatial and temporal patterns of lotic ecosystem community structure and function. Such effects are produced because disturbances alter organic matter, nutrient and contaminant dynamics and the distribution and abundance of bacterial, algal, macroinvertebrate and fish communities. 2. River ice break-up is a seasonal disturbance in rivers at high altitudes and latitudes world-wide and is characterized, in part, by large increases in current velocity, stage, water temperature, concentrations of suspended materials and substrate scouring. 3. These abiotic factors are likely to have important effects on primary producers, consumers, and food-web dynamics of river biota. Despite the potential importance of river ice break-up on community structure and function, detailed information describing the magnitude of their effects and underlying causal mechanisms is scarce. 4. The objective of this paper is to provide a hydrological and ecological review and perspective on the potential effects of ice break-up on lotic ecosystems. Specifically, the potential importance of break-up on water temperature, river sediments and geomorphology, riverine energy sources, contaminants, and its effects on river biota and food-web dynamics are evaluated.

Scruton, D.A., C.J. Pennell, M.J. Robertson, L.M.N. Ollerhead, K.D. Clarke, K. Alfredsen, A. Harby, and R.S. McKinley, 2005. Seasonal Response of Juvenile Atlantic Salmon to Experimental Hydropeaking Power Generation in Newfoundland, Canada. *North American Journal of Fisheries Management* 25, 964–974.

Abstract: Variable hydropower production leads to hydropeaking, which causes discharge fluctuations that are potentially harmful to aquatic organisms. In this study, an experimental approach was used to investigate hydropeaking effects and associated hydraulic and habitat conditions on the home range and movement of juvenile Atlantic salmon Salmo salar. Prior studies examined the responses of Atlantic salmon and brook trout Salvelinus fontinalis to experimental hydropeaking during summer and autumn. The present study focused on Atlantic salmon, involved more rapid and extreme discharge manipulation, and included winter experiments to reflect influences of reduced temperature, ice conditions, and seasonal differences in behavior and habitat selection. Experiments were conducted over a range in discharge (0.5–5.0 m3/s) that resulted in dramatic habitat changes in the wide, shallow, boulder-strewn study reach. Experiments were repeated in summer and winter; however, the winter range in discharge was narrower due to constraints on water release. Fish response was monitored using manual telemetry in both seasons, and fixed telemetry was used to monitor fine-scale diel winter movements. Atlantic salmon had larger home ranges and were more mobile during all flow conditions and over diel cycles in summer than in winter, and there was

anecdotal evidence of stranding in isolated pools in summer. Stream morphology, in addition to the magnitude of discharge change, was an important determinant of the propensity to move. In our study, there were considerable refugia from increased velocity and dewatering, which may have reduced the need to move. In winter, fish remained relatively sedentary in comparison with the summer foraging period, and this behavior may increase the likelihood for dewatering, stranding, and freezing. A secondary concern with hydropeaking regimes is the energetic cost to fish of moving to find suitable habitats, and during summer this cost could affect stored energy reserves, which could, in turn, affect overwinter survival.

Seiler, D., S. Neuhauser, and L. Kishimoto, 2003. *Annual Report 2003 Skagit River Wild 0+ Chinook Production Evaluation*.

Abstract: A description of the fisheries field data that is collected and used to inform and refine hydro-operations and flow management.

Servizi, J.A., and D.W. Martens, 1992. Sublethal responses of coho salmon (*Oncorhynchus kisutch*) to suspended sediments. *Canadian Journal of Fisheries and Aquatic Sciences* 49, 1389–1395.

Abstract: Underyearling coho salmon (*Oncorhynchus kisutch*) were exposed to sublethal concentrations of Fraser River suspended sediments (SS) in the laboratory. Comparisons with other rivers indicated that Fraser River sediments caused the lowest turbidity for a given SS value. Blood sugar levels (y) were elevated and directly proportional to SS exposure (x) according to y = 5.79 + 4.23(x). Published blood sugar data for adult sockeye salmon (O. nerka) exposed to Fraser River SS were in agreement with the linear relationship for underyearling coho. Cough frequency was elevated approximately eightfold over control levels at 0.24 g SS·L−1. No increase in cough frequency was observed at 0.02 g SS·L−1. Avoidance was defined by movement to the surface to escape higher SS at depth. Mean avoidance (y) was related to SS by y = 0.077+4.457(x) − 1.547(x2) + 0.202(x3). Mean avoidance was less than 5% up to the inflection point at 2.55g SS·L−1 but rose to approximately 25% at 7.0g SS·L−1. Laboratory results indicated that sublethal responses could be expected at naturally occurring SS levels in the Fraser River.

Sharma, R., A.B. Cooper, and R. Hilborn, 2005. A quantitative framework for the analysis of habitat and hatchery practices on Pacific salmon. *Ecological Modelling* 183, 231–250.

Abstract: We developed a model to capture the interaction of two factors (habitat and hatchery indicators) on salmon abundance, and provide a framework for evaluating alternative restoration actions for salmon in the northwestern United States, assuming specific ocean conditions and harvest rates. We modeled different hypothetical coho salmon population trajectories in Issaquah creek (King County, western Washington, USA) as a function of land-use change and hatchery supplementation. The model can be tailored to address individual problems, areas and questions.

She, Y., F. Hicks, and R. Andrishak, 2012. The role of hydro-peaking in freeze-up consolidation events on regulated rivers. *Cold Regions Science and Technology* 73, 41–49.

Abstract: Periods of rapid frazil production followed by sudden warming can instigate the consolidation of a developing river ice cover. Although empirical evidence suggests that hydro-peaking operations can also precipitate or exacerbate such events, little is actually known about the specific implications of hydro-peaking during ice cover development because, until recently, numerical ice process models could not simulate such events reliably. Nevertheless, given that fluctuating water levels can destabilize a fragile developing ice cover, resulting in a severe freeze-up ice jam and associated flooding, winter is typically a time of severely constrained flow-peaking operations for hydro-power facilities.
The Peace River in northern Alberta presents just such a case; the river has been regulated for hydro-power production since 1972 and numerous consolidation events have been documented along the river over the past few decades, including a particularly extreme event in January 1982. As a consequence of that event, voluntary flow controls have since been implemented each winter during the ice cover development period. In this study, recently developed hydrodynamic ice process modeling tools are used to diagnose such events in order to explore the relative importance of the causative factors and to facilitate a more comprehensive understanding of this phenomenon. Based on this analysis, it appears that meteorological factors may play an equally important role as hydro-peaking in precipitating ice cover consolidation events.

Sheer, M.B., and E.A. Steel, 2006. Lost Watersheds: Barriers, Aquatic Habitat Connectivity, and Salmon Persistence in the Willamette and Lower Columbia River Basins. *Transactions of the American Fisheries Society* 135, 1654–1669.

Abstract: Large portions of watersheds and streams are lost to anadromous fishes because of anthropogenic barriers to migration. The loss of these streams and rivers has shifted the distribution of accessible habitat, often reducing the diversity of accessible habitat and the quantity of high-quality habitat. We combined existing inventories of barriers to adult fish passage in the Willamette and Lower Columbia River basins and identified 1,491 anthropogenic barriers to fish passage blocking 14,931 km of streams. We quantified and compared the stream quality, land cover, and physical characteristics of lost versus currently accessible habitat by watershed, assessed the effect of barriers on the variability of accessible habitats, and investigated potential impacts of habitat reduction on endangered or threatened salmonid populations. The majority of the study watersheds have lost more than 40% of total fish stream habitat. Overall, 40% of the streams with spawning gradients suitable for steelhead (anadromous rainbow trout *Oncorhynchus mykiss*), 60% of streams with riparian habitat in good condition, and 30% of streams draining watersheds with all coniferous land cover are no longer accessible to anadromous fish. Across watersheds, hydrologic and topographic watershed characteristics were correlated with barrier location, barrier density, and the impacts of barriers

on habitat. Population-based abundance scores for spring Chinook salmon O. tshawytscha were strongly correlated with the magnitude of habitat lost and the number of lowland fish passage barriers. The characteristics of barrier and habitat distribution presented in this paper indicate that barrier removal projects and mitigation for instream barriers should consider both the magnitude and quality of the lost habitat.

Sigler, J.W., T.C. Bjornn, and F.H. Everest, 1984. Effects of chronic turbidity on density and growth of steelheads and coho salmon. *Transactions of the American Fisheries Society* 113, 142–150.

Abstract: Chronic turbidity in streams during emergence and rearing of young anadromous salmonids could affect the numbers and quality of fish produced. We conducted laboratory tests to determine the effect of chronic turbidity on feeding of 30–65 mm long steelheads *Salmo gairdneri* and coho salmon *Oncorhynchus kisutch* in straight and oval channels. Fish subjected to continuous clay turbidities grew less well than those living in clear water, and more of them emigrated from channels during the experiments.

Sikder, M.T., and K.M. Elahi, 2013. Environmental degradation and global warming-consequences of Himalayan mega dams. *American Journal of Environmental Protection* 2, 1–9.

Abstract: Mega dams have been considered as the greener energy source than most alternatives. But, responses of environment to dams are complex and varied, as it may result a wide range of environmental degradation. as they depend on local climate, dam structure and operation, and key attributes of the biota. We review our research and that of others to illustrate the fact of environmental impacts due to the existing and proposed mega dams of the Himalayas and also to investigate the sustainability of the dams. Being the youngest and fastest changing mountain, the Himalayas and it mighty glaciers, sources of important rivers, are highly susceptible to global warming. Recently, there are plans to transform the Himalayan Rivers into the powerhouse of South Asia by building hundreds of mega dams to generate 150,000-megawatt electricity in the next 20 years. These dams pose severe environmental risks in the Himalayan region and mostly in the downstream and the climate change associated with the global warming threatens the safety and viability of these hydropower projects. Dams and their associated reservoirs impact freshwater biodiversity and hydrogeology; changing turbidity, sediment levels, nutrient levels; causing flash flood and prolonged submergence; severe drought in dry season; affecting local ecology and habitat; contribute greenhouse gases and the resulting global warming; dry up the rivers for even longer lengths; impact traditional livelihoods, agriculture, irrigation and fisheries; threat political, regional and geo-strategic stability; increase the rate of disaster associated with the dam failure, land sliding, earthquake in the downstream. The study investigates the fact that the next hydrological projects in the Himalayas need proper EIA and information sharing to decrease the environmental impacts, to ensure water distribution of rivers, the riparian countries, to make the projects sustainable and to ensure benefits for all with proper negotiations and commitment.

Smith, S.G., W.D. Muir, E.E. Hockersmith, R.W. Zabel, R.J. Graves, C.V. Ross, W.P. Connor, and B.D. Arnsberg, 2003. Influence of River Conditions on Survival and Travel Time of Snake River Subyearling Fall Chinook Salmon. *North American Journal of Fisheries Management* 23, 939–961.

Abstract: From 1995 to 2000, subyearling fall Chinook salmon *Oncorhynchus tshawytscha* reared at Lyons Ferry Hatchery were PIT-tagged at the hatchery, trucked upstream, acclimated, and released into free-flowing sections of the Snake River weekly from early June to mid-July. We estimated survival probabilities and travel time through the lower Snake River and detection probabilities at dams for each weekly release group. The average median time between release and arrival at Lower Granite Dam was 43.5 d. For each group, we split this time into two nearly equal (on average) periods: one when most fish in the group were rearing and one when most fish had apparently begun active seaward migration. The estimated survival for hatchery fish from release to the tailrace of Lower Granite Dam decreased with release date each year. The estimated survival through this reach was significantly correlated with three environmental variables: survival decreased as discharge ("flow") decreased, as water transparency increased, and as water temperature increased. Because the environmental variables were highly correlated among themselves, we were unable to determine whether any factors were more important than the others. All three factors have plausible biological consequences for rearing and actively migrating fish, and survival is probably influenced by all of them and possibly by interactions among them as well. Summer flow augmentation will increase discharge and decrease water temperature (provided the additional water is not too warm) and probably increase the speed of seaward migration of smolts, all of which are beneficial to the recovery of threatened Snake River fall Chinook salmon

Sommer, T.R., M.L. Nobriga, W.C. Harrell, W. Batham, and W.J. Kimmerer, 2001. Floodplain rearing of juvenile Chinook salmon: evidence of enhanced growth and survival. *Canadian Journal of Fisheries and Aquatic Sciences* 58, 325–333.

Abstract: In this study, we provide evidence that the Yolo Bypass, the primary floodplain of the lower Sacramento River (California, U.S.A.), provides better rearing and migration habitat for juvenile Chinook salmon (*Oncorhynchus tshawytscha*) than adjacent river channels. During 1998 and 1999, salmon increased in size substantially faster in the seasonally inundated agricultural floodplain than in the river, suggesting better growth rates. Similarly, coded-wire-tagged juveniles released in the floodplain were significantly larger at recapture and had higher apparent growth rates than those concurrently released in the river. Improved growth rates in the floodplain were in part a result of significantly higher prey consumption, reflecting greater availability of drift invertebrates. Bioenergetic modeling suggested that feeding success was greater in the floodplain than in the river, despite increased metabolic costs of rearing in the significantly warmer floodplain. Survival indices for coded-wire-tagged groups were somewhat higher for those released in the floodplain than for those released in the river, but the differences were not statistically significant. Growth, survival, feeding success, and prey availability were higher in 1998 than in 1999, a year in which flow was more moderate, indicating that hydrology affects the quality of floodplain rearing habitat. These findings support the predictions of the flood pulse concept and provide new insight into the importance of the floodplain for salmon.

Steel, E.A., B.E. Feist, D.W. Jensen, G.R. Pess, M.B. Sheer, J.B. Brauner, and R.E. Bilby, 2004. Landscape models to understand steelhead (*Oncorhynchus mykiss*) distribution and help prioritize barrier removals in the Willamette basin, Oregon, USA. Canadian *Journal of Fisheries and Aquatic Sciences* 61, 999–1011.

Abstract: We use linear mixed models to predict winter steelhead (*Oncorhynchus mykiss*) redd density from geology, land use, and climate variables in the Willamette River basin, Oregon. Landscape variables included in the set of best models were alluvium, hillslope < 6%, landslide-derived geology, young (<40 years) forest, shrub vegetation, agricultural land use, and mafic volcanic geology. Our approach enables us to model the temporal correlation between annual redd counts at the same site while extracting patterns of relative redd density across sites that are consistent even among years with varying strengths of steelhead returns. We use our model to predict redd density (redds per kilometre) upstream of 111 probable migration barriers as well as the 95% confidence interval around the redd density prediction and the total number of potential redds behind each barrier. Using a metric that incorporates uncertainty, we identified high-priority barriers that might have been overlooked using only stream length or mean predicted fish benefit and we clearly differentiated between otherwise similar barriers. We show that landscape features can be used to describe and predict the distribution of winter steelhead redds and that these models can be used immediately to improve decision-making for anadromous salmonids.

Stella, J.C., J.J. Battles, B.K. Orr, and J.R. McBride, 2006. Synchrony of Seed Dispersal, Hydrology and Local Climate in a Semi-arid River Reach in California. *Ecosystems* 9, 1200–1214.

Abstract: The temporal availability of propagules is a critical factor in sustaining pioneer riparian tree populations along snowmelt-driven rivers because seedling establishment is strongly linked to seasonal hydrology. River regulation in semi-arid regions threatens to decouple seed development and dispersal from the discharge regime to which they evolved. Using the lower Tuolumne River as a model system, we quantified and modeled propagule availability for Populus fremontii (POFR), Salix gooddingii (SAGO), and Salix exigua (SAEX), the tree and shrub species that dominate near-channel riparian stands in the San Joaquin Basin, CA. A degree-day model was fit to field data of seasonal seed density and local temperature from three sites in 2002–2004 to predict the onset of the peak dispersal period. To evaluate historical synchrony of seed dispersal and seasonal river hydrology, we compared peak spring runoff timing to modeled peak seed release periods for the last 75 years. The peak seed release period began on May 15 for POFR (range April 23–June 10), May 30 for SAGO (range May 19–June 11) and May 31 for SAEX (range May 8–June 30). Degree-day models for the onset of seed release reduced prediction error by 40–67% over day-of-year means; the models predicted best the interannual, versus site-to-site, variation in timing. The historical analysis suggests that POFR seed release coincided with peak runoff in almost all years, whereas SAGO and SAEX dispersal occurred during the spring flood recession. The degree-day modeling approach reduce uncertainty in dispersal timing and shows potential for guiding flow releases on regulated rivers to increase riparian tree recruitment at the lowest water cost.

Stewart, I.T., D.R. Cayan, and M.D. Dettinger, 2004. Changes in Snowmelt Runoff Timing in Western North America under a 'Business as Usual' Climate Change Scenario. *Climatic Change* 62, 217–232.

Abstract: Spring snowmelt is the most important contribution of many rivers in western North America. If climate changes, this contribution may change. A shift in the timing of springtime snowmelt towards earlier in the year already is observed during 1948–2000 in many western rivers. Streamflow timing changes for the 1995–2099 period are projected using regression relations between observed streamflow-timing responses in each river, measured by the temporal centroid of streamflow (CT) each year, and local temperature (TI) and precipitation (PI) indices. Under 21st century warming trends predicted by the Parallel Climate Model (PCM) under business-as-usual greenhouse-gas emissions, streamflow timing trends across much of western North America suggest even earlier springtime snowmelt than observed to date. Projected CT changes are consistent with observed rates and directions of change during the past five decades, and are strongest in the Pacific Northwest, Sierra Nevada, and Rocky Mountains, where many rivers eventually run 30–40 days earlier. The modest PI changes projected by PCM yield minimal CT changes. The responses of CT to the simultaneous effects of projected TI and PI trends are dominated by the TI changes. Regression-based CT projections agree with those from physically-based simulations of rivers in the Pacific Northwest and Sierra Nevada.

