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TECHNICAL MEMORANDUM

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RE: **Snoqualmie River Chinook Salmon Conceptual Model**

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1. Introduction

The Snoqualmie River Chinook salmon conceptual model provides a structure for organizing information about Chinook life stages including how and when they utilize habitats in the Snoqualmie River watershed and Snohomish River estuary. The conceptual model is based on scientific information detailing life-stage and life-history patterns, highlighting what we known, what we think we know, and what still needs to be determined. The model focuses on patterns specific to Snoqualmie River Chinook; however, when applicable and relevant, we discuss information from the Snohomish River estuary, other areas of the Snohomish Basin, Puget Sound, and the broader Salish Sea. Information included in the Snoqualmie River Chinook salmon conceptual model is organized as follows:

- **What we know** – Information specific to Snoqualmie watershed and Snohomish estuary Chinook salmon life-stage and life-history patterns, habitat associations, limiting factors, and driving variables. This category also includes information based on well-established and published understandings of Chinook salmon behavior, ecology, and related driving variables from areas outside the Snoqualmie watershed and Snohomish Basin, which can be confidently applied to Snoqualmie/Snohomish Chinook populations.
- **What we think we know** – Assumptions and inference made about Chinook salmon behavior, ecology, limiting factors, and driving variables, either based on Snoqualmie watershed and Snohomish estuary information or drawn from other basins and Chinook populations. This category also includes regional evaluations and assessments that include information from the Snoqualmie watershed, Snohomish estuary, and/or Snohomish Basin.
- **What still needs to be determined** – Ongoing questions and information needs that require further evaluation and assessments. This category also includes assumptions and inference that need to be assessed and validated in the Snoqualmie watershed, Snohomish estuary, and/or Snohomish Basin.

Information was grouped into these categories based on subjective best professional judgement by the author and from thorough input from reviewers. By organizing information into these categories, we can better pinpoint where we are relying on assumptions rather than watershed-specific evidence, and where the critical information gaps may be. Growth and survival in marine environments including the Puget Sound, Salish Sea, and Pacific Ocean are critical and largely influential for Chinook population viability; however, these portions of the life cycle were beyond the scope of this conceptual model and thus received limited discussion. The model focuses on freshwater, estuarine, and nearshore parts of the Chinook life cycle to align with habitat improvement strategies supported by the Snoqualmie Watershed Forum and outlined in the Snohomish River Basin Chinook Salmon Conservation Plan (SBSRF 2005). Information specific to harvest, hatcheries, and marine/oceanic conditions will be critical for salmon conservation efforts but are not adequately discussed in this conceptual model. The model is aimed at supporting Snoqualmie River and Snohomish Basin salmon conservation planning and strategy development, as well as supporting the formulation of monitoring studies, research ideas, and strategic assessments. Aligning understandings, assumptions, and information gaps with planning and strategy development will help to ensure recovery efforts are informed, strategic, and based on up-to-date information and assumptions.

2. Viable Salmonid Population

Throughout this document, we use the concept of *viable salmonid population* and related viability metrics to evaluate the Snoqualmie River Chinook population. The concept is a regionally accepted standard used to evaluate attributes of salmonid populations. A viable salmonid population is defined as "an independent population of any Pacific salmonid (genus *Oncorhynchus*) that has a negligible risk of extinction due to threats from demographic variation, local environmental variation, and genetic changes over a 100-year time frame" (McElhany et al. 2000). Population viability is characterized by abundance, productivity, spatial structure, and diversity.

- **Abundance** is a measure of the number of fish at various life stages or at certain points in time and helps to ensure a population can persist when faced with environmental fluctuations and anthropogenic alterations to the environment. A population should be large enough to maintain genetic diversity over the long term and to provide ecological functions.
- **Productivity** is the ratio of abundance in the next generation to current abundance, capturing the ability for a population to replace itself through survival across all life stages. Population growth rate across the entire life cycle is based on stage-specific productivity and survival, with juvenile survival largely based on growth and size, and adult survival/productivity based on condition and reproductive success.
- **Spatial structure** comprises the geographic distribution of individuals in the population and the processes that generate that distribution. Spatial structure reduces vulnerability to environmental fluctuation and catastrophic events, and is largely dependent on habitat quality/quantity, spatial configuration, and dynamics, as well as the dispersal characteristics of individuals in the population.
- **Diversity** includes variation in genetic characteristics, behavior, morphology, physiology, development, life histories, life-stage transitions, and distribution patterns. Diversity allows a species to use a variety of environments and protects against both short- and long-term environmental changes.

3. Overview of Snoqualmie River Chinook Salmon Adult and Juvenile Life Histories

Chinook salmon exhibit a wide variety of patterns across life stages including the age and season of spawning migration, length of freshwater, estuarine, and oceanic residence, the age when most juveniles begin their seaward outmigration, as well as ocean distribution and migratory patterns (Healey 1991; Myers 1998; Quinn 2018). Variation in residence and migration patterns in freshwater and estuarine habitats may be a result of phenotypic plasticity to environmental conditions and to genetic variation in the population (Ricker 1972; Taylor 1990; Healey 1991).

Across the Chinook salmon life cycle, life history patterns can be framed around specific life stages (e.g., adults, egg, and juveniles), the primary habitat areas they occupy (e.g., river, estuary, Puget Sound), as well as how long they reside in those areas. Snoqualmie River Chinook salmon display a variety of life history patterns (Figure 1). Life history diversity is critical for the long-term persistence of Chinook populations. A portfolio of life histories helps to buffer inter-annual variability in environmental conditions and population dynamics, which spreads out demographic risks and decreases chances of encountering unsuitable environmental conditions at the population scale (Hilborn et al. 2003; Greene et al. 2010; Schindler et al. 2010). Life history diversity also allows Chinook populations to use a wide array of environments, allowing for a more effective use of resources and greater overall productivity (Ruckelshaus et al. 2003). Additional Chinook life history patterns may have historically existed in the Snoqualmie River watershed and Snohomish River estuary; however, they may not currently exist because habitat types have been reduced or because research has yet to identify additional patterns. The following sections are organized around Snoqualmie Chinook life stages and the primary habitat areas they occupy.

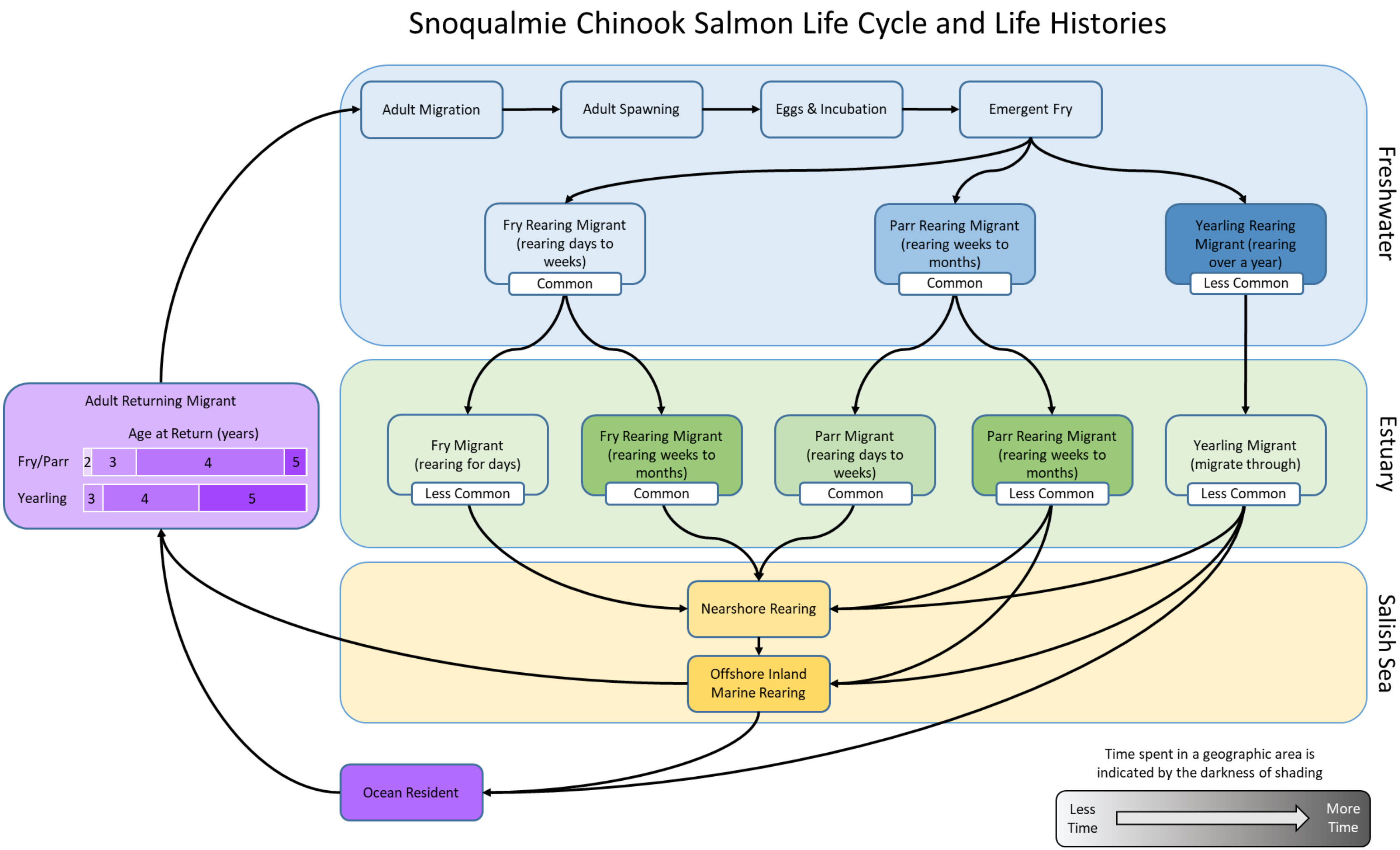

Figure 1: Snoqualmie Chinook salmon life cycle and life histories. Adapted from a life cycle schematic prepared by Tulalip Tribes Natural Resources Department. Adult Chinook age at return data provided by Diego Holmgren, Tulalip Tribes Natural Resources Department.

4. Adult upstream migration and age at return

4.1 What we know

The Snoqualmie Chinook salmon population is considered a fall-run stock (Ruckelshaus et al. 2006), migrating into the Snohomish River basin from August through October (WDFW Spawning Ground Database; PSIT & WDFW 2017; NMFS 2021). Across the Snoqualmie River watershed, adult Chinook distribution extends throughout the mainstem Snoqualmie River up to Snoqualmie Falls, as well as in Cherry Creek, Tuck Creek, Ames Creek, Tolt River, Griffin Creek, Patterson Creek, Raging River, and Tokul Creek (WRIA 7 Salmonid Species Distribution - Technical Advisory Group; Statewide Integrated Fish Distribution database).

Snoqualmie adult Chinook return at either age 2, 3, 4, or 5 years old, with the largest proportion of returns occurring at age 4, followed by age 3 adults (Diego Holmgren, Tulalip Tribes Natural Resources Department). Variability in age at return and the contribution of age classes are influenced by various environmental and genetic factors, including juvenile life history (discussed in *Freshwater Areas – Juvenile life histories, habitat use, and outmigration*). From return year 2006 to 2020, 63% of all unmarked returning adult Chinook were 4 years old and 19% were 3 years old. Variation in age at return helps to maintain genetic diversity and spreads out the population's productivity over several years helping to buffer inter-annual variability in environmental conditions, population dynamics, and catastrophic loss in a particular year (Ruckelshaus et al. 2003; Greene et al. 2010; Schindler et al. 2010).

The Snoqualmie Chinook population also displays a strong component of adults that return at age 5, with age-5 returns from 2006 to 2020 averaging 15% and ranging up to 34% of returning adults (Diego Holmgren, Tulalip Tribes Natural Resources Department). Six years across that period had an age-5 component at or above 15% of all returning adults. However, in recent years the proportion of adults returning at age 5 has been decreasing.

4.2 What we think we know

Across Pacific Chinook populations, there appears to be a decrease in the size of returning adults (Ricker 1981; Bigler et al. 1996; Jeffrey et al. 2017; Oke et al. 2020). Decreases in the age-5 component of the Snoqualmie Chinook population, in addition to the broader reduction in the size of returning adults, likely impacts the productivity and survival of Snoqualmie Chinook. Decrease in the size at return as well as younger age at return can impact Chinook population productivity since smaller and younger adults have fewer eggs per female (Healey and Heard 1984; Beacham and Murray 1993; Oke et al. 2020), dig shallower and more scour-prone redds (DeVries 1997), and have reduced reproductive success (Helle 1979; Forbes and Peterman 1994). Reduction in the age and size of returning adults may be due to increased competition at sea with abundant wild and hatchery salmon (Bigler et al. 1996; Jeffrey et al. 2017), variability in oceanic conditions and productivity (Mantua et al. 1997; Wells et al. 2006; Sharma et al. 2013), and climate warming (Gardner et al. 2011).

Total spawner escapement estimates are based on total redd counts and an assumption that on average there are 2.5 Chinook adults per redd (Pete Verhey, Washington Department of Fish and

Wildlife). While broadly used across the Puget Sound, it would be beneficial to validate the number of adult Chinook associated with each redd in the Snoqualmie River watershed and Snohomish Basin.

4.3 What still needs to be determined

- What are adult Chinook travel times through migratory corridors to spawning grounds?
- What are Chinook survival and pre-spawn mortality rates across migration corridors and holding areas?
- What are the factors influencing the age at return for adult Chinook in the Snoqualmie River watershed and Snohomish Basin?
- What influences the proportion of age at return for adult Chinook in the Snoqualmie River watershed and Snohomish Basin?
- Does decreased size at return as well as age at return impact Snoqualmie Chinook viability?

5. Adult spawning, spawner abundance, and productivity

5.1 What we know

Spawning in mainstem and tributary areas throughout the Snoqualmie River watershed occurs from mid/late-September through early November (WDFW Spawning Ground Database; PSIT & WDFW 2017; NMFS 2021). Across the mainstem Snoqualmie River, Chinook spawning primarily occurs in the lower mainstem upstream of its confluence with the Skykomish River (RM 0 to RM 1), downstream of the Tolt River (RM 20 to RM 23.8), downstream of the Raging River (RM 29 to RM 34.3), and downstream of Snoqualmie Falls (RM 35 to RM 38) (Martin et al. 2004; Peter Verhey, Washington Department of Fish and Wildlife; PSIT & WDFW 2017). Across tributaries, Chinook spawning primarily occurs across the lower mainstems of the Tolt and Raging rivers, with occasional spawning in other tributaries (discussed in *What we think we know*).

Variable timing in adult returns and location of spawning allows Chinook to use a greater variety of spawning habitats (Quinn 2018). Spawning habitat characteristics determine when and where spawning occurs. These characteristic include substrate, velocity, area, temperature, channel type, and others (Bjornn and Reiser 1991; Healey 1991; Montgomery et al. 1999; Cramer 2001). Spawning Chinook commonly use areas with gravel substrate, subsurface water flow, little sand or silt, adequate water depth to cover most or all of the adult fish, adequate velocity (~0.3 – 1.1 m/s), adequate stream area to dig redds (~2.5 – 10 m^2), and declining water temperatures (Bjornn and Reiser 1991; Healey 1991). In the Snoqualmie River watershed, streambed sediment across mainstem and tributary spawning areas is dominated by cobble and gravel (Booth et al. 1991; Solomon and Boles 2002).

Snoqualmie adult Chinook natural spawner abundance estimates are based on natural- and hatchery-origin adult escapement across the Snoqualmie River watershed. Total Snoqualmie Chinook escapement from 1965 to 2020 averaged 1073 adults (geomean) and ranged from 321 to 3589 adults (Figure 2) (Diego Holmgren and Mike Crewson, Tulalip Tribes Natural Resources Department; Pete Verhey, Washington Department of Fish and Wildlife). The 4-year geometric mean of total natural escapement increased from the mid-1990s to the early 2000s and then shifted to a declining trend from the early 2000s to 2015. Of the total escapement from 1997 to 2020 (period where marking allowed for natural- and hatchery-origin differentiation), natural-origin escapement averaged 1066 adults and ranged from 445 to 3284 adults. Since the adoption of the 2005 Snohomish River Basin Salmon Conservation Plan (SBSRF 2005), total Chinook escapement in the Snoqualmie River watershed averaged 1223 adults (geomean from 2005 – 2020), which is only 22% of the high productivity recovery goal and only 5% of the low productivity goal.

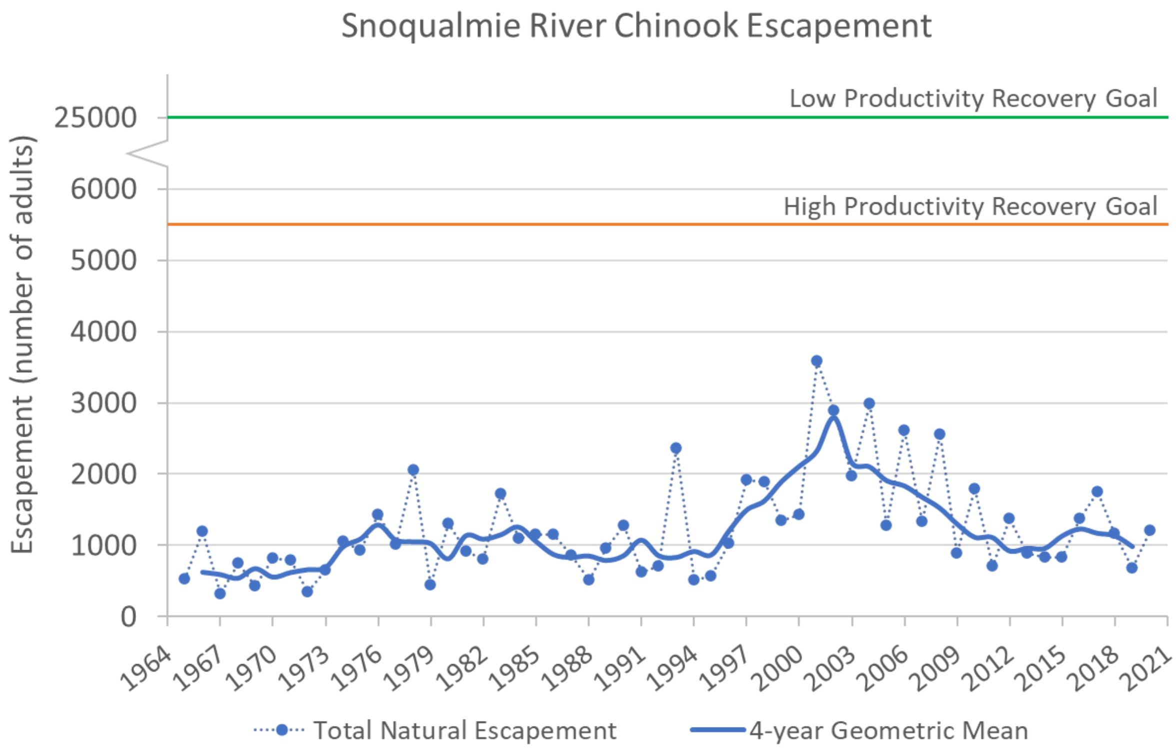

Figure 2: Snoqualmie River Chinook total escapement including natural- and hatchery-origin adults. Data provided by co-managers (Diego Holmgren and Mike Crewson, Tulalip Tribes Natural Resources Department, and Peter Verhey, Washington Department of Fish and Wildlife). Productivity recovery goals outlined in the Snohomish River Basin Salmon Conservation Plan.

The Snoqualmie River doesn't have a Chinook salmon hatchery; however, straying of fish from hatcheries within the Snohomish Basin and from other basins around Puget Sound results in a consistent contribution of hatchery Chinook in total escapement across the Snoqualmie River. The percent hatchery contribution of total escapement averaged 16% from 1997 to 2001 and then increased to 23% from 2005 to 2020 (Diego Holmgren and Mike Crewson, Tulalip Tribes Natural Resources Department, and Pete Verhey, Washington Department of Fish and Wildlife). The increase in percent hatchery contribution is thought to be due in-part to declining natural-origin Chinook (discussed in *What we think we know*).

The productivity of a viable Chinook population should have a spawner cohort-replacement ratio at or above 1.0, indicating that the abundance of progeny from returning adults is greater than the spawning cohort abundance (McElhany et al. 2000). Overall, there has been a negative trend in recruits per spawner for the Snoqualmie River Chinook population (PSIT & WDFW 2017), especially around the turn of the century (Mike Crewson, Tulalip Tribes Natural Resources Department). Since 2000, productivity of Snoqualmie natural-origin Chinook spawners (spawner cohort-replacement ratio) has generally been less than 1.0, with the geometric mean from 2000 to 2014 averaging 0.76, with 10 of the 15 years in that period having ratios at or below 1.0 (Figure 3) (Diego Holmgren, Tulalip Tribes Natural Resources Department).

