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Shoreline Armoring Research Program

Phase II-Conceptual Model Development for Bank Stabilization in Freshwater Systems

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16. ABSTRACT

Armoring involves the placement of erosion resistant materials (e.g., large rocks and boulders, cement, pilings, and large woody debris) or the use of bioengineering techniques along shorelines, streambanks, or in other areas of high flow velocities and/or wave-tidal energy to reduce or eliminate erosion of natural shorelines and risk to human infrastructure. Unfortunately, altering the physical conditions of the streambank or shoreline through armoring, or bank stabilization, can radically alter the local characteristics of natural habitats and may influence the habitat for some distance surrounding the structure. Bank stabilization also affects natural channel processes that are essential to habitat creation and maintenance. As a result, the ecological functions of the impacted area can be altered, including the use of these habitats by fish, macroinvertebrates, birds, and other organisms. Conceptual models are used to organize available information relative to ecosystem impacts. This conceptual model and accompanying text outline relationships between shoreline modification techniques; the physical, chemical, and biological processes and functions of freshwater systems; and the potential impacts to salmonid fitness at both large (reach level) and small (site level) scales. Particular emphasis is placed on the evaluation of effects on salmonid species and their essential habitat.

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INTRODUCTION

Armoring involves the placement of erosion resistant materials (e.g., large rocks and boulders, cement, pilings, and large woody debris) or the use of bioengineering techniques along shorelines, streambanks, or in other areas of high flow velocities and/or wave-tidal energy to reduce or eliminate erosion of natural shorelines and risk to human infrastructure. In general, it has been shown to be an effective method to control erosion and local scour along streams, particularly near bridges where structures induce additional turbulence that may stimulate erosion. Rock and/or debris structures may also be used in the form of groins or barbs to redirect the flow of rivers and tidal channels, or to modify the course of a waterway. Shoreline armoring is also used to reduce erosion from wave energy in the environment.

Unfortunately, altering the physical conditions of the streambank or shoreline through armoring, or bank stabilization, can radically alter the local characteristics of natural habitats and may influence the habitat for some distance surrounding the structure. Bank stabilization also affects natural channel processes that are essential to habitat creation and maintenance (Bolton and Shellberg 2001). As a result, the ecological functions of the impacted area can be altered, including the use of these habitats by fish, macroinvertebrates, birds, and other organisms. Lost opportunity impacts (potential impacts that occur in response to what a channel is NOT allowed to do, including alteration of dynamic river processes and the reduction of the input of sediment and debris) are important for consideration as are their opposite, channel response impacts (impacts caused directly by a protection project). This report will focus on freshwater streambank armoring rather than armoring along marine shorelines. It emphasizes impacts to salmonids, but also impacts to habitat and habitat-forming processes. A thorough review of marine and estuarine shoreline modification issues related to habitat alteration can be found in Williams and Thom (2001).

BACKGROUND

Salmon occupy habitats with very specific attributes that sustain incubation, residence and migration **(Figure 1)**. Many of these habitat attributes (e.g., substrate, current velocity) can be altered by artificial bank protection structures. Effects on fish can be direct, such as a change in velocity that results in different sizes and species of fish utilizing a specific bank area, or indirect, such as altering dynamic river processes and thereby reducing off-channel habitat (Cramer et al. 2002). Conditions under which bank stabilization significantly alters fish habitat are poorly understood (Carrasquero 2001). Similarly, mitigation measures that would reduce or eliminate negative impacts to biota and ecological processes along stabilized banks are poorly understood.

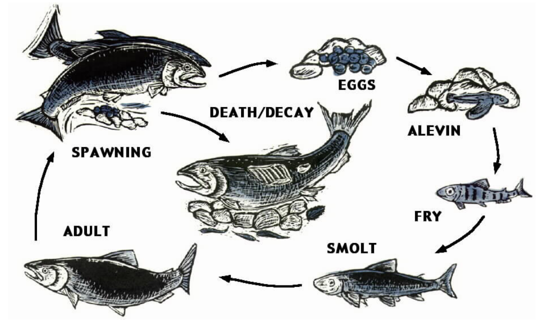


Figure 1. Salmonid life cycle.

A variety of methods has been used along inland streams to control general bank erosion. Until recently, fish and wildlife habitat considerations were not commonly addressed when projects were designed. Streambank stabilization techniques, while reducing streambank erosion, also impact aquatic ecosystems. Negative impacts may include loss of salmonid habitat. Current research indicates that conventional (hard) streambank armoring techniques may also result in a loss of instream habitat complexity and a reduction in juvenile salmonid abundance in the affected stream reach. There are, however, numerous data gaps in the understanding of how hard and soft streambank protection techniques impact aquatic ecosystems and the relative risks and uncertainties associated with each method.

A recently completed Washington state report provides guidance on assessing streambank erosion, and selecting and designing appropriate corrective measures that consider wildlife in the solution to the problem (Cramer et al. 2002). The report emphasizes the need for an integrated approach that acknowledges the natural process of erosion and seeks to maintain fish and wildlife habitat functions while treating the cause of the erosion, rather than merely treating the symptoms.

Though the physical processes affected by armoring have been studied in a variety of freshwater and marine ecosystems (Macdonald et al. 1994), *almost no data exist* on the biological impacts (Thom et al. 1994, Williams and Thom, 2001, Carrasquero 2001). The paucity of case studies highlighted by these authors emphasizes the critical need for development of a conceptual model that highlights conditions where additional research is needed to quantify impacts to salmon. Development and interpretation of the model would be followed by focused field monitoring and quantitative research regarding the potential impacts of shoreline modifications, particularly in relation to salmon species listed under the Endangered Species Act (ESA).

As more shoreline and stream areas come under pressure for armor or other modifications, it is critical that management practices anticipate the effects of these changes. To date, a workshop on the ecological effects of armoring was conducted in November 2001. The results of the workshop provided WSDOT and the participants with a comprehensive bibliography and current state of knowledge and research activities related to shoreline armoring. The next step involves development of a conceptual model for freshwater systems to assess small- and large-scale effects of bank stabilization on system processes. The model is being developed from the extant literature and has the purpose of facilitating understanding of connections between the physical and biological conditions in freshwater systems, with special regard to listed species. Interpretation of the model will allow evaluation of potential effects of bank stabilization and help focus mitigation efforts on areas where they will be most beneficial.

Anthropogenic disturbances, such as bank stabilization, may result in a significant modification of stream morphology, thereby potentially degrading fish habitat and fish populations. Long-term habitat alterations may result in changes to a stream's physical, chemical, and biological processes and functions. Bank stabilization projects impact aquatic (riverine) and riparian (floodplain) habitat at both a small-scale *site-specific level* and at a large-scale *reach level*. Determining effects of bank stabilization on salmon at both scales is important for making permitting decisions, assessing impacts of habitat modification, making design recommendations, and/or deciding on appropriate mitigation. Site-level impacts are of particular concern to WSDOT because each bank stabilization project goes through a permitting process. Large-scale impacts may involve assessment of cumulative effects and a determination of whether or not the stream will retain its "opportunity", or ability, to migrate within the channel and form fish habitat throughout an extensive reach and over time (Cramer et al. 2002). Examining the potential for the stream to migrate over time would allow decision-makers to evaluate the costs/benefits associated with moving a transportation system out of a stream's path.
This conceptual model and accompanying text outline relationships between shoreline modification techniques; the physical, chemical, and biological processes and functions of freshwater systems; and the potential impacts to salmonid fitness at both large (reach level) and small (site level) scales. The results are meant to (1) provide a comprehensive and technically defensible framework illustrating relationships between physical and biological conditions in freshwater systems subjected to stabilization, (2) highlight relationships that are most important and for which scientific data are lacking, not understood, or not agreed on, (3) assist resource managers in assessing potential effects of bank stabilization, and (4) help prioritize WSDOT research and mitigation projects related to bank stabilization in freshwater systems.

Bank stabilization techniques that are evaluated in the model include in-stream flow redirection, structural bank protection, biotechnical bank protection, avulsion and chute cutoff prevention, and channel modification (Cramer et al. 2002). Particular emphasis is placed on the evaluation of effects on salmonid species and their essential habitat.

ECOLOGICAL BASIS FOR THE MODEL

The concerns about bank stabilization in freshwater systems center around a variety of salmon habitat needs associated with different life history stages, which include egg incubation, juvenile rearing, upstream migration by adults, and spawning **(Figure 1)**. Natural ecosystems comprise complex fish habitats, which provide salmon with the opportunity to occupy diverse habitats for a maximum amount of time. When humans alter the stream habitat through armoring, there is generally a simplification of the system for fish species and the organisms they prey upon.

The basic purpose of bank stabilization is to interrupt the erosion process where it is deemed to conflict with social needs or ecological requirements (Fischenich 2001). The initial stabilization project results in alteration of the physical environment and in turn often interrupts or affects other ecological processes. Knowing the direct and ancillary effects of a stabilization technique could help engineers select designs that minimize adverse effects to the structure and function of the environment and to mitigate for unavoidable losses. In addition, it is important to remember that the nature and extent of impacts may be influenced by:

- Local geology;
- Climate;
- Physical characteristics of the stream;
- Physical characteristics of the riparian zone;
- Hydrology, sediment input;
- System stability;
- Watershed and adjacent land use;
- Proximity to control features (bridges, bedrock, etc.,);
- Construction practice;
- Timing; and
- Cumulative nature of stabilization (i.e., scale effects).

Evaluation of freshwater systems and the impact of their condition on salmon fitness is complex; hence the need for a conceptual model. Roughly, the evaluation can be divided into analysis of the physical status and the biological habitat quality of the system. Initial assessments would generally be small-scale or "site-based" (includes channel processes), but results could be aggregated and analyzed at a larger, "reach-based" scale that includes analysis of cumulative effects.

Changes to freshwater systems can arise through natural and anthropogenic means. For example, streambank armoring is anthropogenic, but floods, landslides, and fires are natural impacts that occur over a short time period (and may admittedly be exacerbated by humans). Large-scale, long-term natural processes such as climate change and tectonics also act on stream systems in the Pacific Northwest and salmon have adapted to these changes over time. For the purpose of this model, a number of bank stabilization techniques are assessed. Generally, each stabilization technique can be expected to have some immediate effect on the streambank or bottom. These effects will result in a physical process response, such as alteration of flow velocity or loss of riparian vegetation. The physical responses may alter salmon habitat, which may in turn induce a biological response in the fish.

Some parameters considered in the conceptual model include:

- Erosion
- Sediment/organic nutrient transport
- Streambed degradation/scour
- Flow velocity
- Water elevation
- Channel roughness
- Meander formation/channel migration
- Turbidity
- Vegetative cover
- Woody debris presence and supply
- Riparian complexity
- River/floodplain connection
- Juvenile salmon rearing habitat
- Salmon food sources
- Salmon spawning habitat
- Juvenile salmon predation
- Prey species
- Habitat diversity
- Salmon species
- Habitat needs of different species and life stages

Alterations to fish habitat and biological response may be framed in a more generalized model of salmon in Northwest systems. In developing ecological assessment criteria for restoring anadromous salmon habitat, Simenstad and Cordell (2000) advocated the use of measures directly relatable to the ecological and physiological responses of juvenile salmonids to restored habitats. They proposed the use of three categories – *capacity*, *opportunity* and *realized functions*.

<u>Capacity</u> metrics include habitat attributes that promote juvenile salmon production through promotion of foraging, growth, and growth efficiency, and/or decreased mortality (Simenstad and Cordell 2000). The capacity category is an extension of the ecological concept of carrying capacity. Examples of capacity metrics include the productivity and density of prey, physical and chemical conditions that promote high assimilation

efficiencies, and structural conditions that provide protection from predation.

Opportunity metrics appraise the ability of salmon to access and benefit from the habitat's capacity (Simenstad and Cordell 2000). Opportunity incorporates the principles of landscape ecology (Forman and Godron 1986). Examples of metrics include the extent of morphometric features such as habitat edge length and the amount of refugia from predation.

Finally, realized function metrics include any direct measures of physiological or behavioral responses that can be attributable to fish occupation of the habitat and that promote fitness and survival (Simenstad and Cordell 2000). Survival is the ultimate metric, but related metrics include habitat-specific residence time, foraging success, growth, and reproduction.

For bank stabilization projects, the fundamental question is "Will the structure significantly reduce the overall fitness of salmon?" This question can be framed according to Simenstad and Cordell's (2000) capacity-opportunity-function (COF) model (Table 1). One assessment metric is whether a structure affects the growth and/or survival of a fish. Sampling of this metric is generally not feasible. Therefore, surrogates must be chosen from the impacts to salmon related to capacity and opportunity from Table 1.

This model also follows the conceptual model outlined by Williams and Thom (2001) for assessing the effects of shoreline armoring on estuarine and marine ecological conditions. This model states that ecosystem functions are correlated with habitat structures, and habitat structure is dependent on physical and chemical controlling factors (e.g., flow velocity, hydraulic roughness, solar irradiance). Habitat structure can be impacted directly through placement of material on a habitat, or by alteration in habitat forming processes. In summary, it is important to keep in mind that assessments of the physical, chemical, and biological components of a system are complementary and none provides a complete picture when analyzed in isolation. The conceptual model integrates these components to provide an overall assessment of the impacts of bank stabilization at different scales on the fitness of salmon species in the system.

The basic approach involved reviewing literature on physical, chemical, and biological impacts of bank stabilization at large and small scales and developing a conceptual model based on the findings. Much of the literature has been summarized in Currasquero (2001) and in WDFW's Integrated Streambank Protection Guidelines (Cramer et al. 2002). The conceptual model revolves around the need to determine the impacts to overall salmon fitness from bank stabilization at one or more project sites in a given freshwater system.

Table 1. Category of metrics used to assess effects of bank stabilization on salmonid growth and survival.

Category	Potential Stabilization Impact	Potential Impact to Salmon
Capacity	Altered habitat type Altered habitat forming process Altered habitat production	Change in prey species Change in prey production Change in prey abundance Change in prey distribution Change in predator abundance
Opportunity	Altered access Altered migration route Altered habitat size Altered habitat location Altered refugia from predators	Change in ability to find prey Change in rate of migration Change in predation rate
Realized Function	Altered residence time Altered foraging success	Change in growth rate and survival

OBJECTIVE OF A CONCEPTUAL MODEL

> *"Conceptual models help to clarify loose thoughts about how a system is composed and how it operates…"* (Huggett 1993)

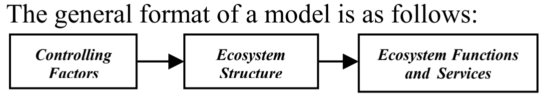
A conceptual model can significantly help to organize the available information on armoring relative to ecosystem impacts. The objective of this conceptual model is to contribute to the determination of how ecosystem structure or functions could be altered by modification of the streambank. The conceptual model is used to identify the connection between the physical manipulations and the physical and biological reactions to such actions, based on the best available information on qualitative and conceptual relationships. As recommended (Simenstad et al. 1991, Thom 2000, Gentile et al. 2001), a conceptual model is a "living" entity that should be refined and revised as new insight and interpretation becomes available.

Conceptual models have been used widely in ecology to depict ecosystems and food webs (e.g., Odum 1988; Odum and Hornbeck 1997; Jackson, et al. 2001). The National Research Council (NRC 2000) relied on a conceptual model to develop recommendations for a national ecological monitoring program. The NRC used the model to identify and justify key metrics to be monitored. Although not graphically developed, Simenstad et al. (1991) used a conceptual approach to develop environmental monitoring protocols for Puget Sound. Their approach identified measurable characteristics (termed *attributes*) of estuarine habitats that promote fish and wildlife utilization and fitness. The attributes were selected based on a rigorous assessment (reviewing literature and consulting regional experts) of factors proven to serve these functions. A recent workshop examining methods for evaluating effects of multiple stressors on populations and ecosystems provided examples of studies where conceptual models were useful (Reinert et al. 1998). In addition, Thom (1997, 2000) proposed that conceptual models are a key component of an adaptive management program associated with coastal ecosystem restoration projects, and strongly recommended them for understanding factors that affect the conditions at a site and for providing guidance on adjustments to improve conditions or minimize project impacts.

A conceptual model provides an integrated picture of the major ecosystem components and those factors that affect ecosystem structure and functioning. A version of an integrated conceptual model emphasizing the role of the estuary in support of salmon was developed for the Biological Assessment for the Columbia River Navigation Channel Improvements project (USACE 2001). The model in the BA represents a reformatting and linking of existing models developed by others for the Columbia and coastal systems in the Pacific Northwest (Sherwood et al. 1990, Proctor et al. 1980).

Most conceptual models consist of a simple set of diagrams illustrating relationships among the components of the ecosystem; its components highlight the more important linkages for the model output (e.g., restoration of natural ecosystem structure and function). In addition to graphically displaying the ecosystem, a model provides a guide for determining what data may be most important in understanding long-term component relationships and could be gathered during a monitoring program.

