Prioritizing Chinook Salmon Habitat Restoration for Southern Resident Killer Whale Recovery

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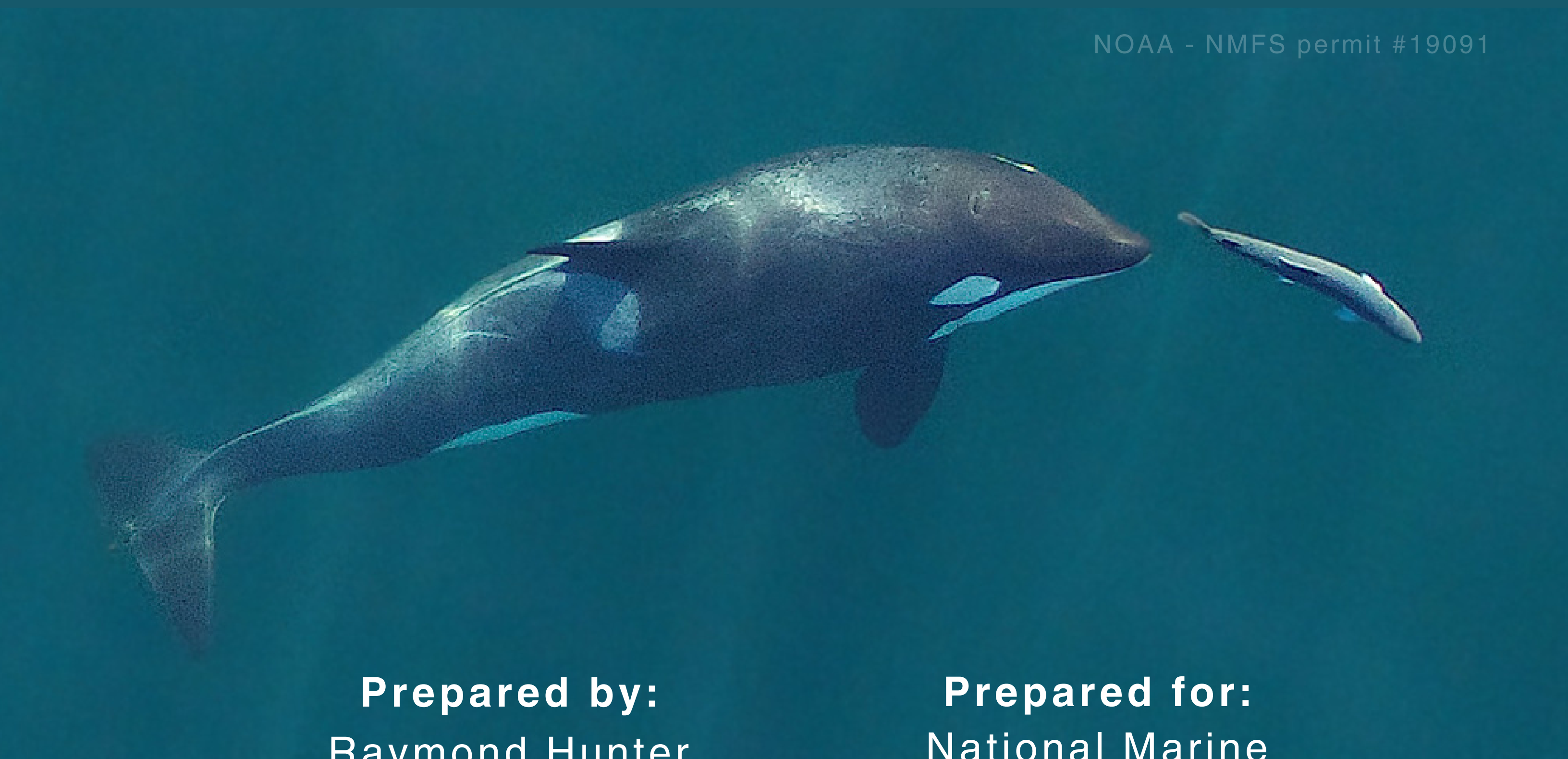

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A Group Project submitted in partial satisfaction of the requirements for the degree of Master of Environmental Science & Management for the Bren School of Environmental Science and Management

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Signature Page

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The Group Project is required of all students in the Master of Environmental Science and Management (MESM) Program. The project is a year-long activity in which small groups of students conduct focused, interdisciplinary research on the scientific, management, and policy dimensions of a specific environmental issue. This Group Project Final Report is authored by MESM students and has been reviewed and approved by:

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Abstract

The 60-year population decline of Southern Resident Killer Whales (SRKW) (*Orcinus orca*) has had critical environmental, economic, and cultural impacts on the Puget Sound region of Washington State. The decline of this endangered killer whale ecotype is strongly correlated with the reduced abundance of their main prey base, Chinook Salmon (*Oncorhynchus tshawytscha*). Puget Sound Chinook salmon are endangered primarily due to habitat degradation and overharvest. Despite federal agencies directing billions of dollars to recovery projects for SRKW and Chinook since both species' ESA listings, they continue to decline. Chinook spawning habitat restoration is among the targeted interventions for both species' recovery. Given the high costs of restoring Chinook spawning habitat, the increase in spawner abundance that results from habitat restoration should be considered when funding restoration projects. We addressed this by estimating the cost-effectiveness of three common restoration interventions: floodplain restoration, riparian planting, and engineered log jams. We applied these analyses to the Stillaguamish River basin in the Northern Puget Sound. We used the Habitat and Restoration Planning (HARP) model to predict the costs and increases in spawning age Chinook that would result from restoring the Stillaguamish River basin. We also examined each subbasin's land use costs and local demographics to consider restoration projects' feasibility and social impacts. Intervention costs and increased spawner abundance varied by subbasin. Our analyses showed that floodplain restoration would generally produce the highest number of spawners for the lowest price, with an average cost-effectiveness ratio of $25,345 per spawner, particularly in the Jim Creek subbasin. These methodologies provide restoration managers with a framework to compare potential projects' cost-effectiveness when selecting Chinook habitat restoration projects directed toward SRKW recovery.

Key Words
Southern Resident Killer Whales, Chinook salmon, Washington, cost-effectiveness, cost model, spawner, floodplain restoration, engineered log jams, riparian planting, conservation

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Objectives

The overall project goal of this project and the following report is to inform our clients at the National Marine Fisheries Service, NOAA on which Chinook spawning habitat restoration interventions in the Stillaguamish will be the most cost-effective. We hope to effectively inform their decisions for distributing restoration funds that are directed toward SRKW recovery. Our aim was to determine a dollar amount per additional spawning Chinook for each subbasin in the Stillaguamish River as a result of specific restoration actions. Supporting objectives include:

1. Provide recommendations that promote Chinook salmon spawner abundance for the benefit of expanding SRKW prey base at the most effective economic cost
2. Model expected costs and resulting changes in salmon abundance using environmental variables and historic costs data of restoration interventions
3. Map key locations in the Stillaguamish River basin by costs and restoration potential to recommend where to prioritize funding

Significance

The Southern Resident Killer Whales (SRKW) (*Orcinus orca*) are listed as Endangered under the Endangered Species Act (ESA) and are currently a top priority for recovery efforts (NMFS, 2021b). In addition to their economic and cultural value, SRKW serve as an indicator species for ecosystem health of the Puget Sound region (US EPA, 2021b). The population has declined by 10 percent since 2008, leaving only 74 individuals as of 2023 (Center for Whale Research, 2023; Worley II, 2023).

Limited prey availability is one of the primary drivers of the SRKW decline (NMFS, 2021a). Chinook salmon (*Oncorhynchus tshawytscha*) are an essential base of the SRKW diet, making up 80 percent (Hanson et al., 2021). The Puget Sound (PS) Chinook Evolutionary Significant Unit (ESU) is one of 22 genetically distinct Chinook salmon populations (NMFS, 2017). The decline of PS Chinook is strongly linked to SRKW health, population dynamics, and movement (Stewart et al., 2021). Beyond providing sustenance for SRKWs, Chinook salmon support marine, freshwater, and terrestrial nutrient cycles. Additionally, they are an important fishery for commercial and recreational harvest, and have immense cultural significance for indigenous peoples in the region (Columbia River Inter-Tribal Fish Commission, 2021). Recent estimates of PS Chinook salmon populations estimated 473,000 adults, representing a reduction of 60% since the first population record in 1984 (US EPA, 2021a). An estimated 1,700 spawning age Chinook returned to spawn in the Stillaguamish River basin in 2022. The Stillaguamish Chinook population has oscillated between 900 and 2,200 fish since 1993 (SIRC, 2005).