Stewart, I.T., D.R. Cayan, and M.D. Dettinger, 2005. Changes toward earlier streamflow timing across western North America. *Journal of Climate* 18, 1136–1155.

Abstract: The highly variable timing of streamflow in snowmelt-dominated basins across western North America is an important consequence, and indicator, of climate fluctuations. Changes in the timing of snowmelt derived streamflow from 1948 to 2002 were investigated in a network of 302 western North America gauges by examining the center of mass for flow, spring pulse onset dates, and seasonal fractional flows through trend and principal component analyses. Statistical analysis of the streamflow timing measures with Pacific climate indicators identified local and key large-scale processes that govern the regionally coherent parts of the changes and their relative importance. Widespread and regionally coherent trends toward earlier onsets of springtime snowmelt and streamflow have taken place across most of western North America, affecting an area that is much larger than previously recognized. These timing changes have resulted in increasing fractions of annual flow occurring earlier in the water year by 1–4 weeks. The immediate (or proximal) forcings for the spatially coherent parts of the year-to-year fluctuations and longer-term trends of streamflow timing have been higher winter and spring temperatures. Although these temperature changes are partly controlled by the decadal-scale Pacific climate mode [Pacific decadal oscillation (PDO)], a separate and significant part of the variance is associated with a springtime warming trend that spans the PDO phases.

Stickler, M., K.T. Alfredsen, T. Linnansaari, and H.P. Fjeldstad, 2010. The influence of dynamic ice formation on hydraulic heterogeneity in steep streams. *River Research and Applications* 26, 1187–1197.

Abstract: During winter, different types of ice formation are commonly observed in northern boreal stream systems. Although largely overlooked today, river ice has profound effects on in-stream hydraulics and therefore ice processes should be considered in freshwater stream management and assessment. In particular, limited knowledge exists about the impacts of dynamic ice formation on stream environments. Results presented from the changes of in-stream heterogeneity in three steep stream environments caused by dynamic ice formation demonstrate that the formation of anchor ice and anchor ice dams may induce significant backwater effects by increasing wetted areas (maximum 43%) and water depths (maximum 241%) and reducing water velocities (maximum 70%); independent of minimal changes in discharge. Consequently, stream environments are transformed from fast-flow to slow-flow areas, even on a short temporal scale (<12 h). Furthermore, the anchor ice build-up initiated static (surface) ice formation due to reduced local water velocities upstream ice dams. Thus, dynamic ice formation plays a key role in the balanced ice regime in steep stream environments and contributes largely to stable static ice cover in these environments. Observations from the present study suggest that the current paradigm emphasizing the role of discharge as the main controller of in-stream heterogeneity may call for a modification in steep streams that experience seasonal ice formation. This is particularly important if future hydraulic-/habitat models and assessment tools are to be implemented in freshwater management to realistically characterize steep stream environments in cold climate regions on a seasonal scale.

Stickler, M., E.C. Enders, C.J. Pennell, D. Cote, K. Alfredsen, and D.A. Scruton, 2008. Stream Gradient-Related Movement and Growth of Atlantic Salmon Parr during Winter. *Transactions of the American Fisheries Society* 137, 371–385.

Abstract: There has been considerable focus on winter studies of Atlantic salmon Salmo salar parr during the last two decades. However, a lack of knowledge exists about the linkage between the physical conditions, including ice, and parr behavior in flow environments during the cold season. In this study, the movement and growth of Atlantic salmon parr were studied

during winter in two stream sections with different gradients (0.3% and 1.8%) in a small natural river. Passive integrated transponder (PIT) technology was implemented by using both fixed antennae and mobile tracking devices. In the low-gradient section, the formation of surface ice dominated and created stable conditions, whereas in the high-gradient section, the formation of anchor ice and anchor ice dams occurred periodically and produced a dynamic environment. The results indicated a relationship between parr movement and river gradient. Movement by parr was negatively correlated with time from autumn to late winter but increased as spring approached. The level of movement was considered low (median = 0.9 m), but larger movements (up to 125.6 m) were recorded, indicating individual variation. Furthermore, parr inhabiting the low-gradient section with the static ice formation exhibited larger movement than parr in the high-gradient section with dynamic ice formation. Parr showed high site fidelity to both high- and low-gradient sections but were less attracted to pool habitats. Finally, from late autumn to spring, parr demonstrated a specific growth rate close to 0.0%, indicating suitable conditions in both sections. As this study implies, the complexity of physical conditions during winter may lead to variability in individual fish response (i.e., movements). However, the results also imply that winter is not a limiting factor in parr performance if fish have access to suitable cover, such as areas with low substrate embeddedness.

Stone, R.S., E.G. Dutton, J.M. Harris, and D. Longenecker, 2002. Earlier spring snowmelt in northern Alaska as an indicator of climate change. *Journal of Geophysical Research* 107, 1984-2012.

Abstract: [1] Predictions of global circulation models (GCMs) that account for increasing concentrations of greenhouse gases and aerosols in the atmosphere show that warming in the Arctic will be amplified in response to the melting of sea ice and snow cover. There is now conclusive evidence that much of the Arctic has warmed in recent decades. Northern Alaska is one region where significant warming has occurred, especially during winter and spring. We investigate how the changing climate of northern Alaska has influenced the annual cycle of snow cover there and in turn, how changes in snow cover perturb the region's surface radiation budget and temperature regime. The focus is on Barrow, Alaska, for which comprehensive data sets exist. A review of earlier studies that documented a trend toward an earlier disappearance of snow in spring is given. Detection and monitoring activities at Barrow are described, and records of snow disappearance from other sites in the Alaskan Arctic are compared. Correlated variations and trends in the date of final snowmelt (melt date) are found by examining several independent time series. Since the mid-1960s the melt date in northern Alaska has advanced by ~8 days. The advance appears to be a consequence of decreased snowfall in winter, followed by warmer spring conditions. These changes in snowfall and temperature are attributed to variations in regional circulation patterns. In recent decades, there has been a higher frequency of northerly airflow during winter that tends to diminish snowfall over northern Alaska. During spring, however, intrusions of warm moist air from the North Pacific have become more common, and these tend to accelerate the ablation of snow on the North Slope of Alaska. One result of an earlier melt date is an increase in the net surface radiation budget. At Barrow, net

radiative forcing can exceed 150 W m−2 on a daily basis immediately following the last day of snowmelt, and as a result of an 8-day advance in this event, we estimate an increase of ~2 W m−2 on an annual basis. Our results are in general agreement with earlier analyses suggesting that reductions in snow cover over a large portion of the Arctic on an annual basis have contributed to a warming of the Northern Hemisphere (NH). In addition, the terrestrial ecosystems of the region are very sensitive to snow cover variations. There is growing concern that these perturbations are anthropogenically forced and adapting to these environmental changes will have significant social and economic consequences. While observed decreases in NH snow cover are in broad agreement with GCM simulations, our analyses suggest that internal (or natural) shifts in circulation patterns underlie the observed variations. Continued monitoring and further study is needed to determine whether the earlier disappearance of snow cover in spring in northern Alaska is an indicator of greenhouse-forced global warming or is a manifestation of a more natural, long-term cycle of climate change.

Stratton, M.E., 1986. *Summary of Juvenile Chinook and Coho Salmon Winter Studies in the Middle Susitna River, 1984-1985*. Report to Alaska Power Authority by Alaska Department of Fish and Game, Susitna Hydro Aquatic Studies, Anchorage, Alaska. 148 pp.

Abstract: Historic winter sampling efforts to evaluate habitat use by overwintering Chinook and coho salmon in the middle Susitna River. Part of broader winter studies that were conducted from October 15, 1984 through May 15, 1985 on juvenile salmon and resident fish species of the Susitna River.

Suchanek, P.M., K. Kuntz, and J.P. McDonnell, 1984. *The relative abundance, distribution and instream flow relationships of juvenile salmon in the lower Susitna River*. Report #7, part 2. Alaska Dept. of Fish and Game, Susitna River Aquatic Studies Program, Anchorage, Alaska.

Abstract: Historic evaluation of the interaction between abundance and distribution of juvenile salmonids and instream flow in the lower Susitna River.

Sui, J., B.W. Karney, and D. Fang, 2005. Variation in water level under ice-jammed condition – field investigation and experimental study. *Nordic Hydrology* 36, 65–84.

Abstract: This paper presents the impacts of frazil ice jams on the variation in water level at the Hequ Reach of the Yellow River in China. Based on both field observations and experimental studies, it is found that both the evolution of frazil ice jams and the associated variation in water level depend upon an interesting interaction between hydraulic variables during the ice-jammed period. In particular, the critical Froude number governing the formation of river ice jams and their upstream propagation is about 0.09. The water level during ice-jammed periods depends not only on the slope of the water surface and the water level under open-water conditions with the same discharge, but also on the length of the ice jam and the ice concentration in the water. Moreover, the field investigations show that the thickness of river ice strongly influences the variation in water level during icejammed periods. Empirical relationships are derived to quantify the relationship between the highest water level during ice periods and related physical parameters. To confirm the field results, and to explore the influence of ice discharge on the variation in water level, experimental studies were also conducted. These results confirm that the ice concentration plays a key role in the variation in water level and the jam thickness. Given the complexity of the jamming processes, surprisingly good agreement is observed between field and experimental investigations.

Tappel, P.D., and T.C. Bjornn, 1983. A New Method of Relating Size of Spawning Gravel to Salmonid Embryo Survival. *North American Journal of Fisheries Management* 3, 123–135.

Abstract: A new method for describing the size composition of salmonid spawning gravel was developed. For gravel samples from Idaho and Washington streams, cumulative distributions of particle sizes for gravel smaller than 25.4 mm were consistently plotted as straight lines on log-probability paper. Because of the lognormal distribution of the particle sizes in this range, the size composition of material smaller than 25.4 mm was closely approximated by two points on a regression of cumulative particle size distribution. The two size classes that best reflected the composition of the spawning gravel size were the percentage of the substrate smaller than 9.50 ram and the percentage smaller than 0.85 mm.
Salmonid embryo survival was related to these two groups of particle size in laboratory tests. In these tests, 90-93% of the variability in embryo survival was correlated with changes in substrate size composition. Equations were developed to describe the effect of spawning gravel size composition on Chinook salmon (*Oncorhynchus tshawytscha*) and steelhead (*Salmo gairdneri*) survival to emergence in a wide range of spawning gravel mixtures.
Gravel mixtures containing high percentages of fine sediment produced slightly smaller steelhead fry than gravels containing low percentages of fine sediment, but the difference was not significant (P = 0.05). There was no relationship between changes in gravel size composition and the size of Chinook salmon emergents. In gravels containing large amounts of fine sediment, many of the steelhead and Chinook salmon fry emerged before yolk sac absorption was complete.

Tetra Tech, 2013a. *Appendix 1. Lower River Habitat Area Tables. Synthesis of the 1980s Lower Susitna River Segment Aquatic Habitat Information 2012 Study Technical Memorandum*. Susitna-Watana Hydroelectric Project (FERC No. 14241). Alaska Energy Authority.

Abstract: A summary of historic aquatic habitat information presented in tables and figures.

Tetra Tech, 2013b. *Development of Sediment-Transport Relationships and an Initial Sediment Balance for the Middle and Lower Susitna River Segments*. Susitna-Watana Hydroelectric Project (FERC No. 14241). Alaska Energy Authority.

Abstract: The purpose of the study effort was to make preliminary estimates of the overall sediment balance in the Middle and Lower River segments under pre-Project conditions and the potential magnitude of the changes that will occur under Maximum Load Following Operating Scenario (OS)-1 hydrologic conditions. A sediment balance is the determination of the difference between the inflowing sediment (supply) to a reach and the outflowing sediment from the reach (transport). If the sediment inflow to the reach is greater than the outflow, then sediment is stored within the reach. If the sediment supply into the reach is less than the sediment outflow from the reach, then sediment is removed from the reach. In the former case, the reach is considered depositional and in the latter case it is considered aggradational. If the sediment inflow and outflow are nearly equal, the reach is considered in balance with its sediment supply and transport.

Tetra Tech, 2013c. *Fluvial Geomorphology Modeling Approach Draft Technical Memorandum*. Susitna-Watana Hydroelectric Project (FERC No. 14241). Alaska Energy Authority.

Abstract: To develop the fluvial geomorphology modeling approach, specific issues that need to be addressed have been identified. These issues have been further differentiated into reach-scale and local-scale issues since the scale influences the proposed approach. The reach scale modeling will be performed using 1-D models, as they are well suited for long term simulations over long river reaches. The 1-D models will be used to assess reach-scale sediment transport conditions, potential changes in bed and water surface elevations, and potential changes in bed material gradation. The 1-D models will also provide boundary conditions for the local scale modeling (i.e., the Focus Areas) that will be performed using 2-D models. The detailed results of the 2-D models will provide more localized information on changes in hydraulic and bed conditions over a range of flows for existing and with-project conditions.

Tetra Tech, 2013d. *Initial Geomorphic Reach Delineation and Characterization, Middle and Lower Susitna River Segments*. 2012 Study Technical Memorandum. Susitna-Watana Hydroelectric Project (FERC No. 14241). Alaska Energy Authority.

Abstract: This report provides the results of the Delineate Geomorphically Similar (Homogeneous) River Reaches tasks in the 2012 Aquatic Habitat and Geomorphic Mapping of the Middle River using Aerial Photography Study (G-S2) and the 2012 Reconnaissance-Level Geomorphic and Aquatic Habitat Assessment of Project Effects on Lower River Channel (G-S4), based on work outlined in the Revised Study Plan

Tetra Tech, 2013e. *Reconnaissance Level Assessment of Potential Channel Change in the Lower Susitna River Segment, 2012 Study Technical Memorandum*. Alaska Energy Authority.

Abstract: This effort synthesized results from the Development of Sediment-Transport Relationships and an Initial Sediment Balance for the Middle and Lower Susitna River Segments technical memorandum and the Stream Flow Assessment technical memoranda within an analytical framework to perform an initial assessment of potential Project-related changes in channel morphology of the Lower River.

Tetra Tech, 2013f. *Stream Flow Assessment*. Susitna-Watana Hydroelectric Project (FERC No. 14241). Alaska Energy Authority.

Abstract: The purpose of the Stream Flow Assessment was to identify the potential Project related changes in Susitna River flows and stage in the Lower River (the portion of the river downstream of the Susitna, Chulitna and Talkeetna river confluence). The analysis performed was an initial assessment to inform the study planning and early execution phases of the integrated licensing process (ILP). Of primary interest was whether the results of the analysis indicate the need to extend portions of Fluvial Geomorphology Modeling Study and other studies further downstream in the Lower River.

Tetra Tech and Watershed GeoDynamics, 2014. *Initial Study Report*. Geomorphology Study (Section 6.5): Figures. Susitna-Watana Hydroelectric Project, FERC Project No. 14241. Prepared for Alaska Energy Authority. February 2014 Draft.

Abstract: The document provides figures referenced in the Geomorphology Study. The overall goal of the Geomorphology Study is to characterize the geomorphology of the Susitna River, and to evaluate the effects of the Project on the geomorphology and dynamics of the river by predicting the trend and magnitude of geomorphic response.

Thompson, F.M., S.N. Wick, and B.L. Stratton, 1986. *Adult salmon investigations: May-October 1985*. Technical Data Report No. 13, Alaska Department of Fish and Game, Susitna Hydro Aquatic Studies, Anchorage, Alaska.

Abstract: A historic evaluation of adult salmon life histories and habitat associations in the Susitna River. This report concludes five years of data collection on adult salmon in the Susitna River, Southcentral Alaska, by the Susitna Aquatic Studies Team of the Alaska Department of Fish and Game

Todd, G.L., S.R. Carlson, P.A. Shields, D.L. Westerman, and L.K. Brannian, 2001. *Sockeye and coho salmon escapement studies in the Susitna drainage 1998*. Alaska Department of Fish and Game, Division of Commercial Fisheries, Regional Information Report 2A01-11, Anchorage.

Abstract: A recent evaluation of sockeye and coho fishery escapement for the Susitna River.

Trihey, E.W., 1982. *Preliminary assessment of access by spawning salmon to side slough habitat above Talkeetna: draft report*. Prepared for Acres American Inc.

Abstract: A historic compilation of field data and habitat associations for fish in the Susitna River. Includes descriptions of potential fish impacts and changes to habitat resulting from the proposed project.

Trihey & Associates and Entrix, 1985. *Instream Flow Relationships Report*. Final Report to Alaska Power Authority, Anchorage, Alaska. 228 pp.

Abstract: This document comprises Volume II of the Instream Flow Relationships Report (IFRR), a two-volume series on instream flow processes in the middle Susitna River. The objectives of the IFRR are twofold: 1) to identify the relative importances of salient physical processes to fish resources, and 2) to evaluate and, where possible, quantify the influences of incremental changes in important variables on fish habitat.

Trombulak, S.C., and C.A. Frissell, 2000. Review of ecological effects of roads on terrestrial and aquatic communities. *Conservation Biology* 14, 18–30.