The general format of a model is as follows:



Huggett (1993) terms the model developed here as a box-and-arrow model, where boxes stand for system components and arrows depict important links and relations between the components. This format highlights the point that the structure, functions and services provided are dependent on key environmental (controlling) factors. For example, in order for a river riparian forest to develop a natural structure (i.e., species mix and species abundances typical of a natural riparian community) and function properly (e.g., primary productivity, nutrient processing, sediment trapping, flood attenuation, food web support, refuge, bank stability), there must be present the appropriate conditions. These conditions include elevation, hydrodynamics, soils, temperature and nutrients. Furthermore, in order to make the forest self-sustaining, the natural (habitat) forming processes must be active. These processes are both internal (e.g., plant stems cause eddies that trap sediments and organic matter) and external (e.g., sediment supply from upstream sources) to the forest. Therefore, to understand the effects of potential alterations to the riparian forest, **it is imperative to understand completely the types, levels, and future conditions of controlling factors most relevant to this habitat.**

THE CONCEPTUAL MODEL

Formulating a conceptual model involves identifying the relationships between parameters of concern (e.g. salmon survival, growth, and reproduction) and factors that likely control or influence the parameter (e.g., water quality, food sources, habitat structure) (Baird and Burton 2001). The conceptual model developed in our study is focused on salmonid survival, growth, and reproduction as the endpoint affected by the environmental conditions associated with armoring a streambank. It is important to realize that the connections made between the physical, chemical, and biological conditions represented in the model make up one step in our learning process. Baird and Burton (2001) point out that it is very difficult to pinpoint the influence of a single stressor or group of stressors in a complex ecosystem. It will take time and directed research to pinpoint how specific shoreline activities (stressors) manifest themselves as a habitat or organism's response to exposure in the environment **(Figure 2)**. In the case of streambank armoring, the impacts of channel alterations and land use that result from individual and cumulative armoring activities, will ultimately affect the endpoint (i.e., overall ability of salmonids to survive, grow, and reproduce when exposed to the armoring technique).

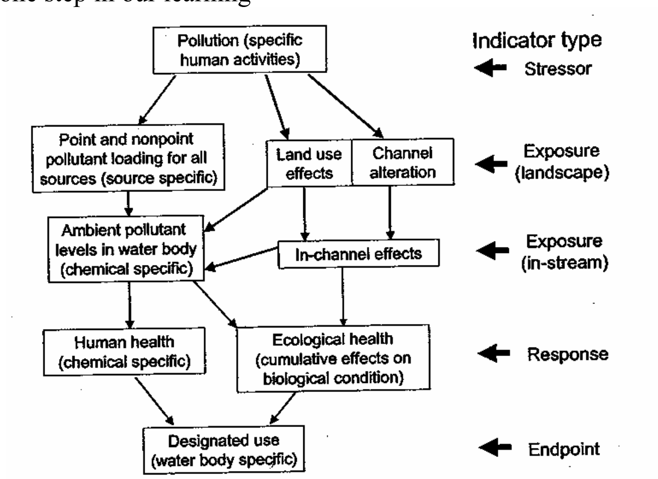


Figure 2. Position of the criterion (stressor, exposure, or response) illustrating relationships between human activities, types of criteria, and designated uses that define the endpoint of interest to society (modified from NRC 2000).

Overview Model

In the overview model **(Figure 3)**, seven factors were considered important influences for salmon survival, growth, and reproduction. They include:

- *Biotic Interactions*: the inter- and intraspecific competition for food and habitat by fish and aquatic invertebrates, predator/prey relationships, and how diseases and parasites affect fish health.
- *Flow Regime*: the day-to-day and seasonal variation in water level or rates of flow for a particular stream, as determined by climate, geology, topography, and vegetation.
- *Food (Energy) Source*: the availability of salmon prey items.
- *Habitat Structure*: the organization and arrangement of the fish habitat, including the presence, order, and proportion of pools, riffles, and runs; substrate size, type, and stability; presence or absence of overwater and instream cover; and amount of hydraulic complexity.
- *Migration/Movement Barriers*: the natural and manmade obstructions (physical and behavioral) that slow or prevent salmon access to parts of the stream system.

- *Natural/Manmade Changes to Habitat*: the ways a stream system may be modified, including fire, flood, and landslides as well as engineering or restoration projects that improve, degrade, or have no impact on the quality of the aquatic habitat on a small or large scale.
- *Water Quality*: the physical and chemical parameters that indicate the quality of water as it relates to the well being of organisms living in the stream (e.g., dissolved oxygen, nutrients, pH, pollutants, temperature, turbidity).

Eight submodel diagrams depict how each factor affects salmonid survival, growth and reproduction. Tables accompany most submodel diagrams and provide additional information about the impacts of each contributing factor on salmonids, as well as the salmon life stages most likely to be impacted. While mostly qualitative in nature, quantitative data obtained from the literature are provided when possible. The tables provide insight into the scale at which conditions become problematic for salmonid growth, survival, and reproduction. For example, the table that accompanies the water quality submodel diagram indicates that at temperatures greater than 22°C, chinook salmon are unable to spawn successfully. However, temperatures between 5.6°C and 13.9°C are considered optimal for chinook spawning. If the temperature of a stream with a spawning chinook population regularly approaches 22°C during the spawning season, in the region where spawning occurs, then the continuation of the species may be in jeopardy. However, if temperatures only rarely approach 22°C during the spawning season, and do so only in shallow slow-moving sections not normally used by spawning adults, the impact to the species is likely to be small. To help define critical time periods for salmonid species, a table indicating the range of salmonid life stages in freshwater (by month) for seven Washington species is provided in **Appendix A**.

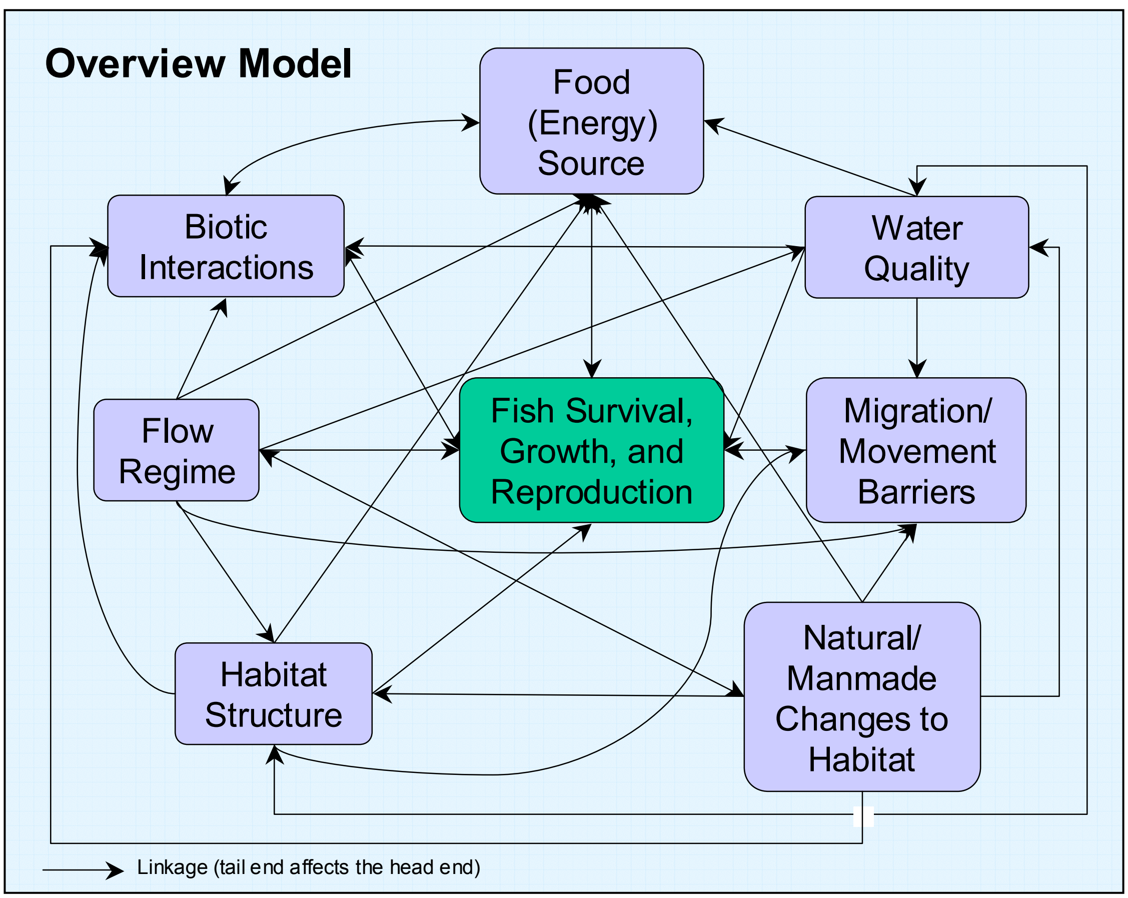


Figure 3. Seven factors affecting salmonid survival, growth, and reproduction.

Project Size and Scale Considerations

The size and scale of individual shoreline armoring projects also affects the factors in the conceptual model **(Table 2)**. The goal for project planners will be to define the scope of the issues (direct and indirect effects) associated with the proposed project, the geographic scope of the project and region to be considered in the analysis of possible impacts, the time frame for the analysis, and whether other actions in the region may affect the resource. A good description of the affected environment will help project planners understand present conditions and the historical context of salmon habitat in the region of a proposed project. This conceptual model can then be used to identify important cause-and-effect relationships between natural and human activities and the fishery resource, determine the magnitude and significance of the effects, and indicate ways a project could be modified to minimize or mitigate for negative impacts.

Table 2 is a matrix that describes the potential qualities of shoreline armoring projects for small, intermediate, and large-scale projects (based on the amount of shoreline impacted and the time the project is in place) that are expected to have small, medium, or large adverse impacts on salmonid growth, survival, or reproduction. Project examples are given, but are only a small representative of the types of projects currently being considered today. Individual project planners and resource managers can use the matrix as a guideline for estimating the scale of their own project and the potential effects on salmonids in their stream system.

Table 2. Matrix linking impacts to salmon with scale and modification techniques.

Large Adverse Impact	Detectible impacts to multiple factors that affect salmon fitness.[a] •Impacts detectable at project site and up- or downstream. •Impacts persist for more than a season •Other projects with medium to large adverse impacts, or many projects with small adverse impacts, are already present. Major localized impact leading to scour or infilling. May induce larger scale feature change.	Detectible impacts to multiple factors that affect salmon fitness. •Impacts detectable at project site and up- or downstream. •Impacts persist for more than a season. •Other projects with medium to large adverse impacts, or many projects with small adverse impacts, are already present. Major change in sedimentation regime leading to loss of desirable habitat. Change in flow characteristics along reach.	Detectible impacts to multiple factors that affect salmon fitness. •Impacts detectable at project site and up- or downstream. •Impacts persist for more than a season. •Other projects with medium to large adverse impacts, or many projects with small adverse impacts, are already present. Major regime shift with possible bank failure, and modification of ecosystem function.
Medium Adverse Impact	Detectible impacts to one factor affecting salmon fitness. •Impacts detectable at project site and up- or downstream. •Impacts persist less than one season. •Few other projects with small adverse impacts already present. Localized scour or sediment trapping. Seasonal effects.	Detectible impacts to one factor affecting salmon fitness. •Impacts detectable at project site and up- or downstream. •Impacts persist less than one season. •Few other projects with small adverse impacts already present. Minor-moderate down cutting or sedimentation along reach. Changes in the flow regime.	Detectible impacts to one factor affecting salmon fitness. •Impacts detectable at project site and up- or downstream. •Impacts persist less than one season. •Few other projects with small adverse impacts already present. Minor-moderate down cutting or sedimentation along length. Changes in the flow regime.
Small Adverse Impact	Little or no impact to factors affecting salmon fitness. •Impacts detectable at the project site but not up- or downstream. •Impacts persist less than one season. •No other armoring projects present.	Little or no impact to factors affecting salmon fitness. •Impacts detectable at the project site but not up- or downstream. •Impacts persist less than one season •No other armoring projects present.	Little or no impact to factors affecting salmon fitness.[b] •Impacts detectable at the project site but not up- or downstream. •Impacts persist less than one season •No other armoring projects present.
Project and Time Scale	***Small-scale project (<10m)*** ***Time scale: (Days – seasons)***	***Intermediate-scale project (10-100m)*** ***(Seasons – year)***	***Large-scale project (100m - kms)*** ***(Year – decades)***
Example Projects	***Training structure*** ***Single barb*** ***Drop structure*** ***Culvert designed for fish passage***	***Debris removal (extensive)*** ***Dredging*** ***Bank alignment*** ***Flow augmentation*** ***Seasonal diversion*** ***Bank stabilization*** ***Bed stabilization***	***Channelization*** ***Dredging*** ***River diversion*** ***Dam removal or placement*** ***Major realignment***

(a) This could happen if the actions were very disruptive of critical processes, contributed inordinately to WQ impairment, or was developed in a highly critical location resulting in sustained impacts over an area much larger than the project site.

(b) The project may not be at a critical point in the system or it may be designed to avoid and minimize impairment of factors contributing to salmon fitness. Example: an armoring project designed to reduce erosion rates only during extremely rare flood events, thus having an adverse impact only during extreme flood events.

Fish Survival, Growth, and Reproduction Submodel

Survival is important to all life stages of salmon. The young fish must grow to compete with one another and with other species for food and for space while rearing and migrating to the sea (most species). Adults of anadromous species must survive the journey upstream with enough energy reserves to spawn.

Many factors impact fish survival, growth, and reproduction and include aquatic habitat structure, water quality, flow regime, migration movement/barriers, biotic interactions, and their food (energy) source **(Figure 4)**. Fish in different life stages require different parameters related to each of these factors. For example, salmon in the embryo/aelvin stages may not be able to survive high scouring flows, while juveniles and adults could easily swim to portions of the stream that are protected, such as off-channel habitat, under the same flow conditions. The different salmon species have different physical, chemical, and biological requirements to thrive in their preferred natural habitat. The different species utilize different parts of the stream system at different times of the year, and have a variety of optimum conditions that promote successful incubation, rearing, and spawning. As stated previously, the magnitude and scale of the armoring project, and the potential for cumulative effects, determines the ultimate impact to fish survival, growth, and reproduction.

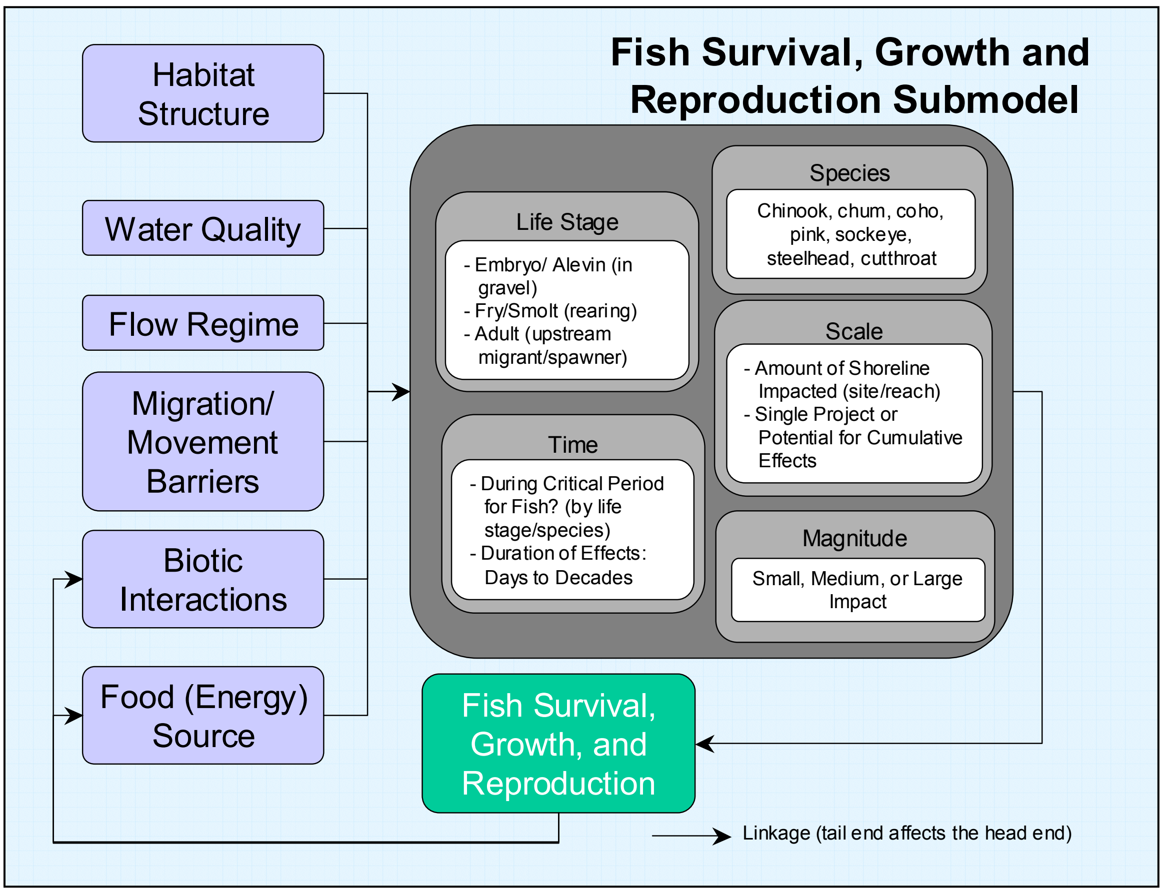


Figure 4. Fish survival, growth, and reproduction submodel

Biotic Interactions Submodel

Biotic interactions relate primarily to juvenile and adult salmonids because the eggs and aelvin are nestled in the gravel. Juveniles and adults must interact with other salmonids as well as other species as they compete for space, food, and maintain their health. Biotic interactions may be directly affected by water quality, food (energy) sources, habitat structure, and the flow regime **(Figure 5)**. All salmonid species have optimal water quality parameters within which they are able to survive, grow and reproduce. Outside and at the margins of these parameters, fish may be stressed to the point they become sick or die, fail to grow, or have too few energy reserves to reproduce. For example, high water temperatures decrease the amount of oxygen available to the fish for uptake. Some species are better adapted to low oxygen conditions than others, which could increase their survival rate over that of other species. High and low water temperatures can affect fish survival in a similar way, as certain fish species are more or less heat and cold tolerant than other species. Increased water temperature may also increase fish metabolism, meaning that the fish require more food to maintain their body weight. If food sources are few, fish may compete inter- and intraspecifically for limited resources. Increased water temperatures may stress fish and increase incidence of disease and parasites, and may affect one species more than another based on their thermal tolerance (Rottmann et al. 1992).

