

Donor stock selection of Chinook Salmon for reintroduction to the Transboundary Reach of the Columbia River



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Executive Summary

Chinook Salmon have been extirpated from the Columbia River basin upstream from the Chief Joseph Dam, and from all areas in the Canadian portion of the basin since the mid 20th century. The Columbia River basin upstream from Chief Joseph Dam contains a large quantity and diversity of habitat, which could potentially support the reintroduction of an equally diverse portfolio of populations. Facilitating the recovery of this diversity of populations requires reintroductions to each area of high habitat potential with appropriately selected donor stocks. One of the few remaining riverine sections of the Columbia River is present from the head of Lake Roosevelt (shortly downstream from the US-Canada border), to the Hugh Keenleyside Dam, 52 km upstream from the US-Canada border. This river reach is commonly referred to as the Transboundary Reach. Chinook Salmon historically used this reach to complete their life cycle, and the habitat appears to remain suitable in the mainstem river for spawning.

In this study, the suitability of sixteen donor stocks was considered, for the objective of reintroducing a self-sustaining population to the Transboundary Reach that would contribute to the long-term recovery and/or viability of Chinook Salmon in the Columbia River basin. Donor stocks were selected to represent a variety of life histories, from interior migrating local or major population groupings from the Columbia, Snake and Fraser River basins. Four main components were considered in the selection framework, using a variety of techniques, from fully quantitative modeling, to literature review.

The first component involved determining the donor stock which shares the closest evolutionary ancestry with the historical stock of the Transboundary Reach. Historical tissue from late 19th century Canadian collections were analyzed, but failed to amplify genetic markers due to degraded DNA. In lieu of using the ancestral stock, the principle of isolation by distance was used as an underlying assumption that the most geographically proximate stock would be the most closely related to the historic stock, and thus could serve as a surrogate for determining ancestry. Two evolutionary lineages of Chinook Salmon are present in the interior Columbia River basin, corresponding to Spring and Summer-Fall runs; both theoretically may have occupied the Transboundary Reach. The genetic divergence between the surrogate stock and all potential donor stocks within each of these lineages was examined using G'ST, based on analysis of microsatellite markers. In general, there was a pervasive pattern of isolation by distance between stocks within each life history. From an ancestry perspective, stocks from the Upper Columbia evolutionary significant units (ESU; for both Spring and Summer-Fall life histories) should be considered as the most appropriate donors, as they may share adaptations for the historic environment.

The second component involved determining adaptive potential of donor stocks. Diversity was estimated for each potential donor stock, through proxy metrics of heterozygosity, allelic richness and population size. The use of multiple stock strategies and adaptive variation of donor stocks were considered by literature review. Summer-Fall run donor stocks from the Columbia River basin appeared to have higher diversity metrics in general than Spring run or those from the Fraser River basin. Stocks of this life history in the interior Columbia River basin also commonly express more diversity of juvenile life history pathways in the contemporary environment. If such diversity is heritable, this may reflect adaptive potential for establishment and buffer the population from further environmental change. Multiple stock introduction strategies may increase adaptive diversity in the founding population.



The third component involved quantitative analysis of the environmental suitability of each donor stock from the Columbia River Basin, based on life history, physical and behavioural adaptations. A model was developed to predict the timing and abundance of each donor stock throughout their freshwater life cycle. The analysis then involved assigning four ordinal categories of suitability to a suite of criteria that were assumed to strongly influence salmon survival or reproductive success. Criteria were scored for each life cycle stage, in each pertinent river reach they were found, according to the adaptations or unique life cycle timing of the donor stock. High uncertainty and strong assumptions necessitated crude and cautious interpretation of the results, so this analysis was not presumed to accurately determine the suitability of any particular local donor stock; however, there were clear results that suggested the suitability of generalized life history types (i.e., Spring vs. Summer-Fall). Spring Run donor stocks were predicted to immigrate to prespawn holding areas without issue; however, during subsequent life cycle stages, their life history adaptations to cold headwater streams may poorly translate to the environment of the Transboundary Reach. This reach is a large mainstem, low elevation, and relatively warm river subject to flow regulation, which is likely more suitable for later spawning (i.e., October-November) life histories that immigrate in the Summer and Fall. Despite their higher predicted contemporary suitability, Summer-Fall Chinook Salmon may have future difficulties during adult immigration in the lower river with climate change, and high contemporary harvest rates may impede reintroduction efforts.

The fourth component involved assessing risks specific stocks may pose. Evolutionary, disease, ecological and demographic risks were reviewed through relevant literature. There was no compelling evidence to suggest differences in ecological risk and minimal differences in disease risk using available literature. Use of stocks from outside of the US Upper Columbia Summer Fall or Spring ESUs is associated with clear increased evolutionary risks. Between these ESUs, small population sizes in Upper Columbia Spring pose demographic and evolutionary risks of taking fish from wild sources for reintroduction. Multiple donor stock strategies carry risk of outbreeding depression in future generations. Some of these risks may be mitigated somewhat by carefully designed reintroduction programs with appropriate hatchery involvement, monitoring and adaptive management.

Integrating results of all components, the use of donor stocks from the Upper Columbia Summer-Fall ESU is predicted to have the highest success of establishing a population in the Transboundary Reach, while posing the least risk. Active reintroduction strategies using multiple stocks within this ESU may increase the probability of establishment, but should be appropriately monitored and managed.

Donor stock selection is just one of many considerations in reintroduction planning. Decisions that relate to donor stock selection are highly intertwined with the decisions made on the strategy undertaken to support recolonization or active reintroduction, as well as the monitoring and assessment tools available to mitigate risk and adaptively manage. Ultimately, there will be social, legal and logistical reasons that may also impact donor stock selection beyond the conservation objectives that drove this study. Harvest objectives in particular are of great importance to First Nations and Tribes, and the use of stocks that are of higher quality for consumption at terminal fisheries or provide opportunities for harvest without providing clear conservation objectives should also be considered. It is important to note that reintroduction programs can successfully satisfy multiple objectives, thus programs that use different donor stocks to fulfill multiple reintroduction objectives are a viable option.



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1 Introduction

Chinook salmon historically occupied the entire length of the Columbia River from its confluence with the Pacific Ocean, to the headwaters 2000 km upstream at Columbia Lake, British Columbia. Throughout this range, multiple spawning populations persisted, each population locally adapted to the conditions of their environment.

Much of the diversity of Chinook Salmon was lost in the Columbia River with hydropower development and unsustainable overharvesting, which depleted and extirpated stocks throughout the early and mid 20th century. A disproportionate loss occurred in headwater systems of the Columbia River basin, where dams were often constructed without fish passage facilities. One of the largest losses occurred with the completion of Grand Coulee Dam, in 1940. This dam occupies the 960th upstream km of the river, so when it was built, it effectively diminished the range of Chinook Salmon by over 50% along its mainstem length. The range was further diminished the subsequent decade, when the Chief Joseph Dam was constructed on the 877th upstream km of the river.

Planning processes for reintroducing Chinook Salmon are currently underway. In addition to the necessary provision of fish passage at the above mentioned dams a suite of initial scientific investigations are recommended, including assessment of potential donor stocks that could be used for reintroduction (Columbia Basin Tribes and First Nations 2015). The selection of donor stocks is a critical consideration because there may be differential success of potential donor stocks, and because there may be significant risks associated with using specific stocks (Nelitz et al. 2007). These are common, and important considerations for any animal reintroduction for conservation purposes (Houde et al. 2015a), especially for salmonid fish (Anderson et al. 2014, Cochran-Biederman et al. 2015), given the unique evolutionary legacy and suite of local adaptations of each stock (Taylor 1991). Unfortunately, the life history diversity and population structure of the historic stocks that would have collectively made up the Columbia River Chinook Salmon metapopulation has been lost upstream from Chief Joseph Dam, and stock structure would need to be rebuilt one population at a time as the entire drainage is potentially recolonized. Thus, donor stock selection should be a consideration at the level of each individual reintroduction attempt for each potential unique habitat that would support a localized spawning population. In this assessment, an attempt is provided to determine donor stock suitability for reintroduction to the Transboundary Reach of the Columbia River (Figure 1-1), one of the few remaining riverine environments along its entire length. This habitat once supported Chinook Salmon (Columbia Basin Tribes and First Nations 2015). An appropriate donor stock for use in reintroduction efforts should have high theoretical fitness in the novel ecosystem, should be logistically feasible to use for reintroduction efforts, and should pose the least genetic and demographic risk to extant downstream populations of Chinook Salmon and the receiving ecosystem. Success could be measured by determining if the donor stock can complete their lifecycle and have a positive population growth rate in the initial stages of colonization. Success should also be measured in terms of how the population will positively contribute to long term viability and/or recovery of the metapopulation, as the reintroduction



environment may be considered contiguous with habitats that currently support downstream, extant populations of Chinook Salmon (Anderson et al. 2014).

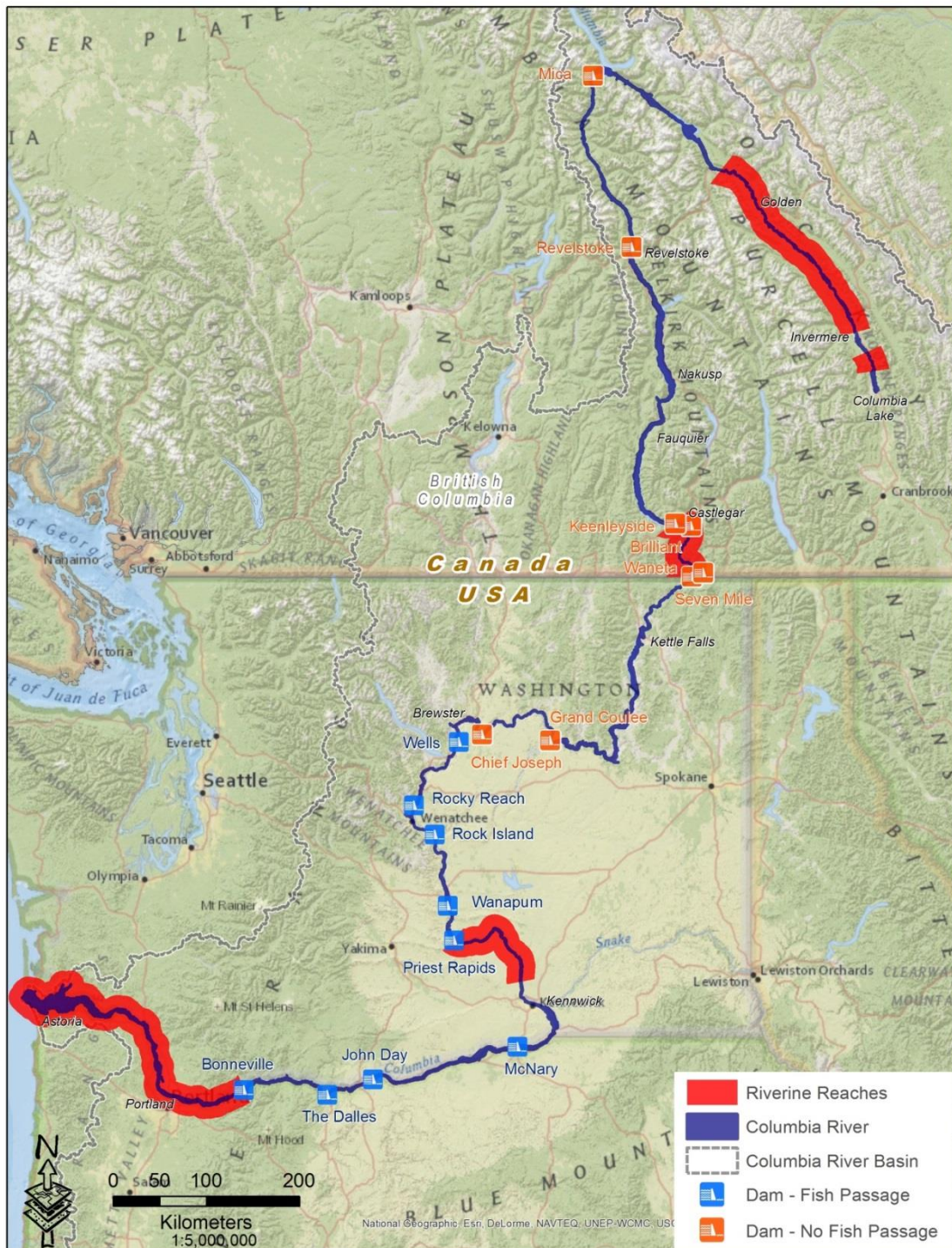


Figure 1-1: Significant remaining free-flowing riverine sections of the Columbia River. The Transboundary Reach is the riverine segment spanning the US-Canada border.



This study is a guidance document that can inform donor stock suitability for the reintroduction purpose of forming a self-sustaining population in the study area that will contribute to conservation of Chinook Salmon in the Columbia River Basin. Donor stock selection to satisfy alternate objectives for reintroduction (e.g., harvest) are not thoroughly explored in the same detail, but much of the assessment in this document can also inform the suitability of stocks for these purposes as well.

1.1 Study area and historic presence of salmon

The Transboundary Reach is one of four major riverine segments of the Columbia River (Figure 1-1); a ~60 km reach of river located between the head of Lake Roosevelt near the U.S.-Canada international border (river km 1197) and Hugh Keenleyside Dam (HLK; river km 1253). HLK is a dam originally built for flood control, but subsequently retrofitted for hydroelectric generation. It is not passable in any functional sense for migratory fish, though a navigation lock allows the incidental passage of some fish when operated. The 52 km stretch between the international border and HLK is the focus of this study. The Columbia River through this stretch is a large river with a mean discharge of ~2800 m³/s at the international border, flowing through an elevation range of 390-420 m and having a continental climate regime. Two major tributaries enter the river in this stretch, the Kootenay River (mean discharge of ~850 m³/s) and the Pend D'Oreille River (mean discharge ~750 m³/s), both of which have impassable hydroelectric dams shortly upstream from their confluences. Several minor (i.e., 3rd-4th stream order) tributaries flow directly into the Columbia River through this stretch, but the majority have natural or anthropogenic fish passage barriers shortly upstream from their confluence with the Columbia River (Thorley and Baxter 2011). The mainstem river reach and its tributaries are habitat for a variety of native and introduced cold and coolwater fishes, including robust populations of resident salmonids (Rainbow Trout and Mountain Whitefish) that locally complete their lifecycles (Golder Associates Ltd. and Poisson Consulting Ltd. 2015). The total available large mainstem river environment accessible to fish in this reach (Columbia, Kootenay and Pend D'Oreille Rivers) is 55.3 km in length, and ~13.9 km² in area. The total available tributary environment accessible to migratory fish in this reach (Blueberry, Beaver, Murphy, China, Norns and Champion Creeks) is 33.2 km in length, and ~0.27 km² in area, the majority of which occurs in Blueberry Creek (Thorley and Baxter 2011). Thus the vast majority of available habitat is centered in the mainstem river. This assessment is therefore an assessment of donor stock suitability for this mainstem river environment.

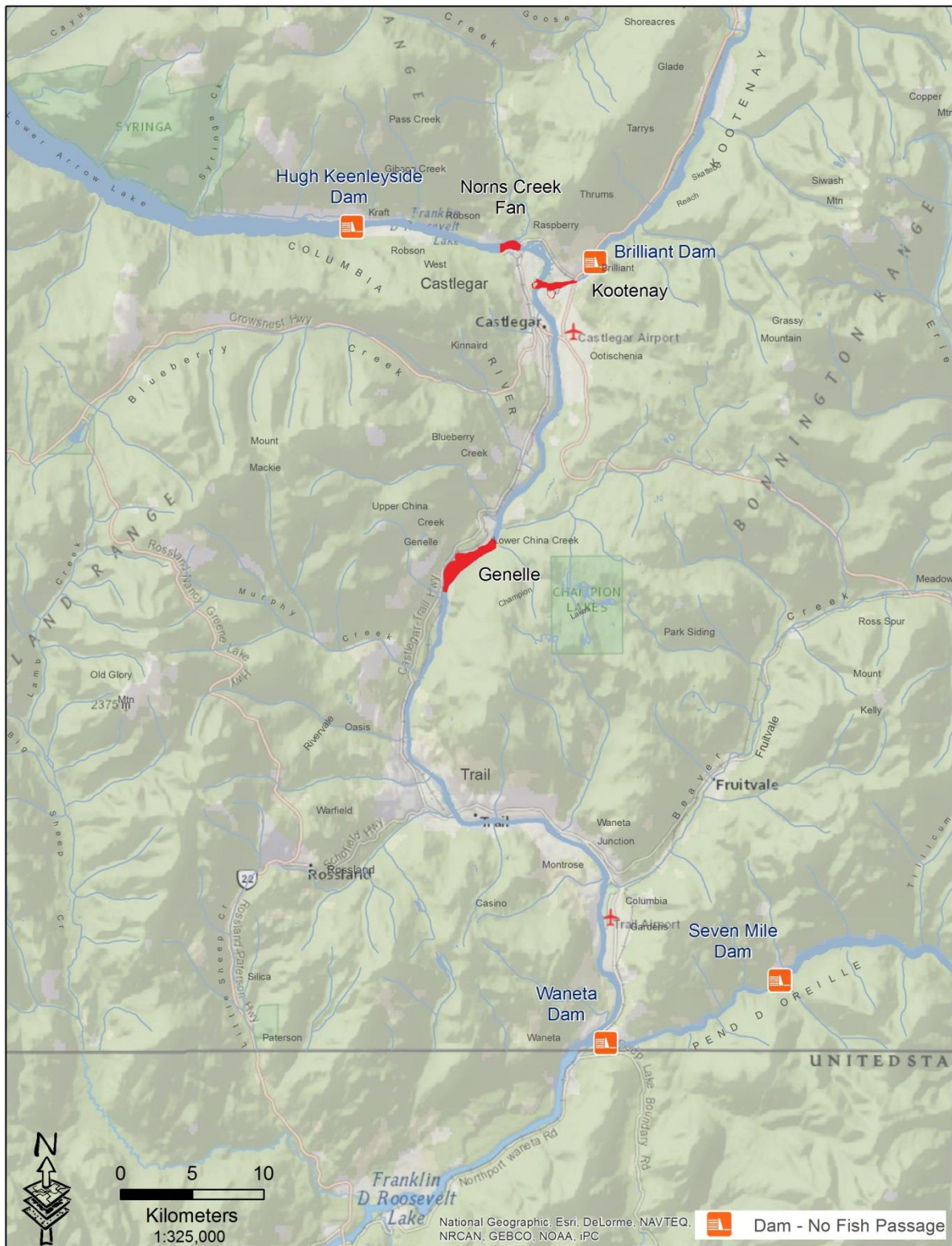


Figure 1-2: The Transboundary Reach, from the head of Lake Roosevelt, to the Hugh Keenleyside Dam. Areas in red indicate riverine sections with high concentrations of Rainbow Trout spawners



Multiple life histories of Chinook Salmon would have historically used the Transboundary Reach for some portion of their lifecycle, as salmon arrived at and ascended Kettle Falls throughout the season. Chinook Salmon arrived at the falls with a preliminary peak in June, followed by a more substantial peak in the last half of August, with fish arriving right until October and spawning locally (Bryant and Parkhurst 1950; Chapman 1943). Kettle Falls is located approximately 50 km downstream of the Transboundary Reach (Figure 1-1). Chinook Salmon did use areas of the mainstem river in the Transboundary Reach for spawning (Columbia Basin Tribes and First Nations 2015).

Abiotic and biotic changes have occurred since salmon were historically abundant. Salmonid habitat and their base foodweb production has been altered due to industrial and urban development and flow manipulation due to the construction of large storage reservoirs upstream (Arndt 2009). Temperature regime has shifted, with higher than historic summer temperatures (Hamblin and McAdam 2003), and biotic community has changed with the introduction of non-native fishes (Golder Associates Ltd. and Poisson Consulting Ltd. 2015). Some species that have been introduced (Walleye, Smallmouth Bass, Northern Pike) are potential predators, which may have impacts on salmon populations (Sanderson et al. 2009). Despite these manipulations, the reach has enriched food production (Olson-Russello et al. 2015) and currently supports multiple, large spawning aggregations (>1000->10000) of native Rainbow Trout (Taylor 2002, Irvine et al. 2014), confirming that habitat remains highly suitable for salmonids. Rainbow Trout have similar habitat and generalized ecological niche requirements to Chinook Salmon during the freshwater portion of their life cycle, but spawn at different times of the year. Recent habitat suitability analyses indicate that there may be large amounts of suitable depths and velocities for Chinook Salmon spawning in the Transboundary Reach during the species' generalized fall spawning period (Golder Associates Ltd. 2016). These locations of high suitability overlap with those of Rainbow trout where assessed in the Kootenay River, upstream from its confluence with the Columbia River, and in the Columbia River at the confluence with Norns Creek, which has deposited an alluvial fan of gravels (Figure 1-2). Additional habitats of high suitability are hypothesized to exist around the vicinity of Genelle (Golder Associates Ltd. 2016). The suitability of habitats for other life cycle stages (embryo incubation through emergence, juvenile rearing etc.) has not been assessed.

1.2 Reintroduction strategy

Reintroduction of Chinook Salmon and re-establishment of sustainable populations above barriers can involve passive or active strategies (Anderson et al. 2014). Passive strategies involve natural recolonization of upstream areas after passage is provided, while active strategies involve transplanting wild fish or artificial propagation. If passive strategies are to be employed, the donor stock would naturally be fish that currently migrate to the base of, and attempt to pass Chief Joseph Dam. If active strategies are to be employed, donor sources can either be from supportive actions of natural recolonization (through hatchery augmentation or targeted translocation of fish that attempt to pass), alternate geographic areas, or a mix of stocks, either from wild or hatchery sources. Active reintroductions could be undertaken by translocating wild adults, eggs or juveniles, or supplementation using artificially hatched and reared eggs/juveniles from a potential donor stock brood (SJRRP 2011), and using combinations of life stages (USFWS and ODFW 2011). It is beyond the scope of this study to



recommend a specific reintroduction strategy, but this study is primarily designed to inform choices made for active strategies if the objective is to form a self-sustaining, natural population. Alternate strategies and reintroduction objectives will be discussed throughout, as they pertain to donor stock selection.

1.3 General framework for donor stock assessment, candidate donor stocks and study objectives

This study assesses the selection of potential donor stock(s) by a four-part process, which considers the following components, as modified from those suggested by Houde et al. (2015a) and Anderson et al (2014):

- 1) Ancestry matching: Selection of stocks due to their evolutionary relationship with the historic stock(s) of the Transboundary Reach.
- 2) Adaptive potential: Selection of stocks that exhibit high within-population genetic diversity or multiple stock introduction strategies to increase adaptive potential.
- 3) Environment matching: Selection of locally adapted stocks which would be able to thrive in the current environmental conditions that will be encountered by Chinook Salmon to complete their life cycle, ultimately successful spawning in this environment.
- 4) Risks: Literature review of the potential genetic, disease and ecological risks associated with reintroducing specific or multiple donor stocks.

Component one involves selecting the donor stock with the closest evolutionary ancestry to the historic stock, as they may theoretically share adaptations that confer fitness in the ancestral habitat. Component two provides an assessment both of the adaptive potential of donor stocks, as well as a theoretical assessment of the use of multiple stocks to increase adaptive potential for the reintroduction. Component three was chosen to model the suitability of each candidate donor stock, based on how their unique behavioural, physical and life history adaptations align with the environment that they would encounter in novel environment of the Transboundary Reach, and through the rest of their life cycle in freshwater. This is important, as it is important to recognize that the adaptations of extant donor stocks may have changed from their ancestral state with anthropogenic modifications that influence selection (e.g., hatchery or habitat effects). If the receiving environment has likewise been fundamentally altered and is a novel ecosystem, ancestral genomes may also have reduced viability for reintroduction. This process of genetic information (from both ancestry and adaptive potential perspectives) and environmental matching takes into account the historic and contemporary features that may be important to selecting the stock with the highest theoretical fitness for reintroduction (similar process reviewed in Houde et al. 2015a). The fourth component will inform of potential risks to reintroducing specific donor stocks, as donor stock selection may be a tool in a comprehensive risk mitigation strategy for reintroduction. Results of these components will be integrated and donor stock recommendations will be made with a weight-of-evidence approach.



A candidate list of donor stocks was compiled early in the process, based on recommendations made directly to the Upper Columbia Aquatic Management Partnership (UCAMP) through engagement with experts in anadromous salmonid biology in the United States and Canada (Nelitz et al. 2007) and screening of various technical reports and status updates for stocks in the Pacific Northwest. Donor stocks are sourced from the Columbia River Basin in Oregon, Washington and Idaho, and the Fraser River Basin in British Columbia (Figure 1-3). Stocks for this analysis were mostly classified at the “major population grouping” level or local stock level in the population hierarchy, depending on the detail of information available. Both these levels of population structure often include multiple local spawning aggregations in proximate habitats, but are not as coarse as major evolutionary units (Evolutionary Significant Units or ESUs in the U.S. or Conservation Units or CUs in Canada). Pre-screening was conducted to choose stocks that represent a range of life histories, major evolutionary units and unique adaptations to a variety of environments. Chinook Salmon life histories are often divided into two major types, corresponding to early adult run (Spring) that predominantly emigrate to the sea after one or more winters, and late adult run (Summer-Fall) whose offspring predominantly emigrate to sea shortly after hatching (Healey 1991). It is now regarded that these oversimplify the diversity of life history pathways of Chinook Salmon and do not form the most basal evolutionary lineages for the species from a range-wide perspective; thus, we used the recommended terminology throughout this document of Moran et al. (2013) to refer to them by adult run timing. In the interior Columbia River basin, there is a deep split in evolutionary lineage between Spring run (traditionally referred to as stream-type) and Summer-Fall run (traditionally referred to as ocean-type) (Waples et al. 2004). We chose multiple potential donor stocks within each of these life history types and refer to their underlying life history by adult run timing throughout the document.

For the Fraser River basin, we generally chose the furthest migrating indicator stock from the Pacific Salmon Commission’s Chinook Technical Committee (CTC 2002) as a representative for each of the general interior CUs unless the stock was exceptionally small (annual escapement <500 fish). These stocks generally have more robust datasets associated with them. Further pre-screening was conducted by selecting the local stock with the highest genetic diversity within its CU (Moran et al. 2013) and qualitatively most compatible ecological criteria with the Transboundary Reach. Fraser River basin stocks were associated with the dichotomy of Spring and Summer-Fall run depending on whether they predominantly emigrate as yearlings or subyearling, respectively. Although reintroduction literature generally suggests avoiding transfers of fish between basins that separate coarse levels of population structure (Moritz 1999, Anderson et al. 2014), there is the possibility of shared evolutionary ancestry between some populations in the Columbia River and Fraser Rivers which may justify their use as donors. We thus began this analysis considering the possibility that Fraser River donor stocks were undifferentiated from extirpated Transboundary Reach Chinook Salmon at very coarse levels of population structure. For the Columbia Basin, we chose several stocks from nearby downstream areas within the Upper Columbia Summer-Fall and Spring ESUs, as well as major population groupings in Snake River and other Columbia River ESUs. Many donor stocks are natural origin with little hatchery influence, while others represent stocks that have regional hatchery supplementation or are in fact artificially derived stocks with a long legacy of artificial selection. Hatchery stocks include those from the Wells Hatchery, the Methow Composite strain and the Carson Hatchery strain. These hatchery strains



were chosen for several reasons. Firstly, their biological attributes are generally well studied, including those of hatchery fish that go on to naturally reproduce. Secondly, they are commonly used for hatchery purposes in the US portion of the Columbia River that is most immediately downstream from the Transboundary Reach (i.e., between Priest Rapids and Chief Joseph Dams) and thus would be logistically feasible to use. Finally, these strains are possibly related to historical stocks that would have been destined for upriver sources, as they have been influenced by the Grand Coulee Fish Maintenance Program (Fish and Hanavan 1948).



Figure 1-3: Geographic origin of donor stocks considered in this study, and the coarse levels of population structure (Conservation Units; Canada, Evolutionary Significant Units; US) to which they belong



Summer-Fall run, representing three ESU/CUs (Upper Columbia Summer-Fall ESU; Snake River Fall ESU; South Thompson summer age 0.3 CU):

- Middle Shuswap River (4₁; DFO CU designation CK-15)
- Wells Hatchery Summer-Fall
- Wenatchee Summer-Fall
- Methow Summer-Fall
- Okanogan Summer-Fall
- Upper Columbia mainstem Summer-Fall (Chief Joseph Dam)
- Hanford Reach Fall
- Snake River Fall

Spring run, representing six ESU/CUs (Upper Fraser Spring 1.3 CU; Middle Fraser summer 1.3 CU; Lower Thompson spring 1.2 CU; Upper Columbia Spring ESU; Mid-Columbia Spring ESU; Snake River Spring-Summer ESU):

- Swift Creek/Tete-Jaune (5₂; DFO CU designation CK-12)
- Stuart River (5₂; DFO CU designation CK-11)
- Nicola River (4₂; DFO CU designation CK-17)
- Wenatchee Spring
- Methow composite (hatchery)
- Carson (hatchery)
- Yakima Spring
- South Fork Salmon River Spring-Summer

All core components of this assessment are only used as a tool to attempt to assess the suitability of each proposed donor stock to naturalize in the Transboundary Reach of the Columbia River and the potential risks; further overview of social, legal, logistical and regulatory aspects which may affect donor stock selection are also reviewed and a stand-alone chapter (section 6), but not formally at the detail of a specific component. The methods used within each component vary, from fully quantitative, to literature review. The primary objective of each component is to recommend a single or suite of donor stocks for consideration that appear to be most suitable for reintroduction for the objective of establishing a self-sustaining population that contributes to conservation of the greater Columbia River metapopulation (Anderson et al. 2014). Alternate considerations such as reintroduction strategies and stocking techniques will also be explored, and the implications for donor stock selection will be discussed throughout. The final section (7) of the document will contain a synthesis of information and a suite of recommendations for selecting donor stocks that can be used for planning purposes for reintroduction of Chinook Salmon to the Transboundary Reach of the Columbia River.



2 Component One: Ancestry Matching

2.1 Introduction

Chinook Salmon throughout North America comprise a wide array of locally adapted populations with unique life histories; their recent evolution having largely been influenced by local and dynamic selective pressures and a legacy of glaciation events (Moran et al. 2013). Within the Columbia River basin, two distinct lineages evolved and persist (Waples et al. 2004). These lineages are characterized by life history, corresponding to early Spring run adult fish that primarily outmigrate as yearling smolts (stream-type) and later migrating Summer-Fall run adult fish that primarily outmigrate as subyearlings (ocean-type). The life histories diverged from one another and have been essentially reproductively isolated for over 10,000 or potentially 100,000 years (Waples et al. 2004). In the Fraser River basin, evidence for such lineages is more limited and the coarse scale population structure of multiple life histories may have more contemporary influence (Waples et al. 2004, Moran et al. 2013). Unique, evolutionary significant units for both life histories are spatially separated into major river basin areas (Mid Columbia, Snake, etc.), with locally adapted stocks spatially nested within these major evolutionary groupings.

Spring run Columbia and Fraser River Chinook Salmon are sister groups from a species wide perspective (Moran et al. 2013), and we undertook this analysis considering the possibility that there may be populations in the Fraser River basin which resemble extirpated interior Columbia River populations at relatively fine levels of population structure (i.e., < ESU). Exceptional evidence of close genetic relationship between Fraser River donor stocks and extirpated populations in the Transboundary Reach would be needed in this analysis, as fundamental concepts in contemporary reintroduction literature suggest avoiding such transfers between basins and coarse levels of population structure (Moritz 1999, Anderson et al. 2014). Thus, the results of this study will heavily influence later sections of the donor stock selection process which focus on risks (section 5.1).

This component describes the quantitative basis for assessment of the suitability of a variety of stocks for both Spring and Summer-Fall run life histories from the perspective of ancestry matching. Assessment criteria are based on the principle of genetic distance to the historic stock (i.e., selection based on closest evolutionary origin) for reintroduced stocks (Houde et al. 2015a). Ancestry is important to consider, as donor stocks sharing recent evolutionary ancestry may also share adaptations necessary for viability in the reintroduction area, thus pre-adapting the donor stock (Houde et al. 2015a). Assessments of genetic resemblance have been employed in informing donor stock selection in previous Chinook Salmon reintroduction assessments (SJRRP 2010, NMFS 2014b).

2.2 Methods

2.2.1 Genetic baseline for assessed stocks

Assembly of allele frequencies for the genetic baseline of the historic stock was first attempted by analyzing historic tissue samples. Samples were available from Chinook Salmon that occupied the



Columbia River in 1892 from collections that were made in the Columbia River at the towns of Golden and Revelstoke (Eigenmann 1895). Note that these fish represent either one or multiple stocks that would have historically spawned in the Upper Columbia River upstream from Revelstoke, and potentially as far as the headwaters of the Columbia River, over 700 km upstream from the US-Canada border; therefore, they would not likely represent the historic genotype of the stock that spawned in the Transboundary Reach. Smolt samples were stored in ethanol, and archived at the British Museum of Natural History, and were loaned for extraction of a small amount of tissue. Scale samples were removed from these smolts and individually stored in ethanol, before analysis. All samples were analyzed independently by two laboratories, at the University of Victoria, for microsatellite markers, and at the Hagerman Genetics Lab (University of Idaho; Columbia River Intertribal Fish Commission), for short nucleotide polymorphism (SNP) markers.

The baseline of contemporary genotypes for potential donor stocks was compiled from genotypic data used by the Genetic Analysis of Pacific Salmonids (GAPS) Consortium (Seeb et al. 2007). This dataset includes an extensive sample archive of 13 microsatellite markers from Chinook Salmon that were collected from 238 local spawning populations throughout North America. Some populations used hatchery selections sourced from the local spawning population. Individual genetic data from potential donor stocks were extracted from this database. This included several hatchery specific stocks that continue to be used in contemporary recovery and supplementation efforts for several populations. Sample sizes for each potential donor stock in the GAPS database are listed below:

Summer-Fall run:

- Middle Shuswap River (n = 119)
- Wells Hatchery summer-fall (n = 138)
- Wenatchee summer-fall (n = 135)
- Methow summer-fall (n = 125)
- Okanogan summer-fall (N/A)
- Upper Columbia mainstem summer-fall (N/A)
- Hanford Reach upriver bright fall (n = 206)
- Snake River Fall (Lyons Ferry; n = 186)

Spring run:

- Swift Creek/Tete-Jaune (n = 128)
- Stuart River (n = 145)
- Nicola River (n = 140)
- Wenatchee spring (n = 62)
- Methow composite (n = 217)
- Carson hatchery (n = 224)



- Upper Yakima spring (Cle Elum; n = 199)
- South Fork Salmon River Spring-Summer (Secesh River; n = 137)

A baseline of the Okanogan Summer-Fall population could not be assembled because it was not part of the GAPS dataset. Given their geographical proximity and similar run size and history of hatchery supplementation, the Wenatchee River will be considered the same stock for the purposes of this analysis. The Okanogan population of Summer-Fall run Chinook Salmon is not significantly differentiated from the Wenatchee population (Marshall 1993, Kassler et al. 2011). A baseline of Upper Columbia Mainstem Summer-Fall donor stock could also not be assembled, and is not formally considered in this analysis because of deficiencies in both genetic and demographic (i.e., escapement) data. It is informally considered in the discussion.

2.2.2 Resemblance to historic stock

As an alternate method to describing the allele frequencies of the actual historic population, a surrogate historic stock was chosen to compare to all potential donor stocks. This was done for both Spring and Summer-Fall life histories of Chinook Salmon. In the proposed donor stock selection framework, the most appropriate surrogate should occupy the closest stream distance to the historic stock. This is based on observation that Chinook Salmon display a pervasive pattern of isolation by distance (Moran et al. 2013), implying that geographically proximate populations are generally the most closely related. For Spring run Chinook, the population used will be Upper Columbia Spring ESU and for Summer-Fall Chinook, the population used will be Upper Columbia Summer-Fall ESU. This primarily includes local stocks from the Wenatchee, Entiat, and Methow Rivers for both ESUs. The Okanogan River currently only supports a viable population of the Summer-Fall ESU, but there is a currently running program attempting to re-establish the Spring life history (NMFS 2014a).

Decades of hatchery practices in the US Upper Columbia River (the river and tributaries upstream from the Yakima River confluence to the Chief Joseph Dam for the purposes of this report) may have altered the historic genetic structure of the individual local stocks that make up US Upper Columbia ESUs. In particular, the Grand Coulee Fish Maintenance Project (GCFMP) homogenized stocks destined for various upriver areas in the 1930-1940s (Utter et al. 1995). This included fish destined for the Transboundary Reach and beyond into the upper reaches of the Canadian Columbia River basin. In addition, subsequent decades of hatchery operations further mixed fish from gene pools outside the Upper Columbia River and artificially selected broodstock. These factors occlude the choice of which exact local stock to use from the Upper Columbia ESUs; however, previous studies have shown a close genetic relationship amongst upper Columbia ESU local stocks for both life history types (Marshall 1993, Beacham et al. 2006, Davis et al. 2007, Kassler et al. 2011). The specific local spawning population we used as the historic surrogate for both life histories is from the wild origin Wenatchee River population (n = 62 for Spring run and n = 135 for Summer-Fall run), even though the Entiat, Methow and Okanogan River populations (and other small local stocks) are geographically closer to the Transboundary Reach.



The Wenatchee populations were selected as the surrogates because they are typically used as a representative stock for their respective ESUs in previous genetic studies (Seeb et al. 2007, Moran et al. 2013), have a genetic baseline with large sample sizes, and receive relatively large returns of natural origin fish for both life histories. In addition to this, the population may trace some of its lineage to Canadian origin spawners, since the Wenatchee River and its tributaries and hatcheries were a main target of relocation and artificial propagation of upriver destined fish from the GCFMP (Fish and Hanavan 1948).

Raw G'_{ST} divergence matrices among donor stocks and the historic (or surrogate) stock were generated in the online program SMOGD (Crawford 2010), as a standardized genetic divergence metric between 0 and 1 (Hedrick 2005), with values approaching 1 representing greater divergence. Since increasing values (i.e., values approaching 1) represent greater divergence, values were subtracted from 1 in order to be meaningful for comparative purposes in this study. This value was then standardized to a genetic “resemblance score,” a relative value to the most divergent population in the analysis (i.e., the most divergent donor stock was given a score of 0). The arithmetic mean of G'_{ST} across all loci was used. Because surrogate stocks were presumed to be the closest extant relatives of historic Transboundary Reach stocks, they received resemblance scores of 1. To characterize relationships amongst an expanded dataset of local stocks from throughout the Columbia and Fraser Basins, a F_{ST} matrix was compiled for population differentiation amongst 32 local stocks (Appendix 1).

2.3 Results

2.3.1 Genetic baseline for assessed stocks

Historic tissue samples failed to amplify either microsatellite or SNP markers due to degraded DNA. As a result, historic tissue could not be used to compare to the baseline of potential donor stocks.

Assessed stocks from the GAPS dataset were extracted by population. Given that historic tissue samples failed to provide a baseline of the historic stock, surrogate stocks were used as detailed above.

2.3.2 Resemblance to surrogate stock

G'_{ST} divergence matrices were assembled independently for Summer-Fall run (Table 2-1) and Spring run (Table 2-2) life histories. Populations that were the most geographically proximate had the highest resemblance scores. Populations from the Fraser Basin were distantly related and had the lowest resemblance to the surrogate stock. An expanded F_{ST} divergence matrix using multiple local spawning populations of both life history types throughout the Fraser, Snake and Columbia Rivers is available, for more detailed reference (Appendix 1).



Table 2-1: G'_{ST} divergence matrix of Summer-Fall stocks assessed. The Wenatchee River Summer-Fall run population was used as the surrogate historic stock to generate resemblance scores for use in the donor stock selection process.

	G'ST						Resemblance score
	Hanford Reach	Lyons Ferry	Middle Shuswap	Methow River	Wells Hatchery	Wenatchee River	
Hanford R	--	0.078	0.458	0.034	0.035	0.049	0.900
Lyons F	--	--	0.470	0.145	0.128	0.148	0.686
M Shuswap	--	--	--	0.461	0.488	0.472	0.000
Methow R	--	--	--	--	0.015	0.008	0.983
Wells H	--	--	--	--	--	0.024	0.950
Wenatchee R/Okanogan	--	--	--	--	--	--	1.000

Table 2-2: G'_{ST} divergence matrix of Spring run stocks assessed. The Wenatchee River Spring run population was used as the surrogate historic stock to generate resemblance scores for use in the donor stock selection process

	G'ST								Resemblance score
	Carson Hatchery	Methow River	Nicola River	Secesh River	Stuart River	Swift Creek	Upper Yakima	Wenatchee River Spring	
Carson H	--	0.073	0.393	0.110	0.268	0.454	0.166	0.073	0.829
Methow R	--	--	0.438	0.142	0.294	0.468	0.216	0.084	0.803
Nicola R	--	--	--	0.377	0.303	0.365	0.426	0.386	0.103
Secesh R	--	--	--	--	0.292	0.431	0.186	0.136	0.684
Stuart R	--	--	--	--	--	0.250	0.312	0.271	0.369
Swift Cr/Tete	--	--	--	--	--	--	0.522	0.430	0.000
U Yakima	--	--	--	--	--	--	--	0.189	0.560
Wenatchee R	--	--	--	--	--	--	--	--	1.000

2.4 Discussion

2.4.1 Patterns of between stock diversity

As with many previous studies, this study identified a generalized, pervasive pattern of isolation by distance of genetic diversity between assessed donor stocks (Beacham et al. 2006, Moran et al. 2013). Resemblance of potential donor stocks to the historic stock could not be directly assessed, as tissue from historic samples was too degraded to analyze. In lieu of historic stock samples, resemblance of donor stocks to surrogate stocks at neutral markers was spatially dependent, as those that were the most geographically proximate had the highest resemblance, while those that were geographically distal



had the lowest resemblance. Populations from the US Upper Columbia tended to have the highest scores, those from the Snake River were moderately related, while those from the Fraser River basin were distantly related and scored low. This supports the overall observation that the geographically most proximate stocks within each life history type are most likely to share recent evolutionary lineage. Out-of-basin donor stocks should therefore be considered to be the least appropriate as donor stocks using the ancestry matching approach. For Summer-Fall run, interior Columbia River fish generally share little ancestry with congruent life histories of Chinook Salmon from the Fraser or other basins further north in British Columbia and Alaska (Appendix 1; Waples et al. 2004, Beacham et al. 2006, Seeb et al. 2007). In fact, studies conducted on large scale patterns of genetic diversity of the species suggest Summer-Fall Chinook Salmon from the Fraser basin (subyearling juvenile emigrant dominant) share more recent evolutionary lineage with interior Columbia Spring run (Moran et al. 2013). The most closely related Spring run stocks from the Fraser River basin examined in this analysis are those of the Middle and Upper Fraser Summer and Spring runs (Appendix 1).

It is unknown how related the historic stocks were to the US Upper Columbia surrogate stocks, and whether the Chinook Salmon that used the Transboundary Reach would have been considered part of the same ESU if data was available (Good et al. 2005). There are reasons to believe that some of these fish may hold genetic resemblance to the historic stock. Firstly, Fall run life histories used mainstem spawning areas immediately downstream from the Transboundary Reach below Kettle Falls, while Spring run Chinook Salmon migrated to tributaries (e.g., Salmo, Slocan) adjacent to this reach (Chapman 1943, Columbia Basin Tribes and First Nations 2015). The geographic proximity to the extant US Upper Columbia ESUs implies that they may have been part of the same ESU (Figure 1-3). Summer-Fall run Chinook Salmon in particular used extensive and largely contiguous mainstem spawning habitats in the Columbia River from near the Canada-US border downstream to the confluence with the Snake River (Chapman 1943, Dauble et al. 2003). Mainstem spawning Summer-Fall life histories would have been abundant in these areas, thus providing a large effective population size and reducing the forces of genetic drift from driving divergence, as it would between smaller populations (Allendorf and Luikart 2007). This geographic proximity and contiguous mainstem spawning habitat use, coupled with large historic effective population size may have reduced the forces that would have driven genetic divergence of Summer-Fall Transboundary Reach Chinook Salmon from those downstream of Kettle Falls. Secondly, the Grand Coulee Fish Maintenance Project (GCFMP) was a large supplementation operation designed to mitigate for the loss of fish that would have returned to upstream sources in the Columbia River (Fish and Hanavan 1948). The implementation of this program involved relocating upriver destined fish (both major life history forms as well as Steelhead and Sockeye) trapped at Rock Island Dam into the Wenatchee, Entiat, Okanogan and Methow River basins, and using them as broodstock for hatchery facilities on these tributaries; most of these fish were destined for areas upstream from Grand Coulee Dam (UCSRB 2007). The genetic consequences of this program likely resulted in a loss of fitness (more general review found in Naish et al. 2007, UCSRB 2007); however, there may be reason to believe that relocation of these fish has resulted in some preservation of alleles that would have been present for stocks spawning in the Columbia River above Grand Coulee Dam, including those stocks that used the Transboundary Reach. Thus, historic Transboundary Reach alleles may be persistent in current Upper Columbia wild fish, and some of their associated integrated hatchery



programs (Drake et al. 2003). On the other hand, there may be reasons to believe that stocks in the Transboundary Reach were in fact divergent ESUs. Kettle Falls separated the historic Transboundary Reach population from current US Upper Columbia Chinook Salmon, and may have restricted historic gene flow by reducing straying and interbreeding with populations above the falls (Figure 1-3). These falls functioned as somewhat of a natural barrier (Chapman 1943), and if they restricted straying of downstream fish to upstream areas to a large enough degree, may have resulted in divergent ESUs in the Transboundary Reach and beyond (Gustafson et al. 2007). With respect to the contemporary involvement of hatchery programs since the GCFMP, decades of further mixing of out-of-basin stocks and hatchery domestication has occurred (Utter et al. 1995), reducing the possible persistence of historic alleles adaptive to, or representative of the Transboundary Reach.

Within each major life history, several patterns of between-population diversity emerge. Stocks within the US Upper Columbia Summer-Fall ESU are very closely related to one another, and within these groups, local stocks and even hatchery stocks are often undifferentiated, implying that gene flow is not strongly restricted (Kassler et al. 2011). The next most closely related out-of-ESU is the Snake River, indicating a possible secondary preference to all within-ESU choices. For Spring run life histories, there were two exceptions to the overall pattern of isolation-by distance. The first exception is that the most geographically proximate out-of-ESU donor stock is from the Upper Yakima, which is a wild population that has extensive historic hatchery influence including supplementation and interbreeding with the Carson stock (HSRG 2009). Despite the proximity and potential homogenization from hatcheries, this stock from the neighboring ESU had a lower resemblance score to the surrogate than a geographically distal stock from the Snake River Spring-Summer ESU. The second exception is the close genetic relationship of the Carson stock, despite the distal geographic location of the hatchery. Our analysis in fact revealed the Carson stock had the highest resemblance score of assessed Spring Run populations, despite the fact that it is considered out-of-ESU. This hatchery specific stock sources its history to multiple ESUs, including those from the Upper Columbia and Snake Rivers as fish were originally taken from Bonneville dam (Utter et al. 1995). In previous studies, it is considered genetically intermediate to the two ESUs (Drake et al. 2003), and has been used extensively throughout the Columbia River basin for reintroduction and supplementation for both conservation and harvest objectives (HSRG 2009).

2.4.2 Stocks not considered

A potential source of broodstock or natural colonists of Summer-Fall Chinook Salmon may exist in the Upper Columbia Mainstem between Rocky Reach and Chief Joseph Dams, and is considered in other components of this analysis (Upper Columbia mainstem Summer-Fall stock). These fish do not have an official population designation, as there is uncertainty as to whether they are a distinct primary population, thus although they are considered part of the Upper Columbia Summer-Fall ESU, they are not recognized as distinct for management purposes (HSRG 2009). Rough escapement estimates from two years of radio-telemetry data suggest spawner numbers of 600-1100 in the area between Wells and Chief Joseph Dams (Mann and Snow 2013); escapement including areas not currently identified by spawner counts and areas between Rocky Reach and Wells dam would expand this number. Tissue was collected for these fish and they were found to be insignificantly differentiated from other populations



within their ESU (Mann et al. 2013), which is consistent with the observation that Upper Columbia Summer-Fall ESU have relatively weak spatial population structure, with most local stocks undifferentiated from one another (Marshall 1993, Kassler et al. 2011). This implies that if escapement and genetic data were available for the wild segment of the Upper Columbia Mainstem Summer-Fall population within this analysis, they would likely receive similar resemblance scores as other Upper Columbia Summer-Fall donor stocks. If natural colonization were to occur once passage is provided, this is a possible founding source of wild fish that would recolonize the Transboundary Reach simply due to proximity.

For Fraser River basin Spring run fish, a possible omission from this analysis was the inclusion of additional representative groups from the North Thompson spring and summer CUs (Holtby and Ciruna 2007). Previous studies have found these interior migrating stocks are not more closely related to US Upper Columbia Chinook Salmon than other selections from the Middle or Upper Fraser Basin CUs (also supported by this analysis; data shown in Appendix 1), so it is unlikely they would score significantly higher than any of the Fraser River Basin stocks we formally assessed in this component.