The National Oceanic and Atmospheric Administration (NOAA) and the Washington State Southern Resident Orca Task Force have listed Chinook salmon recovery as the top priority for SRKW recovery (Southern Resident Orca Task Force, 2019)). NOAA requested $64.2 million for the Pacific Salmon Coastal Recovery Fund in 2023, which includes 16 new and ongoing salmon recovery programs (NMFS, 2023). The Pacific Northwest region now contains one of the highest densities of freshwater restoration projects in the U.S. as a result of the billions of dollars that have been invested to restoration (Bilby et al., 2023).

Restoring PS Chinook spawning habitat is critical to increasing their abundance in that increased spawning habitat allows spawning age fish to complete their life cycle. Successful spawning events have the potential to increase the return of future spawners to their natal streams. Moreover, anthropogenic climate change has hastened the need for restoring Chinook spawning habitat. The population effects of spawning habitat loss is further compounded by degradation of available habitat driven by climate change. Therefore, prioritizing restoration locations and actions that have the greatest potential for increasing Chinook abundance is an important consideration for addressing their recovery. This consideration is important to decision makers when funds for restoration projects are distributed.

A major obstacle for many habitat restoration projects is that a project's scale and desired outcomes often overshoot the necessary available funding. This model of approaching restoration neglects monitoring and evaluation following restoration and the restoration action's long-term impacts are not quantified. Ultimately, funding for restoration is allocated based on desired outcomes over quantifiable results that indicate the ecological return on the financial investment. These difficulties have led to immense funding that is distributed for unsuccessful restoration interventions while both Chinook and SRKW populations continue to decline (Bilby et al., 2023). Identifying restoration locations with high potential of population recovery is, therefore, a critical consideration for funding interventions.

We aimed to address this disconnect between funding distribution and ecological outcomes of habitat restoration by applying the Habitat Assessment and Restoration Planning (HARP) model (Beechie et al., 2023) to the Stillaguamish River basin. We applied the HARP model to three restoration actions for Chinook freshwater habitat: floodplain restoration, engineered log jams (ELJs), and riparian planting. Our analyses produced relative cost-effectiveness ratios for each restoration action within each subbasin of the Stillaguamish. These estimates indicate the annual number of increased Chinook spawners per dollar amount invested in restoration. We used these scores to identify priority subbasins with the greatest potential of increasing spawner abundance for the lowest investment. Identifying priority subbasins can inform how funding for restoring Chinook spawning habitat can be most effectively distributed.

Background

Study Region

The Puget Sound is an inlet of the Pacific Ocean, occurring between the coast of northwest Washington and the Olympic Peninsula to the west (Figure 1). The Sound's watershed spans approximately 42,800 square kilometers, comprising over ten thousand streams and rivers that drain into it from the Cascade and Olympic Mountain Ranges. Rivers drain from 7,000 feet down to sea level within 50 to 70 miles (Shared Strategy Development Committee, 2007). The snow-fed rivers rely on snowpack storage during the dry summer months (Shared Strategy Development Committee, 2007). The climate is temperate with annual precipitation two-thirds of annual precipitation falling between November and March, varying from 17 to over 100 inches.

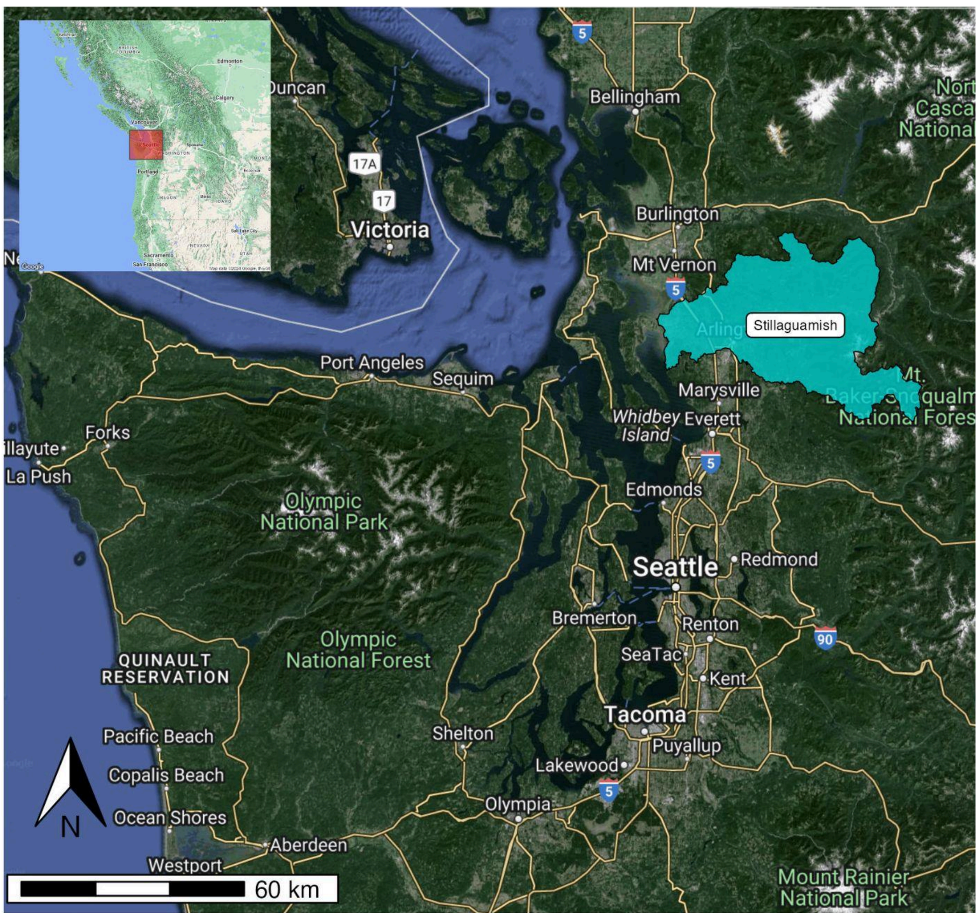

Figure 1. Map of Puget Sound with the Stillaguamish River basin highlighted in teal.

Southern Resident Killer Whales

Description

Southern Resident Killer Whales are one of two ecotypes in the Puget Sound region, along with Bigg's (transient) killer whales. The two co-occurring ecotypes do not socialize or interbreed (Ford et al., 2005). SRKWs are distinguishable from Bigg's by appearance, diet and behavior. SRKW are the smaller of the two ecotypes and their dorsal fins have a rounded tip and sharp rear angle. Their white saddle patch, or cape, behind the dorsal fin and white patches behind their eyes are broader than Bigg's. Adults' teeth are worn down as a result of their piscivorous diet (Bigg et al., 1990; Center for Whale Research, 2023).

The characteristics and behavior of SRKW are largely defined by their diet, comprising 80 percent Chinook salmon. SRKW adults rely on consuming 90 to 130 kilograms of fish per day to sustain their 300 to 500 kilograms mass (Krahn et al., 2022). They specialize in hunting Chinook because of the salmon's large mass and high fat content. Under optimum forage conditions, males can reach lengths of 6 to 8 meters and females 6 to 7 meters. SRKWs hunt in family groups known as pods, using a technique where they corral salmon schools against deepwater shelves (Bigg et al., 1990).

As of the 2023 census, the SRKW population numbered 75 individuals split among three pods (J, K, and L). The J pod comprises 24 individuals, 14 females and 11 males; the K pod comprises 16 individuals, 11 females and five males; and the L pod comprises 34 individuals, 19 females, 14 males, and one calf of unknown sex (Center for Whale Research, 2023). Since the census was conducted, one adult male from K pod has been presumed dead, and the current total number of SRKW is 74 individuals (Worley II, 2023).

SRKW movement patterns align with prey availability. They historically spend spring, summer, and fall months following the salmon runs in the Salish Sea and Puget Sound, ranging as far north as the Strait of Georgia and coastal British Columbia (NMFS, 2008). Their northernmost range overlaps with the southernmost range of the Northern Resident ecotype, but, despite similarities in diet and behavior, the two ecotypes do not interact or interbreed. Winter months are typically spent foraging along the coasts of Washington state and British Columbia, which also corresponds with the movements of Chinook (Ford et al., 2005).