Competition for food between fish of the same or different species occurs, especially when food resources are limited. Fish species better adapted to particular conditions, such as temperature, turbidity, and the variety of food sources available will outcompete others for food. Native species compete with non-native species with mixed results. Sometimes the native species prove better adapted to local conditions. Alternatively, an introduced or hatchery fish may be more aggressive or have no

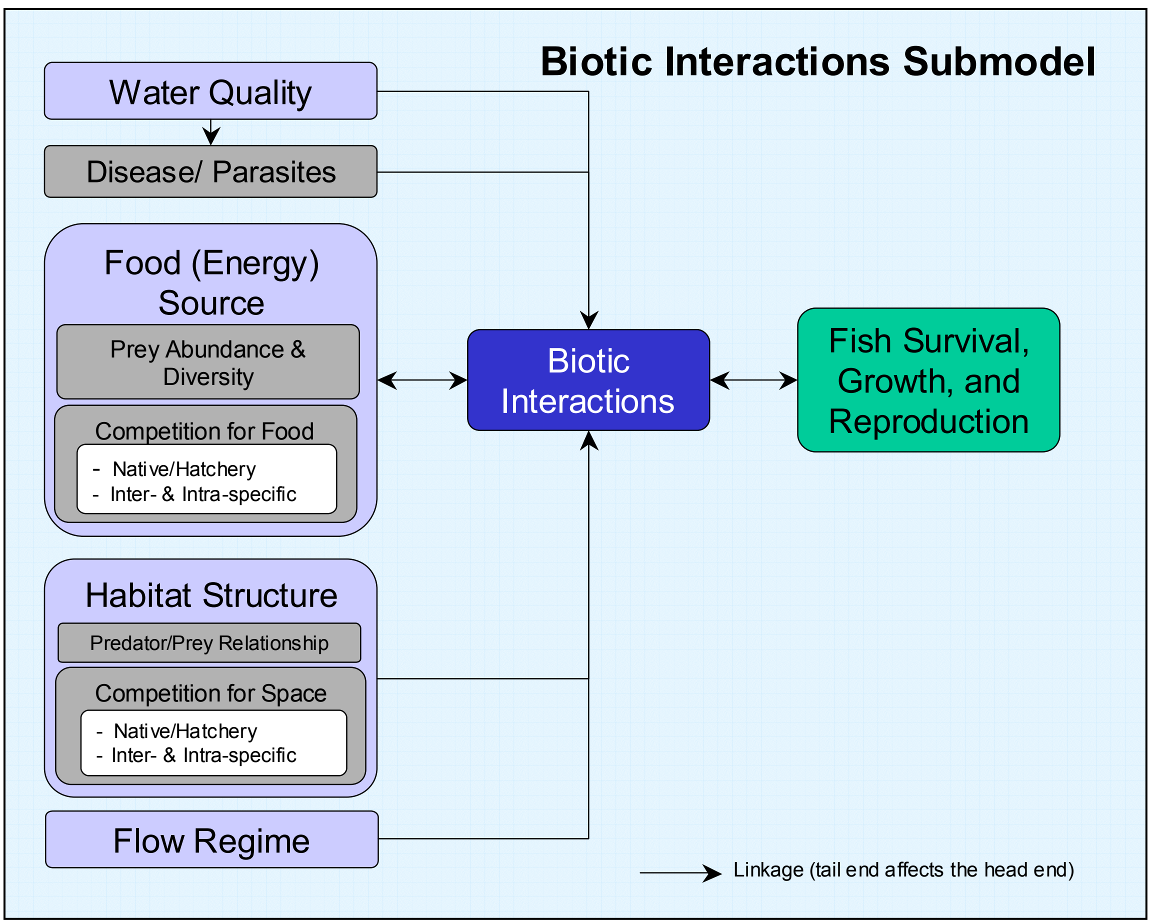


Figure 5. Biotic interactions submodel

natural predators and thus outcompete the native fish for food resources. Fish also compete for space. Resting, feeding, and hiding places are all-important and affect how fish interact with one another. An area with few hiding spaces for very small individuals or with many hiding spaces for predators can decrease survival of the smaller or slower fish when predators are present. Where limited resting areas are available (e.g., behind large boulders, in slow-moving pools, or in side channels), those fish unable to take advantage of the best "holes" will have to swim harder and expend more energy reserves than others. All these factors affecting biotic interactions will ultimately affect fish survival, growth, and reproduction.

The flow regime, too, affects the nature of biotic interactions. Changes in water velocity and depth, and substrate stability provide numerous opportunities for fish to interact and compete with one another. For example, fusiform-shaped species (e.g. salmonids) are often better adapted to locating and capturing prey in swift-moving waters. Those species better adapted to slow-moving water may have difficulties in storm or flood events. On the other end of the spectrum, large fish may find less available deepwater habitat in drought conditions or small fish may lose off-channel rearing habitat when waters are low. When runoff from rains and high waters add additional sediments to streams, the associated turbidity may impair those species with slower reaction times for capturing prey or for avoiding capture that are based on their sight distance. As a final example, extra fine sediments imported during storm events may decrease interstitial spaces where aquatic insects (food items) live, thus reducing the prey base and increasing competition among fish. **Table 3** provides more information. This table provides general guidance on identifying potential effects of changes in subcomponents of the biotic interactions submodel on various life stages of salmon. Armoring may affect one or more of these components and to varying degrees.

Table 3. Biotic interactions ◉ egg/aelvin (in gravel) ▲ juvenile (fry/rearing) ■ adult (migration/spawning)

	Poor Conditions	Moderate Conditions	Optimal Conditions	Discussion
Water Quality	Temperatures conducive to proliferation of disease and parasites	Temperatures sometimes high enough to promote disease or parasites in least hardy fish	Natural stream temperatures, in optimal range for salmon species & life stage, such that disease and parasitism is kept in check	◉▲■ Increased water temperatures have been linked to increased incidence of disease and parasitism in fish[64]. Turbid waters heat more rapidly than clear waters.
	Temperatures outside normal range for time of year	Temperatures fluctuate in and out of normal range for time of year	Temperatures in range for time of year	◉▲■ Temperature influences critical life stage events like incubation time; hatching too early or too late could mean not enough food or too many competitors for food & space[39]
	Warm water that increases salmon metabolism while food sources are limited	Fluctuations in water temperature may cause periods of increased competition between fish for food	Cool waters that allow juvenile salmon to grow steadily to optimal size for eventual life in the sea	▲Increased temperature increases metabolic rate. Fish require relatively more food to maintain body weight or grow; this may increase intra- and interspecific competition for food
	Temperature/dissolved oxygen/pH near tolerance limit of salmon species throughout the reach	Temperatures/dissolved oxygen/pH approaching tolerance limits of salmon in some sites	Temperature/dissolved oxygen/pH within the tolerance limit of salmon species throughout the reach	▲■ All salmonids have optimal WQ parameters. Outside, or at the margins, fish may be stressed to the point they become sick, die, fail to grow, or have too few energy reserves to reproduce. Species better adapted to conditions salmon consider marginal may outcompete salmon for food, shelter, and other resources. Some microhabitats within the stream can provide better conditions for salmon than others (e.g., lower temperature behind boulders, in pools, or in shaded areas). When conditions outside these areas are limiting for salmon, increased competition for the primary resting and feeding places may ensue.
	Low light penetration (high turbidity – from erosion or excessive plankton) that affects food availability, the detection and capture of prey, and juvenile salmon detection of predators[5]	Moderate light penetration due to short-term sediment inputs or transitory plankton blooms, that may affect biotic interactions, but only over a short time period or in a localized site	Adequate light penetration for normal primary productivity and for salmon vision (can see prey and keep an eye out for predators)	▲Salmonids are visual feeders. Fish better adapted to low-light conditions could outcompete salmon[5]

Table 3, continued. Biotic interactions ◉ egg/aelvin (in gravel) ▲ juvenile (fry/rearing) ■ adult (migration/spawning)

Water Quality (cont)	Pollutants present that have noticeable adverse impacts on salmon species and decrease their ability to compete with other fish for food or habitat (e.g., affects reaction time, size, swimming ability). Also pollutants present in concentrations that reduce prey populations.	Pollutants present but in concentrations that do not have a deleterious effect on salmon or prey populations or affect only a small site (i.e., excess phosphates increase algal growth in a backwater area).	No pollutants present that negatively impact salmon or their food resources	▲■ Fish and prey species may be more or less susceptible to pollutants that affect their sensory perception, swimming ability, or growth (e.g. runoff, such as pesticides, herbicides, antifreeze, oil, or PAHs from auto exhaust)
Food (Energy) Source	Limited food sources for juvenile salmon throughout the reach	Food available for juvenile salmon on a site-by-site basis, but little diversity and lesser abundance than optimal	Abundant variety of food resources present; plenty for well-balanced fish population throughout the reach	▲Increased inter- and intraspecific competition for food is the result of limited availability. Salmon may lose weight, react more slowly to avoid predation or capture prey, and be less likely to swim long distances to find better foraging habitat.
	Limited food sources for salmon prey; little primary productivity or input of allochthonous materials	Food available for salmon prey items to feed on in selected sites, but little diversity and less abundant than optimal	Adequate primary productivity and input of allochthonous food materials for invertebrate species throughout the reach	▲When benthic invertebrates and other salmon prey cannot find food, it will not be long before their populations decline, reducing food for salmon
	Fish species or hatchery stock present that can outcompete native salmonids	Other fish present, but competition does not heavily favor hatchery stock or one species over another	Few other fish competing for the same prey items at the same time	▲Fish competing for the same prey items, may expend more energy to find/capture limited prey. One species or stock is generally dominant over the others in particular size classes; the distribution and abundance of fish and their food will determine whether competition occurs and whether it impacts fish growth or survival[65].
	Abundant and successful salmon predators present	Enough salmon predators present to impact juvenile salmon numbers; conversely, lack of salmon predators in the system causes excessive intraspecific competition	Predators present in numbers that keep the salmon population in balance	▲An abundance of predators that prefer to eat salmon will directly decrease the population. However, when no predators are present, high juvenile salmon densities could impact the population by increasing competition for food, and possibly causing the salmon to disperse, with some forced into habitat of lesser quality.
Flow Regime	Unpredictable, extreme change in conditions (depth, discharge, velocity) that occurs rapidly (hours-days)	Unpredictable, but moderate, changes in condition	Predictable, moderate changes in conditions that occur gradually (weeks)	▲Aquatic organisms cannot always adapt to rapid changes in their environment. (e.g., scouring velocities destroy benthic organisms and their preferred habitat; sudden drops in water depth may strand creatures unable to relocate before they desiccate). Species not preferred as food by salmonids may be most tolerant of such changes.
	Frequent high water that creates turbid water conditions throughout the reach	Unpredictable high water that creates localized turbid conditions at a particular site	Occasional high water conditions of short duration that provide a balanced input/output of substrate and organic materials throughout the reach	▲Turbid water can affect fish reaction time (to recognize and capture prey, or to avoid predators). Too much fine sediment can fill in interstitial spaces and destroy habitat for aquatic invertebrates of decrease the amount of hiding/resting places available for juvenile salmon.
	High proportion of slow-moving water throughout the reach	Lower diversity of habitat type (riffle/run/pool) and little or no side channel habitat	Even proportion of pools/ riffles/runs Plenty of space available for rearing salmon and their prey, including side channel habitat	▲■ Diversity in habitat type supports more fish and aquatic organisms simultaneously, allowing the species to partition themselves in different habitat types and reduce competition for resources.

Table 3, continued. Biotic interactions ⦿ egg/aelvin (in gravel) ▲ juvenile (fry/rearing) ■ adult (migration/spawning)

Habitat Structure	Few hiding spaces for juvenile salmon fry (either shallow water or instream cover) and predators present	Some instream cover present, but little side channel or shallow-water habitat to provide a reprieve for small fish from predators	Abundant instream cover and side-channel habitat to protect juveniles from predation	▲Fish may partition themselves in a stream system to avoid competition for food and habitat, but there is often overlap. Expect decreased survival of smaller/slower salmon when few hiding spaces are available for small fish, yet predators are present.
	Limited resting areas for upstream migrants (adults and juveniles)	Some resting areas present, but some salmon are forced to inferior habitat because there is not enough for all fish	Abundant boulders, pools, and in-water structure to provide resting areas for upstream migrants	▲■ Limited habitat that performs a specific function for salmon (e.g. resting areas), increases competition between fish for the best habitat. Those that do not win the competition will have to live in poorer habitat where they may not find enough food or have to expend more energy to survive[45]
	Substrate contains high percent fine materials throughout the reach	Substrate mixed; some fines, but not predominant	Substrate consists primarily of gravel and cobble and supports a healthy benthic invertebrate population	▲Excessive fines can smother benthic food organisms, thus increasing competition for remaining food items
	Little or no riparian habitat along the shoreline throughout the reach	Riparian habitat is fragmented	Riparian habitat is continuous throughout the reach	▲■ Riparian habitat provides cover in the form of shade, as well as habitat for terrestrial insects eaten by juvenile salmon. Lack of shoreline vegetation can increase water temperatures and decrease the amount of food available for fish. This can increase competition for available food & space, between native & hatchery fish or in intra-and inter-specific competition[39]

Flow Regime Submodel

All salmon lifestages are affected by flow regime. The habitat structure and changes made to the habitat determine how the timing of natural flow events affects water depth and velocity, distribution of sediments, and available space for rearing, migrating, and spawning fish and their prey **(Figure 6)**. Any change that affects one of the five critical components of flow regime (i.e., frequency of occurrence, duration, magnitude, timing, predictability, rate of change of hydrologic conditions) that regulate ecological processes in stream ecosystems has the potential to affect salmonid growth, survival, and reproduction (Poff et al., 1997). Fish and other aquatic organisms have adapted over the course of centuries to the natural range of daily and seasonal flows for a particular stream (Miller et al. 2001). Increasingly, human changes to the habitat, including those made to the stream channel and the riparian and/or upland areas, are causing flow conditions to fluctuate outside their natural range of variability. Examples of direct physical change include dams, culverts, dredging, and channelization. Changing land use, particularly the transformation of forested to agricultural and urban lands, with increases in impermeability and runoff, has indirectly altered river flow by affecting the hydrologic pathways, timing, and duration, that generate runoff. These alterations have had adverse effects on native species whose life cycles are dependent upon certain aspects of the flow, such as seasonal high flows that allow adult salmonids to access the upper reaches of a stream for spawning. However, thoughtful planning and construction can also ameliorate the affects associated with such extremes. Maintenance of the natural flow regime should be used as a goal for projects that alter the shoreline (Miller et al. 2001).