2.5 Conclusions and recommendations

While the ancestry component of the donor stock selection process is one of several major components of the selection framework, results from this component generally suggest that locally sourced donor stocks are the most appropriate stocks to consider from an ancestry perspective. Wild populations in the US Upper Columbia Spring and Summer-Fall ESUs are most likely to resemble the historic stocks that used the Transboundary Reach. Thus, donor stocks from these ESUs are more likely than out-of-ESU stocks to share ancestral adaptations that the historic stock would have possessed. If stocks from out of either ESU are considered, the neighboring Snake River basin may be the next most appropriate source for Summer-Fall life histories. In Spring life histories, the next most appropriate source to within-ESU may be from a hatchery specific strain (Carson stock).

Stocks from the Fraser River were distantly related to surrogate stocks in the upper Columbia ESUs relative to even the neighboring within-basin ESUs in the Snake River. Thus, there is no evidence that Fraser River Basin stocks share close enough evolutionary ancestry to be nested within the population structure of the Columbia River basin. This makes these stocks the least suitable of those analyzed from an ancestry perspective.



3 Component Two: Adaptive Potential

3.1 Introduction

Genetic diversity is an important aspect of reintroduction programs, as use of highly diverse donor stocks is associated with higher success of establishing a reintroduced population (Cochran-Biederman et al. 2015). Selection of a single stock or multiple donor stocks that display a wide range of adaptive diversity is especially pertinent to consider when there is uncertainty regarding the suitability of donor stocks during pre-assessment (Houde et al. 2015a).

In this component, we examine the adaptive potential of potential donor stocks according to use of neutral genetic diversity and population size as proxies for adaptive genetic diversity (Houde et al. 2015a). Where aspects of diversity in traits of specific donor stocks are also known, these are reviewed and assessed in the context of whether they would confer adaptive diversity that could facilitate local adaptation in the founding population. We also examine the bet-hedging strategy of using multiple donor stocks as a technique to increase diversity in the founding population.

3.2 Methods

3.2.1 Neutral genetic diversity

For a description of the collection and of genetic baseline data, please refer to section 2.2.1.

Genetic diversity for each stock was quantified using neutral genetic markers: Heterozygosity (H) and Allelic richness (AR). AR was calculated using the program FSTAT 2.9.3 (Goudet 1995), based on a minimum sample size of 49 individuals. H was calculated for all populations in GenAEx 6.5 (Peakall and Smouse 2012). Quantities for the Okanogan Summer-Fall stock were assumed to be the same as the Wenatchee Summer-Fall stock (described in section 2.2.1)

Natural trends of abundance of each wild donor stock were considered to contribute to diversity potential. This was examined according to the well-founded principle that genetic variation is lost with successive generations in small populations, or populations that are on a dwindling trajectory to become small enough to lose genetic diversity (Allendorf and Luikart 2007). Thus, large populations and those with recent population growth, should be demographic attributes should help buffer or reverse losses of diversity in the natural donor stock and provide a reliable, continuing source of diversity to reintroduced populations. Increasing or decreasing trends were based on significant ($p < 0.05$) linear regression of log-transformed natural origin spawner abundance through the last 10 years for which data was available (Good et al. 2005). The threshold size for large population was based on a recommendation from basic genetics literature reviewed in the NOAA Viable Salmonid Population technical memorandum (see McElhany et al. 2000 p. 60 for discussion). In this review, the number of effective breeders per generation which must be present, relative to the numbers of observed breeders was assessed at 0.3. Using this ratio and well established genetic viability criteria (Franklin 1980, Soulé 1980, Lande 1995), it was recommended that 1670-16700 breeders per generation was needed for long term genetic viability.



Since Chinook Salmon in the Columbia typically have a generation time of 4 years, this translates to 417-4170 per year. The upper end of this range was used to designate a population as “large” and the midpoint of this range (2294 fish per year), below which a population was designated as “small.” The geometric mean was used rather than the arithmetic mean due to the large annual variability in salmon return numbers. Spawner estimates were taken from (NOAA 2014, WDFW 2015) and DFO (2011), which use a variety of enumeration techniques. Hatchery stocks often have an obscure regionally derived ancestry, and are not associated with brood or composite production, so were not assessed for population size. The Stuart River stock used the neighboring Nechako River stock returns as a proxy, since counts in the Stuart River were discontinued in 2004 due to persistently poor conditions for enumeration and because the Nechako River had similar counts when the two were taken concurrently (DFO 2011).

3.3 Results

3.3.1 Neutral genetic diversity

Diversity was calculated for all potential Summer-Fall donor stocks, using information on stock return statistics and within population genetic diversity (Table 3-1). The Hanford Reach generally had the strongest diversity metrics, from its large population size and genetic diversity. Spring run populations had lower levels of genetic diversity, and generally had smaller population sizes. Most spring run populations had declining population size trends, but this was only significant for two populations (Nicola and Tete Jaune/Swift).

Table 3-1: Diversity metrics of each potential donor stock, including both Summer-Fall (SF) and Spring run (S) life histories, according to expected heterozygosity (H) and allelic richness (Ar), population size (and according to categorically defined sizes described in the methods), and slope of population size trend (linear regression) over the latest 10 years for which data was available. Stocks are presented ordered from highest to lowest diversity for heterozygosity. Quantities highlighted in green are higher than the average heterozygosity (0.816) or allelic richness (16.4), and those highlighted in red are quantities below the average.

Population	Life History	H	Ar	Population size	Population size category	Slope trend
Wells Hatchery	SF	0.874	19.023	n/a	n/a	n/a
Methow SF	SF	0.872	19.147	2389	Mid	0.011
Hanford Reach	SF	0.865	20.703	64226	Large	0.013
Snake Fall	SF	0.853	18.998	2213	Small	0.039
Wenatchee SF	SF	0.847	18.787	7937	Large	0.012
Okanogan SF	SF	0.847	18.787	6412	Large	0.024
Upper Yakima SPR	S	0.817	15.281	2507	Mid	-0.014
Stuart River	S	0.811	17.561	2168	Small	-0.08
Carson Hatchery	S	0.796	15.425	n/a	n/a	n/a
Nicola River	S	0.792	12.736	3965	Mid	-0.1*
Wenatchee SPR	S	0.784	15.420	572	Small	0.034
Middle Shuswap	SF	0.782	14.069	2427	Mid	-0.1
Methow River SPR	S	0.775	14.523	399	Small	-0.013
Secesh River	S	0.770	14.100	720	Small	0
Tete Jaune/Swift	S	0.749	11.286	2394	Mid	-0.044*

* denotes significant trend at $p < 0.05$.



3.4 Discussion

3.4.1 **Patterns of within-stock neutral genetic diversity**

Upper Columbia ESU stocks for both life histories were among the most genetically diverse, when compared to stocks from the Fraser and Snake River basins. This high diversity persists, despite extensive hatchery involvement in these populations (Naish et al. 2007) and possible loss of diversity through recent population declines. Stocks used in the Fraser River basin tended to have relatively poor diversity metrics. This could have resulted from recent or historic processes that affect diversity (e.g., population bottlenecks, founder effects during colonization etc.) (Moran et al. 2013). For Spring run life histories, the Swift Creek/Tete Jaune, Stuart River, and Nicola River were selected from the Fraser basin to represent their respective (Middle Fraser Summer, Upper Fraser Spring, Lower Thompson Spring) CUs. All of these populations likely represent the highest potential diversity from their respective CUs as they are among the more abundant runs and previous literature suggest they are of the highest diversity (DFO 2011, Moran et al. 2013), so it is unlikely that selecting different local stocks from these CUs would increase quantities of analyzed diversity metrics from the Fraser Basin. The stock selected for the Spring Run life history in the Snake River Basin had amongst the lowest diversity metrics.

In the Columbia River basin, Summer-Fall run stocks had higher overall diversity and abundance than Spring run stocks. Lower diversity in Spring run populations may be due to lower overall neutral genetic diversity, and typically smaller population size and widespread population declines for Spring run fish. Spring run stocks have declined markedly relative to most Summer-Fall stock in the Columbia, largely due to early overfishing and habitat loss impacts into the first half of the 20th century (Healey 1991). This life history type naturally has smaller population sizes, but recent population sizes have been especially and persistently small for a variety of factors (UCSRB 2007), and may result in further loss of genetic diversity for all potential wild Spring run donors. Summer-Fall stocks also had large scale population declines in the mid 20th century, but have recovered substantially in more recent decades (Dauble and Watson 1997). With such declines, it is possible that demographic population bottlenecks may have reduced diversity for both life history types and especially Spring run stocks, which have had a more lengthy and persistent bottleneck; however, this does not appear to be the case, at least in the Snake River Fall run (Narum et al. 2007). Despite population declines to as low as 78 individuals, this population has recently recovered to run sizes $\sim 10^4$ in recent years, due to recovery efforts that include conservation aquaculture (Smith 2014). Generally higher diversity in Summer-Fall life histories relative to Spring run is most likely explained by natural colonization history (larger founding populations and episodic colonization), gene flow (higher straying rates) and effective population size (genetic drift) rather than anthropogenic disturbance such as demographic bottlenecks and hatchery influence, although these factors may have had some influence in combination with natural factors (Narum et al. 2007).

Overall, donor stocks from the Upper Columbia Summer-Fall ESU all appear highly diverse as potential donor stocks for Summer-Fall life histories. These stocks are amongst the most abundant and genetically diverse populations from the species' worldwide distribution (Moran et al. 2013), and as a result appear favorable for diversity potential.



3.4.2 Adaptive diversity

Neutral genetic diversity was used as a proxy for quantifying adaptive variation, and although the results suggest that Summer-Fall donor stocks are the most appropriate from this perspective, underlying functional genetic variation has not been assessed. Future methods that use novel molecular genetic techniques (e.g., genome-wide variation, functional genomics or transcriptomics) may provide a more accurate prediction of the performance of each donor stock in the reintroduction environment (He et al. 2016). Although the framework for this study includes provision for retention of long-term genetic diversity based on abundance and population growth trajectory, this is based on previous population trends. There is no guarantee that these trends will continue into the future. Thus, within-population diversity results of this analysis should be interpreted as a rather crude assessment of the adaptive potential any particular donor stock has when reintroduced to the Transboundary Reach.

With respect to donor stock selection, Summer-Fall donor stocks from the Columbia River basin assessed in the environment matching component analysis appear to express a wide array of juvenile life history diversity (see section 4.2.1.7 for further description). This may be advantageous in allowing the colonizing population to adapt a juvenile life history pathway (or suite/gradient of pathways) that maximizes survival. It is possible that this diversity is inherent to this life history (though interior Columbia River basin Spring run have rarely been demonstrated to exhibit the diversity too as non-viable strategies; Copeland and Venditti 2009), or it is possible that they simply express diversity more commonly (or successfully) under the current environmental conditions that influence proximate cues that dictate transitions in juvenile life history (Bourret et al. 2016). Transitions along the early life history trajectory of juvenile Chinook Salmon are strongly influenced by environmental factors that affect growth rate (Bourret et al. 2016). If a metapopulation of Chinook Salmon uses a variety of thermal or productivity regimes for spawning and rearing, this will lead to variation in emergence timing and growth rate, which in turn will affect the diversity of early life history pathways (Connor et al. 2005, Copeland and Venditti 2009). There may be some diversity in thermal and productivity regimes for specific reaches of the Transboundary Reach and its accessible tributaries or downstream rearing areas, which may result in such diversity if these habitats are colonized. Such diversity may allow the metapopulation to be buffered from environmental variability and change, as different life history strategies have variation in survival to adulthood (Bourret et al. 2016).

Variation in spawn timing or protracted spawn timing may result in expression of diversity within the same spawning habitat, as this will result in similar variation in emergence timing. Thus, it may be useful to provide a diversity of spawn timings during initial colonization, as the resulting juvenile life history diversity will create greater breadth of heritable traits for stabilizing selection to occur on the specific spawn timing(s) that are optimal for the habitat (Brannon 1987, Brannon et al. 2004). The logical approach might therefore be to select a donor stock with protracted spawn timing that corresponds to the thermally suitable window (Schneider 2011). Results from Component Three suggest that the thermally suitable window for spawning occurs in the Transboundary Reach primarily during the months of October and November (section 4.4.2). Alternatively, a suite of donor stocks could be selected which



appear to have spawn timings that cover the full breadth of the thermally suitable period for spawning in the Transboundary Reach (discussed in subsequent section).

3.4.3 Use of multiple stocks

A possible alternative to selecting a single stock may be to select multiple stocks. Multiple stock reintroduction strategies are essentially a form of bet hedging: they increase the likelihood of establishment by providing more adaptive genetic variation to facilitate local adaptation (Houde et al. 2015a). The need for increasing diversity through use of multiple stocks could be pre-assessed by measuring heritable genetic variation in a suite of donor stocks being considered (Houde 2015). Alternatively, the use of multiple stocks is particularly attractive in situations where suitability is uncertain from pre-assessment. In order to avoid risks of outbreeding depression in future generations (discussed in section 5.1.1) or ensure resources are appropriately directed to specific stocks with higher success, monitoring strategy is an important aspect of implementing a multiple stock reintroduction. Multiple stocks could be used in an experimental framework to gauge relative fitness between potential donor stocks (measured for example by spawning success, downstream smolt survival or smolt-to-adult return).

Crossing stocks in hatcheries to form “composites” may be an attractive solution to maximize adaptive potential, particularly when multiple potential single donor stocks exist, and are each of low diversity or too low of abundance to facilitate a reintroduction (Moritz 1999, Houde et al. 2015a). Composite populations have been used in the hatchery system for Upper Columbia Spring run through the Methow Composite group. This stock traces some origin to out-of-basin components (Drake et al. 2003), and is used to aid recovery of the wild stock through integrated programs (UCSRB 2007, HSRG 2009). Such a strategy is likely not necessary in the Summer-Fall life history, as there are multiple donor stock options of high diversity and population size assessed in this component.

3.5 Conclusions and recommendations

Summer-Fall run life histories in the Columbia River basin have more potential options for locally and regionally sourced donor stocks than Spring run, and are generally the more genetically diverse and more abundant life history type of the two. Stocks specifically originating from the Upper Columbia Summer-Fall ESU are the most diverse of all. There is no strong evidence that genetic diversity has been altered by existing supplementation programs in the potential donor stocks assessed from this ESU (Kassler et al. 2011), indicating that many local and hatchery derived stocks within this ESU could be appropriate as donors.

Use of multiple donor stocks is a potential option to increase adaptive potential of the founding population if there is no clear specific donor stock that appears most suitable. Where donor stock options are limited to multiple, small populations with lower diversity, which is the case for Spring run life histories, this can be accomplished by forming composite stocks. Where donor stock options



abound, with multiple, large populations of high diversity and adaptation to diverse environmental conditions, the adaptive potential of a reintroduction can be increased by releasing multiple stocks.

Juvenile life history diversity has a heritable basis, but is also mediated by environmental conditions during early development. Relative to Spring run stocks, previous literature suggests Summer-Fall run life histories in the interior Columbia River basin commonly express more diversity of juvenile life history pathways under contemporary environmental conditions (Waples et al. 2004, Copeland and Venditti 2009). Yearling emigration (“reservoir type”) strategies appear to be contemporarily selected for in some far inland sections of the hydro dam impacted Columbia River basin under some environmental conditions for Summer-Fall life histories (Brannon et al. 2004). Donor stocks displaying protracted spawn timing, or diversity in spawn timing by using donor stocks of this life history, may confer additional diversity, especially in juvenile life history pathways (Bourret et al. 2016). This diversity may be advantageous for creating conditions for stabilizing selection of juvenile life history pathways to occur during initial colonization and for buffering the founding population from further environmental change.



4 Component Three: Environment Matching

4.1 Introduction

Accurately assessing the environmental suitability and feasibility of salmonid reintroductions is extremely challenging and requires a functional understanding of the life history, behavioral, and physical adaptations of each target species and life history, and access to critical habitats necessary to complete their life cycle. Successful reintroduction programs also require a thorough understanding of how the current environment may limit or benefit various life stages in each study area. This information will be used to begin the determination of optimal reintroduction strategies, identify trade-offs to different life history strategies, and define limiting factors in the reintroduction environment that can be compensated or mitigated to increase suitability of the receiving environment and migration corridors for Chinook Salmon to complete their life cycle.

Chinook Salmon display a wide array of physiological and behavioural adaptations, which are manifested in a variety of life history strategies, used to successfully complete their life cycle. The freshwater phase of the life cycle is particularly challenging, and local adaptations are required. In addition to adaptations needed to complete spawning, incubation and rearing in the local environment where these critical life stages take place, stocks must also be adapted to migrate through the rest of the freshwater system while maximizing their survival for those and later life stages. This has resulted in stocks having unique timings for different life cycle stages, including dates at which they immigrate as adults and how quickly they migrate, when and where they spawn, incubate and rear, and when they outmigrate to the estuary and ocean. Immigration and spawn timing are particularly important, as stocks must be able to access spawning grounds, and spawn during a time of year that will result in successful incubation (e.g., not at risk of desiccation, temperature extremes or scour) and optimal emergence timing for juveniles to meet growth and emergence windows (Quinn 2005).

Successfully characterizing watershed and habitat conditions and their capacity to support salmon populations requires an understanding of which life stages and habitats are limiting at a population scale (Beechie et al. 2003). Ideally, there is sufficient background information to identify or hypothesize the exact mechanisms that may limit reintroduction success, and these mechanisms may be tested in an experimental framework to assess the relative performance of potential donor stocks (Houde 2015). In situations where information is more limiting, and reintroduction has not yet been attempted, major factors that contribute to survival throughout the life cycle can be reasonably assumed and the relative performance of donor stocks predicted. Because salmonids are strongly adapted to specific, local environmental conditions (Taylor 1991, Fraser et al. 2011), reintroduced populations should be those with the most compatible expressions of life history, morphological, and behavioral traits, and the greatest similarities of habitat preference between donor and recipient environments (Burger et al. 2000, Schneider 2011, Anderson et al. 2014). This issue of compatibility of the reintroduced stock also applies to the types, timing, and location of critical resources to maximize survival and growth of reintroduced fish, along with the degree of similarity of the aspects between donor and recipient environments (e.g., the Match-Mismatch Hypothesis, Cushing 1975). Evaluation of similarity in



expressed life history traits and the degree of spatial and temporal synchrony between needed and available required habitat conditions and resource availability between donor and recipient environments is consistent with logic described for assessing candidate donor stocks.

In this component, unique life cycle timing, life history attributes, and behavioural and physical adaptations were determined for candidate donor stocks. Donor stock suitability was assessed by the relative advantages or disadvantages of specific adaptations of each stock within the Reintroduction Reach and/or migration corridor, primarily in the freshwater phase of the life cycle. While several different life cycle modeling approaches have been developed to guide salmon recovery planning (e.g., Kareiva et al. 2000, Scheuerell et al. 2006), they have typically focused on areas where survival is lowest, and have not indicated which specific habitat types or habitat attributes are limiting fish production. By contrast, the limiting factors approach of Reeves et. al (1989), Beechie et. al (1994) and others—which is based on habitat area and capacity—provides a straightforward, mechanistic approach to determining which life stages and habitats are limiting fish at the population scale.

4.2 Methods

The general framework of the donor stock evaluation is to determine the suitability of each donor stock if reintroduced into the Transboundary Reach and simulated moving across the migratory corridor within freshwater. Input data on stocks (e.g. timing for life cycle components, physical attributes etc.) were generally compiled from relevant literature or from the PTAGIS database. In the case of hatchery stocks, data were available from the artificial hatchery population. The Carson stock in particular has been used in multiple introductions, and we used data from the Wind River as it had the richest dataset available. Donor stock candidates are originally described in section 1.3, but only a subset of these could be assessed under this component, as the computational and literature review effort required to include all was beyond the budget constraints of this study. In addition, the life cycle model was tailored to have input data of migratory timings and rates from the Columbia River. This would result in higher uncertainty for stocks from the Fraser River if they were included, as stronger assumptions would need to be made of their migratory timings and rates if they were introduced to the Columbia River. For these reasons, we did not assess stocks from the Fraser River Basin in this component.

This component is organized as follows: In section 4.2.1, a life cycle model was constructed to determine the unique timing of each life history variant for each donor stock. Environmental conditions of each reach were queried in section 4.2.2, and, the suitability of reintroduction per stock was assessed in section 4.2.3 by determining how the life history timings, physical and behavioural adaptations unique to each donor stock compared to the environmental conditions present in each reach of the Columbia River.



4.2.1 Life cycle model

A life cycle model was built that related life stages identified in the model from each stock to the environmental conditions it would be exposed to along the expected spawning/incubation, rearing and migratory corridors of the Columbia River.

4.2.1.1 Overview and major assumptions

Selected Chinook Salmon stock(s) must be able to complete all stages of their life cycle to be successful as a population. To calculate the timing at which different life cycle stages of each donor stock would be present in each reach, a life cycle model was constructed (Figure 4-1), which outlined four life history strategies: Spring run (yearling smolts), and Summer-Fall run (subyearling fry and smolt, yearling smolt). While these categories seem finite, the timing of individual stocks in freshwater, the estuary, or moving to the ocean is variable (Bourret et al. 2016).

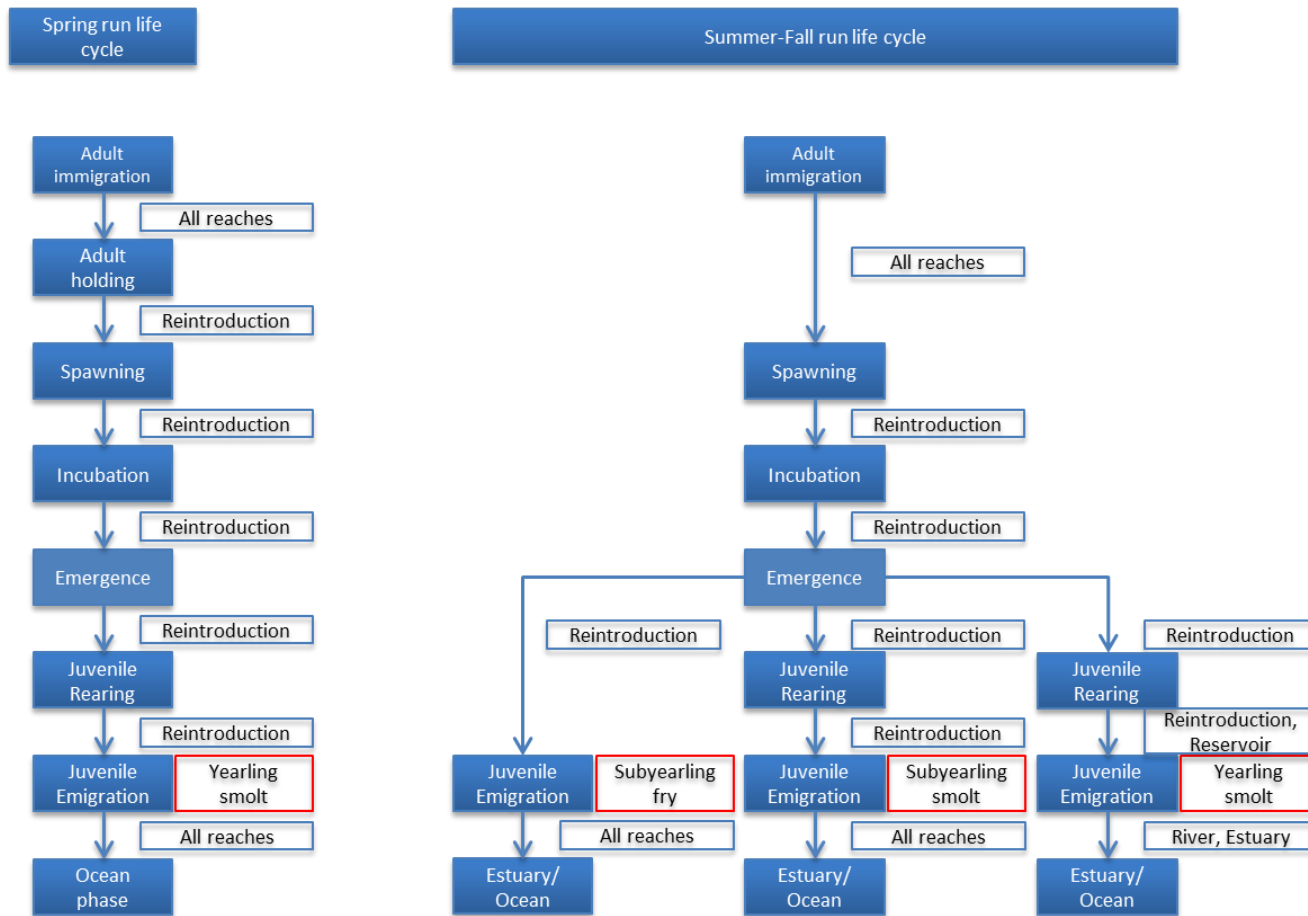


Figure 4-1: Life cycle model used to assess donor stock suitability, with pertinent reaches (blue boxes) in which each stage occurs. Summer-Fall run donor stocks were modeled with three assumed generalized pathways of juvenile life history (red boxes) due to their greater expression of such diversity in wild populations in the interior Columbia River basin relative to Spring run donor stocks.



In considering the life cycle of Chinook Salmon proposed for reintroduction, we separated the Columbia River into large-scale reaches with similar characteristics relevant to the ecology of the species. With consideration of historic salmon observations and general theory of channel processes and Pacific salmonid distribution (Montgomery et al. 1999), we assume the suitability of the Reintroduction Reach will be critical to pre-spawn holding, spawning, incubation, emergence and early rearing. The area outside the Reintroduction Reach (e.g. along the full freshwater migration corridor, the estuary, and the ocean) will support immigrating adults and emigrating juveniles (e.g., fry, parr and smolts). Consequently, the downstream portion of the Columbia River, including its estuary, was divided into 3 separate broad reaches based on similar abiotic and biotic features (Figure 4-2). Due to insufficient data on ocean condition effects on each stock considered in this study, this stage was removed from the model except when considering harvest (see section 4.2.3.1). The freshwater or brackish reaches considered in this model were defined as follows:

- **Estuary Reach:** the estuarine reach between the Pacific Ocean and Bonneville Dam; 234km in length.
- **River Reach:** the mainstem environment of the Columbia River between Bonneville Dam and the tailrace of Grand Coulee Dam. A series of short, very low water residence time reservoirs; 722 km in length.
- **Reservoir Reach:** the mainstem environment of the Columbia River from Grand Coulee Dam and the US-Canada border; comprised of a large hydroelectric reservoir know as Lake Roosevelt; 241 km in length.
- **Reintroduction Reach:** the riverine stretch of the Columbia River from the international border to the tailrace of Hugh Keenleyside Dam; 56 km in length.

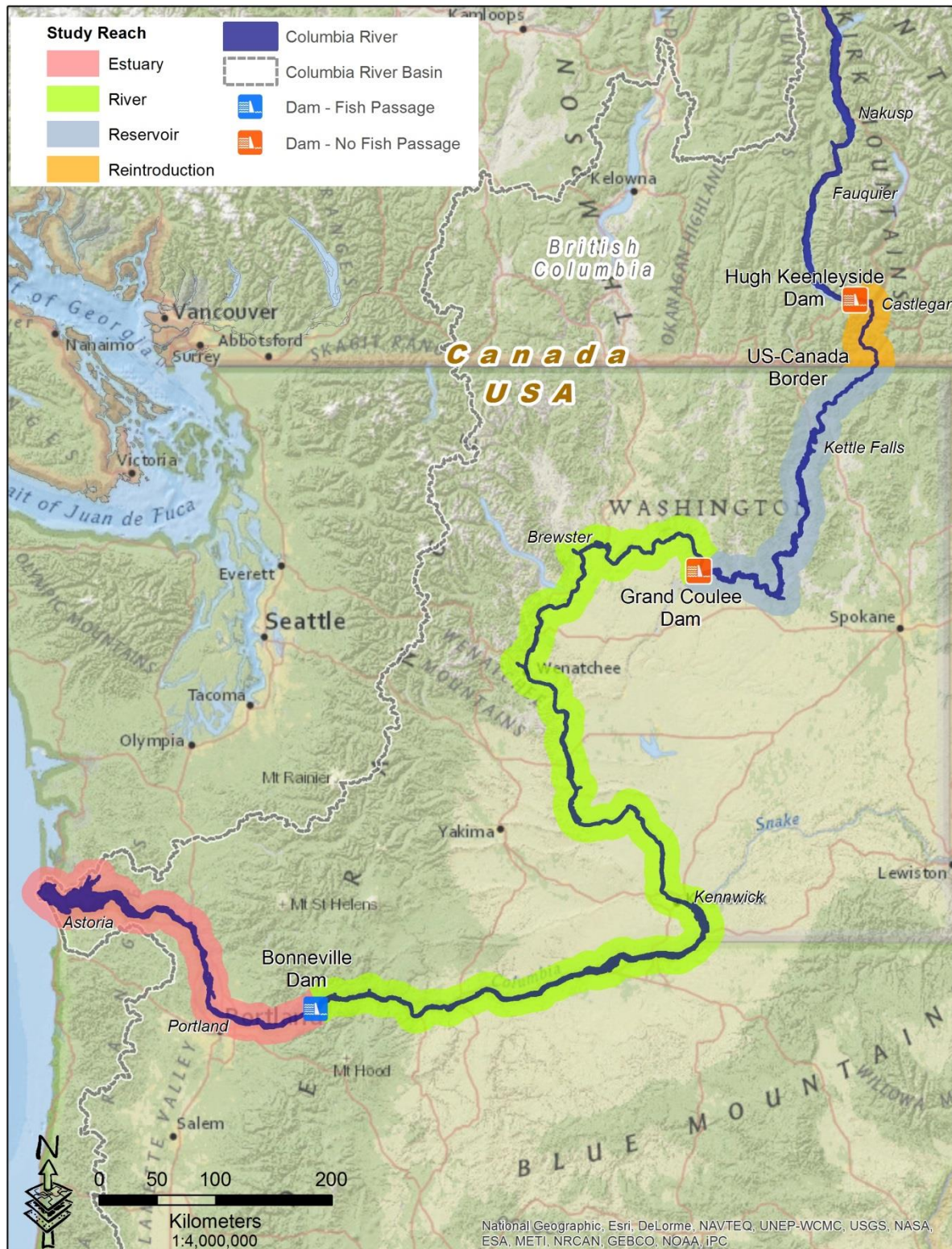


Figure 4-2: River reaches used for life cycle modeling of Chinook Salmon, for reintroduction to the Transboundary Reach of the Columbia River.



We expect that the donor populations may each spawn in distinctly different spatial areas across the Transboundary Reach based on their unique population characteristics (e.g. deeper bodies utilizing deeper waters, etc.; see Montgomery et al. 1999), then emigrate to the estuary and ocean using the same pathway. Each population would also be expected to display distinct migration timing, and hence be exposed to distinct environmental conditions, which forms much of the underlying logic of this comparative model.

In general, Pacific salmon are strongly tied to the immigration rate and spawning timing they have evolved with, thus these traits are highly heritable (Quinn et al. 2002, Quinn 2005). While these traits can adapt relatively quickly (in generations) to new environments (Quinn et al. 2000, Gerson 2012), we assume that the general immigration and spawn timing of Spring and Summer-Fall runs is genetically driven and that the window for these life stages is relatively fixed in the first generation. Indeed, transplanted populations may initially retain ancestral spawn timing in novel environments (Ricker 1972), and reintroduced populations have been shown to be successful when the donor stock spawn timing aligns with spawn timing of the ancestral stock (Schneider 2011). Timing of these life history events is generally evolved to optimize physiological and developmental processes specific to the thermal, biophysical (e.g., to optimize hatch time to optimize growth) and natural disturbance (e.g., flood scour of redds pre-emergence) attributes of the stocks' environment upon emergence (Brannon 1987). Phenotypic plasticity may also explain the natural variability of timing in these traits, or ability to buffer populations from environmental change to some degree (Reed et al. 2010). However, phenotypic plasticity over the timing of these life history events is not understood to the degree that it can be practically considered in models that attempt to predict how environmental changes may influence timing in future generations (Reed et al. 2011).

Juvenile emigration timing can be affected by environmental conditions, but generalities of outmigration timings exist for broadly categorized emigration strategies (i.e. life history type). For the sake of this exercise we assumed stocks that generally emigrate as fry, subyearlings, or yearlings, would continue to do so in the Reintroduction Reach.

Migratory timing was calculated for the four reaches described above using stock-specific timing and travel rates for each relevant life stage (described in sections 4.2.1.2 and 4.2.1.7). Life cycle timings in each reach were expressed in a Gantt chart, by month of the year for each donor stock. We expect there to be natural variability in the timing that each stock exhibits, so we determined when each quartile entered each reach.

4.2.1.2 Adult immigration

4.2.1.2.1 Timing of immigration:

Immigration was calculated by the mean and interquartile range of dates of arrival at Bonneville Dam for each donor stock, where data were available from multiple years (Keefer et al. 2004c, Jepson et al. 2010).



4.2.1.2.2 Rates of migration and progress upstream

Timing of arrival and departure at the river mouth (estuary) and each upstream section in freshwater was then calculated based on generalized or stock specific adult migration rates from literature (Keefer et al. 2004a, Keefer et al. 2004b, Jepson et al. 2010). These travel rates were based on median values from several years of data, as adult travel rate is influenced by river conditions such as temperature or discharge (Goniaea et al. 2006, Keefer et al. 2008). A tabular summary of arrival times, travel rates and specific references pertinent to each donor stock can be found in Appendix 2.

4.2.1.3 Adult Holding

Adult holding is characteristic of early migrating Chinook salmon, many of which mature within freshwater prior to spawning (Healey 1991, Quinn et al. In Press). Certain Summer-Fall populations which run earlier in the summer may also exhibit this behaviour, but it is not known if it is an obligate requirement for maturation prior to spawning for this life history. The adult holding stage was only calculated for stocks of the Spring run life history that were examined (Goniaea et al. 2006; Healey 1991), as “stream-type [Spring run] Chinook ... return to their natal river in the spring or summer, several months prior to spawning” whereas “Ocean-type [Summer-Fall run] Chinook ... return to their natal river in the fall, a few days or weeks before spawning” (Healey 1991). For Spring run fish in this model we calculated holding time as the time window between mean date of arrival at the reach and peak (i.e., mode) spawn dates for each stock. Holding was assumed to occur in the Reintroduction Reach.

4.2.1.4 Spawning

Spawning dates were derived for each donor stock from literature values (Dauble and Watson 1990, Knudsen et al. 2005, Miller 2007, HSRG 2009, Hillman et al. 2011, Young and Blenden 2011, Groves et al. 2012, Mann et al. 2014). Spawn dates were usually based on recurring redd surveys which were conducted throughout the spawning season. Where reports were available, multiple years of data were used. Central tendency of spawn timing for each donor stock depended on reported value, but was most often (preferably) the peak (mode) spawn date. Mean and median spawn dates were occasionally reported, and used if mode was unavailable. Where reported as week of year, the middle day of the week was used to determine the Julian day at which peak spawn occurred. Variability of spawn dates for each population were reported most often as the range of spawning activity for the population (i.e., date of first spawning activity to last date). Unless directly reported in primary literature sources, the 25th and 75th percentile spawn dates were assumed to occur in the middle of the minimum or maximum and peak dates, respectively. A tabular summary of spawning times and specific references pertinent to each donor stock can be found in Appendix 2.

4.2.1.5 Embryo incubation and emergence

Hatch and emergence time is a product of accumulated thermal units (ATUs) while developing in the gravel. Chinook Salmon gravel emergence times were calculated from developmental models (Beer and



Anderson 1997, Beer 1999), from the reference points of the minimum, peak and maximum spawn dates described above and using mean 15 years of daily surface temperature data (1999-2014) collected from a putative spawning area on the Norns Creek Fan (Figure 1-2; Golder et al. 2016). Egg size was assumed to be consistent for all populations. Temperature data were assumed to be an accurate representation of the intragravel thermal units salmonid embryos would be exposed to for the area of measurement, as temperature loggers were buried to a depth of 0.3m approximate the average water temperatures used for calculating salmonid emergence times in the Reintroduction Reach (Irvine et al. 2013). A tabular summary of modeled emergence timings pertinent to each donor stock can be found in Appendix 2.

4.2.1.6 Juvenile Rearing

Juvenile rearing occurs for a period of time as fish grow, prior to physiological processes that trigger downstream emigration and tolerance to the marine environment. There are a variety of juvenile life history strategies for Summer-Fall life histories of Chinook Salmon in the Columbia River Basin, whereas Spring run emigrate in their second year (explained further in section 4.2.1.7.1). Therefore, rearing timing and location within our model were different for each of the two life history types, and multiple emigration strategies were considered for Summer-Fall run. Timing, but not mortality differences between these strategies, was accounted for in the life cycle model. Rearing dates were calculated as the time interval between emergence and emigration for each of these juvenile emigration strategies. Although juvenile life history diversity is most accurately described as a continuum of many alternate pathways (Bourret et al. 2016), it was useful to categorically define three rearing and emigration juvenile life history strategies (Healey 1991): fry, subyearling smolt (i.e., “fingerling”), and yearling smolt, each with specific pathways of life history timing and habitat use.

- **Fry:** involves immediate emigration upon emergence (calculation described in section 4.2.1.5) accompanied by growth during the emigration process. No identified rearing period occurs in the Reintroduction Reach. These fish are generally <55 mm when emigrating from natal streams, and can be a viable juvenile emigration strategy for life cycle completion (Miller et al. 2010)
- **Subyearling smolt:** involves a 2-3 month period of rearing close to the natal habitat life history prior to heading to the ocean, also known as “fingerling” migrants (Healey 1991). These fish are distinctly larger than fry emigrants, generally >75 mm (Miller et al. 2010).
- **Yearling smolt:** involves a full year of rearing (including overwintering) prior to emigration. These fish are able to attain larger sizes by the time they initiate migration in their second year. This is the typical Spring run emigration strategy, though Summer-Fall life histories in the Columbia River Basin also can exhibit this behaviour (Connor et al. 2005).

The yearling smolt strategy can involve variation in habitat preference during the year in freshwater. Juveniles tend to initially rear in close proximity to natal habitat and redistribute downstream to overwintering areas in river environments of their natal mainstem during the fall (Healey 1991, McPhail 2007). Summer-Fall run stocks (e.g. “reservoir-type” life histories) often rear and overwinter in reservoir



environments of the mainstem Columbia and Snake rivers (Connor et al. 2005, Doyle 2013) and thus express yearling smolt emigration pathways. A transient fry-smolt emigrant (“parr”; ~55-75mm) is also documented as an additional, distinct subyearling emigration strategy in some rivers (Miller et al. 2010), but was not explicitly considered in this analysis. In some situations, fish may residualize and become sexually mature as parr or emigrate in their second year, but these are less common pathways (Bourret et al. 2016) and were hence not considered in the model.

4.2.1.7 Emigration, for each of three juvenile life history strategies

4.2.1.7.1 Timing and location of emigration

There are two life histories of Chinook Salmon in the Columbia River Basin with largely divergent life history strategies at different life cycle stages: Spring run and Summer-Fall run. Spring run stocks can be considered fixed to the yearling emigration strategy in contemporary populations in the interior Columbia River Basin because returning adults in these populations exhibit virtually no subyearling outmigration behaviour (Hooff et al. 1999a, Hooff et al. 1999b, Kelsey and Fryer 2001, 2002, 2003, Waples et al. 2004). For example, in the Yakima River Spring population, over 99% of returning adults outmigrated as yearlings (Knudsen et al. 2005). It should be noted that the apparent fixing of these populations to the yearling emigration strategy may simply reflect selection to the contemporary environment, as populations can express non-viable subyearling emigration strategies under the right developmental conditions (Copeland and Venditti 2009). Spring run fish typically rear in the first year of life in their tributary stream, with a redistribution in the fall to mainstem river or natural lake environments for overwintering (Healey 1991, McPhail 2007). The window of emigration in Julian days are assumed to correspond to the generalized outmigration period for yearlings from April 1 to May 31 (Healey 1991, Columbia Basin Research 2016, Fish Passage Center 2016). We assumed a peak (e.g. mode) emigration date of May 1 for all stocks (Healey 1991), as unique stock migration timing was not available for most stocks. For this model, we assumed that yearling smolts of Spring run stocks would initiate migration from the Reintroduction Reach.

For Summer-Fall run donor stocks, there appears to be more flexibility in juvenile life history expression, at least under contemporary environmental conditions. The majority of returning adult fish of this life history emigrate as subyearlings, while a few emigrate as yearlings (Hooff et al. 1999a, Hooff et al. 1999b, Kelsey and Fryer 2001, 2002, 2003, Connor et al. 2005, Doyle 2013). Therefore, lifecycle models were developed for three separately defined Summer-Fall juvenile emigration strategies, independently from one another (Figure 4-1).

Subyearling fry emigrants begin their seaward migration soon after emergence (Miller et al. 2010). These fish emigrate at very small sizes (~40mm FL), and are dispersed downstream by river currents (Healey 1991). For this model, the emigration window was assumed to be the same as the emergence window since there is essentially no territorial feeding position rearing period in the natal environment. Location from which emigration would be initiated was assumed to be the Reintroduction Reach.



Many subyearling fish begin their downstream migration after a period of holding and growth in freshwater. This strategy results in smolts that are larger, but slightly later migrating than their subyearling fry counterparts. Both strategies are observed to be common in Summer-Fall (ocean-type) populations (Healey 1991). The typical time spent for this strategy rearing in natal environments before initiating migration downstream is ~60 days (Healey 1991), which is what we assumed for this model. We also assumed that emigration would be initiated from the Reintroduction Reach.

A final strategy for subyearlings is to migrate as smolts in the spring of the second year of freshwater residence. We used the same timing window as described above for Spring run yearling smolts; however, location differed for initiation of migration. Since reservoir rearing is known to take place for Summer-Fall life history yearling emigrants (termed “reservoir type” life history; Connor et al. 2005), we assumed that the location from which emigration would be initiated is the Reservoir Reach.

4.2.1.7.2 Rates of emigration, and progress downstream

There are some estimates of generalized migration rates from literature sources; however, given that migration rate is heavily influenced by environmental factors that vary annually, emigrant size, points of tagging, downstream detectability, and individual population (Giorgi et al. 1997, Quinn 2005, Crozier et al. 2008), reported values can be strongly biased. In particular, calculating a stocks’ progress downstream must take into account changing juvenile migration rates throughout the migratory season, since month of year strongly influences migration rate (Giorgi et al. 1997). We calculated median monthly migration rates for each of the juvenile emigration strategies considered in this study by using data available from the PIT Tag Information System (PTAGIS) database maintained by the Pacific States Marine Fisheries Commission. This is the largest database of emigration data available, although sample sizes are heavily weighted towards hatchery released fish and smolt sized (>75mm) fish due to methodology constraints of capturing and tagging smaller fish

Juvenile migration rates were derived from travel times between release and detection locations, using ten years of data collected from 2004-2013. Only fish that were tagged and released in the Columbia River mainstem upstream of the Snake River confluence or tagged and released in large river tributaries immediately upstream from their Columbia River confluence (Yakima and Wenatchee rivers) were used in calculations, as these fish use the same migratory corridor that fish in the Reintroduction Reach would use on their route to the ocean.

To make whole-river migration rate estimates, only detection sites from the mainstem lower river (John Day and Bonneville dams or the Towed Estuary Array) were used. These estimates thus take into account travel time through both the slower mid-river phase and the faster lower river phase, since travel times of all fish in the dataset have passed through both river sections. Migration rate was determined by subtracting the release site river km from the detection site river km and divided by the travel time, to express rate in km/day.

To eliminate dataset artifacts or outlier values, several methods were used. First, fish that had negative or excessively fast (>100 km/d) migration rate values were eliminated from the dataset. Large fish may



indicate the presence of tagged returning adults or jacks, thus, fish that had sizes $>200\text{mm}$ were eliminated from the dataset. While capturing and accounting for variability within stocks was of key concern, there were many fish in the PTAGIS database that were held after their tag date for a long period before release. Therefore, we also eliminated fish that were released at dates far exceeding their tag date (>7 days) due to growth and behavioral differences that could have affected data reliability.

Juveniles were assigned to emigration strategies based on their fork length, from reviewing length-frequency histograms for each release month (Figure 4-3). Yearling and subyearling Chinook have different generalized migration timing and size, but there is some overlap between the two life histories. In early (March) and late (June, July) emigration months, the runs are dominated by yearling and subyearling migrants, respectively. In order to eliminate the less common life history from these respective months, quantiles were used to assign size thresholds. For March, fish that fell below the 2.5% quantile were eliminated, and for June and July, fish $>97.5\%$ quantile were eliminated from the dataset. In the middle migration months (April and May), runs have significant overlap and size frequency distributions are thus bimodal owing to significant size differences between yearling and subyearling emigrants. For these months, fish sizes were displayed in binned 5mm fork length increments, and areas of size overlap were identified by a minor secondary peak in the overlapping range of the size distribution (occurs $\sim 95\text{ mm}$; Figure 4-3). The lower and upper limits of these bins were the upper and lower size thresholds for subyearling and yearling migrants, respectively.

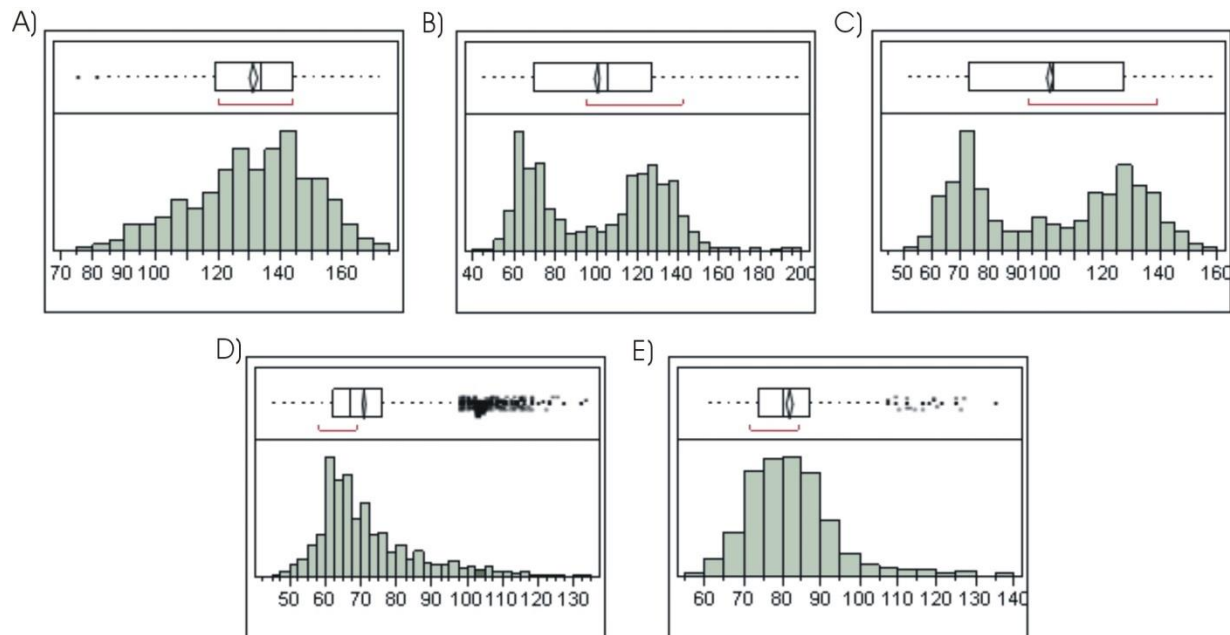


Figure 4-3: Monthly length-frequency histograms/boxplots of tagged fish from PTAGIS database (length in mm), from A) March ($n = 696$), B) April ($n = 3524$), C) May ($n = 1903$), D) June ($n = 5420$), and E) July ($n = 663$). Boxes represent interquartile range; diamonds represent sample mean and 95% confidence interval, while the middle line in the box is the median sample value. Whiskers represent observations outside of the interquartile range, with outlier data points individually plotted outside of the whiskers. The red line is the shortest half, which is the densest 50% of the observations.



After fish were assigned to subyearling or yearling emigration strategies, there was a further need to determine migration rate differences between subyearling fry and subyearling smolt emigration strategies. Subyearling fry migration rates are more challenging to determine because tagging studies are biased to tagging larger fish, although tag miniaturization with advancements in technology is beginning to reduce this bias (Cooke et al. 2013). We initially explored the possibility of treating subyearling fry as a passive particle of water, using reservoir water residence times as a proxy for migration rate; however, after some initial calculations comparing observed subyearling migration rates to water residence times, it became obvious that raw water residence times overestimated fry migration rates relative to the observed smolt migration rates. Indeed, water transit time is not directly translatable in a 1:1 relationship to fish travel time for subyearling emigrants elsewhere in the Columbia River basin, and the ratio can vary substantially from year to year (DeHart 2015). Thus, the dataset of marked fish from PTAGIS that were assigned to subyearlings were further separated into subyearling fry and smolts by using a previously defined biologically relevant size of 55mm that demarcates the upper size threshold of fry emigrants (Miller et al. 2010).