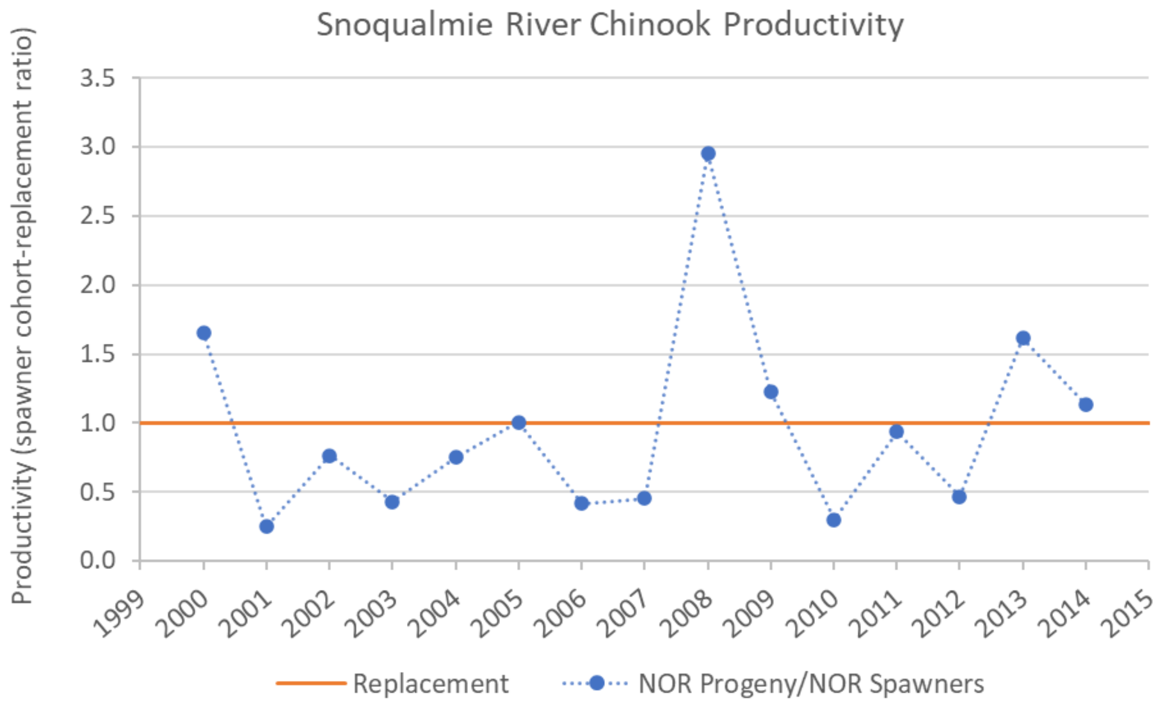

Figure 3: Snoqualmie River Chinook natural-origin recruits (NOR) productivity as indicated by a spawner cohort to replacement ratio. Figure based on analysis conducted by Kit Rawson and Mike Crewson, Tulalip Tribes Natural Resources Department.

5.2 What we think we know

The Snoqualmie Chinook population is considered to have low population viability due to declining abundance of natural-origin Chinook, productivity consistently below replacement, as well as habitat loss and habitat degradation across freshwater and estuarine life stages (discussed in *Limiting factors and driving variables influencing adult migration, spawning, and egg incubation*). Based on low population viability and poor habitat status, the Snoqualmie Chinook population is considered to be in a preservation phase[1] (PSIT & WDFW 2017).

Across the Snohomish River basin, 34 subbasins currently support Chinook spawning; however, Scheuerell et al. (2006) estimated that 37 subbasins had historically supported Chinook spawning. Snoqualmie Chinook spawning is thought to predominately occur across the mainstem Snoqualmie, Tolt, and Raging rivers, as well as Tokul Creek. There may be tributaries or other mainstem areas that support Chinook spawning but are unknown or poorly documented due to limited and inconsistent surveys. For example, Chinook spawning has been occasionally

[1]Phases of recovery refer to the different ecosystem conditions that require different objectives to balance the various risks and opportunities for recovery that occur as the ecosystem changes. The four phases of recovery include: preservation (to retain whatever genetic diversity may have existed in the wild population before its decline), recolonization (there has been increases in suitable habitat and the objective is to colonize the now underutilized habitat), local adaptation (increasing abundance of natural-origin spawners, ecological and genetic diversity, and average relative fitness), and full restoration (fully functional and diverse wild population existing in a fully restored and protected habitat) (Snohomish Chinook Recovery Plan: Phases of Recovery and Integrated Adaptive Management Strategy. DRAFT May 26, 2017).

observed across watercourses either inconsistently surveyed or not included in co-manager Chinook surveys such as Cherry Creek, Griffin Creek, Patterson Creek, and others.

As previously discussed, the percent hatchery contribution of total Snoqualmie Chinook escapement appears to have increased over the last two decades (Diego Holmgren and Mike Crewson, Tulalip Tribes Natural Resources Department, and Pete Verhey, Washington Department of Fish and Wildlife). The increase in percent hatchery contribution may be due in-part to declining returns in natural-origin Chinook, which appear to display a declining trend, especially from 2001 to 2015 (PSIT & WDFW 2017). The geometric mean of natural-origin Chinook escapement declined from 1597 adults (1997 – 2001), to 1284 adults (2005 – 2009), and further declined to 818 adults (2010 – 2014) and 814 adults (2015 – 2020) (Diego Holmgren and Mike Crewson, Tulalip Tribes Natural Resources Department, and Pete Verhey, Washington Department of Fish and Wildlife). During the same annual periods, the number of hatchery-origin spawners has remained relatively stable with the geometric mean ranging from 288 adults (1997 – 2001), to 290 adults (2005 – 2009) and 205 adults (2010 – 2014), and then to 284 adults (2015 – 2020).

Mass marking of hatchery-origin Chinook in the Snohomish Basin has improved over the last 20 years when adipose fin clipping and thermal otolith marking were fully adopted at the WDFW Wallace River hatchery, to align with ongoing efforts at the Tulalip Bernie Kai-Kai Gobin hatchery (NMFS 2021). Hatchery-origin adult Chinook observed across the Snoqualmie River watershed are assumed to be largely from out-of-basin stocks. Recent analyses from 2017 to 2019 indicate that only 6.6% of total Snoqualmie Chinook escapement came from in-basin hatcheries (Tulalip Bernie Kai-Kai Gobin hatchery and WDFW Wallace River hatchery), compared to 12.3%, which came from out-of-basin hatcheries (NMFS 2021). Additional years of analyses will help to further inform contributions from other basins and hatcheries.

Snoqualmie Chinook spawning tends to occur during the same period as pink salmon spawning. During odd years when pink salmon can be numerous, adult Chinook spawning behavior and spawning location may be influenced by redd superposition and interspecific interactions. Differences between Chinook and pink salmon in spawning locations, suitable spawning gravel sizes, and redd depth may help to mitigate redd superposition and interactions; however further investigation is needed to inform if and how Chinook spawning and redds are impacted.

5.3 What still needs to be determined

- What is the full temporal extent of Chinook spawning across the Snoqualmie River watershed, including potential late spawning?
- What is the full spatial extent of Snoqualmie Chinook spawning across mainstem and tributary reaches?
- What are the survival rates across early life stages including the green-egg to eyed-egg stage (first 3 – 4 weeks) and egg-to-emergence?
- Is there spatial variation in survival rates during early Snoqualmie Chinook life stages, especially between mainstem and tributary reaches?

6. Limiting factors and driving variables influencing adult migration, spawning, and egg incubation

6.1 What we know

Water quality (e.g., temperature and dissolved oxygen) and quantity (e.g., low flow conditions) during adult upstream migration and holding can influence geographic distributions, spawning times, susceptibility to disease and pathogens, and the overall survival and spawning success of returning adults (WSDE 2002). Exceedingly high water temperatures (e.g., >21 – 22°C) can delay upriver migration and/or block salmon migration, and daily maximum temperatures exceeding 22.5 to 23°C can result in pre-spawn mortality. Warm temperatures (e.g., 16 – 22°C) can cause sub-lethal effects including increased stress, increased disease susceptibility, and altered spawn timing (WSDE 2002; Quinn et al. 2018).

Temperatures exceeding 11 to 12°C during Chinook spawning can alter egg fertilization through deceased unfertilized egg viability and temperatures exceeding 8 to 9°C during incubation can decrease the survival of fertilized egg to eyed stages (Heming 1982; Boles 1988). In addition, warm temperatures can impact embryo development through metabolic energy deficit from altered growth rates and from increased embryo abnormalities (Seymour 1956; WSDE 2002). Exceedingly warm temperatures during incubation (e.g., >17.5°C) can also result in acute lethality (WSDE 2002). Fertilized eggs incubate in redds from 2 to 4 months, depending on water temperature (Jager 2011), and alevin (newly hatched juveniles with attached yolk sacs) remain in the gravel for 2 to 3 weeks prior to emergence. The number of days from fertilization to emergence is temperature dependent, with Chinook incubation ranging from 120 days at ~9°C to 135 days at ~7°C (Beer and Steel 2018).

Dissolved oxygen is necessary for respiration and metabolism in salmonids. Dissolved oxygen levels less than 4.25 mg/L can be stressful to salmonids and levels less than 2 mg/L can be lethal (Davis 1975; SPU & USACOE 2008).The impacts of elevated and impaired water temperature and reduced DO can limit salmonid reproduction success (Pentec Environmental and GIS NW 1999; Haring 2002; WSDE 2002).

The Snoqualmie River has widespread water temperature impairments, especially downstream of Snoqualmie Falls and throughout summer base-flow periods (Stohr et al. 2011; Kubo et al. 2021). Additionally, several tributaries across the Snoqualmie watershed commonly exceed temperatures likely to result in sub-lethal and potentially lethal impacts to salmonids. Temperature impairments across the Snoqualmie watershed are largely attributed to extensive removal of riparian and forest vegetation, channel simplification and engineering, as well as land use development (Collins and Sheikh 2002; Solomon and Boles 2002; Stohr et al. 2011; King County 2018). The Snoqualmie River has localized areas of cooling and temperature moderation, influenced by groundwater, tributaries, and hyporheic exchange (Stohr et al. 2011; Kubo 2017). The spatial and temporal variation in temperature conditions help to support thermal diversity (Steel et al. 2016; Fullerton et al. 2017b), which is critical for adult Chinook migration and spawning. Temporal and spatial temperature patterns across reaches (Torgersen et al. 1999, 2012), floodplains (Tonolla et al. 2010), stream networks (Isaak et al. 2015), and watersheds

(Fullerton et al. 2015; Woltemade 2017) characterize thermal diversity and influence salmonids across all life-stages.

Salmonids require suitable instream flows at specific times of the year for effective spawning, incubation, and rearing (Haring 2002). Low flow conditions upon entering freshwater habitats affects the distribution and timing of pre-spawning and spawning adult Chinook (Poff et al. 1997; McClure et al. 2008). The removal of water, either directly from the stream channel or from wells, can reduce the amount of instream flow and useable wetted area remaining for adult salmonid spawning. Streamflow limitations are typically greatest during summer and early-fall months when stream flows are lowest. Low flows and physical barriers can limit or add stress to upstream migration (Pentec Environmental and GIS NW 1999; Haring 2002). Low flows in late summer can exacerbate warm temperature impacts, as well as limit access to spawning areas, such as the lower Raging River, which during low-flow conditions can go sub-surface before entering the Snoqualmie River. Lower summer and fall flows during adult holding, redd-building, and spawning can force Chinook to spawn almost exclusively in mainstem thalweg areas, which can exacerbate the vulnerability of eggs and juveniles to the impacts of peak flows, reduce egg-to-emergence and egg-to-migration survival, and can limit rearing areas available to Chinook after emergence (PSIT & WDFW 2017).

Stream temperature and microhabitat characteristics (e.g., gravel size, depth, velocity) are important factors that influence the distribution and timing of Chinook salmon spawning (Montgomery et al. 1999). Additionally, sediment supply can affect the distribution and productive capacity of Chinook spawning and incubation (Dauble et al. 2003). Spawning location establishes the suite of potential rearing habitats available to progeny and distance between spawning areas contributes to reproductive isolation, which is important for genetic and life-history diversity (McElhany et al. 2000). Time of spawning is important because it determines, along with water temperature, the date of egg hatching and emergence of fry from gravels (Ruggerone and Weitkamp 2004), which dictates what food is available as well as environmental conditions experienced during emergence.

Redds are highly vulnerable to peak flows and debris torrents, which scour the stream bed and destroy redds, displace eggs, and smother embryos buried in gravel (DeVries 1997; Pentec Environmental and GIS NW 1999). Egg-to-fry survival is reduced with greater peak flow recurrence interval (Beamer and Pess 1999). In the Snoqualmie River, egg-to-migrant survival has been shown to decrease with higher peak flows during incubation and early rearing (Kubo et al. 2013; Draft Snohomish Hatchery Program and Monitoring and Adaptive Management).

6.2 What we think we know

Habitat supporting spawning and egg-to-fry life stages can directly influence Chinook population viability (i.e., abundance, productivity, diversity, and spatial distribution) (Ruggerone and Weitkamp 2004). The spawning and embryo incubation period may be highly sensitive to habitat disturbances since there is little opportunity to seek alternative habitats. Additionally, some of the highest mortality for fishes occurs during egg deposition, fertilization, and early development shortly after hatching (Bunn et al. 2000). However, in the Snoqualmie River watershed and Snohomish Basin, spawning habitat availability is assumed to be less of a liming factor than juvenile rearing habitat availability and capacity (Scheuerell et al. 2006). Population modelling conducted by Scheuerell et al. (2006) indicated that increased egg-to-fry or fry-to-smolt survival had less of an impact on overall population performance than improved juvenile habitat capacity.

Physical attributes that influence salmon egg-to-fry survival and productivity include fine sediment, dissolved oxygen, gravel size and scour, fitness of parents and their gametes, and differences in hydrologic and thermal regimes (Chapman 1988; Jensen et al. 2009; Sear et al. 2014; Roni et al. 2016). However, Chinook embryos may be less impacted by fine sediment and low dissolved oxygen during incubation compared to other salmonid species (Chapman 1988; Sternecker et al. 2014). The most sensitive incubation stage, especially to scouring flows, is considered to be the green-egg (fertilized egg) to eyed-egg (visible eye spot) stage, which usually occurs in the first 3 to 4 weeks after fertilization (Mike Crewson, Tulalip Tribes Natural Resources Department).

Salmonids spawning in mountain drainage basins of the Pacific Northwest are adapted to, among other things, the timing and depth of channel bed mobility. Salmonids bury eggs below the annual scour depth or avoid egg burial during times of likely bed mobility (Healey 1991; Montgomery et al. 1999). Variations in egg burial depth and redd location may influence egg survival as well as embryo development.

Downstream of Snoqualmie Falls, sediment deposition suitable for Chinook spawning is concentrated in the lower Tolt and Raging rivers, in the mainstem Snoqualmie River immediately downstream of the Raging and Tolt rivers, and near the confluence with the Skykomish River (Booth et al. 1991). Outside of these primary spawning areas, Chinook spawning habitat across the Snoqualmie River watershed is presumed to be limited due to non-optimal gravel sizes, inadequate flow conditions, or high percentage of fines. As previously highlighted, spawning habitat availability is assumed to be less of a limiting factor for Snoqualmie River Chinook than juvenile rearing habitat; however, the quality of spawning habitats may be a factor influencing spawning success. Limited suitable spawning gravels and a high percentage of fine sediments may decrease spawning success and benthic food recourse productivity (Pentec Environmental and GIS NW 1999). Incubation productivity and survival to emergence for Chinook salmon is considerably impaired once fine sediments (<6.3 mm) are greater than 50% of streambed composition (Bjornn 1969).

Climate change and variability is likely to influence water quality/quantity and habitat conditions, all of which impact adult Chinook migration, spawning, and egg incubation. Chinook salmon population viability across all life stages is likely to be impacted by warming stream temperatures, increasing peak flows, and decreasing summer low flows (Greene et al. 2005; Battin et al. 2007; Mauger et al. 2015). Within the Snohomish Basin, climate warming is predicted to decrease adult Chinook spawner abundance (Battin et al. 2007). The frequency and duration of temperature exceedances experienced by Chinook across Puget Sound rivers will likely increase (Mauger et al. 2015), which may delay or block upstream migration (Strange 2010). The amount and quality of spawning habitat may also decline due to reduction in summer flow and temperature exceedances (Mantua et al. 2010). Warming stream temperatures and lower flows may also result in adult Chinook congregating in similar locations, which could increase disease transmission and the probability of infection (McCullough 1999; Miller et al.

2014). Increased stream temperatures can also alter the geographic range and virulence of pathogens (Marcogliese 2008), which when combined with thermally-stresses adult Chinook, may result in increased disease susceptibility.

Climate-related changes to flood magnitude, timing, frequency, and duration is assumed to impact egg survival (Mauger et al. 2015). Increasing flood magnitude and more frequent peak flows are likely to decrease survival through streambed scour and the removal or crushing of salmon eggs (Montgomery et al. 1996; DeVries 1997; Mauger et al. 2015). Projected increases in winter floods and sediment loads may also increase sediment deposition, which could reduce egg survival (Neupane and Yager 2013).

6.3 What still needs to be determined

- How do environmental variables during upstream migration influence pre-spawn holding time and location?
- How do Snoqualmie-specific water quality and quantity conditions impact Chinook migration and spawning location?
- How do Snoqualmie-specific water quality and quantity conditions during migration, holding, and spawning impacts adult Chinook condition, disease susceptibility, survival, and reproductive success? Have warming temperatures and altered hydrologic regimes magnified impacts?
- Which Snoqualmie watershed environmental driver(s) (e.g., hydrologic regimes, thermal regimes, sediment dynamics, or other) are most influential for Chinook egg and embryo survival?
- Does spawning location, perhaps in cooler tributaries and mainstem reaches, result in prolonged incubation and delayed emergence?
- How do sub-basin hydrologic regimes influence the accessibility and availability of spawning habitat as well as survival during incubation?
- Would higher Chinook spawner abundance lead to increased use of currently underutilized spawning habitats?
- What are the effects of climate change on the interactions between pathogens, disease vectors, and Snoqualmie Chinook salmon?

7. Freshwater Areas – Juvenile life histories, habitat use, and outmigration

7.1 What we know

Snoqualmie River juvenile Chinook display three freshwater life-history patterns: fry, parr, and yearling. After emergence, fry generally spend days to 3 months in freshwater habitats and parr spend 3 to 6 months in freshwater habitats prior to migrating downstream (Figure 1) (Kubo et al. 2013; Seay and Pouley 2019; Keith et al. in prep.). Juvenile fry and parr are collectively known as sub-yearling Chinook. Juvenile yearling Chinook remain in freshwater habitats for an entire year prior to outmigration.

The vast majority of juveniles produced in the Snoqualmie River watershed display the sub-yearling (fry/parr) life histories, averaging 86% of outmigrants from 2001 to 2019 (Matt Pouley, Tulalip Tribes Natural Resources Department). However, the yearling cohort is frequently observed across the mainstem Snoqualmie River (King County 2021a, 2021b), and consistently contributes to returning adults in the Snoqualmie River watershed and greater Snohomish Basin (Diego Holmgren and Mike Crewson, Tulalip Tribes Natural Resources Department). The yearling contribution of the Snoqualmie population is relatively high compared to other Puget Sound Chinook populations (PSIT & WDFW 2017; NMFS 2021).

Earlier in the year (Feb – Mar), there are two modes in Snoqualmie juvenile Chinook size classes, with smaller juveniles (35 – 50 mm) being sub-yearling fry which recently emerged from redds and larger juveniles (80 – 120 mm) being yearlings that overwintered in the system from the previous year (Figure 4) (King County 2021a, 2021b). As the spring progresses (Apr – May), there is continued emergence of fry, a greater frequency of medium-sized juveniles or parr (50 – 80 mm), as well as a low frequency of larger yearling Chinook (105 – 125 mm). By late spring and early summer (Jun – Jul), parr are the most frequent size class. During late fall and winter (Oct – Dec), a cohort of larger juvenile Chinook (85 – 125 mm) remain in a range of freshwater habitats. These juveniles contribute to the yearling life history.

The outmigration of sub-yearling Chinook from the Snoqualmie River displays multiple modes, with fry out-migrating in March and early April and parr out-migrating in May and June (Figure 5) (Kubo et al. 2013; Keith et al. in prep.; Matt Pouley, Tulalip Tribes Natural Resources Department). Around 50% of sub-yearling Chinook outmigration occurs by late April and nearly all sub-yearlings out-migrate by late May and early June. Juvenile Chinook characteristic of the yearling life history remain in freshwater for an entire year and then migrate downstream in April and early May. The median fork length of out-migrating sub-yearling Chinook generally increases from February (~40 mm) to June (~75 mm), with the largest increases in size occurred in May (Figure 6) (Kubo et al. 2013; Keith et al. in prep.). Out-migrating juvenile Chinook display a bimodal fork length distribution in May and June, including a smaller cohort of fry and a larger cohort of parr.

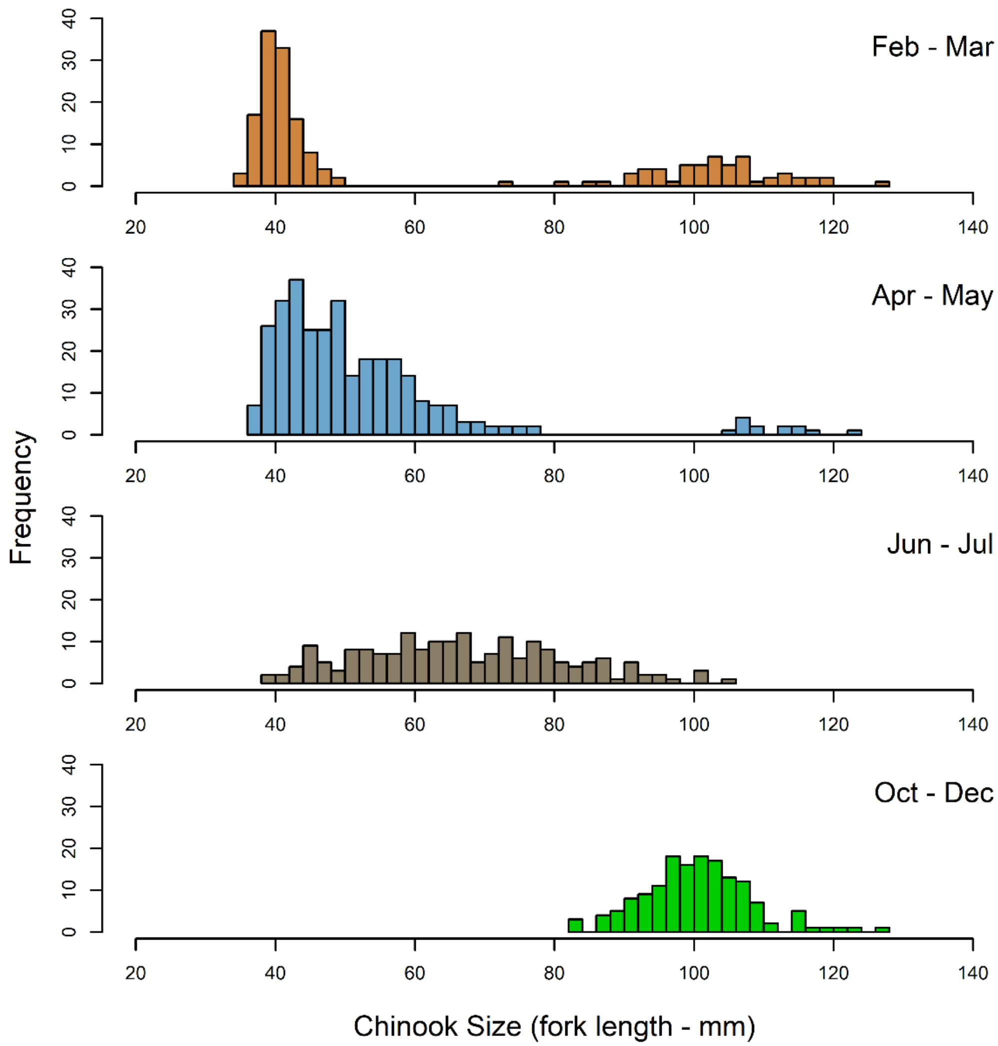

Figure 4: Size frequency plots of juvenile Chinook observed across seasonal periods in the mainstem Snoqualmie River. Figure includes data from King County (2021a) and (2021b).