Natural events that can affect the flow regime include landslides, fire, drought, rainstorms, and snow melt. For example, landslides that push sediment and rocks into a stream may alter the flow by forcing the water into a narrower channel. This, in turn, increases water velocity through that stream section and may cause

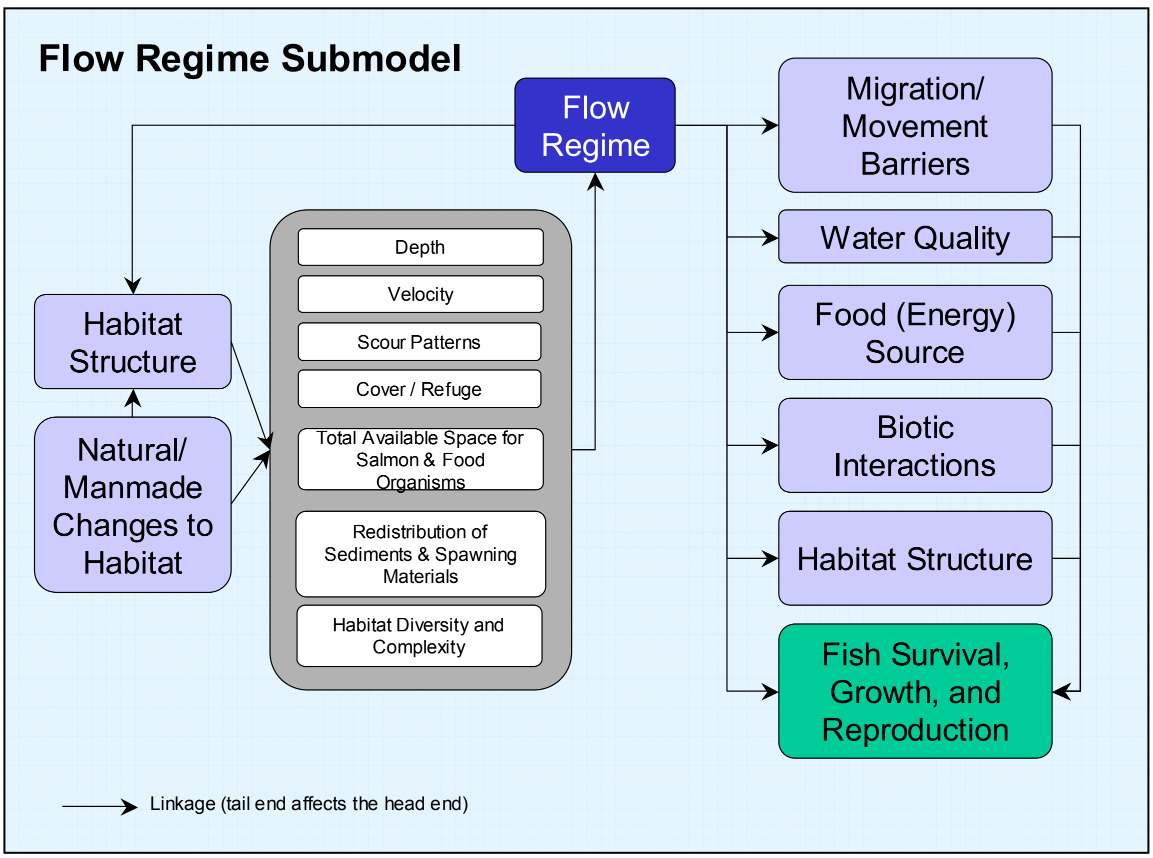


Figure 6. Flow regime submodel

deepening upstream. Fire damage to vegetation surrounding a stream may make banks vulnerable to erosion. The type and amount of substrate washed into the stream as a result, and the overall area of the stream affected, would determine the affects to fish. Drought may decrease the amount of available habitat to salmon by lowering water levels, reducing the abundance of side channels and mainstem shallow-water habitat. If the timing of flows is asynchronous with the natural flow regime, eggs and juvenile fish could be stranded or washed away, or adult migration could become difficult or impossible because of shallow water. If scouring flows occur at unnatural times of the year, predator-resistant insects may be favored over species more palatable for fish (Wootton et al. 1996 *in* Poff et al. 1997).

Depending on the bathymetry of the stream and floodplain, natural floods generally increase the amount of deepwater habitat, but may increase or decrease the amount of shallow water habitat available to juvenile salmon. Water velocities are generally increased during high water periods and additional woody debris and shoreline substrates, including fine silt, may be added to the system.

Manmade changes to shoreline habitats and stream channels can alter the flow regime in many ways. By replacing natural shoreline with impervious surfaces, more runoff reaches the stream than under natural conditions. At the same time, shorelines armored with cement, rocks, or gravel may reduce the amount of natural sediment transport into the stream system. While decreasing the amount of fine silt may be beneficial, depriving the stream of additional gravels, cobbles, boulders, and woody debris is almost certainly detrimental to salmon, especially if they are already lacking. Because the water is always pushing materials downstream, a steady input of new materials from the riparian and upland areas is required to kept the stream functional for salmon. Straightening a stream channel can increase water velocities and force materials to move downstream more quickly. On the other hand, humans may be able to bolster the functionality of a stream by increasing stream complexity. Re-routing a stream so that it includes more curves or off-channel habitat, forcing the stream to slow down in some areas and speed up in others, introducing large woody debris, boulders, and other structural features into the stream are generally beneficial for salmon. Planting vegetation along the shoreline and in upland areas can impact flow regime by reducing the amount of surface runoff that reaches the stream. In most cases, this is considered a positive impact.

While they are not used specifically for bank stabilization, the presence of manmade dams may produce cumulative effects when combined with other bank stabilization techniques. Many dams are constructed specifically for flood control and, therefore, greatly reduce the opportunity for sediment input to streams from high water conditions. Regulated water flows are often more uniform and predictable, although dam operators may raise and lower flows for reasons unrelated to fish passage and survival, occasionally stranding fish in shallow water pools or releasing large volumes of water that could increase velocities and shift substrates. **Table 4** provides more information.

Table 4. Flow regime ◉ egg/alevin (in gravel) ▲ juvenile (fry/rearing) ■ adult (migration/spawning)

	Poor Conditions	Moderate Conditions	Optimal Conditions	Discussion
Habitat Structure and Changes to Habitat	Increase in the homogeneity of stream depth	Decrease in number and extent of pools, but retains some variety in water depth	Natural amount and extent of pools and shallow water habitat	▲■ Salmon require thermal refuge, shallow-water refuge, and slow-water at different life stages. A combination of high and low water satisfies all aspects of their life history. Increasing homogeneity decreases amount of natural habitat change over time as required by salmon of different life stages.
	Narrowing of the channel with high scouring velocities through much of reach	Homogenizing of stream channel width, meaning either mostly slow-, or mostly fast-moving water	Natural variation in channel widths providing a variety of water velocities	◉▲■ Salmon generally begin their lives in shallow, slow-moving water, and move into deeper, faster water as they mature[41]. Streams with a discharge <10ft^3/s combined with a channelized, riprapped stream have lower salmon productivity[22]
	Major reduction in riparian vegetation and increase in impervious surfaces nearby	Only newly planted riparian vegetation present or a moderate reduction in shoreline vegetation	Continuous, mature riparian vegetation present	◉▲■ Reduction in shoreline vegetation and increased impervious surfaces generally means increased rate of lateral erosion[28, 57] and increased surface runoff added to the stream. During high water, vegetation can provide flood refugia.
	Stream straightened	Some meanders lost	Natural meanders present	◉▲■ Straightening a stream may increase water velocities and force needed organic and substrate materials downstream more quickly. Meanders force the stream to slow down in some areas and speed up in others.
	Major reduction in amount of instream large woody debris (LWD)	Moderate reduction in amount of instream LWD, or LWD consists only of single, straight logs	Natural amount of large woody debris that includes rootwads & branches	▲■ Large woody debris can slow water velocity locally and is important cover, especially for small salmon. It is less effective if only single logs or trimmed rootwads[66]
	Completely disconnecting the channel from the floodplain	Limiting connections between channel & floodplain	Natural connection between channel & floodplain	◉▲■ Limiting access to the floodplain can reduce floodplain storage (water and sediment), increase local instream flow (especially during flood events) and increase the flashiness of the flow regime.
	Major change in substrate type or rock size/shape, especially increase in fine sediment (e.g. >13% of particles less than 0.85mm)	Few large rocks present	Large rocks present and interstitial spaces free of fine sediment; natural conditions	◉▲■ Large rocks free of fine sediment provide optimal habitat for many aquatic insects and hiding spaces for juvenile salmon. Spawning materials for salmon species differ by size, but must be less than approximately 13% fine sediment for successful incubation of the eggs[78].
	Major loss of shallow, slow-water habitat	Moderate loss of shallow, slow-water habitat	Natural amount of shallow, slow-water habitat and side channels	▲■ Shallow, slow-water habitat provides needed resting and hiding areas for small salmon. Shoreline vegetation may grow in these areas and provide additional habitat and food for the aquatic organisms salmon feed upon.
	Armoring present or stream channelized along much of reach	Only a few individual sites armored and little or no channelization	No channelization or armoring	◉▲■ Channelization and armoring generally mean there will be accelerated streambank erosion elsewhere as a result of the deepening and straightening that occurs; this often leads to more armoring downstream.
	Major loss of habitat diversity or hydraulic complexity	Moderate loss of habitat diversity and hydraulic complexity	Meanders, hydraulic complexity and diversity, instream and overbank cover	◉▲■ Reduction in habitat diversity can reduce carrying capacity for salmon
	Major reduction in surface roughness	Moderate reduction in surface roughness	Natural amount of surface roughness	▲Steep banks with large rocks and maximum roughness are suitable habitat for most juvenile salmon[66]

Food (Energy) Source Submodel

As embryos and aelvin, young salmonids rely on energy reserves supplied by yolk material to sustain their metabolic needs. Most of their time is spent in the spawning substrate where the eggs were deposited by the adults. As adults migrating upstream to spawn, most salmonids do not consume food, but rely on fatty tissues built up while living in the ocean for energy. Thus, food is of primary concern to salmon in fresh water during their juvenile (fry/smolt) life stage. As juveniles, salmonids must have an adequate food supply to survive and grow. The food provides them with energy to move to optimal habitats, avoid predators, and capture prey. Each salmonid species has individual eating habits and food preferences, though there is some overlap.

- Coho salmon eat aquatic insects (mainly at surface), crustaceans, and small fish (including other salmonids).
- Chinook salmon feed primarily on insects. They are opportunistic drift and benthic feeders (Beauchamp et al. 1983).
- Chum salmon generally feed very little in fresh water. When they do eat, they primarily consume benthic organisms, such as aquatic insects (Pauley et al, 1986).
- Cutthroat trout are opportunistic feeders, and prey especially on aquatic insects (Glova 1984). They will sometimes feed on terrestrial insects, zooplankton, and fish (including sockeye and coho) (Armstrong 1971; Glova 1984; Pauley et al. 1989.
- Pink salmon do not normally feed in fresh water unless distance they must swim to reach marine waters is great; then they feed on larval insects (Bonar et al. 1989).
- Sockeye are a pelagic fish that subsist mainly on zooplankton (Pauley et al. 1989) and aquatic insect larvae (Platts and Rinne 1985; Burgner 1991)
- Steelhead juveniles consume microscopic aquatic organisms, isopods, amphipods, and aquatic and terrestrial insects (mainly on the stream bottom).

The amount and variety of food available is determined by the habitat structure and any changes that disturb the natural habitat, water quality, the flow regime, and biotic interactions **(Figure 7)**.

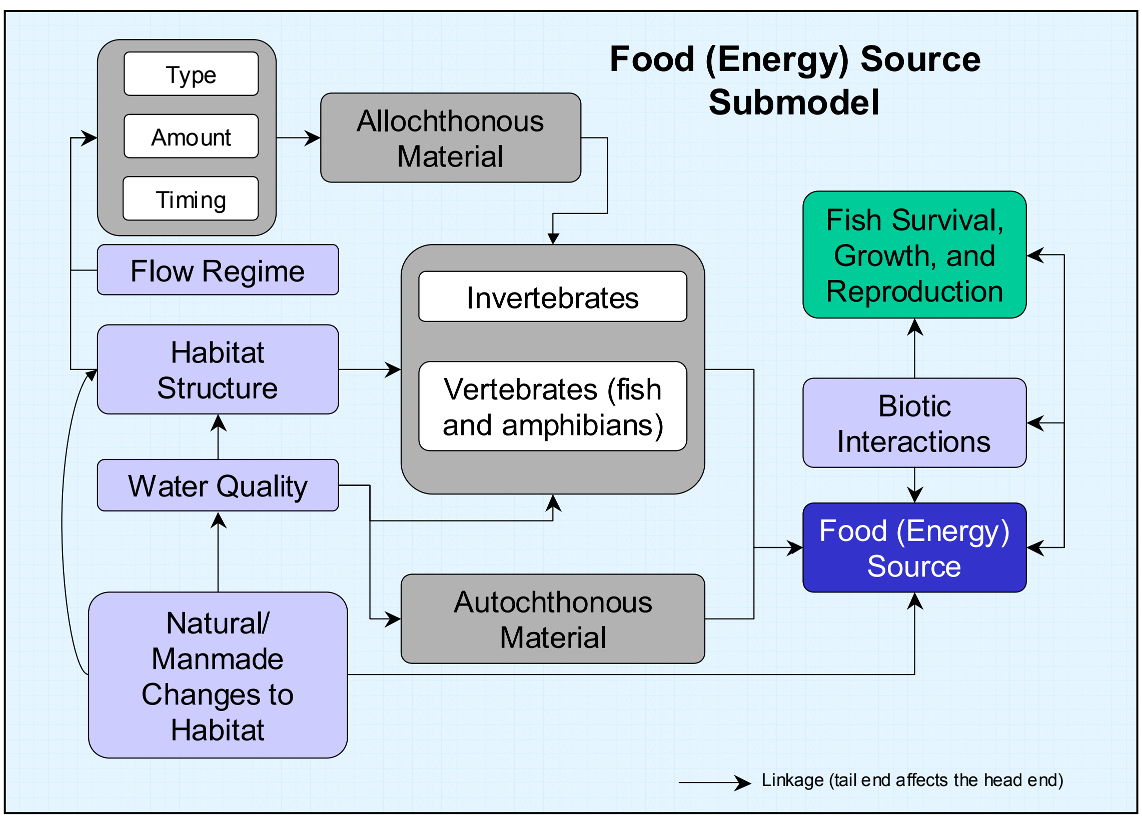


Figure 7. Food (energy) source submodel

Natural changes to habitat may directly affect water quality. Fire can reduce vegetation along the water's edge, increasing the possibility of siltation due to increased runoff and reducing the availability of terrestrial insects as a food source. Landslides and flood events may also increase amounts of fine particulate matter in the water. Water quality, as it relates to salmonids, is generally reduced by increased turbidity. Increased turbidity can decrease the ability of fish to see through the water. Prey items may need to be closer for fish to see them and react quickly enough to capture them. Significant amounts of fine particulates in the water can also increase water temperature (Reed et al. 1983). Changes in water temperature affect a fish's ability to take up oxygen from the water and can affect its metabolic rate, and thus the rate at which it needs to feed. In general, the higher the temperature, the more food the fish requires. There are optimal temperature ranges associated with every plant and animal species. Temperatures outside optimal ranges can impact growth and survival of flora and fauna in the salmon's food web. Temperatures that exceed the fish's optimal range may affect their own growth rates and survival or change the timing of life history events, such as smoltification (see **Table 8,** water quality). Increased water temperatures that stress fish are associated with increased incidence of disease (Rottmann et al. 1992).

Manmade changes to habitat may also directly affect water quality. Examples of changes include land use practices that increase or decrease the amount of nutrients and pollutants that reach the water. Other impacts may be related to modifying the streambank for protecting the bank from erosion or to either enhance or restore natural functions. These impacts may in turn affect temperature, pH, turbidity, and dissolved oxygen. Increased nutrient loading is often responsible for eutrophication of water systems. This affects fish food sources primarily through increased growth of plants that their prey may feed upon, or through a decrease in dissolved oxygen from increased plant uptake, that could affect the growth and survival of prey items. Another impact could be through competition for food with other fish species that are more or less adapted to the changes in water quality. If predators of juvenile salmon are better adapted to the changing conditions, then increased predation could also be considered an impact.

Aquatic habitat structure affects how much suitable habitat is available for juvenile salmon prey items. The substrate type and stability and hydraulic complexity of the habitat determine whether particular invertebrate and vertebrate species are available in numbers great enough to support juvenile salmon survival and growth. Too much fine material settling out in slow-moving water can smother aquatic insects. Structure, such as large woody debris, can provide increased food and habitat for other fish food items.

The flow regime can also affect juvenile salmon food (energy) sources. Changes in flow regime affect the total available space for food organisms by altering water depth, velocity, and distribution of sediments and organic materials in the system. For example, increased water flows can pick up plant material such as leaf litter and woody debris from high on the streambank and move it into the system, thus affecting the type, amount, and timing of allochthonous material input into the system.

Biotic interactions also affect the food (energy) source for salmon in freshwater systems. The presence of fish of similar size and/or feeding preferences can increase interspecific competition for resting and hiding spaces and for prey items. Increases or decreases in salmon survival, growth, and reproduction will also affect intraspecific competition for food. **Table 5** provides additional examples.