Life History

Social structure among SRKWs is shaped by a matriarchal hierarchy, which is established based on the matrilineal lineage of each pod. Individuals remain with their natal pods for life, following the pod's dominant female. Close bonds are maintained between both males and females and their mothers, who teach hunting techniques. Different pods will socialize, forming a "super pod", in which they will hunt together, share food, play, and mate. Individuals return to their natal pod following super pod events (Olesiuk et al., 2005). Pods will temporarily separate when prey is limited, inhibiting opportunities for socializing, mating, and communicating between pod members (Ward et al., 2009).

Mating and calving take place year round and peak in the fall. Births follow a gestation period of 15 to 18 months under optimum nutrition conditions. All pod members participate in rearing calves but calves remain close to their mothers for their first 10 to 13 years. Females reach sexual maturity around age 15 and begin to birth calves in their early 20s. They typically only birth two to three calves in their life, giving birth in 7 to 10 year cycles. They invest heavily in rearing calves and stay close with calves until they reach adolescence.

Males reach sexual maturity around age 13 and, though involved in parenting, are less active than the mothers (Olesiuk et al., 2005). Females remain with their natal pods following reproductive senescence around age 40, and continue to assist in calf rearing with other members of the pod (Bigg et al., 1990). Survival rates for calves are typically low, particularly in their first year of life. Mothers frequently lose their first calf, which, combined with numerous environmental challenges that contribute to calf mortality, continues to impede the recovery of SRKWs (Weiss et al., 2023).

Threats and Conservation

A series of threats have driven the decline of the Southern Residents, beginning in the latter half of the 20th century. Their population was nearly halved between 1962 and 1977, an era marked by live-capture of whales for marine parks and aquaria. During this time, 68 killer whales, 63 of them SRKW, were either captured or killed (Bigg et al., 1990). Since then, SRKWs have been closely monitored through annual censuses. Individuals are identified by annual surveys and accounted for through photographic data (Olesiuk et al., 2005). Their population rose to 97 individuals by 1996, then steeply declined in the late 1990s. Shortly after, SRKWs were listed as endangered under the ESA in 2005 (70 FR 69903).

Habitat restoration for Chinook salmon recovery is among the targeted interventions for SRKW recovery that are outlined in the NMFS' SRKW recovery plan (NMFS, 2008). The aim of improving Chinook fisheries is to increase prey availability for SRKW by recovering PS Chinook fisheries by 15 percent. Increasing the whales' prey base will assist the NMFS recovery goal of annual 2.3 percent SRKW population growth that is consistent over 28 years (two generational cycles). This growth target is necessary for the whales' delisting from the ESA (NMFS, 2008). Chinook recovery supports SRKW recovery through improving available nutrition, supporting the whale's reproduction and calf survival, and reducing energy spent on foraging.

Individuals, calves in particular, have been observed displaying symptoms of malnutrition like collapsed dorsal fins, reduced body size, and a condition called "peanut head", which occurs when whales are emaciated to the point that the area their head behind their blowhole becomes depressed (Raverty et al., 2020). Malnourished SRKW are more susceptible to health complications that are associated with the release of bioaccumulated toxins from the whales' blubber (Ford et al., 2009). Research has found that adrenal and thyroid hormone concentrations in the whales' feces are negatively correlated with poor nutrition. Concentrations of these hormones, which are critical to mammalian regulatory functions, are reduced in times of prey scarcity and increased when prey is available (Ayres et al., 2012). Increasing PS Chinook abundance is necessary to relieve the drivers of the whales' mortality that are associated with malnutrition.

Additional correlations exist between prey availability, its associated stressors, and successful SRKW reproduction (Wasser et al., 2017). A 50 percent reduction in SRKW fecundity had been reported in correlation with years that have suboptimal Chinook runs. Similarly, there is an association between prey availability and the age of reproductive senescence in females. Females entering menopause at a younger age, likewise, negatively affects the overall population's fecundity (Ward et al., 2009). Approximately 69 percent of SRKW pregnancies are unsuccessful, with 33 percent failing in late stages or immediately after birthing. Fecal contents and their hormone concentrations have been used to monitor SRKW reproduction. The data from these monitoring efforts support that prey scarcity drives the low reproductive success in SRKW (Wasser et al., 2017).

SRKW low calf survival is also linked to prey scarcity. New calves are typically born every two to three years and 50 percent do not survive their first year. Malnourishment in the mothers at the time of a calf's birth results in malnourished calves that are unable to recover from the fragile state in which they are born. Malnutrition, as well as contaminant concentrations, are the most common drivers of calf mortality (Lacy et al., 2017). Coupled with low birthrates, poor calf survival demands an increase of prey availability to address these drivers of SRKWs' decline (Lacy et al., 2017; Ward et al., 2009).

SRKWs have experienced diminishing returns on their catch per unit effort of Chinook that coincide with the PS Chinook ESU's decline (Couture et al., 2022). The whales have exhibited more irregular foraging distributions in the years following the PS Chinook ESU collapse (Hauser et al., 2007). As a consequence, more energy is spent in search of prey, yielding less nutrition per successful hunt. Social behaviors, such as playing and mating, are also disrupted by increased foraging efforts. Female whales experience a greater impact from increased foraging stress. They are more inclined to prioritize calf rearing over foraging, which also comes with significant energy costs (Tennessen et al., 2023).

Restoration efforts for PS Chinook habitat represent an important contribution to reaching the 15 percent recovery goal that would relieve SRKW stressors related to prey scarcity (NMFS, 2008). Reaching this recovery goal would enable optimum forage conditions that support SRKWs' healthy bodily functions (Ayres et al., 2012) and reproductive success (Wasser et al., 2017), as well as decrease the energetic costs of foraging (Tennessen et al., 2023). Furthermore, increasing natural Chinook stocks would provide genetic materials for increased Chinook production in hatcheries. Hatchery production will, in turn, further contribute to the 15 percent PS Chinook recovery goal (NMFS, 2008).

A more insidious agent of the SRKW decline are the legacy contaminants polychlorinated biphenyls (PCBs) and other emerging contaminants that were released into the marine environment through industry and agriculture (Ford et al., 2005). The contaminants compound at higher trophic levels and accumulate in the whale's blubber (Lacy et al., 2017). PCBs act as an endocrine disruptor in humans and other mammals, causing stillbirths and other reproductive complications. It is hypothesized that PCBs and other anthropogenic contaminants may factor into poor SRKW reproduction (Mongillo et al., 2012). Moreover, as the whales succumb to starvation from a lack of available prey, the fat stored in their blubber is depleted. The contaminants that accumulate in the blubber are then released, making the whales more susceptible to infections and disease (Alava et al., 2016). Legacy contaminants are especially deadly to calves within their first two years as the contaminants accumulated in their mothers are offloaded to the calf through nursing. Blood samples taken from killer whales in Japan showed that contaminant concentrations are far higher in nursing calves than in their lactating mothers. The calves do not yet have fat stores in blubber and succumb to infections resulting from the toxicity of PCBs in their mother's milk (Haraguchi et al., 2009).

Some SRKW carcasses that have been examined show signs of blunt force trauma caused by vessel strikes, indicating a cause of death (Thornton, 2022). However, vessel crowding can also have significant impacts on the whales' hunting and communication abilities. Females have been documented to forgo foraging, communication, and rest in the presence of boats closer than 400m. This behavioral disruption has considerable implications for reproduction in that a female’s food intake may not meet energetic requirements necessary to reproduce. SRKWs’ response to vessel crowding is exacerbated by commercial and recreational whale watching during summer months (Thornton, 2022).

Recovery efforts for SRKW have demanded a diverse suite of interventions given the complexity of threats driving their decline. Behavioral disruptions caused by vessel crowding have been mitigated by minimum safe distance laws both in United States and Canadian waters (Thornton, 2022). Policies that limit agricultural pesticides and prohibit disposing industrial waste in the ocean and rivers have influenced the addition of further anthropogenic contaminants to the marine environment (Mongillo et al., 2012). The Superfund cleanup of the Duwamish River, south of Seattle, while not directed toward SRKW recovery, may likewise limit further contamination of the Puget Sound (Walters et al., 2008). Addressing declining prey abundance has been a multi-agency collaboration across federal organizations, Washington state, tribal nations, and non-government organizations through investments in habitat restoration for wild Chinook populations and increased hatchery production (NMFS, 2023, 2024). The aim of these efforts is to increase available prey for SRKW by 4 to 5 percent by injecting the PS Chinook population with hatchery-raised fish. Despite these and various other interventions for SRKW recovery, their numbers continue to decline since their ESA listing (NMFS & WDFW, 2018). It is clear that addressing prey scarcity represents a significant factor in the whales’ recovery.