Because there are no known data for travel times in the Upper Columbia between the Transboundary Reach and Chief Joseph Dam, we made several assumptions. First, the arrival dates at each downstream area were based on cumulative daily distance traveled in order to reach the downstream distance of the boundary of each successive reach, given the monthly migration rates that would be encountered. If monthly migration rates were not available beyond a particular month of the year (due to PTAGIS sample size limitations of calculating travel rates in later migration months), the last month's migration rate was used. Dates of arrival were calculated for each quartile of the population, starting from the Julian day from which the migration was initiated. For example, for calculating the time (n days) of presence of juvenile emigrants in the Reservoir Reach:

$$241 \geq \sum_{i=0}^n t_i$$

Where t is the monthly median migration rate (in km/d) at the i th Julian day and n is the ultimate day in the donor stocks' time window (i.e., min, 25th, peak, 75th or max day) for which the 241st km (distance between the limits of the International border and Grand Coulee Dam) is met or surpassed. Monthly median migration rates specific to the juvenile emigration strategy were used.

The emigration window in each reach was determined based on the first Julian day of arrival and last Julian day of leaving the upper and lower boundaries of the reach. Time windows were expressed for each life cycle stage in each reach by month, by quartile abundance.

To compare calculated donor stock estuary arrival times to those of wild populations, we used the same PTAGIS data to determine the 95% confidence interval arrival times at Bonneville Dam, using only tagged wild fish. We used the same size thresholds as calculated above to delineate subyearlings from yearlings, and determine arrival windows for either of these life histories. General time windows were



not separated for subyearling fry and subyearling smolt emigrants, because only a very small sample size was available for subyearling fry ($n = 18$). The estuarine ecology of subyearling fry emigrants is poorly understood, and has changed considerably from historic conditions (Burke 2004, Weitkamp et al. 2012, Weitkamp et al. 2015).

4.2.2 Environmental data

Environmental data were collected on a broad reach scale for the extent of the study area (Estuary up through Transboundary Reach). Temperature, dissolved gas levels and discharge/flow were compiled from a variety of databases and literature sources. We collected as many years of historic data as possible to incorporate historic variation. Other features of the environment play critical roles in the roles of habitat suitability, but we consider these the most critical. Other features that are important for juvenile salmonids which can be improved via focused restoration efforts include: sediment size and sediment quantity, riparian plantings, and connectivity.

Temperature - Temperature was a common environmental variable that was important for several suitability criteria examined. To calculate the average daily temperatures encountered in each reach, datasets from BC Hydro (Norns Creek) and DART (courtesy of USGS and USACE) were used from representative sites at or near the most upstream limit of each reach (Table 4-1). Mean temperature was calculated from underlying hourly averages from years 1997 to 2014, if data were available (Figure 4-4). Monthly and daily mean temperatures were calculated, depending on the data requirements in the suitability analysis.

Table 4-1: Stations used for temperature and dissolved gas data, the underlying timestep and years of data used are noted.

Reach	Station	Timestep	Years
Estuary	Warrendale	hourly	1997-2014
River	McNary Dam (tailrace)	hourly	1997-2014
Reservoir	Grand Coulee Dam (forebay)	hourly	1997-2014
Reintroduction Reach*	Norns Creek Fan	hourly	1999-2014

* Temperature only, see Hatfield Consultants (2008) for Dissolved Gas

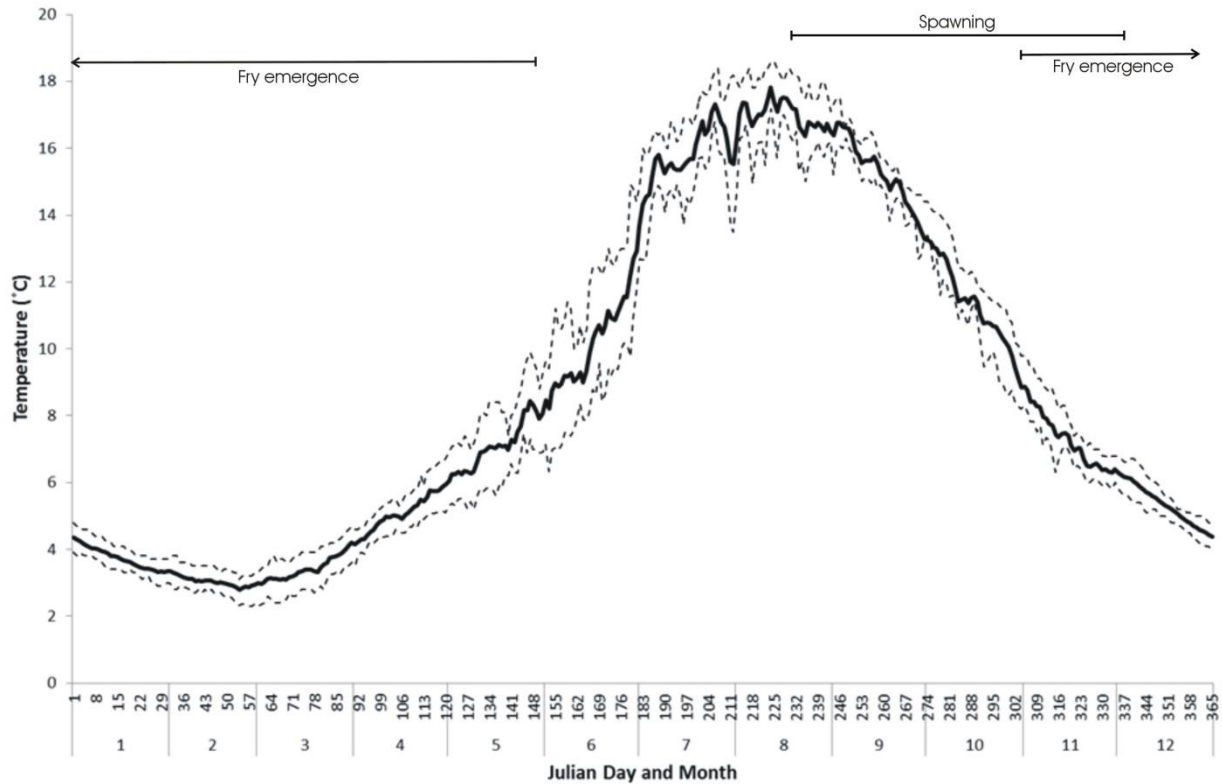


Figure 4-4: Critical timing of life stages of Chinook Salmon donor stocks in the Transboundary Reach, in relation to the thermal regime near the confluence with Norns Creek. The solid line represents the mean temperature at each Julian day of the year from the period between 1999 and 2014. Dashed lines represent upper and lower quartiles. Spawn and emergence timing is the full possible interquartile range observed and modeled (respectively) across all donor stocks.

Dissolved gas - Dissolved gas was used in one ruleset for the suitability analysis and used the same data for all reaches except for the Reintroduction Reach (Table 4-1). These data were collected from DART (courtesy of USGS and USACE). Within the Reintroduction Reach, a blanket assumption was made that 30 day average concentrations of TDG do not exceed 115%, as these concentrations have not been measured since the Arrow Lakes Generating Station was installed at the Hugh Keenleyside Dam (Hatfield Consultants 2008) .

Discharge – Discharge data were collected to evaluate two risks: egg desiccation (e.g. eggs dewatered) and egg scour (i.e. getting “blown out”). To determine relative risk of redd dewatering and scour risk, we collected average flow (e.g. discharge) for each Julian day from 1993 and 2014 for the Hugh Keenleyside Dam (courtesy of BC Hydro; Figure 4-5). Although more years of data are available, these years were used because operations changed in 1993 to protect resident fish from egg dewatering. It was assumed that this area would provide good representation of the flows encountered at a potential spawning area with high habitat suitability (Golder 2016).

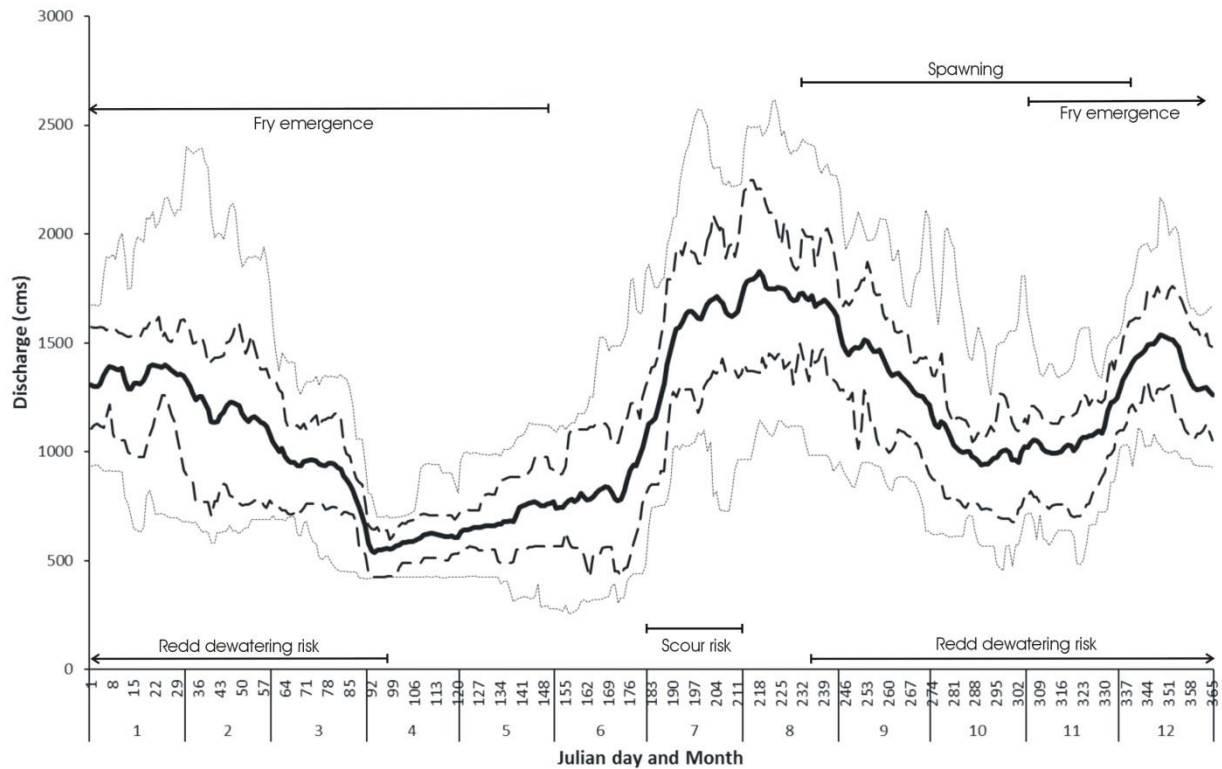


Figure 4-5: Critical timing of life stages of Chinook Salmon donor stocks in the Transboundary Reach, with risk periods due to hydrograph changes at the putative Norns Creek spawning area above the Kootenay River confluence. Solid line represents the mean discharge at each Julian day of the year from Hugh Keenleyside Dam from the period between 1993 and 2014. Dashed lines represent upper and lower quartiles, and dotted lines represent the upper 90th and lower 10th percentile of flows from the analyzed time period. Spawn and emergence timing is the full possible interquartile range observed and modeled (respectively) across all donor stocks.

4.2.3 Suitability analysis

After lifecycle timing of each donor stock was estimated, relative suitability for each stock's life stage per reach was determined. Suitability was quantitatively assessed in many cases by examining the proportion of the population within a reach at a given temporal window, relative to the suitability of the environmental conditions at the reach for each lifecycle stage of each Chinook Salmon donor stock. Suitability levels were determined based on published anatomical, behavioural or physical relationships for Chinook Salmon. Suitability criteria are individually described throughout this section. They are presented in general order in which they appear in the Chinook Salmon life cycle (beginning with adult immigration), except criteria that span multiple life cycle stages are presented last.

Ideally, the exact mechanisms that may limit reintroduction success are known, and the relative performance or heritable genetic variation that may influence donor stock performance in relation to these mechanisms (e.g., tolerance to a specific environmental stressor) could be tested in a controlled



environment (Houde 2015). Unfortunately, we do not know the exact mechanisms that will limit salmon survival when reintroduced the Transboundary Reach, and thus must make assumptions of the major factors. While many pressures affect salmon survival throughout their life cycle, there are generalized environmental aspects that are either well understood, or considered important. The suitability criteria thus chosen were all assumed to be important to affecting salmon survival, and thus would be important aspects that are predicted to regulate their likelihood of establishment in the Transboundary Reach.

Timing and habitat availability are key drivers for this evaluation, and we recognize that there is uncertainty in the forecasting of future conditions, so rather than presenting absolute values, we report donor stock scores based on relative suitability color gradients (i.e. an ordinal assessment), ranging from red (unsuitable) to green (suitable). Summary results for each donor stock were compiled in donor stock individual report cards, as well as in comparative reports which averaged suitability results for all criteria within each lifecycle stage and reach examined.

4.2.3.1 Harvest

Harvest has a large influence on salmon survival, and although there are domestic and international management strategies designed to protect small stocks, bycatch may limit the recovery of such stocks if they co-occur in fisheries with commercially important stocks. Contemporary harvest rates may thus influence the survival of the colonizing population of Chinook Salmon in the Transboundary Reach and hence influence the initial probability of establishment and positive population growth. We assumed that each donor stock would retain their run timing and ocean distributions, and that there would be no salmon fisheries in the Reintroduction Reach, so harvest is assumed to be consistent with current estimates. In-river Columbia River harvest rates for each run time (spring, summer and fall) are based on sliding scales, with respect to meeting escapement targets depending on yearly run size (United States v. Oregon Management agreement 2008-2017):

Fall (upriver bright): 21.5%-45%

Summer (upper Columbia) 5-17%

Spring (upper Columbia) 5.5-17%

Using total combined catch for years 1999-2014, the total mean exploitation rate was calculated for specific and indicator stocks which correspond to the donor stocks selected (Table 4-2). Actual river harvest varies from year to year and does not always meet targets. Total harvest (including ocean fisheries) results in much higher total exploitation rates, and we used these rates to determine average harvest rates. Harvest rates for several indicator stocks are available from the Pacific Salmon Commission Chinook Technical Subcommittee using underlying data from coded wire tag recoveries (PSC 2014b, a). Harvest areas are split into two main areas from aggregate abundance-based management fisheries (AABM; open ocean fisheries where mixed international stocks occur) and individual stock based management fisheries (ISBM; domestic ocean fisheries and terminal river



fisheries). Only in-river domestic fisheries were assumed to occur for Spring run populations, as fish from these populations generally migrate offshore in the ocean and few are captured in near shore fisheries (Healey 1991) subject to the Pacific Salmon Treaty between the United States and Canada.

Table 4-2: Exploitation rates of donor stocks, as estimated from Pacific Salmon Commission (PSC) indicator stocks. Spring run populations are not captured in ocean fisheries, thus their annual exploitation rates are presented according to the current management strategy in domestic fisheries.

Donor stock and run timing	PSC indicator stock	Exploitation rate (%)
Wells Hatchery Summer-Fall	Columbia Summer	52
Wenatchee Summer-Fall	Columbia Summer	52
Methow Summer-Fall	Columbia Summer	52
Okanogan Summer-Fall	Columbia Summer	52
Hanford Reach Fall	Hanford Wild Brights	58
Snake River Fall	Lyons Ferry	47
Upper Columbia Mainstem S-F	Columbia Summer	52
Wenatchee Spring	N/A	5 to 17 *
Methow Spring	N/A	5 to 17 *
Yakima Spring	N/A	5 to 17 *
Carson Spring	N/A	5 to 17 *
South Fork Salmon Spring-Summer	N/A	5 to 17 *

* Total harvest allocation in domestic fisheries U.S. v. Oregon

The ruleset here determines the total exploitation rate of each stock, and applies quartile thresholds to determine suitability, with increasing exploitation decreasing the suitability of the donor stock (Figure 4-6).

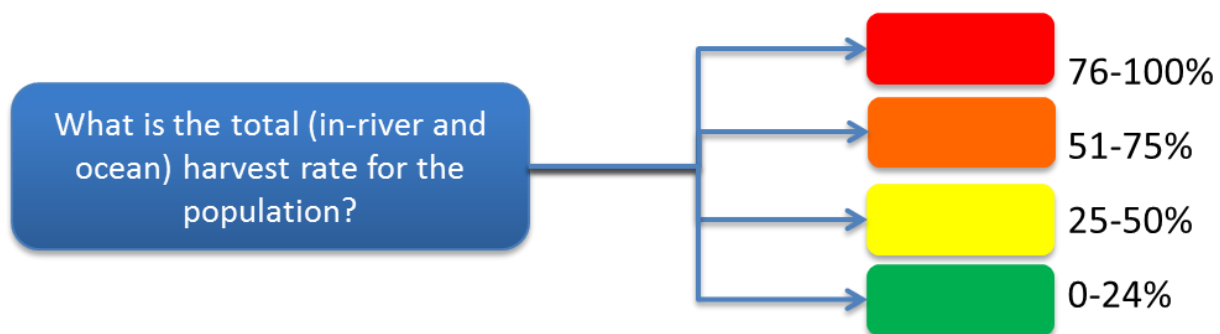


Figure 4-6: Ruleset logic for harvest. Estimates of average exploitation rates are well studied through the Pacific Salmon Commission and other means, and extend into ocean fisheries as well as domestic fisheries, therefore, this ruleset applies to the adult lifecycle stage, regardless of location (i.e., ocean, estuary or river). Color indicates suitability gradient, with green being most suitable and red being least suitable.



4.2.3.2 Body fat content for migration

The Transboundary Reach is a long distance from the ocean, and suitable donor stocks must possess the energy reserves necessary to complete their life cycle in freshwater. Anadromous salmonids are adapted to have substantial energy reserves required to complete migration, maturation (in premature migrants) and spawning, commensurate with the conditions they face and distances traveled prior to spawning (Quinn 2005). Chinook Salmon undertake the most extensive migrations of all salmonids, but there is a large variation in body fat content between stocks. Body fat content is positively associated with both the distance and vertical elevation of spawning sites, as populations migrating greater distances and elevations have an anatomical need for greater energy reserves (Quinn 2005). The Transboundary Reach is a long distance from the ocean, relative to the distances of most Chinook Salmon stocks in North America (Healey 1991, McPhail 2007).

Using data reviewed in Quinn (2005), a body fat content (at time of river entry) regression was established, which predicted a baseline body fat content based on factors of: distance of spawning grounds from ocean and elevation above sea level: $\% \text{ body fat} = (0.0000102)(\text{migration distance [km]} * \text{elevation [m]}) + (5.78)$. Using values from the most upstream boundary of Hugh Keenleyside Dam (1253km, 430m), a target body fat content of 11.4% was calculated as the predicted anatomical requirement for a Chinook Salmon to swim to the Reintroduction Reach.

Measured body fat content was available for two donor stocks in our analysis, from studies that directly measured total somatic body fat. The remainder of the donor stocks assessed did not have measured body fat content available from literature sources, so mean body fat content was estimated based on the regression equation above (assuming the native spawning location of each stock), using maximum freshwater migration distance and elevation of documented spawning areas for each stock, from a variety of literature sources and GIS databases (Table 4-3). The ruleset logic determined suitability based on the body fat content of the donor stock, relative to the predicted anatomical need for the maximum elevation and distance of the Reintroduction Reach (Figure 4-7).

Table 4-3: Maximum migratory distance and elevation ascended by each donor stock in its ancestral habitat, and measured or regression predicted body fat content of adult immigrants at freshwater entry.

Donor stock	Distance from ocean (km)	Elevation ASL (m)	Measured body fat content (%)	Predicted body fat content (%)	References used
Wells Hatchery	830	217	N/A	8	Mann and Snow (2013)
Wenatchee Summer-Fall	840	570	N/A	11	Miller (2010); WDFW (2016b)
Methow Summer-Fall	952.5	540	N/A	11	Mann and Snow (2013); WDFW (2016b)
Okanogan Summer-Fall	988	325	N/A	9	Ashbrook et al. (2008); Davis et al. (2007)
Hanford Reach Fall	630	125	N/A	7	WDFW (2016b)
Snake River Fall	918	452	N/A	10	Good et al. (2005); Dauble et al. (2003)
Chief Joseph Summer-Fall	864	239	N/A	8	Mann et al. (2013, 2014)
Wenatchee Spring	879	845	N/A	13	WDFW (2016b)
Methow Spring	970	1240	N/A	18	WDFW (2016b)
Yakima Spring	845	1100	20	15	Mesa and Magie (2004); WDFW (2016b)
Carson Spring	253	476	N/A	7	WDFW (2016b)
South Fork Salmon Spring	1156	1950	22	29	Mann et al. (2008)

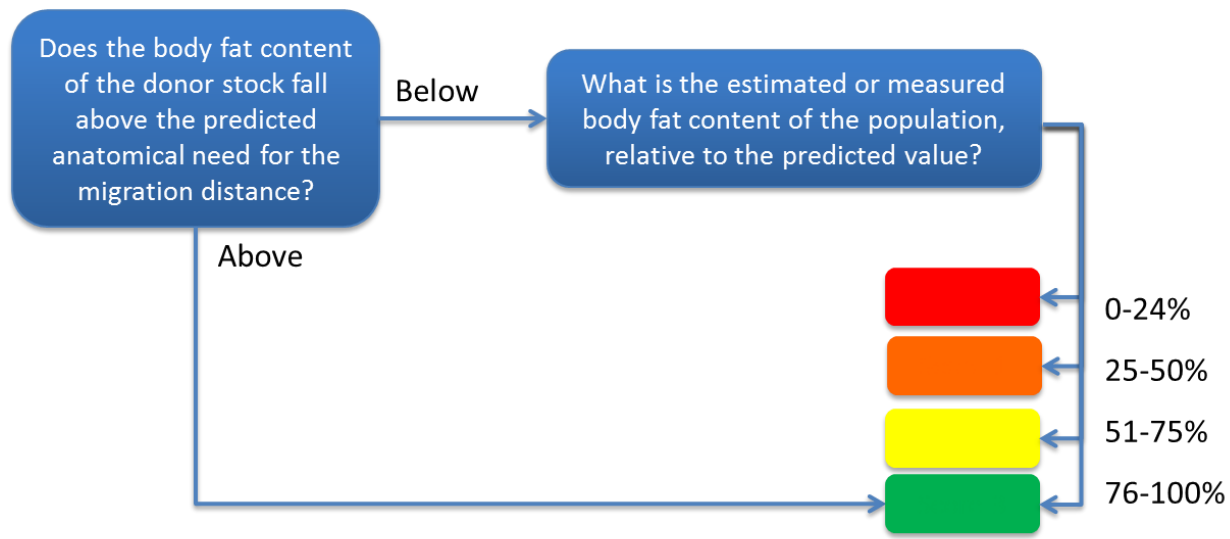


Figure 4-7: Ruleset logic for determining whether donor stocks have sufficient body fat content for the migratory distance and elevation of the Reintroduction Reach. This ruleset applied to the adult immigration lifecycle stage. Color indicates suitability gradient, with green being most suitable and red being least suitable.

4.2.3.3 *Spawn timing/ total holding time*

Immigration timing and spawn timing is highly heritable, and the gap between them allow Chinook Salmon to immigrate to natal spawning grounds with sufficient time to complete maturation or spawn at a time which optimizes survival in the subsequent generation (Quinn 2005). The Transboundary Reach is further upstream than the current spawning grounds for every donor stock assessed. Given the additional time required to migrate this distance, modeled arrival times for each stock were compared to the distribution of spawn timing. For the donor stocks evaluated in this study, we did not have information regarding upstream migration timing upstream of Chief Joseph Dam, so we assumed a constant migration rate, equivalent to the mid-Columbia reaches where data were available, and applied that to the remaining ~390 km of the upper Columbia (see Life Cycle Model section 4.2.1.2.2).

Adult holding is generally displayed in early migrating Chinook Salmon, which mature in freshwater prior to spawning (Quinn et al. In Press). Later migrating Chinook, in contrast, mature primarily in the ocean and do not require an extended holding period to spawn, thus holding may be considered an obligate life history stage for premature migrants (Healey 1991, Goniea et al. 2006, Quinn et al. In Press). We assumed that all fish of the Spring run life history required holding, as the data suggests that they display premature migration. All fish of the Summer-Fall run, we assumed do not require holding to mature, although this assumption is a generalization since some strains migrate somewhat prematurely prior to spawning and it is not known if this is obligate for gonad maturation (Quinn et al. In Press).



The logic of this ruleset tests the underlying question: will the population reach spawning grounds in time to spawn, and if so for the Spring run life history, will they have sufficient time to hold and finish maturation prior to spawning (Figure 4-8). This ruleset was only applicable to the spawning lifecycle stage, in the Reintroduction Reach.

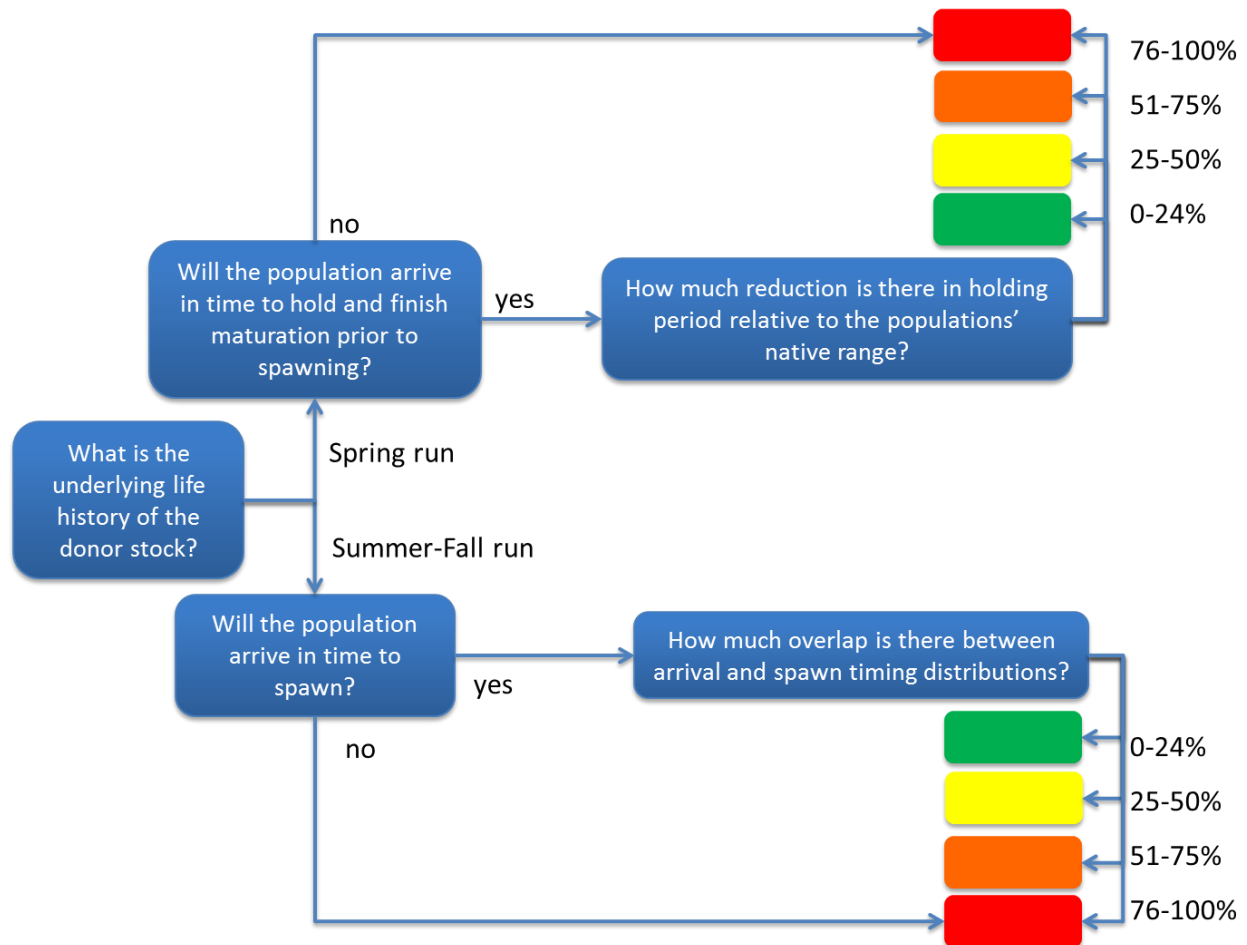


Figure 4-8: Ruleset schematic for spawn timing. The logic is applied differently for the two major Chinook Salmon life histories, due to obligate holding in the Spring run life history. Color indicates suitability gradient, with green being most suitable and red being least suitable.

4.2.3.4 Substrate

Female body size physically governs the ability of salmonids to mobilize sediment during spawning, thus the sediment size distribution of available spawning habitat in the Transboundary Reach may be optimized for a particular size of female (Riebe et al. 2014). As fish size is a heritable trait in salmonids (Quinn 2005), there may be variation in mean female body size between donor stocks assessed in this study, thus influencing their suitability to the substrate size distribution present in the Transboundary Reach.



Spawning substrate size has a significant effect on spawning success and later incubation and emergence success in all salmonids. Fine sediment impacts egg-to-fry survival by impairing intergravel permeability, reducing subsurface flow and dissolved oxygen concentrations, entombing emerging alevins, and multiple other deleterious mechanisms (Phillips et al. 1975, Crouse et al. 1981, Reiser and White 1988, Kondolf 2000, Kemp et al. 2011). At the opposite end of the sediment size spectrum, a female salmonid's ability to excavate a redd is operationally limited by the upper grain size of benthic sediment. As sediment size increases, the force required to mobilize grains during redd excavation also increases, meaning that the minimum size of a female salmon that is capable of spawning in that sediment also increases. Female salmonids can move sediment with a grain size that is roughly 10% of their body length (Kondolf and Wolman 1993, Zeug et al. 2014), meaning that smaller females, including those of smaller species, may be excluded from areas where larger material is used (Riebe et al. 2014, Zeug et al. 2014). Mainstem river spawning populations often are of larger size due to the availability of larger sized substrate and the need to bury embryos below typical scour (Beacham and Murray 1987, Montgomery et al. 1999).

This ruleset determines what proportion of available bed material (e.g. by substrate diameter) can be used by the population, given a mean size of females in the population (Figure 4-9). Mean female size was calculated for each population from a variety of literature sources or databases. Mean female size was then translated to an ideal gravel size based on the regression equation $d_{50}(\text{mm}) = (0.0294) (\text{length mm}) + (7.04)$ (Kondolf et al. 2008). The ideal gravel size could then be compared to the central tendency (D_{50}) of gravel size in the spawning reach. This ruleset only applied to the spawning lifecycle stage and only in the Reintroduction Reach.

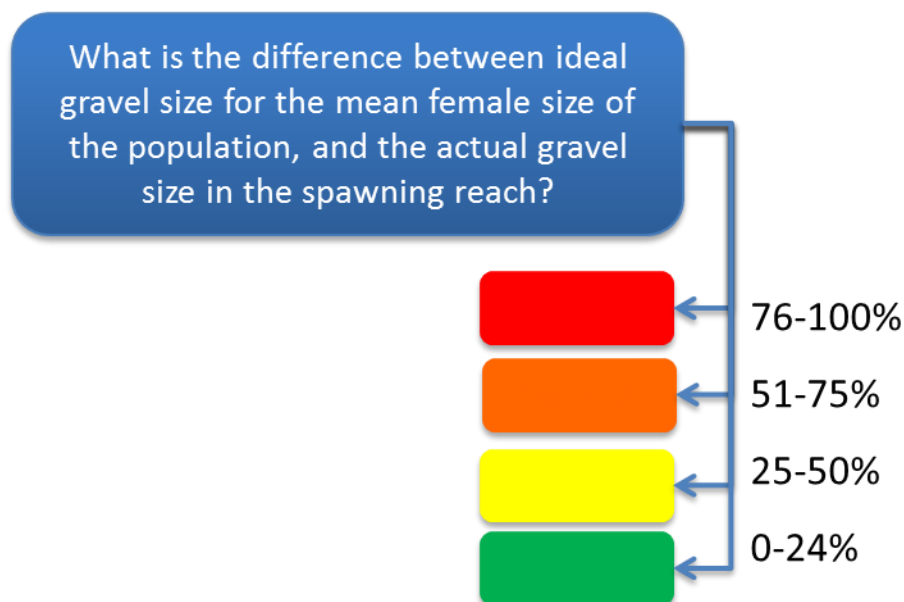


Figure 4-9: Ruleset schematic for substrate suitability for spawning in the Reintroduction Reach. Color indicates suitability gradient, with green being most suitable and red being least suitable.



4.2.3.5 Flood disturbance (scour risk to eggs)

High discharge events can scour redds leaving vulnerable salmon embryos to be crushed or pulled forcefully downstream, and salmonids are adapted to avoid such natural disturbances (Montgomery et al. 1996). While timing of emergence is important to avoid such disturbance, egg burial depth may also allow salmonids to avoid the effects of scour. Both of these may be influenced by heritable traits in spawn timing (hence influence emergence timing in relation to scour; (Fausch et al. 2001) and female body size (in relation to egg burial depth, Beacham and Murray 1987, Montgomery et al. 1999).

The Columbia River at the Transboundary Reach is subject to a snow dominated hydrograph, meaning that periods of high flow occur during the late spring and early summer months. The river is currently regulated, and although freshet is greatly reduced from historic flows due to upstream storage hydroelectric reservoirs, a pulse of flow still occurs during the summer months. Furthermore, increased rainflow-dominated hydrology is predicted across much of the northwest in the USA, but is predicted to be dominated by snowfall in B.C., favoring certain life history strategies over others (Beechie et al. 2009). Maintaining minimum flows for fish passage will likely to become increasingly difficult over much of the USA-managed portions of the lower and middle Columbia Basin due to declining baseflows in summer, but in the Transboundary Reach both AIB and B1 Climate Change models indicate that most precipitation will continue to come in the form of snowmelt, and that precipitation will increase but occur earlier in the year for this area (CIG 2010).

This ruleset applies to incubating embryos, and asks whether emergence occurs prior to initiation of freshet flows in the Reintroduction Reach (Figure 4-10). For the purposes of this 3-step ruleset, we have not evaluated whether the flows that occur now in the reintroduction zone generate shear stresses capable of scouring salmon redds, but for the purposes of this study, we assumed that flows would be sufficient to generate scour (*Step 1*). For the second question in this ruleset (*Step 2*), we used the regression equation: $\text{Nest Depth} = (.345)(\text{female size in mm}) + (-6.33)$ (Berghe and Gross 1984) to determine egg pocket depth for each population, with the assumption that as female size increases, so does the depth that she can build a nest. To refine this ruleset, data related to site-specific scour depths at this reach (for example, using scour chains) are necessary. BC Hydro consistently initiates high discharges from Hugh Keenleyside Dam on July 1 (Figure 4-5), so this is the date that we predicted freshet flows to initiate. The final question in the logic (*Step 3*) uses the above steps to determine what proportion of the population may be affected by emerging after this date.

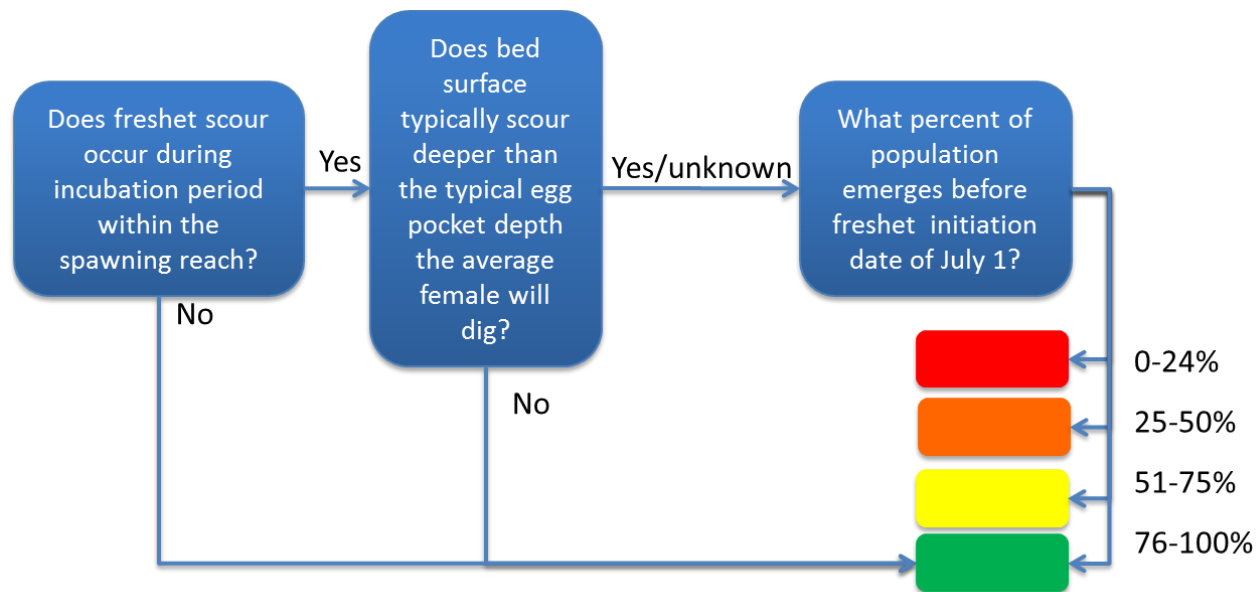


Figure 4-10: Ruleset schematic for assessing suitability of each stock by their ability to avoid flood disturbance by emerging prior to potential freshet scour periods. Color indicates suitability gradient, with green being most suitable and red being least suitable.

4.2.3.6 Food availability (emergence only)

Salmonid emergence time is governed by a suite of factors that optimize embryo incubation survival and emergent fry growth (Brannon 1987, Quinn 2005). Salmonid spawning times are locally adapted to the thermal regime of each population's natal stream, resulting in emergence timing that generally avoids stressors (predation, redd dewatering and thermal stress), while capitalizing on crucial first feeding opportunities when the establishment of feeding territories and positive growth are possible (Brannon 1987, Heggberget 1988, Taylor 1991, Brännäs 1995, Webb and McLay 1996, Quinn et al. 2000). Elevated water temperatures may result in poor fry survival if it results in premature emergence during the previous fall or winter period (Angilletta et al. 2008). The underlying mechanisms for poor survival for prematurely emerging fish may be due to low food availability or temperatures which results in an energy deficit for growth. The data suggest neither abundance, nor biomass of invertebrates are strongly seasonally dependent in the Reintroduction Reach (Olson-Russello 2015) so it was not expected that this ruleset would have a large effect on the overall ranking of stocks in this reach.

The Reintroduction Reach has relatively high prey biomass, abundance and diversity of invertebrates compared to other large river systems suitable for anadromous and resident salmonids in British Columbia (Larratt et al. 2013, Olson-Russello et al. 2015). This includes macroinvertebrates (e.g., chironomids and cladocerans entrained from upstream reservoirs) suitable as prey for Chinook Salmon during their initial feeding (Healey 1991).

The logic of this ruleset addresses how the timing of food needs corresponds with food availability in the Transboundary Reach (i.e. *will food be available?*) (Figure 4-11). The ruleset is only applicable to the



emergence life stage due to the critical need to find food soon after emergence when the yolk sac is depleted.

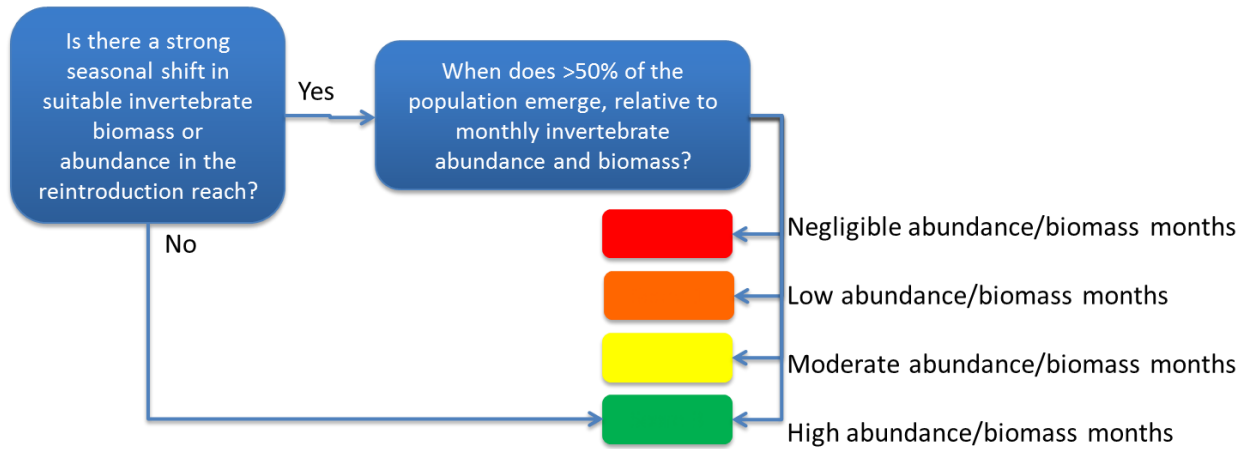


Figure 4-11: Ruleset schematic for food availability in the emergence life stage. Color indicates suitability gradient, with green being most suitable and red being least suitable.

4.2.3.7 Thermal requirements for initial growth

Juvenile Chinook Salmon generally achieve net growth in temperatures between 4.5 °C and 19 °C (McCullough et al. 2001), and emergence above minimum temperature thresholds is important to capitalize on first feeding opportunities (Jensen et al. 1991). This ruleset scores stocks based on how well a population's fry emergence timing corresponds with the thermal period that supports the best positive growth (i.e. *assuming prey are available, will temperatures likely to be suitable for positive growth?*). In the Transboundary Reach, 4.5 °C is exceeded on Julian day 96 most years (mean daily temperature at the Norns Creek fan 1999-2014), and the upper limit of 19 °C is never reached using mean daily temperatures (1999-2014) (Figure 4-12). The logic behind this ruleset is to describe the total percent of the population that would emerge during ideal temperature windows and thus be in a position that would likely support positive growth based on the historic thermal trends.

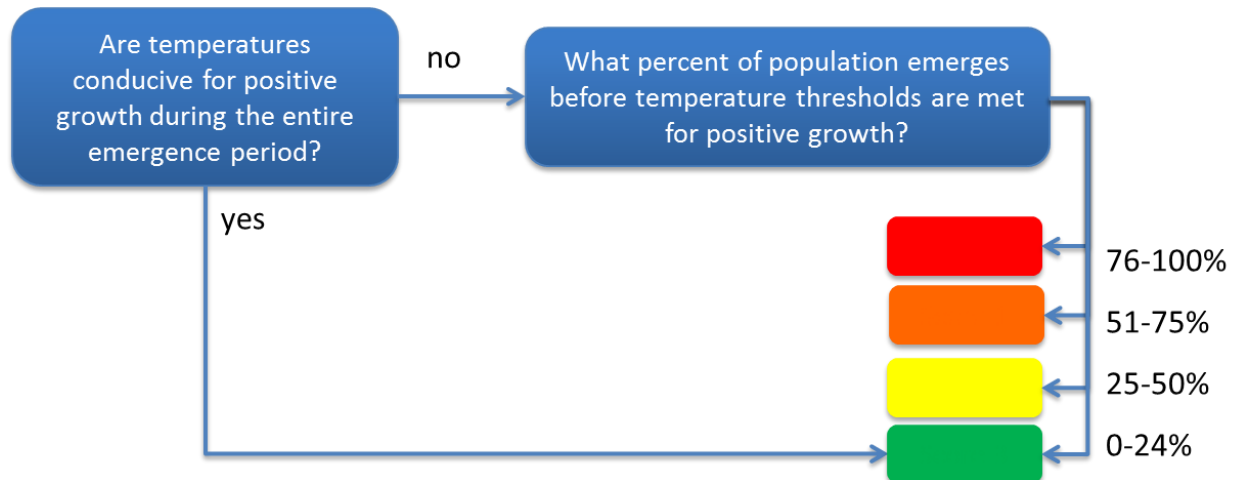


Figure 4-12: Ruleset schematic for thermal requirements during emergence. Color indicates suitability gradient, with green being most suitable and red being least suitable.

4.2.3.8 Spill operations for juvenile passage

Spill is used as an operational tool to increase juvenile survival and migration rates in the Federal Columbia River Power System (FCRPS). Current operations for spill are constantly being refined to optimize survival (NOAA Fisheries 2014), as there are clear tradeoffs with adult fallback or elevated TDG (Boggs et al. 2004, Brosnan 2014). The FCRPS is operated to spill during juvenile emigration months of April-August, thus donor stocks that migrate outside of this time window as juveniles may not be able to take advantage of the currently defined operational management plan to increase juvenile survival and river transit. This ruleset considers the juvenile emigration timing of donor stocks, to determine if they will emigrate during the spill window (Figure 4-13). The ruleset only applies to juvenile emigration life cycle stages, in the River Reach.

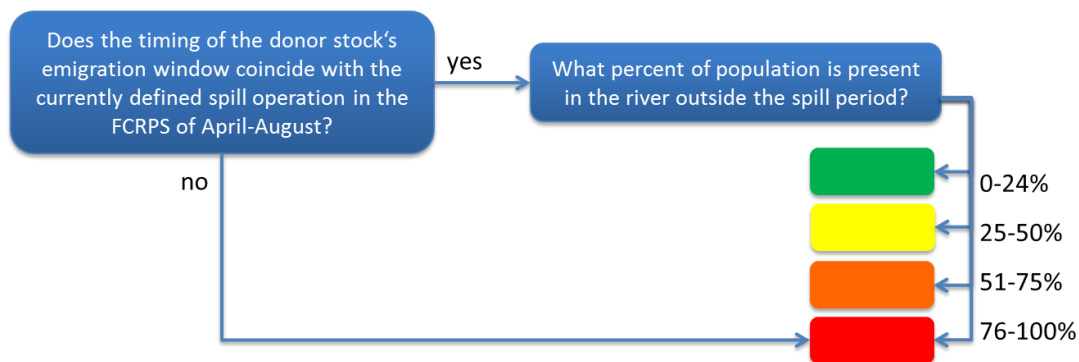


Figure 4-13: Ruleset logic to determine if emigrating juveniles are migrating outside of the current spill operating timeframe in the Columbia River. This spill period is an operation mandated to increase survival of salmon by decreasing travel times to the estuary. It applies only to emigrating juvenile life stages in the River Reach. Color indicates suitability gradient, with green being most suitable and red being least suitable.



4.2.3.9 Generalized thermal suitability

As poikilotherms, temperature is perhaps the paramount environmental regulator of salmonid distributions, life history and local adaptations (Taylor 1991, Brannon et al. 2004), and thresholds which describe optimal, stressful and lethal limits are well researched. We used mean monthly temperature to determine if the donor stock was present in any reaches when these thresholds were exceeded. In an exhaustive study of both laboratory and field studies of temperature effects on salmonids and related species, USEPA (1999, 2001) concluded that temperatures of approximately 22-24°C limit salmonid distribution (i.e., total elimination of salmonids from a location). USEPA (1999) also notes that changes in competitive interactions between fish species can lead to a transition in dominance from salmonids to other species at temperatures 2-4°C lower than the range of total elimination.

Thermal suitability thresholds have been developed for many salmonids, and have been the topic of extensive review for setting water quality guidelines to protect specific stages of fish lifecycles (McCullough et al. 2001). Three thresholds were considered for the various life stages, where temperatures are either considered optimal, stressful, or lethal, and then these metrics were combined into a comprehensive thermal ruleset to evaluate if each stock tended to experience optimal, stressful or lethal mainstream waters during their modeled presence through each reach (Figure 4-14).

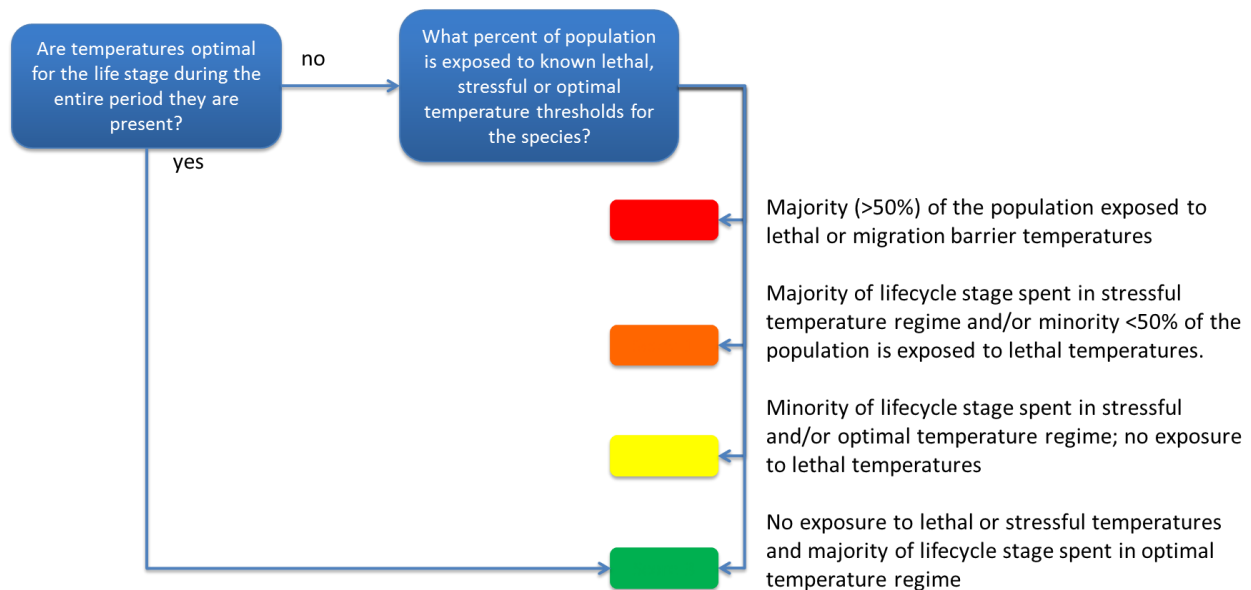


Figure 4-14: Ruleset schematic for generalized thermal requirements for all life stages and reaches. We compiled the temperature ranges reported in various literature review sources, examining thermal effects on each life stage of Chinook Salmon in freshwater (Bjornn and Reiser 1991, McCullough et al. 2001, WDOE 2002, Carter 2005, 2008). Thermal tolerance is often variable depending on thermal acclimation history (Bjornn and Reiser 1991), but generally lethal in all populations (upper incipient lethal temperature) as temperatures approach various thresholds depending on the lifecycle stage. Lower thresholds were not relevant to consider because the reaches in this study are not considered too cold for Chinook Salmon except during initial growth (see previous ruleset); but in other reintroduction areas could be considered. Color indicates suitability gradient, with green being most suitable and red being least suitable.