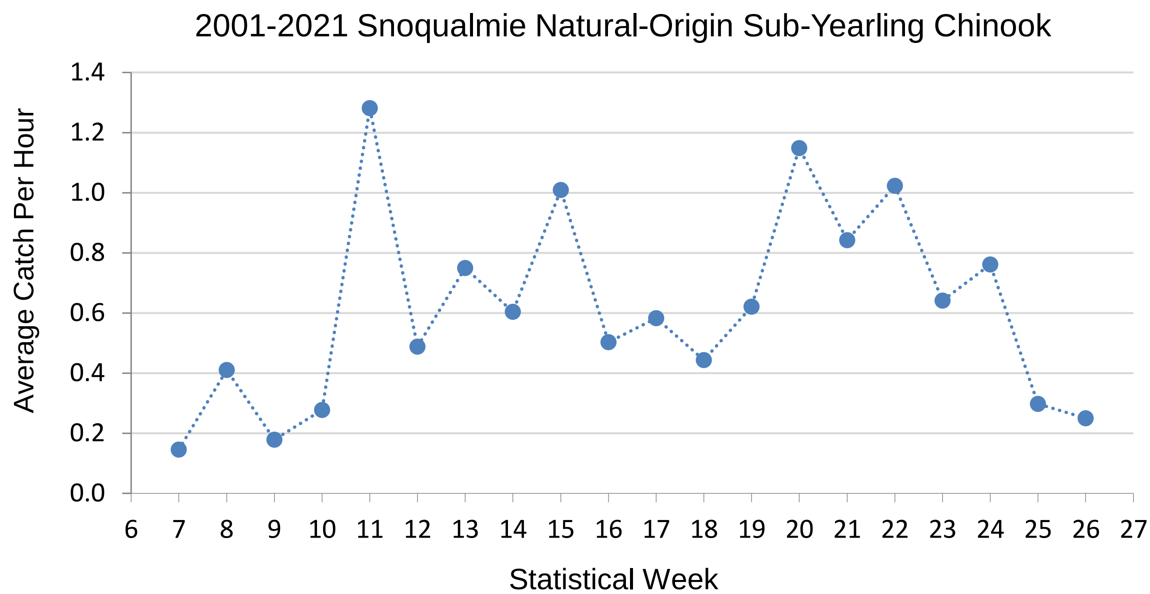

Figure 5: Juvenile sub-yearling Chinook outmigration (average catch per hour) observed in the Snoqualmie River from 2001 – 2021. Statistical weeks (SW) and approximate corresponding months include SW 6 – 9 (February), SW 10 – 13 (March), SW 14 – 17 (April), SW 18 – 22 (May), SW 23 – 26 (June). Figure from Kubo et al. (2013) and Keith et al. in prep.

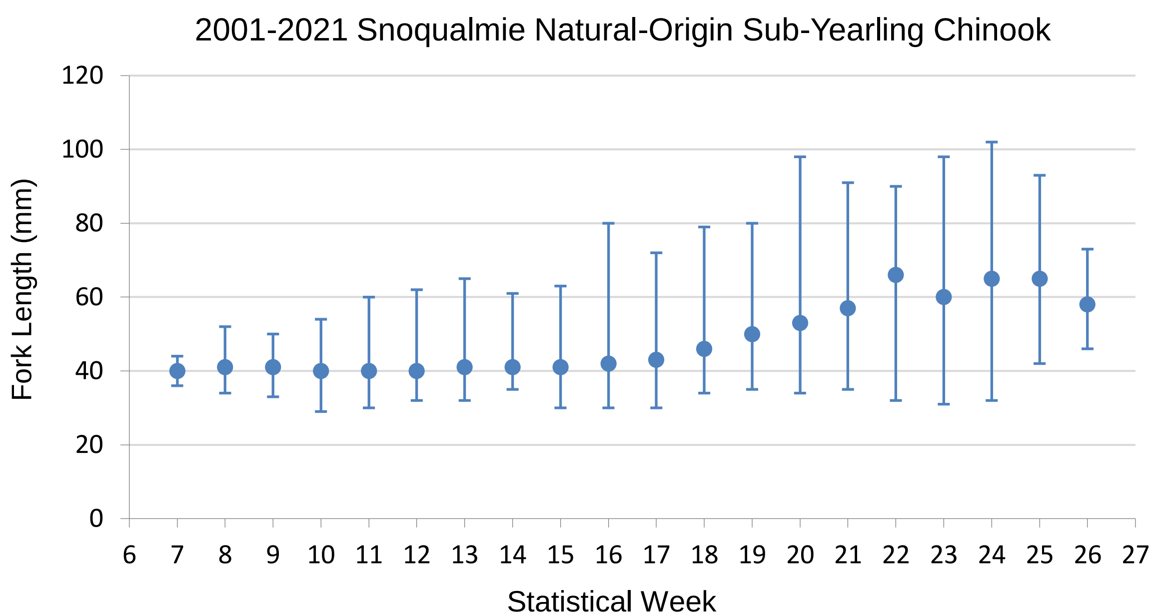

Figure 6: Juvenile sub-yearling Chinook fork lengths (mm) observed in the Snoqualmie River from 2001 – 2021. Dots indicate median fork length with whiskers denoting maximum and minimum lengths. Statistical weeks (SW) and approximate corresponding months include SW 6 – 9 (February), SW 10 – 13 (March), SW 14 – 17 (April), SW 18 – 22 (May), SW 23 – 26 (June). Figure from Kubo et al. (2013) and Keith et al. in prep.

Across mainstem rivers, channel margins are often used by juvenile salmon for rearing during early life stages (Hillman et al. 1987; Bjornn and Reiser 1991). Mainstem edge habitats are critical for juvenile Chinook because they typically have lower water velocities, shallower depths, and greater cover than mid-channel areas (Hayman et al. 1996; Beechie et al. 2005; King County 2021b). Juvenile Chinook have been observed across a variety of mainstem edge habitats throughout the Snoqualmie River including bars, backwaters, unarmored banks, and armored banks (King County 2021a, 2021b). In addition, juvenile Chinook have also been observed in tributaries, side channels, oxbows, and floodplain areas across the lower Snoqualmie River watershed (King County 2021b, 2021a; Kollin Higgins, King County Department of Natural Resources and Parks). Floodplains and related off-channels, sloughs, and wetland features provide important rearing areas for juvenile Chinook, where abundant food resources and refuge from displacement flows can result in elevated growth rates (Sommer et al. 2001; Jeffres et al. 2008; Limm and Marchetti 2009; Takata et al. 2017).

Across the mainstem Snoqualmie River, juvenile Chinook are found in the following edge habitats from highest to lowest abundance: bars, backwaters, unarmored banks, armored banks (King County 2021a, 2021b). Juvenile Chinook are also frequently found in tributary confluences (King County 2021a; Kubo 2021). Across bank types, Snoqualmie juvenile Chinook prefer unarmored banks, compared to armored banks (King County 2021b). This preference is consistent with observations across the region (Knudsen and Dilley 1987; Beamer and Henderson 1998; Quigley and Harper 2004), especially when large wood is present (Beamer and Henderson 1998).

Juvenile Chinook use the diversity of edge habitats throughout the year. During late winter and early spring, sub-yearling fry-sized Chinook are most frequent in backwaters and bars, with peak abundance occurring from March through May (Figure 7) (King County 2021a, 2021b). Bars and backwaters generally have more low-velocity area compared to other edge habitat types. Smaller juveniles likely have limited swimming ability and therefore spend less time in higher-velocity bank habitats where their swimming ability would be challenged. As juveniles grow into parr sizes during spring and early summer, their swimming ability increases and they shift from backwaters and bars to bank habitats, with peak abundance occurring around June. Larger and older juveniles continue to use bars and banks, both unarmored and armored, during fall and winter (King County 2021a).

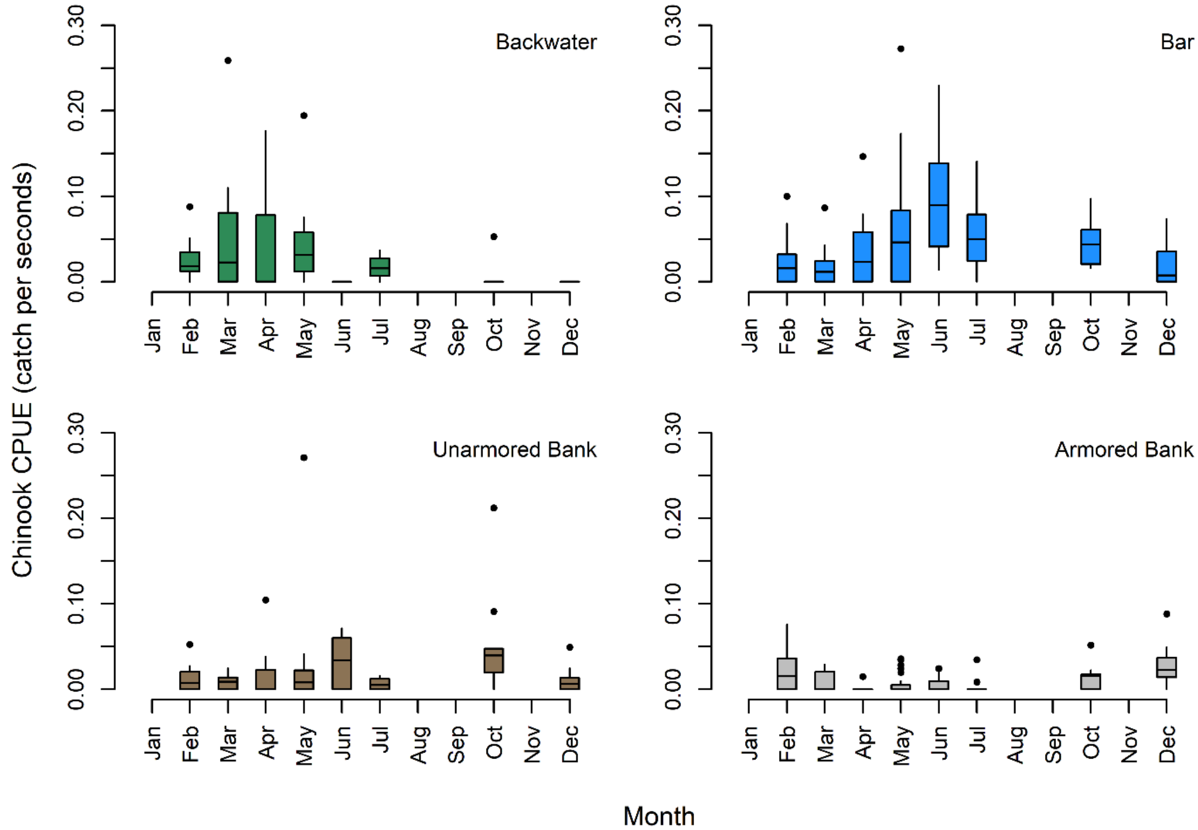

Figure 7: Juvenile Chinook abundance (catch per seconds) across months and edge habitat types observed in the mainstem Snoqualmie River. Figure includes data from King County (2021a) and (2021b). Note: one point for bar habitat in June (0.42 catch/sec) is not included for ease of visual interpretation across edge habitats. Boxes indicate the first quartile, median, and third quartile. The whiskers indicate maximum and minimum values up to 1.5x the inter-quartile range and the points are observations beyond 1.5x the inter-quartile range.

Observations from King County (2021a, 2021b) inform and update prior assumptions of juvenile Chinook habitat use in the Snoqualmie River. For example, juvenile Chinook rearing across the mainstem Snoqualmie River was assumed to predominantly occur from late winter through spring. However, recent observations show that juvenile Chinook not only use mainstem habitats throughout the year, but that juveniles with extended freshwater rearing are distributed throughout the mainstem and use a variety of habitat types (King County 2021a). Additionally, juvenile Chinook abundance was assumed to be minimal in select habitats (e.g., bars), based on observations from other watersheds (Beamer and Henderson 1998 as cited in Beechie et al. 2021); however, juvenile Chinook are quite abundant in bars across the Snoqualmie River (King County 2021a, 2021b). Watershed-specific information that update assumptions on salmon-habitat associations as well as provide information on under-represented habitats (e.g., off-channel habitat) and life histories (e.g., juvenile yearling Chinook) are important for habitat capacity estimates and life cycle modelling (Scheuerell et al. 2006; Bartz et al. 2006; Beechie et al. 2021; Jorgensen et al. 2021).

The estimated abundance of juvenile Chinook produced in the Snoqualmie River watershed has considerable inter-annual variation with production ranging as much as an order or magnitude from tens- to hundreds-of-thousands (Kubo et al. 2013; Keith et al. in prep.; Matt Pouley Tulalip Tribes Natural Resources Department). The abundance of sub-yearling Chinook in the Snoqualmie River was generally low from 2001 to 2016, with abundance only around 5% of estimated historical levels (based on Ecosystem Diagnosis Treatments as cited in Kubo et al. 2013 and Keith et al. in prep.). In addition, the number of juvenile Chinook migrants per adult spawner has only been around 15% of historical estimates. However, juvenile Chinook abundance in recent years (2017 – 2021) has been consistently higher with estimated abundance over twice that of prior periods (Keith et al. in prep.; Matt Pouley, Tulalip Tribes Natural resources Department). Snoqualmie Chinook egg-to-migrant survival from 2001 to 2015 had a median of 4.1% and ranged from 1.2% to 7.8% (Kubo et al. 2013; Keith et al. in prep.; Emily Davis, King County Water and Land Recourses Division). Snoqualmie River egg-to-migrant survival estimates are generally on the lower end of estimates from other Puget Sound watersheds: Skagit River (3.9 – 13.5%), Stillaguamish River (1.5 – 19%), and Cedar River (5.2 – 19.2%) (as cited in Kubo et al. 2013).

Scale and otolith analysis of returning Snoqualmie River Chinook from 2006 to 2020 indicate that the majority of returning adults were characteristic of a sub-yearling juvenile life history (Diego Holmgren, Tulalip Tribes Natural Resources Department). However, the yearling life history was consistently expressed, with on average 15% and up to 35% of returning adults having a yearling juvenile life history. Six years from 2006 to 2020 had a yearling Chinook contribution at or above the overall 15% average. The yearling contribution for the Snoqualmie population is relatively high for such a rare trait among listed fall Chinook populations comprising the Puget Sound Chinook salmon Evolutionary Significant Unit (PSIT & WDFW 2017; NMFS 2021).

Chinook that display the sub-yearling juvenile life history tend to return as 3- or 4-year-old adults, while Chinook that display the yearling life history tend to return as 4- or 5-year-old adults (Figure 1) (Diego Holmgren, Tulalip Tribes Natural Resources Department). From 2006 to 2020, of the returning Snoqualmie River adults that had a sub-yearling life history, 66% were 4 years old and 21% were three years old. During the same period, of the returning adults which had a yearling life history, 45% were 4 years old and 48% were 5 years old. The yearling Chinook life history consistently contributes to returning adults; however, there has been a declining trend in the proportion of returning adults which displayed a juvenile yearling life history. The 3-year average from 1999 to 2019 of returning adults which had a juvenile yearling life history decreased from ~25% to ~10% (Figure 8) (King County 2021a; Mike Crewson, Tulalip Tribes Natural Resources Department).

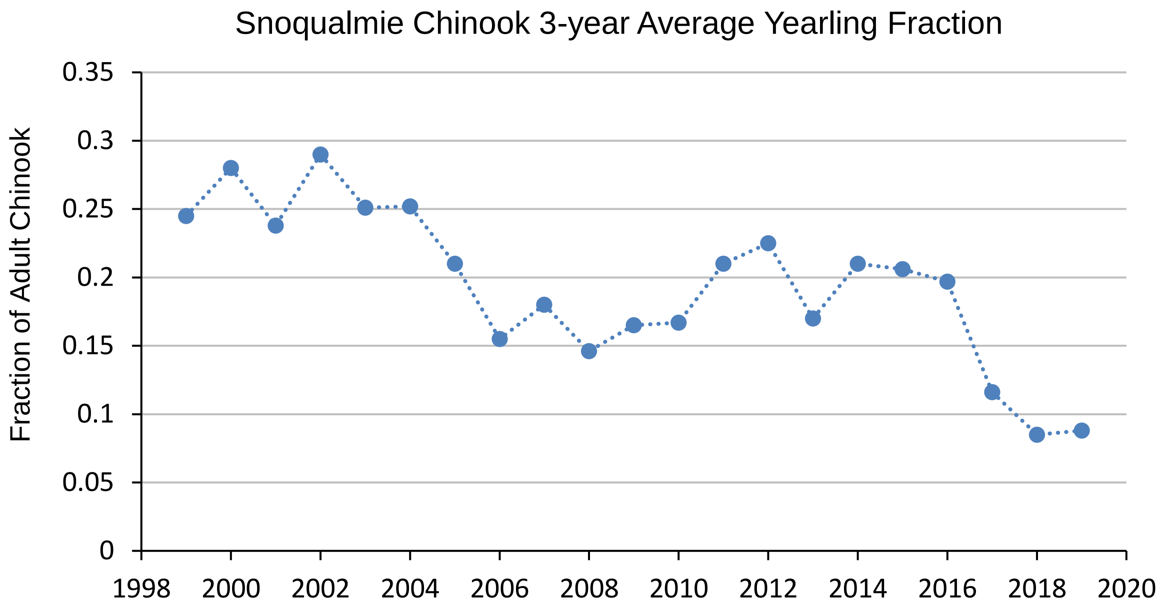

Figure 8: The fraction of returning Snoqualmie adult Chinook (3-year average) which had a juvenile yearling life history. Figure provided by Mike Crewson, Tulalip Tribes Natural Resources Department.

7.2 What we think we know

Juvenile Chinook are assumed to rear throughout wetlands, oxbows, and watercourses across the Snoqualmie River 100-year floodplain (WRIA 7 Salmonid Species Distribution - Technical Advisory Group; Statewide Integrated Fish Distribution database). Juvenile Chinook are also assumed to use non-natal tributaries throughout the Snoqualmie River watershed, especially in areas near tributary confluences (King County 2021a). Juvenile Chinook likely overwinter in off-channel habitats (Swales and Levings 1989), mid-channel pools containing large woody debris (Swales et al. 1986), floodplain channels (Lowery et al. 2020), tributaries, and tributary confluences (Rosberg and Associates 1987; Levings and Lauzier 1991), as well as across mainstem shoreline-edges (Levings and Lauzier 1991; Lowery et al. 2020; King County 2021a).

During spring and summer months, juvenile Chinook are considered primarily diurnal; however, reduced predation risk during dusk and dawn appears to result in crepuscular and even nocturnal foraging (Bradford and Higgins 2001; Metcalfe et al. 2010). Juvenile Chinook are generally associated with mid-channel and covered habitats during the daytime and edge habitats during the evening and night (Bradford and Higgins 2001; Huusko et al. 2007). As juvenile Chinook grow, their improved swimming ability may enable them to take advantage of higher-velocity bank habitats in addition to low-velocity habitats. Bank habitats could be more bioenergetically profitable for larger juvenile Chinook, if the abundance of prey drift is greater than in low-velocity areas. Additionally, bank habitats in the Snoqualmie River are known to have a high abundance of large trout (King County 2021a, 2021b), which larger juvenile Chinook may be less vulnerable to than smaller juveniles, due to greater evading abilities and predator gape limitations. Snoqualmie juvenile Chinook use bank habitats during overwintering periods (King County 2021a), possibly because banks provide microhabitats among coarse substrates, aquatic vegetation, roots, and large wood, as shelter to minimize swimming energy expenditures, reduce predation risks, and to maintain limited foraging (Rosberg and Associates 1987; Muhlfeld et al. 2001, 2003).

Smaller juvenile Chinook (fry and parr) are present in the Snoqualmie River all the way into June and July (King County 2021a, 2021b). These late-emerging Chinook are observed consistently and throughout the mainstem Snoqualmie River. Late emergence could be a result of late-spawning adult Chinook and/or spawning occurring in colder tributaries or reaches. It's been hypothesized that these late-emerging juveniles may contribute to the strong yearling Chinook cohort observed in the Snoqualmie River (King County 2021a). Late emergence may require juvenile to remain in freshwater areas to attain the size and condition necessary prior to outmigration. While juvenile yearling Chinook are consistently observed across the Snoqualmie River, the overall abundance of the yearling cohort as well as the timing of their outmigration is still poorly understood. The yearling component may be underrepresented in outmigration monitoring data due to trap avoidance by larger juveniles (Kurt Nelson and Matt Pouley, Tulalip Tribes Natural Resources Department). These limitations may result in an underestimation of the overall yearling Chinook cohort, which may influence estimated proportions and productivity across life histories. Understanding life history abundance and productivity is important for salmon conservation strategies focused on supporting sensitive life stages and life histories.

Snoqualmie sub-yearling Chinook are known to prefer unarmored banks compared to riprap armored banks (King County 2021b); however, the lower Snoqualmie River has widespread bank armoring, specifically concentrated across spawning reaches (Solomon and Boles 2002; King County 2018). If the availability of certain preferred edge habitats (e.g., unarmored banks) is limited across mainstem reaches, juvenile Chinook may be forced to use other edge habitats. Widespread bank armoring likely limits the availability and proximity of preferred unarmored bank habitat, resulting in juveniles using armored banks or other edge habitats. The use of human-armored banks and degraded habitats may suggest that habitat availability and proximity, in addition to habitat preference, influences juvenile Chinook habitat use and distribution.