Chinook Salmon

Description

Chinook salmon, also known as king salmon, spring salmon, Tyee, winter, Quinnat, and blackmouth, range from Alaska and Western Canada to Northern California (Healey, 1991). They are the largest species of Pacific salmon, with adults measuring a meter in length and averaging 13 kilograms (Healey, 1991). Chinook salmon follow an anadromous lifecycle, beginning as eggs in freshwater streams, migrating to the ocean to mature into adults, and finally returning to freshwater to spawn at the end of their lifespan. (Figure 2). As juveniles, or fry, Chinook have vertical camouflage bars and spots on their sides called parr marks. The parr marks are replaced with dark dorsal coloration and light ventral coloration during the lifecycle stage in which they migrate from freshwater to estuarine nurseries (Healey, 1991). Adult Chinook enter the ocean with blue-green dorsal coloration, silver sides, white bellies, black pigment along the gumline, and black spots on the upper body and tail fin (Healey, 1991). Adults return to their freshwater, natal streams to spawn, typically between age three and five. The pelvic and tail fins of spawning age adults develop a reddish hue, their side coloration is ruddy, and dorsal color is darker green (Healey, 1991). The spawning adult males grow a hooked upper jaw, giving Chinook their scientific name *Oncorhynchus* (“hooked snout”) (Healey, 1991).

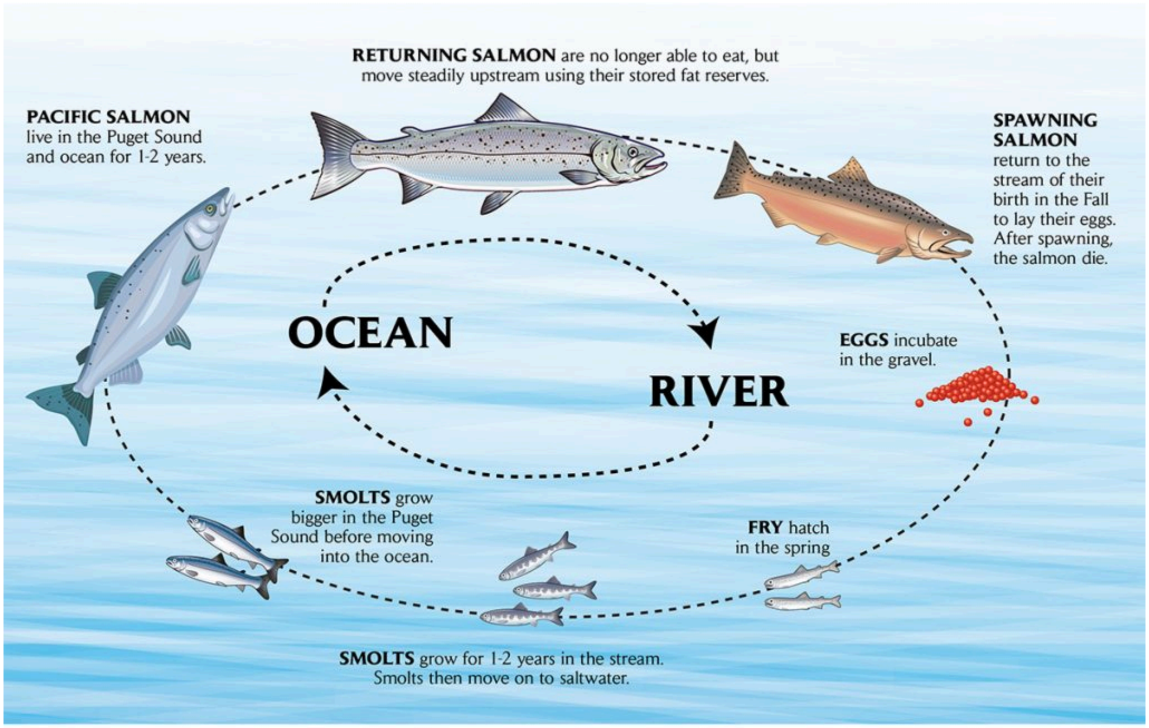

Figure 2. Chinook salmon life cycle (Washington Forest Protection Association, n.d.).

Life History

PS Chinook eggs hatch between one to five months after deposition, and fry emerge from the streambed gravel after two to three weeks. Approximately 75 percent of fry survive their migration from freshwater rivers and streams to estuaries where they undergo a process called smoltification, enabling them to live in marine environments (Shared Strategy Development Committee, 2007). Smolt subsist on terrestrial and aquatic invertebrates while they mature in estuarine habitat. After reaching maturity between three and four years of age, PS Chinook transition to eating other fish as they move out to exposed shoreline habitat and the open ocean (Healey, 1991). Some Chinook remain in the Puget Sound, while most migrate to the open ocean and north along the Canadian coast, making them vulnerable to fishing and predation.

PS Chinook's migration from marine environments back to their natal rivers peaks between spring and late fall (Shared Strategy Development Committee, 2007). Chinook spawn in large rivers like the Columbia and Snake Rivers, as well as in smaller streams and tributaries with suitable conditions (WDFW, 2023a). Once they have reached their freshwater spawning grounds, female Chinook sweet their tails across a stream's benthic substrate to dig nesting holes, called redds. Female Chinook spawners can deposit between 2,000 to 5,500 eggs in their lifetime's single breeding event (Shared Strategy Development Committee, 2007). Chinook are semelparous and die after spawning once. One or more males fertilize the eggs and may fertilize other reds before senescing, while female Chinook guard the redd from 4 to 25 days before they senesce (Shared Strategy Development Committee, 2007). Following senescence, Chinook's bodies degrade and their nutrients enrich the stream food web for following generations (Shared Strategy Development Committee, 2007).

Chinook require clean, cool, oxygen-rich water with tree coverage, graveled substrate, and complex stream channels for their spawning habitat. Chinook that spawn in river mainstems require large streams and rivers that are consistently between 12° and 15 degrees Celsius for 14 to 15 weeks out of the year. They also need large, deep, slow moving, low-gradient streams. For rearing habitat, Chinook spawners prefer large streams with nearby tributaries (WDFW et al., 2021). Habitat complexity and steady streamflow best determine subyearling and parr productivity (output per spawner), potentially because these elements buffer populations from variations in environmental conditions (Hall et al., 2018).

Puget Sound ESU

The range of the Puget Sound Evolutionary Significant Unit (ESU) of Chinook extends from the Nooksack River in the northern reach of the sound, to the sound's southern reach in the Hood River Canal, and connects to the open ocean through the Strait of Juan de Fuca to the west (Shared Strategy Development Committee, 2007). Two out of the 22 genetically distinct populations that make up the Puget Sound ESU occur in the Stillaguamish River basin. Both Stillaguamish populations of PS Chinook differ in genetics, migration, and spawning season. The North Fork population runs in the summer, while the South Fork population runs in the fall (SIRC, 2005).

The Stillaguamish's North Fork Chinook population represents 60 percent to 80 percent of the watershed's total population. The Stillaguamish's South Fork Chinook population represents approximately 30 percent of the river's total population (STAG, 2000). The Pacific Fishery Management Council 2024 preseason forecasts 900 natural and hatchery adult Chinook salmon in the Stillaguamish, which is a decline from the 2023 prediction of 1,200 (Pacific Fishery Management Council, 2024) The river has historically hosted Chinook runs of 9,700 to 13,321 spawning adults before the land in the basin was converted for agriculture and development (SIRC, 2005). The Washington Department of Fish and Wildlife (WDFW) spawner population data shows the 22 Chinook populations of the ESU held roughly 26,000 wild spawners in 2023 (WDFW, 2023c). Both Stillaguamish Chinook populations represent 0.64 percent of the total PS Chinook ESU.