The analysis determined which Julian days of the year had temperatures exceeding each threshold for any life history stage found in applicable reaches (Table 4-4). The following section describes the thermal thresholds (lethal, stressful and optimal range) of each lifecycle stage and literature reviewed.

Table 4-4: Lethal and stressful temperature thresholds and optimal ranges applied to each lifecycle stage. Thresholds were determined from extensive literature review for biologically relevant thresholds for Chinook Salmon.

Temperature	Lethal or life cycle limiting thresholds	Stressful thresholds	Optimal range			
°C						
25	Juvenile rearing and emigration					
24						
23						
22						
21	Adult immigration and holding					
20		Adult immigration, juvenile rearing and emigration				
19						
18						
17						
16	Spawning and Incubation					
15						
14		Adult holding, spawning and incubation	Juvenile rearing and emigration	Adult immigration	Holding and spawning	Incubation
13						
12						
11						
10						
9						
8						
7						
6						
5						
4						
3						
2						
1						



4.2.3.9.1 Adult immigration

USEPA (2001) cited various literature sources that identified thermal blockages to Chinook Salmon migration at temperatures ranging from 19-23.9 °C, with the majority of references citing migration barriers at temperatures around 21 °C. (see references in Bjornn and Reiser 1991, McCullough et al. 2001, Carter 2005). Adults experience mortality soon above this threshold. We considered 21 °C to be an upper acute temperature where migration may be impeded or pre-spawn mortality may be high; however, Chinook Salmon are often able to avoid lethal temperatures by occupying thermal refuges and holding at cooler tributary mouths during their migration (Gonia et al. 2006), and we did not consider this behavioural thermal regulation in the model.

Optimal migration temperatures for Chinook Salmon are commonly reported to fall in the range of approximately 7 to 14.5 °C; Chinook Salmon populations naturally and commonly migrate in temperatures above this, so stressful migration temperatures are generally considered to be close to migration blocking thresholds, appearing to be around 20 °C (Carter 2005).

4.2.3.9.2 Adult holding

Temperatures resulting in high prespawn mortality are assumed to be the same as described for immigration above (21 °C). Stressful holding temperatures may be encountered above 14 °C, as some studies suggest that these temperatures may result in reduced gamete viability and poor maturation during pre-spawn holding (McCullough et al. 2001 and references therein).

Chinook Salmon generally seek cooler water temperatures below 14 °C when holding, prior to spawning (McCullough et al. 2001 and references therein). A range of 6-14 °C is preferred for pre-spawn holding. It should be noted that we did not have detailed temperature data that would allow us to identify thermal refuges holding salmon could potentially use in proximity to spawning areas, as temperature data used in the model were taken at point surface stations (see section 4.2.2). We assumed that such thermal refuges did not exist for the purposes of this study.

4.2.3.9.3 Spawning

Chinook Salmon spawning has been reported in temperatures as high as 17.7 °C, but the vast majority of spawning occurs below 14 °C, when egg mortality is greatly reduced (See reviews in Bjornn and Reiser 1991, McCullough et al. 2001, Carter 2005, 2008). In large river habitats, some spawning may be initiated above 16 °C, but only during periods of when temperatures are rapidly declining. It is highly unlikely that spawning could be initiated above 16 °C in the Transboundary Reach, as the thermal regime is not in rapid decline when this temperature is surpassed (Figure 4-4). Thus, 16 °C was the limiting threshold used in this model, above which no spawning is assumed to occur. Stressful temperatures are assumed to occur between 14 °C and 16 °C, as these are associated with elevated egg



mortality and fewer spawning observations in the wild (Bjornn and Reiser 1991, McCullough et al. 2001, WDOE 2002).

The optimal range of temperatures Chinook Salmon are most often observed spawning in are from 6-14 °C (Bjornn and Reiser 1991, McCullough et al. 2001, WDOE 2002, Carter 2005, 2008), corresponding to favorable initial temperatures for egg incubation.

4.2.3.9.4 Incubation and emergence

While eggs may be initially exposed to somewhat higher incubation temperatures, the optimal range for incubation is 4-12 °C (Murray and McPhail 1988, McCullough et al. 2001, Carter 2005). Eggs can incubate in lower temperatures, but emergence is delayed and mortality is higher when exposed to especially low temperatures (<2 °C)(Murray and McPhail 1988).

Eggs experience acute lethal temperatures when exposed to short term daily maximum temperatures exceeding 17.5 °C, as mortality is extreme above these temperatures (Carter 2005). Given that daily mean temperatures will be lower than short term maximum hourly temperatures; we chose a mean daily lethal temperature threshold of 16 °C.

Stressful temperatures for egg incubation were set at 14 °C for this model, as mortality of embryos increases greatly above these temperatures (see description and references in the above section 4.2.3.9.3).

4.2.3.9.5 Rearing and emigration

Lethal temperature thresholds for juveniles are often a dependent on acclimation temperatures, but the upper incipient lethal temperature is generally found around 25 °C (see references in McCullough et al. 2001).

Stressful temperature is largely a function of acclimation temperatures and the biotic and abiotic environment in which the fish are rearing, leading to wide upper tolerance reported of Chinook Salmon to temperatures in the range of 17-24 °C (see references in Carter 2005). We used 20 °C as a threshold for thermal stress in rearing and emigrating juveniles, at which smolting may be impaired or growth severely inhibited (see references in Carter 2005)

Optimal temperature for growth is influenced by acclimation, resource availability, environmental conditions and biotic factors such as competition. Commonly cited values for optimal growth occur between 10 and 16 °C for Chinook Salmon (Carter 2005).



4.2.3.10 Watered channel (migration barriers and redd dewatering)

All life stages except incubation: Chinook Salmon require a certain depth of watered channel to complete their life cycle. This ruleset generally applies to the life cycle stages of adult immigration, holding, and spawning and juvenile emigration (Figure 4-15), for which minimum depth thresholds have been established. Chinook Salmon require the following minimum depths: adult immigration and spawning: 0.24 m (Bjornn and Reiser 1991); holding: 2 m pools in proximity to spawning areas (Raleigh et al. 1986); incubation and emergence: watered channel, juvenile rearing and emigration: 0.15 m (Bjornn and Reiser 1991).

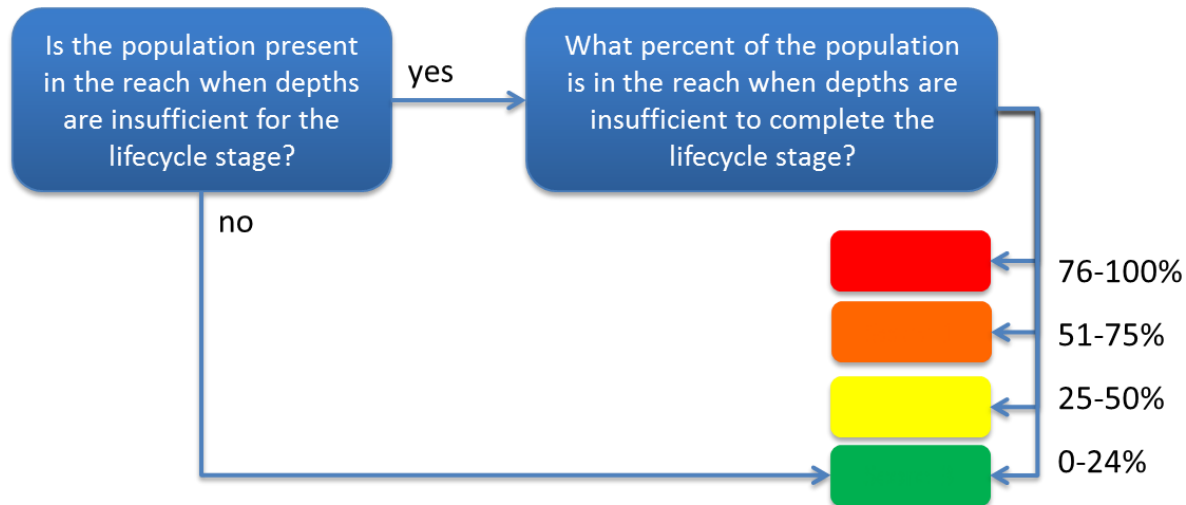


Figure 4-15: Ruleset schematic for assessing whether there is a sufficient depth of watered channel for all lifecycle stages except incubation. Color indicates suitability gradient, with green being most suitable and red being least suitable.

Incubation Lifestage / Redd dewatering: Hydropower operations in the Transboundary Reach have modified the natural flow regime, and there is a risk that this modified flow regime may strand developing embryos as water levels drop below the depths in which Chinook Salmon spawn. To meet minimum depth requirements during the incubation stage, we constructed a bifurcated ruleset that determined the relative risk of redd dewatering (score a = percent of the population at risk; and score b = severity of water reduction) along shoreline areas as a result of hydropower operations.

This ruleset examines whether water levels decline in between the spawning and fry emergence periods (Figure 4-16), and thus if there is a potential risk of dewatering embryos (*Step 1*). If water levels do not decline during the two periods, and redd dewatering is not expected to occur, then the population is given a full score. However, if water levels do decline, then we examine two follow-up questions (*Step 2*): 1) how much of the population is exposed to this reduction?, and 2) what is the expected water level decline between the peak spawning and emergence dates (mean redd dewatering depth)? The ruleset then scores the population based on increasing levels of severity that relate to the spawning depth preferences of each donor stock (*Step 3*).

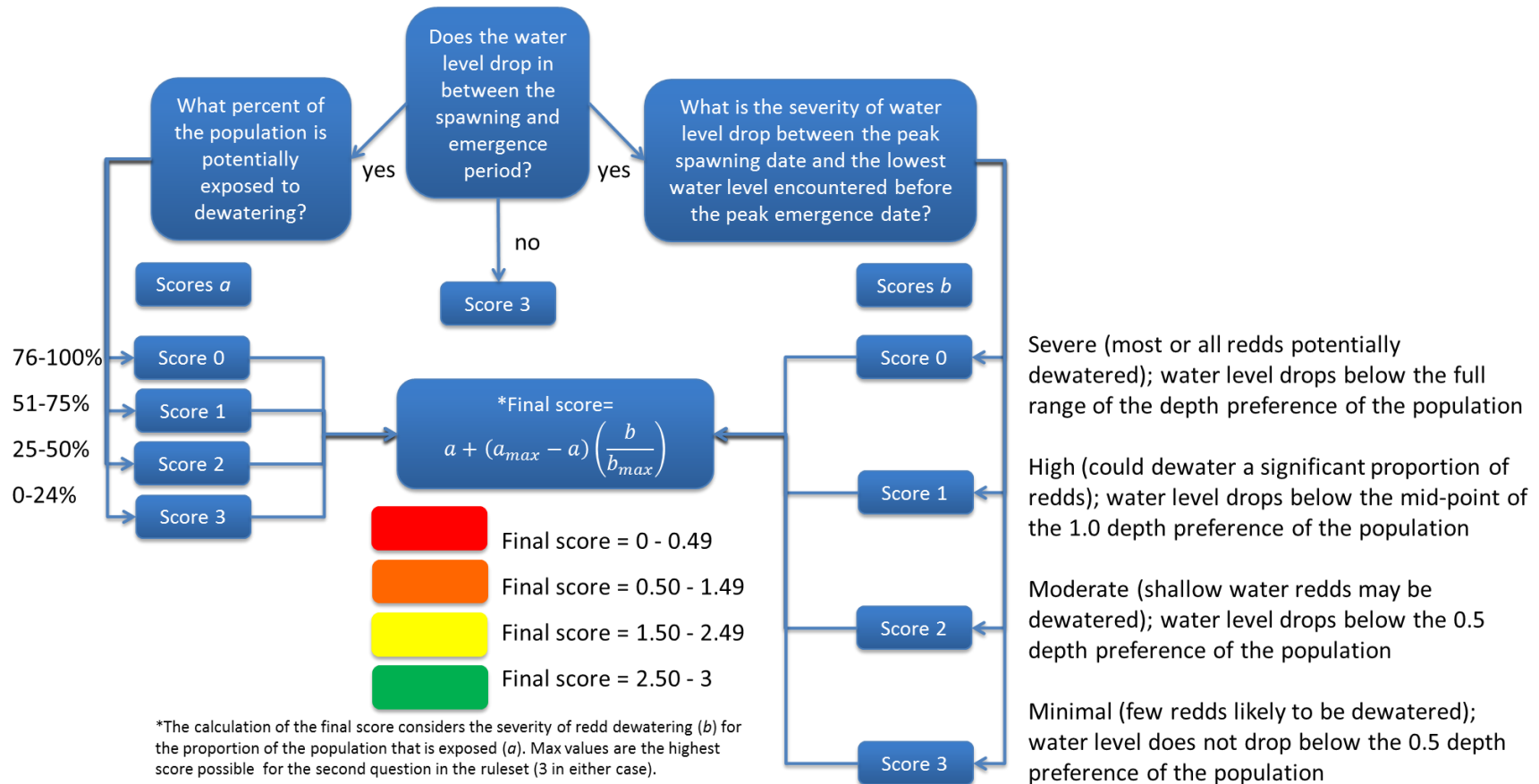


Figure 4-16: Ruleset logic for determining the risk of dewatering during the egg incubation lifecycle stage, in the Reintroduction Reach. The logic considers how much of the population is exposed to dewatering, and what the risk is of dewatering for the proportion of the population that is exposed, based on mean dewatering depth between peak spawning and emergence times, relative to the spawning depth preference of the population. Color indicates suitability gradient, with green being most suitable and red being least suitable.



Determining how much of the population is exposed to water level reduction was a relatively straightforward exercise, by examining the proportion of the population that had emerged after any decline in flow encountered in between the spawning and emergence life cycle stage. Determining severity required both an estimate of the expected redd dewatering depth, as well as the spawning depth preference of the donor stock. Mean redd dewatering depth was calculated for each population based on the difference in flow between the donor's peak spawn date and the minimum flow encountered before the peak emergence date calculated from the egg development model. We used average daily flow from the time period between 1993 and 2014 at Keenleyside Dam as the hydrograph for fish that spawn in the potentially suitable area of the Norns Creek fan (see section 4.2.2; Golder 2016). Difference in flow was then converted to stage difference of water level drop based on the stage-discharge relationship outlined in Hagen and Baxter (2008) of 0.3 m per 5000 ft³s⁻¹ (141.6 m³s⁻¹) at this location.

Chinook Salmon spawning depth varies greatly, from as little as 0.24m, to nearly 10m (Bjornn and Reiser 1991, Geist and Dauble 1998). The donor stocks examined in this analysis spawn in streams that greatly vary in size in their natal habitat. Chinook Salmon spawning depth preference generally increases with river size. Therefore, water level declines might be predicted to impact stocks more severely if they originate from small streams, assuming spawning depth preference is retained in the novel environment. We used depth preference curves for three different stream size classes to determine how the severity of water level decline might impact each donor stock. Depth preference suitability for streams, large rivers and the Columbia/Snake were based on the most recent Washington Department of Fish and Wildlife fallback curves (Figure 4-17) (WDFW 2016), except the stream suitability curve was modified to have a congruent maximum depth preference with the large river suitability curve.

In this model we assigned all Spring run stocks to the stream suitability curve, since these donor stocks are generally observed to spawn in headwater portions of their natal rivers or small tributaries (UCSRB 2007). Summer-Fall stocks use a variety of habitats, from small tributaries to mainstem rivers. Curves were assigned to each stock of this life history based on the mean annual discharge of their natal river. Cut-off values delineating the curves by mean annual discharge correspond to: stream, < 85 m³/s; large river, 85-2800 m³/s; Columbia-Snake, >2800 m³/s (WDFW 2016). Redd dewatering severity was considered to increase with increasing level of water decline, as they correspond to specific suitability thresholds for each donor stock's assigned curve (Table 4-5). The 0.5 suitability threshold on the ascending limb of the curve was assumed to represent a cutoff value, for which few redds would be constructed at shallower depths. The next threshold of severity was assumed to occur at the mid-point of the 1.0 preference on the curve, or the depth of maximum preference, if there is only one point on the curve. If water levels decline below this point, it is assumed that a high amount of redds would be dewatered. The most stringent threshold occurs at depths beyond the entire preference curve, above which all redds would theoretically be constructed and hence dewatered if water levels declined this amount.

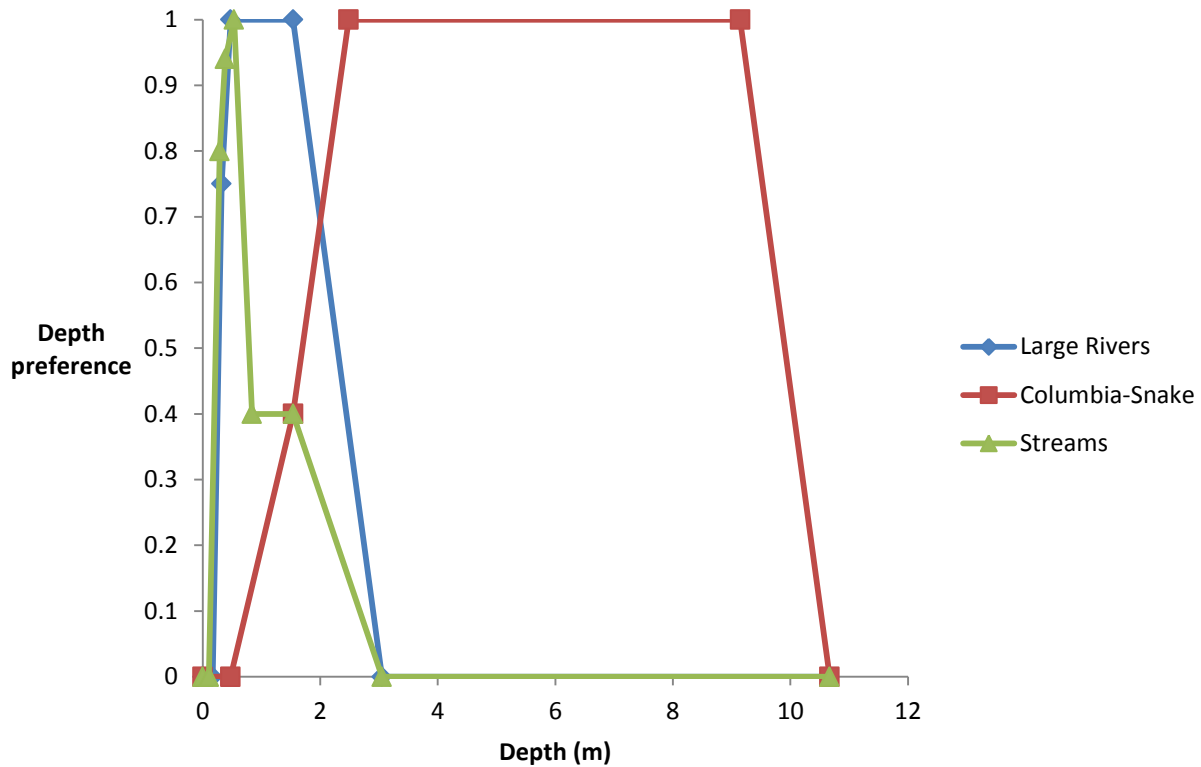


Figure 4-17: Habitat suitability curves defined for three stream size classes, modified from WDFW 2016.

Table 4-5: Suitability curves assigned to donor stocks, and depths corresponding to suitability thresholds on each curve.

Suitability curve	Mean annual discharge (m ³ /s)	Donor stocks	Depth, minimum 0.5 (m)	Depth, mid-point 1.0 (m)	Depth, maximum range (m)
Stream	<85	Methow Summer, Wenatchee Spring, Methow Comp, Carson Hatchery, Upper Yakima Spring, SF Salmon River Spring	0.22	0.53	3.05
Large River	85-2800	Wells Hatchery, Wenatchee Summer, Okanogan Summer	0.27	1.00	3.05
Columbia-Snake	>2800	Hanford Reach, Snake Fall, Upper Columbia Mainstem	1.70	5.81	10.67



4.2.3.11 Predation

Predation pressure throughout the Chinook Salmon freshwater life cycle may be a key driver of survival for rearing and emigrating juvenile salmonids (avian and piscivores), and a potentially significant factor in survival of immigrating adults (pinnipeds) (Fresh 1997). Most predators peak in their activity during specific thermal regimes (predation risk is driven in part by timing), thus the risk of predation for each donor stock depends on their lifecycle timing within each reach and how this relates to the period of greatest predation potential. Additional explanation for how the predation risk categories were determined is in the following section.

In this ruleset, we examine the suitability of donor stocks in each reach based on their seasonal risk of pinniped, avian, and piscivore predation, weighted by the proportion of the population that is present when predators are active (Figure 4-18).

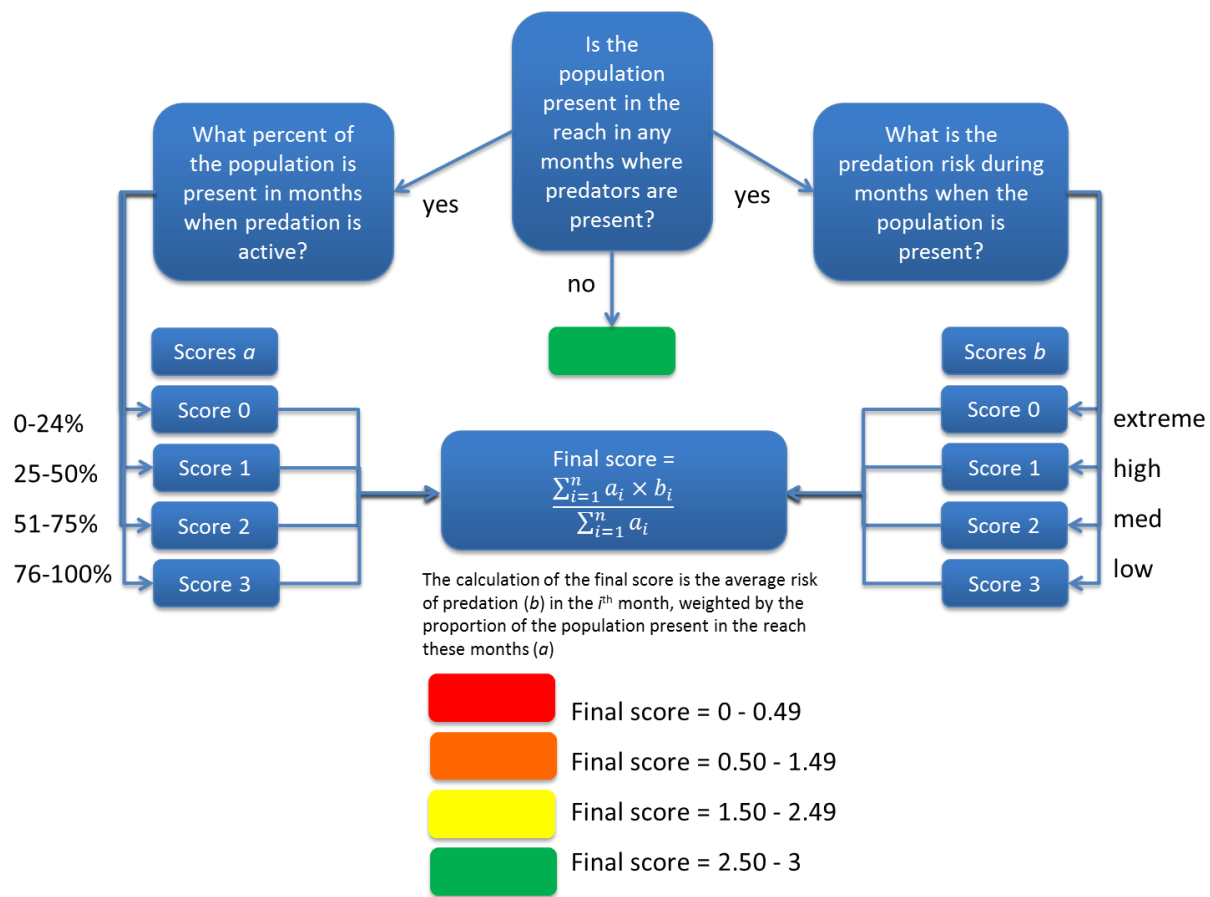


Figure 4-18: Ruleset logic for predation, for adult immigration and juvenile lifecycle stages. This ruleset was independently applied for three predator types: pinnipeds (adults in the estuary); avian predators (for the River and Estuary Reaches during juvenile emigration) and piscivores (for all juvenile lifecycle stages in all reaches). Color indicates suitability gradient, with green being most suitable and red being least suitable.



Pinniped – Monthly pinniped predation risk was determined by literature values for immigrating adult salmon. No data was available on pinniped predation on juvenile life cycle stages, so the impact was only modeled for adult life cycle stages. Monthly predation rates on Chinook Salmon over the time period from 2002-2014 were available from Stansell et al. (2014) for a portion of the immigration period, in the Estuary Reach. Pinniped predation does not extend upstream of this reach. Risk was assessed based on a scale of increasing predation rates from 0-10% (Figure 4-19).

Avian - Seasonal avian predation risk was also determined by literature values from 0-10% (Figure 4-19). Predation is only considered for emigrating juveniles, as this has been identified as a significant source of smolt mortality in the Columbia River (Evans et al. 2012). Information on avian predation rates by reach were available from Evans et al. (2012), which reviewed minimum predation rates of all avian predators for the 2007-2010 time period, and separated impacts on estuary bird colonies relative to inland nesting (i.e., River Reach) colonies. Avian predation would presumably occur upstream in the Reservoir and Reintroduction Reaches, but there is not data that could be used to estimate what rates would be in these areas. The time period of investigation conformed to the nesting period of March-August in the estuary and April-August in the inland colonies.

Piscivore - Although predation rates have been measured in some studies, they are notoriously difficult to measure system-wide. Risk categories as derived above for avian and pinnipeds which are based on measured or estimated rates reach-wide were not available. Piscivores can account for a large proportion of predation on rearing juvenile and outmigrating fry salmon, but rates are highly variable and influenced by the spatial and temporal of overlap between predator and prey, physical gape limitations of the predator (a function of both predator and prey measurements), local habitat features (e.g. cover) and environmental influences (e.g., turbidity, flow, etc.) (Cavallo et al. 2013, Sabal et al. 2016). Due to gape limitation, smaller fish are exposed to a larger number of predators, and predation rates generally increase as temperature increases (assuming prey are available) (Vigg and Burley 1991, Zimmerman 1999, Smith et al. 2003, Marine and Cech 2004, Muir et al. 2006). As an alternative to using actual rates to determine risk, we assumed that relative predation risk across the migration corridor would be correlated with temperature (based on metabolic drivers of most cold blooded piscivores) and limited by predator gape size. Predation of outmigrating salmonids is a function of several piscivores in the migratory portions of the Columbia River system, most notably: Northern Pikeminnow, Walleye, and Smallmouth Bass (Beamesderfer and Rieman 1991, Zimmerman 1999). Specifically within the Reintroduction Reach and neighboring Reservoir Reach, Northern Pike are an emerging piscivore and Walleye are abundant, and both prey on salmonids (Baldwin et al. 2003, Baxter and Neufeld 2015). Sculpin and Burbot also prey on salmonids in the Columbia River system, but were not included in this analysis, as little information is available on these species.

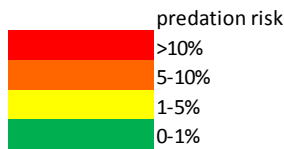
We assumed predation risk increased as various optimal piscivore temperatures were met and exceeded, and metabolic needs peak (Figure 4-19)(reviewed in Hillman et al. 1999): Northern Pike (present in Reintroduction Reach and Lake Roosevelt; 9.0-25.0 °C) Northern Pikeminnow (16.1-24.4 °C), Smallmouth Bass (26-29 °C) and Walleye (20-24 °C). Predation risk categories were assumed higher for subyearlings than yearlings for equivalent temperature thresholds due to their increased exposure to gape limited predation, as there may be a 1-2 order of magnitude greater risk of predation for



subyearlings over yearlings (Sorel et al. 2016). Predation risk for subyearlings was based on the following thresholds: low (<9 °C months for all life stages), medium (9-16 °C), high (16-20 °C) and extreme (>20 °C). Predation risk for yearlings were shifted lower relative to subyearlings: low (<16 °C), medium (16-20 °C), high (>20 °C), and extreme (not encountered; gape limit of predator limits mortality). Piscivory is unlikely to account for a significant source of mortality for immigrating adults, as piscivores are gape limited and there would be few, if any piscivores, that could prey upon large-bodied adult Chinook Salmon in freshwater.

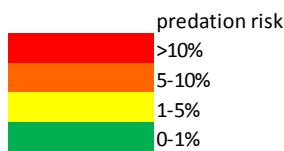
A) Pinnipeds

Reach	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Estuary							data deficient					



B) Avian

Reach	Juvenile age class	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Estuary	yearling												
	subyearling												
River	yearling												
	subyearling												



C) Piscivorous fish

Reach	Juvenile age class	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Estuary	yearling												
	subyearling												
River	yearling												
	subyearling												
Reservoir	yearling												
	subyearling												
Reintro Reach	yearling												
	subyearling												

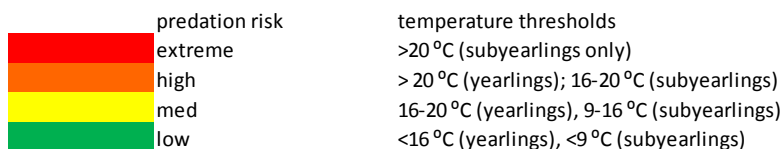


Figure 4-19: Gantt chart of seasonal predation risk assessed from A) Pinnipeds, on immigrating adults in the estuary, B) Avian predators, on emigrating juveniles in the Estuary and River Reaches, and C) Piscivorous fish on rearing and emigrating juveniles in all reaches.



4.2.3.12 Dissolved Gas

Total Dissolved Gas (TDG) is a water quality parameter that, at high levels, can result in elevated salmonid mortality (Carter 2008) by causing gas bubble trauma (GBT). In the regulated environment of the Columbia River, this may be a source of mortality for all life stages (Weitkamp 2008), and thus may affect salmon survival depending on the timing and abundance of donor stocks in any particular reach, relative to the risk of high TDG levels. There have been extensive laboratory, and mesocosm experiments and observational correlative studies to examine the effects of TDG on juvenile salmonids (Weitkamp 2008). Observed levels of GBT are generally low in the Columbia River, but can become substantial when TDG levels meet or exceed 125-130% (Brosnan 2014, FPC 2015). For the Federal Columbia River Power System (USACE 2016), the US Army Corps of Engineers uses a threshold TDG of 115% in the forebay or 120% in the tailrace as guidelines not to be exceeded.

In this ruleset, the suitability of donor stocks was determined based on the percent of the donor stock that were within a reach when the above monthly USACE thresholds were exceeded (Figure 4-20).

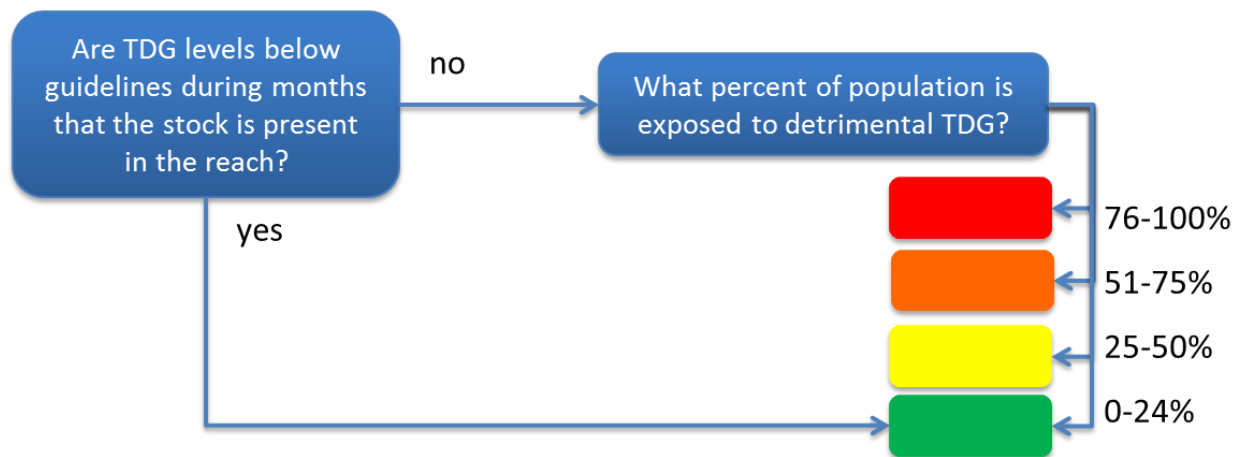


Figure 4-20: Ruleset logic for dissolved gas. This ruleset applies to all lifecycle stages in all reaches, and examines suitability based on the proportion of the population exposed to harmful TDG thresholds currently used in spill management operations. Color indicates suitability gradient, with green being most suitable and red being least suitable.

4.3 Results

4.3.1 Life cycle model

Life cycle timing was calculated for each donor stock and can be visualized in Gantt charts, in section 4.3.2. Specific values of stock adult migration rates, immigration and spawn timing and modeled fry emergence dates can be found in Appendix 2.

Spring run stocks were modeled to reach Bonneville dam from April to June, and reached the Reintroduction Reach between May and July. Summer-Fall stocks had a broader immigration date range, from July to September at Bonneville Dam, and reached the Reintroduction Reach between July and October.



Adults were assumed to hold for the time between when they reached to Reintroduction Reach and spawn timing specific to each population. Spring stocks had the most extended holding periods, followed by Summer migrating stocks, followed by Fall migrating stocks. Spawn periods ranged from as early as mid-August in Spring stocks, to as late as (early) December in Fall migrating stocks.

Egg incubation times were highly variable, depending on the timing of spawning. High temperatures in August and September resulted in early emergence times for Spring run stocks, with most of these stocks emerging from October to January. Summer-Fall stocks all incubated in cooler months, resulting in emergence times as early as March and as late as June.

Rearing and emigration timing varied greatly, depending on the emigration strategy used and specific emigration rates. Using PITAGIS data, examination of length-frequency histograms and quantiles allowed subyearling and yearling life histories to be distinguished in months where the two life histories overlapped. Summary statistics of migration rate was then determined for each life history for each migration month (March-May for yearlings; Table 4-6, and April-July for subyearlings, Table 4-7) As expected, both yearlings and subyearlings moved faster later in the migration season (likely due to increased discharge) and migration rate increased as fish size increased for subyearlings.

Table 4-6: Calculated monthly migration rates of yearling smolt juveniles during downstream emigration life cycle stage. Mean values were calculated from PITAGIS data of juveniles tagged in the Upper Columbia River.

Month	Median rate (km/d)	Mean rate (km/d)	SD rate (km/d)	n	Mean length (mm)	Size range (mm)
Mar	8.7	8.6	3.17	673	132.5	>93
Apr	15.4	16	6.2	1833	126.9	>100
May	28.6	29.2	10.7	921	127.6	>105
Jun	n/a	n/a	n/a	n/a	n/a	n/a
Jul	n/a	n/a	n/a	n/a	n/a	n/a
All seasons	16.7	18.4	10.4	3597	127.4	94-199

Table 4-7: Calculated monthly migration rates of subyearling smolt juveniles during downstream emigration life cycle stage. Mean values were calculated from PITAGIS data of juveniles tagged in the Upper Columbia River.

Month	Median rate (km/d)	Mean rate (km/d)	SD rate (km/d)	n	Mean length (mm)	Size range (mm)
Mar	n/a	n/a	n/a	n/a	n/a	n/a
Apr	4.3	4.8	2	1553	68.2	<90
May	6.3	7.2	4.2	845	72.4	<95
Jun	7.8	9.7	5.3	5267	69.6	<105
Jul	16.4	18.6	9.1	646	80.7	<110
All seasons	7.3	9.2	6.2	8314	70.5	44-110



A small subset of the subyearling smolt dataset was used by selecting only those fish that were below 55mm, to calculate the emigration rates of subyearling fry. This is larger than the size of true fry emigrants, which should be closer to 35-40 mm at the start of their emigration, but insufficient data were available for fish of these sizes, presumably due to tag size limitations. Summary statistics of migration rate was then determined for this emigration strategy, although sample sizes were generally poor and unavailable for July (Table 4-8). Subyearling fry emigrants travelled slower than either subyearling smolts or yearling smolts, as was expected due to smaller size of fry. For calculating travel progress downstream for the month of July, the general subyearling smolt emigration rate was used as a proxy since data was deficient for this month for fish that were of fry size class.

Table 4-8: Calculated monthly migration rates of subyearling fry juveniles during downstream emigration life cycle stage. Mean values were calculated from PITAGIS data of juveniles tagged in the Upper Columbia River.

Month	Median rate (km/d)	Mean rate (km/d)	SD rate (km/d)	n	Mean length (mm)	Size range (mm)
Mar	n/a	n/a	n/a	n/a	n/a	n/a
Apr	4.1	4.4	1.1	52	53.5	<55
May	5.1	7.6	4.2	7	53.9	<55
Jun	5.7	6.1	3.1	251	52.7	<55
Jul	n/a	n/a	n/a	n/a	n/a	n/a
All seasons	5.4	5.9	3	310	52.8	<55

Yearling smolts generally were modeled to reach the estuary by mid-June, whereas subyearlings reached the estuary much later. Subyearling fry were predicted to reach the estuary by August, whereas subyearling smolts reached the estuary later, by September or October. For wild populations, yearlings tagged above the Snake River confluence reached the estuary (Bonneville Dam) between Julian days 113 and 155 (n = 407); subyearlings reached the estuary between Julian days 146 and 249 (n = 1527). Modeled arrival times of yearling and subyearling fry donor stocks were found late in the distribution, or outside the full range of observed arrival times for wild fish (Figure 4-21).

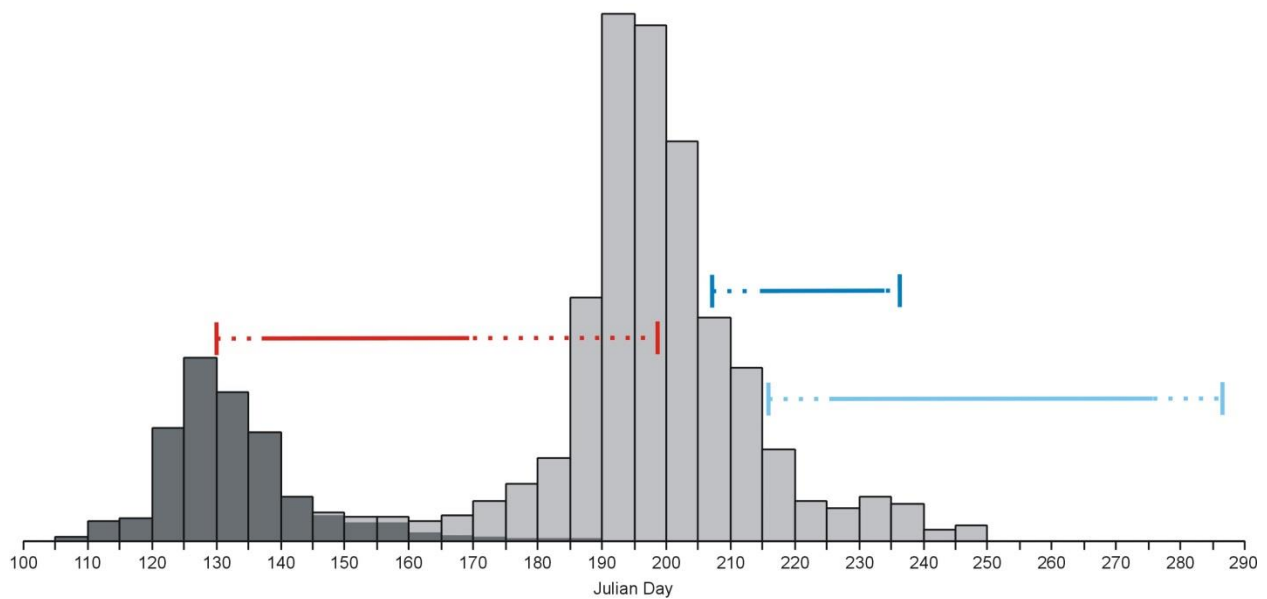


Figure 4-21: Frequency distribution of observed arrival dates of wild yearling smolts (dark shaded bars) and wild subyearlings (light shaded bars) at the estuary (Bonneville Dam) for wild fish tagged in the Columbia River or its tributaries upstream from the Snake River Confluence (release years 2004-2013). Horizontal solid and dotted lines represent the distribution of the interquartile and full range (respectively) of modeled arrival times for all donor stocks examined for the yearling (red), subyearling fry (dark blue) and subyearling smolt (light blue) emigration strategies.

4.3.2 Suitability analysis

Output of the suitability analysis is visually represented for each donor stock in a report card (Figure 4-22 to Figure 4-33), which shows the output of the suitability analysis, as well as a Gantt chart that describes the life cycle timing, as calculated by the life cycle model. In each report card, descriptions for the underlying reasons are provided where a donor stock may have received a poor (red or orange) score for any suitability criteria examined.

Report card for: **Wells Hatchery**

		Donor stock suitability criteria											Harvest, combined total for adults	Body fat content for adult migration	Spill operation for juvenile migration	Dissolved gas
Lifecycle stage	Reach	Spawn Timing	Emergence - food availability	Emergence - thermal suitability for growth	Generalized thermal suitability for life stage	Substrate suitability	Flood disturbance to eggs	Watered channel throughout lifecycle	Predation risk							
									Pinnipeds	Avian	Piscivores					
Adult (immigration)	Estuary				Yellow			Green	Yellow			Orange			Green	
Adult (immigration)	River															
Adult (immigration)	Reservoir															
Adult (immigration)	Reintroduction reach												Yellow			
Adult (spawning)	Reintroduction reach	Green			Green	Grey		Green								
Egg (incubation)	Reintroduction reach				Green		Green	Yellow								
Alevin (emergence)	Reintroduction reach		Green	Green	Green			Green								
Age 0 fry (emigration)	Reintroduction reach				Yellow			Green			Green				Green	
Age 0 fry (emigration)	Reservoir				Green						Yellow					
Age 0 fry (emigration)	River				Yellow					Yellow	Orange					
Age 0 fry (emigration)	Estuary				Orange						Green	Orange				
Age 0 fry (rearing)	Reintroduction reach				Green						Yellow					
Age 0 smolt (emigration)	Reservoir				Yellow			Green			Orange				Green	
Age 0 smolt (emigration)	River				Orange					Green	Orange					
Age 0 smolt (emigration)	Estuary				Yellow						Green	Orange				
Age 0 fry (fry emigration to reservoir)	Reintroduction reach				Yellow						Green					
Age 1 smolt (rearing)	Reservoir				Green			Green			Yellow				Green	
Age 1 smolt (emigration in year 2)	River									Yellow	Green					
Age 1 smolt (emigration in year 2)	Estuary										Yellow					

Key, donor stock suitability: ■ unsuitable ■ low ■ moderate ■ high ■ no data N/A to stage or reach

Explanation of low suitability scores:

Thermal
Subyearling emigration strategies migrate downstream through the sytem during summer months when temperatures are stressful

Predation
Subyearlings are exposed to high predation risk during their summer emigration period in the river corridor and arrival at the estuary

Harvest
This stock has brood yr exploitation rates of >50%

Spill
Subyearling smolts are still migrating in the month of September, after the columbia spill operation has ceased

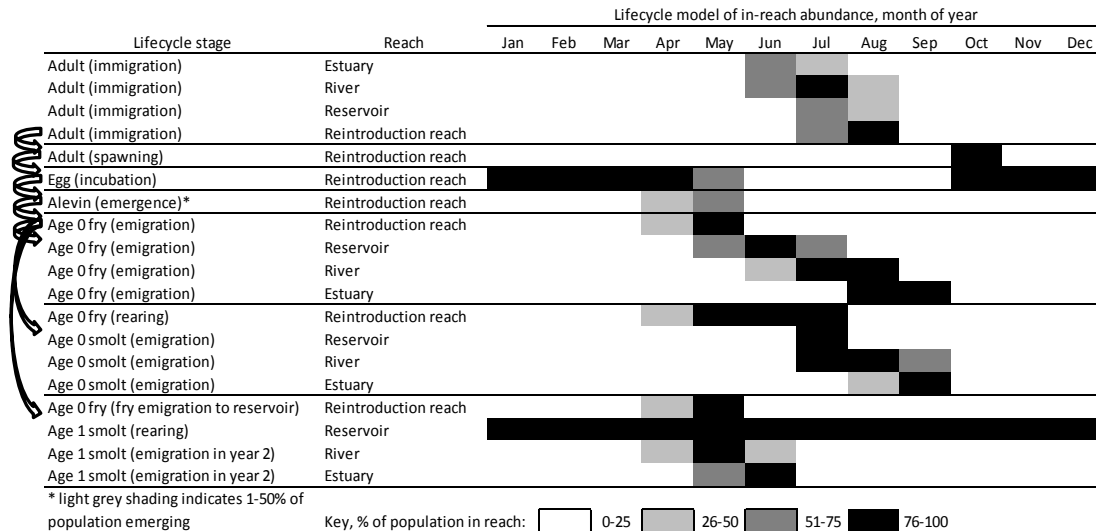


Figure 4-22: Life cycle model results (Gantt chart) and report card of suitability analysis results for the Wells Hatchery Summer-Fall donor stock.