Table 5. Food (energy) resources ⦿ egg/aelvin (in gravel) ▲ juvenile (fry/rearing) ■ adult (migration/spawning)

	Poor Conditions	Moderate Conditions	Optimal Conditions	Discussion
Water Quality	Turbid water combined with low water velocity	Somewhat turbid water, but velocities high enough to keep particles in suspension	Turbidity not greater than 5 NTU over background turbidity when background is 50 NTU or less, or have no more than a 10% increase in turbidity when the maximum is >50 NTU[6] (generally total suspended solids (TSS) should be <25 mg/l[62]	▲ In general, water turbidity <25 mg/l permits good freshwater fisheries[10]. Excessive sand and silt (more settles out in slow water) may limit production of benthic invertebrates necessary for optimum rearing of juvenile salmonids[12, 56, 62]. High turbidity also reduces light penetration, and thus primary productivity
	Temperature above or below thermal tolerance of fish and food resources	Temperatures near the upper or lower tolerance limit of food resources	Temperatures within the natural range for the stream at a particular time of year	▲ Atypical high or low water temperatures may decrease aquatic food resource populations. Shade from riparian vegetation moderates water temperature fluctuations. (For more insight, see temp limits presented in the Water Quality Submodel table)
	Limited or excessive nutrients	Most nutrients in balance; limiting nutrient not critical to aquatic biota in salmonid food web	Balanced nutrients	▲ Limited nutrients restrict food resources for the aquatic invertebrates salmon feed upon. Addition of nitrogen and phosphorus fertilizer can increase production of zooplankton, causing increased production of planktivorous salmonids, such as pink salmon.[37] Excessive nutrients may also result in low dissolved oxygen.
	Toxic chemicals present that negatively impact aquatic biota development, growth, or survival	Toxic chemicals present, but in concentrations below the effect level	No toxic chemicals present	▲ Chronic or acute affects in aquatic biota from exposure to toxic chemicals can ultimately decrease the food resource for salmonids
	pH outside tolerance of food organisms	pH near the limit for food organisms	pH within natural range for the system (often between 6 and 8)	▲ Alteration in amount of woody debris can change pH; some aquatic organisms have narrow pH tolerances and have the potential to be affected
	Low (limiting) dissolved oxygen, generally <3 mg/l in combination with high temperature	Dissolved oxygen below 5 mg/l	Dissolved oxygen at saturation level under natural conditions	▲ Anoxic conditions can kill benthic organisms
Flow Regime	High and/or low flow events timed such that they are detrimental to salmonids and their food web	A mixture of beneficial and detrimental high and/or low flow events	High and/or low flow events timed to be beneficial to salmonids and their food web: the natural flow regime for the system	▲ High and low flow events often serve as ecological "bottle necks" that present critical stresses and opportunities for a wide array of species[58] The natural disturbance regime for the system is considered the best condition.
	Frequent or severe flooding (high magnitude discharge); coincides with sensitive species/life stage, and long in duration	Occasional extreme high waters, but of short duration and outside critical time periods	Predictable (but not severe) flooding at moderate intervals that follow the natural flow regime for the system.	▲ Few species can adapt to frequent flood events, thus abundance or diversity of food organisms may be lowered. Timing may be critical as some plant and invertebrate life stages are more vulnerable than others[48, 58]. Also, if scouring flows occur at unnatural times of the year, predator-resistant insects may be favored over species more palatable for salmonids [81 (in 58)] Human development along stream corridors tends to increase flood and peak flow frequency.
	Infrequent high flows or extremely short in duration	Unpredictable high flows	High waters occur at moderate (~bi-annual) intervals and provide input of new substrate, organic materials, and large woody debris	▲ Occasional high flows are important for adding organic materials and new substrate to the stream, which prey resources use for food and habitat[58] A lack of high waters may limit the amount of outside resources (organic material, sediment, LWD, etc) added to the stream[48].

Table 5, continued. Food (energy) resources ⦿ egg/alevin (in gravel) ▲ juvenile (fry/rearing) ■ adult (migration/spawning)

	Poor Conditions	Moderate Conditions	Optimal Conditions	Discussion
Flow Regime (con't)	High water velocities (>1.22 m/s)[62]	Fluctuating water velocities that sometimes exceed the upper or lower tolerance for invertebrate food organisms	Water velocities considered optimal for invertebrate food organisms (0.5-1.1 m/s)[62]	▲ Water velocities high enough to erode the substrate can displace or kill benthic organisms, but the extent depends upon the instream geomorphology
	Extended drought or low magnitude discharge; coincides with sensitive species/life stage	Occasional or predictable periods of low water that are short in duration	Constant water in riffle areas at optimal depth for salmonid food production (0.5-0.9 m)[62]	⦿▲■ Water depth can impact the availability of off-channel habitat, number and extent of pools, and other areas important for food resource habitat. Water withdrawals are and example of a human impact that affects water depth.
	Poorly regulated water flow can negatively impact aquatic food organisms (e.g. regulated for irrigation, flood control, hydroelectric production[45])	Regulation of water flows to mimic or improve on natural conditions with the benefit of salmonids and their prey organisms in mind	Natural stream conditions; no regulation	▲ Humans can remove too much water from a system (e.g., water withdrawals for irrigation) or create unnatural discharges, depths, and velocities (e.g., at dams) that adversely impact food organisms through stranding, scouring, or altering the conditions to which they are adapted (e.g., light levels, water quality).

Habitat Structure Submodel

All lifestages of salmon may be affected by the habitat structure. Embryos and aelvin require clean gravel and adequate water flow to survive incubation. Juveniles (fry and smolts) require habitat for resting, feeding, and movement, as well as habitat for the prey items upon which they feed. Adults require adequate water depths to navigate upstream to spawning areas that must consist of the clean spawning substrate. Resting areas behind large boulders, other structures, or in slow-moving water are also important for adults as they move upstream against the current.

Two factors that directly affect aquatic habitat structure are natural/manmade changes to habitat and water quality **(Figure 8)**. Another factor, flow regime, can indirectly affect aquatic habitat structure through alteration of hydraulic complexity and habitat diversity (Miller et al. 2001). Overall, the physical structure of the habitat is defined largely by physical processes, especially the movement of water and sediment within the channel and between the channel and floodplain (Poff et al. 1997).

Natural changes that may affect habitat structure include fires, floods, and landslides. Fires may reduce the streamside vegetation that would naturally decrease the amount of runoff into the stream. Erosion generally increases when cover on the slope above a stream is reduced. This often increases turbidity and the amount of suspended solids in the water column. This increased amount of fine sediment can alter the aquatic habitat structure by filling in slow-moving sections with fine particulates, effectively smoothing the channel, increasing embeddedness, and altering the flow regime. Floods may scour streambanks, forcing input of additional materials. Overall, this replenishment of substrate materials is considered beneficial, as it is a natural stream process. Many materials that would be washed into the channel are considered to sustain or improve salmon habitat. For example, gravels and cobble may be used as spawning material and large woody debris increases hydraulic complexity and creates places for young fish to hide from larger predators. However, excess silty material washed into the stream channel can degrade

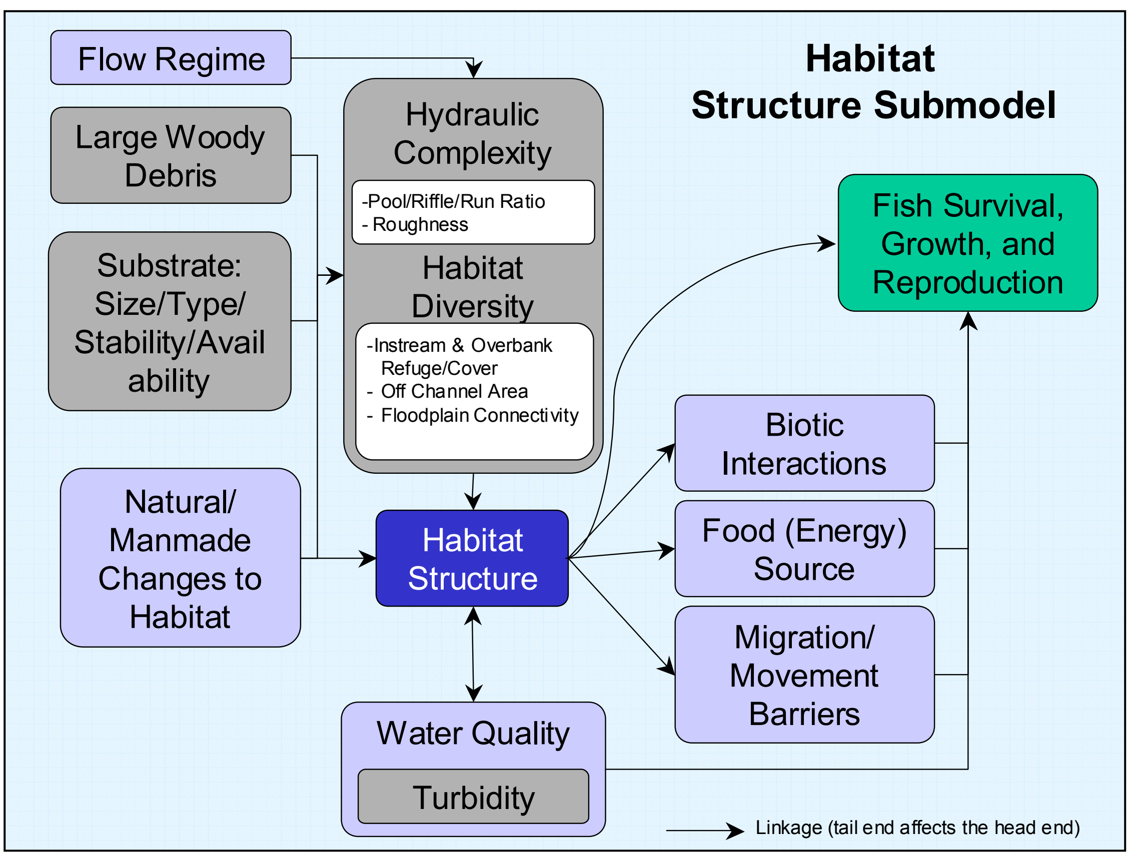


Figure 8. Habitat structure submodel

salmon habitat by increasing turbidity and in some cases by filling in interstitial spaces where aquatic insects and small fish would hide, covering spawning substrates, or possibly smothering embryos, aelvins, and aquatic insects. The flow regime is a factor in determining where and when suspended sediments settle.

Landslides can also transport materials into the channel. As in the flooding example above, transported materials may be considered beneficial or detrimental elements of the aquatic habitat structure as they relate to salmon in various life stages. Sudden large inputs of sediment may block a stream channel or otherwise change the channel and floodplain topography. Shoreline vegetation may end up in the channel.

A wide variety of manmade changes affects aquatic habitat structure. Because of the variation in flow regime within and among rivers, the same human activity in different locations may cause different degrees of change relative to unaltered conditions and, therefore, have different ecological consequences (Poff et al. 1997).
Many of the techniques used to reduce erosion along shorelines are described in the Integrated Streambank Protection Guidelines (Cramer et al. 2002). They include engineering projects designed for

- *Flow Redirection*: groins, buried groins, barbs, engineered log jams, drop structures, and porous weirs
- *Structural Bank Protection*: anchor points, roughness trees, riprap, log toes, rock toes, cribwalls, and manufactured retention systems
- *Biotechnical Bank-Protection*: woody plantings, herbaceous cover, soil reinforcement, coir logs, and bank reshaping
- *Avulsion Prevention* (significant, abrupt change in channel alignment resulting in a new channel across the floodplain): floodplain roughness, floodplain grade control, and floodplain flow spreader
- *Other*: channel modification, riparian buffer management, spawning habitat restoration, off-channel spawning and rearing habitat, and no action

While they are not all what might be considered "armoring' techniques, each alteration impacts habitat structure by increasing or decreasing channel roughness; the amount of cover available; the amount, timing and locations of sediment and organic material input; and the shape of the channel, including its depth, width, sinuosity, and connectedness with the floodplain. Each effect has an impact on salmonid growth, survival, or reproduction.

A natural flow regime usually includes high flows that remove and transport fine sediments that would otherwise fill interstitial spaces in productive gravel habitats (Beschta and Jackson 1979 in Poff et al. 1997). High flows also serve to import woody debris into the channel where it creates new, high-quality habitat used by fish and invertebrates. Alterations in flow regime, generally from human changes to the environment, often decrease habitat variety and degrade habitat structure from a salmonid perspective. For salmon and other river species that rely on an array of different habitat types being available at a particular time to complete their life cycle, a change in flow regime can be devastating. **Table 6** provides more detail how impacts to habitat structure affect salmonids.

Table 6. Habitat structure ◉ egg/alevin (in gravel) ▲ juvenile (fry/rearing) ■ adult (migration/spawning)

	Poor Conditions	Moderate Conditions	Optimal Conditions	Discussion
Water Quality	Turbid water resulting from a landslide or other sudden influx of terrestrial substrate material combined with low water velocity	Somewhat turbid water, but velocities high enough to keep particles suspended	Turbidity not greater than 5 NTU over background turbidity when background is 50 NTU or less, or have no more than a 10% increase in turbidity when the maximum is >50 NTU[6] (generally total suspended solids (TSS) should be <25 mg/l[62])	◉▲■ In general, water turbidity <25 mg/l permits good freshwater fisheries[10]. Excessive sand and silt (more settles out in slow water) may limit production of benthic invertebrates necessary for optimum rearing of juvenile salmonids[12, 56, 62], smother incubating eggs/alevin, or increase competition between fish for suitable habitat. (e.g., spawning habitat)
Flow Regime	Little hydraulic complexity (i.e., no stream braids, meanders, side channels, change in depth or velocity)	Hydraulic complexity absent in all but a few stream sites	Hydraulic complexity & diversity throughout the reach, good riffle: pool ratio and roughness, instream & overbank cover/refuge, side channels & meanders	◉▲■ Completion of the salmon life cycle requires an array of different habitat types (lots of hydraulic complexity). Microhabitat availability over time is regulated by flow regime. Limited habitat may decrease diversity or increase competition for food and space.
	No new channel formation or shifting between channels within the floodplain	Frequent shifting of stream channel within the floodplain over time	Moderate shifting of stream channel within the floodplain over time	▲Shifting of stream channels may strand juvenile salmon, aquatic insects and other invertebrates. The new habitat may or may not be an improvement for salmonids over what existed previously. Some shifting is needed to recruit spawning material, organic material, and other instream cover.
	No influx of large woody debris or gravel/cobble/ boulders	Import of large woody debris and gravel/cobble/boulders exceeds export	Regular import of large woody debris and gravel/cobble/boulders from periodic high water events	▲■ Floods import woody debris into the channel where it creates new, high-quality habitat[58] for fish and invertebrates and provides food for some invertebrates. LWD increases surface area and roughness, which contributes to habitat complexity and carrying capacity[80], especially in winter[63]
	High waters import only fine substrate materials	Fine substrate material imported to the stream results in near 13 percent[78] fines throughout much of the reach	Only small amounts of fine substrate materials added to water during high water events and/or high flows remove and transport fine sediments from interstitial spaces in gravel habitats[11 (in 58)]	◉▲Greater than 13 percent fines may smother eggs/alevin or benthic organisms and fill in interstitial spaces that would otherwise be used by small salmonids for hiding spaces[78]. The resulting lack of food and space increases competition between fish.
	Frequent scouring of substrate material	Infrequent scouring of substrate materials, but at predictable, “natural” times of year	Some export of substrate materials (especially fines) downstream, but few or no scouring events	◉▲■ If scouring flows occur at unnatural times of the year, predator-resistant insects may be favored over species more palatable for salmonids [81 (in 58)] or spawning beds and/or incubating eggs/alevin may be destroyed.

Table 6, continued. Habitat structure ⦿ egg/aelvin (in gravel) ▲ juvenile (fry/rearing) ■ adult (migration/spawning)

	Poor Conditions	Moderate Conditions	Optimal Conditions	Discussion
Flow Regime, continued	No connection between the channel and floodplain	Channel connects with floodplain only in a few sites	Channel and floodplain are connected throughout the reach	⦿▲■ The physical structure of the habitat is defined largely by physical processes, especially the movement of water and sediment within the channel and between the channel and floodplain. The severing of floodplains from main channels can slow or stop the process of sediment erosion and deposition[58]
	Small stream	Middle-sized stream	Large stream	⦿▲■ Impacts are generally more severe in small streams compared to large streams, e.g., construction equipment often IN small streams, but only on bank of large streams[44]
Natural/Manmade Changes to Habitat	See Changes to Habitat Submodel	See Changes to Habitat Submodel	See Changes to Habitat Submodel	⦿▲■ See Changes to Habitat Submodel

Migration/Movement Barriers Submodel

All juvenile and adult stages of salmon can be impacted by barriers to movement and migration. Without the means to move freely in the stream system, fish may not be able to access the habitat best suited to their growth and survival. Movement or migration success may be determined by interactions between the swimming abilities and energy reserves of fish, the amount and pattern of water velocities and resting areas, water quality, and the presence of physical barriers **(Figure 9)**.

Movement occurs in two directions; upstream and downstream. A literature review conducted by Kahler and Quinn (1998) indicated that upstream movement was observed in all salmonid species, age classes, and seasons but varied substantially by drainage. Adult salmon returning to spawn showed the most obvious upstream movement. However, juveniles rearing in streams also showed a propensity for upstream movement. For example, spring upstream movements by coho juveniles can be more prevalent than downstream movements and can range from several meters to several kilometers. Because adults die after spawning, downstream movement is attributed primarily to juvenile salmon life stages as they move to better rearing habitats or migrate to the sea.

Barriers to movement and migration may be natural or manmade. Natural barriers include water flows that are too high or too low; physical obstacles or steep gradients that block passage; and temperature, salinity, or other natural water quality characteristics outside the fish's tolerance limits. Similarly, manmade barriers to movement also involve changes to flow regime, aquatic habitat structure, and/or water quality. Particular manmade obstacles to movement may include increased or decreased flows for flood or irrigation control; installation of weirs, dams, and culverts; excessive turbidity from construction activities; supersaturated gas levels; thermal plumes, and chemical introductions to the stream system. **Table 7** provides more detail on how water quality, flow regime, habitat structure and changes to habitat affect salmon migration and movement.