Conservation

The PS Chinook Salmon ESU was designated as Threatened in 1999 under the Endangered Species Act (50 CFR 223), and its Threatened status was reaffirmed in 2005 and again in 2016 (NMFS, 2017). The PS Chinook ESU is managed separately from other populations of Chinook under the ESA (NMFS, 2017). In addition to its ESA protections, the Puget Sound ESU receives protective measures as a Priority Species under WDFW's Priority Habitat and Species Program (WDFW, 2023a). The Puget Sound ESU is identified as a Species of Greatest Conservation Need under the State Wildlife Action Plan. Despite numerous recovery interventions, PS Chinook have continued to decline. Most of the independent subpopulations of the ESU are significantly below healthy spawner levels and each subpopulation will need to recover significantly in order to remove their ESA designation (NMFS, 2017).

Degraded marine and freshwater quality, impaired access to marine shorelines and functional floodplains, and fragmented stream passage remain the biggest threat for the 22 independent subpopulations of the PS Chinook salmon ESU (NMFS, 2017). PS Chinook salmon will likely remain threatened and continue to decline until significant environmental improvements are made in each of these areas. Furthermore, the PS subpopulations are largely hatchery-raised individuals with 26 artificial propagation programs contributing to the ESU, demonstrating the dependence on human intervention to maintain even marginal populations (Nelson et al., 2019). Hatcheries play a crucial role in sustaining healthy populations of PS Chinook salmon in the region, especially since wild populations alone are insufficient to bring the ESU out of its Threatened status.

Beyond providing sustenance for SRKW, Chinook are a keystone species that support marine and terrestrial food webs through nutrient cycling (Shared Strategy Development Committee, 2007). Spawning salmon provide carbon, nitrogen, and phosphorus that support the food webs, riparian forests, and macroinvertebrates that feed juvenile salmon (Shared Strategy Development Committee, 2007). Chinook not only provide high-energy sustenance for humans and SRKW, but also other wildlife like bears, pinnipeds, sharks, large seabirds, and other fish species. Chinook recovery would benefit over 137 species of wildlife through various means, even beyond marine systems (Shared Strategy Development Committee, 2007). Therefore, Chinook salmon recovery is critical for the overall health and function of the numerous ecosystems represented throughout the Puget Sound and Salish Sea.

Societal Significance

Various stakeholder groups, including farmers, government and state agencies, recreational, and fisheries managers, as well as indigenous communities have all been significantly affected by the decline of the Stillaguamish Chinook population (STAG, 2000). Salmon habitat restoration will likely have significant and mixed effects on the local economy of the Stillaguamish River basin. It could promote biodiversity and salmon stocks, which would benefit ecotourism, commercial, and sport fisheries that rely on a healthy watershed and Chinook stocks for profit. Conversely, restoration actions will likely require private land acquisitions, which may imply decommissioning of local farmland and businesses to convert land into restored floodplains. Effective restoration efforts are expected to boost specific sectors of the economy, such as fisheries and ecotourism, while potentially causing adverse effects on others, like agriculture. However, environmental and societal reliance on this keystone species demonstrates support for restoration efforts.

The Stillaguamish River Basin

The Stillaguamish River basin was chosen as a priority area for PS Chinook recovery because the watershed’s Chinook populations have suffered disproportionately higher losses than other rivers in the Puget Sound region as a result of intense human landscape modification (Figure 3) (STAG, 2000). The Habitat Assessment and Restoration Planning

(HARP) model, developed by NMFS' Northwest Fisheries Science Center, estimates that restoring floodplain habitat, installing ELJs, and replanting native riparian vegetation have strong potential to increase Chinook spawner abundance in the river basin (Beechie et al., 2023).

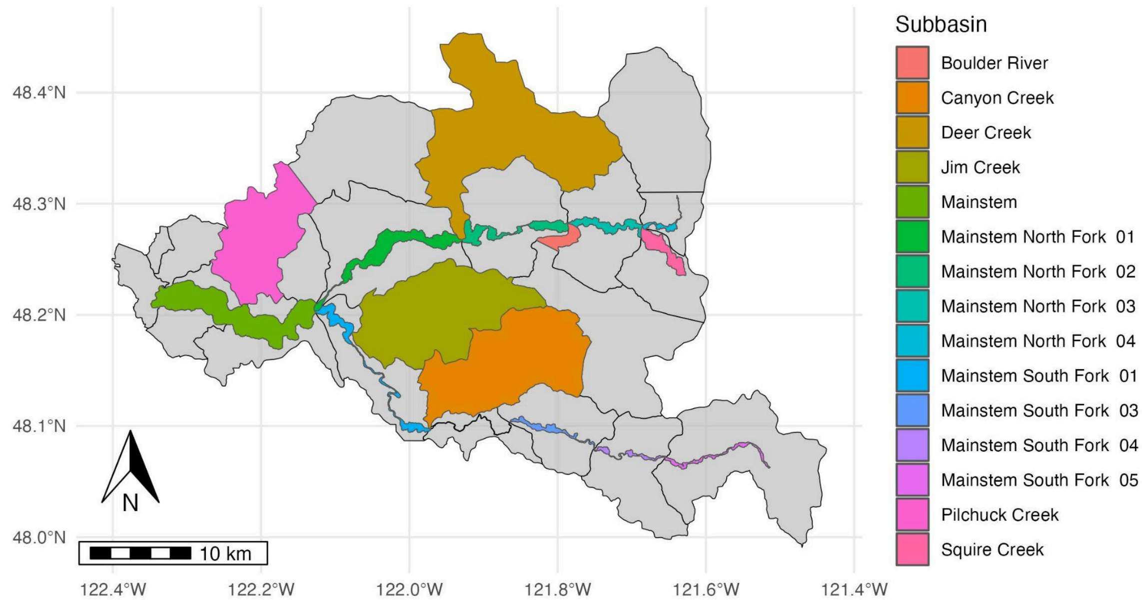

Figure 3. Map of the Stillaguamish River Basin, color coded by subbasins with estimated increase in Chinook spawners resulting from floodplain, ELJs, and/or riparian planting habitat restoration.

Environmental Conditions

The Stillaguamish River spans 67 miles of northwest Washington, flowing west from its headwaters in the North Cascade Mountains to its termini in the Puget Sound Estuary. The Stillaguamish watershed is Washington's fifth largest, containing approximately 700 square miles of streams, creaks, and drainages that feed the river (SIRC, 2005; Stillaguamish Tribe, 2016). Within that watershed is approximately 900 miles of potential anadromous stream habitat (SIRC, 2005). The Stillaguamish supports both wild and hatchery stocks of anadromous salmonids and trout including Chinook, coho, pink, chum and sockeye salmon, and steelhead and cutthroat trout (Stillaguamish Tribe, 2016).

The climate of the Stillaguamish watershed varies in elevation, with mild, maritime climate in the lowland region and greater seasonal variability in the higher elevation, subalpine region. Rainfall in the lowland watershed averages 30 inches annually and 150 inches, including snowfall, in the higher elevations. Streamflow corresponds with precipitation, which is greatest from October to March. The watershed is continually fed by snowmelt from the Cascade Mountains into early summer. Low streamflow corresponds with drier months from July to October. Chinook salmon runs in the river's two forks take place during these drier months due to increased stream navigability resulting from reduced flow velocity (Scofield, 2013).

The watershed consists of three major subbasins, comprising smaller stream systems, along its elevational gradient. The North and South Fork subbasins converge at the city of Arlington in the foothills of the Cascades. The Mainstem subbasin traverses a diversity of landscape types between the confluence and its sea level deltas. The landscape types along the river's path include mixed composition forests, developed and agricultural areas, small areas of urban development, and open lowland areas (Figure 4). The river forks again before its mouth, with the north channel draining in Skagit Bay and the south channel draining in Port Susan in the Northern Puget Sound (SIRC, 2005). The river's path includes the glacial till of the Skagit Valley, much of which has been converted to agriculture and development over the 20th century.

The historical, predevelopment conditions of the Stillaguamish varied with elevation. The baseline landscape surrounding the river basin was forested. The floodplain included mixed deciduous and coniferous forests comprising red alder, black cottonwood, western red cedar, Sitka spruce, and willow species (SIRC, 2005). Many of these floodplain forests were removed by logging and the area is presently used for forestry and food production.