Report card for: **Wenatchee Summer-Fall**

		Donor stock suitability criteria											Harvest, combined total for adults	Body fat content for adult migration	Spill operation for juvenile migration	Dissolved gas
Lifecycle stage	Reach	Spawn Timing	Emergence - food availability	Emergence - thermal suitability for growth	Generalized thermal suitability for life stage	Substrate suitability	Flood disturbance to eggs	Watered channel throughout lifecycle	Predation risk							
									Pinnipeds	Avian	Piscivores					
Adult (immigration)	Estuary															
Adult (immigration)	River															
Adult (immigration)	Reservoir															
Adult (immigration)	Reintroduction reach															
Adult (spawning)	Reintroduction reach															
Embryo (incubation)	Reintroduction reach															
Alevin (emergence)	Reintroduction reach															
Age 0 fry (emigration)	Reintroduction reach															
Age 0 fry (emigration)	Reservoir															
Age 0 fry (emigration)	River															
Age 0 fry (emigration)	Estuary															
Age 0 fry (rearing)	Reintroduction reach															
Age 0 smolt (emigration)	Reservoir															
Age 0 smolt (emigration)	River															
Age 0 smolt (emigration)	Estuary															
Age 0 fry (fry emigration to reservoir)	Reintroduction reach															
Age 1 smolt (rearing)	Reservoir															
Age 1 smolt (emigration in year 2)	River															
Age 1 smolt (emigration in year 2)	Estuary															

Key, donor stock suitability: ■ unsuitable ■ low ■ moderate ■ high ■ no data N/A to stage or reach

Explanation of low suitability scores:

Thermal
Adults hold through warm summer months; Subyearling emigration strategies migrate downstream through the system during summer months when temperatures are stressful

Predation
Subyearlings are exposed to high predation risk during their summer emigration period in the river corridor and arrival at the estuary

Harvest
This stock has exploitation rates of >50%

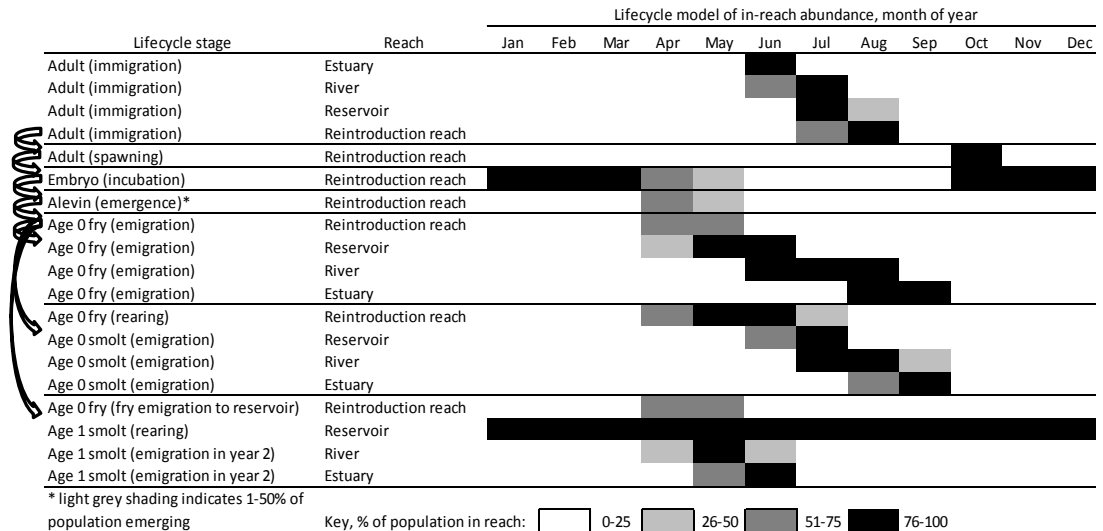
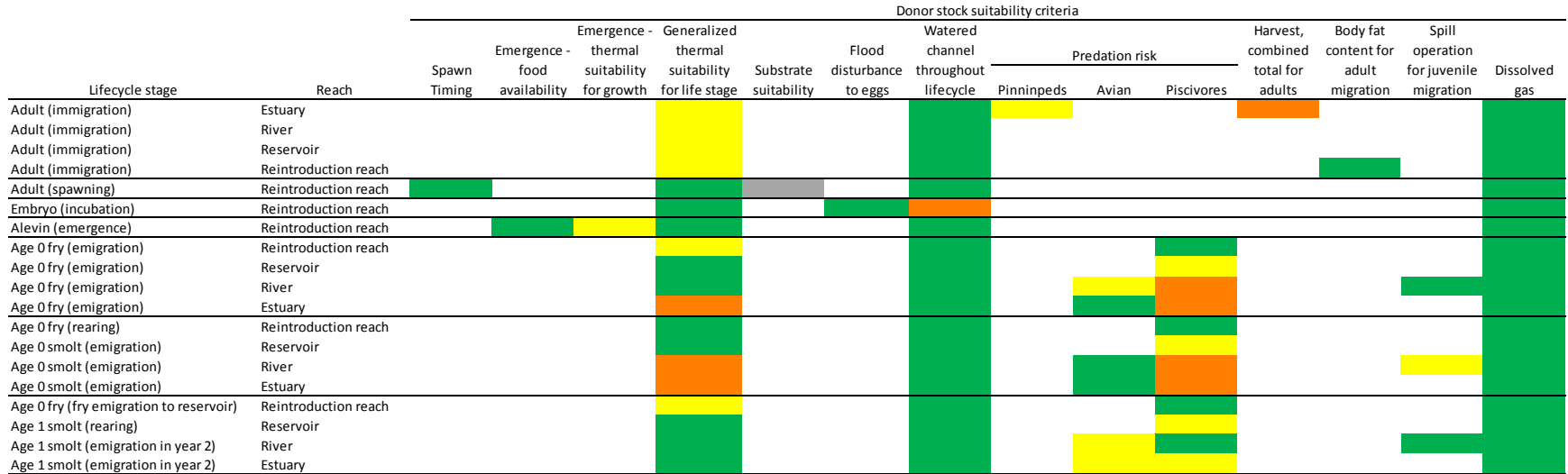


Figure 4-23: Life cycle model results (Gantt chart) and report card of suitability analysis results for the Wenatchee Summer-Fall donor stock

Report card for: **Methow Summer-Fall**



Key, donor stock suitability: ■ unsuitable ■ low ■ moderate ■ high ■ no data N/A to stage or reach

Explanation of low suitability scores:

Thermal
Adults hold through warm summer months; Subyearling emigration strategies migrate downstream through the system during summer months when temperatures are stressful

Watered channel
This population has a high risk of redd dewatering through the egg incubation period

Predation
Subyearlings are exposed to high predation risk during their summer emigration period in the river

Harvest
This stock has brood yr exploitation rates of >50%

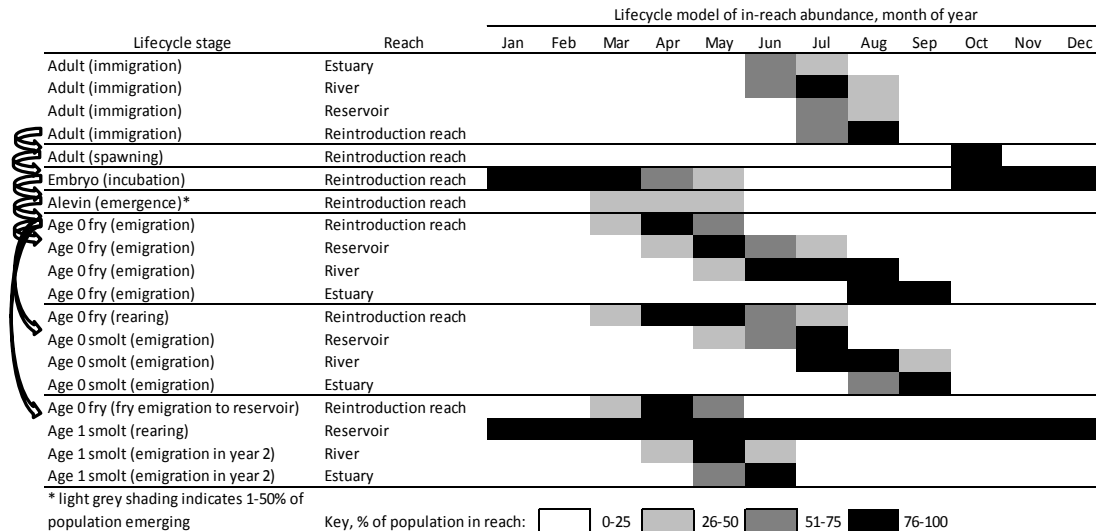
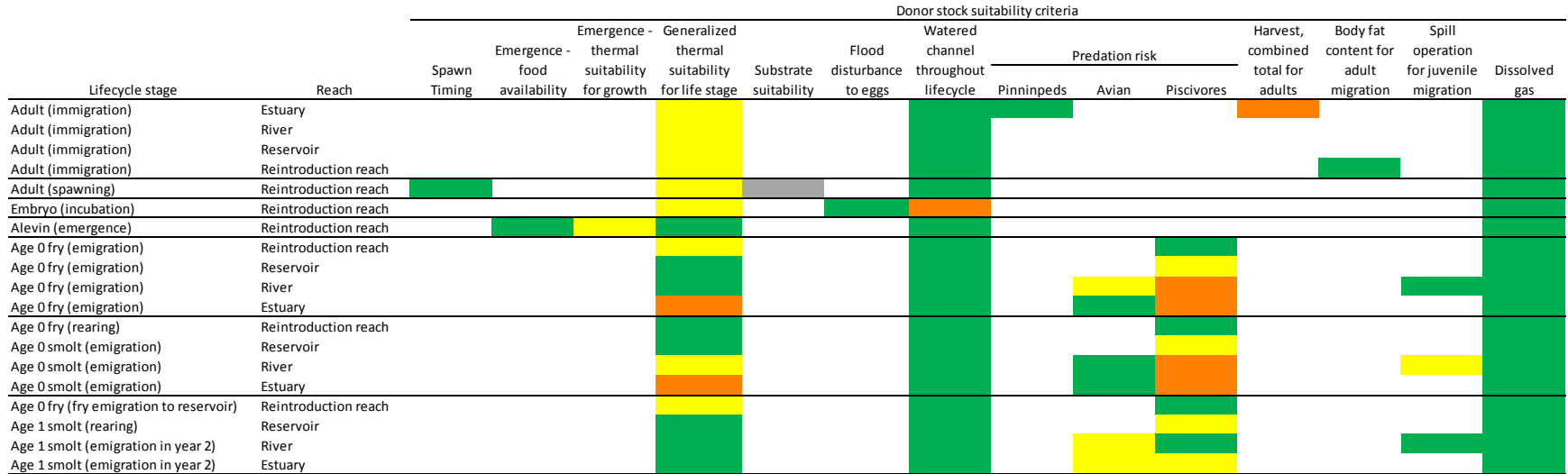


Figure 4-24: Life cycle model results (Gantt chart) and report card of suitability analysis results for the Methow Summer-Fall donor stock

Report card for: **Okanogan Summer-Fall**



Key, donor stock suitability: ■ unsuitable ■ low ■ moderate ■ high ■ no data N/A to stage or reach

Explanation of low suitability scores:

Thermal
Adults hold through warm summer months; Subyearling emigration strategies migrate downstream through the system during summer months when temperatures are stressful

Watered channel
This population has a high risk of redd dewatering through the egg incubation period

Predation
Subyearlings are exposed to high predation risk during their summer emigration period in the river

Harvest
This stock has brood yr exploitation rates of >50%

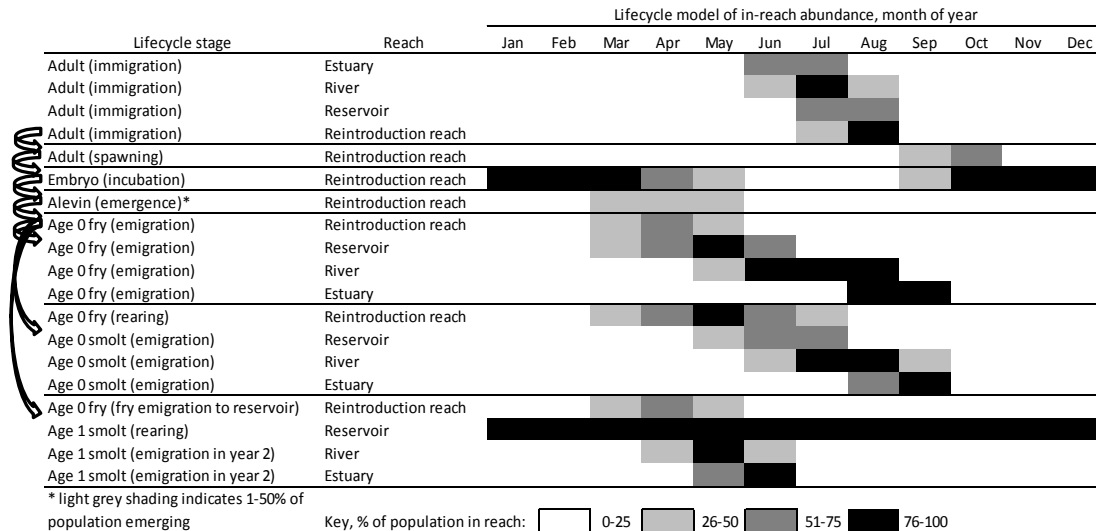


Figure 4-25: Life cycle model results (Gantt chart) and report card of suitability analysis results for the Okanogan Summer-Fall donor stock

Report card for: **Hanford Reach Fall**

		Donor stock suitability criteria													
Lifecycle stage	Reach	Spawn Timing	Emergence - food availability	Emergence - thermal suitability for growth	Generalized thermal suitability for life stage	Substrate suitability	Flood disturbance to eggs	Watered channel throughout lifecycle	Predation risk			Harvest, combined total for adults	Body fat content for adult migration	Spill operation for juvenile migration	Dissolved gas
									Pinnipeds	Avian	Piscivores				
Adult (immigration)	Estuary				Red			Green	Green			Orange			Green
Adult (immigration)	River				Yellow			Green							Green
Adult (immigration)	Reservoir				Yellow			Green							Green
Adult (immigration)	Reintroduction reach				Green			Green					Yellow		Green
Adult (spawning)	Reintroduction reach	Green			Green	Grey		Green							Green
Embryo (incubation)	Reintroduction reach				Green		Green	Green							Green
Alevin (emergence)	Reintroduction reach		Green		Green			Green							Green
Age 0 fry (emigration)	Reintroduction reach				Green			Green							Green
Age 0 fry (emigration)	Reservoir				Green			Green							Green
Age 0 fry (emigration)	River				Yellow			Green							Green
Age 0 fry (emigration)	Estuary				Orange			Green		Green		Orange		Green	Green
Age 0 fry (rearing)	Reintroduction reach				Green			Green							Green
Age 0 smolt (emigration)	Reservoir				Yellow			Green							Green
Age 0 smolt (emigration)	River				Yellow			Green		Green		Orange		Red	Green
Age 0 smolt (emigration)	Estuary				Green			Green		Green		Orange			Green
Age 0 fry (fry emigration to reservoir)	Reintroduction reach				Green			Green							Green
Age 1 smolt (rearing)	Reservoir				Green			Green							Green
Age 1 smolt (emigration in year 2)	River				Green			Green		Yellow				Green	Green
Age 1 smolt (emigration in year 2)	Estuary				Green			Green		Yellow		Green			Green

Key, donor stock suitability: ■ unsuitable ■ low ■ moderate ■ high no data N/A to stage or reach

Explanation of low suitability scores:

Thermal
Adults immigrate to the estuary during the late summer, potentially encountering thermal migration barriers; subyearling emigration strategies migrate downstream through the system during summer months when temperatures are stressful

Predation
Subyearlings are exposed to high predation risk during their summer emigration period in the river

Harvest
This stock has brood yr exploitation rates of >50%

Spill
Subyearling smolts are still migrating in the month of September, after the Columbia spill operation has ceased

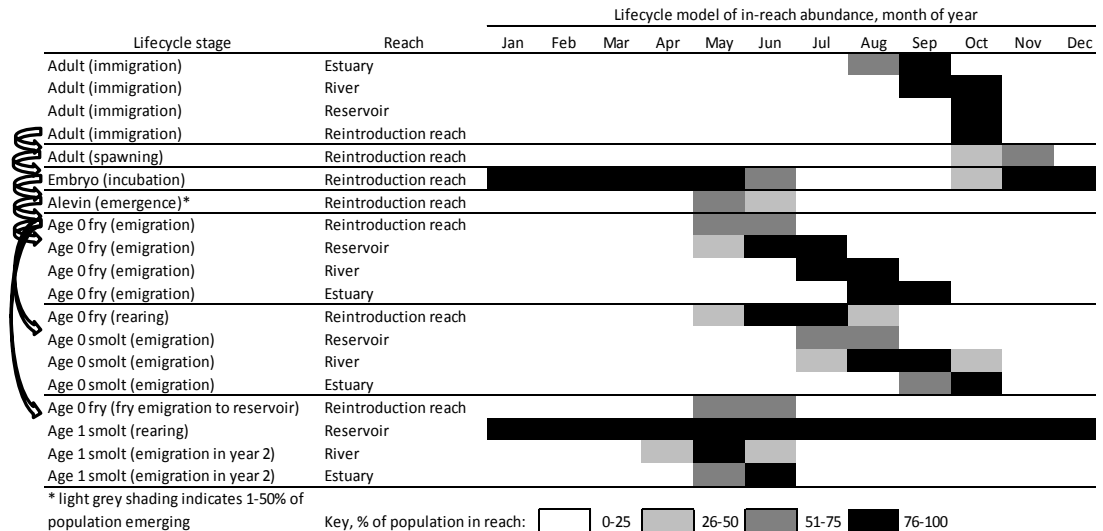


Figure 4-26: Life cycle model results (Gantt chart) and report card of suitability analysis results for the Hanford Reach Fall donor stock

Report card for: **Snake River Fall**

		Donor stock suitability criteria											Harvest, combined total for adults	Body fat content for adult migration	Spill operation for juvenile migration	Dissolved gas
Lifecycle stage	Reach	Spawn Timing	Emergence - food availability	Emergence - thermal suitability for growth	Generalized thermal suitability for life stage	Substrate suitability	Flood disturbance to eggs	Watered channel throughout lifecycle	Predation risk							
									Pinnipeds	Avian	Piscivores					
Adult (immigration)	Estuary															
Adult (immigration)	River															
Adult (immigration)	Reservoir															
Adult (immigration)	Reintroduction reach															
Adult (spawning)	Reintroduction reach															
Embryo (incubation)	Reintroduction reach															
Alevin (emergence)	Reintroduction reach															
Age 0 fry (emigration)	Reintroduction reach															
Age 0 fry (emigration)	Reservoir															
Age 0 fry (emigration)	River															
Age 0 fry (emigration)	Estuary															
Age 0 fry (rearing)	Reintroduction reach															
Age 0 smolt (emigration)	Reservoir															
Age 0 smolt (emigration)	River															
Age 0 smolt (emigration)	Estuary															
Age 0 fry (fry emigration to reservoir)	Reintroduction reach															
Age 1 smolt (rearing)	Reservoir															
Age 1 smolt (emigration in year 2)	River															
Age 1 smolt (emigration in year 2)	Estuary															

Key, donor stock suitability: ■ unsuitable ■ low ■ moderate ■ high no data N/A to stage or reach

Explanation of low suitability scores:

Thermal
Adults immigrate to the estuary during the late summer, potentially encountering thermal migration barriers; subyearling emigration strategies migrate downstream through the system during summer months when temperatures are stressful

Predation
Subyearlings are exposed to high predation risk during their summer emigration period in the river

Spill
Subyearling smolts are still migrating in the month of September, after the Columbia spill operation has ceased

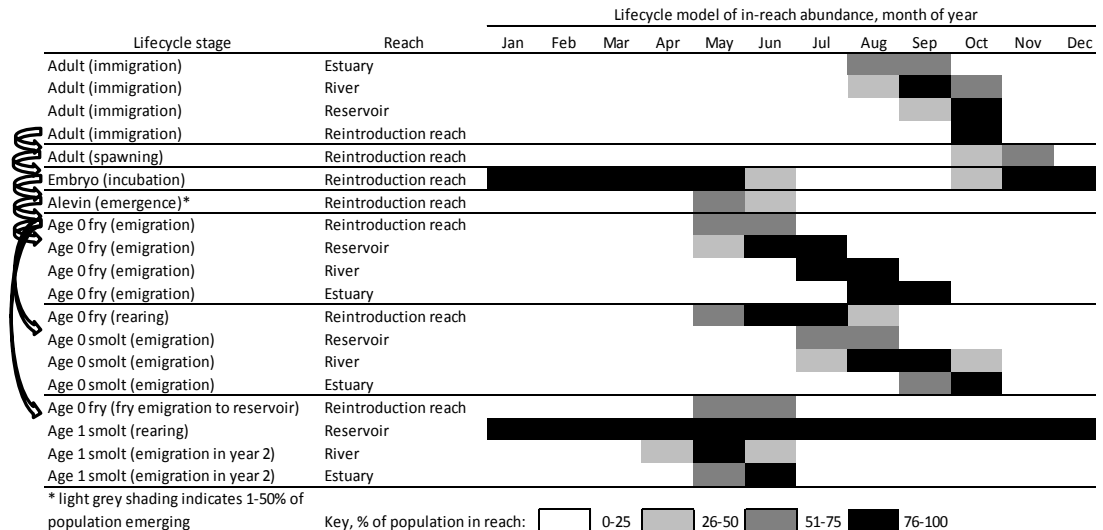
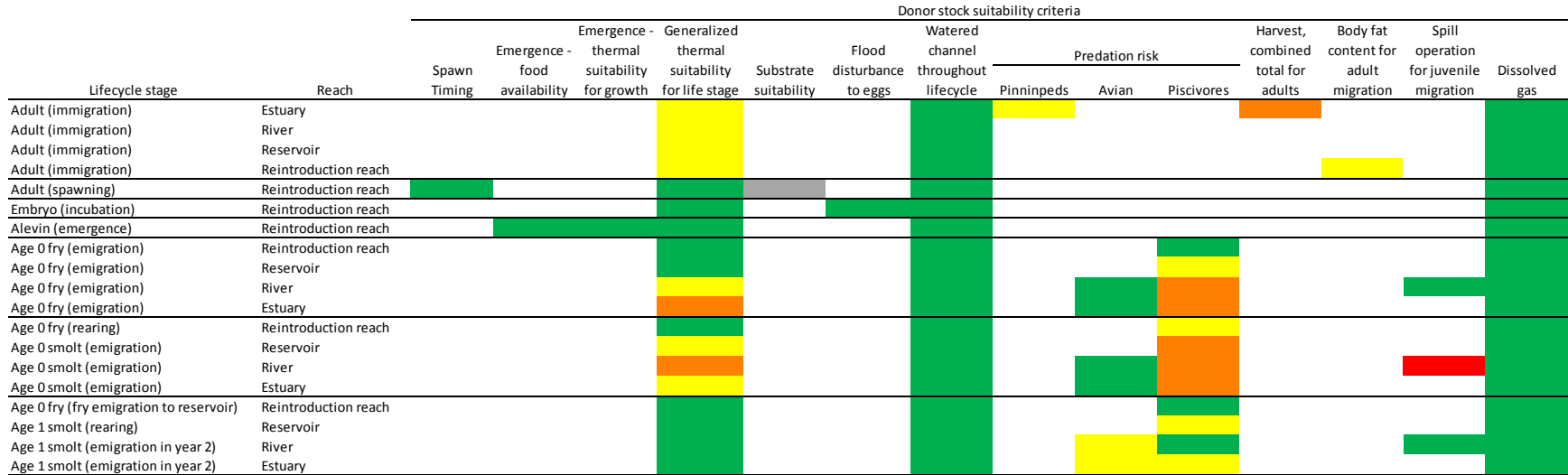


Figure 4-27: Life cycle model results (Gantt chart) and report card of suitability analysis results for the Snake River Fall donor stock

Report card for: Upper Columbia Mainstem Summer-Fall



Key, donor stock suitability: ■ unsuitable ■ low ■ moderate ■ high no data N/A to stage or reach

Explanation of low suitability scores:

Thermal
Adults hold through warm summer months; Subyearling emigration strategies migrate downstream through the system during summer months when temperatures are stressful

Predation
Subyearlings are exposed to high predation risk during their summer emigration period in the river

Harvest
This stock has brood yr exploitation rates of >50%

Spill
Subyearling smolts are still migrating in the month of September, after the Columbia spill operation has ceased

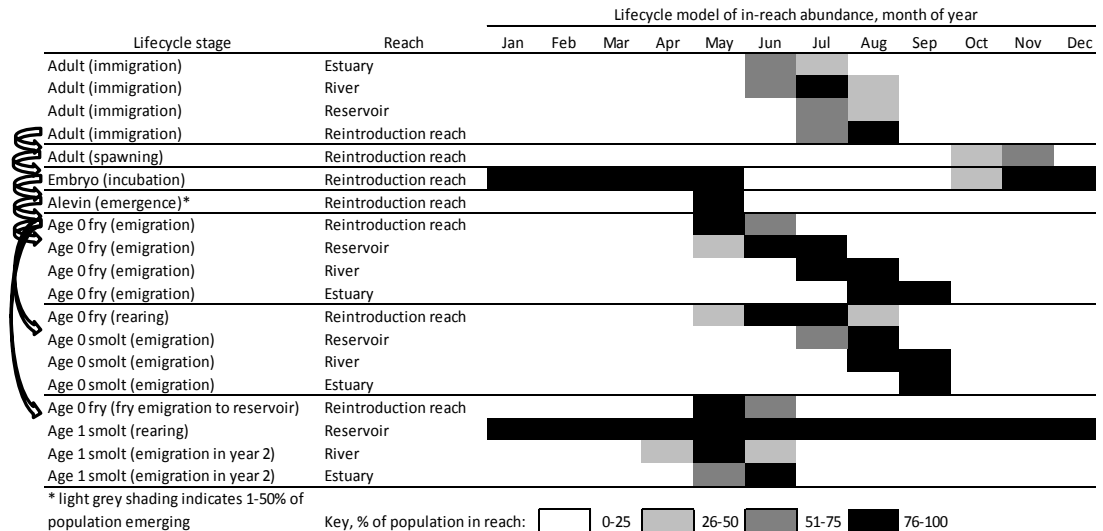


Figure 4-28: Life cycle model results (Gantt chart) and report card of suitability analysis results for the Upper Columbia Mainstem Summer-Fall donor stock

Report card for:

Wenatchee Spring

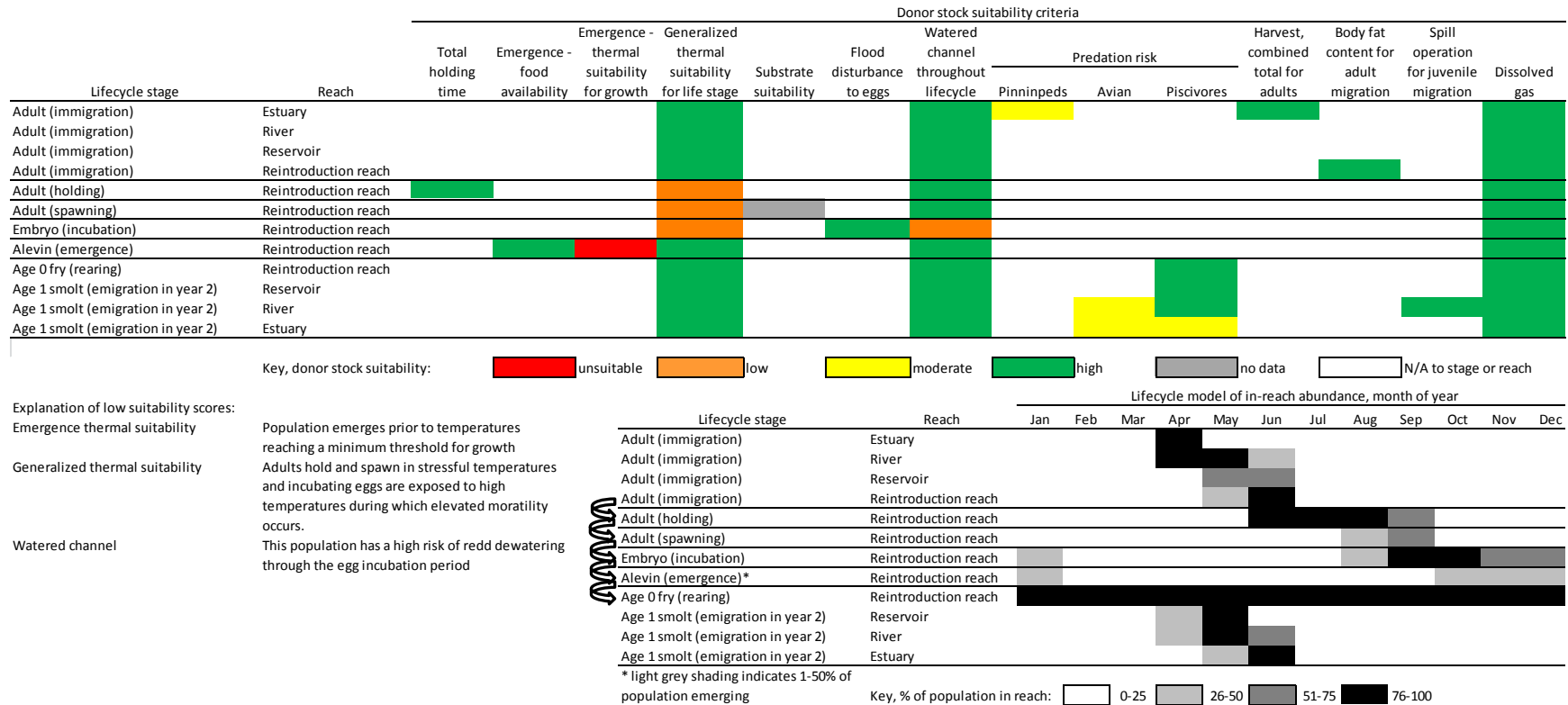


Figure 4-29: Life cycle model results (Gantt chart) and report card of suitability analysis results for the Wenatchee Spring donor stock

Report card for: **Methow Spring**

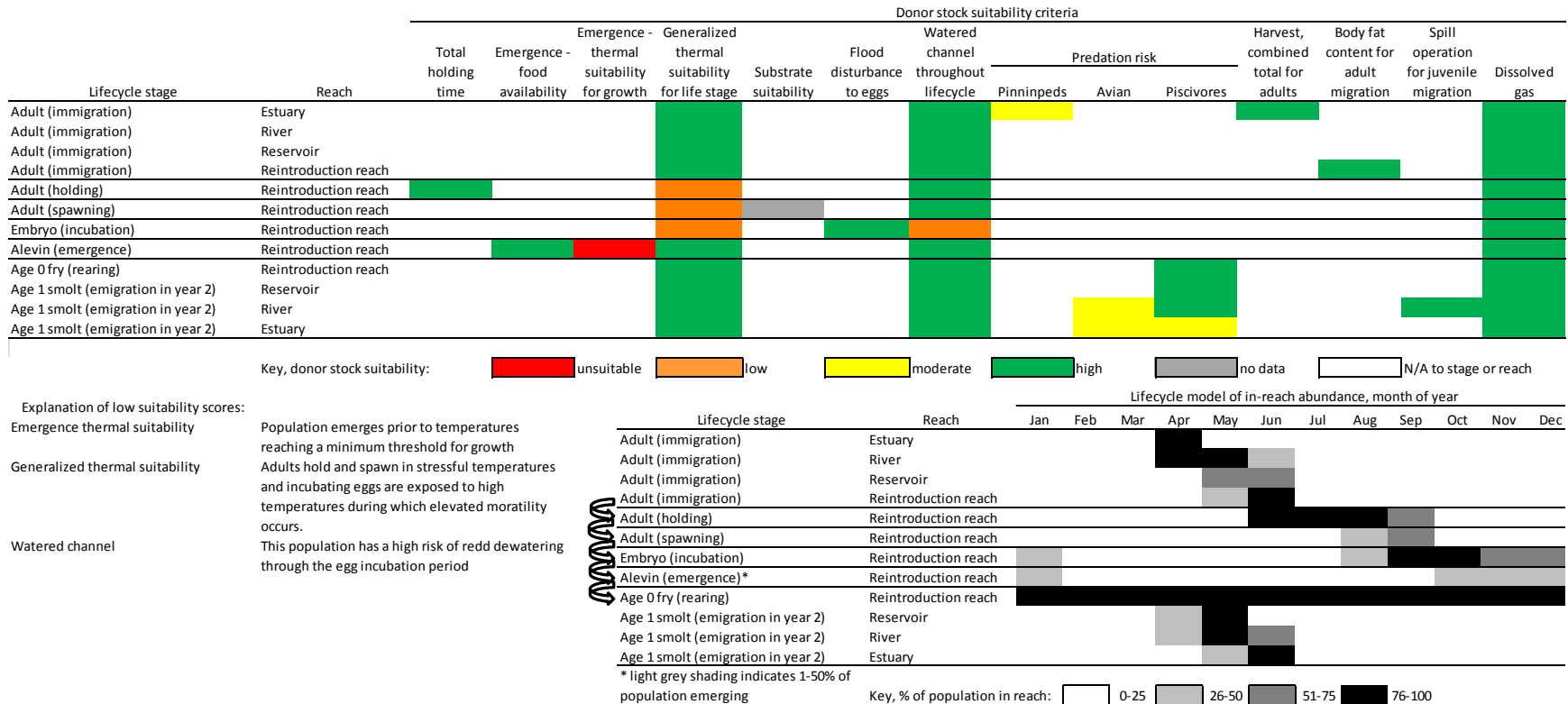


Figure 4-30: Life cycle model results (Gantt chart) and report card of suitability analysis results for the Methow Spring donor stock

Report card for: **Yakima Spring**

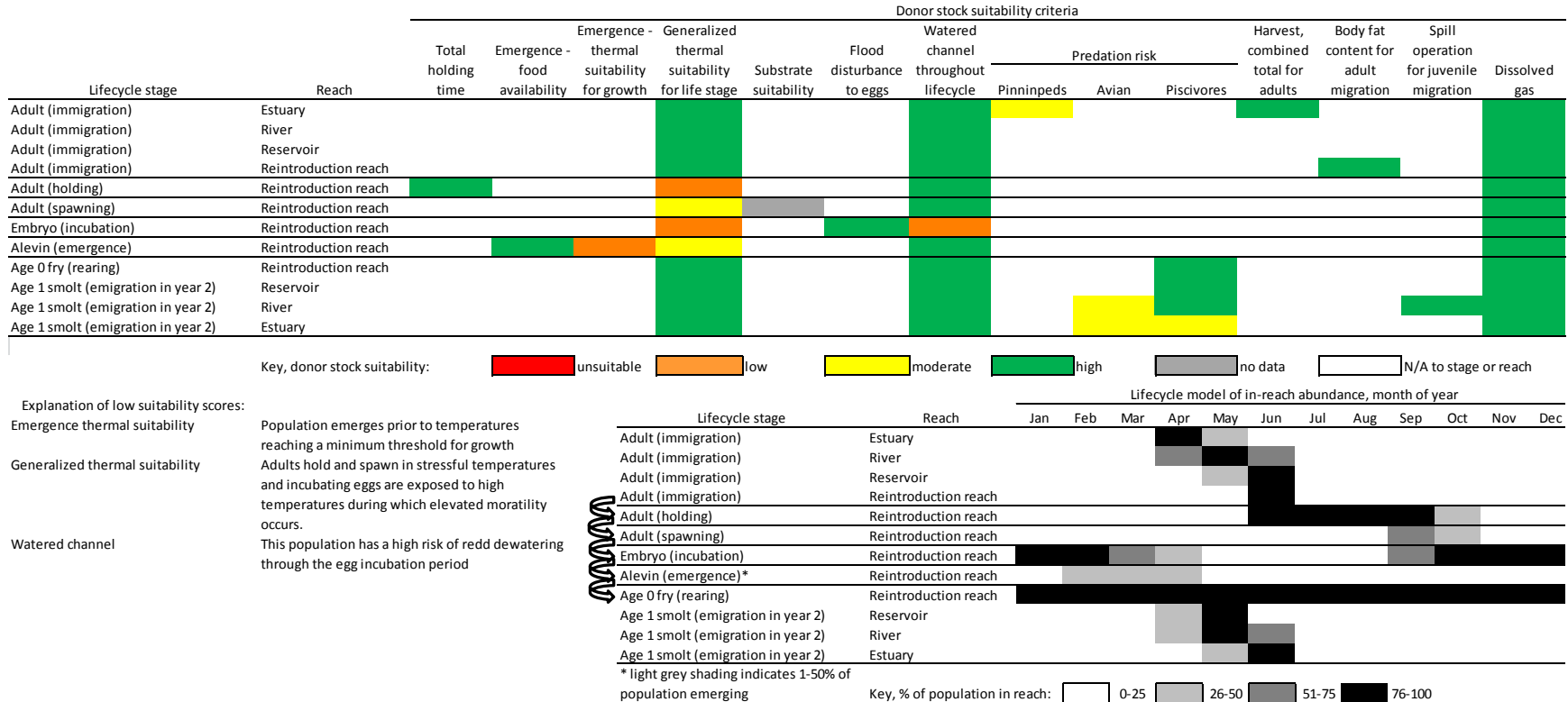


Figure 4-31: Life cycle model results (Gantt chart) and report card of suitability analysis results for the Yakima Spring donor stock

Report card for: **Carson Spring**

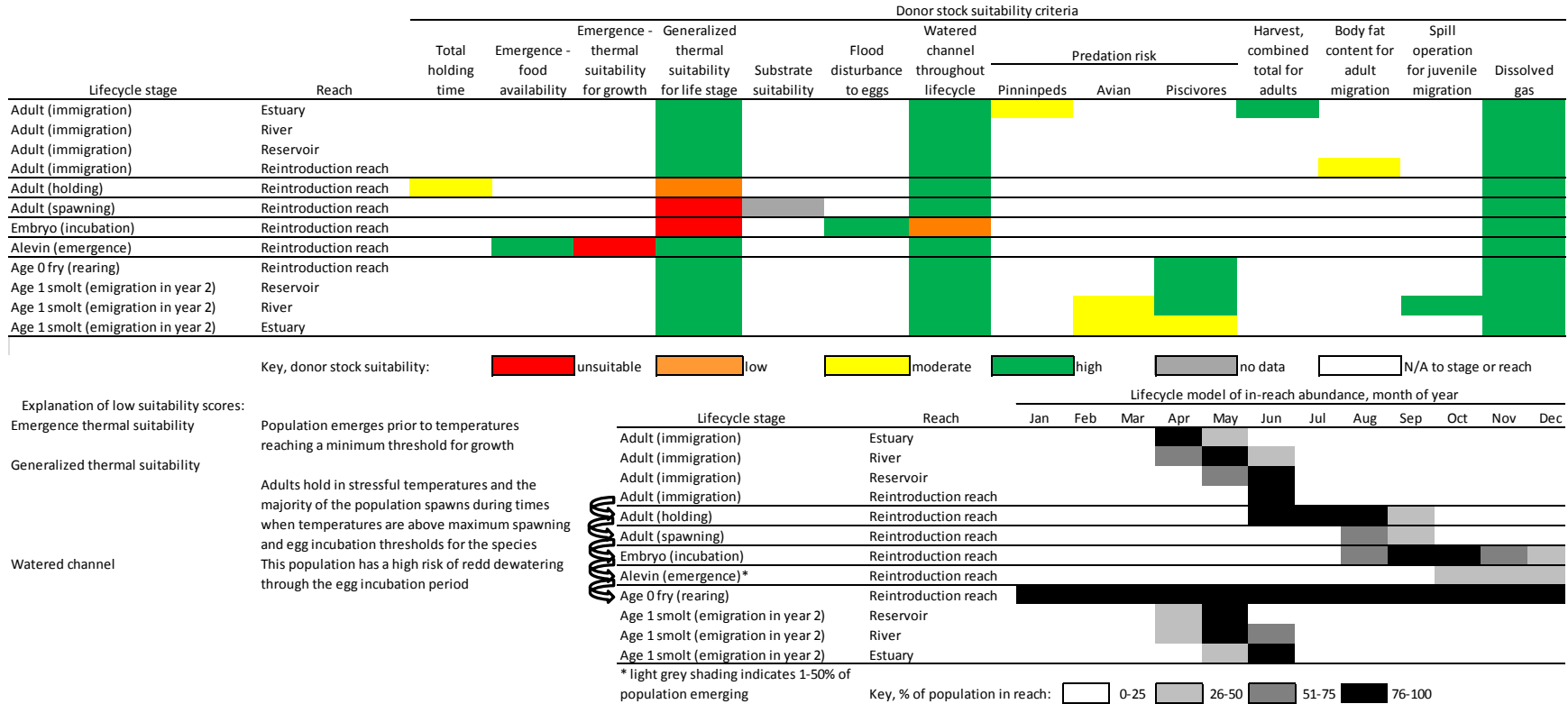


Figure 4-32: Life cycle model results (Gantt chart) and report card of suitability analysis results for the Carson Spring donor stock

Report card for:

South Fork Salmon Spring-Summer

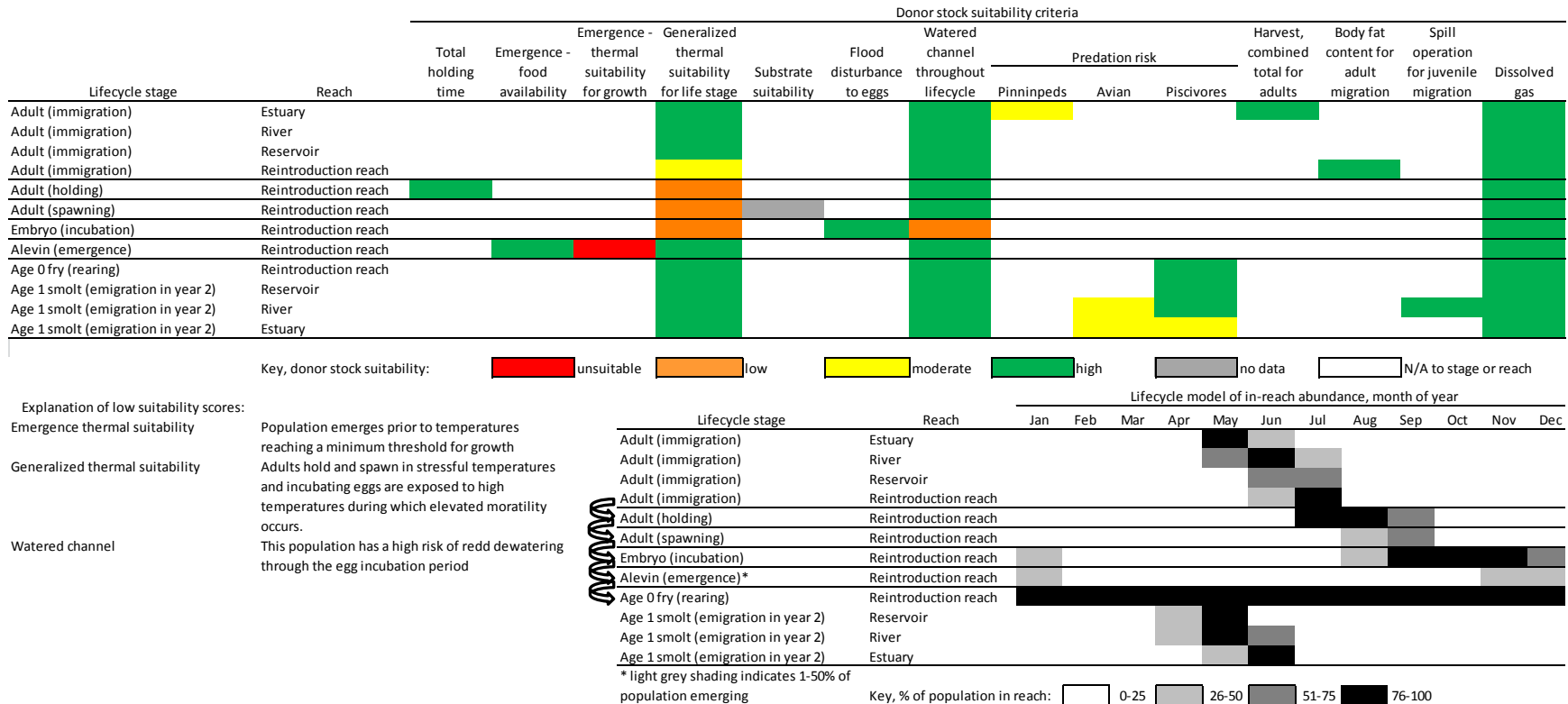


Figure 4-33: Life cycle model results (Gantt chart) and report card of suitability analysis results for the South Fork Salmon Spring donor stock



In order to illustrate the relative suitability of donor stocks, we display the scores by life cycle stage. The averaged suitability within a reach was created along the red-green color spectrum, to derive the rank of each donor stock. Comparative suitability tables are displayed below (Figure 4-34 to Figure 4-45).

Report Card for adult (immigration) lifecycle stage

Rank (within reach)	Stock	Life history	Suitability criteria						Averaged suitability (within reach)
			Generalized thermal suitability	Watered channel	Predation (pinneps)	Harvest	Body fat content for migration	Dissolved gas	
Reach: Estuary									
1	Wenatchee Spring	Spring							
1	Methow Spring	Spring							
1	Carson Spring	Spring							
1	Yakima Spring	Spring							
1	South Fork Salmon Spring-Summer	Spring							
2	Okanogan Summer-Fall	Summer-Fall							
3	Wells Hatchery	Summer-Fall							
3	Wenatchee Summer-Fall	Summer-Fall							
3	Methow Summer-Fall	Summer-Fall							
3	Upper Columbia Mainstem SF	Summer-Fall							
3	Snake River Fall	Summer-Fall							
4	Hanford Reach Fall	Summer-Fall							
Reach: River									
1	Wenatchee Spring	Spring							
1	Methow Spring	Spring							
1	Carson Spring	Spring							
1	Yakima Spring	Spring							
1	South Fork Salmon Spring-Summer	Spring							
2	Wells Hatchery	Summer-Fall							
2	Wenatchee Summer-Fall	Summer-Fall							
2	Methow Summer-Fall	Summer-Fall							
2	Okanogan Summer-Fall	Summer-Fall							
2	Hanford Reach Fall	Summer-Fall							
2	Snake River Fall	Summer-Fall							
2	Upper Columbia Mainstem SF	Summer-Fall							

Key, suitability: Less suitable  More suitable  No data  N/A to reach 

Figure 4-34: Comparative suitability of stocks according to suitability criteria scored during adult immigration in the Estuary and River Reaches. Pinniped predation was assumed to only occur in the Estuary. Note that the suitability criteria of harvest is displayed only in the estuary, but this includes total aggregate harvest of adults in the ocean, estuary and river (i.e., total harvest through adult life cycle stage), and is shown for simplicity.



Report Card for adult (immigration) lifecycle stage

Rank (within reach)	Stock	Life history	Suitability criteria					Averaged suitability (within reach)
			Generalized thermal suitability	Watered channel	Predation (pinnepeds)	Harvest	Body fat content for migration	
Reach: Reservoir								
1	Wenatchee Spring	Spring						
1	Methow Spring	Spring						
1	Carson Spring	Spring						
1	Yakima Spring	Spring						
1	South Fork Salmon Spring-Summer	Spring						
2	Wells Hatchery	Summer-Fall						
2	Wenatchee Summer-Fall	Summer-Fall						
2	Methow Summer-Fall	Summer-Fall						
2	Okanogan Summer-Fall	Summer-Fall						
2	Hanford Reach Fall	Summer-Fall						
2	Snake River Fall	Summer-Fall						
2	Upper Columbia Mainstem SF	Summer-Fall						
Reach: Reintroduction reach								
1	Wenatchee Spring	Spring						
1	Methow Spring	Spring						
1	Yakima Spring	Spring						
1	Snake River Fall	Summer-Fall						
2	Carson Spring	Spring						
2	South Fork Salmon Spring-Summer	Spring						
2	Wenatchee Summer-Fall	Summer-Fall						
2	Methow Summer-Fall	Summer-Fall						
2	Okanogan Summer-Fall	Summer-Fall						
2	Hanford Reach Fall	Summer-Fall						
3	Wells Hatchery	Summer-Fall						
3	Upper Columbia Mainstem SF	Summer-Fall						

Key, suitability: Less suitable  More suitable  No data  N/A to reach 

Figure 4-35: Comparative suitability of stocks according to suitability criteria scored during adult immigration in the Reservoir and Reintroduction Reaches. Note that the suitability criterion of body fat content for migration is displayed only in the Reintroduction Reach, as this is the ultimate location of migration.



Report Card for adult (holding) lifecycle stage

Rank (within reach)	Stock	Life history	Suitability criteria				Averaged suitability (within reach)
			Total holding time	Generalized thermal suitability	Watered channel	Dissolved gas	
Reach: Reintroduction reach							
N/A	Hanford Reach Fall	Summer-Fall					
N/A	Snake River Fall	Summer-Fall					
N/A	Wells Hatchery	Summer-Fall					
N/A	Wenatchee Summer-Fall	Summer-Fall					
N/A	Methow Summer-Fall	Summer-Fall					
N/A	Okanogan Summer-Fall	Summer-Fall					
N/A	Upper Columbia Mainstem SF	Summer-Fall					
1	Wenatchee Spring	Spring					
1	Methow Spring	Spring					
1	Yakima Spring	Spring					
1	South Fork Salmon Spring-Summer	Spring					
2	Carson Spring	Spring					

Key, suitability: Less suitable More suitable No data N/A to life history

Figure 4-36: Comparative suitability of stocks according to suitability criteria scored during adult holding in the Reintroduction Reach.

Report Card for adult (spawning) lifecycle stage

Rank (within reach)	Stock	Life history	Suitability criteria					Averaged suitability (within reach)
			Spawn Timing	Generalized thermal suitability	Substrate	Watered channel	Dissolved gas	
Reach: Reintroduction reach								
1	Wells Hatchery	Summer-Fall						
1	Wenatchee Summer-Fall	Summer-Fall						
1	Methow Summer-Fall	Summer-Fall						
1	Hanford Reach Fall	Summer-Fall						
1	Snake River Fall	Summer-Fall						
1	Upper Columbia Mainstem SF	Summer-Fall						
2	Okanogan Summer-Fall	Summer-Fall						
2	Yakima Spring	Spring						
3	Wenatchee Spring	Spring						
3	Methow Spring	Spring						
3	South Fork Salmon Spring-Summer	Spring						
4	Carson Spring	Spring						

Key, suitability: Less suitable More suitable No data N/A to life history

Figure 4-37: Comparative suitability of stocks according to suitability criteria scored during adult spawning in the Reintroduction Reach. Spawn timing only applied to Summer-Fall life histories, as the analogous suitability criterion was scored under total holding time for Spring life histories.



Report Card for embryo (incubation) lifecycle stage

Rank (within reach)	Stock	Life history	Suitability criteria				Averaged suitability (within reach)
			Generalized thermal suitability	Flood disturbance	Watered channel (redd dewatering)	Dissolved gas	
Reach: Reintroduction reach							
1	Hanford Reach Fall	Summer-Fall					
1	Snake River Fall	Summer-Fall					
1	Upper Columbia Mainstem SF	Summer-Fall					
2	Wells Hatchery	Summer-Fall					
2	Wenatchee Summer-Fall	Summer-Fall					
3	Methow Summer-Fall	Summer-Fall					
4	Okanogan Summer-Fall	Summer-Fall					
5	Wenatchee Spring	Spring					
5	Methow Spring	Spring					
5	Yakima Spring	Spring					
5	South Fork Salmon Spring-Summer	Spring					
6	Carson Spring	Spring					

Key, suitability:

Less suitable

More suitable

No data

N/A to life history

Figure 4-38: Comparative suitability of stocks according to suitability criteria scored during embryo incubation in the Reintroduction Reach.