Abstract: Roads are a widespread and increasing feature of most landscapes. We reviewed the scientific literature on the ecological effects of roads and found support for the general conclusion that they are associated with negative effects on biotic integrity in both terrestrial and aquatic ecosystems. Roads of all kinds have seven general effects: mortality from road construction, mortality from collision with vehicles, modification of animal behavior, alteration of the physical environment, alteration of the chemical environment, spread of exotics, and increased use of areas by humans. Road construction kills sessile and slow-moving organisms, injures organisms adjacent to a road, and alters physical conditions beneath a road. Vehicle collisions affect the demography of many species, both vertebrates and invertebrates; mitigation measures to reduce roadkill have been only partly successful. Roads alter animal behavior by causing changes in home ranges, movement, reproductive success, escape response, and physiological state. Roads change soil density, temperature, soil water content, light levels, dust, surface waters, patterns of runoff, and sedimentation, as well as adding heavy metals (especially lead), salts, organic molecules, ozone, and nutrients to roadside environments. Roads promote the dispersal of exotic species by altering habitats, stressing native species, and providing movement corridors. Roads also promote increased hunting, fishing, passive harassment of animals, and landscape modifications. Not all species and ecosystems are equally affected by roads, but overall the presence of roads is highly correlated with changes in species composition, population sizes, and hydrologic and geomorphic

processes that shape aquatic and riparian systems. More experimental research is needed to complement post-hoc correlative studies. Our review underscores the importance to conservation of avoiding construction of new roads in roadless or sparsely roaded areas and of removal or restoration of existing roads to benefit both terrestrial and aquatic biota.

Ugedal, O., T.F. Næsje, E.B. Thorstad, T. Forseth, L.M. Saksgård, and T.G. Heggberget, 2008. Twenty years of hydropower regulation in the River Alta: long-term changes in abundance of juvenile and adult Atlantic salmon. *Hydrobiologia* 609, 9–23.

Abstract: The River Alta, northern Norway (70°N), was regulated for hydropower in 1987. Densities of juveniles and catches of adult Atlantic salmon have been studied since 1980–1981 to examine the effects of regulation. The need to control environmental variables during electrofishing was emphasized, as flow variables explained up to 42% of the variation in estimated juvenile densities. The number of spawning redds was counted along the river from 1996 to 2005. The annual number of spawning redds was correlated with the catch of multi-sea-winter salmon (predominantly females). In the upper 7 km section, just downstream of the power station outlet, juvenile densities were reduced by 80% from pre-regulation levels to minimum levels in 1992–1996. This was followed by partial recovery during 1997–2005, although not entirely back to pre-regulation levels. In contrast, the general trend in the middle part of the river was a linear increase in juvenile densities during 1981–2005. Decreased juvenile densities in the upper section was subsequently followed by reduced catches of adult salmon in this part of the river. The relative catches of smolt year classes migrating to sea in the upper section was reduced by up to 75% from 1991 onwards. Spawning and recruitment in the upper section have increased in recent years, probably back to the introduction of catch-and-release angling and an increase in salmon runs. However, present day smolt production in the upper section is still reduced compared to the middle part of the river, 18 years after regulation. The decreased densities of juvenile salmon in the upper section were probably caused by several factors, of which stranding mortality due to sudden drops in the water level and increased winter mortality due to changed environmental conditions, especially reduced ice-cover, may be the most important. In conclusion, the regulation caused a considerable reduction of the salmon production in the upper 16% of salmon reaches, but did not affect the salmon population negatively further downstream. This study illustrates that apparently small environmental disturbances can cause large changes in Atlantic salmon abundance in high latitude populations.

URS and Tetra Tech, 2013a. *2012 Susitna River Water Temperature and Meteorological Field Study*. Susitna-Watana Hydroelectric Project (FERC No. 14241).

Abstract: The objective of this study was to provide a foundation for development of reservoir and riverine temperature models for the Project. This work include a review of the previous temperature model studies performed on the river, installation of temperature monitoring stations, and installation of meteorological (MET) monitoring stations.

URS and Tetra Tech, 2013b. *Mercury Assessment and Potential for Bioaccumulation*. Susitna-Watana Hydroelectric Project (FERC No. 14241). Alaska Energy Authority.

Abstract: This report provides the results of the 2012 Mercury Assessment and Potential for Bioaccumulation. The purpose of this study was to begin assessing the occurrence of methylmercury in fish within the proposed Project area. This study represents the first phase of the work, and additional sampling of soil, sediment, water, and fish tissue is planned for 2013.

Valentin, S., J.G. Wasson, and M. Philippe, 1995. Effects of hydropower peaking on epilithon and invertebrate community trophic structure. *Regulated Rivers: Research & Management* 10, 105–119.

Abstract: Hydropower generation induces rapid and frequent fluctuations of hydrodynamic parameters in rivers downstream of hydroelectric impoundments. On the FontauliéGre river (ArdéGche basin, France), water releases come from the Loire basin and the flow varies from 1.3 to 20 m3/s for one reach and from 0.1 to 20 m3/s for another reach. A reference site upstream was chosen to compare the communities with two downstream impacted sites. These two sites enabled two different base flow situations to be studied simultaneously and also the effect of base flow enhancement at one site. Benthic and epilithic samples were collected at the three sites on three dates. Epilithon development was linked to hydraulic regimes, with a major increase in algal biomass, dominated by filamentous algae, linked to the minimum base flow level and to the duration of periods without peaks. The macroinvertebrate communities of impacted reaches were less diversified and more specialized, with predominance of one or two taxa, whereas communities in upstream reaches were more diverse. The different morphological units specificity was attenuated in hydropeaking situations. In the case of a very low base flow, the lentic units with very low velocities (less than 4 cm s−1) had different fauna. The downstream algal development explained part of the change in benthic community structure in trophic groups (i.e. dominance of scrapers) in the site with the higher base flow. When the base flow was too low, a trophic discordance was observed and excess algal biomass represented a limiting factor. Thus, this study indicated that base flow level and duration had important effects on epilithic development and on invertebrate trophic structure in terms of mean velocities and of number of days without peaks.

Vining, L.J., and G.M. Freeman, 1985. *Winter aquatic investigations (September 1983 to May 1984) (Susitna Hydro Aquatic Studies)*. Alaska Department of Fish and Game, Anchorage, AK.

Abstract: This report provides results of the 1983-1984 winter studies conducted by the ADF&G to evaluate and compare existing chum salmon incubation conditions in selected slough, side channel, tributary, and mainstem habitats of the Susitna River between Talkeetna and Devil Canyon (river miles 98-152).

Wangaard, D.B., and C.V. Burger, 1983. *Effects of various water temperature regimes on the egg and alevin incubation of Susitna River chum and sockeye salmon*. US Fish and Wildlife Service, National Fishery Research Center, Alaska Field Station.

Abstract: This historic document assesses potential effects of water temperature alterations (resulting from proposed hydroelectric development) on incubating salmon eggs and alevins in the Susitna River, Alaska.

Waples, R., T. Beechie, and G. Pess, 2009. *Evolutionary History, Habitat Disturbance Regimes, and Anthropogenic Changes: What Do These Mean for Resilience of Pacific Salmon Populations?* Publications, Agencies and Staff of the U.S. Department of Commerce.

Abstract: Because resilience of a biological system is a product of its evolutionary history, the historical template that describes the relationships between species and their dynamic habitats is an important point of reference. Habitats used by Pacific salmon have been quite variable throughout their evolutionary history, and these habitats can be characterized by four key attributes of disturbance regimes: frequency, magnitude, duration, and predictability. Over the past two centuries, major anthropogenic changes to salmon ecosystems have dramatically altered disturbance regimes that the species experience. To the extent that these disturbance regimes assume characteristics outside the range of the historical template, resilience of salmon populations might be compromised. We discuss anthropogenic changes that are particularly likely to compromise resilience of Pacific salmon and management actions that could help bring the current patterns of disturbance regimes more in line with the historical template.

Waples, R.S., G.R. Pess, and T. Beechie, 2008a. Evolutionary history of Pacific salmon in dynamic environments. *Evolutionary Applications* 1, 189–206.

Abstract: Contemporary evolution of Pacific salmon (*Oncorhynchus* spp.) is best viewed in the context of the evolutionary history of the species and the dynamic ecosystems they inhabit. Speciation was complete by the late Miocene, leaving c. six million years for intraspecific diversification. Following the most recent glacial maximum, large areas became available for recolonization. Current intraspecific diversity is thus the product of recent evolution overlaid onto divergent historical lineages forged during recurrent episodes of Pleistocene glaciation. In northwestern North America, dominant habitat features have been relatively stable for the past 5000 years, but salmon ecosystems remain dynamic because of disturbance regimes (volcanic eruptions, landslides, wildfires, floods, variations in marine and freshwater productivity) that occur on a variety of temporal and spatial scales. These disturbances both create selective pressures for adaptive responses by salmon and inhibit long-term divergence by periodically extirpating local populations and creating episodic dispersal events that erode emerging differences. Recent anthropogenic changes are replicated pervasively across the landscape and interrupt processes that allow natural habitat recovery. If anthropogenic changes can be shaped

to produce disturbance regimes that more closely mimic (in both space and time) those under which the species evolved, Pacific salmon should be well-equipped to deal with future challenges, just as they have throughout their evolutionary history.

Waples, R.S., R.W. Zabel, M.D. Scheuerell, and B.L. Sanderson, 2008b. Evolutionary responses by native species to major anthropogenic changes to their ecosystems: Pacific salmon in the Columbia River hydropower system. *Molecular Ecology* 17, 84–96.

Abstract: The human footprint is now large in all the Earth's ecosystems, and construction of large dams in major river basins is among the anthropogenic changes that have had the most profound ecological consequences, particularly for migratory fishes. In the Columbia River basin of the western USA, considerable effort has been directed toward evaluating demographic effects of dams, yet little attention has been paid to evolutionary responses of migratory salmon to altered selective regimes. Here we make a first attempt to address this information gap. Transformation of the free-flowing Columbia River into a series of slackwater reservoirs has relaxed selection for adults capable of migrating long distances upstream against strong flows; conditions now favour fish capable of migrating through lakes and finding and navigating fish ladders. Juveniles must now be capable of surviving passage through multiple dams or collection and transportation around the dams. River flow patterns deliver some groups of juvenile salmon to the estuary later than is optimal for ocean survival, but countervailing selective pressures might constrain an evolutionary response toward earlier migration timing. Dams have increased the cost of migration, which reduces energy available for sexual selection and favours a nonmigratory life history. Reservoirs are a benign environment for many non-native species that are competitors with or predators on salmon, and evolutionary responses are likely (but undocumented). More research is needed to tease apart the relative importance of evolutionary vs. plastic responses of salmon to these environmental changes; this research is logistically challenging for species with life histories like Pacific salmon, but results should substantially improve our understanding of key processes. If the Columbia River is ever returned to a quasinatural, free-flowing state, remaining populations might face a Darwinian debt (and temporarily reduced fitness) as they struggle to re-evolve historical adaptations.

Waythomas, C.F., J.S. Walder, R.G. McGimsey, and C.A. Neal, 1996. A catastrophic flood caused by drainage of a caldera lake at Aniakchak Volcano, Alaska, and implications for volcanic hazards assessment. *Geological Society of America Bulletin* 108, 861–871.

Aniakchak caldera, located on the Alaska Peninsula of southwest Alaska, formerly contained a large lake (estimated volume 3.7 × 109 m3) that rapidly drained as a result of failure of the caldera rim sometime after ca. 3400 yr B.P. The peak discharge of the resulting flood was estimated using three methods: (1) flow-competence equations, (2) step-backwater modeling, and (3) a dam-break model. The results of the dam-break model indicate that the peak discharge at the breach in the caldera rim was at least 7.7 × 104 m3 s−1, and the maximum

possible discharge was ≈1.1 × 106 m3 s−1. Flow-competence estimates of discharge, based on the largest boulders transported by the flood, indicate that the peak discharge values, which were a few kilometers downstream of the breach, ranged from 6.4 × 105 to 4.8 × 106 m3 s−1. Similar but less variable results were obtained by step-backwater modeling. Finally, discharge estimates based on regression equations relating peak discharge to the volume and depth of the impounded water, although limited by constraining assumptions, provide results within the range of values determined by the other methods. The discovery and documentation of a flood, caused by the failure of the caldera rim at Aniakchak caldera, underscore the significance and associated hydrologic hazards of potential large floods at other lake-filled calderas.

Weitkamp, D.E., R.D. Sullivan, T. Swant, and J. DosSantos, 2003a. Behavior of Resident Fish Relative to Total Dissolved Gas Supersaturation in the Lower Clark Fork River. *Transactions of the American Fisheries Society* 132, 856–864.

Abstract: Gas bubble disease (GBD) occurs in the resident fish of the lower Clark Fork River that are exposed to total dissolved gas (TDG) supersaturation produced by the spill at upstream hydroelectric projects. This report describes the incidence and severity of GBD observed in fish routinely collected by electrofishing and other techniques during periods of high supersaturation from 1997 to 2000. These data include GBD observations for 1997, a year of extremely high runoff resulting in TDG levels approaching 150% of saturation, and for 1999, a year of moderately high TDG levels (typically 120–130% of saturation). Although electrofishing only samples that portion of the fish populations present near the river surface (upper 2 m), in a deep stream (3–25 m) like the lower Clark Fork, the observed incidence and severity of GBD was substantially lower than anticipated for the levels of TDG measured. It appears that the majority of fish are spending sufficient time at depths that avoid or mediate both the incidence and severity of GBD when TDG supersaturation is in the range of 120–130% of saturation. Fish also have access to a number of tributaries that have little or no supersaturation and to Lake Pend Oreille, where fish commonly occupy depths that provide hydrostatic compensation, which, in turn, eliminates the effects of exposure to supersaturation.

Weitkamp, D.E., R.D. Sullivan, T. Swant, and J. DosSantos, 2003b. Gas Bubble Disease in Resident Fish of the Lower Clark Fork River. *Transactions of the American Fisheries Society* 132, 865–876.

Abstract: The behavior of resident fish exposed to total dissolved gas (TDG) supersaturation in Pacific Northwest rivers greatly influences the degree of supersaturation these fish actually experience. Because TDG supersaturation is a physical condition that is moderated by hydrostatic pressure, the depths occupied by fish during supersaturation conditions determine the biological effects experienced by members of the exposed population. Data obtained from fish equipped with depth-sensing radio tags showed that many of the fish spent sufficient time at depths of several meters or more, where they are not exposed to TDG supersaturation. These depths also provide an opportunity to recover from the short-term exposure to supersaturation experienced by the fish during the periods they occupy shallower depths. Most species tagged had median and average depth distributions of about 2 m or more, providing compensation for TDG supersaturation in the range of 120% of saturation or more. Tagged rainbow trout *Oncorhynchus mykiss* generally remained in the river for only brief periods before returning to Lake Pend Oreille or to the tributaries of the lower Clark Fork River, where they were no longer exposed to TDG supersaturation.

Welch, D.W., Y. Ishida, and K. Nagasawa, 1998. Thermal limits and ocean migrations of sockeye salmon (*Oncorhynchus nerka*): long-term consequences of global warming. *Canadian Journal of Fisheries and Aquatic Sciences* 55, 937–948.

Abstract: Ocean surveys show that extremely sharp thermal boundaries have limited the distribution of sockeye salmon (*Oncorhynchus nerka*) in the Pacific Ocean and adjacent seas over the past 40 years. These limits are expressed as a step function, with the temperature defining the position of the thermal limit varying between months in an annual cycle. The sharpness of the edge, the different temperatures that define the position of the edge in different months of the year, and the subtle variations in temperature with area or decade for a given month probably all occur because temperature-dependent metabolic rates exceed energy intake from feeding over large regions of otherwise acceptable habitat in the North Pacific. At current rates of greenhouse gas emissions, predicted temperature increases under a doubled CO2 climate are large enough to shift the position of the thermal limits into the Bering Sea by the middle of the next century. Such an increase would potentially exclude sockeye salmon from the entire Pacific Ocean and severely restrict the overall area of the marine environment that would support growth.

Werner, E.E., and J.F. Gilliam, 1984. The Ontogentic Niche and Species Interactions in Size Structured Populations. *Annual Review of Ecology and Systematics* 15, 393–425.

Abstract: A synthesis of the relationships between body size and habitat use for animals at different life history stages.

Whitney, C.K., S.G. Hinch, and D.A. Patterson, 2013. Provenance matters: thermal reaction norms for embryo survival among sockeye salmon *Oncorhynchus nerka* populations: thermal tolerance for *Oncorhynchus nerka* incubation. *Journal of Fish Biology* 82, 1159–1176.

Abstract: Differences in thermal tolerance during embryonic development in Fraser River sockeye salmon *Oncorhynchus nerka* were examined among nine populations in a controlled common-garden incubation experiment. Forcing embryonic development at an extreme temperature (relative to current values) of 16◦ C, representing a future climate change scenario, significantly reduced survival compared to the more ecologically moderate temperature of 10◦ C (55% v. 93%). Survival at 14◦ C was intermediate between the other two temperatures (85%).

More importantly, this survival response varied by provenance within and between temperature treatments. Thermal reaction norms showed an interacting response of genotype and environment (temperature), suggesting that populations of O. nerka may have adapted differentially to elevated temperatures during incubation and early development. Moreover, populations that historically experience warmer incubation temperatures at early development displayed a higher tolerance for warm temperatures. In contrast, thermal tolerance does not appear to transcend life stages as adult migration temperatures were not related to embryo thermal tolerance. The intra-population variation implies potential for thermal tolerance at the species level. The differential inter-population variation in thermal tolerance that was observed suggests, however, limited adaptive potential to thermal shifts for some populations. This infers that the intergenerational effects of increasing water temperatures may affect populations differentially, and that such thermally mediated adaptive selection may drive population, and therefore species, persistence.