Human Use

The foothills and upland areas are primarily used for timber harvest and outdoor recreation, while the fertile lowlands are mostly used for agriculture and rural residential development (Figure 4) (Stillaguamish Tribe, 2016). Present day land use of the area includes 61 percent forestry, 22 percent rural development, 15 percent agriculture, and 2 percent urban development (Shared Strategy Development Committee, 2007). Most of this agricultural land is in the lower Stillaguamish basin, with main industries including timber, livestock, and fisheries products.

As of 2013, 52,000 people live within the Stillaguamish watershed including about 200 Indians in the Stillaguamish Tribe (Stillaguamish Tribe, 2016). Although population growth is highest in urban areas (Stanwood, Arlington, Granite Falls, Darrington) and rural population sprawl is declining, the majority of residents live more than a mile outside of incorporated areas, leading to forest conversion to residential or commercial property development (Stillaguamish Tribe, 2016).

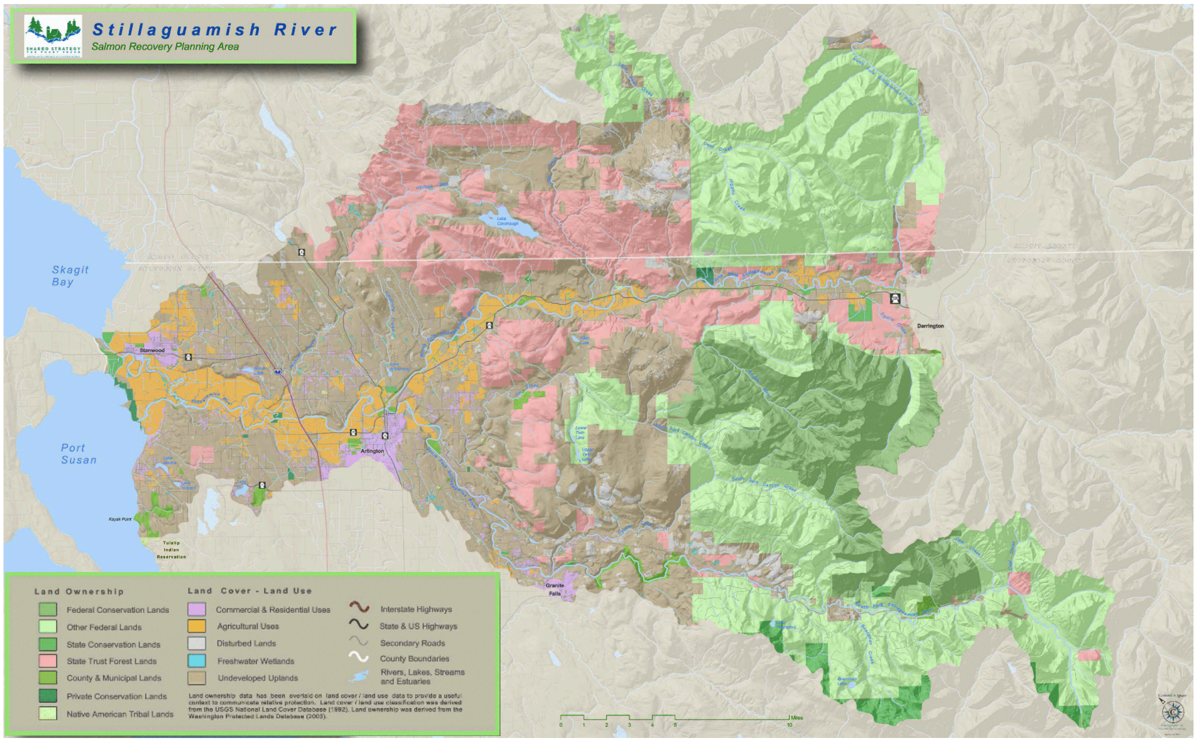

Figure 4. Land ownership and use in the Stillaguamish River basin (Shared Strategy for Puget Sound, 2024).

Environmental Threats

The drivers of degradation to anadromous fish habitat in the Stillaguamish are largely associated with deforestation and land conversion (SIRC, 2005). Deforestation in the floodplain as well as upland sections of the river have caused an excess of sediment to enter the river system. An absence of large woody debris, resulting from deforestation and land conversion, have likewise contributed to increased erosion and turbidity as a result of increased stream flow. Agriculture as well as paved surfaces represent sources of nonpoint pollution, which enter the river as storm runoff (Scofield, 2013). Installation of concrete and other impermeable surfaces along stream banks, referred to as armored banks, further contribute to sediment and pollution entering the river system through runoff. In the last century, the Stillaguamish River Basin has experienced an estimated 40 percent decrease in estuarine rearing habitat for anadromous fish, an 80 percent decrease in floodplain ponds and marshes, a 59 percent decrease in side channel length, and a 90 to 95 percent decrease in beaver ponds compared to the watershed's pre-development baseline (Beechie et al., 2023).

The removal of riparian vegetation and land conversion within the river's estuaries are perhaps the greatest drivers of anadromous habitat degradation in the Stillaguamish. Riparian vegetation plays a vital role in stabilizing stream banks and regulating water temperature. It helps to keep stream banks intact, reducing runoff and preserving water quality. Anadromous fish otherwise have poor reproductive success in overly turbid water (Scofield, 2013).

In agricultural and developed areas, significant decreases in shade levels have increased stream temperatures more than 2 degrees Celsius in 23 percent of reaches in the Stillaguamish River basin (Beechie et al., 2023). The shade provided by riparian vegetation keeps water temperatures cool, particularly in shallow depths. Both spawning age adults and juvenile Chinook salmon can tolerate a temperature gradient of 14 to 22 degrees Celsius. Water that is 27 degrees Celsius or warmer is beyond their tolerance and is no longer habitable or viable as spawning habitat. The PS Chinook ESU is moderately to highly vulnerable to climate change because they have limited tolerance for water temperatures above 19 degrees Celsius. Warmer waters also affect their prey availability, as well as concentrations of dissolved oxygen in the water (NMFS, 2017). Maintaining water at a habitable temperature is especially important for juvenile fish as they use shallow estuarine waters as nursery habitat. Adults, likewise, prefer to spawn in waters at depths between 3 and 6.5 meters and temperature of 12 to 15 degrees Celsius (Richter & Kolmes, 2005; Swan, 1989). Warmer waters, resulting from an absence of shade, limits habitat that is available for both juveniles and spawners.

The estuaries at the mouths of the Stillaguamish represent crucial anadromous fish habitat. They provide refugia and foraging habitat for juveniles. However, the estuaries were diked off from the Puget Sound during the 20th Century and were largely converted to agricultural and development areas. The Stillaguamish estuaries were reduced significantly from their historical baseline (SIRC, 2005). Restoring these estuaries to their approximate baseline conditions represents a critical hurtle for increasing PS Chinook spawners in the Stillaguamish River.

Current Stillaguamish River Restoration

The need for understanding the economics of restoring salmon spawning habitat in the Stillaguamish River basin is further emphasized by the scale of current restoration projects taking place there. Several restoration projects throughout the river basin are directed specifically for SRKW recovery, as well as recovering salmon stocks to support tribal sovereignty in the area. Current recovery projects on the North and South Forks of the Stillaguamish are managed by the Stillaguamish Tribe of Indians, in collaboration with non-profit organizations, county, state, and federal management agencies. The Stillaguamish tribal managers collaborate with state management agencies in a joint organization called Stillaguamish Integrated Conservation and Rebuilding (SiCOR) to restore habitat for salmon across their life stages in the tribe's ancestral home (WDFW, 2023b).

The Stillaguamish tribe has purchased over 1000 acres of their ancestral land along the Stillaguamish River delta for the express purpose of restoring the river's floodplains and estuaries to their predevelopment baselines. The project is described as "decolonizing the landscape" by Stillaguamish spokespeople and they have named the restoration properties "zis a ba", after the tribal leaders that had previously stewarded the area (Cauvel, 2023). The goal of the zis a ba project is to not only convert the land back to its predevelopment state, but to create habitat that is critical for Chinook and other salmonid species (Stillaguamish Tribe of Indians, 2022).

Since 2017, zis a ba has received over $8.4 million in state and federal funding to create

Chinook habitat for SRKW recovery (Washington State Recreation and Conservation Office, 2024). This funding has supported the restoration of over 300 acres of the Stillaguamish delta through as well as dike and building removal and using ELJs, planting native riparian vegetation, and connecting river side channels. Monitoring of the first zis a ba restoration in 2017 showed increases in juvenile salmon in the delta's estuaries as well as neighboring estuaries (Cauvel, 2023). As of 2023, $8.8 million of federal funding has been directed to restoring an additional 537 acres of zis a ba (Washington State Department of Ecology, 2024). The Stillaguamish Tribe's goal for the project is to convert 2,200 acres back to something resembling the landscape's original state by 2026 (Cauvel, 2023).