Report Card for alevin (emergence) lifecycle stage

Rank (within reach)	Stock	Life history	Suitability criteria					Averaged suitability (within reach)
			Food availability	Thermal suitability - initial growth	Generalized thermal suitability	Watered channel	Dissolved gas	
Reach: Reintroduction reach								
1	Wells Hatchery	Summer-Fall						
1	Hanford Reach Fall	Summer-Fall						
1	Snake River Fall	Summer-Fall						
1	Upper Columbia Mainstem SF	Summer-Fall						
2	Wenatchee Summer-Fall	Summer-Fall						
2	Methow Summer-Fall	Summer-Fall						
2	Okanogan Summer-Fall	Summer-Fall						
3	Yakima Spring	Spring						
3	Wenatchee Spring	Spring						
3	Methow Spring	Spring						
3	Carson Spring	Spring						
3	South Fork Salmon Spring-Summer	Spring						

Key, suitability:

Less suitable

More suitable

No data

N/A to life history

Figure 4-39: Comparative suitability of stocks according to suitability criteria scored during emergence in the Reintroduction Reach



Report Card for juvenile lifecycle stage, age 0 fry emigration strategy

			Suitability criteria						
Rank (within reach)	Stock	Life history	Generalized thermal suitability	Watered channel	Predation (avian)	Predation (piscivores)	Spill operations for passage	Dissolved gas	Averaged suitability (within reach)
Reach: Reintroduction reach									
N/A	Wenatchee Spring	Spring							
N/A	Methow Spring	Spring							
N/A	Carson Spring	Spring							
N/A	Yakima Spring	Spring							
N/A	South Fork Salmon Spring-Summer	Spring							
1	Hanford Reach Fall	Summer-Fall							
1	Snake River Fall	Summer-Fall							
1	Upper Columbia Mainstem SF	Summer-Fall							
2	Wells Hatchery	Summer-Fall							
2	Wenatchee Summer-Fall	Summer-Fall							
2	Methow Summer-Fall	Summer-Fall							
2	Okanogan Summer-Fall	Summer-Fall							
Reach: Reservoir									
N/A	Wenatchee Spring	Spring							
N/A	Methow Spring	Spring							
N/A	Carson Spring	Spring							
N/A	Yakima Spring	Spring							
N/A	South Fork Salmon Spring-Summer	Spring							
1	Wenatchee Summer-Fall	Summer-Fall							
1	Okanogan Summer-Fall	Summer-Fall							
2	Wells Hatchery	Summer-Fall							
2	Methow Summer-Fall	Summer-Fall							
2	Hanford Reach Fall	Summer-Fall							
2	Snake River Fall	Summer-Fall							
2	Upper Columbia Mainstem SF	Summer-Fall							

Key, suitability:

Less suitable

More suitable

No data

N/A to reach or life history

Figure 4-40: Comparative suitability of stocks according to suitability criteria scored during juvenile emigration in the Reservoir and Reintroduction Reaches for the subyearling fry life history strategy.



Report Card for juvenile lifecycle stage, age 0 fry emigration strategy

Rank (within reach)	Stock	Life history	Suitability criteria						Averaged suitability (within reach)
			Generalized thermal suitability	Watered channel	Predation (avian)	Predation (piscivores)	Spill operations for passage	Dissolved gas	
Reach: River									
N/A	Wenatchee Spring	Spring							
N/A	Methow Spring	Spring							
N/A	Carson Spring	Spring							
N/A	Yakima Spring	Spring							
N/A	South Fork Salmon Spring-Summer	Spring							
1	Wenatchee Summer-Fall	Summer-Fall							
1	Methow Summer-Fall	Summer-Fall							
1	Okanogan Summer-Fall	Summer-Fall							
1	Hanford Reach Fall	Summer-Fall							
1	Snake River Fall	Summer-Fall							
1	Upper Columbia Mainstem SF	Summer-Fall							
2	Wells Hatchery	Summer-Fall							
Reach: Estuary									
N/A	Wenatchee Spring	Spring							
N/A	Methow Spring	Spring							
N/A	Carson Spring	Spring							
N/A	Yakima Spring	Spring							
N/A	South Fork Salmon Spring-Summer	Spring							
1	Wells Hatchery	Summer-Fall							
1	Wenatchee Summer-Fall	Summer-Fall							
1	Methow Summer-Fall	Summer-Fall							
1	Okanogan Summer-Fall	Summer-Fall							
1	Hanford Reach Fall	Summer-Fall							
1	Snake River Fall	Summer-Fall							
1	Upper Columbia Mainstem SF	Summer-Fall							

Key, suitability:

Less suitable

More suitable

No data

N/A to reach





Key, suitability: Less suitable  More suitable  No data  N/A to reach or life history 

Figure 4-41: Comparative suitability of stocks according to suitability criteria scored during juvenile emigration in the River and Estuary Reaches for the subyearling fry life history strategy. Note that the suitability criterion for spill operations is displayed only in the River Reach, as spill operations are mostly conducted within this reach to aid juvenile passage. Avian predation was applied to both the River and Estuary reaches, but not in the Reintroduction or Reservoir Reaches.



Report Card for juvenile lifecycle stage, age 0 smolt emigration strategy

Rank (within reach)	Stock	Life history	Suitability criteria						Averaged suitability (within reach)
			Generalized thermal suitability	Watered channel	Predation (avian)	Predation (piscivores)	Spill operations for passage	Dissolved gas	
Reach: Reintroduction reach									
N/A	Wenatchee Spring	Spring							
N/A	Methow Spring	Spring							
N/A	Carson Spring	Spring							
N/A	Yakima Spring	Spring							
N/A	South Fork Salmon Spring-Summer	Spring							
1	Wenatchee Summer-Fall	Summer-Fall							
1	Methow Summer-Fall	Summer-Fall							
1	Okanogan Summer-Fall	Summer-Fall							
2	Wells Hatchery	Summer-Fall							
2	Hanford Reach Fall	Summer-Fall							
2	Snake River Fall	Summer-Fall							
2	Upper Columbia Mainstem SF	Summer-Fall							
Reach: Reservoir									
N/A	Wenatchee Spring	Spring							
N/A	Methow Spring	Spring							
N/A	Carson Spring	Spring							
N/A	Yakima Spring	Spring							
N/A	South Fork Salmon Spring-Summer	Spring							
1	Methow Summer-Fall	Summer-Fall							
1	Okanogan Summer-Fall	Summer-Fall							
2	Wenatchee Summer-Fall	Summer-Fall							
3	Wells Hatchery	Summer-Fall							
3	Hanford Reach Fall	Summer-Fall							
3	Snake River Fall	Summer-Fall							
3	Upper Columbia Mainstem SF	Summer-Fall							

Key, suitability:

Less suitable

More suitable

No data

N/A to reach or life history

Figure 4-42: Comparative suitability of stocks according to suitability criteria scored during juvenile emigration in the Reservoir and Reintroduction Reaches for the subyearling smolt life history strategy.



Report Card for juvenile lifecycle stage, age 0 smolt emigration strategy

Rank (within reach)	Stock	Life history	Suitability criteria						Averaged suitability (within reach)
			Generalized thermal suitability	Watered channel	Predation (avian)	Predation (piscivores)	Spill operations for passage	Dissolved gas	
Reach: River									
N/A	Wenatchee Spring	Spring							
N/A	Methow Spring	Spring							
N/A	Carson Spring	Spring							
N/A	Yakima Spring	Spring							
N/A	South Fork Salmon Spring-Summer	Spring							
1	Okanogan Summer-Fall	Summer-Fall							
2	Wenatchee Summer-Fall	Summer-Fall							
2	Methow Summer-Fall	Summer-Fall							
3	Wells Hatchery	Summer-Fall							
3	Hanford Reach Fall	Summer-Fall							
3	Snake River Fall	Summer-Fall							
4	Upper Columbia Mainstem SF	Summer-Fall							
Reach: Estuary									
N/A	Wenatchee Spring	Spring							
N/A	Methow Spring	Spring							
N/A	Carson Spring	Spring							
N/A	Yakima Spring	Spring							
N/A	South Fork Salmon Spring-Summer	Spring							
1	Hanford Reach Fall	Summer-Fall							
1	Snake River Fall	Summer-Fall							
2	Wells Hatchery	Summer-Fall							
2	Upper Columbia Mainstem SF	Summer-Fall							
3	Wenatchee Summer-Fall	Summer-Fall							
3	Methow Summer-Fall	Summer-Fall							
3	Okanogan Summer-Fall	Summer-Fall							

Key, suitability:

Less suitable

More suitable

No data

N/A to reach

Key, suitability: Less suitable More suitable No data N/A to reach or life history

Figure 4-43: Comparative suitability of stocks according to suitability criteria scored during juvenile emigration in the River and Estuary Reaches for the subyearling smolt life history strategy. Note that the suitability criterion for spill operations is displayed only in the River Reach, as spill operations are mostly conducted within this reach to aid juvenile passage. Avian predation was applied to both the River and Estuary reaches, but not in the Reintroduction or Reservoir Reaches



Report Card for juvenile lifecycle stage, age 1 smolt emigration strategy

Rank (within reach)	Stock	Life history	Suitability criteria					Averaged suitability (within reach)
			Generalized thermal suitability	Watered channel	Predation (avian)	Predation (piscivores)	Spill operations for passage	
Reach: Reintroduction reach								
1	Wenatchee Spring	Spring						
1	Methow Spring	Spring						
1	Carson Spring	Spring						
1	Yakima Spring	Spring						
1	South Fork Salmon Spring-Summer	Spring						
1	Hanford Reach Fall	Summer-Fall						
1	Snake River Fall	Summer-Fall						
1	Upper Columbia Mainstem SF	Summer-Fall						
2	Wells Hatchery	Summer-Fall						
2	Wenatchee Summer-Fall	Summer-Fall						
2	Methow Summer-Fall	Summer-Fall						
2	Okanogan Summer-Fall	Summer-Fall						
Reach: Reservoir								
1	Wenatchee Spring	Spring						
1	Methow Spring	Spring						
1	Carson Spring	Spring						
1	Yakima Spring	Spring						
1	South Fork Salmon Spring-Summer	Spring						
2	Wells Hatchery	Summer-Fall						
2	Wenatchee Summer-Fall	Summer-Fall						
2	Methow Summer-Fall	Summer-Fall						
2	Okanogan Summer-Fall	Summer-Fall						
2	Hanford Reach Fall	Summer-Fall						
2	Snake River Fall	Summer-Fall						
2	Upper Columbia Mainstem SF	Summer-Fall						






Key, suitability: Less suitable    More suitable  No data  N/A to reach or life history

Figure 4-44: Comparative suitability of stocks according to suitability criteria scored during juvenile emigration in the Reservoir and Reintroduction Reaches for the yearling smolt life history strategy.



Report Card for juvenile lifecycle stage, age 1 smolt emigration strategy

Rank (within reach)	Stock	Life history	Suitability criteria					Averaged suitability (within reach)
			Generalized thermal suitability	Watered channel	Predation (avian)	Predation (piscivores)	Spill operations for passage	
Reach: River								
1	Wenatchee Spring	Spring						
1	Methow Spring	Spring						
1	Carson Spring	Spring						
1	Yakima Spring	Spring						
1	South Fork Salmon Spring-Summer	Spring						
1	Wells Hatchery	Summer-Fall						
1	Wenatchee Summer-Fall	Summer-Fall						
1	Methow Summer-Fall	Summer-Fall						
1	Okanogan Summer-Fall	Summer-Fall						
1	Hanford Reach Fall	Summer-Fall						
1	Snake River Fall	Summer-Fall						
1	Upper Columbia Mainstem SF	Summer-Fall						
Reach: Estuary								
1	Wenatchee Spring	Spring						
1	Methow Spring	Spring						
1	Carson Spring	Spring						
1	Yakima Spring	Spring						
1	South Fork Salmon Spring-Summer	Spring						
1	Wells Hatchery	Summer-Fall						
1	Wenatchee Summer-Fall	Summer-Fall						
1	Methow Summer-Fall	Summer-Fall						
1	Okanogan Summer-Fall	Summer-Fall						
1	Hanford Reach Fall	Summer-Fall						
1	Snake River Fall	Summer-Fall						
1	Upper Columbia Mainstem SF	Summer-Fall						






Key, suitability: Less suitable    More suitable  No data  N/A to reach or life history

Figure 4-45: Comparative suitability of stocks according to suitability criteria scored during juvenile emigration in the River and Estuary Reaches for the yearling smolt life history strategy. Note that the suitability criterion for spill operations is displayed only in the River Reach, as spill operations are mostly conducted within this reach to aid juvenile passage. Avian predation was applied to both the River and Estuary reaches, but not in the Reintroduction or Reservoir Reaches



4.4 **Discussion**

This study involved modeling the predicted life cycle of each donor stock in freshwater if introduced to the Transboundary Reach, and determined the suitability of each donor stock according to several criteria that were assumed to influence their survival. Examining suitability by life cycle stage indicated that stocks were often segregated into groups with similar suitability, and this generally conformed to their generalized life history (Spring or Summer-Fall run). In general, the earlier migration and spawn timing of donor stocks that are from the Spring run life history appear to result in premature arrival and spawn timings that may expose them to incompatibilities with the thermal and flow regime of the Transboundary Reach. The underlying life history model and suitability analysis were crude tools to objectively and accurately predict small differences in survival between donor stocks. Thus, the analysis did not appear to be a tool that can confidently resolve suitability differences at the individual stock level in most cases, but did suggest there will be differences of generalized life history types.

This evaluation was useful in highlighting the data necessary to perform reintroduction studies and has provided a better understanding of the complexity of the study site, migration corridor, physical and environmental parameters that salmon depend upon, prey populations, and predator populations. When data sources were not available, we made assumptions and applied functional relationships as were deemed appropriate.

4.4.1 **Life cycle timing**

Donor stocks selected in this analysis express a diversity of possible timing of life cycle events the species could display in the Transboundary Reach and in other locations throughout their lifecycle. The timing of these events was critical in scoring of stocks in the subsequent suitability analysis for most criteria assessed. The overarching goal of this assessment is to help to select a stock (or at least generalized life history type) that will be able to adapt to the reintroduction environment with the highest success in the quickest amount of generations, and thus, the goal would be to give relatively *higher* scores for stocks that would have to modify their life cycle components *less*. The two critical life cycle components where life cycle timing was assumed to be retained in the first generation (Ricker 1972) were immigration and spawn timing, which have a strongly heritable basis (Quinn 2005). This is not to say that we don't expect there to be variation around the spawning date immediately due to phenotypic plasticity, or over time due to evolution. In fact, quite the opposite - we expect there to be some plasticity in the first generation, given the common practice of hatcheries to manipulate spawn timing by altering environmental conditions (Flagg and Mahnken 1995). However, the extent which phenotypic plasticity affects timing traits is poorly understood in salmonids, and studies such as this which model responses in timing to environmental changes have not been able to practically consider them (Reed et al. 2011) As a part a complex system, spawn timing is also expected to rapidly evolve in a novel environment given sufficient adaptive variation for spawn timing to be selected upon in the donor stock (Smoker et al. 1998, Quinn et al. 2000), and through this evaluation we hope to reduce the amount of time this takes through selecting a stock that will require the littlest amount of adaptation.



Some populations may have a greater variation in timing than our model was able to utilize, and these components of the population can be selected for or against. Therefore, although some populations may have relatively narrow migration and spawn timings they are adapted to, others may have greater natural variability of these heritable traits and thus may offer greater variation for selection in the natural environment. This aspect of heritable variation for adaptation to the receiving was not accounted for in our analysis, but has important implications for selecting donor stocks for reintroduction (section 3.4.2; Houde 2015).

Immigration, holding and spawn timing

Spring run stocks immigrated early to the Reintroduction Reach, held for extended periods, and spawned earlier than Summer-Fall run, predominantly from early August through September. Spawn timing of Summer-Fall stocks generally mirrored the same sequence of run timing; Summer run stocks tended to spawn slightly earlier (predominantly October) than Fall run stocks (predominantly November).

The only significant outlier from their respective life history timings (Spring, Summer or Fall run) in these life cycle stages occurred in the Carson and Yakima Spring run donor stocks. The Carson donor stock spawned particularly early (August) and the much longer migration in this donor stock relative to its assumed natal habitat resulted in a reduction of holding time. The Yakima donor stock spawned later than most other Spring run donor stocks examined. These two donor stocks, occupying opposite ends of the spectrum in the variation in spawn timing for Spring Run stocks had clear implications in subsequent suitability analysis, as the later spawning stock from the Yakima scored higher due to its spawn timing alignment to more thermally suitable periods in the Transboundary Reach (further discussion in section 4.4.2)

Assumptions were made that immigration would occur at the same stock-specific rate in reaches upstream from Chief Joseph Dam, even though Chinook Salmon migration rates have not been measured in this environment. Since these reaches are primarily slow moving, low residence time reservoirs, it is likely that upstream movement would in fact be rapid (Keefer et al. 2004b), and thus our estimate may be biased to estimate timing of arrival as slightly later than would be the case. We also assumed seamless passage at Chief Joseph and Grand Coulee Dams (i.e., they would pass these dams at the same rate they pass downstream dams), since passage has not yet been investigated at these projects.

Holding was assumed to only occur for Spring Run donor stocks, as these populations exhibit premature migration, completing sexual maturation in freshwater prior to spawning (Quinn et al. In Press). While this was the basis for subsequent suitability analysis in these stocks, it was assumed that all Summer-Fall run donor stocks would immigrate in an advanced state of maturity, and would thus be insensitive to conditions in the holding environment. Nevertheless, some stocks of this life history that migrate earlier (i.e., all Summer run stocks) arrive at spawning grounds well in advance of spawn dates, and thus would have to hold regardless for a period of time. Although these stocks were not considered in the holding



portion of the suitability analysis (see discussion in section 4.4.2 for implications to suitability), they do express characteristics of premature migration and thus our analysis likely oversimplifies their life history. Fall run donor stocks, in contrast, immigrated to spawning areas shortly in advance to their spawning distributions.

Incubation and emergence timing

Emergence timing was highly variable and protracted. Spring run donor stocks that spawn in August or September do so at high temperatures which may result in rapid initial accumulation of thermal units. This places these donor stocks in a developmental trajectory that results in modeled emergence timings in the mid-fall (October) to winter (January) period. The Yakima Spring donor stock had a later spawn timing than is typical for its life history, and thus had emergence times that spanned the late winter period. Summer-Fall donor stocks typically emerged in late winter through spring the following year, with Summer run stocks emerging first and Fall run donor stocks emerging last.

All emergence times were calculated by the underlying developmental models of Beer and Anderson (1997) and Beer (1999); however, the only input into the model we used was the spawn timing and thermal regime of the Norns Creek Fan. Variation in temperatures at other possible spawning locations in the Transboundary Reach were not considered, nor were other growth parameter inputs such as egg size, which may vary between populations and may affect developmental rates (Beer and Anderson 2001). Thus, we expect the modeled emergence times to be an approximation of possible emergence times and not capture the full range of variation that is possible for the reintroduced population.

Rearing, emigration and estuary arrival timing

Juvenile life cycle modeling returned results that clearly separated life cycle timings of the three presumed emigration strategies. Yearling smolts were estimated to have the swiftest migration rates and reach the estuary first. Subyearling smolts were estimated to emigrate at slightly higher rates than subyearling fry emigrants, but the latter reached the estuary first, as their earlier emigration timing was predicted to compensate for their slower travel rates. Thus, subyearling smolt life histories are modeled to arrive at the estuary quite late relative to wild populations (Figure 4-21). In resolving differences between donor stocks, the model did not suggest major life cycle timing differences in yearling and subyearling fry emigration strategies. The model did, however, suggest that stocks which have late hatch timings (i.e., Fall run or predominantly November spawners) would have especially delayed arrival times in the subyearling smolt strategy, as they are predicted to still be emigrating in the Columbia River far upstream from Bonneville dam after spill operations have ceased in the FCRPS. Despite these relatively intuitive results, Juvenile life cycle timing was modeled based on strong assumptions which are discussed throughout this section. Thus, as we project forward into juvenile life histories, our uncertainty increases, suggesting further caution in interpreting results of the life cycle model for juveniles and suitability analysis on which it depends.



The timing component of emigration and immigration are based on a number of assumptions, and migration rates were estimated for areas that do not currently have anadromous fish (Reservoir and Reintroduction Reaches). Thus, without information to suggest otherwise, we applied a constant migration rate based on those observed in the lower river, although Lake Roosevelt in particular is long and is a slower moving section of water. In addition, passage (either upstream for adults or downstream for juveniles) around dams is not accounted for in any way that assumes a different passage rate than those in the River Reach (where salmon already pass multiple dams). The rate of downstream movements is especially uncertain for subyearlings, as emigration rate is largely influenced by flow (Smith et al. 2003), and underlying base data for calculating subyearling fry emigration rates were of much smaller sample size due to tag burden limitations in small fish. It is possible that emigrating subyearling fry (or smolts for that matter) would not attain the migration rates that were applied in our model and we suggest that our calculated rates may be upwardly biased. Another limitation in our analysis is that we could not develop unbiased estimates of stock-specific emigration rates or timings. Instead, we used data from many wild populations to develop a generalized rate of migration specific to the life history, and timing was either standardized (for yearlings) or dependent on hatch time (for subyearlings). The model did suggest that hatch time may disproportionately influence life cycle timing for subyearling smolts, which may have profound influence over driving survival during emigration. For the other life history strategies, donor stock differences in timing in general were relatively minimal and probably underestimate the unpredictable differences that would be present due to other heritable traits or environmental factors that influence emigration (Bourret et al. 2016). A clear direction for early experimental work would be to determine emigration timing and rate for juveniles in the Transboundary Reach and through Lake Roosevelt.

Juvenile rearing strategies were assumed to be fixed for Spring run donor stocks, as smolt to adult survival is not observed for any strategy other than yearling emigration (Waples et al. 2004). While some stocks of the Spring run life history may express subyearling emigration, the pathway that results in survival to adulthood is presumably no longer viable in the contemporary environment of the interior Columbia River Basin (Copeland and Venditti 2009). Thus in Spring run donor stocks, rearing occurring for an entire growing season (perhaps into their second year, depending on emergence timing), and emigration commenced after this year of growth, the following spring. We did assume that emigration timing would be fixed, according to generalized outmigration timing in the spring of the second year, and initiated from rearing environments in the Transboundary Reach. However, it is also important to recognize that emigration timing may vary and rearing location may extend into tributaries or downstream rearing locations (Copeland et al. 2014) and thus our model is a simplification of the possible pathways that Spring run yearling smolts may express. Summer-Fall run stocks were modeled with more flexibility in juvenile life history strategy.

We modeled some flexibility in juvenile emigration strategy for Summer-Fall life histories, but our model was still based on an assumption of rigidly defined life history pathways (e.g. fry, subyearling, yearling). Juvenile life history strategies in Chinook Salmon are most accurately thought of as a continuum, with multiple pathways of rearing and migration through the variety of possible habitats available in freshwater between the natal environment and the ocean (Bourret et al. 2016). Transitions between



developmental stages can potentially occur anywhere along this spatio-temporal continuum. Juveniles have a variety of mainstem and reservoir habitats and tributaries available to them preceding their spring emigration in the second year of life, so it is reasonable to assume that some flexibility in habitat use during the first year of life may occur (Copeland et al. 2014). For example, it is possible that transitions to downstream environments may occur in the first year of life, resulting in a staging for emigration in early spring the following year several hundred km downstream from natal areas of fry emergence (Healey 1991). In this case, modeled downstream travel may underestimate the diversity that the population may express since we made the assumption of a very specific pathway of emigration from the Transboundary Reach, during a generalized spring timeframe. Summer-Fall run stocks were similarly modeled according to three presumed pathways of rearing and emigration, with specific timings and habitat use. Fry emigrants are perhaps the simplest to model, since the assumption for this pathway is that emigration occurs immediately, with rearing and transition to parr and smolt stages occurring as they emigrate downstream. Little is known about these life histories since they are difficult to include in biotelemetry studies due to bias of tagging larger individuals, but they may be a viable or dominant emigration strategy in some years for some populations (Miller et al. 2010). Subyearling smolt strategies were assumed to emigrate after rearing in proximity to natal environments for 60 days, although it should be noted that this is a gross oversimplification of the variety of diversity that may be present for location and timing of rearing that this emigration strategy may employ. Thus, similar to the discussion above, it might be assumed that our model does not take into account the full range of diversity present within this categorically defined strategy. Finally, the strategy of overwinter downstream reservoir rearing is a well demonstrated life history strategy in Summer-Fall run in the Snake River basin (Connor et al. 2005), and presumed to occur in upper Columbia basin Summer-Fall stocks as well (Brannon et al. 2004, CCT 2013). The pathway assumed for this life history type involves reservoir rearing, followed by emigration initiated from the Lake Roosevelt forebay at a specific time the following spring. As above, this defined pathway may not capture the full range of diversity present for this possible juvenile strategy.

A fundamental question that has been the focus of much literature examining match-mismatch hypotheses for Columbia River salmon is whether juveniles reach the estuary or beyond to the ocean plume in a biologically relevant timeframe (Scheuerell et al. 2009, Rechisky et al. 2012, Miller et al. 2014, Weitkamp et al. 2015). We did not formally consider this in the suitability analysis, but the timing of estuary arrival may be important for subsequent survival. Smolt migration timing occurs over a large natural range, and arrival at the estuary outside of the normal range of system-wide variability may have some survival disadvantage. Some studies have found that survival to adulthood markedly decreases for yearling smolts that reach the estuary (i.e., Bonneville Dam) late in the tail of the timing distribution in some years (Zabel and Williams 2002, Williams et al. 2005); later migrating individuals and entire stocks may thus incur a substantial fitness cost, relative to earlier migrating ones that have “optimized” ocean entry timing (Waples et al. 2008). For example, yearling Chinook Salmon smolts migrating in early to mid-May have 4-50 times greater survival (depending on the year) than those migrating in mid June (Scheuerell et al. 2009). In contrast, some studies have found that timing of ocean entry has weak support, relative to other factors that explain survival to adulthood for Spring run populations, and the effect is highly variable depending on year (Miller et al. 2014). For subyearling Chinook Salmon, the link



between estuary arrival timing, ocean arrival timing and survival to adulthood is even more opaque, and the current diversity of life history types and emigration strategies may be much reduced from historic patterns (Burke 2004, Weitkamp et al. 2015). Salmon of all life history types in this analysis were calculated to generally have later arrival times at the estuary, relative to wild populations (Figure 4-21), however, this result is not surprising given that we used generalized travel rates of populations that initiate their migrations further downstream, and several hundred kilometers are added to the length of their migration. The exact mechanisms driving variation in smolt to adult survival, linked to estuary arrival and ocean entry timing continue to be the topic of intense research and debate (Muir et al. 2006, Petrosky and Schaller 2010, Haeseker et al. 2012, Rechisky et al. 2012, Hilborn 2013). We hypothesize that ocean and estuary arrival timing are likely to be important factors that ultimately influence survival at later life cycle stages, and suggest that this hypothesis be carefully examined during initial stages of reintroduction and colonization of Chinook Salmon (see further discussion in section 4.4.3).

4.4.2 Suitability analysis of donor stocks

A suite of 12 suitability criteria were assessed to determine the suitability of each donor stock in the Reintroduction Reach and other freshwater environments occupied throughout the Chinook Salmon life cycle. Overall, there were general trends in suitability across the various lifecycle stages; closely related donor stocks that typified certain categorical life histories (e.g., Spring vs Summer vs Fall Chinook Salmon) tended to score similar to one another. This factor, in combination with above mentioned shortcomings in the model, lead us to recommend that the model be interpreted as suitability by life history type rather than by individual donor stock. When visually interpreting suitability scores by lifecycle stage (Figure 4-34 through Figure 4-45), scores for each donor stock were presented in an averaged and ranked manner. It should be noted that averaging is used for aiding interpretation and should not be interpreted as a strict indicator of relative suitability. Much of this is due to the fact that suitability criteria are not in any way, weighted to the influence each has over survival.

The following section is organized as a discussion of the results of each sequential life cycle stage that was examined, beginning with adult immigration and ending with juvenile emigration, and examining the criteria that appeared to significantly differentiate the suitability of generalized life history types. Suitability scores for specific donor stocks (as opposed to general differences in life history) are discussed in specific instances where a particular donor stock was an outlier from the scores that were associated with their life history. The discussion ends with a description of the general suitability criteria that did not appear to universally be important to the suitability of donor stocks, as well as a discussion of potential environmental mitigations relevant to the suitability of habitats or specific donor stock adaptations/life histories.



Adult Immigration

Suitability analysis identified some differences in stock suitability during adult immigration, particularly in the Estuary Reach, from where immigration is initiated, and the model indicated that earlier migrating stocks have higher suitability, primarily due to avoidance of high temperatures. Stocks that ran progressively later into the summer or early fall were identified as encountering potentially stressful or migrating blocking temperatures in the Estuary. This reflects perhaps overly penalizing suitability criteria for scoring generalized thermal requirements, as it indicates that extant stocks have issues with thermal blockages to migration, particularly fall run stocks. Fall Chinook Salmon in the Columbia and Snake Rivers do indeed encounter high temperatures during migration, but display behaviours that allow them to take advantages of thermal refuges to continue their migration upstream (Gonia et al. 2006, Keefer and Caudill 2015). It is reasonable to assume that any of these donor stocks would be able to use the same thermal refuges during their migration if they retain their ancestral immigration timing and rate. These stocks continue to produce the largest escapements of Chinook Salmon, thus our model has likely underestimated their suitability. Nevertheless, it is important to realize that migration blocking thresholds are reached in the Columbia River during the recent climate regime, and since these thresholds are being approached or surpassed, it is reasonable to assume that stocks migrating in the summer or early fall may face more severe thermal impediments with future climate change (Mantua et al. 2010, Dittmer 2013 and discussed further in section 4.4.3).

Harvest was included in this life cycle stage, and all stocks of the Summer-Fall life history were determined to encounter high harvest rates. The Snake River Fall donor stock appeared to have the lowest harvest rates of those assessed within this life history, but harvest was still significant. Since this life history uses ocean habitats near to the continental shelf and are more abundant, they are subject to higher harvest rates in both marine and estuary/river fisheries than Spring run (Healey 1991, PSC 2014a). Harvest may thus impede efforts to establish a self-sustaining population, so it is possible that there would need to be more involved discussion and international cooperation regarding escapement targets and setting harvest quotas for Summer-Fall rather than Spring run stocks (though both would require discussion regardless).

It is possible that all stocks will have sufficient energy reserves to undertake the longer migration required to immigrate to the Reintroduction Reach, although stocks that initiate immigration later and immigrate shorter distances to their ancestral spawning grounds (e.g., Hanford Reach Fall) are the least suitable in this regard. The Reintroduction Reach occupies a far-inland distance (~1250 km) approaching the limits of what extant populations of interior Columbia and Snake River populations currently migrate; however, elevation acts as a multiplier in determining the energy reserves and associated adaptations required for immigration (Quinn 2005). This reach does not occupy a significantly higher elevation (<430 m) than ancestral spawning grounds of many of the stocks assessed in this study, which ascend tributaries to reach spawning areas. Spring run stocks in particular generally had modeled or measured body fat contents that far exceeded the predicted anatomical need for the distance and elevation of the Reintroduction Reach. In addition, the slow moving reservoirs upstream from Chief



Joseph and Grand Coulee Dams are unlikely to be passed with great difficulty from an energetics perspective due to the low velocities encountered by migrating adults. In fact, it has been suggested that reservoirs created by large hydroelectric projects are more rapidly passed than the historic high velocity habitats that would have been present in the Columbia River, though passage difficulties at dams and high water temperatures may confound these advantages (Keefer et al. 2004b). The historic migration route would have included high velocity habitats such as Kettle Falls, a major migratory impediment that historic stocks would have had to overcome (Chapman 1943). In practice, the difficulty of immigration will be largely influenced by the passage strategy that is implemented at Chief Joseph and Grand Coulee Dams, as passage structures can be associated with increased straying, prespawn mortality, migration delay or fallback depending on environmental conditions during migration (Boggs et al. 2004, Keefer et al. 2004b). If a passage strategy was selected that minimized fallback, energy expenditures and stress for immigrating fish, the anatomical need of additional energy reserves would theoretically be lessened and have less influence over donor stock selection.

Adult holding

With exception of the Carson stock, all Spring run donor stocks had holding periods that appeared sufficiently similar in length to those in their ancestral environments, and thus there may be minimal impacts from the reduction of holding time due to greater distance traveled. This exception for the Carson stock is intuitive, as we used environmental data that was available from the Wind River, although this stock does display smolt to adult survival when reintroduced to upstream locations in the habitat of the Upper Columbia Spring ESU (UCSRB 2007). Therefore, the stock probably has been penalized more than what might be expected; given the Wind River is a proximate tributary to the lower Columbia River.

The suitability analysis of holding in all Spring run donor stocks indicated the holding period is likely to be thermally stressful in the Transboundary Reach. Stream maturing anadromous salmonids are required to hold in especially cool water temperatures to complete maturation, so it is possible that the warmer temperatures that they would encounter for holding in the Transboundary Reach would alter or impair the schedule of maturation (McCullough et al. 2001). Maturation schedule is highly heritable, representing a suite of adaptations to conditions of the spawning and rearing environment, driven largely by water temperature (Sloat et al. 2014). Maturation in premature migrating, Spring run life histories, requires an extended holding period of reduced metabolic activity in cool temperatures and low water velocities in order to minimize energy expenditures (Quinn et al. In Press). This usually occurs in deep holding pools in the headwater stream environments to which Spring run populations are adapted (Healey 1991). Temperatures above 14 °C are generally considered stressful for maturing salmon. Our models made the assumption that thermal refuges below these temperatures do not exist in proximity to spawning areas, and all Spring run populations would have to hold for an extended period through temperatures that well exceed the 14 °C threshold (Figure 4-46). This assumption is likely reasonable, as it is unlikely that a significant amount of habitat would occur in the Reintroduction Reach that could support holding salmon through the mid and late summer months, below these



temperature thresholds. Deep pools located within the mainstem river environment (e.g., Kootenay Eddy) do not contain significantly cooler temperatures than shallow surface water environments (BC Hydro 2013). It is possible that Chinook Salmon could find suitable, cool deep-water environments to hold in Lake Roosevelt, but the reservoir is generally isothermal throughout the summer period, especially in its upper reaches in proximity to the Reintroduction Reach (Blake et al. 2014). Lower in the reservoir (e.g., Spokane Arm), weak patterns of stratification can exist, and temperatures approaching the upper end of the suitable thermal holding threshold (14 °C) can be found at great depths (> 40m) (Blake et al. 2014). If holding fish were to make use of these potential refugia, they would need to migrate long distances (>100 km) to complete their migration prior to spawning. Alternatively, there may be some pockets of cold groundwater upwelling in the downstream reaches of tributaries to the Transboundary Reach, or in the accessible length of Blueberry Creek, but these would be unlikely to have the capacity to hold great numbers of fish. Summer migrating donor stocks from the Upper Columbia Summer-Fall ESU were not scored in this lifecycle stage, despite the fact that they do approach spawning grounds in advance of spawning and thus could be considered to hold for a period of time. Although these stocks can technically be considered premature migrants (Quinn et al. In Press), they all hold for extended periods in warm temperatures prior to spawning in their ancestral environments. These environments are either within the Columbia River mainstem downstream from Chief Joseph Dam (which is warmer than the Transboundary Reach), or in the lower sections of its major tributaries. A more thorough examination of the holding environment for these stocks, compared to those available in the Transboundary Reach, would be an interesting topic of future feasibility research.

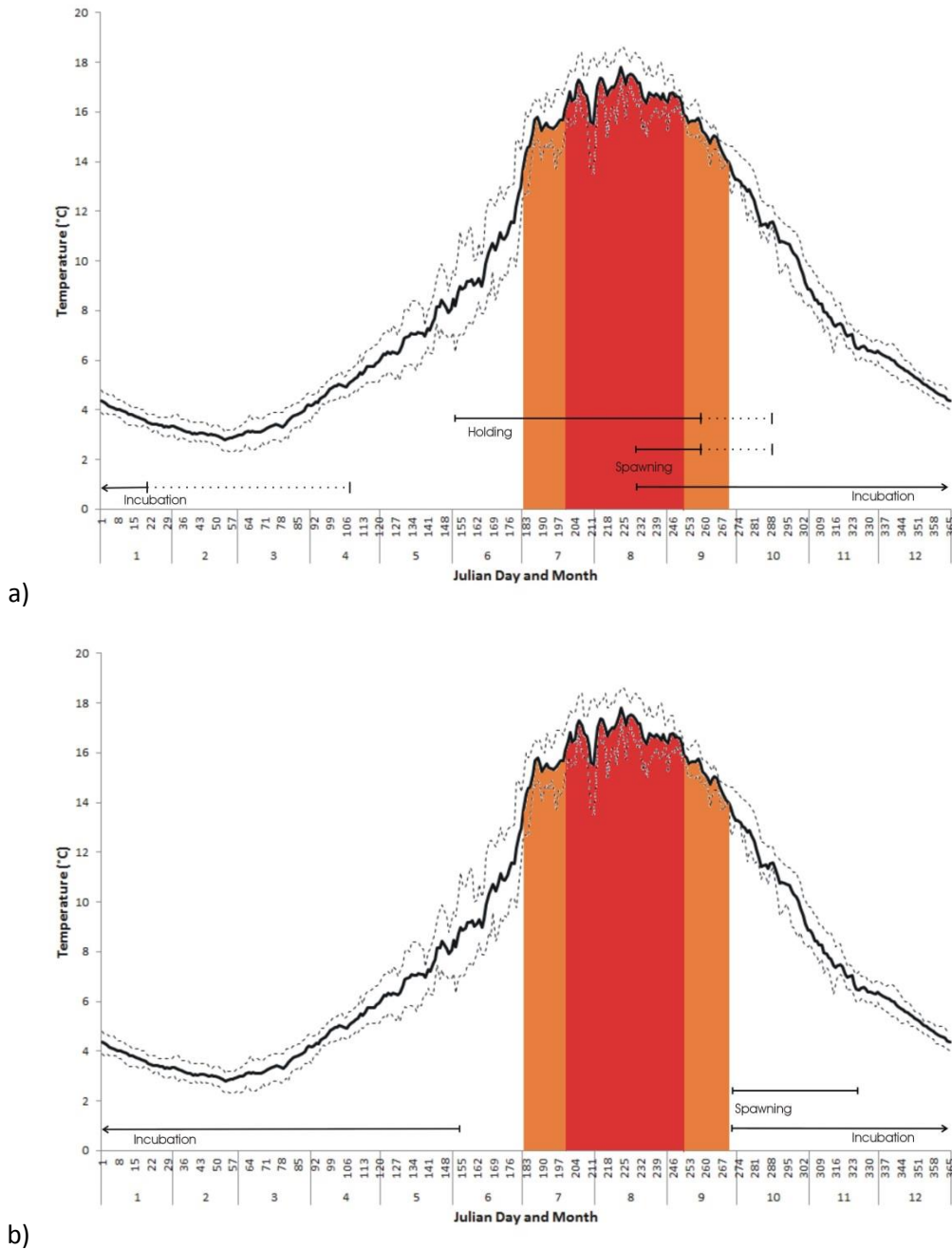


Figure 4-46: Modeled Life cycle stage timing of Chinook Salmon from a) Spring, and b) Summer-Fall donor stocks in the Transboundary Reach, in relation to the thermal regime near the confluence with Norns Creek. The solid line represents the mean temperature at each Julian day of the year from the period between 1999 and 2014. Dashed lines represent upper and lower quartiles. Holding, spawn and incubation timing in solid horizontal lines is the full possible interquartile range across all donor stocks considered within each life history, except for a), where dotted horizontal lines represent values from the later spawning Yakima Spring donor stock. Orange shading under the curve represents dates when temperatures exceed 14 °C, a threshold considered stressful for holding, spawning and incubation. Red shading under the curve represents dates when temperatures exceed 16 °C, a threshold considered lethal for developing embryos and limiting for spawning.



Spawning

Differences in stock suitability of the Transboundary Reach for spawning were driven by the temperatures that would be encountered by the donor stock if they were to retain their spawn timing. Indeed, selection of a donor stock with spawn timing that aligns with a suitable thermal regime to which the ancestral stock was adapted has been identified by previous reintroduction literature as a key driver in reintroduction success (Schneider 2011). Thermally suitable periods for spawn timing occurred primarily in October and November, and thus the suitability analysis ranked Summer-Fall donor stocks higher, as this corresponds to their spawn timing.

Spawn timing is a heritable trait to maximize the survival of emerging fry (Brannon 1987). In fall spawning, interior migrating Chinook Salmon, emergence occurs the subsequent spring (McPhail 2007). The Transboundary Reach has a thermal regime that can be considered a typical low elevation and lake headed environment similar to those which might be present in mainstems or lower reaches of rivers in southern British Columbia. The habitats support spawning of summer or fall run Chinook Salmon are typically timed to spawn in October or November, and are primarily composed of subyearling emigrants (Brannon et al. 2004). Spawning may be initiated in the latter half of September, as mean daily temperatures decline from the upper thermal limit of 16 °C to 14 °C by the end of the month (Figure 4-46); this declining thermal regime to 14 °C is associated with the onset of spawning in wild populations, though the majority of spawning occurs between 14 °C and 6 °C, and median spawn dates are usually associated with temperatures approaching or falling below 10 °C (Brannon et al. 2004). Thus according to these strict thresholds and mean daily temperatures encountered in recent years at the Norns Creek Fan, spawning is thermally most suitable from September 27 to December 7. The Yakima Spring stock was the only Spring run donor stock that had a sufficiently late spawn timing to somewhat align with the suitable thermal regime in the Transboundary Reach. Most Summer-Fall type stocks had the majority of their spawn timing distributions aligned with this optimal thermal regime. It should be noted that the temperatures used to determine suitability for spawning and egg development and project fry emergence are derived from underlying datasets of temperatures at the Norns Creek fan, which is the coldest portion of the Transboundary Reach. Temperatures downstream of the Kootenay River Confluence are warmer, as the input from the Kootenay River is warmer than the Columbia (BC Hydro 2013, Olson-Russello et al. 2015). Thus, we might expect that thermally suitable spawn timing would be initiated even later in the Kootenay River or in the Columbia River downstream from its confluence with the Kootenay River; this downstream remainder of the Transboundary Reach is likely to be even less suitable for the earlier spawn timing of Spring run life histories.

Embryo incubation

Suitability differences in the Transboundary Reach for embryo incubation were strongly influenced by the thermal environment during development. Early spawning stocks were modeled to encounter high temperatures that would presumably result in elevated or complete egg mortality, assuming that donor stocks retained ancestral spawn timing. Incubation temperatures are likely to be lethal to incubating



Chinook Salmon embryos prior to mid-September, and elevated mortality is likely to occur until the last few days of September in a year of average water temperatures (Figure 4-46). Thus, it can be reasonably concluded that if stocks have limited ability to adjust spawn timing through phenotypic plasticity, the majority of spawn timing distributions for Spring run donor stocks would fail to survive in the first generation. The Yakima Spring run donor stock is the only stock in this life history with a reasonable portion of its timing distribution that would avoid these high temperatures.

The other driving factor in determining suitability differences of donor stocks was their risk of encountering flow reductions through the developmental period that would dewater embryos. In this instance, we made the assumption that fish would retain their preference for the depth characteristics of their natal river environment. Spring Chinook Salmon generally spawn in small headwater stream environments, and the summer and fall Chinook Salmon in this analysis spawn in large tributary and large mainstem river (i.e., Columbia or Snake) environments, respectively. Large mainstem river spawning Chinook Salmon have a tendency to spawn at greater depths than those in smaller rivers. Although this may simply reflect a lack of deep-water habitat in smaller streams that meet other suitability criteria (velocity, substrate), so depth preference may be plastic and unaccounted for in our analysis. Stocks that spawn especially early also encounter the most potentially severe effect of redd dewatering, as flows decline from freshet through summer, reaching base fall flows by early October (Figure 4-5). Later spawning stocks (i.e., after early October) encounter periods of rising flow through the developmental window in the winter due to flow regulation, but would encounter an abrupt drop in flow at the end of March, below most flows encountered in fall and prior to the majority of fry emergence. In addition, flows during the fall are somewhat unpredictable and fluctuating, which may increase the variability in susceptibility to redd dewatering. Thus, all stocks are presumed to be at some risk from redd dewatering, but those that spawn earlier and those that might have preferences for shallower depths are at the greatest risk (i.e., Spring run donor stocks). We assume dewatering effects to be muted downstream from the confluence with the Kootenay River, which has a more naturalized flow regime. In an alternate putative spawning area downstream of the confluence of the Kootenay River such as Genelle (Figure 1-2), redd dewatering and scour risk are likely to be lower than in the putative Norns Creek fan spawning area, which is downstream from the more regulated flows of Keenleyside Dam. In this area, discharge and thus stage differences between the fall low flow period and spring low flow periods are negligible in average years, decreasing the likelihood of redd dewatering for late spawners (Figure 4-47). It should be noted that river regulation can be used to mitigate egg loss, and detailed hydraulic models can be used to simulate and refine optimal operations, based on depth preference curves developed for the impacted population (Tiffan et al. 2002, Golder Associates Ltd. 2014). Models that incorporate habitat suitability information of specific donor stocks or life histories of Chinook Salmon are available for specific areas of the Transboundary Reach, and the operational impact of flow regulation on embryo survival could be undertaken in future studies (Golder Associates Ltd. 2016). Strategies include holding water at a constant or rising level prior to emergence in order to keep embryos wetted, dropping flows during the spawning season to concentrate spawning into depths that would not be later susceptible to dewatering, and/or stabilizing flows. This would be especially useful to research during initial stages of colonization when depth preference curves can be built for the population.

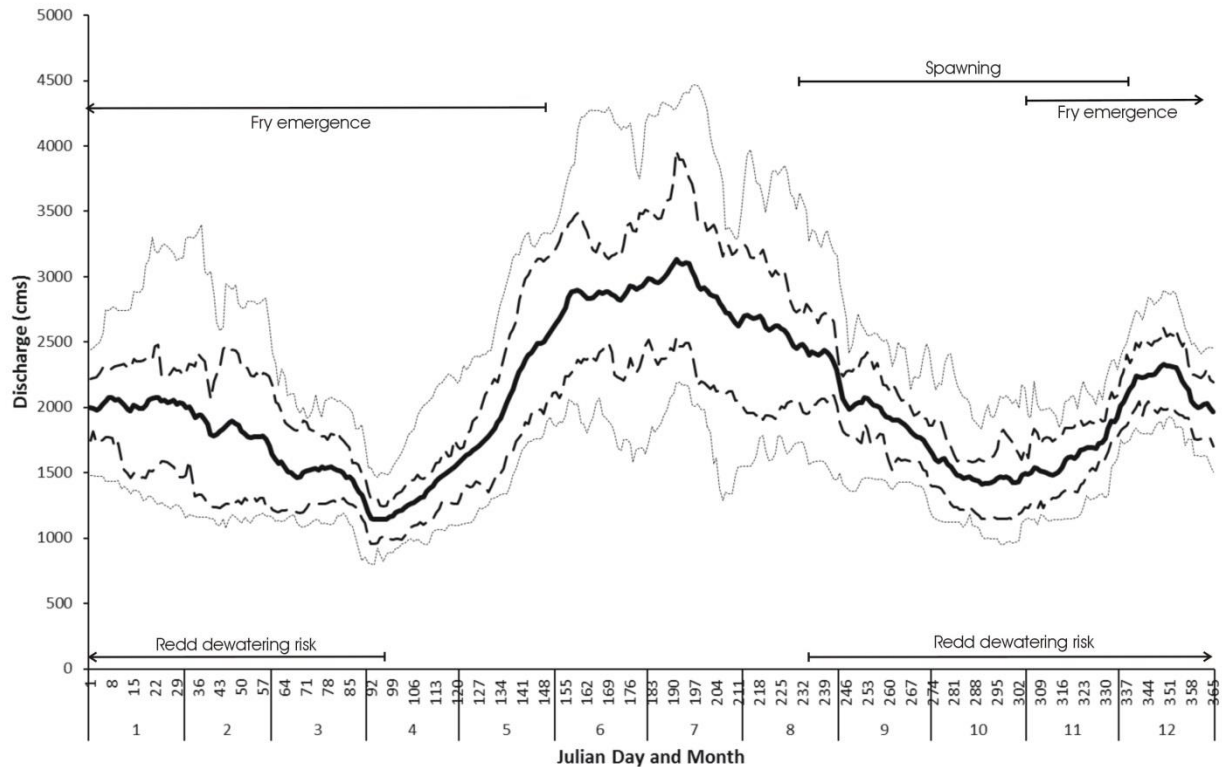


Figure 4-47: Critical timing of life stages of Chinook Salmon donor stocks in the Transboundary Reach downstream from the Kootenay River Confluence, with risk periods due to hydrograph changes. This hydrograph is from Birchbank, near a putative spawning area at Genelle. Solid line represents the mean discharge at each Julian day of the year from Hugh Keenleyside Dam from the period between 1993 and 2014. Dashed lines represent upper and lower quartiles, and dotted lines represent the upper 90th and lower 10th percentile of flows from the analyzed time period. Spawn and emergence timing is the full possible interquartile range observed and modeled (respectively) across all donor stocks.