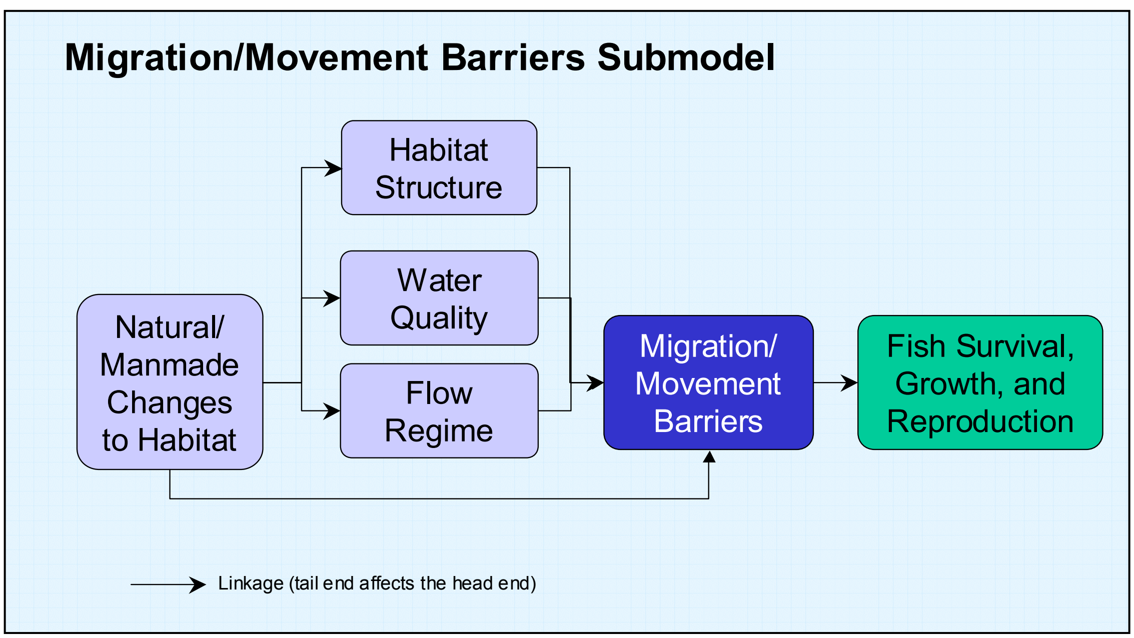


Figure 9. Migration/movement barriers submodel

Table 7. Migration/movement barriers ◉ egg/aelvin (in gravel) ▲ juvenile (fry/rearing) ■ adult (migration/spawning)

	Poor Conditions	Moderate Conditions	Optimal Conditions	Discussion
Water Quality	High turbidity (total suspended solids >4,000 mg/l)[10]	Turbidity generally between 25 and 4,000 mg/l	Turbidity within 5 NTU of background levels when background is 50 NTU or less; generally low turbidity is considered <25 mg/l[1, 62]	▲■ High concentrations of suspended sediments can stop adult migration[1] or inhibit juvenile movement and smolt outmigration
	High (upper lethal) temperature (23.8°C chum[53]; 23.9°C steelhead[10]; 24.4°C sockeye[56]; 25.1°C chinook[8]; 25.8°C coho and pink[10,2]; 28-30°C cutthroat[55])	Temperatures outside optimal range for migration	Cool temperatures in optimum range for salmon migration (7.2-15.6°C adult coho migration[62]; 5.6-14.6°C overall preferred range for pink[62]; 15°C optimum for sockeye[15]; 9-12°C optimum for cutthroat[10]; 8.3-15.6°C adult chum migration[10,62])	▲■ Thermal barriers may halt adult migration and inhibit juvenile movement[54]
	Low dissolved oxygen (<4.3 mg/l[7] or <50% saturation[56]) or gas supersaturation (>120%[21])	Dissolved oxygen levels at the upper or lower margins of species tolerance (generally <6 mg/l[24] or >110% saturation)	100% oxygen saturation or ≥ 7.8 mg/l[24]	▲■ Salmon may not enter stream section with low dissolved oxygen. Gas supersaturation may disorient salmon thus slowing or misdirecting movement.[10] EPA TMDLs for the Columbia and Snake Rivers is 110% total dissolved gas.
	Chemical concentrations that impair fish sensory perception (e.g., arsenic trioxide)[50]	Chemicals present with the potential for impairing fish sensory perception	Chemical concentrations below those that impair fish sensory perception	▲■ Some chemicals, often those used as pesticides or herbicides, (e.g., arsenic trioxide or diazinon) may impair sensory perception and slow or misdirect adult upstream migration[50]
Flow Regime	Overall adverse timing of flow events	Unpredictable timing of flow events	Overall predictable (and beneficial) timing for flow events	▲■ The timing of flow events is important to salmon because migratory and reproductive behaviors must coincide with access to and availability of particular habitat types[58]

Table 7, continued. Migration/movement barriers ◉ egg/aelvin (in gravel) ▲ juvenile (fry/rearing) ■ adult (migration/spawning)

Flow Regime, continued	Shallow water during adult migration (<18 cm, steelhead[54]; <20 cm pink salmon migration[14]; <18 cm for adult coho salmon migration[62]; <10 cm cutthroat[55]; <23 cm chum[72])	Water depth near the lower limit, causing fish to expend extra energy	Water deep enough for unimpeded adult fish movement (≥0.5m is optimal), while retaining near 1:1 riffle/pool ratio[54, 62] (or a ratio natural for the system) for juvenile downstream movement & resting areas for juvenile & adult upstream movement/ migration	▲■ Upstream adult migration and juvenile movement can be blocked if water is not deep enough for fish to move; the problem is most severe if over an extended period of time (months), or across the entire width of the stream below suitable spawning or optimal rearing sites. Low water and high-velocity water in culverts have been identified as a critical fish passage issue[4].
	Rapid decrease in water level during juvenile rearing	Unpredictable fluctuations in water level	No extreme fluctuations in water levels; changes are predictable and there is a consistent base flow	▲Rapid lowering of water levels, often due to human regulation, can strand juveniles and cause mortality
	High water velocity (>2.4 m/s for adult steelhead[54]; >2.1 m/s for pink salmon[14]; >2.44 m/s for adult coho salmon)	Water velocities between sustained swimming speeds and the maximum migration speed	Water velocities are within the swimming capability of the fish and suitable resting areas are available (adult coho sustained swimming speed is 1.04-3.23 m/s)[62]	▲■ Water velocities that exceed adult or juvenile swimming capability prohibit upstream movement. Floods, poor regulation of water past dams, and water channeled through small culverts at critical times[4] (during adult migration and juvenile rearing periods) can have severe impacts. Slow-moving water may lengthen the time required for both upstream and downstream movement, and increase total energy spent by fish, but does not stop salmonid movement/migration.
Habitat Structure and Changes to Habitat	Riffle/pool ratio not near 1:1[62] or within natural ratio for the stream	Riffle/pool ratio heavy on the riffle side, with few resting areas	Riffle/pool ratio near 1:1[62] or within natural ratio for the stream	▲■ Juvenile and adult fish require pools for holding and resting. When the ratio is heavy on the riffle side, there may be increased competition for holding/resting areas or fish may deplete reproductive energy reserves through constant swimming against the current.
	Dams or weirs without fish passage facilities, culverts, or irrigation canals/ditches present	Weirs, dams, irrigation screens with bypass or other fish passage facilities present	Weirs, dams, culverts, and irrigation canals/ditches absent[54]	▲■ Fish cannot swim upstream past weirs higher than they can jump, or past dams lacking fish passage facilities. Even those dams with fish passage facilities may be significant obstacles for fish, such as chum. Fish may bypass irrigation canals that are screened and have an approved bypass system. Culverts can be upstream movement/migration obstacles for both juveniles and adults depending on the slope, flow, length, and other culvert configurations[4].

Water Quality Submodel

Good water quality is essential to the survival of all salmon life stages. As the fish mature, they can often tolerate a wider variation of many water quality parameters, but there are limits within which fish survive and grow, and outside of which fish may not reproduce, grow, or even survive. Natural and manmade changes to habitat and the flow regime have the most influence on water quality **(Figure 10)**. Water quality as a whole is affected by a number of individual properties, many of which influence each other. For example, increased turbidity decreases light penetration, thereby increasing the rate (to some extent) at which the water's temperature increases (Reed et al. 1983). Reduced shading of water, brought about through removal of streamside vegetation, may increase the amount of solar radiation reaching the water and thereby increasing the water temperature. Because warm water has less capacity for oxygen, decreased dissolved oxygen levels could be a second product of vegetation clearing.

Armoring a streambank affects water quality. When streambanks are cleared of vegetation during construction, there is often increased surface runoff into the stream in addition to an increase in water temperature if natural shading is reduced. Depending on what the upland land uses are, the increased runoff may mean increased inputs of nutrients (e.g. fertilizers and pesticides) or other chemicals into the water. The amount of suspended solids in the water column could be decreased over time if the armoring prevents natural sloughing of bank materials into the water channel. Armoring with natural materials that are placed to purposefully mimic natural stream conditions (e.g. placement of large woody debris or boulders at stream bends and planting of the shoreline with native species) may have a smaller negative impact to water quality while still providing the means to keep a stream where people want it to be.

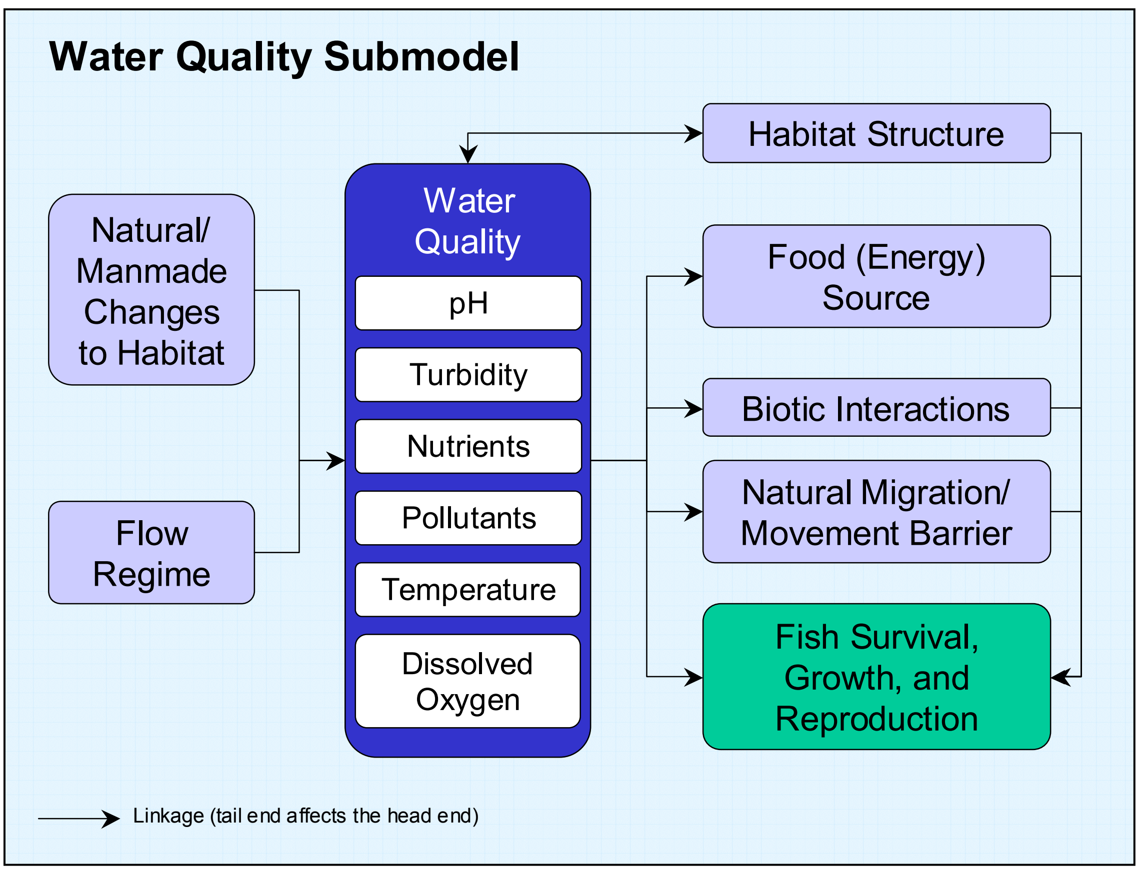


Figure 10. Water quality submodel

Natural changes, such as fire and landslides, can also affect water quality. As in the manmade examples, loss of streamside vegetation may directly increase water temperature, decrease dissolved oxygen, and facilitate the transport of nutrients and pollutants into the stream system through surface runoff. Landslides can increase turbidity, thus indirectly increase water temperature, and potentially decrease dissolved oxygen. The overall area affected by the manmade and natural changes to habitat will dictate the extent of the impact to salmon in the stream. Additional examples of how factors impact water quality and salmonid fitness are provided in **Table 8.**

Table 8. Water quality ◉ egg/alevin (in gravel) ▲ juvenile (fry/rearing) ■ adult (migration/spawning)

Factor / WQ Parameter	Poor Conditions	Optimal Conditions	Discussion
Natural/ Manmade Changes to Habitat	Increased input (source or non-point) of nutrients or pollutants to stream at levels detrimental to fish and other aquatic organisms	Only natural input of nutrients and no pollutants	▲■ Nutrients can increase populations of phytoplankton or macrophytes that some aquatic organisms feed on, but too much growth can cause eutrophication and overall decreased dissolved oxygen, increased turbidity, and changes in pH.
	Gas supersaturation resulting from dam spill	No human regulation of water conditions that result in gas supersaturation	▲Gas bubble disease in juvenile salmon has been associated with supersaturated water below some large dam spillways[21]
	Dissolved oxygen (DO) below 5 mg/l (i.e., due to high temperatures, eutrophication)	DO >7.8 mg/l or near 100% saturation	◉▲■ Human activities can affect dissolved oxygen levels. Dissolved oxygen levels are most critical to incubating eggs/alevin, but there are limiting levels for juveniles and adults as well. If levels are too low, migration and movement may cease, or aquatic food organisms may die and be unavailable for salmonids.
	Construction practices increase input of fine sediment to the stream	Stable slopes minimize chance of landslides and/or best management practices limit sedimentation during construction and other human activities	◉▲Increased amounts of fine sediment can increase turbidity, possibly decreasing a salmon's ability to see prey or predators. It may also settle out in slow-moving waters and smother eggs/alevin or other aquatic organisms living in the gravel and interstitial spaces. Deposition of fine sediment can also cause a stream channel to meander[26]
	Water temperature near or above fish or aquatic organism upper limit by: ▪ Loss of riparian vegetation (fire or cutting) ▪ Drought ▪ Increased turbidity (landslide, construction, or other human input)	Water temperature within natural range for the stream at that time of year	◉▲■ High temperatures can affect fish growth and survival, timing of important life events[69] (e.g., time to hatch, movement, spawning), and the availability of habitat and food resources.
Flow Regime	Frequent high water events	Moderate, predictable high water events	◉▲Flooding generally means increased input of fine sediment to the stream. Too much fine sediment fills interstitial spaces and smothers eggs/alevin and the benthic invertebrates that live there[78].
	Input of large woody debris that alters pH to levels outside the tolerance limits of native species	Large woody debris contributes to habitat diversity and hydraulic complexity, provides food and shelter for aquatic organisms, and does not alter the natural pH of the stream	▲Some aquatic organisms may have narrow tolerance limits for pH; however a pH change this extreme would be a rare case
Temperature	COHO ≥25.8°C STEELHEAD ≥23.9°C PINK ≥25.8°C SOCKEYE <7.2°C and >23°C for juveniles and adults[56] CUTTHROAT >22°C continuous or >26-30°C upper lethal[9, 55] CHUM <0 and >23.8°C[53] CHINOOK >22°C unable to spawn; 25.1°C upper lethal	COHO: 11.8-14.6°C [10] STEELHEAD: 3.9-9.4°C spawning[62]; 7.2-14.5°C for rearing[10] PINK: 7.2-12.8°C for spawning[62] 4.4-13.3°C for incubation[62] 5.6-14.6°C for adults[62] SOCKEYE: 10.6-12.2°C for spawning[62] 4.4-13.3°C for incubation[62] approx. 9-18°C best overall[15,56] CUTTHROAT: 9-12°C overall[10] 6-17°C for spawning[10] 10-11°C for incubation[55] 15°C for rearing[55] CHUM: 8.3-15.6°C for adult migration[10,62] 7.2-12.8°C for spawning[62] 4.4-14°C for incubation[62] CHINOOK: 5.6-13.9°C for spawning[62] 5-14.4°C for incubation[62]	◉▲■ High temperatures can affect fish growth and survival, timing of important life events[69] (e.g., time to hatch, movement, spawning), and the availability of habitat and food resources. ◉Incubation time varies with temperature. ◉In general, optimal incubation temperatures for salmonids are 4.0-14.0°C[62] ▲Unusual temperatures can alter the time of migration[69], retard maturation, and lead to outbreaks of disease[62, 64] ▲During rearing, temperature influences growth rate, population density, swimming ability, ability to capture and use food, and ability to withstand disease outbreaks[62, 64]

		11-17°C for rearing[8]	

Table 8, continued. Water quality ◉ egg/aelvin (in gravel) ▲ juvenile (fry/rearing) ■ adult (migration/spawning)