Similar to the Snoqualmie River watershed, the greater Snohomish Basin shows a decline in number of returning adults that displayed a juvenile yearling life history (Mike Crewson, Tulalip Tribes Natural Resources Department). Additionally, as previously discussed, the Snoqualmie River watershed and Snohomish Basin show a decline in the age-5 component of returning adult Chinook. Reduced life history diversity and age at return likely impacts the productivity of Chinook populations by making them more vulnerable to inter-annual variability in environmental conditions and population dynamics as well as to anthropogenic alterations to the environment (Hilborn et al. 2003; Greene et al. 2010; Schindler et al. 2010).

Since the quantity, quality, and connectivity of optimal rearing habitat is limited across the Snoqualmie River watershed (discussed below in *Freshwater Areas – Limiting factors and driving variables influencing juvenile life histories, habitat use, and outmigration*), as habitat areas fill up with fry and parr, additional juveniles likely disperse to more marginal habitats or continue out-migrating downstream. When freshwater habitats are limited, impaired, or inaccessible, juvenile Chinook have fewer habitats rearing opportunities, which can result in a predominance of juveniles that out-migrate early (i.e., fry migrants) (Greene et al. 2021).

7.3 What still needs to be determined

- Are there differences in growth and survival across Snoqualmie Chinook juvenile life histories, freshwater habitat types, and by major spawning areas? If so, do faster growing juveniles and/or greater survival among early life stages translate to a greater likelihood of returning as adults?
- What is the inter-annual abundance of yearling Chinook in the Snoqualmie River watershed and how can monitoring efforts better target this life history?
- Do Snoqualmie yearling Chinook consistently show better marine survival than sub-yearling Chinook?
- What are the reasons for the decline in returning adults which displayed a juvenile yearling life history?
- What is the distribution and habitat use of juvenile Chinook during day periods?
- What is the spatial and temporal extent of juvenile rearing in floodplain areas, tributaries, and wetlands across the Snoqualmie River watershed?
- Are late-emerging juveniles observed from May through July the result of later-spawning adults, spawning in colder tributary areas, or from other mechanisms?
- What are outmigration and distribution patterns during higher and flood flows?
- Are juvenile Chinook diets and available prey resources different across freshwater habitat types? Are prey resources different between degraded and functioning riparian area?
- How does habitat restoration across the Snoqualmie River influence juvenile Chinook growth and survival? Are growth rates and survival different between impaired and restored areas?
- What are juvenile Chinook habitat use and out-migration patterns across the lower Snoqualmie River (Duvall downstream to the Skykomish River confluence)?
- What are potential Chinook life history patterns that may have historically existed in the Snoqualmie River watershed? Could historic life histories be determined from historic watershed conditions?

8. Freshwater Areas – Limiting factors and driving variables influencing juvenile life histories, habitat use, and outmigration

8.1 What we know

All Snoqualmie Chinook population viability parameters (i.e., abundance, productivity, spatial structure, and diversity) have been reduced by anthropogenic activities over the last century and are further threatened by on-going developmental actions in the watershed as well as by human-induced climate change (SBSRF 2005; Scheuerell et al. 2006; Bartz et al. 2006). These historic and ongoing pressures have resulted in widespread habitat loss and degradation. Salmonid habitat degradation throughout the Snoqualmie River watershed has primarily occurred due to the construction of fish passage barriers, bank and floodplain modifications, loss of wetlands, altered channel conditions including large wood removal, and altered riparian functions and conditions (Haring 2002, SBSRTC 2004, SBSRF 2005).

Channel condition and complexity (i.e., number and diversity of features and their spatial organization) have been dramatically altered throughout much of the watershed by channelization, loss of large wood, and by a loss of bank stability and complexity due to a variety of land use practices (Haring 2002; Solomon and Boles 2002; King County 2018). Channel and floodplain engineering and modification reduces habitat complexity and variability, limits large wood recruitment, and limits the connectivity of watercourses to off-channel habitats and floodplain areas (Spence et al. 1996; Beechie et al. 2010). Additionally, the lower Snoqualmie River has a paucity of large wood (Solomon and Boles 2002; King County 2018) due to a century of snagging, dredging, removal of wood jams, and degradation of riparian forests. Large wood and jams are important for salmonids because they provide hydraulic heterogeneity critical for instream habitat features and channel processes, dissipate hydraulic energy during peak flows, and provide high quality cover and habitat diversity (Harmon et al. 1986; Bilby and Ward 1991; Bilby and Bisson 1998). Furthermore, woody debris and overhead vegetated cover provide prey and nutrient inputs for juvenile salmonids (Haring 2002).

Landscape and habitat connectivity (e.g., connectivity of watercourses and floodplain areas, frequency of inundation across floodplains, and flows supporting channel engagement) influences juvenile Chinook growth, rearing, mobility, and food resource availability (Sommer et al. 2001; Jeffres et al. 2008; Limm and Marchetti 2009; Takata et al. 2017). In addition, landscape and habitat connectivity directly affects thermal regimes, which influence the quality of habitats and subsequent juvenile Chinook growth (Fullerton et al. 2010). Connectivity across floodplain areas, tributaries, and mainstem reaches has been altered, reduced, or eliminated across much the Snoqualmie River watershed by a combination of diking, bank armoring, roads, mainstem channel incision, and by a variety of fish passage barriers (Haring 2002). Additionally, floodplain habitat in the Snoqualmie River and across watersheds in the Puget Sound have been impaired due to the conversion of floodplains and wetlands to residential/commercial development and agriculture, in addition to draining, ditching, and channelizing floodplain areas (Beechie et al. 2001; Haas and Collins 2001; Haring 2002; Pess et al. 2002).

Hydrology affects the distribution and dispersal of juvenile Chinook across freshwater rearing habitats and their migration to estuarine, nearshore, and offshore marine habitats (McClure et al.

2008). Seasonal high and low flows are a primary control influencing the distribution and timing of fish rearing, growth, and survival (Poff et al. 1997). Additionally, local variation in sediment delivery rates, routing, and composition determines the type and quality of habitat (Sullivan et al. 1987) as well as the development and persistence of habitat features that support salmon reproduction (Poff et al. 1997).

8.2 What we think we know

Juvenile Chinook rearing habitat in freshwater and estuarine areas is considered the primary limiting factor impacting Snoqualmie River and Snohomish Basin Chinook population performance (Haring 2002; SBSRTC 2004; SBSRF 2005). Increasing and improving juvenile Chinook rearing habitat, specifically across mainstem reaches and the Snohomish estuary, will likely result in the greatest improvement to overall Chinook population performance (Scheuerell et al. 2006). Improvements to juvenile Chinook rearing habitat are assumed to directly benefit juvenile growth and survival (SBSRF 2005, SBSRTC 2004). However, the availability and accessibility of well-functioning rearing habitat is considerably impaired in many areas of the Snoqualmie watershed due to widespread habitat loss and degradation (as discussed in *What we know*).

Across the Snoqualmie River watershed, mainstem, tributary, and floodplain areas are assumed to provide the resources and habitat diversity needed to support juvenile Chinook (SBSRTC 2004; SBSRF 2005). Restoring habitats and improving connectivity increases the capacity for juvenile rearing, which can translate to better juvenile growth, survival, and likelihood of returning as an adult spawner (Scheuerell et al. 2006). Much of the historic Chinook production capacity in the Snoqualmie River watershed was thought to been associated with the vast presence of floodplains and wetlands (Haas and Collins 2001). Degradation across floodplain areas, as well as alteration in the duration of floodplain habitat availability, has resulted in an estimated 40% to 60% loss in production capacity (Haas and Collins 2001).

The Snoqualmie River may provide conditions more conducive for sub-yearling life histories, including generally warmer temperatures and longer photoperiods, compared to northern latitudes and snow-dominated systems where the yearling life history is more common (Healey 1991; Taylor 1991). However, the yearling life history is consistently expressed in the Snoqualmie River watershed. Life-history diversity, including extended freshwater rearing, may be a result of both genetic variation and local adaptations to environmental conditions (Ricker 1972; Healey 1991; Taylor 1991). Differences in gene expression and growth rates can influence the timing of volitional out-migration, condition at out-migration, and subsequent smoltification (Carl and Healey 1984; Taylor 1990). Additionally, differences in growth rates can translate to variation in survival across latter life stages.

Juvenile yearling Chinook can have greater marine survival than sub-yearling Chinook (Beamer et al. 2005; Kilduff et al. 2014), suggesting that larger and older juveniles may have higher survival rates. However, this relationship hasn’t been thoroughly studied in the Snoqualmie River watershed and Snohomish River basin. Generally, the larger size of yearling Chinook is thought to benefit juveniles by lessening vulnerability to predation, increasing the speed of emigration, and improving foraging ability (Bugert et al. 1997; Connor et al. 2005).

Habitat diversity, availability, and connectivity associated with extended freshwater rearing are likely integral for yearling Chinook growth and survival in the Snoqualmie River watershed (Kubo 2017; King County 2021a). Specifically, habitat quality and quantity across seasons likely influence yearling Chinook since they display extended freshwater rearing. Factors like distance upstream from major river confluences, wetted width, wood cover, and vegetation cover appear to be associated with juvenile yearling Chinook presence and abundance (Beamer et al. 2010; Lowery et al. 2020). In addition, stream stability, stream flow, stream and air temperature regime, stream productivity, and general weather regimes are thought to influence yearling Chinook expression and persistence (Taylor 1990b; Myers et al. 1998).

The widespread removal and degradation of riparian forests is assumed to be the primary driver resulting in increased water temperature throughout the lower Snoqualmie River watershed (Solomon and Boles 2002; Stohr et al. 2011; King County 2018). Warmer temperature conditions and altered thermal regimes during juvenile Chinook life stages likely alters growth and feeding rates, timing of life-stage transitions, increases susceptibility to disease, and reduces survival (WSDE 2002; Steel et al. 2012). Altered growth rates and life-stage transitioning during relatively warmer springs and summers may cause earlier juvenile Chinook outmigration, which can result in potential asynchronies with food resources as well as truncated growth seasons (Fullerton et al. 2017a; Hawkins et al. 2020). Altered growth and life-stage transitioning may also result in emergence and outmigration during unsuitable flow conditions, increased competitive or predator interactions, and spatiotemporal overlap with native and non-native fish species (Steel et al. 2019). Warmer water temperatures in spring, as well as prolonged warm periods, likely confer a competitive advantage to warm-water predators, which may become more active and effective at preying on salmonids (SPU & USACOE 2008; Steel et al. 2017).

Contaminants in the Snoqualmie River watershed may also influence juvenile Chinook growth and survival. Concentrations of PBDEs (polybrominated diphenyl ethers) among juvenile Chinook sampled in the Snoqualmie and Skykomish rivers were found to be near critical tissue levels that are detrimental to salmon health (Arkoosh et al. 2010; Carey et al. 2018). Elevated PBDE levels may result in altered behavior, reduce growth, increased disease susceptibility, and altered thyroid function. In addition to the mainstem Snoqualmie River, elevated PBDEs were also found in the Snohomish estuary (discussed in *Estuarine and Nearshore Areas – Limiting factors and driving variables influencing life histories, habitat use, density dependence, habitat capacity, and outmigration*).

Water quantity in the Snohomish Basin has been impacted by instream water withdrawals, altered hydrology associated with increased impervious surfaces, and shifting hydrologic and precipitation regimes (Haring 2002). Reduction in instream flow and useable wetted area from water withdrawals (surface and groundwater) can reduce the availability of summer rearing habitat, contribute to temperature-related impacts, and can limit habitat connectivity. Changes in peak flows, including the timing and duration, can displace juvenile Chinook downstream altering the timing of outmigration and life-stage transitions. The frequency and magnitude of peak flows can also alter stream stability, which can benefit habitat formation and persistence, but under altered regimes can result in negative impacts on salmon habitats and early life stages.

Degraded habitats, reduced complexity, and altered connectivity may influence food availability and predator pressures for juvenile Snoqualmie Chinook. Food resources in degraded habitats may be limited in quantity or quality, especially if the available prey assemblages are different from well-functioning habitats. Limited and poor-quality food resources could impact juvenile Chinook growth and condition, resulting in lower survival and productivity. In addition, degraded riparian forests may influence the quality and quantity of prey fall-out and drift available for juvenile Chinook. Degraded habitats may support a greater abundance of predatory fish. For example, riprap armored banks are known to support larger predatory fish such as trout and sculpin (King County 2021b). Larger fish may easily prey on juvenile Chinook, especially during the early life stages. Complex edge habitats such as unarmored banks with large wood as well as shallower edge habitats such as bars and backwaters may provide areas for juvenile Chinook to hide and avoid predators.

Oxbow ponds throughout the Snoqualmie River floodplain can support juvenile Chinook; however, non-native species are common and numerous in oxbows (Kollin Higgins, King County Department of Natural Resources and Parks). The abundance of non-native species among oxbows and floodplain areas is assumed to limited juvenile Chinook growth and survival. Non-native species can compete with juvenile Chinook for food as well as directly prey on juveniles. The broad distribution and abundance of non-native species may greatly reduce the productivity of these otherwise highly productive floodplain habitats.

The impacts of climate change are assumed to reduce Chinook habitat quality and quantity as well as the overall productivity of Snohomish Basin Chinook populations (Battin et al. 2007). Total winter and early-spring streamflow across Puget Sound drainages are projected to increase, which may reduce the extent and availability of slow-water habitat in rivers, reduce the duration of freshwater rearing, and could displace juveniles downstream (Mauger et al. 2015). Reduced freshwater rearing can impair juvenile Chinook growth and survival, and involuntary displacement downstream can result in altered life-stage transitions.

Temperatures in Puget Sound streams and rivers are projected to increase substantially during the 21st Century due to climate change (Isaak et al. 2011; Mauger et al. 2015). Increased stream temperatures can alter food web dynamics as well as juvenile Chinook metabolism and energetic requirements. Warm temperatures can lead to increased juvenile Chinook growth (Beer and Anderson 2013); however, warm temperatures can also alter life-stage transitions, resulting in potential asynchronies with food resources and truncated growth seasons (Mantua et al. 2010; Fullerton et al. 2017a). Altered life-stage transitions in freshwater areas can also have negative consequences for subsequent survival in estuarine or coastal areas (Crozier et al. 2008). Climate change is also projected to decrease summer streamflow across Puget Sound watersheds, which may reduce rearing habitat for juvenile Chinook, including the quantity and connectivity of pools and off-channel features (Hamlet et al. 2013; Mauger et al. 2015). Reduced flows during juvenile rearing periods can also increase competition for food resources (Crozier et al. 2008), shift the timing of outmigration, and decrease overall migration success (Crozier and Zabel 2006). Additionally, reduced streamflow may favor the spread of warm-adapted invasive fish, which compete with or prey on native salmonid species (Petersen and Kitchell 2001; Rahel et al. 2008; Lawrence et al. 2012, 2014).

8.3 What still needs to be determined

- What are the genetic and/or environmental drivers of juvenile Chinook life history expression and persistence?
- How do freshwater habitat conditions and environmental variability during juvenile Chinook early life stages influence survival in latter life stages?
- Which freshwater limiting factors are most influential year-on-year for juvenile Chinook?
- How do habitat and environmental conditions influence food availability, quantity, and quality?
- How do habitat and environmental conditions influence predator presence, abundance, and spatiotemporal overlap with juvenile Chinook?
- Is prey resource abundance and availability during freshwater life stages a limiting factor for juvenile Chinook growth?
- What is the abundance and distribution of non-native fish populations across the Snoqualmie River floodplain?
- Does contaminant exposure by juvenile Chinook in the Snoqualmie River watershed affect growth and survival?
- What are the primary drivers for inter-annual differences in juvenile Chinook production? How much is production based on adult abundance, environmental drivers such as high flows during incubation and early rearing, or other mechanisms?
- Are there freshwater habitat conditions or freshwater limiting factors influencing the decline in returning adults which displayed a juvenile yearling life history?

9. Estuarine and Nearshore Areas – Juvenile life histories, habitat use, and outmigration

9.1 What we know

Juvenile Chinook emigrating from freshwater areas and migration through or rearing in the Snohomish estuary display several life-history patterns: fry migrants, fry rearing migrants, parr migrants, parr rearing migrants, and yearling migrants (Figure 1). Fry migrants, generally smaller in size, tend to reside in the Snohomish estuary for only short periods before entering nearshore and marine areas. Some fry migrants rear in pocket estuary habitat (Beamer et al. 2006) or non-natal coastal streams (Beamer et al. 2013). Fry migrants are generally less common than fry rearing migrants. Fry rearing migrants are also small when they enter the Snohomish estuary but tend to reside for extended periods (weeks to months) before moving to nearshore marine habitats (Chamberlin et al. 2021). Fry rearing migrants are the primary juvenile Chinook life history to use and benefit from estuarine habitats (Quinn 2018). After spending weeks to months in freshwater habitats, parr migrants enter the Snohomish estuary at larger sizes (~55 mm) and later in the season (~Apr/May), where they reside for a relatively short period before moving to nearshore and marine areas (Chamberlin et al. 2021). Parr rearing migrants are less common and reside for longer periods in the estuary. Yearling Chinook, which remained in freshwater for up to a year, migrate through the estuary relatively quickly (Beamer et al. 2005). The larger and older juvenile Chinook are at the time of riverine out-migration, the shorter they tend to reside in estuarine habitats (Kjelson et al. 1982; Levy and Northcote 1982; Healey 1991). Across the Puget Sound, younger and smaller juvenile Chinook are more likely to use the estuary, while older and larger juveniles are more likely to use nearshore and offshore areas (Gamble et al. 2018).

Juvenile Chinook fry migrants from the Snohomish Basin have been observed in non-natal coastal streams that drain directly into possession Sound and the Whidbey Basin (Beamer et al. 2013). Juvenile Chinook rearing among non-natal coastal streams tend to reside for extended periods, averaging 33 to 42 days across late winter and early spring. Juveniles begin to show up in non-natal coastal streams in January with abundance peaking in February and March, and then declining in April and May. Years of relatively greater abundance shift the peak to later in spring. Prior to outmigration into marine waters, juveniles can either remain in a specific non-natal costal stream, travel to a different non-natal stream or estuary, or transition to other nearshore habitats.

Seasonal juvenile Chinook density across the Snohomish estuary displays two primary trends (Figure 9) (Chamberlin et al. 2021). The first trend highlights a steady increase in juvenile Chinook density from February through early June (aligning with riverine outmigration patterns) before decreasing into mid-summer. The first trend peaks around mid-April or early May and is most apparent in areas near and in the mainstem Snohomish River. The first trend highlights migration through the estuary with steady increases in juvenile Chinook density earlier in the season representing the continual input of fry migrants and declines in density later in spring reflecting the more directed migration of parr migrants. The second trend in juvenile Chinook density has a similar timing of peak abundance (late April/early May); however, density in the estuary is less aligned with riverine outmigration and density in the estuary remains near the peak for a protracted period. The second trend is most apparent throughout the lower Snohomish estuary and highlights extended juvenile Chinook rearing with fry rearing migrants initially filling habitats in late winter/early spring and then remaining in the Snohomish estuary for an extended period.

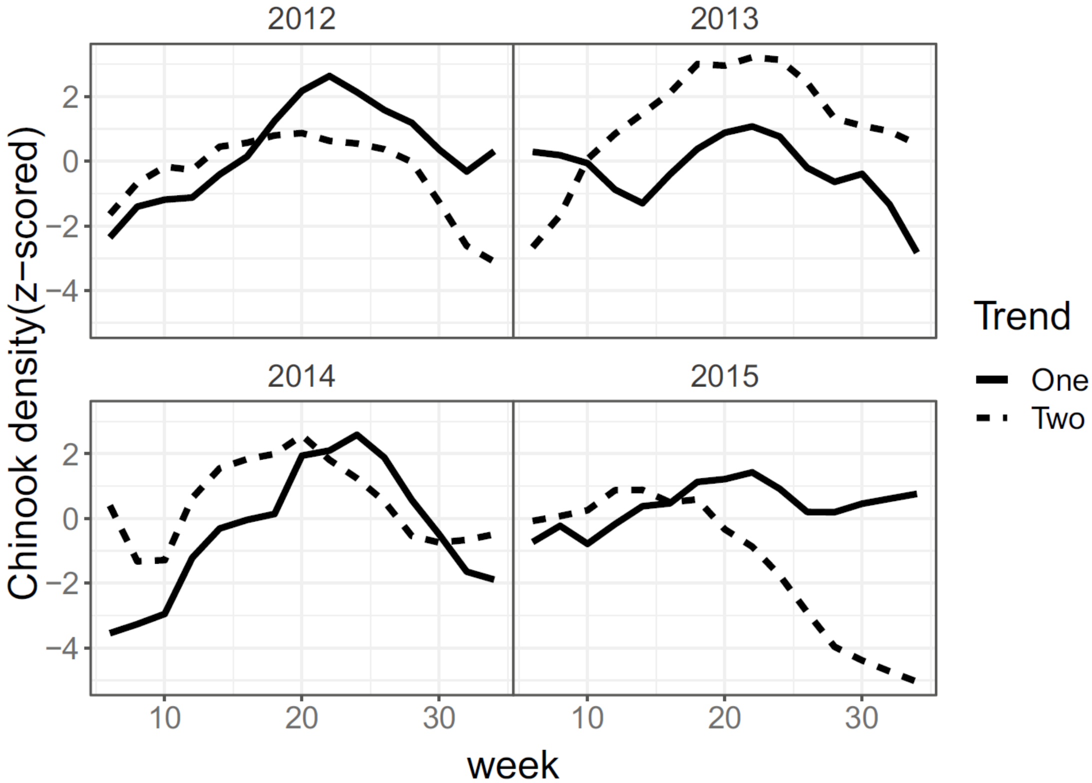

Figure 9: Seasonal variation in juvenile Chinook density across the Snohomish estuary for Trend 1 (solid line) and Trend 2 (dashed line) by year. Figure from Chamberlin et al. (2021). Note: 2012 was a relatively colder year and 2015 was a relatively warmer year.

Habitat areas in the upstream portion of the Snohomish estuary typically display a constant increase in juvenile Chinook density through late May and early June before a steep decrease into mid-summer. Habitat areas in the upper estuary are most associated with the mainstem Snohomish River, which accounts for ~57% of the tidal and flow transport throughout the delta (Yang et al. 2010), and likely represents the primary migratory pathway through the estuary (Chamberlin et al. 2021). Additionally, habitat is limited in the upper Snohomish estuary; thus, these areas are largely used as migration corridors and as limited habitats are fill up, additional migrants continue to disperse into other downstream habitat areas (Chamberlin et al. 2021).