Fry emergence

Fry emergence is a critical period during the Chinook Salmon lifecycle, where young are vulnerable to predators and natural disturbance, but must also capitalize on vital first feeding opportunities (Quinn 2005). The results of this modeling exercise suggest that, while the Reintroduction Reach does not appear to have any seasonal food limitations, there may be thermal limitations to growth. The ability for emergent Chinook Salmon to convert the calories available in the environment to growth may be limited by their inability to metabolize those calories at the ambient temperatures they encounter if emergence timing is especially early. The date at which temperatures become suitable for positive growth of Chinook Salmon occurs in early April in the Transboundary Reach. This roughly translates to an early-mid October spawning timeframe in order to emerge after this date. No Spring run donor stocks assessed, except the Yakima Spring stock, would thus have any of their distributions emerging after this date if ancestral spawn timing is retained. This may limit survival further in donor stocks of this life history during the first generation. Indeed, most of these populations spawn so early that the majority of their



emergence distributions would occur within fall or winter of the same year of spawning. This may well be a critical driver in determining the optimal spawning window, based on conformance to an emergence window that allows growth of emergent fry (Brannon 1987, Brännäs 1995). This supports the earlier finding with respect to thermal preference for spawning, that the optimal spawn timing window is likely to occur in October or November. All Summer-Fall run stocks assessed appear to spawn within this generalized timeframe, and later spawning stocks (mid-October through November) within this life history type are modeled to emerge at particularly thermally suitable times for growth of emergent fry.

Juvenile rearing and emigration

Predicting juvenile emigration strategy was not possible in this study, due to the many factors that control expression of the pathway(s) that result in survival to adulthood (Bourret et al. 2016). Temperature may have a strong influence over generalized (i.e., yearling vs subyearling) pathway (Connor et al. 2005). In a large-scale analysis of multiple wild Chinook Salmon populations, it appears that those which experience mean rearing temperatures (April 1 – September 30) below 11 °C tend to emigrate as yearlings; those that experience mean rearing temperatures exceeding 12 °C tend to emigrate as subyearlings (Brannon et al. 2004). The Transboundary Reach at the upstream end at the Norns Creek Fan is 11.8 °C, and at the downstream end at the U.S. Canada border is 13.4 °C through this same time period. Thus according to those thresholds hypothesized by Brannon et al. (2004), the thermal regime of upstream locations in the Transboundary Reach habitat is somewhat ambiguous as to which of the two emigration strategies would prevail. Warmer locations available for rearing downstream may favour subyearling emigration strategies. In lieu of attempting to predict the exact pathway chosen, we modeled some flexibility of juvenile life history pathways, according to some generalized assumptions of rearing location, emigration timing and rate that are categorically common (Bourret et al. 2016).

While the analysis did not reveal many significant overall differences in donor stock suitability, there appears to be very significant differences between juvenile emigration strategies we assessed, which is mainly driven by differences in suitability during emigration in the River and Estuary reaches. Yearling smolts were projected to have minimal limitations on survival since major mortality sources from predation and thermal stress were modeled to occur later in the season, after smolts were predicted to reach the estuary. Yearlings are more vulnerable to avian predation than subyearlings, although system-wide predation rates are still relatively low when considering total survival (Evans et al. 2012). In contrast, subyearlings encounter more difficulties during migrating, mainly due to their assumed later migration initiation timings, calculated migration rates and smaller size. These factors may expose them to detrimental temperatures and high predation from piscivores which are gape limited. Indeed, yearlings may experience orders of magnitude lower predation pressure from gape limited piscivores than subyearlings (Sorel et al. 2016). Of the two subyearling strategies, fry appeared to be the more suitable strategy, since their earlier emigration timing may allow more rapid progress downstream, avoiding the highest predation rates of the later summer months in the lower river and taking advantage of the spill operations in place in the FCRPS to assist passage (USACE 2016).



Although the analysis suggested that subyearlings may encounter more difficulties to survival during emigration, it should be noted that emigration life cycle stages occur over a much shorter portion of the life cycle than rearing in life histories that emigrate as yearlings. Our analysis did not reveal any major incompatibilities in rearing life cycle stages for yearling emigrants, but rearing occurs over a protracted period. Cumulative mortality imposed because of density dependent interactions or predation over this extended rearing period may reduce overall survival, and this was not accounted for in our analysis in any way that may differentiate suitability between life history types. Detailed studies examining the capacity of habitat to support juvenile rearing would be an obvious and important aspect of research in the near future. Alternatively, these factors could be experimentally or observationally assessed during initial stages of colonization.

Suitability criteria that did not influence the analysis and opportunities for environmental mitigation

An interesting finding in this analysis is that there were several suitability criteria (dissolved gas, flood scour, food resources) that appeared to not limit any identified donor stocks. Dissolved gas levels are closely monitored in the Columbia system, and spill operations are balanced to manage the survival trade-offs of dissolved gas and fish migration relating to spill (USACE 2016). This modeling exercises also suggests that during egg incubation, flood scour would not pose a risk to populations under the current flow regime, as fry emergence is likely to occur preceding freshet flows for even the latest spawning stocks. Lastly, this model suggests that food is likely to be abundant in the current environment of the Transboundary Reach, as the habitat is very productive for the items that emergent fry and juvenile salmon would consume (Olson-Russello et al. 2015); although this ignores the density dependent interactions that might occur for both food and feeding territories in the Reintroduction Reach (or downstream reaches for subyearling emigrants), which may limit rearing capacity (ISAB 2015).

This model was built on the belief that we can increase abundance through intentional and well-thought out reintroduction efforts as well as by taking actions to restore the spatial extent that is needed to support a salmon completing its life cycle. Tangible increases in survival can be obtained through careful management actions, including perhaps altering the timing associated with discharge to meet the needs of all life cycle stages. These actions can serve as an immediate benefit to salmon populations undergoing reintroduction and/or restoration activities thoughtfully designed to bring about population-level change. The analysis did provide some insight into environmental features that may be manipulated or restored, in order to promote salmon restoration. Criteria that are influenced by river regulation, such as redd dewatering and juvenile travel rate, may have impacts mitigated by adopting alternate flow regimes that minimize the impact of these or aid fish passage. Although we were data deficient for substrate suitability criteria, this is an environmental feature that can be manipulated by restoring spawning habitats with gravel augmentation (Zeug et al. 2014), with substrate sizes tailored to female size in the donor stock. Biotic factors can also be manipulated to increase salmon survival, such as predator removal programs (Williams 2014), which are currently not aggressively pursued upstream from Chief Joseph Dam. If future models are refined to the point that they are able to more confidently resolve differences between donor stocks with slightly different life histories, the analyses used here



may inform strategic habitat restoration that may be apparent to increase suitability for some donor stocks.

4.4.3 Refinement opportunities

Further refinements to the life cycle model could be realized by incorporating more robust data on travel rates and migration timing. A life cycle survival model could be constructed to determine the relative suitability of certain donor stocks in relation to current environmental conditions, although slight modifications in experimental design would be required. For example, the outmigration timing of Okanogan Summer-Fall smolts is too late for adequate detections at the towed estuary trawl event (DeHart 2015). Populations on the extreme end of their range (e.g. Upper Columbia stocks in this circumstance) will by definition have timings that occur on the extreme ends of other more central-tendency populations. Thus, data collection events in the estuary will have to align with when these fish would be passing through. Data on actual migration rates of various juvenile life history pathways in the reaches above Chief Joseph Dam are a major uncertainty. Hydraulic modeling to assess likely movement rates of drifting fry would be beneficial to further refine the projected migration rates of this emigration strategy in particular, and could perhaps be conducted in concert with concurrent efforts to model larval drift of White Sturgeon (UCWSRI 2015). Incorporating data on travel times during initial, experimental releases would also greatly increase our certainty in life cycle modeling and suitability analyses for juvenile life stages. Estimating juvenile survival from release (e.g. Transboundary Reach or Grand Coulee Dam) to Bonneville Dam is an additional benefit that has profound power to test hypothesis of the underlying criteria that influence survival and could help refine this model or more fully quantitative iterations greatly.

Data deficiencies were present for some criteria assessed in this suitability analysis. Substrate data were not available for the Transboundary Reach, so we are uncertain about the suitability of the substrate for spawning. Different donor stocks may have different availability of spawning habitat based on the mean size of females in the donor population, as this influences the particle sizes they are able to mobilize during spawning (Kondolf 2000). This data would support future modeling efforts in determining habitat suitability for Chinook Salmon, and appropriateness of habitats for different potential donor stocks.

Underlying data used in life cycle modeling, environmental data as well as suitability analysis of particular donor stocks generally used average conditions, or some crude estimate of variability (e.g., quartiles of donor stock abundance in a reach). Future refinements to models could include more robust accounting of variability, which could help gain a more thorough understanding of the specific responses of donor stocks to changing environmental conditions. In particular, more thorough incorporation of the full range of adaptations a donor stock may possess may increase our understanding of how donor stocks may survive when faced with environmental variability. This would allow us to integrate the adaptive potential component of Component Two with the modeling approach of Component Three. For example, it is possible that the central tendency of spawn timing is less important than the range in spawn timing for allowing a donor stock to successfully adapt to the novel environment. A clear example in our analysis occurred in the Summer Chinook Salmon populations, where the Okanogan population was found to have a broader spawn timing distribution than neighboring stocks. Rather than being scored higher for this greater variation, the population was penalized because a greater proportion of



their spawn timing distribution overlapped with a month that was thermally stressful. Such adaptive potential is difficult to quantify, especially when phenotypic plasticity regulates the expression of behaviours or traits (Reed et al. 2010). Ideally, specific criteria that are especially important to limiting factors to survival are known, and the heritable basis governing stock performance is understood well enough to be modeled or experimentally assessed accordingly (Houde 2015).

This stock evaluation was unable to evaluate all factors that have significant effects on Chinook Salmon survival, and could continue to be a work in progress. Key factors unaccounted for in our analysis are summarized well in the last cumulative survival study and recent upper Columbia reports generated by the Fish Passage Center (FPC) (DeHart 2015), as well as in large scale, multi-factorial analyses of salmon survival that incorporate both freshwater and marine variables (Burke et al. 2013, Miller et al. 2013, Miller et al. 2014). Select factors that drive ocean survival of Chinook Salmon, and could be included in future donor stock evaluations may include: whether the fish was an in-river migrant or actively transported (e.g. truck-and-haul), surface passage rates (e.g. versus turbine passage), pacific decadal oscillation (PDO), and upwelling index (UWI) related to ocean entry timing or other factors that drive bottom-up foodweb processes (Burke et al. 2013). Further, hydro system operations (e.g. fish guidance efficiency and the fraction of fish passing through the powerhouse - bypass and turbine routes) may have an effect on early ocean stage mortality (Tuomikoski et al. 2012). The exact nature of the factors that influence salmon survival throughout their lifecycle is complex, operating over a variety of temporal and spatial scales (Skalski et al. 2013). These factors continue to be debated in the literature depending on the nature of the analysis and scope of the study (Haeseker et al. 2012, Rechisky et al. 2012, Hilborn 2013, Skalski et al. 2013).

There are likely a suite of additional criteria that were not assessed within freshwater in this study, as the influence over survival is either difficult to quantify, data deficient, or not characterized to the level that it could be assessed within our methodology. For example, Chinook Salmon may presumably possess adaptations to migrate through lake systems, which may pre-adapt them for extensive migrations through Lake Roosevelt. There is some evidence to suggest that Chinook Salmon have unique behaviours to hold or rear in natural lake systems (Koehler et al. 2006), but it is uncertain whether these represent unique adaptations that would confer a heritable advantage in the reintroduction environment. In addition, Lake Roosevelt, although a large standing body of water, behaves unusually for a lake of its size due to low water residence time, fluctuating water levels, atypical fauna and flow manipulation (Blake et al. 2014). Although straying was initially considered as a suitability factor to include in this analysis, investigations of literature offered no strong basis to conclude that some donor stocks intrinsically stray more than others (see section 5). Hypotheses testing of stray rates should be an area of careful designed research when planning introductions. An additional suitability factor that was initially explored, but was not included in the analysis was whether the donor stock spawned in headwater tributary environments, or large mainstem river environments, as the majority of habitat available in the Transboundary Reach is the latter. Although this may seem intuitive, it is only quantifiable by breaking it into a subset of other criteria that resolve differences between these environments, relative to the pertinent adaptations of individual populations. Examples include our criteria of holding time length, substrate size and redd dewatering. Nevertheless, there likely remain a



suite of “intangible” criteria that remain difficult to quantify or predict and hence resolve donor stock suitability. The Transboundary Reach is a low elevation (<430 m), large mainstem river environment (~1000 to 2800 m³/s mean annual discharge depending on location), despite its far-inland position in the Columbia River Basin. These habitat types (at least contemporaneously) support runs of Summer or Fall run Chinook Salmon, with primarily subyearling emigrant juvenile life history strategies in both the Columbia and Fraser River basins (Dauble et al. 2003, Brannon et al. 2004, Good et al. 2005, DFO 2011). It is intuitive to suggest that the habitat should have limited suitability to the Spring run life history of Chinook Salmon in the interior Columbia River basin, as this life history typically immigrates to headwater environments of tributaries to spawn and initially rear in interior river systems (Healey 1991, Good et al. 2005, UCSRB 2007). Further testing of this hypothesis may be possible with further refinements to the model by including more descriptive rulesets and data, or by hypothesis testing of differential success of colonizing donor stocks during reintroduction. Once limiting factors are identified, relative performance of potential donor stocks could be assessed in controlled laboratory environments to determine the underlying causes of why certain donor stocks fail while others succeed in the novel environment (Houde 2015).

Climate change impacts on Chinook Salmon are diverse, but variable depending on the life history (Mantua et al. 2010). Incorporation of climate change scenarios is possible within the analytical framework of this study, and could allow us to project the future suitability of each donor stock, under varying climate change mediated flow and temperature scenarios (Crozier et al. 2008). It is relatively intuitive which suitability criteria might result in further differences between assessed stocks. During adult immigration, Summer-Fall migrating donor stocks would be further penalized due to higher temperatures which will last longer and further upstream in the basin under climate change (Mantua et al. 2010). During holding, Spring run stocks that are premature migrants may encounter high prespawn mortality or issues with egg maturation, although our analysis suggests that current conditions may already be limiting. Extended warm temperatures into the fall may shift optimal spawn timing and changes in temperature regime may alter the optimal time of emergence. The effects of the latter are rather unpredictable as it applies to donor stock selection, but the former effect clearly indicate that early spawners (Spring run donor stocks) will be most severely affected since the thermal regime of the Transboundary Reach is already unsuitable for spawning and egg incubation until late September, at the tail of their natural spawn timing distribution. It is also possible that increased incidence of winter flooding will increase scour risk to developing eggs, and this may either be buffered or exacerbated by operations of upstream dams; however, it is also recognized that the majority of the Columbia River basin upstream from the potential spawning areas will still be dominated by snowfall with near-term climate change forecasts, thus may be naturally buffered relative to populations at lower latitudes (Columbia Basin Tribes and First Nations 2015). Thus winter flood risk is highly uncertain with respect to donor stock selection. During juvenile rearing and emigration, increased temperatures from climate change may increase predation rates by creating favorable bioenergetic conditions for native and non-native piscivores (Petersen and Kitchell 2001). It is thus reasonable to assume that the stocks and life histories (i.e., subyearling emigrants) that currently have the highest predation rates from piscivores will have even higher predation rates in the future. This may be exacerbated by declining flow available for swift downstream passage in the mainstem of the Columbia River (Mantua et al. 2010) and further



spread and establishment of non-native piscivores. Finally, there are many impacts of climate change on later life cycle transitions and stages that were beyond the scope of this exercise to fully capture, including estuary residence (Bottom et al. 2005), transition from estuary and to ocean plume, and adult ocean residence (Hare and Francis 1995). Donor stocks have a wide variety of life history strategies during these life cycle stages, and all of these may be affected differently by climate change. If additional suitability criteria can be modeled in further refined and expanded donor stock selection analysis applicable to these stages, the theoretical scenarios of how those criteria are affected by climate change may also be modeled. Alternatively, increasing genetic diversity may allow practical bet hedging by increasing the ability of the founding population to adapt to climate change (section 3.5).

Although they are considered in other components of this study, stocks from the Fraser River were omitted from this component. Incorporating Fraser River stocks would be an interesting topic of future study, but strong assumptions would need to be made about the timing and rate of immigration. This would increase uncertainty of life cycle modeling for these stocks, relative to those for which data is already available to estimate timing.

4.4.4 Conclusions and recommendations

Life cycle models and suitability analyses developed in this component were built in order to make inferences about the generalized fit of each donor stock to the physical, environmental, and biotic factors they would be exposed to if they were to complete their life cycles. Commensurate with the resolution of the analysis, and uncertainty about plasticity of modeled traits and timing in the novel environment, we only make general conclusions on general life history strategies that appear to have greater suitability than others at each lifecycle stage and reach that Chinook Salmon will occupy in freshwater. In previous introductions, adaptation to the novel environment can be rapid, as selection will be strong during colonization (Quinn et al. 2000). Therefore, while we do not recommend this analysis identify the use of a specific donor stock, we do recommend using a donor stock(s) of the Summer-Fall life history, as it would be more likely to result in quicker and perhaps higher success (i.e. better early generation survival) than use of any stocks from the Spring run life history. Summer-Fall run stocks have generalized life history patterns that appear to be more closely pre-adapted to those required to successfully colonize the Transboundary Reach.

Donor stocks that arise from Spring run life histories were modeled to be highly suitable during immigration, as they reach pre-spawn holding areas with little apparent impediments. In fact, Spring run populations are generally adapted to not only migrate long distances inland, but also ascend to high elevations. These stocks probably overshoot the anatomical need of energy reserves (i.e., body fat) predicted to be necessary to immigrate to the inland distance and elevation of the Reintroduction Reach. Subsequently, the suitability of Spring run stocks was predicted to decline for the remainder of their life cycle. These populations require specialized coldwater habitats for holding to complete maturation through the summer months. Such habitats are likely to be limited in proximity to spawning areas in the reintroduction environment. The lack of these habitats is likely to cause thermal stress, possibly upsetting maturation schedule, reducing gamete viability, or resulting in prespawn mortality during the lengthy holding period. These stocks are also primarily adapted to spawn about a month earlier than when the thermal regime initially becomes suitable for Chinook Salmon spawning and



embryo development. This may lead to life cycle incompatibilities during these and later life cycle stages for Spring run donor stocks. A notable exception occurs in the Yakima River, which is timed to spawn at least partially in the thermally suitable period, but the stock is still predicted to be exposed to the same adverse holding conditions as other Spring stocks.

Donor stocks from Summer-Fall life histories were predicted to encounter some difficulties in accessing spawning areas, primarily due to high water temperatures in the estuary. This is particularly true for Fall Chinook, which migrate during later, warmer periods. These life histories are likely to further encounter difficulties with climate change scenarios. However, once these populations access the Reintroduction Reach, they generally have the diversity of adaptations and life history timing that appear suitable for the environment. In particular, their spawn timing appears pre-adapted to the suitable thermal regime of the Reintroduction Reach for spawning, subsequent embryo development, and fry emergence the following spring when conditions are bioenergetically favorable for growth (Brannon et al. 2004). They may also possess spawn timing and microhabitat preferences that minimize the impacts of current flow management strategies on embryo dewatering. High harvest rates may impede colonization success of this life history type, as they are intercepted in mixed stock ocean and river fisheries.

Life cycle modeling and donor stock suitability analysis for early life stage rearing and juvenile emigration life cycle stages was highly uncertain, but several model results were predictable. It does appear that the additional freshwater migration distance from the Reintroduction Reach, relative to distances extant stocks emigrate, may result in protracted or delayed emigration timings. This may result in disproportionate survival disadvantages for subyearling smolts during their emigration downstream, as these fish will be emigrating during later summer months when predation pressure is elevated, water temperatures become physiologically stressful, and current flow management strategies to aid smolt passage have ceased. All juvenile life histories may also be delayed in their timing of estuary arrival relative to basin-wide timing distributions of wild fish, although the effects of this on smolt to adult survival are largely linked to ocean survival and thus were not captured by this analysis. During colonization, we predict that juvenile life history strategy (e.g., rearing location, initiation of migration timing or migration rate) will quickly evolve to stabilize to the strategy(ies) that optimize smolt to adult survival.

There are further opportunities to refine the life cycle model and suitability analysis used here, which may lead to more specific donor stock recommendations. In addition, it is important to note that these tools highlight mitigations or restoration activities that may be beneficial to reintroducing Chinook Salmon. This analysis has highlighted flow manipulation in particular as a mitigation strategy that could potentially increase suitability for all stocks during embryo development and juvenile emigration. Another opportunity for enhancing salmon reintroduction survival would be to increase focused predator control. The ability of a model such as this to incorporate such changes, as well as predicted environmental conditions from climate change is particularly powerful. While we did not formally assess climate change scenarios within our model, we do predict that there may be differing impacts to the life history adaptations of donor stocks, and thus recommend that these scenarios be more thoroughly considered in future analyses.



5 Component Four: Risks

In this component, we describe the four major categories of risk, as described in Anderson et al. (2014) as evolutionary, disease, ecological or demographic. Risk can be either to the recipient ecosystem where anadromy is restored, to neighboring or downstream ecosystems where strays or other life cycle stages must pass through to complete their life cycle, or to the donor stock itself. Within each major risk category, the risks are described, and we consider whether donor stock selection affects these risks. We then consider the relative risk that donor stocks considered in this analysis may pose.

Many of the risks are associated with the possible impacts of adult straying. There are population-level variation in stray rates, and in general, the subyearling dominant (i.e., Summer-Fall run) life history of Chinook Salmon is more commonly observed to stray than the yearling dominant (i.e., Spring run) life history (Westley et al. 2013), although this may be greatly confounded by the bias of study to hatchery populations and not necessarily reflect an equivalent trend in wild populations (Westley et al. 2015). In addition, even if straying were more prevalent in Summer-Fall run populations, the consequence of this straying may be lessened by higher effective population sizes in neighboring wild populations, relative to the small populations of the Spring run life history (Narum et al. 2010). Straying is further strongly influenced by artificial production, environmental conditions and management strategies (Keefer and Caudill 2014, Westley et al. 2015). Hatchery fish are more likely to stray than their wild counterparts (Ford et al. 2015), suggesting that the use of hatchery populations for reintroduction poses higher stray-associated risks (McClure et al. 2008, Anderson et al. 2014, Keefer and Caudill 2014). However, there may be environmental or epigenetic reasons for this related to release strategy, rather than heritable traits inherent to the stock *per se* (Ford et al. 2015). For artificially produced populations, release strategy may influence straying (Dittman et al. 2010), and acclimation is a strategy used to increase the efficacy of imprinting and reduce straying (but see Clarke et al. 2011, Clarke et al. 2016). Transportation of juvenile fish artificially downstream through the hydrosystem also increases the probability of straying, particularly when extensive spill operations result in higher adult fallback at dams (Keefer et al. 2008, Keefer and Caudill 2014). Overall, we suggest that donor stock selection is not as important as other factors in risk mitigation for reducing straying, and there is no compelling evidence to suggest that any stocks evaluated in this study inherently stray at different rates.

5.1 Evolutionary

Reintroduction to foster long-term viability is best taken using metapopulation theory as a guiding principle (Anderson et al. 2014). Selecting populations of high diversity and with the highest chances of rapidly producing naturally self-sustaining populations increases their influence over the greater metapopulation. If the reintroduced source population shares recent evolutionary ancestry with extant populations within the metapopulation, the influence can be positive, as the reintroduced population can positively contribute to neighboring populations through demographic or genetic exchange. This is a strategy to conserve the underlying historic evolutionary and demographic processes that confer spatial and temporal stability to the greater metapopulation (Moritz 1999, Schindler et al. 2010). Selecting a



donor stock that is distantly related to neighboring extant stocks increases risks to neighboring populations, as outbreeding depression may result due to straying. This suggests If the donor stock is unlikely to naturally persist in the reintroduced habitat or shares little evolutionary ancestry with neighboring stocks, there may be further potential negative genetic effects to the greater metapopulation

There are unlikely to be genetic risks to resident fish in the Transboundary Reach, as none of these hybridize with Chinook Salmon. In terms of the reintroduced population itself, there is risk of poor fitness in the founding population (inbreeding depression) if the population size of founding individuals is small. Spring run donor stocks in this analysis arise from small, fragmented populations occupying diverse environments and have lower genetic diversity. These stocks are thus theoretically more likely to display such deleterious genetic effects in the founded population and should be considered less suitable as donors from this perspective (Houde et al. 2015a). This includes all stocks from the Columbia River basin Spring run life history, and most donor stocks from the Fraser River basin (section 3.3.1).

The risk to neighboring ecosystems would arise from straying of reintroduced fish, and interbreeding with extant populations. This could result in genetic homogenization and reduced fitness in neighboring populations, and risks of this increase as: 1) the stray rate increases; 2) the effective population size of the neighboring population is small, and 3) the genetic distance of the introduced stock increases. The basis for this fitness loss is generally the loss of local adaptation (Taylor 1991). In terms of donor stock selection for 1) we find no compelling evidence that any of the candidate stocks have higher inherent straying tendencies than any others (see opening discussion of this component). In terms of 2) Several assessed donor stocks (section 3.3.1; Snake River Fall, Stuart River, Wenatchee River Spring, Methow River Spring, South Fork Salmon River Spring/Summer) have small population sizes. These stocks are at inherent risk from interbreeding with strays because of the proportional effect those migrants would have on these small effective population sizes. Finally, in terms of 3), using stocks from increasing geographic (and therefore genetic) distance increases risk. We therefore recommend that using stocks from the neighboring ESUs in the Upper Columbia River is the least risk alternative. This is also consistent with the greater perspective of metapopulation dynamics, if in the future, management strategies for the reintroduced population is integrated with those guiding recovery of salmon in the basin (Anderson et al. 2014).

If any stocks from outside the neighboring Upper Columbia Spring or Summer-Fall ESUs are considered, our analysis suggests that stocks should be considered less appropriate from an evolutionary risk perspective with increasing geographic distance from the ESU, as this is a useful proxy for genetic distance (section 2.1). Stocks from the Fraser River should have the highest risks of all those considered.

5.1.1 Reintroduction strategy, evolutionary risks and donor stock selection

There are several options for reintroduction strategies above dams, both in the short and long term. Short and/or long term reintroduction efforts can either be passive or active (Anderson et al. 2014). Passive strategies allow for natural recolonization of upstream habitats after fish passage has been



provided. In this situation, the most geographically proximate populations would naturally be the donor stocks, as these are likely to contribute the greatest amount of strays to the Transboundary Reach. Passive strategies have resulted in successful and rapid recolonization of upstream habitats for Chinook Salmon (Burton et al. 2013), providing the source population is proximate and abundant and there is connectivity to high quality habitat upstream (Pess et al. 2008). Proximity and abundance makes natural recolonization of the Transboundary Reach by Summer-Fall life histories more likely than Spring run; however, the presence of a two dams (Chief Joseph and Grand Coulee) as well as the length of Lake Roosevelt complicate passage efforts and reduce the likelihood of rapid natural recolonization for any life history. This increases the likelihood that passive reintroduction would be slow (multi-decadal), and possibly result in long-term genetic consequences that reduce variation in the founding population (founder events, genetic bottlenecks or stochastic loss of multiple generations, etc.) and its capacity to develop local adaptations to the Transboundary Reach. Active reintroduction strategies in the short term and long term can involve either translocating wild fish at any lifecycle stage in freshwater, or from releases of hatchery juveniles. Active reintroduction may hasten recovery efforts and increase diversity in the founding population (Young 1999). Higher diversity increases the potential for locally adapted traits to be selected for in the incipient population.

Introduction of multiple stocks to the reintroduction area could allow for a bed-hedging strategy, to allow for maximum diversity in the founding population (concept reviewed in section 3.4.3). Using this strategy, loss of fitness may result in subsequent generations from outbreeding depression, and these risks may be mitigated through avoiding selecting donor stocks that are distantly related or inhabit significantly different environments (Houde et al. 2015a). This would suggest not using multiple ESUs for reintroduction unless they are predicted to strongly segregate temporally and spatially and not interbreed (e.g., introducing both Summer-Fall and Spring run life histories) (Moritz 1999, Anderson et al. 2014). Within ESUs, there are multiple donor stock options of the Upper Columbia Summer-Fall ESU that would possibly be appropriate for a multiple stock strategy. Given their largely homogenous population structure (Kassler et al. 2011), spatial proximity and relative similarity of occupied environments, a multiple donor stock approach using this ESU may have comparatively lower risks of outbreeding depression in latter generations than the Spring run ESU.

Multiple donor stock approaches can involve mixing gametes in a hatchery setting, or conducting concurrent releases of multiple stocks. Intentional mixing of gametes would not be necessary for the Summer-Fall ESU, as such a technique is typically undertaken out of necessity to raise diversity if the donor stock sources are small or of especially low diversity (Houde et al. 2015a). Populations exhibiting extreme ends of adaptations within this ESU (i.e., summer versus fall run) exhibit different adaptations to similar environments, which also support the possibility that both could display life history adaptations necessary for the receiving environment.

Regardless of which specific strategy is used, any introduction that uses multiple donor stocks should have robust monitoring programs in place to be able to detect differential success of translocated populations and the possible negative consequences of outbreeding depression (Houde et al. 2015a). The ability to detect both of these allows adaptive management of the reintroduction program, in order to maximize effectiveness and minimize risk.



Use of hatchery programs can be involved initially in the short term, as well as long term. Initial programs can use selected broodstock from a hatchery operation associated with one of the wild donor stocks analyzed in this study (e.g., Methow Composite). Alternatively, there is the potential to use a hatchery specific strain that is not associated with a native local spawning population or any specific ESU (e.g., Carson strain). For example, Spring run Chinook Salmon were extirpated in the Umatilla and Walla Walla Rivers, and hatchery Carson strain were used for initial reintroduction; however, the ability of these populations to provide natural self-sustaining wild populations has had poor initial success and relies upon continual supplementation by hatcheries (HSRG 2009). Use of purely hatchery strains also may have negative genetic consequences to downstream stocks if they contribute a significant number of strays to those populations (Naish et al. 2007). At neutral markers, the hatchery specific Carson stock indeed closely resembles current wild stocks in the Upper Columbia Spring run ESU (at least relative to out-of-basin populations in the Snake and Fraser River basins; section 2.3.2), and does not appear to have lower amounts of variation at neutral markers (section 3.3.1). These findings are consistent with those of studies in the Columbia that have examined the relationships between hatchery and wild strains (Drake et al. 2003). Nevertheless, there is strong evidence that hatchery specific strains have negative fitness consequences on neighboring wild populations (Naish et al. 2007), suggesting that such hatchery specific strains are associated with higher risk. Negative fitness consequences can at least be partially mitigated through maintaining distinct breeding segregation from wild populations (HSRG 2009), and possibly minimizing further negative interactions (e.g., competition) by a variety of best management strategies.

The conservation goal of a reintroduction program will need to consider management objectives when considering the long-term strategy used and involvement of hatchery (HSRG 2009). Transition to integrated hatchery practices can be used as an ongoing recovery tool after reintroduction, as they may provide a management objective tool to increase natural origin spawner abundance and hasten recovery of the population (Young 1999, Fast et al. 2015). Transitional reintroduction of purely hatchery strain Carson stock to integrated local broodstock is currently underway in the Walla Walla and Umatilla Rivers (HSRG 2009). In the Okanogan basin, a within-ESU population from the Methow Composite is being used to develop an integrated program for reintroduction of Spring run Chinook Salmon (CJHP 2009a). Integrated programs select a higher proportion of natural origin fish into broodstock than the proportion of natural spawning fish that are of hatchery origin. The management goal is to keep reproductive success dominated by wild fish in order to promote natural local adaptation. The use of an integrated strategy can be particularly effective when habitat capacity is high, and demographic risk of extinction is also high (HSRG 2009).

Another strategy involving hatcheries is to rely on a segregated program, that is, to establish a genetically distinct reintroduced hatchery population. The management objective in this program is to create an artificially propagated population for harvest objectives. In this strategy, local adaptation principles still apply by transitioning to locally returning broodstock; however, no fish would ideally spawn in the wild, or with any incipient established wild population, thus minimizing risk. Segregation may be maintained through a variety of strategies, including remote smolt rearing acclimation ponds and directed adult harvest on the hatchery returns (e.g., through fin clips). The risks of segregated



programs to small local wild spawning populations are high if improperly managed (Naish et al. 2007). Segregated and integrated programs for Summer-Fall and Spring run Chinook Salmon are currently being carried out in the Chief Joseph Hatchery facility, located at the most upstream distribution limit on the Columbia River (CJHP 2009a, b). These programs use a variety of strategies using hatchery and natural origin broodstocks and have multiple management objectives.

5.2 Disease

The diversity, prevalence and virulence of anadromous salmonid diseases are highly variable, both spatially and temporally. The pathogens that cause disease in these fish often can cause disease in other fish species, and pathogen strains have unique evolutionary histories with the diversity of fish they infect. Emerging diseases are a problem when considering movement of fishes, as they may introduce exotic pathogens (either the species or a novel strain) into a naïve environment. Disease history in both donor stocks and the receiving environment are an important consideration in reintroduction programs (Chandler and Abbott 2003), and can be used as a criteria to determine donor stock suitability if there are clear risks associated with certain stocks (Huntington et al. 2006, NMFS 2014b). Anadromy also may not necessarily introduce novel pathogens, but it may increase their prevalence.

The Transboundary Reach once had anadromous fish, so the community may not necessarily be totally naïve to pathogens typically associated with anadromous salmonids (*sensu* Chandler and Abbott 2003); however, the ecosystem has changed markedly, and virulence may be high in resident fish communities if any diseases are reintroduced, exotic new diseases or strains are introduced, or if the community has shifted to favor the presence of alternate parasite hosts or reservoirs of disease.

Disease transmission pathway is important, as it may influence the risks of introduction depending on the reintroduction method used, and life cycle stages of fish that are introduced (i.e., translocation of wild fish vs hatchery reared). Viruses and bacteria are transmitted horizontally (fish to fish) or vertically (parent to offspring via eggs), whereas myxozoan parasites often have complex lifecycles in which an intermediate host must be infected to complete the lifecycle of the pathogen. Thus, while it is beyond the scope of this study, reintroduction strategy is a more important consideration than donor stock selection in mitigating risk of introduction of pathogens.

The following section provides a description of commonly considered diseases that anadromous salmonids may introduce to upper portions of the basin in Canada, with most diseases selected from their importance in previous reintroduction pre-assessments (Chandler and Abbott 2003). Previous workshops have identified particular concern with introduction of specific pathogens, including whirling disease and IPNV (Nelitz et al. 2007). Within each description is a review of whether the pathogen is known to occur in the Transboundary Reach, or if it has been documented within or in close proximity to the donor stocks being considered in this analysis. Literature sources, communications with fish health experts and publicly available databases were used to determine presence or absence of pathogens, including the US Fish and Wildlife Service's National Wild Fish Health Survey Database (USFWS 2016), and the Molecular epidemiology of Aquatic Pathogens (MEAP) IHNV database (NACSE and USGS 2016).



In general, available data was sparse, especially in the Fraser River basin. Thus, pathogen screening in donor stocks or in aquatic species in the receiving environment have not been tested in a standardized, systematic manner which would allow quantitative assessment of the relative risks of donor stocks. This review should therefore only be used as a guide to pre-screening of stocks, and not viewed as a comprehensive analysis of the disease risks of potential donor stocks.

Infectious hematopoietic necrosis (IHN)

IHN is a virus that most commonly affects salmonids in the genus *Oncorhynchus*. The disease is found commonly throughout the Pacific coast, and has been detected upstream from the Reintroduction Reach in Kootenay Lake, the upper Kootenay watershed, and Kinbasket Reservoir (NACSE and USGS 2016; R. Breyta and K. Bray, pers. comm.). Steps have been taken to reduce vertical transmission of this disease in an artificial spawning channel that supports the majority (in most years) of kokanee spawners in the lake. The disease can be transmitted vertically as well as horizontally. Chinook Salmon have been identified as carriers of the virus, even if they do not show signs of disease (St-Hilaire et al. 2001). It is assumed that all potential donor stocks could introduce IHN, although it is important to determine whether the introduction would result in an exotic strain being introduced to the ecosystem. While testing of wild fish has not as been extensive, all hatchery populations examined in this analysis have had positive detections of IHN, and prevalence of IHN is generally much higher in areas with current anadromy (NACSE and USGS 2016). There are distinct clades of IHN in the Columbia River Basin, with geographic distributions that may not overlap in interior watersheds (Garver et al. 2003). In addition, virulence can vary between isolates of the same clade (Kent 2011), and different strains or clades may have different virulence between fish species or populations (Garver et al. 2006). The U clade of IHN is the major genotype of the virus present in the Kootenay River watershed, upstream from the reintroduction area (R. Breyta, pers. comm.), and this is the same clade (but not necessarily the same exact isolate) of IHN that is present in stocks that are proximate to the Transboundary Reach (i.e., Upper Columbia stocks) (Garver et al. 2003), and (rarely) present in Chinook Salmon in the Fraser River basin (NACSE and USGS 2016). Thus, there appears to be increased risk of introducing a novel strain of IHN by using stocks from greater geographic distance within the Columbia River basin, but not necessarily the Fraser River basin. The U clade genotype is less virulent in Rainbow Trout, but more virulent in Sockeye and Kokanee Salmon (Garver et al. 2006).

Infectious salmon anemia (ISA)

ISA is a virus that was originally recognized in European aquaculture operations, but has been recently detected as an emerging disease on the west coast of North America (Kibenge et al. 2016). The Washington Department of Fish and Wildlife has recently monitored wild salmon but has not detected its presence in the Columbia River. Testing of wild and aquaculture salmon in British Columbia reveals that ISA is present provincially in wild Chinook Salmon (Kibenge et al. 2016), but it is unknown whether the virus is present in any of the specific donor stocks we examined in the Fraser River. Unless new



information becomes available, there appears to be no differences in risk between donor stocks at this time.

Infectious pancreatic necrosis virus (IPNV)

IPNV is a viral disease commonly associated with all species of salmonid fishes, though can be transmitted to other fish species (Hnath 1983). It is found throughout the northern hemisphere, though it remains undocumented in British Columbia (K. Garver, pers. comm.) it is a concern for anadromous salmon reintroduction (Nelitz et al. 2007). It has been recently detected in resident salmonids in the Pend D'Oreille River drainage, upstream from the Transboundary Reach, but has not been recently detected in downstream locations (USFWS 2016) or in the neighboring Okanagan River basin (K. Garver, pers. comm.), so the risk of introduction by re-establishing anadromy is probably low. The disease can be transmitted vertically.

Bacterial kidney disease (BKD)

Bacterial Kidney Disease is caused by the bacterium *Renibacterium salmoninarum*, and can be transmitted horizontally or vertically (Warren 1983). Number of pathogens present, environmental and water conditions, as well as the strain of fish affect the severity of infection. The hatchery operation associated with the Snake River Fall stock has experienced problems with *Renibacterium salmoninarum* in the past (Chandler and Abbott 2003). Chinook Salmon in the mid and upper Columbia River have high incidence of BKD (UCSRB 2007), and the pathogen is extremely common in the Columbia Basin as a whole (USFWS 2016). The pathogen is found extensively in resident salmonids upstream from Grand Coulee Dam, thus Chinook Salmon may not necessarily be introducing a novel pathogen to the area (USFWS 2016).

Columnaris

Columnaris disease is caused by the bacterium *Flavobacterium columnare*. The disease is common worldwide and infects almost all species of freshwater fish (Schachte 1983a). Although omnipresent, infections in salmonid fishes are typically associated with environmental stressors such as crowding, high water temperatures and low oxygen (Schachte 1983a). The pathogen has been found in Chinook Salmon in the Columbia River basin, but no positive detections could be found in any of the potential donor populations examined in this study (USFWS 2016). In the neighboring Okanagan River Basin, Sockeye Salmon have been detected with the presence of Columnaris (K. Garver, pers. comm.).



Bacterial cold water disease

Bacterial cold water disease is caused by *Flavobacterium psychrophilum*, related to the bacterium causing Columnaris. Like Columnaris, it generally is associated with environmental stressors, but unlike Columnaris, it occurs at cooler temperatures (Bernardet and Bowman 2006). The pathogen has been found in the Pend D'Oreille River drainage upstream from the Transboundary Reach. The only donor stock it has been positively detected in, according to the US Fish and Wildlife Service's National Wild Fish Health Survey Database is in the Yakima basin (USFWS 2016). In the neighboring Okanagan River Basin, Sockeye Salmon have been detected with the presence of BKD (K. Garver, pers. comm.).

Furunculosis

Furunculosis is caused by the bacterium *Aeromonas salmonicida*. It is found worldwide, and most commonly infects salmonid fishes, associated with hatchery operations (Schachte 1983b). The disease can be transmitted horizontally. The only donor stock it has been positively detected in, according to the US Fish and Wildlife Service's National Wild Fish Health Survey Database is in the Yakima basin (USFWS 2016). The pathogen has also been detected immediately downstream from the Transboundary Reach, as it was found in burbot in Lake Roosevelt (USFWS 2016).

Piscirickettsiosis

Piscirickettsia salmonis is an intracellular bacterium, recently described and once thought to be a problematic isolate from aquaculture operations in Chile, it is increasingly being detected outside this range worldwide in salmonid and non-salmonid fishes (Mauel and Miller 2002, Chandler and Abbott 2003). The risk of introduction is likely low at this point. The pathogen is transmitted horizontally.

Whirling disease

Whirling disease is caused by a parasitic infection of the myxosporidean protozoan *Myxobolus cerebralis*. The parasite has caused mortality to salmonids in interior watersheds in Montana and Colorado. The species requires an alternate *Tubifex* worm host to complete its lifecycle. Whirling disease has not been detected anywhere in British Columbia, though it is present in the U.S. portion of the Columbia River basin (Bartholomew and Reno 2002), including tributaries that are directly upstream or downstream of the Transboundary Reach, in the Pend D'Oreille and tributaries to Lake Roosevelt (USFWS 2016). In the Deschutes River basin, a comprehensive program of investigating the risk of spreading whirling disease with anadromous fish reintroduction was undertaken prior to proceeding (Engelking et al. 2002, Bartholomew et al. 2005). In particular, the presence of the intermediate host and parasite should be screened in both downstream or donor areas as well as the Reintroduction Reach (Zielinski et al. 2010, Zielinski et al. 2011). The possible donor stocks that may have had exposure



to the parasite given its presence in nearby river basins include the Snake River Fall and South Fork Salmon Spring stocks, even though the parasite has not been detected directly in these populations (Chandler and Abbott 2003), as well as the Okanogan (only detected in alternate species and not in Chinook Salmon directly) (USFWS 2016).

Ceratomyxa Shasta

C. Shasta is a potentially virulent myxosporean protozoan, commonly associated with Chinook Salmon in lower latitudes of their distribution in North America. Salmonid stocks and species have varying resistance to *C. Shasta* (Bartholomew 1998), but virulence is mediated by environmental factors and strain of the parasite itself (Stinson and Bartholomew 2012, Chiaramonte et al. 2016). Currently found in the lower Columbia River and its tributaries, it is unknown whether the infectious stage of *C. Shasta* is present in the Upper Columbia River. The parasite is present in portions of the upper Snake River, where anadromous salmonids have been extirpated, as is the parasite's polychaete worm alternate host (Chandler and Abbott 2003). The only donor stock in which this parasite has been detected is in the Yakima basin (USFWS 2016). A risk assessment from both potential donor and the reintroduction areas would need to be completed, including determining if the alternate host and/or parasite is present before concluding whether there is a risk of introducing this parasite (Bartholomew and Kerans 2015). In the neighboring Okanogan River Basin, Sockeye Salmon have been detected with the presence of *C. Shasta* (K. Garver, pers. comm.).

5.3 Ecological

Ecological risks include risks both to the recipient ecosystem in the Transboundary Reach and surrounding ecosystems that salmon use for alternate parts of their lifecycle. Competitive interactions may occur between reintroduced salmon and other species in the Reintroduction Reach, and native salmon downstream for Chief Joseph Dam. Competitive interactions can include additional demand for resources including food and feeding territories, and substrates for spawning. The risk becomes compounded with possible residualization and spread of landlocked Chinook Salmon. The risk also may increase by outplanting large numbers of hatchery fish, if there are density dependent interactions with resident fish or downstream neighboring populations where rearing may be communal (Anderson et al. 2014, ISAB 2015). These interactions are thus strongly influenced by reintroduction strategy, but may also be influenced by donor stock choice, if different donor stocks would result in the expression of different life history pathways. For example, a tributary rearing, yearling emigrant strategy would place more density dependent interactions on the immediate reintroduction environment than a downstream reservoir rearing emigration strategy. The carrying capacity of either habitat before density dependence is encountered is likely different, thus the risks to recipient ecosystems may be different. However, if stabilizing selection occurs to favor one life history type, regardless of donor stock used, these differences are unlikely to persist beyond initial reintroduction attempts. Because it is impossible to pre-determine the success of any life history pathway variant, it is also impossible to determine which donor



stock would display the highest suitability. If hatchery juveniles are used, a possible assessment of carrying capacity may help inform stocking targets in order to reduce the negative effects of density dependent foodweb interactions (Naiman et al. 2012, ISAB 2015). In addition to variation in juvenile life history pathway, salmonid fish can exhibit population-level variability in competitive ability with native and non-native salmonids (Warnock and Rasmussen 2014). Stocks that have a recent evolutionary history of competing with salmonids in the target reintroduction area may have increased success of colonization due to their greater ability to coexist when competing for resources (Houde et al. 2015b). Domestication may also occur that alters competitive interactions of hatchery fish with wild fish, although this is also potentially influenced by other hatchery practices (e.g., size and timing of release)(Pearsons et al. 2007). The species with the highest potential for niche overlap with introduced Chinook Salmon in the Transboundary Reach is Rainbow Trout, and potential overlap could occur with Mountain Whitefish. Non-native salmonid species are not currently abundant. All potential donor stocks assessed in this study are assumed to have histories of co-occurrence with Rainbow Trout in their ancestral habitats, as the species is omnipresent in the interior Columbia River basin.

In addition to competitive interactions, direct and indirect impacts on recipient and neighboring systems may occur through predation. It is unlikely that rearing juvenile Chinook Salmon would directly consume significant numbers of fish, as diet is dominated by zooplankton or other invertebrates (Healey 1991, Koehler et al. 2006, McPhail 2007). However, ecological changes may occur by predation on rearing salmonids, increasing production of “native invaders” (Carey et al. 2012) or potentially other predators (Pearsons 2010), including non-native piscivores. No literature could be found specifically examining these risks in the context of reintroduction, but there have been attempts to study the benefits of swamping non-native piscivores to reduce predation on wild juvenile salmon (Fritts and Pearsons 2008). With respect to donor stock selection, it is possible that hatchery populations may have reduced anti-predator responses, increasing their risk of predation, although this may be influenced by release strategy and the hatchery practices themselves that influence domestication selection (Fritts et al. 2007).

Residualization is a possible risk to recipient ecosystems if Chinook Salmon become “land-locked,” completing their lifecycle as adfluvial piscivores entirely within freshwater. Residualization is also used to refer to especially late emigrants (e.g., year 2; Bourret et al. 2016) and precocious parr (Larsen et al. 2004), but these are unlikely to be associated with significant adverse ecological effects because they are a relatively rare component of the population where the phenomena occur. Two large standing bodies of water are potentially accessible to Chinook Salmon, in the Arrow Lakes Reservoir (by colonizing through the navigation lock at Hugh Keenleyside Dam), and in Lake Roosevelt. Chinook Salmon could presumably residualize as adults, becoming piscivores in these environments. This would not constitute a successful reintroduction attempt; rather, it would be the introduction of an additional, non-native adfluvial piscivore to these systems.

Residualization is most commonly encountered at low levels, following the introduction of hatchery juveniles. The size and stage at which juveniles are released may influence their likelihood of residualizing. In systems where Chinook Salmon are intentionally released to provide an in-lake fishery, juveniles may be held in controlled hatchery conditions until they mature beyond a smolting stage



(WDFW 2002), thus risk could be mitigated by using less interventionist hatchery practices. The overall risk of residualization may be low in both Arrow Lakes and Lake Roosevelt. The Arrow Lakes contain appropriate foodweb and habitat characteristics for adfluvial Chinook Salmon, as populations of piscivorous Rainbow Trout and Bull Trout are supported by a large pelagic prey base of Kokanee Salmon. The only colonization route for a residualized population is through the navigation lock at Hugh Keenleyside Dam. Since the navigation lock only functions as an incidental fish passage route, it is likely that it would restrict the propagule pressure of colonizing fish. In contrast, Lake Roosevelt is directly connected, but may not present as appropriate an environment for adfluvial Chinook Salmon. Lake Roosevelt contains low densities of pelagic prey (e.g., Kokanee Salmon) and does not support a self sustaining population of any species of large bodied salmonid piscivore (J. McLennan, personal communication). The thermal regime of Lake Roosevelt is also warmer than most other large lakes that support these fish, and thermal stratification is weak or not present in most of the reservoir (Blake et al. 2014), further limiting the suitability of the habitat. A residualized adfluvial population of Chinook Salmon has inhabited the Columbia River basin upstream from the reintroduction location, in Lake Coeur d'Alene, since at least 1990, when redd counts began (stocking began in 1982; IDFG 2008). Thus, landlocked Chinook Salmon may have colonized from this source if environmental suitability was high. It should be noted, however, that propagule pressure may be low since fish would be required to emigrate from Lake Coeur d'Alene and stray to an appropriate spawning tributary of Lake Roosevelt.