Factor / WQ Parameter	Poor Conditions	Optimal Conditions	Discussion
Dissolved Oxygen (DO)	STEELHEAD 6.5-7.0 mg/l = decreased swim performance[54] >125% saturation (supersaturation) CHINOOK <4.5 mg/l (at 20°C) = avoidance in juveniles[8]	COHO >5 mg/l (near saturation) for incubation 4-9 mg/l for juvenile weight gain & food conversion PINK >6 mg/l for incubation[62] SOCKEYE >5 mg/l for incubation[62] O_2 reduced to 50% saturation at high temperatures severely limits energy available for migrating and feeding[56] CHINOOK >5 mg/l for incubation[8]	▲■ In general, initial distress for salmonids may be observed at 6.0 mg/l, and adverse effects below 4.25 mg/l, in temps between 0 and 20°C[25]. ◉DO in substrate is a function of the DO in the stream, rate of intergravel water flow, and biological demand for O_2 in the immediate area[14] ◉O_2 supply rate may be more important than concentration for eggs/aelvin[53] ◉▲■ Low DO levels can affect the rate of metabolism, swimming performance, growth rate, food consumption rate, efficiency of food utilization, behavior, and ultimately the survival of salmonids[62] ■ Adult salmon mortalities may occur when low DO is combined synergistically with high temperature[14] ▲Fry reared in low DO may be smaller, weaker, and have lower survival than those raised in optimal conditions[62] ◉Reduced DO may increase the incubation period and delay hatching[62] ◉Low DO may increase incidence of anomalies in early development[62] ▲Conditions of supersaturation can cause the serious histopathological problems associated with gas bubble disease[54] ▲ Gas bubble disease in juvenile salmon has been associated with supersaturated water below some large dam spillways[21] ◉▲■ Human activities can affect dissolved oxygen levels. Dissolved oxygen levels are most critical to incubating eggs/alevin, but there are limiting levels for juveniles and adults as well. If levels are too low, migration and movement may cease, or aquatic food organisms may die and be unavailable for salmonids.
Turbidity	▪ >4000 mg/l[10] ▪ Less productive pink salmon streams generally contain >15.0% by volume of fine sediments (<0.8 mm)	▪ Turbidity not greater than 5 NTU over background turbidity when background is 50 NTU or less, or have no more than a 10% increase in turbidity when the maximum is >50 NTU[6] (generally total suspended solids (TSS) should be <25 mg/l[62]) ▪ Productive pink salmon streams generally contain less than 5.0% by volume of fine sediments (<0.8 mm)	◉Low siltation is important for survival of eggs and alevin. Too much silt can restrict oxygen flow to eggs and fry or trap alevin in the gravel[45, 78]. ▲High turbidity may lower salmonid growth rate[68] by curtailing feeding[62] or reducing their ability to locate and capture prey ▲■ Turbid water may decrease salmonid ability to detect predators ▲■ Fine particles can clog and abrade gills[62] ▲■ Salmon may avoid areas of high turbidity, thus restricting salmonid movement and/or migration[62]. ▲Food supplies may be destroyed through scouring or smothering[45]. ◉▲When fine sediment fills interstitial spaces, habitat opportunity is lost and increased competition may ensue. ◉▲■ Water temp increases at a greater rate with increasing turbidity[60].
pH	pH altered by pollutants or too much large woody debris	pH within natural conditions for the stream	◉▲■ Alteration of the amount of woody debris in streams can change pH[20]
Nutrient Load	Limited or excessive nutrient input from point or non-point sources	Nutrients from natural sources, with none considered limiting	▲■ Nutrient load affects primary productivity, which in turn affects food resources for salmon[73]. Nutrients can increase populations of phytoplankton or macrophytes that some aquatic organisms feed on, but too much growth can cause eutrophication and overall decreased dissolved oxygen, increased turbidity, and changes in pH.
Pollutants	Concentrations affect fish growth, survival, reproduction, or behavior[50]	No pollutants in the stream	◉▲■ Pollutants are just one factor considered detrimental to salmonid habitat[45] and have potential to alter salmon behavior. One example, arsenic trichloride, can decrease salmon migration success[50]

Natural/Manmade Changes to Habitat Submodel

Natural and manmade changes affect every life stage of salmon. Eggs and embryos are affected by anything that impacts water quality, water depth and velocity, and the substrate type and redistribution. Juveniles are affected by changes in water quality; availability of suitable resting, rearing, and feeding habitats; presence of sufficient prey resources; the abundance of predators and other fish competing for food and space; and also barriers to movement and migration. Similarly, adults are limited to particular water quality conditions, and require suitable resting and spawning habitats, plus passage during migration **(Figure 11)**.

Cumulative Impacts Model

The scale of the habitat changes may determine whether the impacts are considered negligible, positive, or negative as they relate to salmon. Another conceptual model highlighting connections between streambank armoring and cumulative impacts to salmonid populations and habitat is shown in **Figure 12**. **Tables 9 through 13** present examples of manmade changes to habitat designed for flow redirection, structural bank protection, biotechnical bank protection, avulsion prevention, and other reasons, respectively. Inside the tables are examples of potential effects of the erosion prevention techniques on water quality, biotic interactions, food sources, habitat structure, migration/movement barriers, and flow regime.

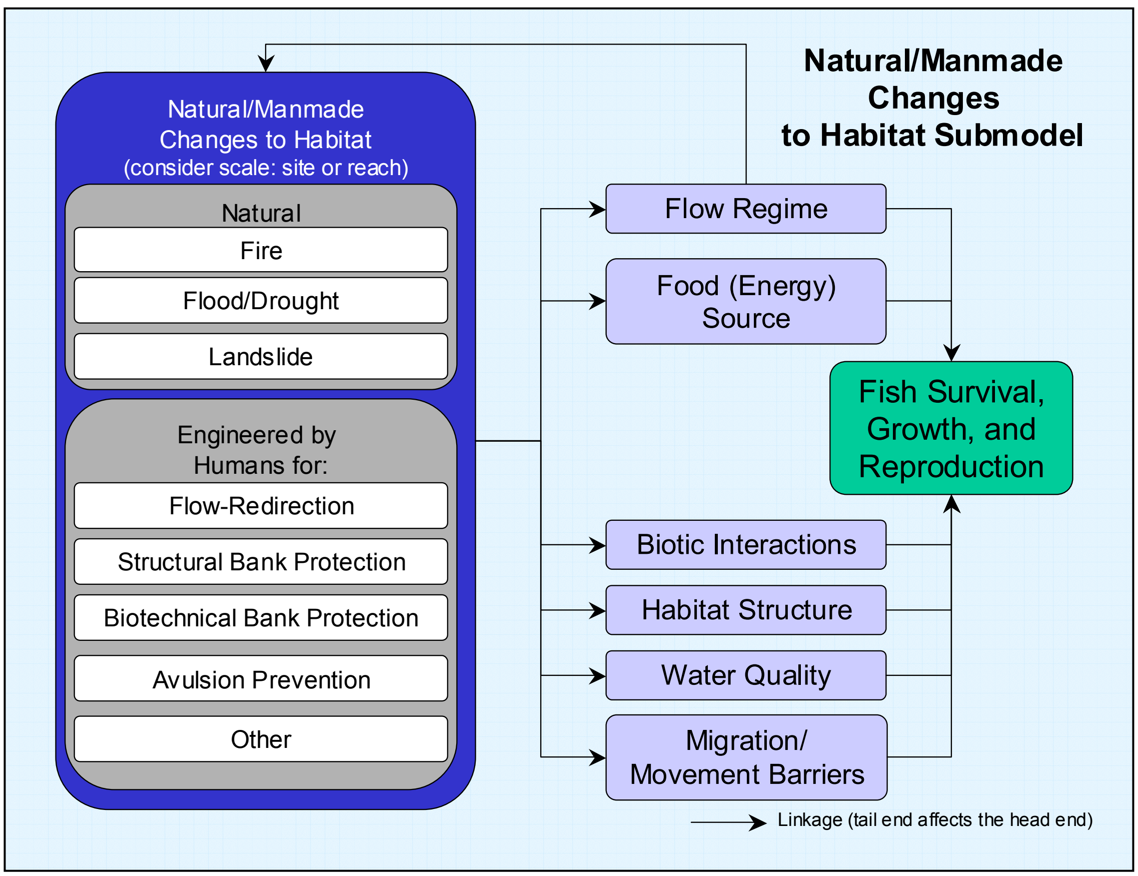


Figure 11. Natural/manmade changes to habitat submodel

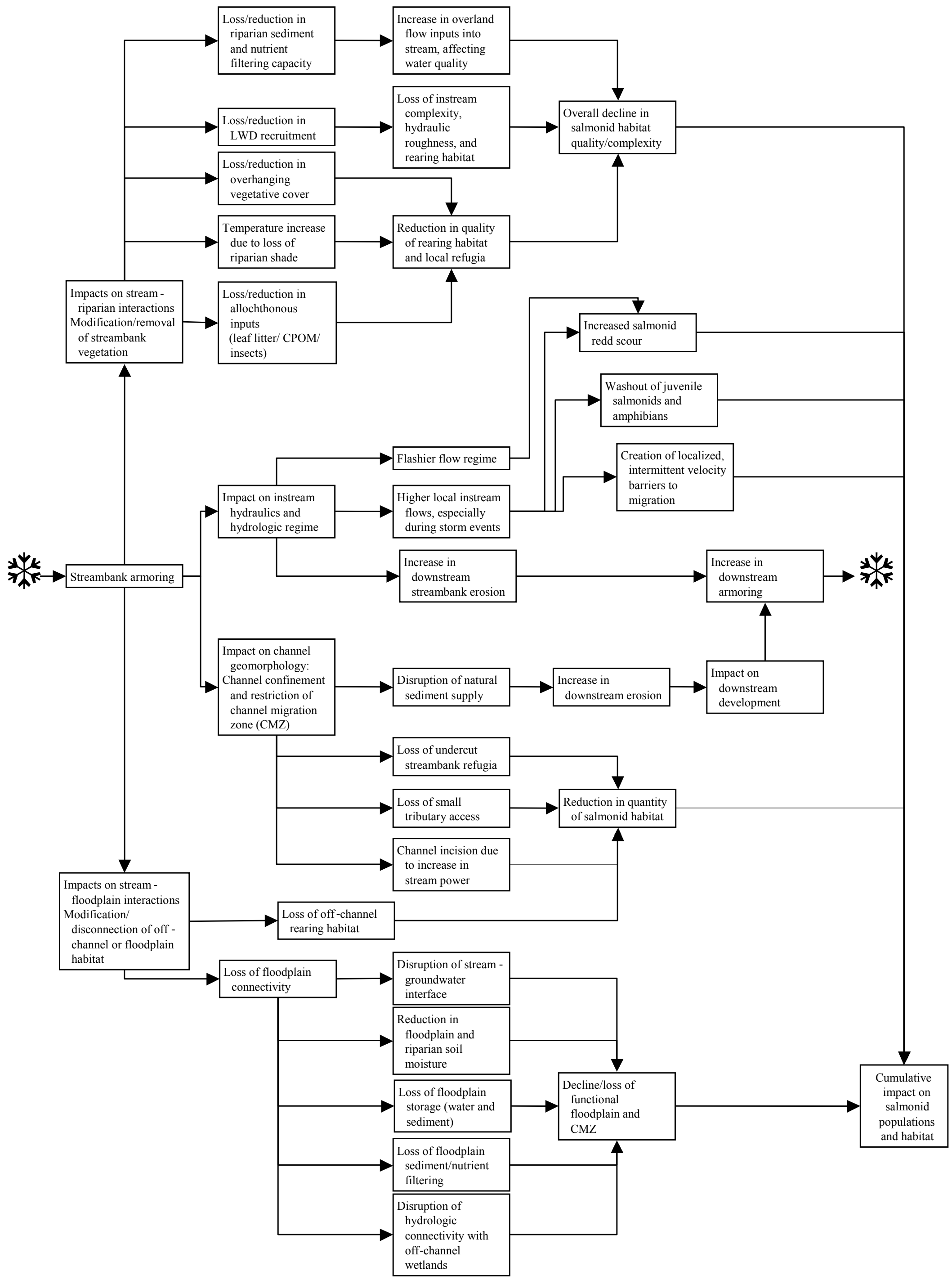


Figure 12. Conceptual model indicating streambank armoring connections to cumulative impacts on salmonid populations and habitat.

Table 9. Manmade change to habitat: flow redirection

Techniques for Erosion Prevention & Typical Materials	Water Quality	Biotic Interactions	Food (Energy) Source	Habitat Structure	Migration/ Movement Barriers	Flow Regime
Groins - Angular rock, LWD, or concrete	• Construction may temporarily increase turbidity • Increased sediment deposition in slower waters may increase turbidity along shore and downstream • Scour holes = lower local water temperatures • Any loss of riparian habitat can increase water temperature downstream; extent likely small, unless a series of groins are constructed throughout a reach or banks are not revegetated	• May provide more slow-water feeding areas along bank and in scour holes • Scour holes can provide resting space for adults or juveniles (more holes = less competition for space) • Small fish may find shelter from predators in interstitial spaces if rocks are large enough • Backwater areas can provide refuge from flood waters for smaller fish	• LWD, if added, can provide food & habitat for aquatic organisms • Interstitial space between rocks or logs can provide refuge for fish and aquatic organisms • Removal of riparian vegetation can decrease organic input and terrestrial insects	• Constricts channel • Increases upstream water depth • Decreases downstream velocity • Creates roughness (surface turbulence provides cover) • Can erode opposite bank & may destroy existing spawning habitat or redds (depends on timing) through scour or fine sediment deposition • Forms scour hole near groin tip – timing of construction may impact whether existing redds are destroyed • Lost opportunity for sediment/ gravel & LWD recruitment (may reduce spawning habitat, decrease habitat complexity if it was already present) • May reduce or prevent side channel formation if opportunity exists • May accrete spawning gravels along banks and increase spawning habitat • Removal of riparian vegetation decreases cover for fish	• Generally does not impact migration or movement	• Constricts or redirects flow with possible increase in stream power
Buried Groins - large rock, LWD, or concrete	Factors same as for groins, once it is exposed	Factors same as for groins, once it is exposed	• Factors same as for groins, once it is exposed	• Allows natural channel and floodplain function until groin is exposed • Other factors same as for groins, once it is exposed	• Generally does not impact migration or movement	• Constricts or redirects flow with possible increase in stream power
Barbs - large angular rocks, logs	• Factors same as for groins	• Factors same as for groins	• Factors same as for groins	• Effects generally the same as for groins, but less extreme	• Generally does not impact migration or movement	• Constricts or redirects flow with possible increase in stream power

Table 9, continued. Manmade changes to habitat: flow redirection

Techniques for Erosion Prevention & Typical Materials	Water Quality	Biotic Interactions	Food (Energy) Source	Habitat Structure	Migration/ Movement Barriers	Flow Regime
Engineered Log Jams - LWD (anchored or unanchored)	• Removal of riparian vegetation decreases shade & increases water temperature • Construction may temporarily increase turbidity	• Increased instream cover (LWD) decreases competition for space and generally increases the food supply	• LWD provides cover for aquatic organisms • Detritus accumulates in LWD (food for aquatic invertebrates) • Removal of riparian vegetation can decrease organic input and terrestrial insects	• Act like groins when anchored to shore • Least effective if straight, single logs[7]; most effective if includes root wads and/or branches • LWD provides rearing habitat for juveniles • May cause temporary scouring of spawning areas	• Generally does not impact migration or movement	• May constrict or redirect flow with possible increase in stream power
Drop Structures - angular or round rock, logs, sheet pile, or concrete that span entire stream width	• Excavation of streambed temporarily increases turbidity	• Loss of juvenile downstream rearing habitat (shallower pools) may increase competition for food or space • May increase hiding areas along shore	• Riparian areas generally undisturbed; provides organic material to aquatic organisms and terrestrial insects for fish food	• New scour patterns may destroy existing redds or spawning areas • Reduces erosion • Decreases depth of downstream nearshore pools (loss of juvenile rearing habitat) • Increases depth of water upstream (backwatering) • Increases surface turbulence = cover for fish • Streambed excavation can destroy redds or spawning habitat • Increased turbulence during high flows decreases flood refuge for fish • Increases habitat complexity if breaks up a long glide or riffle • Sorts & captures spawning-sized gravels downstream of scour holes • Banks accrete (may destroy spawning areas) • Creates uniform (not diverse) habitat across the stream width; more problematic if several built in a series	• Potential barrier to upstream movement or migration	• May constrict or redirect flow with possible increase in stream power

Table 9, continued. Manmade changes to habitat: flow redirection

Techniques for Erosion Prevention & Typical Materials	Water Quality	Biotic Interactions	Food (Energy) Source	Habitat Structure	Migration/ Movement Barriers	Flow Regime
Porous Weirs - boulders arranged loosely across stream width	• Not much effect on water quality	• Slower, shallower water along shore may provide shelter for small fish from predators • Boulders generally provide cover for juveniles and adults in scour pools & low-flow regions immediately downstream (more resting spaces = less competition)	• More diverse habitat (behind boulders, and difference between slow (shore) and fast (center) water provides shelter & conditions for more aquatic organisms	• Energy dissipation along shore increases bank sediment deposition (may lose some pools) • Increases sediment transport capacity by accelerating stream flow (at weir site) • May be topped in high flow events (allows channel-forming events to take place, at a moderated level) • New scour patterns can affect spawning areas & redds, but temporary in nature because material can flow through, creating new spawning areas • Increases habitat complexity if breaks up a long glide or riffle	• A center opening allows fish passage	• May constrict or redirect flow with possible increase in stream power