Habitat areas located in the lower Snohomish estuary (downstream extent) generally display a gradual increase in juvenile Chinook density into early April before leveling off and decreasing in mid-June and early July (Chamberlin et al. 2021). Over 95% of current rearing habitat in the Snohomish estuary is located across the lower Snohomish estuary. Habitat areas in the lower estuary tend to display extended rearing and abundance, supporting sustained use throughout the early part of the out-migration period. Landscape connectivity (i.e., distance of a particular site/area from the source population as well as the complexity of the pathway) across the Snohomish estuary is positively related to juvenile Chinook density, with areas of greater connectivity having higher juvenile Chinook density (Greene et al. 2021; Chamberlin et al. 2021).

Across the Snohomish estuary, juvenile Chinook densities tend to be greatest in forested riverine tidal areas, compared to estuarine forest transition areas, which both support greater densities than estuarine emergent marshes (Greene et al. 2021). Juvenile Chinook fry primarily use off channel or blind-tidal channel habitats for rearing during estuary residence (Beamer et al. 2005; Bottom et al. 2005; Greene et al. 2021). Densities in blind-tidal channels across the Snohomish estuary are greatest from early March to mid-April (Greene et al. 2021). During early rearing, juvenile Chinook fry tend to rear in blind-tidal channels and later in the rearing season they use distributaries, as they transition out of rearing habitats and into migratory pathways.

9.2 What we think we know

The travel time from the mainstem Snoqualmie River at ~ RM 11.3 (outmigration monitoring trap) to the Snohomish River estuary is estimated to be around one week (Chamberlin et al. 2021); however, travel times likely vary across life histories. The estimated rate of travel from riverine areas to and throughout the Snohomish estuary varies considerably, ranging from 0.0 to 17.2 km/day with a median of 0.3 km/day (Zackey et al. 2021).

The fry migrant life history is thought to contribute only a small proportion of returning adults in the Snohomish Basin, compared to fry rearing migrants (Mike Crewson, Tulalip Tribes Natural Resources Department). Despite this small proportion, the fry migrant life history in addition to all life histories expressed in the Snoqualmie River and Snohomish Basin are likely critical for life-history diversity. We may expect that the contribution of a given life history may fluctuate over time with variability in environmental conditions and population dynamics.

Since most hatchery Chinook in the Snohomish Basin are reared to parr and smolt size before being released, the presence of juvenile hatchery Chinook in the estuary is generally later in spring with overall residence likely limited, compared to natural-origin Chinook (Beamer et al. 2005; Rice et al. 2011). This suggests there may be a limited period when natural-origin and hatchery-origin Chinook interact in the Snohomish estuary. However, overlap in the presence of natural-origin and hatchery-origin Chinook has been observed across Puget Sound estuaries, including the Snohomish estuary (Greene et al. 2021). There is high variability in the spatial and temporal overlap of natural- and hatchery-origin juvenile Chinook; however, this overlap may influence the duration of natural-origin juvenile Chinook rearing, timing of estuarine outmigration, and growth rates during estuarine residence. The impacts of potential overlaps are likely also tied to habitat and food recourse availability. Interactions between natural- and hatchery-origin juvenile Chinook in the Snohomish estuary require further research to improve certainty of potential impacts.

9.3 What still needs to be determined

- What is the range in travel time across Snoqualmie juvenile Chinook life histories from freshwater areas to the Snohomish estuary?
- What are the differences in marine survival and rate of adult return across estuarine life history types?
- How does spatial and temporal overlaps between natural- and hatchery-origin juvenile Chinook influence growth rates, rearing time, and outmigration patterns?
- What are potential Chinook life history patterns that may have historically existed in the Snohomish estuary? Could historic life histories be determined from historic estuarine conditions?

10. Estuarine and Nearshore Areas – Diet, growth, habitat capacity, and density dependence

10.1 What we know

Growth rates for juvenile Chinook in the Snohomish estuary from February through July average 0.45 mm/day, with averages across months ranging from 0.25 to 0.63 mm/day (Zackey et al. 2021). Growth rates in spring and summer are generally higher than in late-winter and early spring. In terms of weight, growth rates varying between 0.02 and 7.38 g/day; however, growth rates are highly skewed with nearly 70% of individuals experiencing growth at <1 g/day. (Greene et al. 2021). Growth pattern depends upon arrival date in the estuary with earlier arrival at larger size correlating with more overall growth. Growth tends to be higher in estuarine emergent marshes and estuarine forested transition areas, compared to forested riverine tidal areas; however, mean growth potential is highest in forested riverine tidal areas early in the outmigration period (Greene et al. 2021). Juvenile Chinook generally rear in estuaries to achieve a minimum size of ~70 mm before emigrating to the marine areas (Healey 1978, 1980, Levings 2016).

As previously discussed, Chinook fry migrants from the Snohomish Basin can rear in non-natal coastal streams that drain directly into Possession Sound and the Whidbey Basin (Beamer et al. 2013). Across these non-natal coastal streams, juvenile Chinook body size and growth early in the year is similar to adjacent nearshore habitats (Beamer et al. 2013). Later in spring (e.g., after April) juvenile Chinook found in nearshore habitats are generally larger than those in non-natal coastal streams. However, the abundance of Chinook in non-natal streams considerably declines after April, which may reflect the movement of larger juveniles out of streams and into marine waters of the Whidbey Basin. Daily growth of juvenile Chinook in non-natal coastal streams average 0.23 mm/day, with growth rates increasing later in spring. However, juvenile Chinook growth rates in non-natal coastal streams tend to be lower than growth rates in the Snohomish estuary.

10.2 What we think we know

The diets of juvenile Chinook across select Puget Sound estuaries, including the Snohomish estuary, seem to be different than the available prey assemblage (Greene et al. 2021). Across these select estuaries, Green et al (2021) found that juvenile Chinook diets consistently had higher proportions of insects, vs non-insect prey. In the Snohomish estuary, >80% of individual Chinook diets across estuarine habitat types were insects, with dipteran flies representing the majority of diets (Greene et al. 2021). Across estuarine wetland types, the forested riverine tidal areas had the least overlap between prey assemblages and juvenile Chinook diets while estuarine forested transition areas had the most overlap. Marine prey (e.g., crustaceans, amphipods, decapods, and mysids) were generally more abundant in juvenile Chinook diets in estuarine emergent marshes. Juvenile Chinook diets can become more diverse with increasing juvenile density, possibly due to juveniles switching to alternative prey types if resources become limiting. Across nearshore areas, terrestrial insects can also contribute a large portion of juvenile Chinook diets (Gamble 2016).

The density of juvenile Chinook in habitats across Puget Sound estuaries show considerable variation in respect to habitat type and freshwater outmigration abundance (Greene et al. 2021). Generally, forested riverine tidal areas and estuarine forested transition areas support a greater density of juvenile Chinook, compared to estuarine emergent marshes, especially during early rearing periods. Estuarine emergent marshes generally support more juvenile Chinook later in the rearing period. Additionally, blind-tidal channels support more juvenile Chinook than distributary channels.

It's hypothesized that juvenile Chinook residence and migration in the Snohomish estuary may be density dependent (Greene et al. 2021). A collective evaluation of several Puget Sound estuaries suggests that density dependence occurs in some estuaries (e.g., Skagit estuary) and may occur in other such as the Snohomish estuary (Greene et al. 2021). If there is a time when density dependence may be a factor in the Snohomish estuary, it is likely between May and June, especially during parr outmigration (Greene et al. 2021). Habitat availability and resource limitations are the primary mechanism by which density dependence influences juvenile Chinook residence/migration behavior, foraging performance, growth, and survival. However, further evidence is needed to verify juvenile Chinook density dependence in the Snohomish estuary as well as if there are density-dependent changes in residence, migration, growth, and early mortality.

The spatial and temporal overlap of hatchery-origin and natural-origin juvenile Chinook may cause competitive interactions for prey resources, which could result in density-dependent responses to individual growth (Greene et al. 2021). Since prey/diet similarity generally increase with increasing juvenile Chinook density, growth could be impacted with greater spatial and temporal overlap. However, density-dependent effects seems to be largely a function of habitat condition and availability rather than hatchery/wild competition (Greene et al. 2020). Migrant parr and hatchery-origin juveniles may contribute to competition later in the season; however, these associations need to be evaluated.

The Snohomish estuary supports out-of-basin juvenile Chinook, with between 38% to 49% of juveniles observed from 2012 to 2014 being of non-natal origins (Chamberlin 2021; Greene et al. 2021; Zackey et al. 2021). These non-natal juvenile Chinook were predominantly from natural-origin Chinook populations from adjacent watershed (Mike Crewson, Tulalip Tribes Natural Resources Department). Additional years of evaluation will help to further inform inter-annual variation in out-of-basin Chinook presence. The potential interactions between natal- and non-natal juvenile Chinook in the Snohomish estuary requires further evaluation.

10.3 What still needs to be determined

- Across Snoqualmie juvenile Chinook life history types, are there differences in growth during estuarine residence? If so, does life history and differences in growth translate to greater likelihood of returning as adults?
- Do Snoqualmie juvenile Chinook display differences in growth and behavior across estuarine habitat types?
- If the Snohomish estuary displays density dependence for juvenile Chinook rearing and migration, are there related changes in growth and survival?

- How do out-of-basin juveniles that rear in the Snohomish estuary influence Snohomish-origin juvenile Chinook? Do out-of-basin juvenile salmonids influence the diet, growth, rearing, outmigration timing, and/or survival of Snohomish Basin Chinook?
- To what degree do Snohomish Basin juvenile Chinook use non-natal estuaries and coastal streams? How frequently do these juveniles contribute to returning adults?
- Do spatial and temporal overlaps between natural-origin and hatchery-origin Chinook influence density dependent interactions and are there any related changes in behavior, outmigration, growth, and survival?

11. Estuarine and Nearshore Areas – Limiting factors and driving variables influencing life histories, habitat use, density dependence, habitat capacity, and outmigration

11.1 What we know

The magnitude and duration of rearing in the Snohomish estuary depends on several factors including population abundance, habitat availability/capacity, habitat connectivity, environmental conditions (e.g. temperature), and life history (Chamberlin et al. 2021). For example, the density of juvenile Chinook in the Snohomish estuary is related to both the abundance of juvenile Chinook out-migrating from freshwater areas, the availability/capacity of estuarine habitats, and estuarine landscape connectivity (Greene et al. 2021; Chamberlin et al. 2021b). Lost and degraded habitat in the Snohomish estuary has directly impaired the fry rearing migrant components of the Snoqualmie and Skykomish Chinook populations (Haas and Collins 2001; Haring 2002).

Habitat areas across the Snohomish estuary have either been lost or considerably degraded due to filling, diking, log raft storage, and channelization, as well as the loss or alteration of tidal connectivity due to tidegates and levees (Haring 2002). Additionally, nearshore habitat has been degraded due to bulkheads, overwater structures, filling, dredging, contamination from industrial activities, and alterations of longshore sediment processes. Habitat loss and degradation across the Snohomish estuary and nearshore areas can impact all Chinook population viability parameters (SBSRF 2005).

The spatial and temporal variation of temperature conditions has a strong influence on the distribution, densities, rearing duration, and growth potential of juvenile salmonids (David et al. 2014; Roegner and Teel 2014). Spring through summer surface water temperatures across the Snohomish estuary has a significant effect on juvenile Chinook density, with increased temperatures resulting in decreased local density and earlier seasonal declines in abundance (Chamberlin et al. 2021). Juvenile Chinook presence and density in the Snohomish estuary decline rapidly after temperatures exceed 15°C, with the effect more evident as a threshold rather than an incremental linear relationship. In addition to water temperature, dissolved oxygen, turbidity, river discharge, and tidal range can also influence juvenile Chinook abundance and distribution across estuarine habitats (Greene et al. 2021).

Juvenile Chinook migrating through the Snohomish estuary accumulate higher concentrations of persistent organic pollutants compared to Chinook migrating thorough relatively less developed estuaries, such as the Skagit and Nisqually (O’ Neill et al. 2018; O’Neill et al. 2020; PSP 2021). Among Puget Sound basins, including the Snohomish, juvenile Chinook transiting contaminated estuaries from 1972 to 2008 exhibited an overall survival rate 45% lower than Chinook moving through uncontaminated estuaries (Meador 2014). Juvenile Chinook from the Snohomish estuary have some of the highest PBDE (polybrominated diphenyl ether) levels measured across select watershed in the Puget Sound (O’ Neill et al. 2018; O’Neill et al. 2020). 2018). Concentrations of PBDEs and TPCBs (total polychlorinated biphenyls) in juvenile Chinook from the Snohomish Basin were generally higher in fish from the estuary compared to those in nearshore habitats. However, PAH (polycyclic aromatic hydrocarbon) levels were highest in nearshore habitats, with the estuary and offshore areas having similar levels. Juvenile Chinook rearing in urbanized estuaries across the Puget Sound are exposed to PCB levels above adverse effects thresholds and PCB accumulation continues as juveniles rear in marine waters of the Puget Sound (Pearsall et al. 2021). Juvenile Chinook exposure to contaminants including PCBs, PBDEs, and PAHs at levels found in the Snohomish estuary and across urbanized estuaries of Puget Sound can affect juvenile behavior, reduce growth, reduce disease resistance, and alter hormone and protein levels (Arkoosh et al. 1994, 2001, 2010, 2017). All of these impacts can ultimately reduce juvenile Chinook survival (Meador 2014).

11.2 What we think we know

As previously discussed in *Freshwater Areas – Limiting factors and driving variables influencing juvenile life histories, habitat use, and outmigration*, juvenile rearing habitat in freshwater and estuarine areas is considered the primary limiting factor impacting Snoqualmie River and Snohomish Basin Chinook population performance (Haring 2002; SBSRTC 2004; SBSRF 2005). The greatest improvement to overall Chinook population performance will likely result from increasing and improving habitats across mainstem reaches and the Snohomish estuary (Scheuerell et al. 2006). Increased habitat availability in both freshwater and estuarine areas will result in greater juvenile Chinook rearing habitat capacity in both the Snoqualmie River watershed and Snohomish estuary. Additionally, estuarine habitat availability may determine if there are density-dependent rearing and migration patterns as well as the strength of density dependence (Reimers 1971; Greene and Beechie 2004).

Seasonal and annual environmental variation within tidal deltas can strongly affect juvenile Chinook residence time (Greene et al. 2021). Across the Snohomish estuary, temperature is more variable seasonally than it is spatially within a season (Hall et al. 2018), suggesting that habitat use and distribution may be influenced more by seasonal differences in temperature than habitat- or area-specific temperature patterns. Increasing temperature during estuary residence may contract the suitable rearing period, thereby reducing residence time (Chamberlin et al. 2021). Warm years could compress migrations, resulting in short periods of residence and higher densities when fish are present (Munsch et al. 2019). Additionally, cooler years could result in a longer seasonal rearing period, resulting in the accumulation of migrants moving downstream over the season (Munsch et al. 2020). Variation in environmental condition may also alter prey abundance, timing and duration of prey availability, and prey assemblage, which may all result in altered juvenile Chinook growth, condition, and life-stage transition. Climate-related changes in precipitation, streamflow, and stream temperatures could also affect the timing of juvenile Chinook migration into the Snohomish estuary, which may result in potential asynchronies with prey resources.

Juvenile Chinook fry migrants that use non-natal coastal stream, which drain directly into Possession Sound and the Whidbey Basin, are generally found in watershed with areas greater than 45 hectares, in channels with less than 6.5% slope, and in non-natal streams less than 7km away from the natal river mouth (Beamer et al. 2013). Additionally, juvenile Chinook presence tends to be higher in non-natal streams without longshore deposition or culverts at their mouths.

Across the Snohomish estuary, climate change and variability will likely impact several drivers (e.g., temperature, salinity, nutrient inputs, freshwater/tidal exchange, others) that influence juvenile Chinook habitat use, distribution, and life-stage transitions. Sea-level rise related to climate change is projected to expand some tidal wetland areas while reducing others (Glick et al. 2007; Mauger et al. 2015). Across the Pacific Northwest, salt marshes, transitional marshes, and tidal flats are projected to increase; however, estuarine beaches, brackish marshes, tidal swamps, and tidal freshwater marshes are expected to decrease (Glick et al. 2007). The shifts in extent, composition, and availability of diverse estuarine habitats will likely impact juvenile Chinook growth, survival, and productivity throughout estuarine life stages (Mauger et al. 2015). In combination with sea-level rise, projected changes in the timing and magnitude of streamflow throughout upstream drainages, could alter sediment delivery and tidal wetland formation (Mauger et al. 2015). Changes in nutrient inputs, carbon dioxide levels, temperatures, and other related drivers are all likely to influence estuarine habitat productivity.

11.3 What still needs to be determined

- Does contaminant accumulation in the Snohomish estuary affect Chinook growth and survival across latter life stages?
- How does prey resource availability, food-web interactions, and environmental variability influence Snoqualmie/Snohomish juvenile Chinook growth and survival during residence in the Snohomish estuary, as well as across Puget Sound nearshore and pelagic areas?
- What are the residence times, rearing extent, and growth patterns of juvenile Chinook in nearshore and offshore habitats?

12. Puget Sound, Salish Sea, and Pacific Ocean – Distribution, diet, and limiting factors/driving variables influencing growth, diet, and survival

12.1 What we know

Across the Puget Sound, the presence of juvenile Chinook peaks between early May and late July (Gamble et al. 2018). Younger and smaller juvenile Chinook are more likely to use estuarine habitats while older and larger juveniles are more likely to use nearshore and offshore habitats. Additionally, growth rates for juvenile Chinook were found to be highest in offshore pelagic regions compared to nearshore and estuary habitats (Gamble et al. 2018). Juvenile Chinook use many nearshore and offshore areas across Puget Sound; however, stocks primarily rear in basins near their natal-origin streams through summer (Rice et al. 2011). While the majority of juvenile Chinook eventually migrate from the Puget Sound to the Salish Sea and Pacific Ocean, up to 30% can spend their lives in Puget Sound (O'Neill and West 2009; Chamberlin et al. 2011).

Conditions during early marine residency are important determinants of marine survival and year-class strength (Sharma et al. 2013; Quinn 2018). Juvenile Chinook in the Puget Sound and Salish Sea experience a critical period in their first summer where they need to achieve a growth threshold and condition in order to avoid size-selective predation and to build up enough fat to survive the subsequent fall and winter periods (Holtby et al. 1990; Beamish and Mahnken 2001; Tomaro et al. 2012). Between these, juvenile Chinook growth rather than size-selective mortality is considered the most influential determinant of overall marine survival (Pearsall et al. 2021). Specifically, growth achieved during this critical period regulates marine survival and is largely driven by food resource supply and overall predation.

Marine survival of juvenile Chinook in the Puget Sound and Salish Sea showed a significant decline from the 1970s through the 1990s and has continued to decline to the present (Ruggerone and Goetz 2004; Sharma et al. 2013; Sobocinski et al. 2021; Welch et al. 2021). Similar steep declines in marine survival have not been observed across Chinook population in adjacent regions (i.e., west coast of Vancouver Island and coast of Washington) (Kilduff et al. 2014; Ruff et al. 2017); however, marine survival has declined across many Chinook populations throughout the northeast Pacific coast (Welch et al. 2021). Declines in marine survival across the Puget Sound and Salish Sea are due to various driver including large-scale environmental conditions, climate-related changes to water temperatures, flow regimes, and primary production, changes in prey resource availability, competition, and mismatch, as well as contaminants and disease (Pearsall et al. 2021).

Juvenile Chinook survival in the Puget Sound is correlated with size and growth during the first marine summer, both within years (Beamish and Mahnken 2001; Woodson et al. 2013) and among years (Duffy and Beauchamp 2011; Tomaro et al. 2012). Specifically, Duffy and Beauchamp (2011) found a positive relationship between Puget Sound juvenile Chinook size in July and smolt-to-adult returns, with larger juveniles having greater overall survival. In addition, Claiborne et al. (2021) found that Chinook growth during the first year at sea was related to overall survival, with above average growth resulting in higher overall marine survival. Juvenile

Chinook body size and growth in marine areas influences foraging behavior and foraging success (Schabetsberger et al. 2003; Chittenden et al. 2018). Based on extensive research conducted across the Puget Sound and Salish Sea, Pearsall et al. (2021) concluded that juvenile Chinook marine survival was influenced less by absolute size and more by early marine growth rates and related reserves for migration and overwintering.

Water temperature, diet, feeding rate, and prey availability are the primary ecological drivers influencing juvenile Chinook growth rates (Connelly et al. 2018; Pearsall et al. 2021). Additionally, weather, water conditions, nutrients, and productivity determine prey resource availability and abundance. During early marine residence in the Puget Sound, juvenile Chinook diets are largely composed of euphausiids, crab larvae, hyperiid and gammarid amphipods, large copepods, and an increasing proportion of small fish as they grow (Simenstad et al. 1982; Daly et al. 2009; Duffy et al. 2010). The abundance and availability of zooplankton (Keister et al. 2019; Perry et al. 2021) and Pacific herring (Chamberlin et al. 2017; Duguid et al. 2021) have been shown to influence marine survival in the Puget Sound and Salish Sea (Pearsall et al. 2021). In offshore areas, juvenile Chinook feeding rate has a greater influence on growth than prey energy content (Beauchamp and Duffy 2011; Duffy and Beauchamp 2011). As juvenile Chinook transition to piscivory, the availability and abundance of Pacific herring is important for growth (Chamberlin et al. 2017). Switching to piscivory increases juvenile Chinook growth (Litz et al. 2017; Davis et al. 2020), which results in greater marine survival (Duffy and Beauchamp 2011).

Predation-related mortality impacts Chinook in the Puget Sound and Salish Sea. Pinniped populations in the Salish Sea have increased seven to tenfold since the 1970s (Olesiuk 1993; Jeffries et al. 2003). As a result, pinniped predation on juvenile and adult Chinook has increased by an order of magnitude over the last 50 years with consumption contributing a primary source of mortality (Chasco et al. 2017a, 2017b; Nelson 2020; Nelson et al. 2021). Harbor seals eat more juvenile Chinook than any other pinniped species (Chasco et al. 2017a), and the abundance of harbor seals is negatively correlated with juvenile Chinook marine survival (Sobocinski et al. 2021). Consumption by harbor seals is highest in early/mid-spring with a steady decline into late spring and summer (Nelson et al. 2021). Strong predatory pressures and competition from increased pinniped populations results in decreased productivity and survival across Puget Sound Chinook populations (Nelson et al. 2019).