It is possible that certain donor stocks may carry higher risk of residualization. We could find no literature that has tested the hypothesis that certain donor stocks or Chinook Salmon life history types residualize more readily than others. We reviewed all cases for which literature was available on residualized examples of adfluvial Chinook Salmon, and attempted to determine whether this was associated with any of the donor stocks examined in this study. The underlying life history of the founding donor stock in each landlocked population was also noted to see if generalized patterns exist of certain life history forms residualizing, and thus could be interpreted as influencing risk.

Examples of adfluvial residualization were documented in nine locations (Table 5-1). One example was associated with a donor stock being assessed in this study, the Okanogan Summer-Fall population, as adfluvial spawners have been (rarely) documented in the Canadian portion of the basin, above Lake Osoyoos (Davis et al. 2007). Four of the nine examples resulted from the establishment from an underlying Summer-Fall run life history, one resulted from an underlying Spring run life history, and four were unknown. The Laurentian Great Lakes is an example where several different strains, with multiple life history characteristics have been introduced (Crawford 2001), although the established metapopulation is a collection of now locally divergent populations that trace their common ancestry back to the introduction of Chinook Salmon from the Green River, Washington (Suk et al. 2012). The underlying life history of this founding population was Summer-Fall, subyearling dominant (Quinn et al. 2002), and subyearling smolt emigration strategies are retained in the newly founded population (Sharron 2015). Summer-Fall subyearling dominant life histories also probably founded the wild population now found in Lake Cour d'Alene, though this cannot be confirmed. The only documented example found of an underlying Spring run, yearling dominant life history establishing an adfluvial residual spawning run was in the Willamette River basin, and occurred with reintroduction attempts



above dams (Romer and Monzyk 2014). Unlike populations of the interior Columbia Basin, Spring run Willamette River basin Chinook Salmon show great flexibility and diversity in juvenile emigration strategy, with a significant proportion emigrating as subyearlings (Schroeder et al. 2015). Given the review of underlying life history diversity of founding populations, it appears that either subyearling dominant life histories, or populations with juvenile life history diversity that includes subyearling emigration, have developed self-sustaining adfluvial populations of Chinook Salmon. It is beyond the scope of this study to determine whether these subyearling dominant or highly diverse populations inherently residualize, but this is an interesting hypothesis that warrants further study.

Table 5-1: Literature review of examples of residualized adfluvial Chinook Salmon populations

Adfluvial residualization example	Underlying life history of donor stock	References
Lake Chelan (upper Columbia)	Summer-Fall, subyearling dominant	(WDFW 2002)
Lake Cour d'Alene (upper Columbia)	Unconfirmed; likely Summer-Fall from sources reported in stocking records	(IDFG 2008, 2014)
Lake Osoyoos (upper Columbia)	Summer-Fall, subyearling dominant	(Davis et al. 2007)
Folsom Reservoir (California Central Valley)	Summer-Fall, subyearling dominant	(Williams 2001, Perales et al. 2015)
Green Peter River (Willamette River)	Spring run, yearling dominant	(Romer and Monzyk 2014)
Great Lakes (Laurentian)	Summer-Fall, subyearling dominant	(Crawford 2001, Suk et al. 2012)
Lake Cushman (Puget Sound)	Unknown	(Skokomish Tribe and WDFW 2007)
Lakes Dunstan and Colridge (New Zealand)	Unknown; initial donor stock was Sacramento River (Battle Creek), which has a variety of life histories	(Quinn et al. 1996, Graynoth 1999, Quinn et al. 2001)
Lake Puyehue (Chile)	Unknown; General region was colonized from multiple populations, primarily from aquaculture escapes	(Soto et al. 2007, Di Prinzio et al. 2015)

Overall, we did not find compelling evidence to suggest that any specific donor stocks have increased ecological risks, although literature does suggest that there may be theoretical differences between stocks in competitive ability, vulnerability to predation and inherent tendency to residualize. Most of this literature has focused on the differences between hatchery and wild stocks. In considering mitigating ecological risk, donor stock selection is a less important consideration than reintroduction strategy or the actual hatchery practices that result in increased risk.



5.4 Demographic

The primary risk to donor populations arises from taking of individuals or their gametes, which could reduce their viability if demographic impacts are significant (Anderson et al. 2014). This must be considered in a metapopulation framework. If wild fish were taken from a neighboring population, is the founding population likely to be a sink, or become a source that strengthens the overall metapopulation? Regarding the reintroduced population as an investment for long-term viability of the metapopulation to which the donor belongs may justify the removal of some fish in the interim. In the case of totally segregated and domesticated hatchery donor stocks, the risk is negligible. In the case of wild donor stocks, risk decreases markedly as the population size of the donor stock increases, and the numbers of fish or gametes required decreases. Likewise, hatchery stocks that are integrated with wild production are also dependent on returning fish and thus subject to the same considerations as wild stocks. It is difficult to determine the minimum number of fish needed for successful colonization, but insufficient numbers could result in demographic depensation in the founding population and inbreeding (Deredec and Courchamp 2007). Thus, reintroduction should maximize the availability of fish for transplanting, while minimizing risk to the donor population (Anderson et al. 2014).

Given the theoretical basis outlined above, donor stocks can be considered higher risk if they have smaller population sizes or recent negative population trends, are less likely to establish in the Transboundary Reach. Many Spring run donor stocks examined in this analysis and stocks from the Fraser River basin have small population sizes (section 3.3.1), and would likely be of high risk for use in a reintroduction program. The lower environmental suitability of the Spring run life history (section 4.4.4) also implies that their use in this area would possibly create a sink for the overall metapopulation, further increasing risk to these populations. In contrast, locally derived Summer-Fall run donor stocks from the Upper Columbia Summer-Fall ESU, especially those from the Wenatchee, Okanogan and Hanford Reach are all large (section 3.3.1), and are more likely to have surplus individuals or gametes that could be used for reintroduction purposes. All are likewise considered possibly suitable for most life cycle stages.

Demographic risks are by definition negligible to strictly hatchery stocks such as the Carson stock. For hatchery stocks that are integrated with wild production, they may represent lower risk than the wild population itself since egg to fry survival is enhanced, creating more opportunity to have surplus fish available for reintroduction. However, it should be noted that surplus fish are a goal of these programs, in order to increase the abundance of wild fish, thus use of these fish are possibly an impediment to recovery. An example of such a situation in a reintroduction program is in the Okanogan River for Spring Chinook Salmon. In this program, the Methow Composite stock is being used from eggs that are surplus to recovery needs within the Methow River basin (NMFS 2014a). It is possible that such a source would be available for Spring Chinook Salmon of this stock, with the further expansion of aquaculture operations at the Chief Joseph Hatchery and in the Okanogan River basin.



5.5 Conclusions and recommendations

Risks can be somewhat mitigated by donor stock selection, but mitigation of risks is also strongly influenced by technique of the reintroduction itself (e.g., hatchery practices, release strategies, number of fish introduced etc.). Thus, while the recommendations here focus on donor stock selection, this is not a replacement for a comprehensive risk management program, including extensive pathogen screening and modeling exercised to determine numbers of fish (or gametes) used for reintroduction purposes. We reviewed four main categories of risk (evolutionary, disease, ecological and demographic).

There are compelling reasons to suggest higher risk of using stocks from increasing geographic distance for evolutionary reasons. We do not recommend the use of stock from outside the most proximate neighboring ESUs (i.e., Upper Columbia) for both Spring and Summer-Fall Chinook Salmon.

Review of literature on the described diseases suggests that certain donor stocks tend to have higher incidence of pathogens than others examined in this analysis. In particular, the Yakima donor stock tended to have more positive detections of the pathogens described, and use of out-of-basin stocks from within the interior Columbia River basin may increase the probability of introducing a different clade of IHN. Despite these findings, some of these results may be biased by the increased surveillance effort or available literature for some of these stocks. Thus, we suggest that most stocks should be considered as data deficient. The methodology of our assessment is not designed to, nor intended to be, a replacement for a comprehensive pathogen screening and mitigation strategy (Anderson et al. 2014), which may include decisions of introducing only certain life stages which inherently carry lower risk of introducing novel diseases. We recommend the development of a thorough strategy, regardless of the donor stock chosen.

Clear demographic risks arise by using wild donor stocks that have small population sizes, as their use may reduce the viability of the donor stocks in their native populations. Use of donor populations from small wild populations may also pose unacceptable evolutionary risks to both the donor and founding population, as small numbers of fish in either case could increase inbreeding and reduce genetic diversity. Some of these risks may be at least partially mitigated by using interventionist reintroduction strategies involving hatcheries or possibly by mixing gametes to form composites within ESUs. Multiple donor stock introduction techniques in general may aid the success of any reintroduction program by maximizing diversity in the founding population. Use of these increasingly interventionist reintroduction strategies inherently carry their own risks, and careful design of reintroduction programs and monitoring, coupled with adaptive management are recommended if any are to be employed. Several donor stocks assessed in this study from the Upper Columbia Summer-Fall ESU appear to be associated with least risk in general because of their geographic proximity, homogenous population structure, and large population sizes.



6 Other Factors Influencing Donor Stock Assessment

This donor stock assessment was largely focused on selecting a donor stock which would be most likely to naturalize in the Transboundary Reach of the Columbia River, while posing the least amount of risk to the receiving and surrounding ecosystems and to the donor population itself. There are other factors which may influence the choice of donor stock selection, beyond what has been explicitly and thoroughly considered in this study.

Reintroduction strategy will heavily influence the reintroduction process. Passive reintroduction using natural colonization may be identified as preferred least-risk alternative (Anderson et al. 2014). In the context of reintroducing a population to the Transboundary Reach, it is highly uncertain whether this would result in short-term success given the lack of immediate proximity of spawning areas to the most downstream barrier, and the propagule size of the founding population of strays that would be passed above Chief Joseph Dam. Increased evolutionary risk to the founding population may also reduce the suitability of this strategy if propagule size is very limited. An intuitive source of fish may be found by selecting wild origin fish that attempt to ascend the ladder at the Chief Joseph Hatchery, near the base of Chief Joseph Dam (i.e., the Upper Columbia mainstem Summer-Fall donor stock assessed in this study). Rapid DNA analysis could determine the origin of these fish, and if they conform to a population of donor stocks considered acceptable for reintroduction to the Transboundary Reach (sensu DeHaan et al. 2011). There might be greater probability of success if adult fish are directly transported to putative spawning locations at the Transboundary Reach or if propagule size could be artificially increased by treating these fish as broodstock for hatchery. Initial reintroduction phases should investigate the feasibility, benefits and risks of these potential strategies for such a spectrum of intervention in supporting recolonization. Some of these risks are explored in section 5.1.1.

Donor stock selection may be influenced by the active strategy taken for situations of translocating donors, particularly considering what acceptable genetic, or demographic risks there are to donor populations by taking a given target number of any specific lifecycle stage (sections 5.1, 5.4). Regardless of the donor stock used, stocking practices do influence the success of the reintroduction, and persistent, long term stocking efforts are likely to have more success than short term, limited efforts (Cochran-Biederman et al. 2015). Conceptual target numbers of translocated or brood donor fish have been calculated for reintroduction planning in the San Joaquin River, including numbers needed for translocating various lifecycle stages (SJRRP 2010, 2011). A similar consideration was made in the Clackamas River, when reintroducing Bull Trout (USFWS and ODFW 2011). These programs have very specific allocations on the numbers of fish taken for reintroduction purposes, and can span multiple techniques (introduction of juveniles, translocated adults, etc.). These allocations are realistically driven by the projected demographic impacts to the donor population, as well as the target numbers which are considered necessary for successful reintroduction. Thus, the selection of donor stocks is intimately interwoven with the reintroduction strategy taken, especially when considering availability of fish or gametes for translocation or brood.



Further introductions beyond the Transboundary Reach are also likely to require further donor stock suitability assessments. The nature of these assessments is yet to be determined, but is highly dependent on integrated basin-wide reintroduction planning. If reintroductions are planned to occur sequentially upstream through the basin, an established population in the Transboundary Reach could provide an opportunity to act as a “stepping stone” as a donor for habitats further upstream. The suitability of this approach is highly uncertain, and would ideally be assessed using a basin-wide perspective. The same logic applies to tributaries or riverine habitats found downstream of the Transboundary Reach but upstream from Chief Joseph Dam (Hanrahan et al. 2004), which may be colonized prior to the Transboundary reach from concurrent or prior reintroduction attempts. Thus, there could be additional donor stock sources that arise in the interim for a Transboundary Reach reintroduction.

Donor stock availability may change, and it may be desirable to allow reintroduction efforts to coincide with periods that are favorable for certain life histories of Chinook Salmon to thrive (Anderson et al. 2014). For instance, recent recovery and large escapements of Fall Chinook Salmon in particular in the Columbia Basin may reflect a favorable time period for reintroducing these life history forms due to availability of donor stocks and high contemporary survival. If these trends change significantly in the future, this may point to obvious shifts in suitability of certain types of donor stocks (i.e., life histories) that will be resilient to future change or dominant conditions that influence survival. Along with natural regime changes (e.g., North Pacific Gyre Oscillation; Kilduff et al. 2015) that influence salmon survival, climate change may further change the reference points that determine survival of certain life history pathways of Chinook Salmon. Increasing temperatures in the lower river may create extended periods of migration blocking temperatures for later migrating (summer and fall) Chinook Salmon. The same increasing temperatures may also disrupt maturation or create high prespawn mortality for premature migrants (e.g., Spring run) in the Reintroduction Reach, thus reducing their suitability as well. Further changes in shifts to incubation temperatures, natural disturbance regimes, fish community change or changes in lower river, estuarine or ocean conditions due to climate change further increase uncertainty of the life history pathways that may ultimately persist in the Transboundary Reach. Thus, when considering donor stocks, it is important to recognize that salmon survival is temporally variable among stocks, and thus reintroduction strategies must adapt to this variation.

There are social, ceremonial and cultural aspects clearly influence the long term management objectives for the reintroduced population, and this in turn may influence the choice of donor stock. Providing harvest opportunity is a key objective of science based indigenous fisheries conservation and management programs which have been developed throughout the Columbia River basin (Smith 2014). There may be more important times for fishing for ceremonial purposes or timings that are more conducive for a fishery, or to limit bycatch on native species of conservation concern (e.g., White Sturgeon). In addition, quality of meat for consumption at terminal fisheries may be an important consideration for donor stock selection when harvest is a clear objective of the reintroduction. Chinook Salmon that immigrate in an advanced state of maturity (e.g. Fall Chinook Salmon) typically are of poor quality for human consumption at terminal fisheries, relative to premature immigrants and would thus be less desirable to meet harvest objectives (C. Baldwin, personal communication). This is especially



important for Tribes and First Nations, for which harvest satisfies multiple social objectives including ceremonial, health and economic values (Columbia Basin Tribes and First Nations 2015). Hatchery programs can exist with the goal of having them completely isolated from wild production, if the population is segregated from any existing wild populations (HSRG 2009). The segregation of these stocks can be enhanced by hatchery practices that may reduce straying and interactions with wild populations, thus reducing the risks these populations may pose to wild fish (section 5.1.1). Segregated hatchery stocks are managed for harvest purposes, and there are many examples of their use in the Columbia River Basin (HSRG 2009).

Legal considerations will almost certainly influence donor stock selection, or at least the regulatory process for using certain donor stocks. In reintroductions in the United States, which applied to species or populations listed under the Endangered Species Act (ESA), special designations of reintroduced populations as experimental, nonessential 10(j) were granted to Bull Trout in the Willamette River basin (USFWS and ODFW 2011), Spring Chinook Salmon in the Okanogan River basin (NMFS 2014a), as well as other programs in the Deschutes and San Joaquin Rivers. A similar approval process may be necessary if donor stocks considered in this analysis that are listed under the ESA were selected for reintroduction; however, their introduction beyond an international border would likely warrant further regulatory uncertainties. 10(j) programs are approved because rigorous pre-assessment suggests their implementation will further the conservation and recovery of the species. In the example of the Bull Trout reintroduction, wild donor stock sources were used for reintroduction, using a variety of reintroduction strategies, as a nearby (but out of basin) donor population existed which was found to have acceptable population sizes to support taking of wild fish (USFWS and ODFW 2011). In the example of the Spring Chinook Salmon reintroduction in the Okanogan River basin, no such neighboring populations from within the upper Columbia Spring ESU were used for taking of wild individuals, and only use of excess production from an integrated hatchery program were available. In this analysis, we examined several donor populations from the Upper Columbia Spring ESU; as in the case of the Okanogan River, it is highly unlikely that reintroduction strategies would be able to make use of wild fish for the purposes of reintroduction. Therefore, if any donor populations from this ESU were used, they would likely arise from an integrated hatchery program (e.g., Methow composite) with excess production. This narrows the options of Spring Chinook Salmon considerably. With respect to any of the ESA listed populations that are from out of basin (e.g., Snake River fall ESU or Snake River Spring ESU), it is highly uncertain whether 10(j) status would be granted, especially considering how the reintroduced population would justifiably contribute to the recovery and conservation of the listed species. Although Okanogan Chinook Salmon have been assessed by the Committee on the Status of Endangered Wildlife in Canada, Canada has no formal corresponding listing status to the ESA for Chinook Salmon in the Columbia River basin under the Species at Risk Act (SARA); however, there are species listed under SARA (e.g., Upper Columbia White Sturgeon) which may be affected, and hence the impact of differing donor stocks on these species would have to be considered. Both SARA and ESA listings are subject to regular review, thus recovery of potential donor populations (or other affected species) may allow revisiting the suitability of donor stocks assessed in this study in the future. Other regulatory processes within Canada would likewise also consider aspects of donor stock selection. For instance, introductions that involve transfers of fish within Canada would be subject to review by the federal-provincial Introductions and



Transfers Committee, following provisions of the National Code on Introductions and Transfers of Aquatic Organisms. For any introduction that will result in fish crossing an international border, a review through the International Council for the Exploration of the Sea process may need to be undertaken, which the National Code mirrors, and consultation between the US and Canada would need to occur. Other departments, such as the Canadian Food Inspection Agency, may also be required to participate in a regulatory capacity depending on the reintroduction strategy. With respect to all these pieces of legislation, the intent is generally to reduce risk, which component four of this document could help inform with respect to mitigating risks through appropriate donor stock selection.



7 Synthesis of Components, Conclusions and Recommendations

The four components of this study considered different aspects of donor stock suitability for reintroduction to the Transboundary Reach of the Columbia River for the purposes of forming a self-sustaining population that contributes to existing metapopulation viability. Genetic (ancestry) suitability of potential donor stocks was first considered, followed by the adaptive potential of donor stocks or use of multiple donor stock introduction strategies. Both of these components relied heavily on information available from genetic analysis of neutral microsatellite markers. Environmental or ecological suitability of each donor stock was then considered (Houde et al. 2015a) based on quantitative modeling, and finally we determined risks associated with the use of potential donor stocks (Anderson et al. 2014) by literature review. Although we make no attempt to weight the relative importance of any of these components, weight of evidence suggests those originating from the Upper Columbia Summer-Fall ESU (Wells Hatchery Summer-Fall, Wenatchee Summer-Fall, Methow Summer-Fall, Okanogan Summer-Fall, Upper Columbia Mainstem Summer-Fall, Hanford Reach Fall) have consistently the highest suitability (Table 7-1; Appendix 3). Within this ESU, the most suitable stock is not apparent from our study, and use of any particular stock or suite of these stocks is heavily influenced by the reintroduction strategy taken. Interventionist reintroduction strategies using hatcheries or multiple donor stocks, alternate reintroduction objectives (e.g., harvest), legal and logistical reasons may justify the use of stocks deemed less suitable by various components of this analysis. These strategies may correspondingly increase some risks, which require careful reintroduction planning and implementation.



Table 7-1: Suitability of each assessed donor stock, according to the results of each component. Higher (green) or lower (red) suitability classifications are based on key rationales summarized in Appendix 3. Higher or lower classifications for the risk component refer to suitability (i.e., the inverse of literal reference to higher or lower risk). Unknown suitability (uncolored) arises from insufficient information, and conflicting suitability (uncolored) arises where there are relatively balanced, but conflicting suitability results within the component.

Donor stock	Component 1: Ancestry matching	Component 2: Adaptive potential	Component 3: Environment matching	Component 4: Evolutionary Risks	Component 4: Disease Risks	Component 4: Ecological Risks	Component 4: Demographic Risks
Middle Shuswap River (Fraser)	Lower	Lower	Unknown	Lower	Unknown	Unknown	Unknown
Wells Hatchery Summer-Fall	Higher	Higher	Higher	Conflicting	Unknown	Unknown	Higher
Wenatchee Summer-Fall	Higher	Higher	Higher	Higher	Unknown	Unknown	Higher
Methow Summer- Fall	Higher	Higher	Higher	Higher	Unknown	Unknown	Unknown
Okanogan Summer-Fall	Higher	Higher	Higher	Higher	Unknown	Unknown	Higher
Upper Columbia Mainstem Summer-Fall	Unknown	Unknown	Higher	Higher	Unknown	Unknown	Unknown
Hanford Reach Fall	Higher	Higher	Higher	Higher	Unknown	Unknown	Higher
Snake River Fall	Lower	Conflicting	Higher	Lower	Lower	Unknown	Lower
Swift Creek/Tete Jaune (Fraser)	Lower	Lower	Unknown	Lower	Unknown	Unknown	Lower
Stuart River (Fraser)	Lower	Conflicting	Unknown	Lower	Unknown	Unknown	Lower
Nicola River (Fraser)	Lower	Lower	Unknown	Lower	Unknown	Unknown	Lower
Wenatchee Spring	Higher	Lower	Lower	Conflicting	Unknown	Unknown	Lower
Methow composite	Higher	Lower	Lower	Conflicting	Unknown	Unknown	Unknown
Carson	Higher	Lower	Lower	Lower	Unknown	Unknown	Higher
Yakima Spring	Lower	Conflicting	Conflicting	Lower	Lower	Unknown	Unknown
South Fork Salmon Spring-Summer	Lower	Lower	Lower	Lower	Lower	Unknown	Lower



In the first component of this study, suitability was assessed based on the theory of ancestry matching, where the closest related extant stock should be the most appropriate because they are most likely to share adaptations with the ancestral stock (Houde et al. 2015a). Thus the use of stocks locally derived from the most proximate ESUs (Upper Columbia of both life history types) is recommended from this perspective. These stocks are likely to share the closest evolutionary ancestry with the historic stock(s) that completed their life cycles within the Transboundary Reach. Use of neighboring stocks also allows for integrated management of the greater metapopulation of these ESUs, which could help foster viability and/or recovery in the future, and reduce evolutionary risks (Anderson et al. 2014).

The second component of the study provided a quantitative analysis of adaptive potential, using neutral genetic diversity and population size as proxies for adaptive variation. The overarching result from this component is that Summer-Fall life histories in the Interior Columbia River basin are of the highest diversity when compared to stocks from the Fraser River Basin and those from the Spring run life history in the Columbia River basin. While our methodology is commonly practiced using molecular tools in contemporary molecular ecology, it is important to note that neutral genetic diversity and population size are not a perfect proxies for adaptive diversity, and novel genomic tools which are not commonly used today may allow for more detailed assessment of adaptive potential in future donor stock analyses (He et al. 2016). Use of multiple donor stocks may increase the adaptive potential of the founding population, which could allow more rapid exploitation of vacant niches. Probability of establishment and positive population growth may also be increased by selecting stocks that express more diversity in traits that are heritable and known to influence survival or reproductive success. Because Summer-Fall run life histories in the interior Columbia River basin contemporaneously express high diversity in juvenile life history pathway, this may similarly reflect increased adaptive potential of these populations if the underlying basis for this diversity is heritable. Selection of stocks that are of low diversity may increase evolutionary risks and demographic risks to both the donor and newly founded population, especially if establishment success is limited.

In the third component of the analysis, we determined the potential suitability of donor stocks to complete their lifecycle in the Transboundary Reach, based on a quantitative modeling assessment. Life cycle modeling and suitability analysis suggested that donor stocks that are Spring run in the Columbia River basin appear to have no potential difficulties in accessing the Reintroduction Reach to hold prior to spawning; however, they were predicted to have heritable life cycle timing which expose them to adverse conditions during the lengthy pre-spawn holding period, spawning, incubation and fry emergence. Most of this lack of suitability predicted in our analysis is driven by the thermal regime of the Transboundary Reach, which is a low elevation, mainstem river environment which remains much warmer into the fall than the typical headwater streams in which Spring run life histories complete their life cycle. Indeed, previous assessments have found that thermal regime in freshwater is the overriding abiotic variable that drives life history in Chinook Salmon (Brannon et al. 2004), and spawn timing to capitalize on thermally suitable periods is a key predictor of the success of donor stocks in reintroduction efforts (Schneider 2011). For these reasons, Spring run donor stocks are unlikely to meet the reintroduction objectives of forming a self-sustaining population in the mainstem river of the Transboundary Reach. Their use may satisfy other reintroduction outcomes (e.g., segregated harvest) or



result in successful colonization elsewhere in the basin that is outside of the geographic area this study focused on. Stocks from the Fraser River basin were not considered in the third component, so we are uncertain whether they would present an environment match. Life cycle modeling suggests delayed estuary arrival timing of all modeled juvenile life history pathways, and protracted migration timing beyond the currently managed spill period and into later summer months may result in survival challenges to subyearlings in particular. The relative suitability of juvenile life history pathways is relatively uncertain, as smolt to adult survival is heavily dependent on later life cycle stages in the estuary and ocean which were not modeled. A key shortcoming of our environment match component is the basis of comparing the average condition of donor stock traits (e.g., spawn timing) to average conditions in the environment they encounter. Both of these elements are quantified and assessed without accounting for the full range of variability or phenotypic plasticity that may result when transplanted to a novel environment. For these and other reasons, the environment match component does not provide the methodology to suggest any particular donor stock, but strongly suggests the higher suitability of Summer-Fall run life histories from the interior Columbia River basin. Further refinements to the models used, incorporation of additional stocks (i.e., Fraser River) or integration with adaptive potential considerations, are recommended courses of further research to refine recommendations of specific locally adapted donor stocks, or the practical use of multiple stocks.

Donor stocks of the Summer-Fall run life history have multiple, highly diverse and locally derived options within the proximate Upper Columbia Summer-Fall ESU. These stocks appear largely pre-adapted to the receiving environment from both ancestry and environment matching perspectives, and their availability makes them potentially suitable for a variety of reintroduction strategies while posing lower evolutionary and demographic risk, as outlined in component four. Since these stocks migrate as adults later than Spring Chinook Salmon, they may encounter thermally stressful or migration blocking temperatures in the estuary or lower river environment during immigration, particularly with climate change. These stocks are also typically heavily exploited in fisheries, possibly creating impediments to colonization through bycatch in mixed-stock ocean and river fisheries. Thus Summer-Fall stocks may have higher suitability for the reintroduction objectives of forming a self-sustaining population in the near-term, but the specific stocks that may be successful are uncertain and the suitability of the life history in general may be further constrained or altered by climate change and harvest. The specific stock within the Upper Columbia Summer-Fall ESU with the highest probability of success cannot be confidently projected given the crudity and uncertainty of the various components of this study, so it may be advisable to select a variety of stocks and experimentally determine the most suitable option or simply allow selection to work upon the diversity of multiple stocks. The tactic that may indeed allow the greatest breadth of life history diversity available for local adaptation during colonization would be to select stocks representing a variety of life history adaptations and timings (e.g., one of each summer and fall runs, or multiples of each). Ideally, stocks within this ESU should be selected to cover the full breadth of the thermally suitable spawning period (primarily October and November) in the Transboundary Reach, which may maximize expression of diversity in prior and subsequent life stages and conditions for stabilizing selection to occur.



Donor stock selection analyses in this report may be further refined, but donor stock choices are also realistically constrained by logistics, regulatory approval processes and availability of surplus donor fish (or their gametes) and subject to the reintroduction strategy used. It should be noted that decisions of donor stock selection are highly intertwined with decisions regarding the reintroduction strategy taken (Anderson et al. 2014). The strategies available are discussed throughout this document, and range from benign (natural recolonization by providing passage) to interventionist (e.g., hatchery outplanting). A recommendation of reintroduction strategy is beyond the scope of this study, but discussion is provided throughout as to how donor stock selection relates to the chosen strategies for reintroduction. Donor stock selection analyses used in this study are also based on models which use imperfect data and assumptions that approximate, but do not fully capture, the fundamental biological aspects or range of diversity and plasticity that influence survival of Chinook Salmon. Models and quantitative diversity data used also provide a contemporary suitability estimate, largely influenced by recent stock attributes and environmental conditions. In reality, these are dynamic, often unpredictable, and reintroduction programs must be flexible to adapt to changing conditions which might favor the life histories or other adaptations of alternate donor stocks in the future (Anderson et al. 2014). In the case of forming a self-sustaining population, rapid exploitation of a vacant niche for Chinook Salmon and selection or plasticity to optimize life history strategy(s) is likely to take place if habitat carrying capacity is high (Quinn et al. 2000, Anderson et al. 2014), and some degree of phenotypic plasticity is to be expected. In the case of some stocks that appear to have limited probability of success for the objective of forming a self-sustaining population (e.g., Spring run stocks), these stocks may not necessarily be discounted as candidates, as they may fulfill other objectives for reintroduction (e.g., harvest opportunities), and there may be environmental niches outside our geographic area of focus that could potentially support colonization of these life history forms.

We do recommend considering the use of a multi-stock approach if active reintroduction strategies are chosen. Additional pre-assessment of risks and careful attention to monitoring programs are a necessity if multiple stock approaches are taken, as is being considered in Chinook Salmon reintroductions elsewhere along the Pacific coast (SJRRP 2010, NMFS 2014b). Multiple-stock approaches may allow for practical bet hedging in cases where pre-assessment does not suggest the use of any particular donor stock (Houde et al. 2015a), as is the case in this study with respect to population structure at the local stock level. However, using multiple stocks may also complicate monitoring efforts in reintroduction and lead to possible undesirable evolutionary effects such as outbreeding depression which may not be detected until the second generation or beyond (Houde 2015, Houde et al. 2015a). The likelihood of such negative effects may be mitigated in advance through donor stock selection if closely related stocks or stocks sharing similar environments are used. Stocks originating from the Upper Columbia Summer-Fall ESU may be at the least risk of those examined, as these stocks inhabit similar environments, and population structure is estimated to be relatively homogenous in this ESU at least at neutral genetic markers, suggesting high levels of contemporary gene flow or large effective population size (Kassler et al. 2011). Additional pre-assessment of heritable genetic variation may also help inform whether multiple stock techniques are likely to result in increasing adaptive potential in the founding population (Houde 2015), and novel genomic tools are increasingly available as assessment tools (He et al. 2016). Monitoring must be carefully designed, with processes in place for decision making to adapt the



reintroduction program if outbreeding depression is detected or donor stocks have differences in survival (SJRRP 2010), which would allow resources to be focused on the donor stock with the highest success.

Donor stock selection is just one of many considerations in evaluating whether reintroduction will succeed or how it is best implemented (Cochran-Biederman et al. 2015). The definition of success in and of itself is also highly subjective, as there may be multiple goals of reintroduction, some of which may be for conservation or recovery purposes and others entirely for social purposes. The goal of this study was primarily to determine which stocks would be most appropriate as donors for a reintroduction focused on establishing a self-sustaining population. The underlying driver of such a reintroduction would be to enhance long-term resiliency and recovery of Chinook Salmon in the Columbia River Basin (Anderson et al. 2014). Ultimately, there will be social, legal and logistical reasons that may also impact donor stock selection, and there is discussion throughout this document on the suitability of stocks given some of these potential aspects. Harvest objectives in particular are of great importance to First Nations and Tribes, and the use of stocks that have higher quality of meat for consumption at terminal fisheries or provide opportunities for harvest without providing clear conservation objectives must also be considered. It is important to note that reintroduction programs can successfully satisfy multiple objectives, including harvest (Galbreath et al. 2014), thus programs that use different donor stocks to fulfill multiple reintroduction objectives are a viable option to reintroducing Chinook Salmon to the Transboundary Reach.



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9 Appendices

9.1 Appendix 1

FST matrix of 32 populations from throughout the Columbia Basin and Fraser Basin

FST matrix - all

pop	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	
2	0.0424																															
3	0.0633	0.0550																														
4	0.0873	0.0991	0.0710																													
5	0.0618	0.0608	0.0450	0.0611																												
6	0.0113	0.0497	0.0770	0.0964	0.0696																											
7	0.0925	0.0960	0.0661	0.0049	0.0623	0.0966																										
8	0.0976	0.0938	0.0623	0.0443	0.0574	0.1099	0.0395																									
9	0.0945	0.0992	0.0703	0.0045	0.0642	0.0989	-0.0005	0.0413																								
10	0.1025	0.1048	0.0891	0.0832	0.0479	0.1133	0.0876	0.0852	0.0895																							
11	0.0821	0.0896	0.0697	0.0026	0.0634	0.0881	0.0079	0.0469	0.0060	0.0862																						
12	0.1004	0.0967	0.0693	0.0654	0.0705	0.1053	0.0656	0.0260	0.0655	0.0987	0.0655																					
13	0.0028	0.0388	0.0675	0.0947	0.0675	0.0133	0.0960	0.1056	0.0978	0.1105	0.0890	0.1064																				
14	0.1025	0.1044	0.0724	0.0149	0.0709	0.1076	0.0047	0.0424	0.0053	0.1001	0.0177	0.0737	0.1043																			
15	0.0516	0.0301	0.0586	0.0940	0.0543	0.0618	0.0972	0.0846	0.0994	0.0921	0.0909	0.0824	0.0535	0.1089																		
16	0.0321	0.0122	0.0380	0.0792	0.0435	0.0428	0.0777	0.0760	0.0802	0.0839	0.0746	0.0808	0.0321	0.0866	0.0175																	
17	0.0635	0.0622	0.0472	0.0679	0.0099	0.0715	0.0706	0.0744	0.0730	0.0491	0.0718	0.0834	0.0688	0.0806	0.0579	0.0441																
18	0.0386	0.0187	0.0357	0.0866	0.0487	0.0480	0.0860	0.0782	0.0886	0.0931	0.0824	0.0839	0.0384	0.0949	0.0227	0.0097	0.0466															
19	0.0565	0.0449	0.0148	0.0679	0.0372	0.0677	0.0630	0.0552	0.0682	0.0844	0.0671	0.0662	0.0601	0.0688	0.0543	0.0313	0.0396	0.0302														
20	0.0490	0.0287	0.0442	0.0735	0.0437	0.0578	0.0754	0.0610	0.0766	0.0820	0.0704	0.0658	0.0515	0.0854	0.0147	0.0178	0.0472	0.0207	0.0385													
21	0.0124	0.0417	0.0696	0.0994	0.0614	0.0192	0.1017	0.1106	0.1055	0.1105	0.0930	0.1077	0.0125	0.1131	0.0521	0.0341	0.0650	0.0418	0.0620	0.0505												
22	0.0647	0.0641	0.0487	0.0617	0.0144	0.0752	0.0648	0.0671	0.0662	0.0409	0.0634	0.0770	0.0700	0.0750	0.0631	0.0466	0.0102	0.0548	0.0443	0.0491	0.0676											
23	0.0341	0.0163	0.0374	0.0826	0.0428	0.0437	0.0811	0.0755	0.0842	0.0858	0.0786	0.0824	0.0349	0.0910	0.0260	0.0024	0.0424	0.0099	0.0287	0.0233	0.0369	0.0478										
24	0.0724	0.0404	0.0632	0.1092	0.0652	0.0852	0.1116	0.0970	0.1149	0.1091	0.1061	0.0973	0.0755	0.1225	0.0207	0.0299	0.0651	0.0290	0.0530	0.0277	0.0702	0.0750	0.0328									
25	0.0439	0.0250	0.0498	0.0828	0.0424	0.0537	0.0857	0.0738	0.0884	0.0812	0.0816	0.0785	0.0466	0.0965	0.0039	0.0113	0.0450	0.0183	0.0404	0.0128	0.0449	0.0526	0.0165	0.0167								
26	0.0166	0.0499	0.0893	0.1178	0.0903	0.0311	0.1183	0.1291	0.1207	0.1292	0.1087	0.1277	0.0093	0.1265	0.0679	0.0472	0.0942	0.0552	0.0838	0.0701	0.0267	0.0947	0.0518	0.0908	0.0630							
27	0.0168	0.0482	0.0607	0.0833	0.0611	0.0220	0.0839	0.0893	0.0860	0.1021	0.0771	0.0967	0.0172	0.0959	0.0565	0.0360	0.0642	0.0397	0.0551	0.0533	0.0214	0.0657	0.0380	0.0792	0.0493	0.0358						
28	0.0206	0.0539	0.0671	0.0841	0.0619	0.0269	0.0822	0.0960	0.0830	0.1064	0.0776	0.1036	0.0200	0.0936	0.0637	0.0424	0.0650	0.0452	0.0608	0.0588	0.0286	0.0661	0.0455	0.0884	0.0554	0.0411	0.0014					
29	0.0961	0.1007	0.0715	0.0138	0.0712	0.1022	0.0039	0.0440	0.0041	0.0974	0.0158	0.0742	0.0985	0.0007	0.1060	0.0834	0.0805	0.0920	0.0692	0.0841	0.1067	0.0742	0.0877	0.1203	0.0943	0.1204	0.0895	0.0899				
30	0.0102	0.0374	0.0656	0.0905	0.0582	0.0202	0.0916	0.1038	0.0931	0.1027	0.0878	0.1043	0.0089	0.0999	0.0484	0.0292	0.0603	0.0376	0.0571	0.0467	0.0162	0.0613	0.0301	0.0669	0.0404	0.0228	0.0222	0.0277	0.0977			
31	0.1040	0.1078	0.0745	0.0164	0.0704	0.1078	0.0058	0.0440	0.0062	0.1004	0.0192	0.0745	0.1061	0.0007	0.1106	0.0888	0.0820	0.0969	0.0710	0.0873	0.1146	0.0759	0.0934	0.1247	0.0990	0.1301	0.0957	0.0929	0.0014	0.1014		
32	0.0075	0.0384	0.0702	0.0964	0.0628	0.0178	0.0983	0.1105	0.0996	0.1017	0.0916	0.1084	0.0041	0.1074	0.0516	0.0314	0.0648	0.0398	0.0623	0.0529	0.0151	0.0671	0.0349	0.0730	0.0443	0.0168	0.0202	0.0234	0.1034	0.0018	0.1093	

Indices for populations:

1	CarsonH	11	LyonsFer	21	SeceshR	31	Wenatchee Fall
2	ChilkoR	12	MShuswap	22	SpiusH	32	Wenatche Spring
3	Clearwater Fraser	13	MethowR spr	23	StuartR		
4	Clearwater Sanke	14	MethowR s/f	24	SwiftR		
5	DeadmanH	15	MorkillR	25	TorpyR		
6	EntiatH	16	NechakoR	26	TwispRSp		
7	HanfordR	17	NicolaH	27	UYakimaH		
8	LAdamsH	18	QuesnelR	28	Uyakima Spr		
9	LYakimaF	19	RaftR	29	WellsH		
10	LouisCr	20	SalmonRs	30	Wenatchee Hatchery		



9.2 Appendix 2

Timing of critical life history events for assessed donor stocks. Dates refer to Julian day of the year.

Donor Stock	Dates of arrival at Bonneville Dam			trav el rate (km/ d)	Spawn dates			References used
	25th quart ile (or rang e) (Julia n Day)	Mea n, medi an or peak (Julia n Day)	75th quart ile (or rang e) (Julia n Day)		Minim um (Julian Day)	Mea n or pea k (Juli an Day)	Maxim um (Julian Day)	
Wells hatchery Summer-Fall; wild component mainstem wells	169	180	191	31	286	298	303	(Keefer et al. 2004a, Keefer et al. 2004b, Keefer et al. 2004c, Miller 2007)
Wenatchee Summer-Fall	170	177	183	28	272	286	307	(Keefer et al. 2004a, Keefer et al. 2004b, Keefer et al. 2004c, Hillman et al. 2011)
Methow Summer-Fall	162	179	196	28	265	286	314	(Keefer et al. 2004a, Keefer et al. 2004b, Keefer et al. 2004c, Hillman et al. 2011)
Okanogan Summer-Fall	178	184	191	29	265	279	321	(Keefer et al. 2004a, Keefer et al. 2004b, Keefer et al. 2004c, Hillman et al. 2011)
Hanford Reach upriver bright Fall	245	253	260	24	289	315	335	(Dauble and Watson 1990, Jepson et al. 2010)
Snake River Fall	239	247	253	26	288	308	338	(Jepson et al. 2010, Groves et al. 2012)
Upper Columbia Mainstem Summer-Fall *	169	180	191	31	295	312	326	(Keefer et al. 2004a, Keefer et al. 2004b, Keefer et al. 2004c, Mann et al. 2014)
Wenatchee Spring (natural)	105	112	120	22	216	244	272	(Keefer et al. 2004a, Keefer et al. 2004b, Keefer et al. 2004c, Hillman et al. 2011)
Methow Composite Spring (wild component associated with hatchery)	105	112	120	22	216	244	272	(Keefer et al. 2004a, Keefer et al. 2004b, Keefer et al. 2004c, Hillman et al. 2011)
Carson Hatchery (Wind River)	109	118	126	22	213	236	258	(Keefer et al. 2004a, Keefer et al. 2004b, Keefer et al. 2004c, HSRG 2009)
Upper Yakima Spring	110	119	128	22	261	270	309	(Keefer et al. 2004a, Keefer et al. 2004b, Keefer et al. 2004c, Knudsen et al. 2005)
South Fork Salmon River Spring-Summer	137	148	158	29	228	246	267	(Keefer et al. 2004a, Keefer et al. 2004b, Keefer et al. 2004c, Young and Blenden 2011)

* dates of arrival at Bonneville Dam assumed to correspond to those for the Wells Dam



Modeled emergence timings for donor stocks, based on egg development models of (Beer and Anderson 1997, Beer 1999). Negative dates indicate the number of Julian Days prior to January 1, where emergence occurs during the same year of spawning (i.e., eggs are not modeled to overwinter).

Donor Stock	Modeled emergence dates				
	Minimum (Julian Day)	25th (Julian Day)	Mean or peak (Julian Day)	75th (Julian Day)	Maximum (Julian Day)
Wells hatchery Summer-Fall; wild component mainstem wells	110	120	130	133	136
Wenatchee Summer-Fall	76	93	110	126	142
Methow Summer-Fall	55	83	110	128	146
Okanogan Summer-Fall	55	76	96	125	153
Hanford Reach upriver bright Fall	115	132	149	156	163
Snake River Fall	113	128	142	154	165
Upper Columbia Mainstem Summer-Fall	125	135	145	151	157
Wenatchee Spring (natural)	-102	-68	-34	21	76
Methow Composite Spring (wild component associated with hatchery)	-102	-68	-34	21	76
Carson Hatchery (Wind River)	-106	-83	-60	-17	26
Upper Yakima Spring	38	55	72	107	143
South Fork Salmon River Spring-Summer	-80	-52	-25	19	63



9.3 Appendix 3

Primary rationale for suitability classifications of higher (green), lower (red), or unknown/conflicting (uncolored) as outlined in Table 7-1. Higher or lower classifications for the risk component refer to suitability (i.e., the inverse of literal reference to higher or lower risk). Unknown suitability (uncolored) arises from insufficient information, and conflicting suitability (uncolored) arises where there are relatively balanced, but conflicting suitability results within the component.

Donor stock	Component 1: Ancestry matching	Component 2: Adaptive potential	Component 3: Environment matching	Component 4: Evolutionary Risks	Component 4: Disease Risks	Component 4: Ecological Risks	Component 4: Demographic Risks
Middle Shuswap River	Distantly related to surrogate stock	Low allelic diversity and heterozygosity	Not assessed	Out of ESU	No clear evidence of introducing a novel pathogen, but limited information on the stock	No compelling evidence to suggest donor stocks differ in risk	Mid population size
Wells Hatchery Summer-Fall	Closely related to surrogate stock	High allelic diversity and heterozygosity, life history expresses diverse juvenile pathways	Compatibility of environmental conditions with generalized life cycle timing	Within ESU; dependent on hatchery practices so possible risks if poorly managed	No clear evidence of introducing a novel pathogen, but limited information on the stock	No compelling evidence to suggest donor stocks differ in risk	Hatchery strain
Wenatchee Summer-Fall	Closely related to surrogate stock	High allelic diversity and heterozygosity, large population size, life history expresses diverse juvenile pathways	Compatibility of environmental conditions with generalized life cycle timing	Within ESU	No clear evidence of introducing a novel pathogen, but limited information on the stock	No compelling evidence to suggest donor stocks differ in risk	Large population size



Donor stock	Component 1: Ancestry matching	Component 2: Adaptive potential	Component 3: Environment matching	Component 4: Evolutionary Risks	Component 4: Disease Risks	Component 4: Ecological Risks	Component 4: Demographic Risks
Methow Summer-Fall	Closely related to surrogate stock	High allelic diversity and heterozygosity, life history expresses diverse juvenile pathways	Compatibility of environmental conditions with generalized life cycle timing	Within ESU	No clear evidence of introducing a novel pathogen, but limited information on the stock	No compelling evidence to suggest donor stocks differ in risk	Mid population size
Okanogan Summer-Fall	Closely related to surrogate stock	High allelic diversity and heterozygosity, large population size, life history expresses diverse juvenile pathways	Compatibility of environmental conditions with generalized life cycle timing	Within ESU	Novel pathogens have been detected in alternate species in the basin	No compelling evidence to suggest donor stocks differ in risk	Large population size
Upper Columbia Mainstem Summer-Fall	Not assessed	Not assessed	Compatibility of environmental conditions with generalized life cycle timing	Within ESU	No clear evidence of introducing a novel pathogen, but limited information on the stock	No compelling evidence to suggest donor stocks differ in risk	Population size unknown
Hanford Reach Fall	Closely related to surrogate stock	High allelic diversity and heterozygosity, large population size, life history expresses diverse juvenile pathways	Compatibility of environmental conditions with generalized life cycle timing	Within ESU	No clear evidence of introducing a novel pathogen, but limited information on the stock	No compelling evidence to suggest donor stocks differ in risk	Large population size



Donor stock	Component 1: Ancestry matching	Component 2: Adaptive potential	Component 3: Environment matching	Component 4: Evolutionary Risks	Component 4: Disease Risks	Component 4: Ecological Risks	Component 4: Demographic Risks
Snake River Fall	Distantly related to surrogate stock	High allelic diversity and heterozygosity, small population size, life history expresses diverse juvenile pathways	Compatibility of environmental conditions with generalized life cycle timing	Out of ESU	Possibility of introducing novel clade of IHN	No compelling evidence to suggest donor stocks differ in risk	Small population size
Swift Creek/Tete Jaune	Distantly related to surrogate stock	low allelic diversity and heterozygosity, negative population trend	Not assessed	Out of ESU	No clear evidence of introducing a novel pathogen, but limited information on the stock	No compelling evidence to suggest donor stocks differ in risk	Recent negative population trend from mid size
Stuart River	Distantly related to surrogate stock	High allelic diversity, Small population size, low heterozygosity	Not assessed	Out of ESU	No clear evidence of introducing a novel pathogen, but limited information on the stock	No compelling evidence to suggest donor stocks differ in risk	Small population size
Nicola River	Distantly related to surrogate stock	low allelic diversity and heterozygosity, negative population trend	Not assessed	Out of ESU	No clear evidence of introducing a novel pathogen, but limited information on the stock	No compelling evidence to suggest donor stocks differ in risk	Recent negative population trend from mid size
Wenatchee Spring	Closely related to surrogate stock	low allelic diversity and heterozygosity, small population size	Incompatibility of environmental conditions with generalized life cycle timing	Within ESU; diversity risks to founding and donor population	No clear evidence of introducing a novel pathogen, but limited information on the stock	No compelling evidence to suggest donor stocks differ in risk	Small population size



Donor stock	Component 1: Ancestry matching	Component 2: Adaptive potential	Component 3: Environment matching	Component 4: Evolutionary Risks	Component 4: Disease Risks	Component 4: Ecological Risks	Component 4: Demographic Risks
Methow composite	Closely related to surrogate stock	low allelic diversity and heterozygosity, small wild population size	Incompatibility of environmental conditions with generalized life cycle timing	Within ESU; dependent on hatchery practices	No clear evidence of introducing a novel pathogen, but limited information on the stock	No compelling evidence to suggest donor stocks differ in risk	Hatchery strain integrated with wild production; dependent on excess production from existing programs
Carson	Closely related to surrogate stock	low allelic diversity and heterozygosity	Incompatibility of environmental conditions with generalized life cycle timing	Out of ESU	No clear evidence of introducing a novel pathogen, but limited information on the stock	No compelling evidence to suggest donor stocks differ in risk	Hatchery Strain
Yakima Spring	Distantly related to surrogate stock	High heterozygosity, low allelic diversity	Life cycle timing partially overlaps with potentially thermally suitable spawn timings, but pre- spawn holding in high temperatures still may ultimately limit suitability	Out of ESU	Positive detections of several pathogens unknown to occur in reintroduction area	No compelling evidence to suggest donor stocks differ in risk	Mid population size
South Fork Salmon Spring- Summer	Distantly related to surrogate stock	low allelic diversity and heterozygosity, small population size	Incompatibility of environmental conditions with generalized life cycle timing	Out of ESU	Possibility of introducing novel clade of IHN	No compelling evidence to suggest donor stocks differ in risk	Small population size