Willette, T.M., R. DeCino, and N. Gove, 2003. *Mark-recapture population estimates of coho, pink, and chum salmon runs to upper Cook Inlet in 2002*. Alaska Department of Fish and Game, Division of Commercial Fisheries, Regional Information Report 2A03-20, Anchorage.

Abstract: This project estimated the total population sizes, escapements, and exploitation rates for coho, pink, and chum salmon returning to Upper Cook Inlet (UCI) in 2002 as a first step toward determining escapement levels needed to achieve sustained yields for these species.

Williams, J.G., R.W. Zabel, R.S. Waples, J.A. Hutchings, and W.P. Connor, 2008. Potential for anthropogenic disturbances to influence evolutionary change in the life history of a threatened salmonid. *Evolutionary Applications* 1, 271–285.

Abstract: Although evolutionary change within most species is thought to occur slowly, recent studies have identified cases where evolutionary change has apparently occurred over a few generations. Anthropogenically altered environments appear particularly open to rapid evolutionary change over comparatively short time scales. Here, we consider a Pacific salmon population that may have experienced life-history evolution, in response to habitat alteration, within a few generations. Historically, juvenile fall Chinook salmon (*Oncorhynchus tshawytscha*) from the Snake River migrated as subyearlings to the ocean. With changed riverine conditions that resulted from hydropower dam construction, some juveniles now migrate as yearlings, but more interestingly, the yearling migration tactic has made a large contribution to adult returns over the last decade. Optimal life-history models suggest that yearling juvenile migrants currently have a higher fitness than subyearling migrants. Although phenotypic plasticity likely accounts for some of the change in migration tactics, we suggest that evolution also plays a significant role. Evolutionary change prompted by anthropogenic alterations to the environment has general implications for the recovery of endangered species. The case study we present herein illustrates the importance of integrating evolutionary considerations into conservation planning for species at risk.

Willson, M.F., S.M. Gende, and B.H. Marston, 1998. Fishes and the Forest. *BioScience* 48, 455–462.

Abstract: A synthesis of the importance of marine derived nutrients to riparian and terrestrial ecosystems.

Willson, M.F., and K.C. Halupka, 1995. Anadromous fish as keystone species in vertebrate communities. *Conservation Biology* 9, 489–497.

Abstract: Many wildlife species feed on anadromous fishes of several life-history stages. There is evidence for some wildlife species that the availability of anadromous fish is critically important for survival or reproduction. In some regions anadromous fishes in fresh water appear to be keystone food resources for vertebrate predators and scavengers, forging an ecologically significant link between aquatic and terrestrial ecosystems. The spatial distribution of anadromous fish in fresh water, including the occurrence of runs in very small streams, has important consequences for wildlife biology (social interactions, distribution, activity patterns, possibly survivorship) and conservation of biodiversity.

Winder, M., and D.E. Schindler, 2004. Climate Change Uncouples Trophic Interactions in an Aquatic Ecosystem. *Ecology* 85, 2100–2106.

Abstract: The largest uncertainty in forecasting the effects of climate change on ecosystems is in understanding how it will affect the nature of interactions among species. Climate change may have unexpected consequences because different species show unique responses to changes in environmental temperatures. Here we show that increasingly warmer springs since 1962 have disrupted the trophic linkages between phytoplankton and zooplankton in a large temperate lake because of differing sensitivity to vernal warming. The timing of thermal stratification and the spring diatom bloom have advanced by more than 20 days during this time period. A long-term decline in Daphnia populations, the keystone herbivore, is associated with an expanding temporal mismatch with the spring diatom bloom and may have severe consequences for resource flow to upper trophic levels.

Wipfli, M.S., J. Hudson, and J. Caouette, 1998. Influence of salmon carcasses on stream productivity: response of biofilm and benthic macroinvertebrates in southeastern Alaska, USA. *Canadian Journal of Fisheries and Aquatic Sciences* 55, 1503–1511.

Abstract: This study was conducted to determine if salmon carcasses (from spawning adults) increased stream biofilm ash-free dry mass (AFDM) and benthic macroinvertebrate abundance in southeastern Alaska, U.S.A. Thirty-six once-through artificial streams were situated along, and received water and drifting invertebrates from, a natural stream. Two treatments (salmon carcass, control) were sampled six times during a 3-month period in a randomized incomplete block design with a 2 x 6 factorial treatment structure. Additionally, two natural stream sites were sampled once for biofilm and macroinvertebrates, one site receiving 75 000 adult salmon migrants during 1996 and the other upstream of spawning salmon. While biofilm AFDM was 15 times higher in carcass-enriched reaches of Margaret Creek, there were no detectable treatment differences in the artificial streams. Total macroinvertebrate densities were up to eight and 25 times higher in carcass-enriched areas of artificial and natural streams, respectively; Chironomidae midges, Baetis and Cinygmula mayflies, and Zapada stoneflies were the most abundant taxa. The increased biofilm in Margaret Creek and macroinvertebrate abundance in both systems suggest that salmon carcasses elevated freshwater productivity. This marine-based positive feedback mechanism may be crucial for sustaining aquatic riparian ecosystem productivity and long-term salmonid population levels.

Wofford, J.E., R.E. Gresswell, and M.A. Banks, 2005. Influence of barriers to movement on within-watershed genetic variation of coastal cutthroat trout. *Ecological Applications* 15, 628–637.

Abstract: Because human land use activities often result in increased fragmentation of aquatic and terrestrial habitats, a better understanding of the effects of fragmentation on the genetic heterogeneity of animal populations may be useful for effective management. We used eight microsatellites to examine the genetic structure of coastal cutthroat trout (*Oncorhynchus clarki clarki*) in Camp Creek, an isolated headwater stream in western Oregon. Our objectives were to determine if coastal cutthroat trout were genetically structured within streams and to assess the effects of natural and anthropogenic barriers on coastal cutthroat trout genetic variation. Fish sampling occurred at 10 locations, and allele frequencies differed significantly among all sampling sections. Dispersal barriers strongly influenced coastal cutthroat trout genetic structure and were associated with reduced genetic diversity and increased genetic differentiation. Results indicate that Camp Creek coastal cutthroat trout exist as many small, partially independent populations that are strongly affected by genetic drift. In headwater streams, barriers to movement can result in genetic and demographic isolation leading to reduced coastal cutthroat trout genetic diversity, and potentially compromising long-term population persistence. When habitat fragmentation eliminates gene flow among small populations, similar results may occur in other species.

Woo, M., R. Thorne, K. Szeto, and D. Yang, 2008. Streamflow hydrology in the boreal region under the influences of climate and human interference. *Philosophical Transactions of the Royal Society* B 363, 2249–2258.

Abstract: The boreal region has a subarctic climate that is subject to considerable inter-annual variability and is prone to impacts of future warming. Climate influences the seasonal streamflow regime which typically exhibits winter low flow, terminated by spring freshet, followed by summer flow recession. The effects of climatic variation on streamflow cannot be isolated with confidence but the impact of human regulation of rivers can greatly alter the natural flow rhythm, changing the timing of flow to suit human demands. The effect of scenario climate change on streamflow is explored through hydrological simulation. Example of a Canadian basin under warming scenario suggests that winter flow will increase, spring freshet dates will advance but peak flow will decline, as will summer flow due to enhanced evaporation. While this simulation was site specific, the results are qualitatively applicable to other boreal areas. Future studies should consider the role of human activities as their impacts on streamflow will be more profound than those due to climate change.

Yanusz, R.J., R.A. Merizon, T.M. Willette, D.G. Evans, and T.R. Spenser, 2011. *Inriver abundance and distribution of spawning Susitna River sockeye salmon Oncorhynchus nerka, 2007*. Fishery Data Series No. 11-19. Alaska Department of Fish and Game, Anchorage, Alaska. 50 pp.

Abstract: In 2006, capture-recapture experiments using passive integrated transponder (PIT) tags, fish wheels, and weirs were conducted to estimate sockeye salmon escapement in the entire Susitna River independent of the combined sonar and fish wheel estimate.

Yanusz, R.J., P. Clearly, S. Ivey, J.W. Erickson, D.J. Reed, R.A. Neustel, and J. Bullock, 2013. *Distribution of Spawning Susitna River Chinook Oncorhynchus tshawytscha and Pink Salmon O. gorbuscha, 2012*. Susitna-Watana Hydroelectric Project (FERC No. 14241). Prepared by Alaska Department of Fish and Game Division of Sport Fish for Alaska Energy Authority. April 2013.

Abstract: This report provides the results of Alaska Department of Fish and Game's (ADF&G's) Chinook and pink salmon tasks of the 2012 Adult Salmon Distribution and Habitat Utilization Study (Chinook and Pink Salmon Spawning Distribution).

Yarnell, S.M., J.H. Viers, and J.F. Mount, 2010. Ecology and Management of the Spring Snowmelt Recession. *BioScience* 60, 114–127.

Abstract: We present a conceptual model for the ecology of the spring snowmelt recession based on the natural flow regime that relates the quantifiable components of magnitude, timing, and rate of change to abiotic and biotic factors that govern riverine processes. We find that shifts in the magnitude of the recession largely affect abiotic channel conditions, whereas shifts in the timing of the snowmelt primarily affect biotic conditions. Shifts in the rate of change affect both abiotic and biotic conditions, creating the largest observed changes to the stream ecosystem. We discuss these components with regard to the success of riverine species in California's Mediterranean-montane environment. We then present two scenarios of change to the spring snowmelt recession—effects of flow regulation and climate warming—and discuss their potential implications for riverine ecology. Our conceptual model can help guide watershed stakeholders toward a better understanding of the impacts of changing spring recession conditions on stream ecosystems.

Young, D.B., and C.A. Woody, 2007a. Dynamic in-lake spawning migrations by female sockeye salmon. *Ecology of Freshwater Fish* 16, 155–164.

Abstract: Precise homing by salmon to natal habitats is considered the primary mechanism in the evolution of population-specific traits, yet few studies have focused on this final phase of their spawning migration. We radio tagged 157 female sockeye salmon (*Oncorhynchus nerka*) as they entered Lake Clark, Alaska, and tracked them every 1–10 days to their spawning locations. Contrary to past research, no specific shoreline migration pattern was observed (e.g., clockwise) nor did fish enter a tributary unless they spawned in that tributary. Tributary spawning fish migrated faster (mean = 4.7 km•day−1, SD = 2.7, vs. 1.6 km•day−1, SD = 2.1) and more directly (mean linearity = 0.8, SD = 0.2, vs. 0.4, SD = 0.2) than Lake Clark beach spawning fish. Although radio-tagged salmon migrated to within 5 km of their final spawning location in an average of 21.2 days (SD = 13.2), some fish migrated five times the distance necessary and over 50 days to reach their spawning destination. These results demonstrate the dynamic nature of this final phase of migration and support studies indicating a higher degree of homing precision by tributary spawning fish.

Young, D.B., and C.A. Woody, 2007b. Spawning Distribution of Sockeye Salmon in a Glacially Influenced Watershed: The Importance of Glacial Habitats. *Transactions of the American Fisheries Society* 136, 452–459.

Abstract: The spawning distribution of sockeye salmon *Oncorhynchus nerka* was compared between clear and glacially turbid habitats in Lake Clark, Alaska, with the use of radiotelemetry. Tracking of 241 adult sockeye salmon to 27 spawning locations revealed both essential habitats and the relationship between spawn timing and seasonal turbidity cycles. Sixty-six percent of radio-tagged sockeye salmon spawned in turbid waters (≥5 nephelometric turbidity units) where visual observation was difficult. Spawning in turbid habitats coincided with seasonal temperature declines and associated declines in turbidity and suspended sediment concentration. Because spawn timing is heritable and influenced by temperature, the observed behavior suggests an adaptive response to glacier-fed habitats, as it would reduce embryonic exposure to the adverse effects of fine sediments.

Young, P.S., J.J. Cech Jr., and L.C. Thompson, 2011. Hydropower-related pulsed-flow impacts on stream fishes: a brief review, conceptual model, knowledge gaps, and research needs. *Reviews in Fish Biology and Fisheries* 21, 713–731.

Abstract: The societal benefits of hydropower systems (e.g., relatively clean electrical power, water supply, flood control, and recreation) come with a cost to native stream fishes. We reviewed and synthesized the literature on hydropower-related pulsed flows to guide resource

managers in addressing significant impacts while avoiding unnecessary curtailment of hydropower operations. Dams may release pulsed flows in response to needs for peaking power, recreational flows, reservoir storage adjustment for flood control, or to mimic natural peaks in the hydrograph. Depending on timing, frequency, duration, and magnitude, pulsed flows can have adverse or beneficial short and long-term effects on resident or migratory stream fishes. Adverse effects include direct impacts to fish populations due to (1) stranding of fishes along the changing channel margins, (2) downstream displacement of fishes, and (3) reduced spawning and rearing success due to redd/nest dewatering and untimely or obstructed migration. Beneficial effects include: (1) maintenance of habitat for spawning and rearing, and (2) biological cues to trigger spawning, hatching, and migration. We developed a basic conceptual model to predict the effects of different types of pulsed flow, identified gaps in knowledge, and identified research activities to address these gaps. There is a clear need for a quantitative framework incorporating mathematical representations of field and laboratory results on flow, temperature, habitat structure, fish life stages by season, fish population dynamics, and multiple fish species, which can be used to predict outcomes and design mitigation strategies in other regulated streams experiencing pulsed flows.

1.2 Best Available Information

Table A-1 provides the scores for each piece of literature reviewed, based on the criteria described in the narrative portion of the ERA. The *Best Available Information Score* refers to the sum of the individual criteria scores (see Table 2 of the ERA). The *Search Category* describes the original process or attribute that was reviewed and led to inclusion. The *External or Project Source* column refers to whether the material was related to the Susitna-Watana Hydroelectric Project or was external to that project.

Table A-1

Best Available Information Scores for Literature Reviewed

Reference	Scientific Quality	Geographic Relevance	Species Relevance	Temporal Relevance	Best Available Information Score	Search Category	External or Project Source
ABR 2013	1	3	0	3	7	Riparian	Project
Achord et al. 2003	3	2	3	3	11	Habitat Attributes	External
Adam et al. 2009	3	2	0	3	8	Climate Change	External
ADF&G 1983a	2	3	3	1	9	Habitat Attributes	Project
ADF&G 1983b	2	3	3	3	11	Habitat Attributes	Project
ADF&G 2013a	2	3	3	3	11	Habitat Attributes	Project
ADF&G 2013b	2	3	3	3	11	Habitat Attributes	Project
ADF&G 2013c	2	3	3	3	11	Habitat Attributes	Project
ADF&G 2013d	2	3	3	3	11	Habitat Attributes	Project
AEA 2011	1	3	3	3	10	Project Description	Project
AEA 2012	1	3	3	3	10	Habitat Attributes	Project
AEA 2013a	1	3	3	3	10	Habitat Attributes	Project
AEA 2013b	1	3	3	3	10	Construction	Project
AEA 2013c	1	3	3	3	10	Habitat Attributes	Project
AEA 2013d	1	3	0	3	7	Habitat Attributes	Project
AEA 2013e	1	3	0	3	7	Catastrophic	Project
AEA 2013f	1	3	3	3	10	Riparian	Project
AEA 2013g	1	3	3	3	10	Habitat Attributes	Project
AEIDC 1984	1	3	3	1	8	Habitat Attributes	Project
Al-Chokhachy et al. 2013	3	1	2	3	9	Habitat Attributes	External
Alderdice et al. 1958	3	1	3	0	7	Habitat Attributes	External
Andersson et al. 2000	3	0	0	3	6	Riparian	External

Reference	Scientific Quality	Geographic Relevance	Species Relevance	Temporal Relevance	Best Available Information Score	Search Category	External or Project Source
Andrew and Geen 1960	3	2	3	0	8	Barrier	External
Arntzen et al. 2006	3	2	3	3	11	Flow	External
Barnes et al. 1985	3	1	2	1	7	Flow	External
Barnett et al. 2005	3	2	0	3	8	Climate Change	External
Barnett et al. 2008	3	1	0	3	7	Climate Change	External
Barrett et al. 1984	2	3	3	1	9	Habitat Attributes	Project
Barrett et al. 1985	2	3	3	1	9	Habitat Attributes	Project
Bartz et al. 2006	3	2	3	3	11	Catastrophic	External
Battin et al. 2007	3	2	3	3	11	Climate Change	External
Beacham and Murray 1989	3	2	3	1	9	Habitat Attributes	External
Beamish and Mahnken 2001	3	2	3	3	11	Climate Change	External
Beamish 1995	3	2	3	3	11	Climate Change	External
Beamish and Bouillon 1993	3	2	3	2	10	Climate Change	External
Beechie et al. 1994	3	2	3	2	10	Habitat Attributes	External
Beechie and Bolton 1999	3	2	3	2	10	Habitat Attributes	External
Bell et al. 2008	3	2	3	3	11	Flow	External
Bell 1985	3	2	3	2	10	Barrier	External
Bell 1990	2	2	3	2	9	Habitat Attributes	External
Ben-David et al. 1998	3	2	3	2	10	Biological Feedback	External
Berg 1994	3	2	3	2	10	Ice	External
Berggren and Filardo 1993	3	2	3	2	10	Flow	External
Bilby et al. 1996	3	2	3	2	10	Biological Feedback	External
Bjornn and Reiser 1991	3	2	3	2	10	Habitat Attributes	External
Blair et al. 1993	3	2	3	2	10	Habitat Attributes	External
Boulton et al. 1998	3	0	0	2	5	Flow	External