Adult Chinook acquire almost all of their contaminants through bioaccumulation in marine waters (Cullon et al. 2009; O'Neill and West 2009). Specifically, extended residence by adult Chinook in the Puget Sound and Salish Sea result in elevated contaminant levels compared to adults residing elsewhere along the Pacific coast (O'Neill and West 2009; PSP 2021). Contaminant concentration in Puget Sound Chinook tend to increase with greater distance from oceanic waters.

Disease and pathogens considerably impact juvenile and adult Chinook survival (Pearsall et al. 2021). In adult Chinook, pathogens and disease result in enhanced stress, shifts in osmoregulation and immunosuppression, earlier arrival at spawning grounds, and premature mortality (Teffer et al. 2018). Pathogens have direct impacts on juvenile Chinook survival including death from disease as well indirect effects including infection-related changes to physiological performance and behavior.

In the Pacific Ocean, Chinook salmon have consistent year-to-year distributions with hatchery-origin and natural-origin fish displaying similar oceanic distributions (Trudel et al. 2009; Weitkamp 2010). Oceanic survival rates among Chinook populations are affected by environmental conditions at ocean basin, regional, and local scales (Wells et al. 2006; Sharma et al. 2013). Drivers include large-scale environmental conditions such as the El Niño Southern Oscillation and Pacific Decadal Oscillation, as well as finer-scale drivers like localized temperature, upwelling, lower-trophic level production, competition, and predation.

12.2 What we think we know

Across the Puget Sound, there is little evidence of size-selective mortality during the first summer across nearshore, estuary, and offshore habitats (Gamble et al. 2018). While there is considerable juvenile Chinook mortality during the first summer and early marine period; size-selective mortality does not seem to be operating. Gamble et al. (2018) noted that size-selective mortality could affect juvenile Chinook in years with low overall survival, which may suggest that other factors, such as density dependence and/or oceanic conditions, are likely more important drivers of survival (Quinn et al. 2005; Claiborne et al. 2011; Miller et al. 2013; Woodson et al. 2013).

As previously discussed, pinniped predation on juvenile and adult Chinook is a primary driver impacting survival. While juvenile salmon contribute a relatively small component of harbor seal diets (<5%), due to the vast number of seals and their energetic demand, the overall amount of juvenile Chinook lost to seal predation is estimated to be large, ranging between 22% to 49% (Nelson et al. 2021). Consumption estimates based on seal population sizes and bioenergetic modelling suggest that seals contribute a significant source of mortality for out-migrating Chinook (Chasco et al. 2017). Specifically, Chasco et al. (2017a) converted juvenile Chinook salmon targeted by harbor seals to adult equivalents, via assumed survival rates, and estimated that by 2015, consumption by pinnipeds was twice that of resident killer whales and six times greater than fishery catches. In addition to direct seal predation from targeted feeding, juvenile Chinook are likely impacted by competition with seals for prey resources (e.g., Pacific herring) and from incidental mortality associated with seal predation on other species that co-occur with Chinook (Thomas et al. 2017).

The availability of crab larvae (Gamble 2016; Beauchamp et al. 2018; Connelly et al. 2018) and amphipods (Weil et al. 2019; Costalago et al. 2020) seem to be important for juvenile Chinook growth, feeding, and survival. These prey resources tend to be abundance in juvenile Chinook diets and the availability of crab larvae in June and July appear to influence variability in juvenile Chinook growth, feeding, and survival (Beauchamp and Duffy 2011; Duffy and Beauchamp 2011). Additionally, it’s hypothesized that juvenile Chinook may be dependent on late-spawning herring (April through June) since they can be smaller and thus easier for juvenile Chinook to prey on (Chamberlin et al. 2017).

As discussed, Chinook salmon accumulate contaminants while residing in the Puget Sound and Salish Sea (O’Neill and West 2009; PSP 2021). Contaminant accumulation may be considerable for resident Chinook, which spend most of their life in the Puget Sound rather than coastal waters of the Pacific Ocean (O'Neill and West 2009; Chamberlin et al. 2011). Elevated contaminant concentrations for resident Chinook may cause reproductive or growth impairments and premature mortality (Berninger and Tillitt 2019).

Several studies suggest there may be density-dependent interactions between Chinook and pink salmon in the Salish Sea and Pacific Ocean (Ruggerone and Goetz 2004; Ruggerone et al. 2019; Kendall et al. 2020). Specifically, from the 1980s through 1990s, during years when pink salmon were abundant (even years), juvenile Chinook marine survival was 60% lower than in odd years (Ruggerone and Goetz 2004). It was predicted that abundant pink salmon acted as competitors for juvenile Chinook. However, since the late-1990s this pattern has switched with juvenile Chinook marine survival being higher in even years than in odd years. Recent hypotheses suggest that the switch in survival is likely attributable to large-scale changes in prey availability, and if inter- or intra-species competition is occurring in the Salish Sea then it's most likely occurring in places where food supply or habitat are limited (Pearsall et al. 2021).

Climate change is likely to influence Chinook viability through increased prevalence of marine heat waves, increase coastal freshwater and marine temperatures, and changed in salinity and dissolved oxygen levels (Pearsall et al. 2021). These processes influence Chinook growth and survival across life stages. Additionally, warming conditions will likely increase pathogen presence, abundance, and virulence, since warmer temperatures result in higher replication and stronger disease impacts (Stocking et al. 2006; Crossin et al. 2008; Ray et al. 2012). Warming water temperatures across rivers, coastal marine areas, and the open ocean are becoming increasingly common in the northeast Pacific Ocean region (Laufkötter et al. 2020). The impacts of climate change on Chinook may be most dramatic across marine stages (Crozier et al. 2021), as ocean temperature can impact Chinook though a combination of bottom-up and top-down trophic processes, which regulate growth and survival (Ottersen et al. 2010; Ruzicka et al. 2016; Chasco et al. 2017b).

12.3 What still needs to be determined

- What are the growth patterns, productivity, and survival of Snohomish Basin and Snoqualmie River Chinook across the Puget Sound, Salish Sea, and Pacific Ocean?
- How do growth rates, productivity, and survival of Snohomish Basin and Snoqualmie River Chinook compare to adjacent populations and regions?
- What are the ultimate impacts of pinniped predation on the overall survival and abundance of Snohomish Basin and Snoqualmie River Chinook?
- What is the timing and magnitude of various sources of mortality during the marine stage for Snohomish Basin and Snoqualmie River Chinook?
- How do broad-scale and fine-scale environmental during residence in the Puget Sound, Salish Sea, and Pacific Ocean specifically influence Snohomish Basin and Snoqualmie River Chinook?

References

Arkoosh, M.R., Boylen, D., Dietrich, J., Anulacion, B.F., Bravo, C.F., Johnson, L.L., Loge, F.J., and Collier, T.K. 2010. Disease susceptibility of salmon exposed to polybrominated diphenyl ethers (PBDEs). Aquatic Toxicology 98(1): 51–59. Elsevier.

Arkoosh, M.R., Casillas, E., Clemons, E., Huffman, P., Kagley, A.N., Collier, T., and Stein, J.E. 2001. Increased susceptibility of juvenile chinook salmon (*Oncorhynchus tshawytscha*) to vibriosis after exposure to chlorinated and aromatic compounds found in contaminated urban estuaries. Journal of Aquatic Animal Health 13: 257–268.

Arkoosh, M.R., Clemons, E., Myers, M., and Casillas, E. 1994. Suppression of B-cell mediated immunity in juvenile chinook salmon (*Oncorhynchus tshawytscha*) after exposure to either a polycyclic aromatic hydrocan or to polychlorinated biphenyls. Immunopharmacology and Immunotoxicology 16(2): 293–314. Taylor & Francis.

Arkoosh, M.R., Van Gaest, A.L., Strickland, S.A., Hutchinson, G.P., Krupkin, A.B., and Dietrich, J.P. 2017. Alteration of thyroid hormone concentrations in juvenile chinook salmon (*Oncorhynchus tshawytscha*) exposed to polybrominated diphenyl ethers, BDE-47 and BDE-99. Chemosphere 171: 1–8.

Bartz, K.K., Lagueux, K.M., Scheuerell, M.D., Beechie, T., Haas, A.D., and Ruckelshaus, M.H. 2006. Translating restoration scenarios into habitat conditions: an initial step in evaluating recovery strategies for Chinook salmon (*Oncorhynchus tshawytscha*). Canadian Journal of Fisheries and Aquatic Sciences 63(7): 1578–1595. doi:10.1139/f06-055.

Battin, J., Wiley, M.W., Ruckelshaus, M.H., Palmer, R.N., Korb, E., Bartz, K.K., and Imaki, H. 2007. Projected impacts of climate change on salmon habitat restoration. Proceedings of the national academy of sciences 104(16): 6720–6725. National Acad Sciences.

Beacham, T.D., and Murray, C.B. 1993. Fecundity and egg size variation in North American Pacific salmon (*Oncorhynchus*). Journal of Fish Biology 42(4): 485–508. Wiley Online Library.

Beamer, E., Hayman, B., and Smith, D. 2005. Linking freshwater rearing habitat to Skagit Chinook salmon recovery. Appendix C of the Skagit Chinook recovery plan.

Beamer, E., Shannahan, J.-P., Wolf, K., Lowery, E., and Pflug, D. 2010. Freshwater Habitat Rearing Preferences for Stream Type Juvenile Chinook Salmon (*Oncorhynchus tshawytscha*) and Steelhead (O. *mykiss*) in the Skagit River Basin: Phase 1 Study Report.

Beamer, E.M., and Henderson, R.A. 1998. Juvenile salmonid use of natural and hydromodified stream bank habitat in the mainstem Skagit River, northwest Washington. Skagit System Cooperative. LaConner, Washington.

Beamer, E.M., McBride, A., Henderson, R., Griffith, J., Fresh, K., Zackey, T., Barsh, R., Wyllie-Echeverria, T., and Wolf, K. 2006. Habitat and Fish Use of Pocket Estuaries in the Whidbey Basin and North Skagit County Bays, 2004 and 2005. Skagit River System Cooperative, Skagit, WA.

Beamer, E.M., and Pess, G.R. 1999. Effects of peak flows on Chinook (*Oncorhynchus tshawytscha*) spawning success in two Puget Sound river basins. Watershed Management to Protect Declining Species. Am Water Resour Assoc, Middleburg: 67–70. Citeseer.

Beamer, E.M., Zackey, W.T., Marks, D., Teel, D., Kuligowski, D., and Henderson, R. 2013. Juvenile chinook salmon rearing in small non-natal streams draining into the Whidbey Basin. Skagit River System Cooperative, LaConner, WA.

Beamish, R.J., and Mahnken, C. 2001. A critical size and period hypothesis to explain natural regulation of salmon abundance and the linkage to climate and climate change. Progress in Oceanography 49(1–4): 423–437. Elsevier.

Beauchamp, D.A., and Duffy, E.J. 2011. Stage-specific growth and survival during early marine life of Puget Sound Chinook salmon in the context of temporal-spatial environmental conditions and trophic interactions. Final report to the Pacific Salmon Commission, Pacific Salmon Commission.

Beauchamp, D.A., Elder, N., Wittmond, M., Wetzel, L., Hoy, M., Stenberg, K., Lind-Null, A., and Larsen, K.A. 2018. Effects of Seasonal Availability and Energy Content of Key Prey on Growth Performance during Critical Periods for Juvenile Chinook Salmon.

Beechie, T.J., Collins, B.D., and Pess, G.R. 2001. Holocene and recent geomorphic processes, land use, and salmonid habitat in two north Puget Sound river basins. Geomorphic Processes and Riverine Habitat Water Science and Application 4: 37–54.

Beechie, T.J., Liermann, M., Beamer, E.M., and Henderson, R. 2005. A classification of habitat types in a large river and their use by juvenile salmonids. Transactions of the American Fisheries Society 134(3): 717–729. Taylor & Francis.

Beechie, T.J., Nicol, C., Fogel, C., Jorgensen, J., Thompson, J., Seixas, G., Chamberlin, J., Hall, J., Timpane-Padgham, B., and Kiffney, P. 2021. Modeling Effects of Habitat Change and Restoration Alternatives on Salmon in the Chehalis River Basin Using a Salmonid Life-Cycle Model.

Beechie, T.J., Sear, D.A., Olden, J.D., Pess, G.R., Buffington, J.M., Moir, H., Roni, P., and Pollock, M.M. 2010. Process-based principles for restoring river ecosystems. BioScience 60(3): 209–222. American Institute of Biological Sciences Circulation, AIBS, 1313 Dolley ….

Beer, W.N., and Steel, E.A. 2018. Impacts and Implications of Temperature Variability on Chinook Salmon Egg Development and Emergence Phenology. Transactions of the American Fisheries Society 147(1): 3–15. doi:10.1002/tafs.10025.

Berninger, J.P., and Tillitt, D.E. 2019. Polychlorinated biphenyl tissue-concentration thresholds for survival, growth, and reproduction in fish. Environmental toxicology and chemistry 38(4): 712–736. Wiley Online Library.

Bigler, B.S., Welch, D.W., and Helle, J.H. 1996. A review of size trends among North Pacific salmon (*Oncorhynchus spp.*). Canadian Journal of Fisheries and Aquatic Sciences 53(2): 455–465. NRC Research Press Ottawa, Canada.

Bilby, R.E., and Bisson, P.A. 1998. Function and distribution of large woody debris. River ecology and management. Springer-Verlag.

Bilby, R.E., and Ward, J.W. 1991. Characteristics and function of large woody debris in streams draining old-growth, clear-cut, and second-growth forests in southwestern Washington. Canadian Journal of Fisheries and Aquatic Sciences 48(12): 2499–2508. NRC Research Press.

Bjornn, T.C. 1969. Embryo survival and emergence studies. Salmon and Steelhead Investigations, Job Completion Report. Project F-49-R-7. Idaho Department of Fish and Game, Boise, Idaho, USA.

Bjornn, T.C., and Reiser, D.W. 1991. Habitat requirements of salmonids in streams. American Fisheries Society Special Publication 19(837): 138.

Boles, G.L. 1988. Water temperature effects on chinook salmon (*Oncorhynchus tshawytscha*) with emphasis on the Sacramento River : a literature review. California Dept. of Water Resources, Northern District.

Booth, D.B., Bell, K., and Whipple, K. 1991. Sediment Transport Along the South Fork and Mainstem of the Snoqualmie River. King County Surface Water Management Division, Seattle, WA.

Bottom, D.L., Jones, K.K., Cornwell, T.J., Gray, A., and Simenstad, C.A. 2005. Patterns of Chinook salmon migration and residency in the Salmon River estuary (Oregon). Estuarine, Coastal and Shelf Science 64(1): 79–93. Elsevier.

Bradford, M.J., and Higgins, P.S. 2001. Habitat-, season-, and size-specific variation in diel activity patterns of juvenile chinook salmon (*Oncorhynchus tshawytscha*) and steelhead trout (*Oncorhynchus mykiss*). Canadian Journal of Fisheries and Aquatic Sciences 58(2): 365–374. NRC Research Press Ottawa, Canada.

Bugert, R.M., Mendel, G.W., and Seidel, P.R. 1997. Adult returns of subyearling and yearling fall Chinook salmon released from a Snake River hatchery or transported downstream. North American Journal of Fisheries Management 17(3): 638–651. Wiley Online Library.

Bunn, N.A., Fox, C.J., and Webb, T. 2000. A literature review of studies on fish egg mortality: implications for the estimation of spawning stock biomass by the annual egg production method. Centre for Environment, Fisheries and Aquaculture Science Lowestoft, UK.

Carey, A.J., West, J.E., Fisk, R.J., Langness, M.M., Ylitalo, G.M., and O'Neill, S.M. 2018. Input of PBDE exposure in juvenile Chinook salmon along their out-migrant pathway through the Snohomish River, WA.

Carl, L.M., and Healey, M.C. 1984. Differences in enzyme frequency and body morphology among three juvenile life history types of chinook salmon (*Oncorhynchus tshawytscha*) in the Nanaimo River, British Columbia. Canadian Journal of Fisheries and Aquatic Sciences 41(7): 1070–1077. NRC Research Press Ottawa, Canada.

Chamberlin, J. 2021. Snohomish estuary synthesis: Chinook salmon in tidal deltas. Snohomish River Basin Salmon Recovery Technical Committee.

Chamberlin, J., Gamble, M., Connelly, K., Gardner, J., Barsh, R., O'Connell, M., Keister, J., Beauchamp, D., Schmidt, M., Beckman, B., and Warheit, K. 2017. Assessing early marine growth in juvenile Chinook salmon: factors affecting variability in individual growth in Northern Puget Sound. Available via Long Live the Kings, Seattle, WA.

Chamberlin, J., Hall, J., Zackey, T., Leonetti, F., Rustay, M., and Rice, C. 2021a. Broad scale spatial and temporal variability in Chinook salmon abundance reflects important life history distinctions relevant to restoration in an estuarine landscape. NOAA Fisheries, Northwest Fisheries Science Center, Mukilteo Research Station, Mukilteo, WA.

Chamberlin, J.W., Essington, T.E., Ferguson, J.W., and Quinn, T.P. 2011. The Influence of Hatchery Rearing Practices on Salmon Migratory Behavior: Is the Tendency of Chinook Salmon to Remain within Puget Sound Affected by Size and Date of Release? Transactions of the American Fisheries Society 140(5): 1398–1408.

Chamberlin, J.W., Hall, J., Zackey, W.T., Leonetti, F., Rustay, M., and Rice, C. 2021b. Spatial and Temporal Variability in Chinook Salmon Abundance Reflects Opportunity to Support Life History Diversity in an Estuarine Landscape. Estuaries and Coasts.

Chapman, D.W. 1988. Critical review of variables used to define effects of fines in redds of large salmonids. Transactions of the American Fisheries Society 117(1): 1–21. Wiley Online Library.

Chasco, B., Kaplan, I.C., Thomas, A., Acevedo-Gutiérrez, A., Noren, D., Ford, M.J., Hanson, M.B., Scordino, J., Jeffries, S., and Pearson, S. 2017a. Estimates of Chinook salmon consumption in Washington State inland waters by four marine mammal predators from 1970 to 2015. Canadian Journal of Fisheries and Aquatic Sciences 74(8): 1173–1194. NRC Research Press.

Chasco, B.E., Kaplan, I.C., Thomas, A.C., Acevedo-Gutiérrez, A., Noren, D.P., Ford, M.J., Hanson, M.B., Scordino, J.J., Jeffries, S.J., and Marshall, K.N. 2017b. Competing tradeoffs between increasing marine mammal predation and fisheries harvest of Chinook salmon. Scientific Reports 7(1): 1–14. Nature Publishing Group.

Chittenden, C.M., Sweeting, R., Neville, C.M., Young, K., Galbraith, M., Carmack, E., Vagle, S., Dempsey, M., Eert, J., and Beamish, R.J. 2018. Estuarine and marine diets of out-migrating Chinook Salmon smolts in relation to local zooplankton populations, including harmful blooms. Estuarine, Coastal and Shelf Science 200: 335–348. Elsevier.

Claiborne, A.M., Campbell, L., Stevick, B., Sandell, T., Losee, J.P., Litz, M., and Anderson, J.H. 2021. Correspondence between scale growth, feeding conditions, and survival of adult Chinook salmon returning to Puget Sound and coastal Washington: Implications for forecasting. Progress in Oceanography 198: 102443. Elsevier.

Claiborne, A.M., Fisher, J.P., Hayes, S.A., and Emmett, R.L. 2011. Size at Release, Size-Selective Mortality, and Age of Maturity of Willamette River Hatchery Yearling Chinook Salmon. Transactions of the American Fisheries Society 140(4): 1135–1144.

Collins, B.D., and Sheikh, A.J. 2002. Mapping historical conditions in the Snoqualmie River valley (RM 0 - RM 40).

Connelly, K.A., Gardner, J.R., Gamble, M.M., Chamberlin, J.W., Winans, A., Keister, J., and Beauchamp, D.A. 2018. Marine survival of Puget Sound Chinook: size-selective mortality growth limitation and bioenergetics of sub-yearling Chinook salmon in Puget Sound, Washington. Prepared for Long Live the Kings, Seattle. WA, Tech Rep LLTK-SSMSP-9.

Connor, W.P., Sneva, J.G., Tiffan, K.F., Steinhorst, R.K., and Ross, D. 2005. Two alternative juvenile life history types for fall Chinook salmon in the Snake River basin. Transactions of the American Fisheries Society 134(2): 291–304. Taylor & Francis.

Costalago, D., Forster, I., Nemcek, N., Neville, C., Perry, R.I., Young, K., and Hunt, B.P. 2020. Seasonal and spatial dynamics of the planktonic trophic biomarkers in the Strait of Georgia (northeast Pacific) and implications for fish. Scientific reports 10(1): 1–12. Nature Publishing Group.

Cramer, S.P. 2001. The relationship of stream habitat features to potential for production of four salmonid species. SP Cramer and Associates, Gresham, Oregon.

Crossin, G.T., Hinch, S.G., Cooke, S.J., Welch, D.W., Patterson, D.A., Jones, S.R.M., Lotto, A.G., Leggatt, R.A., Mathes, M.T., and Shrimpton, J.M. 2008. Exposure to high temperature influences the behaviour, physiology, and survival of sockeye salmon during spawning migration. Canadian Journal of Zoology 86(2): 127–140.

Crozier, L.G., Burke, B.J., Chasco, B.E., Widener, D.L., and Zabel, R.W. 2021. Climate change threatens Chinook salmon throughout their life cycle. Communications biology 4(1): 1–14. Nature Publishing Group.

Crozier, L.G., Hendry, A.P., Lawson, P.W., Quinn, T.P., Mantua, N.J., Battin, J., Shaw, R.G., and Huey, R.B. 2008. Potential responses to climate change in organisms with complex life histories: evolution and plasticity in Pacific salmon. Evolutionary Applications 1(2): 252–270.

Crozier, L.G., and Zabel, R.W. 2006. Climate impacts at multiple scales: evidence for differential population responses in juvenile Chinook salmon. Journal of Animal Ecology 75(5): 1100–1109. Wiley Online Library.