Another restoration project under the Stillaguamish Tribe's management is the Trafton floodplain restoration project on the North Fork of the Stillaguamish River, which began in 2018. The Trafton project utilized $1.8 million in funding from the Pacific Salmon Treaty Orca Recovery Habitat Grant from the Salmon Recovery Funding Board as well as the EPA's National Estuary Program (Puget Sound National Estuary Program, 2018. Snohomish County Department of Public Works, 2020). The Trafton floodplain project restored 250 acres of the North Fork by connecting braided side channel streams, installing ELJs, and replanting native riparian vegetation to increase Chinook and other salmonid's spawning habitat (Snohomish County Conservation and Natural Resources, 2023).

The Gold Basin Habitat Restoration project was co-managed by the Stillaguamish Tribe in the river's South Fork in 2022. The project used $280 thousand from the Pacific Salmon recovery fund to repair a section of the river that had been damaged by a landslide. The tribal effort installed ELJs and diverted streams away from the landslide area to remediate the influx of sediments the landslide had caused. This project was also directed toward Chinook recovery (NOAA, 2022).

Stillaguamish spokespeople express the importance of the Tribe's commitment to restoring salmon habitat throughout their river's watershed. Restoring the landscape to its state when the Stillaguamish were its stewards represents more to the tribe than resource assurance. It represents the tribe's past and future by recovering sovereignty over their ancestral home and increasing agency over how that land is managed (Northwest Treaty Tribes, 2023). The restoration efforts the Stillaguamish tribe manages, furthermore, prepares their communities for resilience in the advent of anthropogenic climate change and secures access to traditional cultural practices for future generations. The hope in their efforts are to ensure that salmon remain available not just for tribal members, but for members of other Puget Sound communities and the wildlife they cohabitate with (Northwest Treaty Tribes, 2023).

Historically, many restoration projects have been completed throughout the Stillaguamish basin. Acquisition projects are most expensive per acre in the upper Mainstem, but more common in the Upper North Fork (Figure 5). Most acquisitions are between 40 and 400 acres. Past restoration projects overwhelmingly restore riparian habitat, especially in the Mainstem, Upper and Lower North Fork (Figure 6). Estuarine projects are common at the bay, while site stewardship projects are common in the Upper North Fork.

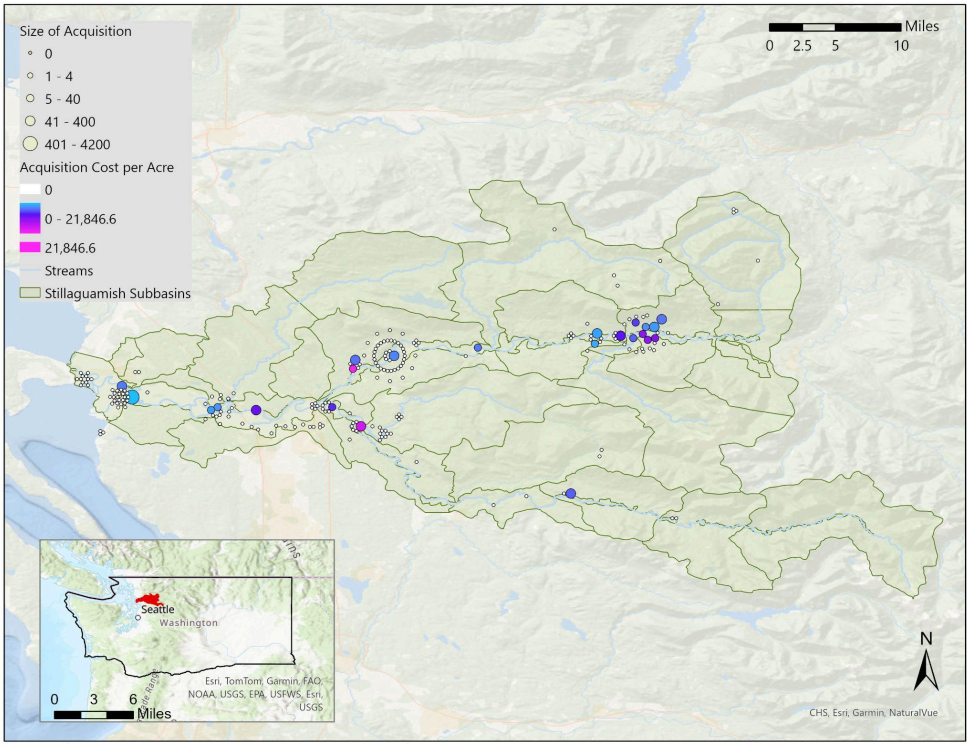

Figure 5. Acquisition costs per acre in the Stillaguamish river basin, 2000-2019. Size 0 white points are general restoration sites, not acquisition sites. Data requested from Washington State Recreation and Conservation Office, 2024.

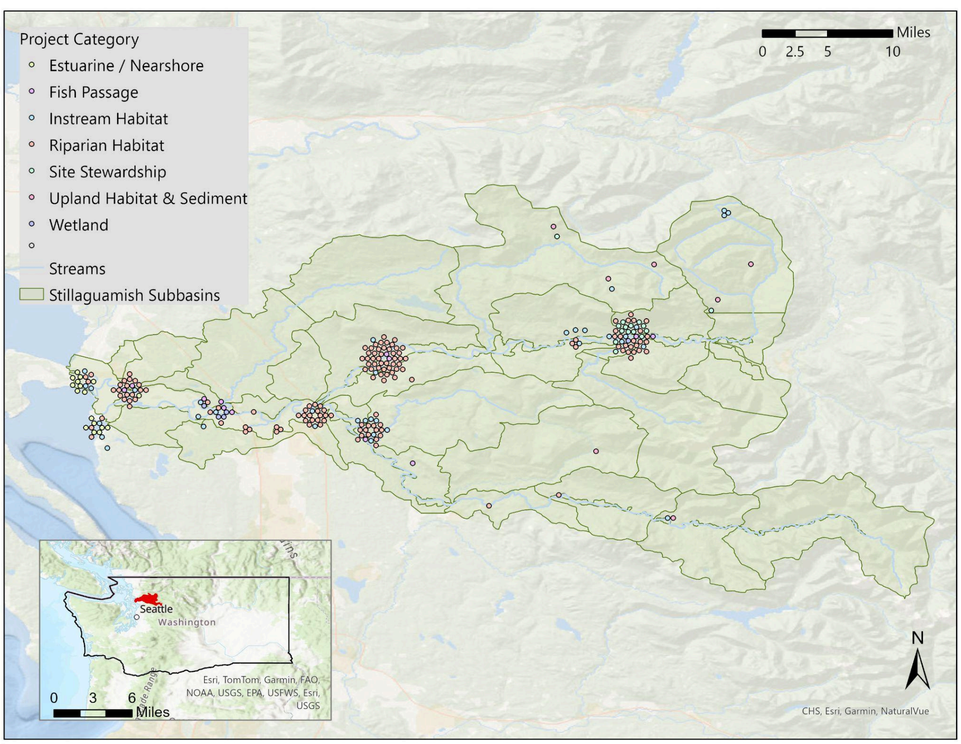

Figure 6. Restoration Project Types in the Stillaguamish River Basin, 2000-2019. Data requested from Washington State Recreation and Conservation Office, 2024.

Restoration Interventions

Our analyses compared restoration actions that support Chinook spawning habitat functions to the estimated costs of each action. A list of common restoration interventions detailed by the Stillaguamish Watershed Council's 10-year Watershed Enhancement Projects include riparian planting, estuary restoration, ELJs, armor bank removal, landslide and forest road treatment, and conservation easements (Stillaguamish Tribe, 2016). We evaluated three restoration interventions with high potential to increase Chinook spawner abundance in the Stillaguamish, including floodplain restoration, ELJs, and riparian planting (Beechie et al., 2023).

The Habitat Assessment and Restoration Planning (HARP) model predicts high increases in spawner abundance for summer and fall-run Chinook would result from actions that restore wood loading (34 percent), floodplain habitat (31 percent), and shade areas (14 percent) to pre-1900s levels (Beechie et al., 2023). Different habitat parameters affect different Chinook life stages, as described in Table 1.