Reference	Scientific Quality	Geographic Relevance	Species Relevance	Temporal Relevance	Best Available Information Score	Search Category	External or Project Source
Bradford et al. 2001	3	2	3	2	10	Habitat Attributes	External
Bradford et al. 1995	3	2	3	2	10	Flow	External
Brown and Mote 2009	3	2	0	3	8	Climate Change	External
Brown et al. 1993	1	2	3	2	8	Habitat Attributes	External
Bryant 2009	3	2	3	3	11	Climate Change	External
Buckwalter 2011	2	3	3	3	11	Habitat Attributes	Project
Bunn and Arthington 2002	3	2	3	3	11	Flow	External
Burgner 1991	3	2	3	2	10	Habitat Attributes	External
Burke et al. 2009	3	2	0	3	8	Flow	External
Busch et al. 2008	2	2	3	3	10	Population Parameters	External
Cederholm et al. 1989	3	2	3	1	9	Biological Feedback	External
Cederholm et al. 1999	3	2	3	2	10	Biological Feedback	External
Clarke 1991	3	3	0	2	8	Climate Change	Project
Cleary et al. 2013	2	3	3	3	11	Habitat Attributes	Project
Collins et al. 2012	3	2	3	3	11	Riparian	External
Connor and Pflug 2004	3	2	3	3	11	Flow	External
Connor et al. 2003	3	2	3	3	11	Flow	External
Crossin et al. 2008	3	2	3	3	11	Water Quality	External
Cushman 1985	3	1	3	1	8	Trophic and Nutrients	External
Dauble et al. 2003	3	2	3	3	11	Flow	External
Dauble et al. 1999	3	2	3	2	10	Flow	External
Delaney et al. 1981a	2	3	3	1	9	Habitat Attributes	Project
Delaney et al. 1981b	2	3	3	1	9	Habitat Attributes	Project
Dittman and Quinn 1996	3	2	3	2	10	Habitat Attributes	External
Doyle et al. 2005	3	2	2	3	10	Catastrophic	External

Reference	Scientific Quality	Geographic Relevance	Species Relevance	Temporal Relevance	Best Available Information Score	Search Category	External or Project Source
Dugan et al. 1984	2	3	3	1	9	Habitat Attributes	Project
Eatonand Scheller 1996	3	2	3	2	10	Climate Change	External
Edmundson and Mazumder 2001	3	2	3	3	11	Habitat Attributes	External
Eliason et al. 2011	3	2	3	3	11	Habitat Attributes	External
Ellis and Jones 2013	3	1	0	3	7	Flow	External
Enders et al. 2012	3	0	2	3	8	Ice	External
Enders et al. 2008	3	1	2	3	9	Habitat Attributes	External
Engström et al. 2011	3	0	0	3	6	Riparian	External
Ettema 2002	3	2	0	3	8	Ice	External
Evans and Clague 1994	3	2	0	2	7	Catastrophic	External
Evenden 2004	3	2	3	3	11	Catastrophic	External
Fagan 2002	3	2	3	3	11	Habitat Attributes	External
Fair et al. 2010	2	3	3	3	11	Habitat Attributes	Project
FERC 2012	2	3	3	3	11	Project Description	Project
Fetherston et al. 1995	3	2	3	2	10	Habitat Attributes	External
Finger et al. 2006	3	0	0	3	6	Habitat Attributes	External
Finney et al. 2000	3	2	3	3	11	Climate Change	External
Finstad et al. 2004	3	0	2	3	8	Ice	External
Fisher and Lavoy 1972	3	1	0	0	4	Trophic and Nutrients	External
Flory and Milner 1999	3	2	3	2	10	Riparian	External
Foerester 1968	3	2	3	3	11	Habitat Attributes	External
Freeman et al. 2003	3	2	3	3	11	Trophic and Nutrients	External
Fukushima and Smoker 1997	3	2	3	2	10	Habitat Attributes	External
Fulton 1968	2	2	3	0	7	Barrier	External
Geist 2000	3	2	3	3	11	Flow	External

Reference	Scientific Quality	Geographic Relevance	Species Relevance	Temporal Relevance	Best Available Information Score	Search Category	External or Project Source
Geist and Dauble 1998	3	2	3	2	10	Habitat Attributes	External
Geist et al. 2010	3	2	3	3	11	Water Quality	External
Geist et al. 2002	3	2	3	3	11	Flow	External
Geist et al. 2008	3	2	3	3	11	Flow	External
Giorgi et al. 1997	3	2	3	2	10	Flow	External
Gislason 1985	3	2	0	1	6	Trophic and Nutrients	External
Goniea et al. 2006	3	2	3	3	11	Water Quality	External
Good et al. 2008	3	2	3	3	11	Catastrophic	External
Grant et al. 2003	3	2	2	3	10	Sediment	External
Greene and Beechie 2004	3	2	3	3	11	Habitat Attributes	External
Gregory and Levings 1998	3	2	3	2	10	Water Quality	External
Greig et al. 2005	3	0	2	3	8	Sediment	External
Groot et al. 1995	3	3	3	2	11	Habitat Attributes	External
Gross et al. 1998	3	2	3	2	10	Biological Feedback	External
Groves and Chandler 1999	3	2	3	2	10	Flow	External
Groves et al. 2008	3	2	3	3	11	Water Quality	External
Gustafson et al. 2007	3	2	3	3	11	Catastrophic	External
Hamilton et al. 2005	3	2	3	3	11	Barrier	External
Hanrahan et al. 2004	3	2	3	3	11	Barrier	External
Hare et al. 1999	3	2	3	2	10	Climate Change	External
Harris et al. 1987	3	2	0	1	6	Riparian	External
Harrison et al. 1983	3	3	0	1	7	Climate Change	Project
Hasler et al. 2012	3	2	3	3	11	Water Quality	External
HDR 2013a	1	3	3	3	10	Habitat Attributes	Project
HDR 2013b	1	3	3	3	10	Ice	Project

Reference	Scientific Quality	Geographic Relevance	Species Relevance	Temporal Relevance	Best Available Information Score	Search Category	External or Project Source
HDR 2013c	1	3	3	3	10	Barrier	Project
HDR 2013d	1	3	3	3	10	Barrier	Project
HDR 2013e	1	3	3	3	10	Habitat Attributes	Project
HDR 2013f	1	3	3	3	10	Habitat Attributes	Project
HDR 2013g	1	3	3	3	10	Habitat Attributes	Project
HDR 2013h	1	3	3	3	10	Habitat Attributes	Project
HDR 2013i	1	3	3	3	10	Habitat Attributes	Project
HDR 2013j	1	3	3	3	10	Barrier	Project
HDR 2013k	1	3	3	3	10	Habitat Attributes	Project
HDR 2013l	1	3	3	3	10	Habitat Attributes	Project
Healey 1991	3	2	3	2	10	Habitat Attributes	External
Healey 2009	3	2	3	3	11	Habitat Attributes	External
Healy and Hicks 2007	3	0	0	3	6	Ice	External
Heard 1991	3	2	3	2	10	Habitat Attributes	External
Hedger et al. 2013	3	1	2	3	9	Ice	External
Helfield and Naiman 2001	3	2	3	3	11	Biological Feedback	External
Higgs et al. 1995	3	2	3	2	10	Habitat Attributes	External
High et al. 2006	3	2	3	3	11	Water Quality	External
Hilborn et al. 2003	3	2	3	3	11	Habitat Attributes	External
Hill et al. 1998	3	2	0	2	7	Riparian	External
Hinch and Rand 1998	3	2	3	2	10	Flow	External
Hoar 1958	3	2	3	0	8	Habitat Attributes	External
Hodgson and Quinn 2002	3	2	3	3	11	Habitat Attributes	External
Hoem Neher et al. 2013	3	2	3	3	11	Habitat Attributes	External
Holbrook et al. 2009	3	1	2	3	9	Water Quality	External

Reference	Scientific Quality	Geographic Relevance	Species Relevance	Temporal Relevance	Best Available Information Score	Search Category	External or Project Source
Honea et al. 2009	3	2	3	3	11	Barrier	External
Horne et al. 2004	3	2	3	3	11	Water Quality	External
Hughes et al. 2008	3	1	0	3	7	Sediment	External
Huusko et al. 2007	3	0	2	3	8	Ice	External
Hvidsten 1993	3	0	2	2	7	Habitat Attributes	External
Isaak et al. 2007	3	2	3	3	11	Habitat Attributes	External
Jager and Rose 2003	3	2	3	3	11	Flow	External
Jakober et al. 1998	3	2	3	2	10	Ice	External
Jansson et al. 2000a	3	0	0	3	6	Riparian	External
Jansson et al. 2000b	3	0	0	3	6	Riparian	External
Jansson et al. 2005	3	0	0	3	6	Riparian	External
Jeffres et al. 2008	3	2	3	3	11	Habitat Attributes	External
Jennings 1985	1	3	3	1	8	Habitat Attributes	Project
Jensen 2003	3	0	2	3	8	Water Quality	External
Jones et al. 2000	3	2	3	3	11	Construction	External
Jones 2012	3	1	0	3	7	Trophic and Nutrients	External
Jones 2014	3	1	0	3	7	Flow	External
Kaeriyama et al. 2004	3	2	3	3	11	Climate Change	External
Karrenberg et al. 2002	3	0	0	3	6	Riparian	External
Keefer et al. 2008	3	2	3	3	11	Habitat Attributes	External
Kiell 1982	3	1	2	1	7	Flow	External
Kimmerer 2002	3	2	3	3	11	Habitat Attributes	External
Kline et al. 1993	3	2	3	2	10	Biological Feedback	External
Kondolf 1997	3	2	3	2	10	Sediment	External
Kondolf and Wolman 1993	3	2	3	2	10	Habitat Attributes	External

Reference	Scientific Quality	Geographic Relevance	Species Relevance	Temporal Relevance	Best Available Information Score	Search Category	External or Project Source
Konecki et al. 1995	3	2	3	2	10	Habitat Attributes	External
Konrad et al. 2011	3	2	0	3	8	Flow	External
Korman and Campana 2009	3	1	3	3	10	Flow	External
Korman et al. 2011	3	1	3	3	10	Flow	External
Kovach et al. 2013	3	2	3	3	11	Climate Change	External
Larsen et al. 2008	3	3	0	3	9	Climate Change	External
Lehner et al. 2005	3	0	0	3	6	Climate Change	External
LGL 2011	1	3	3	3	10	Habitat Attributes	Project
LGL 2013	1	3	3	3	10	Habitat Attributes	Project
Ligon et al. 1995	3	2	3	2	10	Habitat Attributes	External
Linnansaari et al. 2009	3	1	2	3	9	Ice	External
Linnansaari and Cunjak 2010	3	1	2	3	9	Ice	External
Lloyd et al. 1987	3	2	0	1	6	Water Quality	External
Lorenz and Filer 1989	3	2	3	1	9	Habitat Attributes	External
Lytle and Poff 2004	3	2	3	3	11	Flow	External
Maeck et al. 2013	3	0	0	3	6	Habitat Attributes	External
Mantua et al. 2010	3	2	3	3	11	Climate Change	External
Mantua and Hare 2002	3	2	3	2	10	Climate Change	External
Mantua et al. 1997	3	2	3	3	11	Climate Change	External
Marchetti and Moyle 2001	3	2	3	3	11	Flow	External
McElhany et al. 2000	3	2	3	3	11	Population Parameters	External
McGlauflin et al. 2011	3	2	3	3	11	Habitat Attributes	External
McMichael et al. 2005a	3	2	3	3	11	Flow	External
McMichael et al. 2005b	3	2	3	3	11	Flow	External
Meixler et al. 2009	3	2	3	3	11	Barrier	External

Reference	Scientific Quality	Geographic Relevance	Species Relevance	Temporal Relevance	Best Available Information Score	Search Category	External or Project Source
Merizon et al. 2010	1	3	3	3	10	Habitat Attributes	Project
Mesa et al. 2000	3	2	3	3	11	Water Quality	External
Milner and Petts 1994	3	2	3	2	10	Habitat Attributes	External
Molnia 2007	3	3	0	3	9	Climate Change	External
Montgomery et al. 1996	3	2	3	2	10	Sediment	External
Moog 1993	3	0	1	2	6	Trophic and Nutrients	External
Moore et al. 2010	3	2	3	3	11	Habitat Attributes	External
Moore et al. 2004	3	2	3	3	11	Biological Feedback	External
Morgan et al. 1991	3	1	0	2	6	Trophic and Nutrients	External
Morrow 1980	3	3	3	0	9	Habitat Attributes	External
Moser 1899	0	2	3	0	5	Catastrophic	External
Mote 2006	3	2	0	3	8	Climate Change	External
Mundie and Bell-Irving 1986	3	2	3	1	9	Habitat Attributes	External
Murchie et al. 2008	3	2	3	3	11	Flow	External
Murphy et al. 2006	3	2	3	1	9	Habitat Attributes	External
Murphy et al. 1989	3	2	3	2	10	Habitat Attributes	External
Murphy et al. 1997	3	1	2	3	9	Ice	External
Murray and McPhail 1988	3	2	3	1	9	Habitat Attributes	External
Naiman et al. 1999	3	2	3	2	10	Habitat Attributes	External
Naiman et al. 2008	3	2	3	3	11	Flow	External
Neal et al. 2010	3	3	0	3	9	Climate Change	External
Neal et al. 2002	3	2	0	3	8	Climate Change	External
Nickelson and Lawson 1998	3	2	3	2	10	Habitat Attributes	External
Nielsen et al. 2013	3	2	3	3	11	Climate Change	External
Nilsson and Berggren 2000	3	2	3	3	11	Habitat Attributes	External

Reference	Scientific Quality	Geographic Relevance	Species Relevance	Temporal Relevance	Best Available Information Score	Search Category	External or Project Source
Nilsson et al. 1991	3	0	0	3	6	Riparian	External
Nilsson and Svedmark 2002	3	2	3	2	10	Riparian	External
O'Connor 2004	3	2	3	3	11	Catastrophic	External
Owens et al. 2005	3	2	3	3	11	Sediment	External
Paragamian 2002	3	1	1	3	8	Trophic and Nutrients	External
Pinay et al. 2002	3	1	0	3	7	Trophic and Nutrients	External
Poff et al. 1997	3	2	3	2	10	Flow	External
Poff and Zimmerman 2010	3	2	3	3	11	Flow	External
Power 2006	3	2	3	3	11	Trophic and Nutrients	External
Power et al. 1996	3	2	3	3	11	Flow	External
Prowse et al. 2011	3	1	0	3	7	Climate Change	External
Prowse and Beltaos 2002	3	2	3	2	10	Ice	External
Prowse and Conly 1998	3	1	0	3	7	Ice	External
Prowse and Culp 2003	3	1	0	3	7	Ice	External
Quinn 2011	3	2	3	2	10	Habitat Attributes	External
Quinn and Dittman 1990	3	2	3	2	10	Habitat Attributes	External
R2 Resource Consultants 2013a	1	3	3	3	10	Flow	Project
R2 Resource Consultants 2013b	1	3	3	3	10	Riparian	Project
R2 Resource Consultants 2013c	1	3	3	3	10	Habitat Attributes	Project
R2 Resource Consultants et al. 2013	1	3	3	3	10	Flow	Project
Ramstad et al. 2009	3	2	3	3	11	Habitat Attributes	External
Regetz 2003	3	2	3	3	11	Habitat Attributes	External
Richterand Kolmes 2005	3	2	3	3	11	Habitat Attributes	External
Riis and Friese 1977	2	3	3	0	8	Habitat Attributes	Project

Reference	Scientific Quality	Geographic Relevance	Species Relevance	Temporal Relevance	Best Available Information Score	Search Category	External or Project Source
Rogers et al. 2013	3	2	3	3	11	Climate Change	External
Rood et al. 2003	3	1	0	3	7	Riparian	External
Rood et al. 2007	3	1	0	3	7	Riparian	External
Rørslett et al. 1989	3	0	0	1	4	Ice	External
Rosenfeld and Boss 2001	3	2	2	3	10	Habitat Attributes	External
Roth et al. 1986	2	3	3	1	9	Habitat Attributes	Project
Roussel et al. 2004	3	1	2	3	9	Ice	External
Ryan et al. 2000	3	2	1	3	9	Water Quality	External
Salo 1991	3	3	3	2	11	Habitat Attributes	External
Sandercock 1991	3	3	3	2	11	Habitat Attributes	External
Scheuerell et al. 2006	3	2	3	3	11	Habitat Attributes	External
Scheuerell et al. 2005	3	2	3	3	11	Biological Feedback	External
Schick and Lindley 2007	3	2	3	3	11	Habitat Attributes	External
Schindler et al. 2010	3	2	3	3	11	Habitat Attributes	External
Schindler et al. 2005	3	2	3	3	11	Habitat Attributes	External
Schindler et al. 2003	3	2	2	3	10	Biological Feedback	External
Schindler 2001	3	2	3	3	11	Habitat Attributes	External
Schmidt and Bingham 1983	3	3	3	1	10	Habitat Attributes	Project
Schmidt et al. 1984	3	3	3	1	10	Habitat Attributes	Project
Scott et al. 1996	3	1	0	2	6	Sediment	External
Scrimgeour et al. 1994	3	1	2	2	8	Ice	External
Scruton et al. 2005	3	1	2	3	9	Flow	External
Seiler et al. 2003	1	2	3	3	9	Habitat Attributes	External
Servizi and Martens 1992	3	2	3	2	10	Water Quality	External
Sharma et al. 2005	3	2	3	3	11	Habitat Attributes	External