Cullon, D.L., Yunker, M.B., Alleyne, C., Dangerfield, N.J., O'Neill, S., Whiticar, M.J., and Ross, P.S. 2009. Persistent organic pollutants in Chinook salmon (*Oncorhynchus tshawytscha*): implications for resident killer whales of British Columbia and adjacent waters. Environmental Toxicology and Chemistry: An International Journal 28(1): 148–161. Wiley Online Library.

Daly, E.A., Brodeur, R.D., and Weitkamp, L.A. 2009. Ontogenetic shifts in diets of juvenile and subadult coho and Chinook salmon in coastal marine waters: important for marine survival? Transactions of the American Fisheries Society 138(6): 1420–1438. Taylor & Francis.

Dauble, D.D., Hanrahan, T.P., Geist, D.R., and Parsley, M.J. 2003. Impacts of the Columbia River hydroelectric system on main-stem habitats of fall Chinook salmon. North American Journal of Fisheries Management 23(3): 641–659. Taylor & Francis.

David, A.T., Ellings, C.S., Woo, I., Simenstad, C.A., Takekawa, J.Y., Turner, K.L., Smith, A.L., and Takekawa, J.E. 2014. Foraging and growth potential of juvenile Chinook salmon after tidal restoration of a large river delta. Transactions of the American Fisheries Society 143(6): 1515–1529. Taylor & Francis.

Davis, J.C. 1975. Minimal dissolved oxygen requirements of aquatic life with emphasis on Canadian species: a review. Journal of the Fisheries Board of Canada 32(12): 2295–2332. NRC Research Press.

Davis, M.J., Chamberlin, J.W., Gardner, J.R., Connelly, K.A., Gamble, M.M., Beckman, B.R., and Beauchamp, D.A. 2020. Variable prey consumption leads to distinct regional differences in Chinook salmon growth during the early marine critical period. Marine Ecology Progress Series 640: 147–169.

DeVries, P. 1997. Riverine salmonid egg burial depths: review of published data and implications for scour studies. Canadian Journal of Fisheries and Aquatic Sciences 54(8): 1685–1698. NRC Research Press Ottawa, Canada.

Duffy, E.J., and Beauchamp, D.A. 2011. Rapid growth in the early marine period improves the marine survival of Chinook salmon (*Oncorhynchus tshawytscha*) in Puget Sound, Washington. Canadian Journal of Fisheries and Aquatic Sciences 68(2): 232–240.

Duffy, E.J., Beauchamp, D.A., Sweeting, R.M., Beamish, R.J., and Brennan, J.S. 2010. Ontogenetic diet shifts of juvenile Chinook salmon in nearshore and offshore habitats of Puget Sound. Transactions of the American Fisheries Society 139(3): 803–823. Taylor & Francis.

Duguid, W.D., Iwanicki, T.W., Qualley, J., and Juanes, F. 2021. Fine-scale spatiotemporal variation in juvenile Chinook Salmon distribution, diet and growth in an oceanographically heterogeneous region. Progress in Oceanography 193: 102512. Elsevier.

Forbes, L.S., and Peterman, R.M. 1994. Simple size-structured models of recruitment and harvest in Pacific salmon (*Oncorhynchus spp.*). Canadian Journal of Fisheries and Aquatic Sciences 51(3): 603–616. NRC Research Press Ottawa, Canada.

Fullerton, A.H., Burke, B.J., Lawler, J.J., Torgersen, C.E., Ebersole, J.L., and Leibowitz, S.G. 2017a. Simulated juvenile salmon growth and phenology respond to altered thermal regimes and stream network shape. Ecosphere 8(12): e02052. Wiley Online Library.

Fullerton, A.H., Burnett, K.M., Steel, E.A., Flitcroft, R.L., Pess, G.R., Feist, B.E., Torgersen, C.E., Miller, D.J., and Sanderson, B.L. 2010. Hydrological connectivity for riverine fish: measurement challenges and research opportunities. Freshwater biology 55(11): 2215–2237. Wiley Online Library.

Fullerton, A.H., Torgersen, C.E., Lawler, J.J., Faux, R.N., Steel, E.A., Beechie, T.J., Ebersole, J.L., and Leibowitz, S.G. 2015. Rethinking the longitudinal stream temperature paradigm: region-wide comparison of thermal infrared imagery reveals unexpected complexity of river temperatures. Hydrological Processes 29(22): 4719–4737. Wiley Online Library.

Fullerton, A.H., Torgersen, C.E., Lawler, J.J., Steel, E.A., Ebersole, J.L., and Lee, S.Y. 2017b. Longitudinal thermal heterogeneity in rivers and refugia for coldwater species: effects of scale and climate change. Aquatic Sciences 80(1): 3.

Gamble, M.M. 2016. Size-selective mortality and environmental factors affecting early marine growth during early marine life stages of sub-yearling Chinook salmon in Puget Sound, Washington.

Gamble, M.M., Connelly, K.A., Gardner, J.R., Chamberlin, J.W., Warheit, K.I., and Beauchamp, D.A. 2018. Size, growth, and size-selective mortality of subyearling Chinook Salmon during early marine residence in Puget Sound. Transactions of the American Fisheries Society 147(2): 370–389. Wiley Online Library.

Gardner, J.L., Peters, A., Kearney, M.R., Joseph, L., and Heinsohn, R. 2011. Declining body size: a third universal response to warming? Trends in ecology & evolution 26(6): 285–291. Elsevier.

Glick, P., Clough, J., and Nunley, B. 2007. Sea-level rise and coastal habitats in the Pacific northwest. National Wildlife Federation.

Greene, C., Beamer, E., Chamberlin, J., Hood, G., Davis, M., Larsen, K., Anderson, J., Henderson, R., Hall, J., Pouley, M., Zackey, T., Hodgson, S., Ellings, C., and Woo, I. 2021. Landscape, density-dependent, and bioenergetic influences upon Chinook salmon in tidal delta habitats: Comparison of four Puget Sound estuaries.

Greene, C., Curry, B., Sobocinski, K., Newton, J., Keister, J., Kemp, I., Beauchamp, D., Lessard, E., Stark, K., and Hannah, G. 2020. Linking environmental and biotic variation to growth and survival of juvenile Chinook salmon in Puget Sound. Salish Sea Marine Survival Project Technical Report.

Greene, C.M., and Beechie, T.J. 2004. Consequences of potential density-dependent mechanisms on recovery of ocean-type Chinook salmon (*Oncorhynchus tshawytscha*). Canadian Journal of Fisheries and Aquatic Sciences 61(4): 590–602. NRC Research Press Ottawa, Canada.

Greene, C.M., Hall, J.E., Guilbault, K.R., and Quinn, T.P. 2010. Improved viability of populations with diverse life-history portfolios. Biology Letters 6(3): 382–386. The Royal Society.

Greene, C.M., Jensen, D.W., Pess, G.R., Steel, E.A., and Beamer, E. 2005. Effects of environmental conditions during stream, estuary, and ocean residency on Chinook salmon return rates in the Skagit River, Washington. Transactions of the American Fisheries Society 134(6): 1562–1581. Taylor & Francis.

Haas, A., and Collins, B.D. 2001. A Historical Analysis of Habitat Alteration in the Snohomish River Valley, Washington since the mid-19th Century: Implications for Chinook and Coho Salmon. Snohomish County Department of Public Works, Surface Water Management Division.

Hall, J.E., Khangaonkar, T.P., Rice, C.A., Chamberlin, J., Zackey, T., Leonetti, F., Rustay, M., Fresh, K., Kagley, A., and Rowse, M. 2018. Characterization of salinity and temperature patterns in a large river delta to support tidal wetland habitat restoration. Northwest Science 92(1): 36–52. BioOne.

Hamlet, A.F., Elsner, M.M., Mauger, G.S., Lee, S.-Y., Tohver, I., and Norheim, R.A. 2013. An overview of the Columbia Basin Climate Change Scenarios Project: Approach, methods, and summary of key results. Atmosphere-ocean 51(4): 392–415. Taylor & Francis.

Haring, D. 2002. Salmonid Habitat Limiting Factors Analysis: Snohomish River Watershed Water Resource Inventory Area (WRIA) 7 Final Report. Prepared for the Washington State Conservation Commission.

Harmon, M.E., Franklin, J.F., Swanson, F.J., Sollins, P., Gregory, S.V., Lattin, J.D., Anderson, N.H., Cline, S.P., Aumen, N.G., and Sedell, J.R. 1986. Ecology of coarse woody debris in temperate ecosystems. *In* Advances in ecological research. Elsevier. pp. 133–302.

Hawkins, B.L., Fullerton, A.H., Sanderson, B.L., and Steel, E.A. 2020. Individual-based simulations suggest mixed impacts of warmer temperatures and a nonnative predator on Chinook salmon. Ecosphere 11(8): e03218. doi:10.1002/ecs2.3218.

Hayman, R.A., Beamer, E.M., and McClure, R.E. 1996. FY 1995 Skagit River Chinook restoration research progress report No. 1. Skagit System Cooperative, La Conner Washington. 113p plus appendices.

Healey, M.C. 1991. Life history of chinook salmon (*Oncorhynchus tshawytscha*). Pacific salmon life histories: 311–394. University of British Columbia Press Vancouver.

Healey, M.C., and Heard, W.R. 1984. Inter-and intra-population variation in the fecundity of chinook salmon (*Oncorhynchus tshawytscha*) and its relevance to life history theory. Canadian journal of fisheries and aquatic sciences 41(3): 476–483. NRC Research Press Ottawa, Canada.

Helle, J.H. 1979. Influence of marine environment on age and size at maturity, growth, and abundance of chum salmon, *Oncorhynchus keta* (Walbaum), from Olsen Creek, Prince William Sound, Alaska.

Heming, T.A. 1982. Effects of temperature on utilization of yolk by chinook salmon (*Oncorhynchus tshawytscha*) eggs and alevins. Canadian Journal of Fisheries and Aquatic Sciences 39(1): 184–190. NRC Research Press.

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

Hillman, T.W., Griffith, J.S., and Platts, W.S. 1987. Summer and winter habitat selection by juvenile chinook salmon in a highly sedimented Idaho stream. Transactions of the American Fisheries Society 116(2): 185–195. Wiley Online Library.

Holtby, L.B., Andersen, B.C., and Kadowaki, R.K. 1990. Importance of smolt size and early ocean growth to interannual variability in marine survival of coho salmon (*Oncorhynchus kisutch*). Canadian Journal of Fisheries and Aquatic Sciences 47(11): 2181–2194. NRC Research Press Ottawa, Canada.

Huusko, A.R.I., Greenberg, L., Stickler, M., Linnansaari, T., Nykänen, M., Vehanen, T., Koljonen, S., Louhi, P., and Alfredsen, K. 2007. Life in the ice lane: the winter ecology of stream salmonids. River research and applications 23(5): 469–491. Wiley Online Library.

Isaak, D.J., Wenger, S.J., Peterson, E.E., Ver Hoef, J.M., Hostetler, S., Luce, C.H., Dunham, J.B., Kershner, J., Roper, B.B., and Nagel, D. 2011. NorWeST: An interagency stream temperature database and model for the Northwest United States. US Fish and Wildlife Service, Great Northern Landscape Conservation Cooperative Grant.

Isaak, D.J., Young, M.K., Nagel, D.E., Horan, D.L., and Groce, M.C. 2015. The cold-water climate shield: delineating refugia for preserving salmonid fishes through the 21st century. Global Change Biology 21(7): 2540–2553. Wiley Online Library.

Jager, Y. 2011. Quantifying Temperature Effects on Fall Chinook Salmon. Oak Ridge National Lab. (ORNL), Oak Ridge, TN (United States).

Jeffres, C.A., Opperman, J.J., and Moyle, P.B. 2008. Ephemeral floodplain habitats provide best growth conditions for juvenile Chinook salmon in a California river. Environmental Biology of Fishes 83(4): 449–458. Springer.

Jeffrey, K.M., Côté, I.M., Irvine, J.R., and Reynolds, J.D. 2017. Changes in body size of Canadian Pacific salmon over six decades. Canadian Journal of Fisheries and Aquatic Sciences 74(2): 191–201. NRC Research Press.

Jeffries, S., Huber, H., Calambokidis, J., and Laake, J. 2003. Trends and status of harbor seals in Washington State: 1978-1999. The Journal of wildlife management: 207–218. JSTOR.

Jensen, D.W., Steel, E.A., Fullerton, A.H., and Pess, G.R. 2009. Impact of fine sediment on egg-to-fry survival of Pacific salmon: a meta-analysis of published studies. Reviews in Fisheries Science 17(3): 348–359. Taylor & Francis.

Jorgensen, J.C., Nicol, C., Fogel, C., and Beechie, T.J. 2021. Identifying the potential of anadromous salmonid habitat restoration with life cycle models. Plos one 16(9): e0256792. Public Library of Science San Francisco, CA USA.

Keister, J.E., Winans, A.K., Herrmann, B., Bos, J., and Kemp, I. 2019. Bottom-up links to juvenile salmon growth and survival in Puget Sound, WA, USA.

Keith, J., Seay, E., Pouley, M., Finley, K., and Nelson, K. in prep. 2000-2021 Skykomish and Snoqualmie Rivers Chinook and Coho Salmon Out-migration Study. Tulalip Tribes Natural Resources Department.

Kendall, N.W., Nelson, B.W., and Losee, J.P. 2020. Density-dependent marine survival of hatchery-origin Chinook salmon may be associated with pink salmon. Ecosphere 11(4): e03061. Wiley Online Library.

Kilduff, D.P., Botsford, L.W., and Teo, S.L. 2014. Spatial and temporal covariability in early ocean survival of Chinook salmon (*Oncorhynchus tshawytscha*) along the west coast of North America. ICES Journal of Marine Science 71(7): 1671–1682. Oxford University Press.

King County. 2018. Aquatic Habitat Conditions in the Lower Snoqualmie, Tolt, and Raging Rivers. Prepared by Josh Kubo, Water and Land Resources Division. Seattle, Washington, Seattle, WA.

King County. 2021a. Snoqualmie River Juvenile Chinook with Extended Freshwater Rearing. Prepared by Josh Kubo, Water and Land Resources Division. Seattle, Washington.

King County. 2021b. Snoqualmie River Project Effectiveness Evaluation – Aquatic Habitat and Juvenile Salmonid Observations. Prepared by Josh Kubo, Water and Land Resources Division. Seattle, Washington.

Kjelson, M.A., Raquel, P.F., and Fisher, F.W. 1982. Life history of fall-run juvenile chinook salmon, *Oncorhynchus tshawytscha*, in the Sacramento-San Joaquin estuary, California. *In* Estuarine comparisons. Elsevier. pp. 393–411.

Knudsen, E.E., and Dilley, S.J. 1987. Effects of riprap bank reinforcement on juvenile salmonids in four western Washington streams. North American Journal of Fisheries Management 7(3): 351–356. Taylor & Francis.

Kubo, J. 2017. 2016 Snoqualmie River Water Temperature Study: Results and Findings. King County Department of Natural Resources and Parks, Water Land and Resources Division, Seattle, WA.

Kubo, J. 2021. Tolt Pipeline Protection/Winkelman Revetment Reconstruction Project: Year 3 Post-Project Aquatic Habitat and Juvenile Salmonid Monitoring Results. King County Department of Natural Resources and Parks, Water Land and Resources Division.

Kubo, J., Finley, K., and Nelson, K. 2013. 2000-2012 Skykomish and Snoqualmie Rivers Chinook and Coho Salmon Out-migration Study. Tulalip Tribes Natural Resources Department.

Kubo, J., Miller, A., and Davis, E. 2021. Water Temperature Conditions in the Snohomish River Basin. King County Department of Natural Resources and Parks, Water Land and Resources Division, Seattle, WA.

Laufkötter, C., Zscheischler, J., and Frölicher, T.L. 2020. High-impact marine heatwaves attributable to human-induced global warming. Science 369(6511): 1621–1625. American Association for the Advancement of Science.

Lawrence, D.J., Olden, J.D., and Torgersen, C.E. 2012. Spatiotemporal patterns and habitat associations of smallmouth bass (*Micropterus dolomieu*) invading salmon-rearing habitat. Freshwater Biology 57(9): 1929–1946. Wiley Online Library.

Lawrence, D.J., Stewart-Koster, B., Olden, J.D., Ruesch, A.S., Torgersen, C.E., Lawler, J.J., Butcher, D.P., and Crown, J.K. 2014. The interactive effects of climate change, riparian management, and a nonnative predator on stream-rearing salmon. Ecological Applications 24(4): 895–912. Wiley Online Library.

Levings, C.D., and Lauzier, R.B. 1991. Extensive use of the Fraser River basin as winter habitat by juvenile chinook salmon (*Oncorhynchus tshawytscha*). Canadian Journal of Zoology 69(7): 1759–1767. NRC Research Press Ottawa, Canada.

Levy, D.A., and Northcote, T.G. 1982. Juvenile salmon residency in a marsh area of the Fraser River estuary. Canadian Journal of Fisheries and Aquatic Sciences 39(2): 270–276. NRC Research Press Ottawa, Canada.

Limm, M.P., and Marchetti, M.P. 2009. Juvenile Chinook salmon (*Oncorhynchus tshawytscha*) growth in off-channel and main-channel habitats on the Sacramento River, CA using otolith increment widths. Environmental biology of fishes 85(2): 141–151. Springer.

Litz, M.N., Miller, J.A., Copeman, L.A., and Hurst, T.P. 2017. Effects of dietary fatty acids on juvenile salmon growth, biochemistry, and aerobic performance: a laboratory rearing experiment. Journal of Experimental Marine Biology and Ecology 494: 20–31. Elsevier.

Lowery, E., Thompson, J., Connor, E., Pflug, D., Donahue, B., and Shannahan, J.-P. 2020. Seasonal Distribution and Habitat Associations of Salmonids with Extended Juvenile Freshwater Rearing in Different Precipitation Zones of the Skagit River, WA January, 2020.

Mantua, N., Tohver, I., and Hamlet, A. 2010. Climate change impacts on streamflow extremes and summertime stream temperature and their possible consequences for freshwater salmon habitat in Washington State. Climatic Change 102(1–2): 187–223. Springer.

Mantua, N.J., Hare, S.R., Zhang, Y., Wallace, J.M., and Francis, R.C. 1997. A Pacific interdecadal climate oscillation with impacts on salmon production. Bulletin of the American Meteorological Society 78(6): 1069–1080. American Meteorological Society.

Marcogliese, D.J. 2008. The impact of climate change on the parasites and infectious diseases of aquatic animals. Rev Sci Tech 27(2): 467–484.

Martin, D., Benda, L., and Shreffler, D. 2004. Core Areas: A Framework for Identifying Critical Habitat for Salmon. King County Department of Natural Resources and Parks, Water Land and Resources Division, Seattle, WA.

Mauger, G.S., J. H. Casola, H. A. Morgan, R. L. Strauch, B. Jones, B. Curry, T. M. Busch Isaksen, L. Whitely Binder, M. B. Krosby, and A. K. Snover. 2015. State of Knowledge: Climate Change in Puget Sound. Report prepared for the Puget Sound Partnership and the National Oceanic and Atmospheric Administration, University of Washington, Seattle.

McClure, M.M., Carlson, S.M., Beechie, T.J., Pess, G.R., Jorgensen, J.C., Sogard, S.M., Sultan, S.E., Holzer, D.M., Travis, J., and Sanderson, B.L. 2008. Evolutionary consequences of habitat loss for Pacific anadromous salmonids. Evolutionary Applications 1(2): 300–318. Wiley Online Library.

McCullough, D.A. 1999. A review and synthesis of effects of alterations to the water temperature regime on freshwater life stages of salmonids, with special reference to Chinook salmon. US Environmental Protection Agency, Region 10.

McElhany, P., Rucklelshaus, M.H., Ford, M.J., Wainwright, T.C., and Bjorkstedt, E.P. 2000. Viable salmonid populations and the recovery of evolutionarily significant units. NOAA Technical Memorandum NMFS-NWFSC, US Department of Commerce.

Meador, J.P. 2014. Do chemically contaminated river estuaries in Puget Sound (Washington, USA) affect the survival rate of hatchery-reared Chinook salmon? Canadian Journal of Fisheries and Aquatic Sciences 71(1): 162–180. NRC Research Press.

Metcalfe, C.D., Chu, S., Judt, C., Li, H., Oakes, K.D., Servos, M.R., and Andrews, D.M. 2010. Antidepressants and their metabolites in municipal wastewater, and downstream exposure in an urban watershed. Environmental Toxicology and Chemistry 29(1): 79–89.

Miller, J.A., Teel, D.J., Baptista, A., and Morgan, C.A. 2013. Disentangling bottom-up and top-down effects on survival during early ocean residence in a population of Chinook salmon (*Oncorhynchus tshawytscha*). Canadian Journal of Fisheries and Aquatic Sciences 70(4): 617–629. NRC Research Press.

Miller, K.M., Teffer, A., Tucker, S., Li, S., Schulze, A.D., Trudel, M., Juanes, F., Tabata, A., Kaukinen, K.H., and Ginther, N.G. 2014. Infectious disease, shifting climates, and opportunistic predators: cumulative factors potentially impacting wild salmon declines. Evolutionary Applications 7(7): 812–855. Wiley Online Library.

Montgomery, D.R., Beamer, E.M., Pess, G.R., and Quinn, T.P. 1999. Channel type and salmonid spawning distribution and abundance. Canadian Journal of Fisheries and Aquatic Sciences 56(3): 377–387. NRC Research Press Ottawa, Canada.

Montgomery, D.R., Buffington, J.M., Peterson, N.P., Schuett-Hames, D., and Quinn, T.P. 1996. Stream-bed scour, egg burial depths, and the influence of salmonid spawning on bed surface mobility and embryo survival. Canadian Journal of Fisheries and Aquatic Sciences 53(5): 1061–1070. NRC Research Press Ottawa, Canada.

Muhlfeld, C.C., Bennett, D.H., and Marotz, B. 2001. Fall and winter habitat use and movement by Columbia River redband trout in a small stream in Montana. North American Journal of Fisheries Management 21(1): 170–177. Taylor & Francis.

Muhlfeld, C.C., Glutting, S., Hunt, R., Daniels, D., and Marotz, B. 2003. Winter diel habitat use and movement by subadult bull trout in the upper Flathead River, Montana. North American Journal of Fisheries Management 23(1): 163–171. Taylor & Francis.