Table 10. Manmade changes to habitat: structural

Techniques for Erosion Prevention & Typical Materials	Water Quality	Biotic Interactions	Food (Energy) Source	Habitat Structure	Migration/ Movement Barriers	Flow Regime
Anchor Points - tree, rock outcrop, rock, or log trench	• Preserved pools means localized thermal refuge (cooler waters) • Decreased local scour can decrease local turbidity • Generally little loss of riparian vegetation; temporary impact	• Preserved pools are resting areas for fish; the more there are the less competition for space • Accumulated debris may provide hiding spaces for small fish	• Preserved pools are usually good habitat for food organisms • Accumulations of debris provide organic material (food) for aquatic organisms as well as shelter	• May deepen existing pools (preserves pool and therefore cover) • May accumulate debris (structure = habitat for fish and aquatic organisms) • Decreases local scour	• Generally does not impact migration or movement	• May constrict or redirect flow with possible increase in stream power
Roughness Trees - trees, rootwads	Reduces erosion and turbidity except during construction	May provide hiding spaces for small fish	Adds habitat for aquatic organisms and provides organic material for food	• Slows water along bank • Introduces roughness (cover for fish)	• Generally does not impact migration or movement	• May constrict or redirect flow with possible increase in stream power
Riprap - graded angular rock & filter material	• Destroys riparian habitat; decreases shading and may increase water temperature	• Loss of riparian habitat decreases overhead cover and food supply for aquatic invertebrates (increases competition for space and food among fish) • Interstitial space size determines if fish can use it for hiding/resting areas; less space may make juveniles more vulnerable to predation • Increased velocity may cause fish that can't find refuge to swim harder & use energy reserves faster (need to eat more food to grow) • Large fish may be better able to utilize non-structural cover than small fish[44]	• Fewer microhabitat types support fewer aquatic organisms and life stages (fish and invertebrates)[27, 66] • Reduced input of organic materials, especially LWD, reduces food for aquatic organisms	• Offers little habitat diversity or complexity; can lose undercut banks and log snags[44, 66], channel is usually straightened[27] • Streams often adjust down (incise), which can sever floodplain connection[27] • Permanently alters & interferes with natural channel migration, off-channel habitat formation, LWD & sediment recruitment • Often causes erosion down-stream (causing more shoreline to be armored) • Increases water velocity; smaller and/or more homogeneous rocks = less roughness, faster water[27] • Generally more difficult to establish vegetation on riprap than on natural banks[27]	• Generally does not impact migration or movement	• May constrict or redirect flow with possible increase in stream power

Table 10, continued. Manmade changes to habitat: structural

Techniques for Erosion Prevention & Typical Materials	Water Quality	Biotic Interactions	Food (Energy) Source	Habitat Structure	Migration/ Movement Barriers	Flow Regime
Log Toes - logs and gravel fill	• If riparian vegetation is not affected, increases in water temperature & turbidity are not expected	• If logs incorporate rootwads or branches, there will be additional refuge for small fish • Increased velocity may cause fish that can't find refuge to swim harder & use energy reserves faster (need to eat more food to grow)	• Logs supply organic material and habitat for aquatic organisms that fish feed on	• Not permanent (last years to decades); off channel habitat, natural channel migration, LWD & spawning substrate recruitment will eventually be restored • Stops downstream meander; increases up- and/or down-stream erosion along the reach • May produce deep scour • Increases water velocity • Decreases habitat complexity	• Generally does not impact migration or movement	• Constricts or redirects flow with possible increase in stream power
Roughened Rock Toes - angular rock & filter material (fabric or gravel)	Riparian vegetation not affected, so increases in water temperature & turbidity are not expected	• Decreased habitat complexity generally means increased competition among fish for food and space • Increased velocity may cause fish that can't find refuge to swim harder & use energy reserves faster (need to eat more food to grow) • Scour may create pools for fish to use as refuge	• Riparian habitat remains to provide organic material to the stream • Decreased habitat complexity reduces prey base for fish	• More permanent; off channel habitat, natural channel migration, recruitment of LWD & spawning substrate are reduced or eliminated • Stops downstream meander; increases up-and/or down-stream erosion along the reach • Increases water velocity • Decreases habitat complexity • Increases scour	• Generally does not impact migration or movement	• Constricts or redirects flow with possible increase in stream power
Log Cribwalls - logs backfilled with soil & rock	• Excavation of bank generally required, so there is at least temporary loss of riparian vegetation (decreased shading = warmer waters; temporary increase in turbidity	• Decreased habitat complexity generally means more competition among fish for food and space • Increased velocity may cause fish that can't find refuge to swim harder & use energy reserves faster (need to eat more food to grow) • Scour may create pools for some fish to use as refuge	• Loss of riparian habitat means less organic matter (food) for aquatic invertebrates • Decreased habitat complexity reduces prey base for fish	• Semi-permanent (decades); lost opportunity for formation of off channel habitat, channel migration, and recruitment of LWD & spawning substrate • Stops downstream meander and increases upstream and/or downstream erosion (reach) • If smooth (not planted), decreases habitat complexity • Increases water velocity • May deepen the channel • Initial scour can scour or bury adjacent or downstream spawning areas	• Deepened channel may facilitate adult upstream migration	• May constrict or redirect flow with possible increase in stream power

Table 10, continued. Manmade changes to habitat: structural

Techniques for Erosion Prevention & Typical Materials	Water Quality	Biotic Interactions	Food (Energy) Source	Habitat Structure	Migration/ Movement Barriers	Flow Regime
Manufactured Retention Systems - Fabric & reinforcement mats - Geogrids - Articulated concrete blocks - Geocellular containment - Concrete armor units	Dewatering is usually required for construction; temporary increase in temperature and turbidity • Riparian habitat (cover & shade) is lost during construction and takes time to become revegetated; more difficult with concrete systems	• Decreased habitat complexity generally means more competition among fish for food and space • Increased velocity may cause fish that can't find refuge to swim harder & use energy reserves faster (need to eat more food to grow)	• Loss of riparian habitat means less organic matter (food) for aquatic invertebrates • Decreased habitat complexity reduces prey base for fish	• Fabrics & mats are generally temporary, especially those that are biodegradable • Nondeformable types alter & interfere with natural channel migration, off-channel habitat formation, LWD and sediment recruitment • Decreases habitat complexity because banks are uniform Minimizes scour	• Generally does not impact migration or movement	• May constrict or redirect flow with possible increase in stream power

Table 11. Manmade changes to habitat: biotechnical

Techniques for Erosion Prevention & Typical Materials	Water Quality	Biotic Interactions	Food (Energy) Source	Habitat Structure	Migration/ Movement Barriers	Flow Regime
Woody Plantings - willows, other trees & shrubs	• Increases shade (cooler water temperatures) • May slow or trap overland runoff (decreases fine sediment & chemical/nutrient input)	• Shore plantings increase cover for fish • May provide some flood refuge for fish	• Eventually contribute woody debris to the stream (organic material for aquatic invertebrate food) • Provides terrestrial habitat for insects	• Adds structural habitat diversity to banks & floodplain • May increase roughness (slows water and increases sediment deposition) • May take a year or more to become established; before then, high flows or drought could harm plantings	• Generally does not impact migration or movement	• Generally does not impact migration or movement
Herbaceous Cover - grasses & grass-like wetland plants	May slow or trap overland runoff (decreases fine sediment & chemical/nutrient input)	Shore plantings could increase cover for fish	• Provides terrestrial habitat for insects	• May take a year or more to become established; before then, high flows or drought could harm plantings	• Generally does not impact migration or movement	• Generally does not impact migration or movement
Soil Reinforcement - soil wrapped in natural or synthetic fabrics	• Excavation may cause initial loss of riparian vegetation (decreases shade and increases temperature), but banks can be planted • Construction may temporarily cause increase in turbidity	• Decreased habitat complexity generally means more competition among fish for food and space	• Loss of riparian habitat means less organic matter (food) for aquatic invertebrates • Decreased habitat complexity reduces prey base for fish	• Creates smooth banks with little roughness or cover for fish • Nondeformable types alter & interfere with natural channel migration, off-channel habitat formation, LWD and sediment recruitment • May improve sediment transport	• Generally does not impact migration or movement	• Generally does not impact migration or movement
Coir Logs - rolled coconut fiber	• Some increased sedimentation (turbidity) can occur during construction • May improve riparian growth, moderating stream temperatures	• Do not provide much additional habitat for fish	• May improve riparian areas, increasing organic matter input to the stream and providing habitat for terrestrial insects	• Temporary (last ~12 years) • Traps sediment during overbank flows; increases soil for growth of shoreline vegetation • May improve sediment transport and/or retention (beneficial for spawning) • May lose some overhanging banks	• Generally does not impact migration or movement	• May constrict or redirect flow with possible increase in stream power

Table 11, continued. Manmade changes to habitat: biotechnical

Techniques for Erosion Prevention & Typical Materials	Water Quality	Biotic Interactions	Food (Energy) Source	Habitat Structure	Migration/ Movement Barriers	Flow Regime
Bank Reshaping - often used in conjunction with other surface treatments	• Extensive construction can increase turbidity and water temperature (through loss of riparian vegetation)	• Loss of undercut banks can mean less cover for fish (more competition for space) • Increase in amount of shallow water habitat may provide refuge for small fish from predators or swift currents	• Loss of riparian habitat means less organic matter (food) for aquatic invertebrates • Potential for vegetation growth along shallower banks means more diverse habitat and food for aquatic invertebrates	• Increased surface area slows local water velocity and increases likelihood of sediment deposition • May lose some undercut banks • May improve bankline habitat complexity (if vegetation grows on shallower slope)	• Generally does not impact migration or movement	• May constrict or redirect flow with possible increase in stream power

Table 12. Manmade changes to habitat: avulsion prevention

Techniques for Erosion Prevention & Typical Materials	Water Quality	Biotic Interactions	Food (Energy) Source	Habitat Structure	Migration/ Movement Barriers	Flow Regime
Floodplain Roughness - LWD & riparian plants	• May increase shade and thereby moderate water temperatures	• Can provide refuge from flood waters for fish • Eventual input of LWD provides cover and refuge for fish	• Can spread out and slow flood waters, reducing loss of aquatic organisms from scour • Provides terrestrial habitat for aquatic insects • Eventual input of LWD provides organic material (food) and cover for aquatic invertebrates	• Slows water during flood events • Allows natural channel movement within the floodplain • May eventually provide input of LWD, increasing instream habitat structure and diversity	• Generally does not impact migration or movement	• May constrict or redirect flow with possible increase in stream power
Floodplain Grade Control - rocks or LWD (subsurface)	Construction may initially destroy some riparian vegetation, but because not generally at the streambank, turbidity and increased temperatures are not a problem	• Because subsurface and in the floodplain, does not have much effect on biotic interactions	• Because subsurface and in the floodplain, does not have much effect on food resources	• Interferes with natural stream processes that would occur during flood events (may be lost opportunity for new side channel habitat)	• Generally does not impact migration or movement	• May constrict or redirect flow with possible increase in stream power
Floodplain Flow Spreaders - planted trees, compacted soil or rock	• Trees could provide additional shade that moderates water temperature	• Can provide refuge for fish in flood events	• Allows recruitment of LWD and substrate materials that provide cover and habitat for aquatic organisms	• Eliminates concentration of flow and high velocity in the floodplain during high water events • Moderates flows in streams that experience rapid fluctuations in discharge • Can hinder development of off-channel habitat • Returns complexity to the floodplain	• Generally does not impact migration or movement	• Generally does not impact migration or movement

Table 13. Manmade changes to habitat: other techniques

Techniques for Erosion Prevention & Typical Materials	Water Quality	Biotic Interactions	Food (Energy) Source	Habitat Structure	Migration/ Movement Barriers	Flow Regime
Channel Modification - often used in conjunction with other surface treatments	• If channel is completely moved, it may take years to restore riparian habitat (shade for temperature modification) • May increase turbidity during construction and for some period afterward, until the substrate stabilizes	• Increased habitat complexity and diversity should result in decreased competition for food and space among fish and balance out predator-prey relationships	• Can cause extensive damage to macroinvertebrates, fish, and other organisms due to instream disturbance, fine sediment deposition, channel abandonment, and loss of riparian habitat • Once the stream recovers (months to years), habitat conditions may be improved	• If done correctly, will restore equilibrium to the stream system • Can increase habitat diversity and complexity • Dissipates excess stream energy • Modifies sediment transport capability at site or downstream • May reactivate the floodplain • Can provide improved spawning areas • May reduce overall impacts by confining modifications to one smaller reach, instead producing cumulative impacts at multiple project sites	• Should improve fish passage conditions	• May constrict or redirect flow with possible increase in stream power
Channelization - involves straightening and sometimes armoring the streambanks	• Often increases water velocity and depth	• Fewer pools can mean increased competition for space, especially overwintering habitat for juveniles[18]	• Less instream habitat diversity equates to less habitat for aquatic organisms and less food for salmonids • Destruction of riparian habitat means loss of organic input and habitat for terrestrial insects	• Decreases density of pools • Homogenizes stream habitat and provides less instream cover for salmonids • Construction generally destroys riparian vegetation • May accelerate streambank erosion downstream as a result of deepening and straightening[18]	• Fewer pools can impede upstream movement/ migration[18]	• Possible increase in stream power

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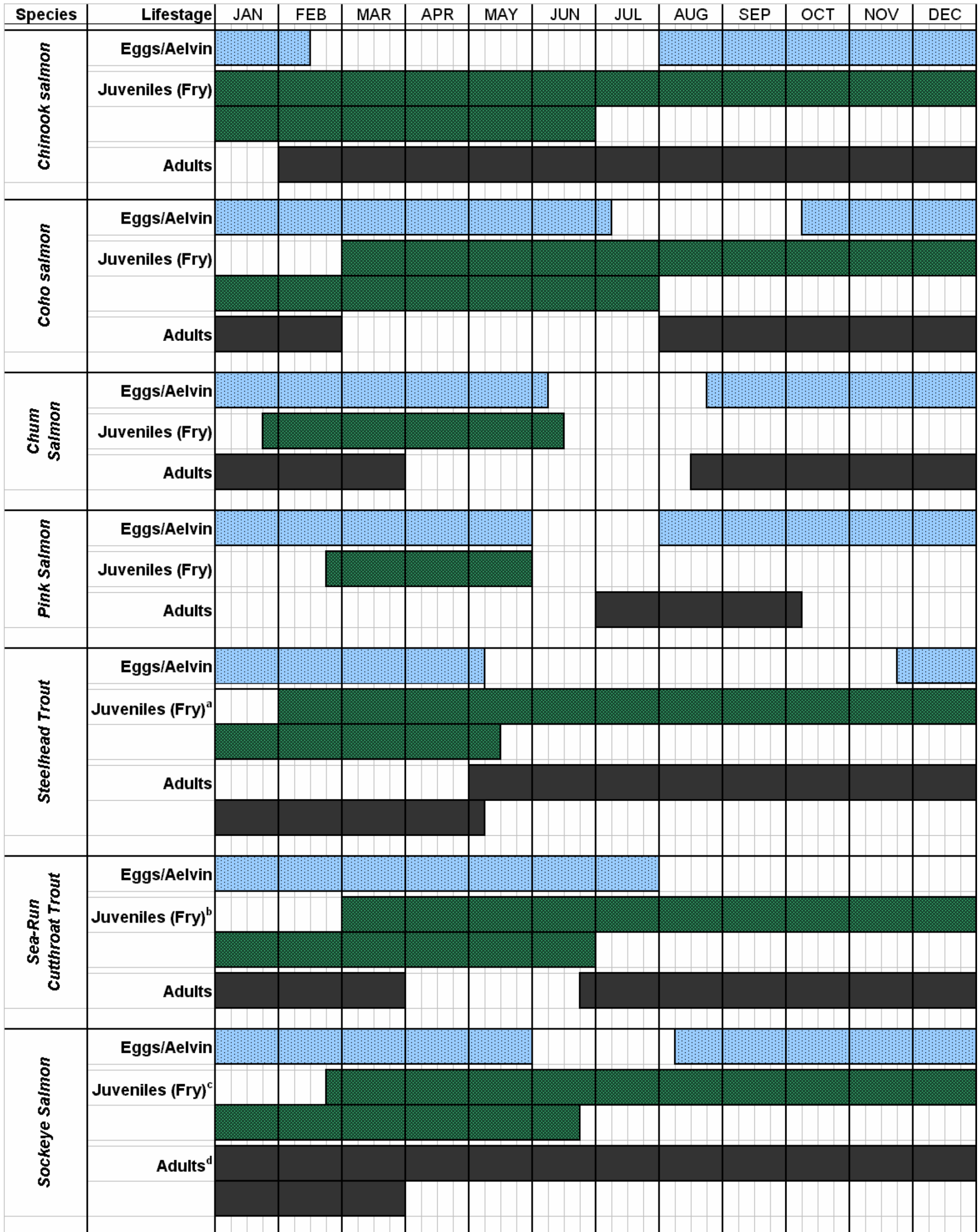
APPENDIX A: Lifestage and Timing for Salmon in Washington Freshwaters



[a]Juveniles may reside in freshwater for up to seven years, though most remain only 1 to 4 years before moving to seawater some time in the spring

[b]Smolting generally first occurs between age I and age IV, though juveniles may move back & forth between estuaries (spring/summer) and tributaries (fall/winter) over several years before entering the ocean

[c]Juveniles rear in or near lakes for 1 to 3 years before migrating to the ocean, generally between March and June

[d]Freshwater entry is generally between January and September; spawning generally occurs between September and March

Figure A- 1. Range of dates when fish have been observed in freshwater systems (Washington). Data from Weitkamp et al. 1995, Busby et al. 1996, Hard et al. 1996, Gustafson et al. 1997, Johnson et al. 1997, Meyers et al. 1998, and Johnson et al. 1999.