Reference	Scientific Quality	Geographic Relevance	Species Relevance	Temporal Relevance	Best Available Information Score	Search Category	External or Project Source
She et al. 2012	3	1	0	3	7	Ice	External
Sheer and Steel 2006	3	2	3	3	11	Barrier	External
Sigler et al. 1984	3	2	3	1	9	Water Quality	External
Sikder and Elahi 2013	3	0	0	3	6	Climate Change	External
Smith et al. 2003	3	2	3	3	11	Flow	External
Sommer et al. 2001	3	2	3	3	11	Flow	External
Steel et al. 2004	3	2	3	3	11	Barrier	External
Stella et al. 2006	3	1	0	3	7	Riparian	External
Stewart et al. 2004	3	2	0	3	8	Climate Change	External
Stewart et al. 2005	3	2	0	3	8	Climate Change	External
Stickler et al. 2010	3	1	2	3	9	Ice	External
Stickler et al. 2008	3	1	2	3	9	Ice	External
Stone et al. 2002	3	2	0	3	8	Climate Change	External
Stratton 1986	2	3	3	1	9	Habitat Attributes	Project
Suchanek et al. 1984	2	3	3	1	9	Habitat Attributes	Project
Sui et al. 2005	3	0	0	3	6	Ice	External
Tappel and Bjornn 1983	3	2	3	1	9	Habitat Attributes	External
Tetra Tech 2013a	1	3	3	3	10	Habitat Attributes	Project
Tetra Tech 2013b	1	3	3	3	10	Sediment	Project
Tetra Tech 2013c	1	3	3	3	10	Sediment	Project
Tetra Tech 2013d	1	3	3	3	10	Sediment	Project
Tetra Tech 2013e	1	3	3	3	10	Flow	Project
Tetra Tech 2013f	1	3	3	3	10	Flow	Project
Tetra Tech and Watershed Geodynamics 2014	1	3	3	3	10	Habitat Attributes	Project

Reference	Scientific Quality	Geographic Relevance	Species Relevance	Temporal Relevance	Best Available Information Score	Search Category	External or Project Source
Thompson et al. 1986	2	3	3	1	9	Habitat Attributes	Project
Todd et al. 2001	2	3	3	3	11	Habitat Attributes	Project
Trihey 1982	1	3	3	1	8	Habitat Attributes	Project
Trihey & Associates and Entrix 1985	1	3	3	1	8	Habitat Attributes	Project
Trombulak and Frissell 2000	3	2	3	3	11	Construction	External
Ugedal et al. 2008	3	0	2	3	8	Flow	External
URS and Tetra Tech 2013a	1	3	0	3	7	Water Quality	Project
URS and Tetra Tech 2013b	1	3	3	3	10	Sediment	Project
Valentin et al. 1995	3	0	0	2	5	Trophic and Nutrients	External
Vining and Freeman 1985	2	3	3	1	9	Habitat Attributes	Project
Wangaard and Burger 1983	2	3	3	1	9	Habitat Attributes	Project
Waples et al. 2009	3	2	3	3	11	Catastrophic	External
Waples et al. 2008a	3	2	3	3	11	Catastrophic	External
Waples et al. 2008b	3	2	3	3	11	Catastrophic	External
Waythomas et al. 1996	3	2	0	2	7	Catastrophic	External
Weitkamp et al. 2003a	3	2	3	3	11	Habitat Attributes	External
Weitkamp et al. 2003b	3	2	3	3	11	Habitat Attributes	External
Welch et al. 1998	3	2	3	2	10	Climate Change	External
Werner and Gilliam 1984	3	0	2	1	6	Habitat Attributes	External
Whitney et al. 2013	3	2	3	3	11	Habitat Attributes	External
Willette et al. 2003	2	3	3	3	11	Habitat Attributes	Project
Williams et al. 2008	3	2	3	3	11	Catastrophic	External
Willson et al. 1998	3	2	3	2	10	Biological Feedback	External
Willson and Halupka 1995	3	2	3	2	10	Biological Feedback	External

Reference	Scientific Quality	Geographic Relevance	Species Relevance	Temporal Relevance	Best Available Information Score	Search Category	External or Project Source
Winder and Schindler 2004	3	2	3	3	11	Climate Change	External
Wipfli et al. 1998	3	2	3	2	10	Biological Feedback	External
Wofford et al. 2005	3	2	3	3	11	Barrier	External
Woo et al. 2008	3	2	0	3	8	Climate Change	External
Yanusz et al. 2013	2	3	3	3	11	Habitat Attributes	Project
Yanusz et al. 2011	2	3	3	3	11	Habitat Attributes	Project
Yarnell et al. 2010	3	2	3	3	11	Climate Change	External
Young and Woody 2007a	3	2	3	3	11	Habitat Attributes	External
Young and Woody 2007b	3	2	3	3	11	Habitat Attributes	External
Young et al. 2011	3	2	3	3	11	Habitat Attributes	External

APPENDIX B
SPECIES HABITAT ATTRIBUTE AND PERIODICITY TABLES

Table B-1

Habitat Attributes Required for Chinook Salmon Freshwater Life History Stages

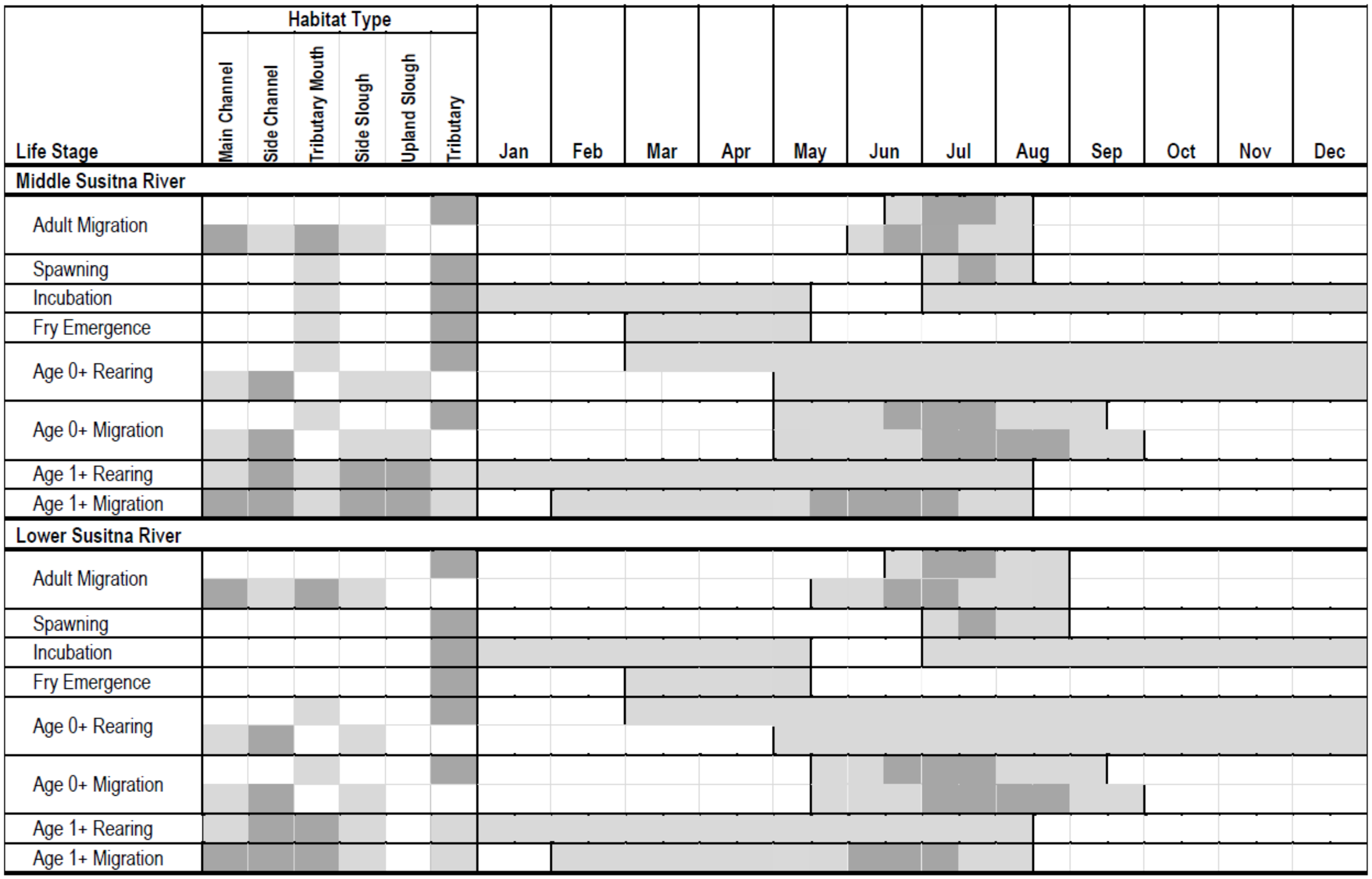
Life History Stage	Water Quality	Water Quantity	Habitat Connectivity	Habitat Structure
Fertilization to hatch	Survival highest at 5° to 11°C (Murray and McPhail 1988) Thermal tolerance 0°C to 16°C (AEIDC 1984) Preferred 4°C to 12°C (AEIDC 1984) Incubation occurs between 38 to 202 days at 14°C and 2°C, respectively (Murray and McPhail 1988) The thermal environment in Snake River redds is similar to surface water (Groves et al. 2008) Water temperature and the origin of a stock play an important role in embryonic development and emergence timing and explain variation therein (Beacham and Murray 1989) Sufficient dissolved oxygen level to support embryonic development; minimum of >5 mg/L (Bjornn and Reiser 1991; Quinn 2011) Reduced intragravel dissolved oxygen concentrations occur when oxygen consuming material infiltrates spawning and incubation gravels (Greig et al. 2005)	Continuous surface flow or upwelling to oxygenate embryos (Bjornn and Reiser 1991) Sufficient depth to cover eggs and prevent dewatering or freezing (Bjornn and Reiser 1991; Vining and Freeman 1985) Dewatering egg mortality varies (McMichael et al. 2005) and is related to other environmental conditions (i.e., temperature and humidity) Stable flows to preserve the integrity of egg-gravel matrices	Spawning substrates require connection with surface water or groundwater to promote hyporheic flow (Bjornn and Reiser 1991)	Substrate interstices for hyporheic flow supporting respiration (Quinn 2011) Appropriately sized spawning substrates (Kondolf and Wolman 1993) Low proportion of fines (Bjornn and Reiser 1991) Stable substrate (Montgomery et al. 1996) Incubation success is inhibited by the impact of fine sediment accumulation on gravel permeability and the impact of fine particles (clay) on the exchange of oxygen across the egg membrane (Greig et al. 2005)
Hatch to emergence	Survival is highest at 2° to 14°C (Murray and McPhail 1988) Post-hatch to emergence lasts between 25 to 114 days at 14°C and 2°C, respectively (Murray and McPhail 1988)	Continuous surface flow or upwelling to oxygenate embryos (Bjornn and Reiser 1991) Sufficient depth to cover eggs and prevent dewatering or freezing (Bjornn and Reiser 1991; Vining and Freeman 1985)	Connectivity between spawning gravels and migratory corridors and rearing habitat (Bjornn and Reiser 1991)	Substrate interstices for movement through gravel (Bjornn and Reiser 1991)
Emergence to smolting	Upper weekly thermal tolerance is 24°C (Eaton and Scheller 1996) Thermal tolerance 2°C to 16°C (AEIDC 1984) Preferred 7°C to 14°C (AEIDC 1984) Growth in constant thermal regimes is potentially	Adequate flow to maintain carrying capacity and buffer temperatures (Bjornn and Reiser 1991) Variation in stream velocity and depth to provide resting areas, high-flow refugia, predator refugia and mobilize prey items (Bjornn and Reiser 1991)	Connections among rearing habitats, refugia, and migratory corridors (Bjornn and Reiser 1991) Winter ice can temporarily disrupt connectivity causing changes in behavior, distribution and survival in winter (Berg 1994; Bradford et al. 2001; Jakober et al. 1998; Linnansaari and Cunjak 2010; Whelan et al. 1999)	Previous Susitna studies noted habitat use by juvenile Chinook according to the following categories (percent is based on relative density within the habitats sampled): side channels 23.0%, side sloughs 9.3%, tributaries 61%, and upland sloughs 6.7%. In the glacial Taku River, Alaska, juvenile Chinook were most abundant in habitats with faster currents (1 to 20 cm/s),

Life History Stage	Water Quality	Water Quantity	Habitat Connectivity	Habitat Structure
	higher than fluctuating regimes, even when daily average temperatures are similar (Geist et al. 2010). Turbidity refugia (Bjornn and Reiser 1991) Water temperature affects the mobility and distribution of juvenile salmonids in winter (Enders et al. 2008). Exposures to total dissolved gas of 120% elicit progressively worsening symptoms of gas bubble disease in fishes (Mesa et al. 2000; Ryan et al. 2000)		Ephemeral connections between floodplains and river channels may contribute to growth (Jeffres et al. 2008)	particularly channel edges (Murphy et al. 1989) Within the Susitna River, juvenile Chinook salmon summer and fall diets are dominated by adult insects and immature insects. (Riis and Friese 1977 cited in R2 Resource Consultants 2013) Both inwater and riparian cover (i.e., trees, boulders, large woody debris) to stage for feeding, avoid predators, create flow heterogeneity (Bjornn and Reiser 1991) Habitat complexity to support ontogenetic niche shifts (Rosenfeld and Boss 2001; Werner and Gilliam 1984) Appropriate substrates to provide hiding areas, support production of benthic invertebrate prey, and cover during winter and summer (Bjornn and Reiser 1991) Space for foraging, avoiding predators and exhibiting territories; larger fish need more space (Bjornn and Reiser 1991) Ice cover may increase overwinter survival of salmonids by preserving energy reserves (Hedger et al. 2013) Floodplains rearing may enhance the growth and survival of juvenile salmon (Jeffres et al. 2008; Sommer et al. 2001) Surface ice may represent an important structural habitat element for overwintering salmonids (Linnansaari et al. 2009) Lower river areas of large glacial rivers can provide essential rearing habitat for juvenile salmon spawned upriver (Murphy et al. 1997)
Smolting	Thermal tolerance 4^{o}C to 16^{o}C (AEIDC 1984) Preferred 7^{o}C to 14^{o}C (AEIDC 1984) Seasonal temperature cues may contribute to smoltification and synchronization of outmigration (Groot et al. 1995) Turbidity during outmigration reduces exposure to predation (Gregory and Levings 1998)	Smolting and outmigration to the marine environment may be synchronized with increasing flows (Quinn 2011)	Connectivity between freshwater and marine environments/lack of barriers (Quinn 2011)	

Life History Stage	Water Quality	Water Quantity	Habitat Connectivity	Habitat Structure
Migration from ocean to spawning grounds	Upper weekly thermal tolerance is 24°C (Eaton and Scheller 1996) Thermal tolerance is 2°C to 16°C (AEIDC 1984) Preferred range is 7°C to 13°C (AEIDC 1984) In the absence of cool water refugia, some Chinook successfully migrate in temperatures of 21°C (Hasler et al. 2012) Median migration rates through the lower Columbia River slowed significantly when water temperatures were above about 20°C (Goniea et al. 2006) Adequate dissolved oxygen (>5 mg/L) (Bjornn and Reiser 1991) Turbidity may delay migrations (Bjornn and Reiser 1991)	Sufficient flow (high or low) to allow passage of natural barriers (Bjornn and Reiser 1991) Sufficient flows to meet minimum depth and maximum velocity criteria for each species (Bjornn and Reiser 1991)	Maximum velocity for passage into Susitna River tributary spawning habitats was 2.4 m/s for Chinook (R2 Resource Consultants 2013b) Minimum depth for passage to Susitna River tributary spawning habitats was 24 cm for Chinook salmon (R2 Resource Consultants 2013b) Access to spawning habitats/absence of barriers to passage (Bjornn and Reiser 1991; Evenden 2004; O'Connor 2004) Access to spawning habitats/absence of barriers to passage (Bjornn and Reiser 1991; Evenden 2004; Holbrook et al. 2009; O'Connor 2004) Lack of thermal barriers (Hodgson and Quinn 2002)	Cool water tributaries appear to represent critical thermal refugia in warm years (Goniea et al. 2006) Channel complexity sufficient to create holding areas, flow refugia, and staging areas for passing barriers (Bjornn and Reiser 1991)
Spawning	Thermal tolerance 5°C to 14°C (AEIDC 1984) Preferred 7°C to 12°C (AEIDC 1984) Fall Chinook spawning occurred in areas of the Hanford Reach of the Columbia River, where hyporheic dissolved oxygen concentrations were 9 mg/L (Geist 2000); in the Snake River, fall Chinook spawning begins at 16.0°C, and concludes as temperatures approach 5.0°C (Groves and Chandler 1999)	Chinook salmon often spawn in areas with hyporheic flow (Geist 2000) Adequate flow and depth for movement and predator avoidance (Bjornn and Reiser 1991) Adequate flow to cover spawning grounds and maximize spawning habitat (Bjornn and Reiser 1991)	Spawning habitat size and connectivity plays an important role in buffering the effects of habitat degradation (Isaak et al. 2007)	Chinook salmon spawning habitat is primarily within tributaries of the Susitna River (R2 Resource Consultants 2013b) In the Snake River, spawning occurs in substrates with relatively homogenous particle diameters between 2.5 to 15.0 cm (Groves and Chandler 1999) Redd site selection is dependent on microhabitat characteristics that reflect the interaction between geomorphic features and hydraulic processes (Geist 2000) Adequate space to reduce superimposition (Bjornn and Reiser 1991) Cover from disturbance and predation (Bjornn and Reiser 1991) There is wide variation in spawning substrate size utilized by spawners, both within and among species, but in general larger fish can use larger substrates (Kondolf and Wolman 1993)

Notes:
mg/L – milligrams per liter
m/s – meters per second

Table B-2
Periodicity of Chinook Salmon Utilization among Macrohabitat Types in the Middle (RM 184 to 98.5) and Lower (RM 8.5 to 0.0) Segments of the Susitna River by Life History Stage



Note: In the upper segment (RM 260 to RM 184), adult Chinook are believed to exhibit similar habitat use to that shown for the middle segment, while juvenile Chinook rearing and migration timing in this segment is not known. Light gray shaded areas indicate timing of utilization by macrohabitat type, and dark gray areas represent areas and timing of peak use (R2 Resource Consultants 2013c).