Munsch, S.H., Greene, C.M., Johnson, R.C., Satterthwaite, W.H., Imaki, H., and Brandes, P.L. 2019. Warm, dry winters truncate timing and size distribution of seaward-migrating salmon across a large, regulated watershed. Ecological Applications 29(4): e01880. Wiley Online Library.

Munsch, S.H., Greene, C.M., Johnson, R.C., Satterthwaite, W.H., Imaki, H., Brandes, P.L., and O'Farrell, M.R. 2020. Science for integrative management of a diadromous fish stock: interdependencies of fisheries, flow, and habitat restoration. Canadian Journal of Fisheries and Aquatic Sciences 77(9): 1487–1504. NRC Research Press 1840 Woodward Drive, Suite 1, Ottawa, ON K2C 0P7.

Myers, J.M. 1998. Status review of chinook salmon from Washington, Idaho, Oregon, and California.

National Marine Fisheries Service (NMFS). 2021. Endangered Species Act (ESA) Section 7(a)(2) Biological Opinion and Magnuson-Stevens Fishery Conservation and Management Act Essential Fish Habitat (EFH) Consultation: National Marine Fisheries Service (NMFS) Evaluation of Seven Hatchery and Genetic Management Plans for Snohomish River basin Salmon under Limit 6 of the Endangered Species Act Section 4(d) Rule. National Marine Fisheries Service, West Coast Region.

Nelson, B.W. 2020. Predator-prey interactions between harbour seals (*Phoca vitulina*) and Pacific salmon (*Oncorhynchus spp.*) in the Salish Sea. University of British Columbia.

Nelson, B.W., Pearson, S.F., Anderson, J.H., Jeffries, S.J., Thomas, A.C., Walker, W.A., Acevedo-Gutierrez, A., Kemp, I.M., Lance, M.M., and Louden, A. 2021. Variation in predator diet and prey size affects perceived impacts to salmon species of high conservation concern. Canadian Journal of Fisheries and Aquatic Sciences (ja).

Nelson, B.W., Walters, C.J., Trites, A.W., and McAllister, M.K. 2019. Wild Chinook salmon productivity is negatively related to seal density and not related to hatchery releases in the Pacific Northwest. Canadian Journal of Fisheries and Aquatic Sciences 76(3): 447–462. NRC Research Press.

Neupane, S., and Yager, E.M. 2013. Numerical simulation of the impact of sediment supply and streamflow variations on channel grain sizes and Chinook salmon habitat in mountain drainage networks. Earth Surface Processes and Landforms 38(15): 1822–1837. Wiley Online Library.

O' Neill, S.M., Carey, A.J., Lanksbury, J.A., James, A., Fisk, R., Langness, M., Niewolny, L.A., and West, J.E. 2018, April 5. Assessing the threat of contaminants of emerging concern to early marine survival of Chinook salmon in the Salish Sea. PowerPoint presentation.

Oke, K.B., Cunningham, C.J., Westley, P.A.H., Baskett, M.L., Carlson, S.M., Clark, J., Hendry, A.P., Karatayev, V.A., Kendall, N.W., and Kibele, J. 2020. Recent declines in salmon body size impact ecosystems and fisheries. Nature communications 11(1): 1–13. Nature Publishing Group.

Olesiuk, P.F. 1993. Annual prey consumption by harbor seals (*Phoca vitulina*) in the Strait of Georgia, British Columbia. Fishery Bull 91: 491–515.

O'Neill, S.M., Carey, A.J., Harding, L.B., West, J.E., Ylitalo, G.M., and Chamberlin, J.W. 2020. Chemical tracers guide identification of the location and source of persistent organic pollutants in juvenile Chinook salmon (*Oncorhynchus tshawytscha*), migrating seaward through an estuary with multiple contaminant inputs. Science of The Total Environment 712: 135516. Elsevier.

O'Neill, S.M., and West, J.E. 2009. Marine distribution, life history traits, and the accumulation of polychlorinated biphenyls in Chinook salmon from Puget Sound, Washington. Transactions of the American Fisheries Society 138(3): 616–632. Taylor & Francis.

Ottersen, G., Kim, S., Huse, G., Polovina, J.J., and Stenseth, N.C. 2010. Major pathways by which climate may force marine fish populations. Journal of Marine Systems 79(3–4): 343–360. Elsevier.

Pearsall, I., Schmidt, M., Kemp, I., and Riddell, B. 2021. Factors Limiting Survival of Juvenile Chinook Salmon, Coho Salmon, and Steelhead in the Salish Sea: Synthesis of Findings of the Salish Sea Marine Survival Project.

Pentec Environmental, and GIS NW. 1999. Snohomish River Basin Conditions and Issues Report. Revised Final Report. Prepared for the Snohomish River Basin Work Group. Edmonds, WA.

Perry, R.I., Young, K., Galbraith, M., Chandler, P., Velez-Espino, A., and Baillie, S. 2021. Zooplankton variability in the Strait of Georgia, Canada, and relationships with the marine survivals of Chinook and Coho salmon. Plos one 16(1): e0245941. Public Library of Science San Francisco, CA USA.

Pess, G.R., Montgomery, D.R., Beechie, T.J., and Holsinger, L. 2002. Anthropogenic alterations to the biogeography of salmon in Puget Sound. Restoration of Puget Sound Rivers: 129–154. University of Washington Press: Seattle.

Petersen, J.H., and Kitchell, J.F. 2001. Climate regimes and water temperature changes in the Columbia River: bioenergetic implications for predators of juvenile salmon. Canadian Journal of Fisheries and Aquatic Sciences 58(9): 1831–1841. NRC Research Press Ottawa, Canada.

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

Puget Sound Indian Tribes, and Washington Department of Fish and Wildlife (PSIT & WDFW). 2017. Comprehensive Management Plan for Puget Sound Chinook: Harvest Management Component.

Puget Sound Partnership (PSP). 2021. Toxins in fish vital sign. Available from https://vitalsigns.pugetsoundinfo.wa.gov/VitalSign/Detail/11.

Quigley, J.T., and Harper, D.J. 2004. Streambank protection with rip-rap: an evaluation of the effects on fish and fish habitat. Citeseer.

Quinn, T., George, W., and Kirk, K. 2018. Riparian Ecosystems, Volume 1: Science Synthesis and Management Implications. 1: 293.

Quinn, T.P. 2018. The behavior and ecology of Pacific salmon and trout. University of Washington press.

Quinn, T.P., Dickerson, B.R., and Vøllestad, L.A. 2005. Marine survival and distribution patterns of two Puget Sound hatchery populations of coho (*Oncorhynchus kisutch*) and chinook (*Oncorhynchus tshawytscha*) salmon. Fisheries Research 76(2): 209–220. Elsevier.

Rahel, F.J., Bierwagen, B., and Taniguchi, Y. 2008. Managing aquatic species of conservation concern in the face of climate change and invasive species. Conservation Biology 22(3): 551–561. Wiley Online Library.

Ray, R.A., Holt, R.A., and Bartholomew, J.L. 2012. Relationship between temperature and *Ceratomyxa shasta*–induced mortality in Klamath River salmonids. Journal of Parasitology 98(3): 520–526. American Society of Parasitologists.

Reimers, P.E. 1971. The length of residence of juvenile fall chinook salmon in Sixes River, Oregon.

Rice, C.A., Greene, C.M., Moran, P., Teel, D.J., Kuligowski, D.R., Reisenbichler, R.R., Beamer, E.M., Karr 1, J.R., and Fresh, K.L. 2011. Abundance, stock origin, and length of marked and unmarked juvenile Chinook salmon in the surface waters of greater Puget Sound. Transactions of the American Fisheries Society 140(1): 170–189. Taylor & Francis.

Ricker, W.E. 1972. Hereditary and environmental factors affecting certain salmonid populations. The stock concept in Pacific salmon: 19–160.

Ricker, W.E. 1981. Changes in the average size and average age of Pacific salmon. Canadian Journal of Fisheries and Aquatic Sciences 38(12): 1636–1656. NRC Research Press Ottawa, Canada.

Roegner, G.C., and Teel, D.J. 2014. Density and Condition of Subyearling Chinook Salmon in the Lower Columbia River and Estuary in Relation to Water Temperature and Genetic Stock of Origin. Transactions of the American Fisheries Society 143(5): 1161–1176. doi:10.1080/00028487.2014.918055.

Roni, P., Johnson, C., De Boer, T., Pess, G., Dittman, A., and Sear, D. 2016. Interannual variability in the effects of physical habitat and parentage on Chinook salmon egg-to-fry survival. Canadian journal of fisheries and aquatic sciences 73(7): 1047–1059. NRC Research Press.

Rosberg, G.E., and Associates. 1987. Sampling of Juvenile Salmonids in the Frasier River Mainstem Over the Winter of 1986–1987. Data report prepared for Fisheries and Oceans Canada, Vancouver, B. C.

Ruckelshaus, M., McElhany, P., and Ford, M.J. 2003. Recovering Species of Conservation Concern—Are Populations Expendable? Agencies and Staff of the U.S. Department of Commerce.

Ruckelshaus, M.H., Currens, K.P., Graeber, W.H., Fuerstenberg, R.R., Rawson, K., Sands, N.J., and Scott, J.B. 2006. Independent populations of Chinook salmon in Puget Sound.

Ruff, C.P., Anderson, J.H., Kemp, I.M., Kendall, N.W., Mchugh, P.A., Velez-Espino, A., Greene, C.M., Trudel, M., Holt, C.A., and Ryding, K.E. 2017. Salish Sea Chinook salmon exhibit weaker coherence in early marine survival trends than coastal populations. Fisheries Oceanography 26(6): 625–637. Wiley Online Library.

Ruggerone, G., and Weitkamp, D. 2004. WRIA 9 Chinook Salmon Research Framework. Natural Resources Consultants and Parametrix; Prepared for the WRIA 9 Steering Committee.

Ruggerone, G.T., and Goetz, F.A. 2004. Survival of Puget Sound Chinook salmon (*Oncorhynchus tshawytscha*) in response to climate-induced competition with pink salmon (*Oncorhynchus gorbuscha*). Canadian Journal of Fisheries and Aquatic Sciences 61(9): 1756–1770.

Ruggerone, G.T., Springer, A.M., Shaul, L.D., and van Vliet, G.B. 2019. Unprecedented biennial pattern of birth and mortality in an endangered apex predator, the southern resident killer whale, in the eastern North Pacific Ocean. Marine Ecology Progress Series 608: 291–296.

Ruzicka, J.J., Daly, E.A., and Brodeur, R.D. 2016. Evidence that summer jellyfish blooms impact Pacific Northwest salmon production. Ecosphere 7(4): e01324. Wiley Online Library.

Schabetsberger, R., Morgan, C.A., Brodeur, R.D., Potts, C.L., Peterson, W.T., and Emmett, R.L. 2003. Prey selectivity and diel feeding chronology of juvenile chinook (*Oncorhynchus tshawytscha*) and coho (*O. kisutch*) salmon in the Columbia River plume. Fisheries Oceanography 12(6): 523–540. Wiley Online Library.

Scheuerell, M.D., Hilborn, R., Ruckelshaus, M.H., Bartz, K.K., Lagueux, K.M., Haas, A.D., and Rawson, K. 2006. The Shiraz model: a tool for incorporating anthropogenic effects and fish–habitat relationships in conservation planning. Canadian Journal of Fisheries and Aquatic Sciences 63(7): 1596–1607. NRC Research Press Ottawa, Canada.

Schindler, D.E., Hilborn, R., Chasco, B., Boatright, C.P., Quinn, T.P., Rogers, L.A., and Webster, M.S. 2010. Population diversity and the portfolio effect in an exploited species. Nature 465(7298): 609–612. Nature Publishing Group.

Sear, D.A., Pattison, I., Collins, A.L., Newson, M.D., Jones, J.I., Naden, P.S., and Carling, P.A. 2014. Factors controlling the temporal variability in dissolved oxygen regime of salmon spawning gravels. Hydrological Processes 28(1): 86–103. Wiley Online Library.

Seattle Public Utilities, and U.S. Army Corps of Engineers (SPU & USACOE). 2008. Synthesis of Salmon Research and Monitoring. Investigations Conducted in the Western Lake Washington Basin. Seattle, Washington.

Seay, E., and Pouley, M. 2019. Snoqualmie River Juvenile Salmon Out-Migration Study Progress Report. Tulalip Tribes Natural Resources Department.

Seymour, A.H. 1956. Effects of temperature upon young chinook salmon. PhD Thesis, University of Washington.

Sharma, R., Velez-Espino, L.A., Wertheimer, A.C., Mantua, N., and Francis, R.C. 2013. Relating spatial and temporal scales of climate and ocean variability to survival of Pacific Northwest Chinook salmon (*Oncorhynchus tshawytscha*). Fisheries Oceanography 22(1): 14–31. Wiley Online Library.

Simenstad, C.A., Fresh, K.L., and Salo, E.O. 1982. The role of Puget Sound and Washington coastal estuaries in the life history of Pacific salmon: an unappreciated function. *In* Estuarine comparisons. Elsevier. pp. 343–364.

Snohomish Basin Salmon Recovery Forum (SBSRF). 2005. Snohomish River Basin Salmon Conservation Plan. Snohomish County Department of Public Works, Surface Water Management Division. Everett, WA.

Snohomish Basin Salmonid Recovery Technical Committee (SBSRTC). 2004. Snohomish River Basin Ecological Analysis for Salmonid Conservation. Snohomish County Surface Water Management Division.

Sobocinski, K.L., Greene, C.M., Anderson, J.H., Kendall, N.W., Schmidt, M.W., Zimmerman, M.S., Kemp, I.M., Kim, S., and Ruff, C.P. 2021. A hypothesis-driven statistical approach for identifying ecosystem indicators of coho and Chinook salmon marine survival. Ecological Indicators 124: 107403. Elsevier.

Solomon, F., and Boles, M. 2002. Snoqualmie Watershed Aquatic Habitat Conditions Report: Summary of 1999-2001 Data. King County Department of Natural Resources and Parks, Water Land and Resources Division.

Sommer, T.R., Nobriga, M.L., Harrell, W.C., Batham, W., and Kimmerer, W.J. 2001. Floodplain rearing of juvenile Chinook salmon: evidence of enhanced growth and survival. Canadian Journal of Fisheries and Aquatic Sciences 58(2): 325–333. NRC Research Press Ottawa, Canada.

Spence, B.C., G. A. Lomnicky, R. M. Hughes, and R. P. Novitzki. 1996. An ecosystem approach to salmonid conservation. ManTech Environmental Research Services Corp. (Available from the National Marine Fisheries Service, Portland, OR.), Corvallis OR.

Steel, E.A., Beechie, T.J., Torgersen, C.E., and Fullerton, A.H. 2017. Envisioning, quantifying, and managing thermal regimes on river networks. BioScience 67(6): 506–522. Oxford University Press.

Steel, E.A., Marsha, A., Fullerton, A.H., Olden, J.D., Larkin, N.K., Lee, S.-Y., and Ferguson, A. 2019. Thermal landscapes in a changing climate: biological implications of water temperature patterns in an extreme year. Canadian Journal of Fisheries and Aquatic Sciences 76(10): 1740–1756. NRC Research Press.

Steel, E.A., Sowder, C., and Peterson, E.E. 2016. Spatial and temporal variation of water temperature regimes on the Snoqualmie River network. JAWRA Journal of the American Water Resources Association 52(3): 769–787. Wiley Online Library.

Steel, E.A., Tillotson, A., Larsen, D.A., Fullerton, A.H., Denton, K.P., and Beckman, B.R. 2012. Beyond the mean: The role of variability in predicting ecological effects of stream temperature on salmon. Ecosphere 3(11): 1–11. Wiley Online Library.

Sternecker, K., Denic, M., and Geist, J. 2014. Timing matters: species-specific interactions between spawning time, substrate quality, and recruitment success in three salmonid species. Ecology and Evolution 4(13): 2749–2758. Wiley Online Library.

Stocking, R.W., Holt, R.A., Foott, J.S., and Bartholomew, J.L. 2006. Spatial and temporal occurrence of the salmonid parasite *Ceratomyxa shasta* in the Oregon–California Klamath River basin. Journal of Aquatic Animal Health 18(3): 194–202. Taylor & Francis.

Stohr, A., Kardouni, J., and Svrjcek, R. 2011. Snoqualmie River Basin Temperature Total Maximum Daily Load Water Quality Improvement Report and Implementation Plan. Washington State Department of Ecology, Olympia, WA.

Strange, J.S. 2010. Upper thermal limits to migration in adult Chinook salmon: evidence from the Klamath River basin. Transactions of the American Fisheries Society 139(4): 1091–1108. Taylor & Francis.

Sullivan, K., Lisle, T.E., Dolloff, C.A., Grant, G.E., and Reid, L.M. 1987. Stream channels: the link between forests and fishes. *In* Chapter Three, In: Ernest O. Salo and Terrance W. Cundy (eds.), Streamside Management: Forestry and Fishery Interactions, Proceedings of a Symposium held at University of Washington, 12-14 February 1986. Contribution no. 57, Institute of Forest Resources, Seattle, Washington. p. 39-97.

Swales, S., Lauzier, R.B., and Levings, C.D. 1986. Winter habitat preferences of juvenile salmonids in two interior rivers in British Columbia. Canadian Journal of Zoology 64(7): 1506–1514. NRC Research Press Ottawa, Canada.

Swales, S., and Levings, C.D. 1989. Role of off-channel ponds in the life cycle of coho salmon (*Oncorhynchus kisutch*) and other juvenile salmonids in the Coldwater River, British Columbia. Canadian Journal of Fisheries and Aquatic Sciences 46(2): 232–242. NRC Research Press Ottawa, Canada.

Takata, L., Sommer, T.R., Conrad, J.L., and Schreier, B.M. 2017. Rearing and migration of juvenile Chinook salmon (*Oncorhynchus tshawytscha*) in a large river floodplain. Environmental Biology of Fishes 100(9): 1105–1120. Springer.

Taylor, E.B. 1990. Phenotypic correlates of life-history variation in juvenile chinook salmon, *Oncorhynchus tshawytscha*. The Journal of Animal Ecology: 455–468. JSTOR.

Taylor, E.B. 1991. A review of local adaptation in Salmonidae, with particular reference to Pacific and Atlantic salmon. Aquaculture 98(1–3): 185–207. Elsevier.

Teffer, A.K., Bass, A.L., Miller, K.M., Patterson, D.A., Juanes, F., and Hinch, S.G. 2018. Infections, fisheries capture, temperature, and host responses: multistressor influences on survival and behaviour of adult Chinook salmon. Canadian Journal of Fisheries and Aquatic Sciences 75(11): 2069–2083. NRC Research Press.

Thomas, A.C., Nelson, B.W., Lance, M.M., Deagle, B.E., and Trites, A.W. 2017. Harbour seals target juvenile salmon of conservation concern. Canadian Journal of Fisheries and Aquatic Sciences 74(6): 907–921. NRC Research Press.

Tomaro, L.M., Teel, D.J., Peterson, W.T., and Miller, J.A. 2012. When is bigger better? Early marine residence of middle and upper Columbia River spring Chinook salmon. Marine Ecology Progress Series 452: 237–252.

Tonolla, D., Acuna, V., Uehlinger, U., Frank, T., and Tockner, K. 2010. Thermal heterogeneity in river floodplains. Ecosystems 13(5): 727–740. Springer.

Torgersen, C.E., Ebersole, J.L., and Keenan, D. 2012. Primer for identifying cold-water refuges to protect and restore thermal diversity in riverine landscapes. U.S. Environmental Protection Agency, Seattle, WA.

Torgersen, C.E., Price, D.M., Li, H.W., and McIntosh, B.W. 1999. Multiscale thermal refugia and stream habitat associations of chinook salmon in northeastern Oregon. Ecological Applications 9(1): 3011–319.

Trudel, M., Fisher, J., Orsi, J.A., Morris, J.F.T., Thiess, M.E., Sweeting, R.M., Hinton, S., Fergusson, E.A., and Welch, D.W. 2009. Distribution and migration of juvenile Chinook salmon derived from coded wire tag recoveries along the continental shelf of western North America. Transactions of the American Fisheries Society 138(6): 1369–1391. Taylor & Francis.

Washington State Department of Ecology (WSDE). 2002. Evaluating Standards for Protecting Aquatic Life in Washington's Surface Water Quality Standards – Temperature Criteria. Washington State Department of Ecology Water Quality Program.

Weil, J., Duguid, W.D.P., and Juanes, F. 2019. A hyperiid amphipod acts as a trophic link between a scyphozoan medusa and juvenile Chinook Salmon. Estuarine, Coastal and Shelf Science 223: 18–24. Elsevier.

Weitkamp, L.A. 2010. Marine distributions of Chinook salmon from the west coast of North America determined by coded wire tag recoveries. Transactions of the American Fisheries Society 139(1): 147–170. Taylor & Francis.

Welch, D.W., Porter, A.D., and Rechisky, E.L. 2021. A synthesis of the coast-wide decline in survival of West Coast Chinook Salmon (*Oncorhynchus tshawytscha,* Salmonidae). Fish and Fisheries 22(1): 194–211. Wiley Online Library.

Wells, B.K., Grimes, C.B., Field, J.C., and Reiss, C.S. 2006. Covariation between the average lengths of mature coho (*Oncorhynchus kisutch*) and Chinook salmon (*O. tshawytscha*) and the ocean environment. Fisheries Oceanography 15(1): 67–79. Wiley Online Library.

Woltemade, C.J. 2017. Stream temperature spatial variability reflects geomorphology, hydrology, and microclimate: Navarro River watershed, California. The Professional Geographer 69(2): 177–190. Taylor & Francis.

Woodson, L.E., Wells, B.K., Weber, P.K., MacFarlane, R.B., Whitman, G.E., and Johnson, R.C. 2013. Size, growth, and origin-dependent mortality of juvenile Chinook salmon *Oncorhynchus tshawytscha* during early ocean residence. Marine Ecology Progress Series 487: 163–175.

Yang, Z., Khangaonkar, T., Calvi, M., and Nelson, K. 2010. Simulation of cumulative effects of nearshore restoration projects on estuarine hydrodynamics. Ecological Modelling 221(7): 969–977. Elsevier.

Zackey, T., Chamberlin, J., and Totman, M. 2021. Population-Specific Distribution and Individual Growth and Residency of Juvenile Chinook Salmon in the Snohomish Estuary.