Table B-3

Habitat Attributes Required for Chum Salmon Freshwater Life History Stages

Life History Stage	Water Quality	Water Quantity	Habitat Connectivity	Habitat Structure
Fertilization to hatch	Survival highest at 8° to 14°C (Murray and McPhail 1988) Thermal tolerance 0°C to 12°C (AEIDC 1984) Preferred 2°C to 8°C (AEIDC 1984) Incubation occurs between 46 to 97 days at 14°C and 5°C, respectively (Murray and McPhail 1988) Dissolved oxygen at 7.19 mg/L near time of hatching (Alderdice et al. 1958) Water temperature and the origin of a stock play an important role in embryonic development and emergence timing and explain variation therein (Beacham and Murray 1989) Sufficient dissolved oxygen level to support embryonic development; minimum of >5 mg/L (Bjornn and Reiser 1991; Quinn 2011) Reduced intragravel dissolved oxygen concentrations occur when oxygen consuming material infiltrates spawning and incubation gravels (Greig et al. 2005)	Continuous surface flow or upwelling to oxygenate embryos (Bjornn and Reiser 1991) Sufficient depth to cover eggs and prevent dewatering or freezing (Bjornn and Reiser 1991; Vining and Freeman 1985) Dewatering egg mortality varies (McMichael et al. 2005) and is related to other environmental conditions (i.e., temperature and humidity) Stable flows to preserve the integrity of egg-gravel matrices	Spawning substrates require connection with surface water or groundwater to promote hyporheic flow (Bjornn and Reiser 1991)	Substrate interstices for hyporheic flow supporting respiration (Quinn 2011) Appropriately sized spawning substrates (Kondolf and Wolman 1993) Low proportion of fines (Bjornn and Reiser 1991) Stable substrate (Montgomery et al. 1996) Incubation success is inhibited by the impact of fine sediment accumulation on gravel permeability and the impact of fine particles (clay) on the exchange of oxygen across the egg membrane (Greig et al. 2005)
Hatch to emergence	Survival highest at 5°C to 8°C (Murray and McPhail 1988) Post-hatch to emergence lasts between 40 to 64 days at 14°C and 5°C, respectively (Murray and McPhail 1988)	Continuous surface flow or upwelling to oxygenate embryos (Bjornn and Reiser 1991) Sufficient depth to cover eggs and prevent dewatering or freezing (Bjornn and Reiser 1991; Vining and Freeman 1985)	Connectivity between spawning gravels and migratory corridors and rearing habitat (Bjornn and Reiser 1991)	Substrate interstices for movement through gravel (Bjornn and Reiser 1991)
Emergence to outmigration	Upper weekly thermal tolerance is 19.8°C (Eaton and Scheller 1996) Thermal tolerance 1.5°C to 16.0°C (AEIDC 1984) Preferred 5°C to 15°C (AEIDC 1984)	Adequate flow to maintain carrying capacity and buffer temperatures (Bjornn and Reiser 1991) Variation in stream velocity and depth to provide resting areas, high-flow	Connections among rearing habitats, refugia, and migratory corridors (Bjornn and Reiser 1991) Winter ice can temporarily disrupt connectivity causing changes in behavior,	Previous Susitna studies noted habitat use by juvenile chum salmon according to the following categories (percent is based on relative density within the habitats sampled): side channels 4.1%, side sloughs 59.3%, tributaries 34.1%, and upland sloughs 2.5% (Dugan et al. 1984) Juvenile chum salmon feed on insects, primarily chironomids and some

Life History Stage	Water Quality	Water Quantity	Habitat Connectivity	Habitat Structure
	Turbidity refugia (Bjornn and Reiser 1991) Water temperature affects the mobility and distribution of juvenile salmonids in winter (Enders et al. 2008). Exposures to total dissolved gas of 120% elicit progressively worsening symptoms of gas bubble disease in fishes (Mesa et al. 2000; Ryan et al. 2000)	refugia, predator refugia and mobilize prey items (Bjornn and Reiser 1991).	distribution and survival in winter (Berg 1994; Bradford et al. 2001; Jakober et al. 1998; Linnansaari and Cunjak 2010; Whelan et al. 1999) Ephemeral connections between floodplains and river channels may contribute to growth (Jeffres et al. 2008)	crustaceans; in general their diet consists of benthic or epibenthic detritivores (Higgs et al. 1995) Both inwater and riparian cover (i.e., trees, boulders, large woody debris) to stage for feeding, avoid predators, and create flow heterogeneity (Bjornn and Reiser 1991) Habitat complexity to support ontogenetic niche shifts (Rosenfeld and Boss 2001; Werner and Gilliam 1984) Appropriate substrates to provide hiding areas, support production of benthic invertebrate prey, and cover during winter and summer (Bjornn and Reiser 1991) Space for foraging, avoiding predators, and exhibiting territories. Larger fish need more space.(Bjornn and Reiser 1991) Ice cover may increase overwinter survival of salmonids by preserving energy reserves (Hedger et al. 2013) Floodplains rearing may enhance the growth and survival of juvenile salmon (Jeffres et al. 2008; Sommer et al. 2001) When water temperatures drop, surface ice may represent an important structural habitat element for overwintering salmonids (Linnansaari et al. 2009) Lower river areas of large glacial rivers can provide essential rearing habitat for juvenile salmon spawned upriver (Murphy et al. 1997)
Outmigration (chum salmon do not have a distinct smolt phase)	Thermal tolerance 3°C to 13°C (AEIDC 1984) Preferred 5°C to 12°C (AEIDC 1984) Seasonal temperature cues may contribute to smoltification and synchronization of outmigration (Groot et al. 1995) Turbidity during outmigration reduces exposure to predation (Gregory and Levings 1998)	Smolting and outmigration to the marine environment may be synchronized with increasing flows (Quinn 2011)	Connectivity between freshwater and marine environments/lack of barriers (Quinn 2011)	
Migration from ocean to spawning grounds	Upper weekly thermal tolerance is 19.8°C (Eaton and Scheller 1996) Thermal tolerance 1.5°C to 18.0°C (AEIDC 1984) Preferred 6°C to 13°C (AEIDC 1984)	Sufficient flow (high or low) to allow passage of natural barriers (Bjornn and Reiser 1991) Sufficient flows to meet minimum depth and maximum velocity criteria	Maximum velocity for passage into Susitna River tributary spawning habitats was 2.4 m/s for chum salmon (R2 Resource Consultants 2013b) Minimum depth for passage to Susitna	Channel complexity sufficient to create holding areas, flow refugia and staging areas for passing barriers (Bjornn and Reiser 1991)

Life History Stage	Water Quality	Water Quantity	Habitat Connectivity	Habitat Structure
	Adequate dissolved oxygen (>5mg/L) (Bjornn and Reiser 1991) Turbidity may delay migrations (Bjornn and Reiser 1991)	for each species (Bjornn and Reiser 1991)	River tributary spawning habitats was estimated at 18 cm for chum salmon (R2 Resource Consultants 2013b) Access to chum salmon spawning habitats in sloughs is controlled by Susitna River mainstem discharge (R2 Resource Consultants 2013b) Access to spawning habitats/absence of barriers to passage (Bjornn and Reiser 1991; Evenden 2004; Holbrook et al. 2009; O'Connor 2004) Lack of thermal barriers (Hodgson and Quinn 2002)	
Spawning	Thermal tolerance 1°C to 14°C (AEIDC 1984) Preferred 6°C to 13°C (AEIDC 1984) Chum salmon may use temperature cues from upwelling to choose specific spawning locations (Geist et al. 2002)	Adequate flow and depth for movement and predator avoidance (Bjornn and Reiser 1991) Adequate flow to cover spawning grounds and maximize spawning habitat (Bjornn and Reiser 1991)	Spawning habitat size and connectivity plays an important role in buffering the effects of habitat degradation (Isaak et al. 2007)	Primary spawning habitats in tributary and side sloughs with secondary habitats in side channel and mainstem habitats of Susitna River (R2 Resource Consultants 2013b) Adequate space to reduce superimposition (Bjornn and Reiser 1991) Cover from disturbance and predation (Bjornn and Reiser 1991) There is wide variation in spawning substrate size utilized by spawners, both within and among species, but in general larger fish can use larger substrates (Kondolf and Wolman 1993)

Notes:
mg/L – milligrams per liter
m/s – meters per second

Table B-4

Periodicity of Chum Salmon Utilization among Macrohabitat Types in the Middle (RM 184 to 98.5) and Lower (RM 98.5 to 0.0) Segments of the Susitna River by Life History Stage

Life Stage	Habitat Type						Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
	Main Channel	Side Channel	Tributary Mouth	Side Slough	Upland Slough	Tributary												
Middle Susitna River																		
Adult Migration																		
Spawning																		
Incubation																		
Fry Emergence																		
Age 0+ Rearing																		
Age 0+ Migration																		
Lower Susitna River																		
Adult Migration																		
Spawning																		
Incubation																		
Fry Emergence																		
Age 0+ Rearing																		
Age 0+ Migration																		

Note: Light gray shaded areas indicate timing of utilization by macrohabitat type, and dark gray areas represent areas and timing of peak use (R2 Resource Consultants 2013c).

Table B-5

Habitat Attributes Required for Coho Salmon Freshwater Life History Stages

Life History Stage	Water Quality	Water Quantity	Habitat Connectivity	Habitat Structure
Fertilization to hatch	Survival highest at 5°C to 11°C (Murray and McPhail 1988) Thermal tolerance 0°C to 14°C (AEIDC 1984) Preferred 4°C to 10°C (AEIDC 1984) Incubation occurs between 32 to 115 days at 14°C and 2°C, respectively (Murray and McPhail 1988) Water temperature and the origin of a stock play an important role in embryonic development and emergence timing and explain variation therein (Beacham and Murray 1989) Sufficient dissolved oxygen level to support embryonic development; minimum of >5 mg/L (Bjornn and Reiser 1991; Quinn 2011) Reduced intragravel dissolved oxygen concentrations occur when oxygen consuming material infiltrates spawning and incubation gravels (Greig et al. 2005)	Continuous surface flow or upwelling to oxygenate embryos (Bjornn and Reiser 1991) Sufficient depth to cover eggs and prevent dewatering or freezing (Bjornn and Reiser 1991; Vining and Freeman 1985) Dewatering egg mortality varies (McMichael et al. 2005) and is related to other environmental conditions (i.e., temperature and humidity) Stable flows to preserve the integrity of egg-gravel matrices	Spawning substrates require connection with surface water or groundwater to promote hyporheic flow (Bjornn and Reiser 1991)	Substrate interstices for hyporheic flow supporting respiration (Quinn 2011) Appropriately sized spawning substrates (Kondolf and Wolman 1993) Low proportion of fines (Bjornn and Reiser 1991) Stable substrate (Montgomery et al. 1996) Incubation success is inhibited by the impact of fine sediment accumulation on gravel permeability and the impact of fine particles (clay) on the exchange of oxygen across the egg membrane (Greig et al. 2005)
Hatch to emergence	Survival highest at 2°C to 8°C (Murray and McPhail 1988) Post-hatch to emergence lasts between 29 to 113 days at 14°C and 2°C, respectively (Murray and McPhail 1988)	Continuous surface flow or upwelling to oxygenate embryos (Bjornn and Reiser 1991) Sufficient depth to cover eggs and prevent dewatering or freezing (Bjornn and Reiser 1991; Vining and Freeman 1985)	Connectivity between spawning gravels and migratory corridors and rearing habitat (Bjornn and Reiser 1991)	Substrate Interstices for movement through gravel (Bjornn and Reiser 1991)
Emergence to smolting	Observed thermal limit to 29.2°C (Konecki et al. 1995) Upper weekly thermal tolerance of 23.4°C (Eaton and Scheller 1996) Thermal tolerance 2°C to 18°C (AEIDC 1984) Preferred 7°C to 15°C (AEIDC 1984)	Adequate flow to maintain carrying capacity and buffer temperatures (Bjornn and Reiser 1991) Variation in stream velocity and depth to provide resting areas, high-flow refugia, predator refugia and mobilize prey items (Bjornn and Reiser 1991)	Connections among rearing habitats, refugia, and migratory corridors (Bjornn and Reiser 1991) Winter ice can temporarily disrupt connectivity causing changes in behavior, distribution and survival in winter (Berg 1994; Bradford et al. 2001; Jakober et al. 1998; Linnansaari and Cunjak 2010; Whelan	Previous Susitna studies noted habitat use by juvenile coho salmon according to the following categories (percent is based on relative density within the habitats sampled): side channels 4.0%, side sloughs 9.8%, tributaries 51.0%, and upland sloughs 35.3% (Dugan et al. 1984) In the glacial Taku River, Alaska, juvenile coho were most abundant in beaver ponds and upland sloughs (Murphy et al. 1989) Within the Susitna River, juvenile coho salmon summer diets are dominated by

Life History Stage	Water Quality	Water Quantity	Habitat Connectivity	Habitat Structure
	Turbidity refugia (Bjornn and Reiser 1991) Water temperature affects the mobility and distribution of juvenile salmonids in winter (Enders et al. 2008). Exposures to total dissolved gas of 120% elicit progressively worsening symptoms of gas bubble disease in fishes (Mesa et al. 2000; Ryan et al. 2000)		et al. 1999) Ephemeral connections between floodplains and river channels may contribute to growth (Jeffres et al. 2008)	adult insects and immature insects; fall diets are also dominated by adult insects followed by other non-insect and crustacean prey (Riis and Friese 1977 cited in R2 Resource Consultants 2013a) Both inwater and riparian cover (i.e., trees, boulders, large woody debris) to stage for feeding, avoid predators, and create flow heterogeneity (Bjornn and Reiser 1991) Habitat complexity to support ontogenetic niche shifts (Rosenfeld and Boss 2001; Werner and Gilliam 1984) Appropriate substrates to provide hiding areas, support production of benthic invertebrate prey, and cover during winter and summer (Bjornn and Reiser 1991) Space for foraging, avoiding predators and exhibiting territories; larger fish need more space (Bjornn and Reiser 1991) Ice cover may increase overwinter survival of salmonids by preserving energy reserves (Hedger et al. 2013) Floodplains rearing may enhance the growth and survival of juvenile salmon (Jeffres et al. 2008; Sommer et al. 2001) When water temperatures drop, surface ice may represent an important structural habitat element for overwintering salmonids (Linnansaari et al. 2009) Lower-river areas of large glacial rivers can provide essential rearing habitat for juvenile salmon spawned upriver (Murphy et al. 1997)
Smolting	Thermal tolerance 2°C to 16°C (AEIDC 1984) Preferred 6°C to 12°C (AEIDC 1984) Seasonal temperature cues may contribute to smoltification and synchronization of outmigration (Groot et al. 1995) Turbidity during outmigration reduces exposure to predation (Gregory and Levings 1998)	Smolting and outmigration to the marine environment may be synchronized with increasing flows (Quinn 2011)	Connectivity between freshwater and marine environments/lack of barriers (Quinn 2011)	
Migration from ocean to spawning grounds	Upper weekly thermal tolerance of 23.4°C (Eaton and Scheller 1996) Thermal tolerance 2°C to 18°C (AEIDC 1984)	Sufficient flow (high or low) to allow passage of natural barriers (Bjornn and Reiser 1991)	Maximum velocity for passage into Susitna River tributary spawning habitats was 2.4 m/s for coho salmon (R2 Resource Consultants 2013b)	Channel complexity sufficient to create holding areas, flow refugia and staging areas for passing barriers (Bjornn and Reiser 1991)

Life History Stage	Water Quality	Water Quantity	Habitat Connectivity	Habitat Structure
	Preferred 6°C to 11°C (AEIDC 1984) Adequate dissolved oxygen (>5 mg/L) (Bjornn and Reiser 1991) Turbidity may delay migrations (Bjornn and Reiser 1991)	Sufficient flows to meet minimum depth and maximum velocity criteria for each species (Bjornn and Reiser 1991)	Minimum depth for passage to Susitna River tributary spawning habitats was estimated at 18 cm for coho salmon (R2 Resource Consultants 2013b) Access to spawning habitats/absence of barriers to passage (Bjornn and Reiser 1991; Evenden 2004; Holbrook et al. 2009; O'Connor 2004) Lack of thermal barriers (Hodgson and Quinn 2002)	
Spawning	Thermal tolerance 2°C to 17°C (AEIDC 1984) Preferred 6°C to 13°C (AEIDC 1984)	Adequate flow and depth for movement and predator avoidance (Bjornn and Reiser 1991) Adequate flow to cover spawning grounds and maximize spawning habitat (Bjornn and Reiser 1991)	Spawning habitat size and connectivity plays an important role in buffering the effects of habitat degradation (Isaak et al. 2007)	Coho salmon primarily spawn in tributary streams, with relatively little use of main channel, side channels, or sloughs (R2 Resource Consultants 2013b) Adequate space to reduce superimposition (Bjornn and Reiser 1991) Cover from disturbance and predation (Bjornn and Reiser 1991) There is wide variation in spawning substrate size utilized by spawners, both within and among species, but in general larger fish can use larger substrates (Kondolf and Wolman 1993)

Notes:
mg/L – milligrams per liter
m/s – meters per second

Table B-6

Periodicity of Coho Salmon Utilization among Macrohabitat Types in the Middle (RM 184 to 98.5) and Lower (RM 98.5 to 0.0) Segments of the Susitna River by Life History Stage

Life Stage	Habitat Type: Main Channel	Side Channel	Tributary Mouth	Side Slough	Upland Slough	Tributary	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Middle Susitna River																		
Adult Migration																		
Spawning																		
Incubation																		
Fry Emergence																		
Age 0+ Rearing																		
Age 0+ Migration																		
Age 1+ Rearing																		
Age 1+ Migration																		
Age 2+ Rearing																		
Age 2+ Migration																		
Lower Susitna River																		
Adult Migration																		
Spawning																		
Incubation																		
Fry Emergence																		
Age 0+ Rearing																		
Age 0+ Migration																		
Age 1+ Rearing																		
Age 1+ Migration																		
Age 2+ Rearing																		
Age 2+ Migration																		

Note: Light gray shaded areas indicate timing of utilization by macrohabitat type, and dark gray areas represent areas and timing of peak use (R2 Resource Consultants 2013c).

Table B-7

Habitat Attributes Required for Pink Salmon Freshwater Life History Stages

Life History Stage	Water Quality	Water Quantity	Habitat Connectivity	Habitat Structure
Fertilization to hatch	Survival highest at 5º to 11ºC (Murray and McPhail 1988) Thermal tolerance 0ºC to 13ºC (AEIDC 1984) Preferred 4ºC to 10ºC (AEIDC 1984) Incubation occurs between 40 and 99 days at 14ºC and 5ºC, respectively (Murray and McPhail 1988) Water temperature and the origin of a stock play an important role in embryonic development and emergence timing and explain variation therein (Beacham and Murray 1989) Sufficient dissolved oxygen level to support embryonic development; minimum of >5 mg/L (Bjornn and Reiser 1991; Quinn 2011) Reduced intragravel dissolved oxygen concentrations occur when oxygen consuming material infiltrates spawning and incubation gravels (Greig et al. 2005)	Continuous surface flow or upwelling to oxygenate embryos (Bjornn and Reiser 1991) Sufficient depth to cover eggs and prevent dewatering or freezing (Bjornn and Reiser 1991; Vining and Freeman 1985) Dewatering egg mortality varies (McMichael et al. 2005) and is related to other environmental conditions (i.e., temperature and humidity) Stable flows to preserve the integrity of egg-gravel matrices	Spawning substrates require connection with surface water or groundwater to promote hyporheic flow (Bjornn and Reiser 1991)	Substrate interstices for hyporheic flow supporting respiration (Quinn 2011) Appropriately sized spawning substrates (Kondolf and Wolman 1993) Low proportion of fines (Bjornn and Reiser 1991) Stable substrate (Montgomery et al. 1996) Incubation success is inhibited by the impact of fine sediment accumulation on gravel permeability and the impact of fine particles (clay) on the exchange of oxygen across the egg membrane (Greig et al. 2005)
Hatch to emergence	Survival highest at 5º to 11ºC (Murray and McPhail 1988) Post-hatch to emergence lasts between 32 and 74 days at 14ºC and 5ºC, respectively (Murray and McPhail 1988)	Continuous surface flow or upwelling to oxygenate embryos (Bjornn and Reiser 1991) Sufficient depth to cover eggs and prevent dewatering or freezing (Bjornn and Reiser 1991; Vining and Freeman 1985)	Connectivity between spawning gravels and migratory corridors and rearing habitat (Bjornn and Reiser 1991)	Substrate Interstices for movement through gravel (Bjornn and Reiser 1991)
Emergence to outmigration (pink salmon have a short juvenile freshwater life history and migrate almost immediately upon emergence)	N/A	N/A	N/A	N/A

Life History Stage	Water Quality	Water Quantity	Habitat Connectivity	Habitat Structure
Outmigration	Thermal tolerance 4°C to 13°C (AEIDC 1984) Preferred 4°C to 10°C (AEIDC 1984) Turbidity during outmigration reduces exposure to predation (Gregory and Levings 1998)		Connectivity between freshwater and marine environments/lack of barriers (Quinn 2011)	
Migration from ocean to spawning grounds	Upper weekly thermal tolerance is 21°C (Eaton and Scheller 1996) Thermal tolerance 5°C to 18°C (AEIDC 1984) Preferred 7°C to 13°C (AEIDC 1984) Adequate dissolved oxygen (>5 mg/L) (Bjornn and Reiser 1991) Turbidity may delay migrations (Bjornn and Reiser 1991)	Sufficient flow (high or low) to allow passage of natural barriers (Bjornn and Reiser 1991) Sufficient flows to meet minimum depth and maximum velocity criteria for each species (Bjornn and Reiser 1991)	Maximum velocity for passage into Susitna River tributary spawning habitats was 2.1 m/s for pink salmon (R2 Resource Consultants 2013b) Minimum depth for passage to Susitna River tributary spawning habitats was estimated at 18 cm for coho salmon (R2 Resource Consultants 2013b) Access to spawning habitats/absence of barriers to passage (Bjornn and Reiser 1991; Evenden 2004; Holbrook et al. 2009; O'Connor 2004) Lack of thermal barriers (Hodgson and Quinn 2002)	Channel complexity sufficient to create holding areas, flow refugia and staging areas for passing barriers (Bjornn and Reiser 1991)
Spawning	Thermal tolerance 7°C to 18°C (AEIDC 1984) Preferred 8°C to 13°C (AEIDC 1984) Mortality observed at temperatures over 15°C (Fukushima and Smoker 1997)	Spawner stream lives are longer with higher discharges (Fukushima and Smoker 1997). Adequate flow and depth for movement and predator avoidance (Bjornn and Reiser 1991) Adequate flow to cover spawning grounds and maximize spawning habitat (Bjornn and Reiser 1991)	High temperatures can limit access to spawning areas (Fukushima and Smoker 1997) Spawning habitat size and connectivity plays an important role in buffering the effects of habitat degradation (Isaak et al. 2007)	Primary spawning habitats in tributary with secondary habitats in side channel and side slough habitats of Susitna River (R2 Resource Consultants 2013b) Adequate space to reduce superimposition (Bjornn and Reiser 1991) Cover from disturbance and predation (Bjornn and Reiser 1991) There is wide variation in spawning substrate size utilized by spawners, both within and among species, but in general larger fish can use larger substrates (Kondolf and Wolman 1993)

Notes:
mg/L – milligrams per liter
m/s – meters per second

Table B-8

Periodicity of Pink Salmon Utilization among Macrohabitat Types in the Middle (RM 184 to 98.5) and Lower (RM 98.5 to 0.0) Segments of the Susitna River by Life History Stage

	Habitat Type																	
Life Stage	Main Channel	Side Channel	Tributary Mouth	Side Slough	Upland Slough	Tributary	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Middle Susitna River																		
Adult Migration																		
Spawning																		
Incubation																		
Fry Emergence																		
Age 0+ Migration																		
Lower Susitna River																		
Adult Migration																		
Spawning																		
Incubation																		
Fry Emergence																		
Age 0+ Migration																		

Note: Light gray shaded areas indicate timing of utilization by macrohabitat type, and dark gray areas represent areas and timing of peak use (Table and caption from: R2 Resource Consultants 2013b).

Table B-9

Habitat Attributes Required for Sockeye Salmon Freshwater Life History Stages

Life History Stage	Water Quality	Water Quantity	Habitat Connectivity	Habitat Structure
Fertilization to hatch	Survival highest at 8°C (Murray and McPhail 1988) Thermal tolerance 0°C to 14°C (AEIDC 1984) Preferred 4.5°C to 8.0°C (AEIDC 1984) Incubation occurs between 47 and 206 days at 14°C and 2°C, respectively (Murray and McPhail 1988) Water temperature and the origin of a stock play an important role in embryonic development and emergence timing and explain variation therein (Beacham and Murray 1989) Sufficient dissolved oxygen level to support embryonic development; minimum of >5 mg/L (Bjornn and Reiser 1991; Quinn 2011) Reduced intragravel dissolved oxygen concentrations occur when oxygen consuming material infiltrates spawning and incubation gravels (Greig et al. 2005)	Continuous surface flow or upwelling to oxygenate embryos (Bjornn and Reiser 1991) Sufficient depth to cover eggs and prevent dewatering or freezing (Bjornn and Reiser 1991; Vining and Freeman 1985) Dewatering egg mortality varies (McMichael et al. 2005) and is related to other environmental conditions (i.e., temperature and humidity) Stable flows to preserve the integrity of egg-gravel matrices	Spawning substrates require connection with surface water or groundwater to promote hyporheic flow (Bjornn and Reiser 1991)	Substrate interstices for hyporheic flow supporting respiration (Quinn 2011) Appropriately sized spawning substrates (Kondolf and Wolman 1993) Low proportion of fines (Bjornn and Reiser 1991) Stable substrate (Montgomery et al. 1996) Incubation success is inhibited by the impact of fine sediment accumulation on gravel permeability and the impact of fine particles (clay) on the exchange of oxygen across the egg membrane (Greig et al. 2005)
Hatch to emergence	Survival highest at 5° to 11°C (Murray and McPhail 1988) Post-hatch to emergence lasts between 25 and 76 days at 14°C and 2°C, respectively (Murray and McPhail 1988)	Continuous surface flow or upwelling to oxygenate embryos (Bjornn and Reiser 1991) Sufficient depth to cover eggs and prevent dewatering or freezing (Bjornn and Reiser 1991; Vining and Freeman 1985)	Connectivity between spawning gravels and migratory corridors and rearing habitat (Bjornn and Reiser 1991)	Substrate interstices for movement through gravel (Bjornn and Reiser 1991)
Emergence to smolting	Thermal tolerance 2°C to 16°C (AEIDC 1984) Preferred 7°C to 14°C (AEIDC 1984) Water temperature in rearing environments plays a significant role in predicting smolt size (Edmundson and Mazumder 2001) Water temperature affects the mobility and	Adequate flow to maintain carrying capacity and buffer temperatures (Bjornn and Reiser 1991) Variation in stream velocity and depth to provide resting areas, high-flow refugia, predator refugia and mobilize prey items (Bjornn and Reiser 1991).	Access between river/lake incubation habitat and lake rearing habitat (Burgner 1991) Connections among rearing habitats, refugia, and migratory corridors (Bjornn and Reiser 1991) Winter ice can temporarily disrupt	Sockeye frequently utilize rearing lakes (Burgner 1991) In the glacial Taku River, Alaska, juvenile sockeye occupied upland sloughs, beaver ponds, and tributary mouth habitats (Murphy et al. 1989) Within the Susitna River, juvenile sockeye salmon summer diets are dominated by immature insects and crustaceans; fall diets are dominated by adult insects followed by immature insects (Riis and Friese 1977 cited in R2 Resource Consultants 2013b)

Life History Stage	Water Quality	Water Quantity	Habitat Connectivity	Habitat Structure
	distribution of juvenile salmonids in winter (Enders et al. 2008). Turbidity refugia (Bjornn and Reiser 1991) Water temperature affects the mobility and distribution of juvenile salmonids in winter (Enders et al. 2008). Exposures to total dissolved gas of 120% elicit progressively worsening symptoms of gas bubble disease in fishes (Mesa et al. 2000; Ryan et al. 2000)		connectivity causing changes in behavior, distribution and survival in winter (Berg 1994; Bradford et al. 2001; Jakober et al. 1998; Linnansaari and Cunjak 2010; Whelan et al. 1999) Ephemeral connections between floodplains and river channels may contribute to growth (Jeffres et al. 2008)	Both inwater and riparian cover (i.e., trees, boulders, large woody debris) to stage for feeding, avoid predators, create flow heterogeneity (Bjornn and Reiser 1991) Habitat complexity to support ontogenetic niche shifts (Rosenfeld and Boss 2001; Werner and Gilliam 1984) Appropriate substrates to provide hiding areas, support production of benthic invertebrate prey, and cover during winter and summer (Bjornn and Reiser 1991) Space for foraging, avoiding predators, and exhibiting territories. Larger fish need more space (Bjornn and Reiser 1991) Ice cover may increase overwinter survival of salmonids by preserving energy reserves (Hedger et al. 2013) Floodplains rearing may enhance the growth and survival of juvenile salmon (Jeffres et al. 2008; Sommer et al. 2001) When water temperatures drop, surface ice may represent an important structural habitat element for overwintering salmonids (Linnansaari et al. 2009) Lower river areas of large glacial rivers can provide essential rearing habitat for juvenile salmon spawned upriver (Murphy et al. 1997)
Smolting	Thermal tolerance 4°C to 18°C (AEIDC 1984) Preferred 5°C to 12°C (AEIDC 1984)	Sockeye smolt migration rate is correlated with flow in the Columbia River (Giorgi et al. 1997) Smolting and outmigration to the marine environment may be synchronized with increasing flows (Quinn 2011)	Connectivity between freshwater and marine environments/lack of barriers (Quinn 2011)	
Migration from ocean to spawning grounds	Thermal tolerance 2.5°C to 16°C (AEIDC 1984) Upper thermal tolerance of 21.5°C (Eliason et al. 2011) Preferred 6°C to 12°C (AEIDC 1984) Adequate dissolved oxygen (>5 mg/L) (Bjornn and Reiser 1991) Turbidity may delay migrations (Bjornn and Reiser 1991)	Sufficient flow (high or low) to allow passage of natural barriers (Bjornn and Reiser 1991) Sufficient flows to meet minimum depth and maximum velocity criteria for each species (Bjornn and Reiser 1991)	Maximum velocity for passage into Susitna River tributary spawning habitats was 2.1 m/s for sockeye salmon (R2 Resource Consultants 2013b) Minimum depth for passage to Susitna River tributary spawning habitats was estimated at 18 cm for sockeye salmon (R2 Resource Consultants 2013b) Access to sockeye salmon spawning	Channel complexity sufficient to create holding areas, flow refugia and staging areas for passing barriers (Bjornn and Reiser 1991)

Life History Stage	Water Quality	Water Quantity	Habitat Connectivity	Habitat Structure
			habitats in sloughs is controlled by Susitna River mainstem discharge (R2 Resource Consultants 2013b) Channel constrictions may reduce swimming efficiency (Hinch and Rand 1998)	
Spawning	Thermal tolerance 4°C to 14°C (AEIDC 1984) Preferred 6°C to 12°C (AEIDC 1984) Low turbidity during spawning (Young and Woody 2007)	Adequate flow and depth for movement and predator avoidance (Bjornn and Reiser 1991) Adequate flow to cover spawning grounds and maximize spawning habitat (Bjornn and Reiser 1991)	Spawning habitat size and connectivity plays an important role in buffering the effects of habitat degradation (Isaak et al. 2007)	Spawning habitat is primarily within tributaries of the Susitna River (R2 Resource Consultants 2013b) Sockeye utilize a high diversity of spawning habitats in Alaska including island beaches, rivers (Blair et al. 1993) and glacial habitats (Ramstad et al. 2009) Sockeye may spawn in substrates with a large proportion of fines if upwelling is present (Lorenz and Filer 1989) Adequate space to reduce superimposition (Bjornn and Reiser 1991) Cover from disturbance and predation (Bjornn and Reiser 1991) There is wide variation in spawning substrate size utilized by spawners, both within and among species, but in general larger fish can use larger substrates (Kondolf and Wolman 1993)

Table B-10

Periodicity of Sockeye Salmon Utilization among Macrohabitat Types in the Middle (RM 184 to 98.5) and Lower (RM 98.5 to 0.0) Segments of the Susitna River by Life History Stage

	Habitat Type																		
Life Stage	Main Channel	Side Channel	Tributary Mouth	Side Slough	Upland Slough	Tributary	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Middle Susitna River																		
Adult Migration																		
Spawning																		
Incubation																		
Fry Emergence																		
Age 0+ Rearing																		
Age 0+ Migration																		
Age 1+ Rearing																		
Age 1+ Migration																		
Lower Susitna River																		
Adult Migration[1]																		
Spawning																		
Incubation																		
Fry Emergence																		
Age 0+ Rearing																		
Age 0+ Migration																		
Age 1+ Rearing																		
Age 1+ Migration																		

Notes:

1 First run sockeye migration timing occurs during May and June and second run sockeye migration is July through September.

Light grey shaded areas indicate timing of utilization by macrohabitat type, and dark gray areas represent areas and timing of peak use (R2 Resource Consultants 2013c).