Table 1. Chinook life stage capacities (c) and productivities (p) affected by habitat factors, indicated by "Y" (Beechie et al., 2023).

Habitat Factor	**Spawn. Capacity**	**Egg Incub.**	**Subyearling Rearing**		**Yearling Summer Rearing**		**Yearling Winter Rearing**	
	C_{egg}	**P**	**C**	**P**	**C**	**P**	**C**	**P**
Shade				Y	Y	Y		
Bank Condition			Y	Y	Y	Y	Y	Y
Wood loading	Y		Y	Y	Y	Y	Y	Y
Floodplain	Y	Y	Y	Y	Y	Y	Y	Y

Floodplain Restoration

Floodplains are flat wetland areas that contain side channels and braided stream networks, as well as oxbow lakes that occur next to tributaries and streams. Floodplains capture the river's overflow during storm events, filter water, and provide refugia for young salmonids (Shared Strategy Development Committee, 2007).

Floodplains support Chinook in their juvenile lifecycle stage by providing abundant insect prey, shade for temperature regulation, and refuge from predators. This habitat-type also helps juvenile salmonids adjust to salinity before migrating to the ocean. Floodplains, furthermore, attenuate high streamflow during wet months and provide refuge from high flow areas in a river's main channel (Ward et al., 2009).

Armoring streambanks with concrete for flood control and development disrupts many floodplain processes. In the Stillaguamish River basin, 9 percent of large river bank length is armored, this includes banks in estuarine habitat (Beechie et al., 2023). Modified floodplain channels reduce riparian vegetation recruitment, fragment habitat within the stream networks, and increase sediment mobility through storm runoff (Shared Strategy Development Committee, 2007).

Floodplain restoration can take many forms, including connecting side stream channels to the rest of a stream network and stabilizing stream banks. Floodplain tributary reconnection is the process of restoring connections between a river's main channel and adjacent water bodies. Common costs for floodplain restoration include land acquisition and maintenance. Restoring floodplains can be advantageous for both salmon and communities by serving as stormwater retention areas that mitigate flooding (Nisqually River Council, 2016).

Engineered Log Jams

Deforestation and log jam removal in the Stillaguamish River have resulted in increased streamflow in areas, as well as increased water temperature that drives decreased dissolved oxygen content. Furthermore, salmonid eggs and juveniles become more susceptible to predation as a result of limited refuge that log jams may otherwise provide (Shared Strategy Development Committee, 2007). ELJs address this problem by adding woody materials that provide refuge habitat for salmonid juveniles and improve spawning habitat suitability for adults by buffering stream velocity (Abbe et al., 2018). ELJs, additionally, create pools that slow erosion along streambanks, which reduces sediment entering the stream (Nisqually River Council, 2016). The channel stability and complexity that ELJs provide diversifies salmonid habitat that is available resting and foraging, provides refuge, and maintains large-grain gravel for spawning salmon (Nisqually River Council, 2016). Some drawbacks of ELJs are their potential to capture floating anthropogenic debris, such as plastic bottles and trash, as well as their limited lifespan depending on environmental conditions (Roni et al., 2015).

Riparian Planting

Riparian zones describe land that is adjacent to water bodies, including embankments and floodplains. Riparian vegetation filters excess nutrients and sediment, stabilizes streambanks, and reduces water velocity and turbidity (National Park Service, 2022). Shade from riparian vegetation cools water temperature, supports production of invertebrates that juvenile salmon feed on, and provides cover from predators (Shared Strategy Development Committee, 2007). Planting riparian trees also supports beaver activity, which expands and supports juvenile and spawning salmon habitat in a way that is similar to natural log jams (Nisqually River Council, 2016). Riparian deforestation for timber harvest and vegetation removal for armored bank installation has resulted in a loss of salmonid freshwater habitat functions like cover. Furthermore, riparian degradation prevents organic inputs like woody debris and detritus entering the food web (Nisqually River Council, 2016). Nutrient additions to streams, like vegetation detritus, enhance trophic productivity that is beneficial to growth in juvenile salmonids (Bilby et al., 2023).

Challenges to riparian planting are young plants' vulnerability to being outcompeted by invasive species, browsing by wildlife and domestic livestock, and limited soil moisture availability in the first two growing seasons. Maintenance requires weed control and monitoring early on, but after four years reintroduced vegetation is fully established (Shared Strategy Development Committee, 2007). The full suite of environmental benefits from restored riparian forests provide may not be observed for another 25 years after planting takes place (Justice et al., 2016). Large woody debris entering stream channels may take up to 80 years following planting (Bilby et al., 2023).

Fish Passage

There are 2,086 documented fish passage barriers in Washington State, including 1,536 culverts that block over 200 miles of upland stream habitat (WSDOT, 2023b). In 2013, the U.S. District Court required Washington State to refrain from building culverts under state-maintained roads. The order also required the state to remove state-owned culverts that block passage to salmonid habitat by 2030 (WSDOT, 2023a). The Washington State Department of Transportation, and other managing agencies, have removed 114 culverts as of June 2023. These actions have resulted in opening over 500 miles of salmonid freshwater habitat in western Washington (WSDOT, 2023b). Although these efforts have yielded results for recruiting salmonid spawners, fish passage was not chosen for our analyses because only 1 percent of summer and fall run Chinook habitat in the Stillaguamish is above man-made barriers (Beechie et al., 2023). Chinook prefer to spawn lower in the watershed in larger mainstem streams, where fewer obstacles are present.

Subsurface culverts are historically a common infrastructure adaptation for salmon passage. Urban infrastructure in the Puget Sound Region has been adapted with culverts that direct streams underground to allow connectivity to salmonid spawning habitat. Restoring surface streams, however, as opposed to installing culverts for fish passage can be more effective in connecting sexually mature Chinook salmon from nearshore habitat to freshwater spawning habitat (Tabor et al., 2022). Research has shown that spawning salmon are likely to avoid culverts as they have no access to light and are at a greater depth than they prefer for spawning habitat. Spawning salmon are more likely to favor an open, surface level stream system than culvert passages (Honea et al., 2009).

No major dams exist in the Stillaguamish river basin. However, dams elsewhere in the Puget Sound represent significant barriers for anadromous fish despite adaptations to accommodate fish passage. The case study of the Elwha and Glines Canyon dam removals, between 2011 and 2014, offers support for the efficacy of dam removal. The two dams were removed to enable fish passage into the upper Elwha River. Within five years of dam removal, Chinook had recolonized the upper reaches of the Elwha and its tributaries, ranging over 30 miles further up the river than the dams had previously allowed. By 2019, their densities in middle sections of the river outnumbered their density at the river's mouth pre-dam removal (Duda et al., 2021). The dam removals on the Elwha River took twenty years to implement and cost an estimated $100 million. While removing large dams is an important recovery intervention to consider, it is politically intensive and financially costly, making for a slow moving implementation process.

Limitations of Restoration

Researchers have identified two primary limitations in salmon species' responses to restoration efforts. The first limitation is insufficient resources for comprehensive restoration and the inadequate scope of project implementation. The second limitation is misalignment of timing, location, and restoration type (Bilby et al., 2023). Managers tend to prioritize less expensive projects that address symptoms of ecological degradation rather than more costly interventions that address underlying causes. The effectiveness of habitat restoration is consequently often hindered by inappropriate project selection, where restoration actions fail to address both ecosystem and species population needs that have been identified in habitat assessments and recovery plans (Barnas et al., 2015; Bilby et al., 2023). A study in 2015 revealed that freshwater salmonid habitat restoration in many Pacific Northwest watersheds only addressed portions of the target species' ecological parameters, without considering deeper implications of ecological processes that successful restoration should address (Barnas et al., 2015). These efforts targeted individual factors, like shade from riparian vegetation, without focusing on how restoration actions might affect a target system's nutrient cycling or projecting changes in population dynamics (Bilby et al., 2023).

Despite the publication of recovery plans that are directed to match a target species' needs with appropriate recovery actions, a significant gap remains, particularly with regard to restoring watersheds for anadromous fish (Barnas et al., 2015). According to Bilby et al. 78 percent of recovery plans for anadromous fish match a species' identified needs with appropriate actions but only 31 percent matched at a finer scale within a watershed (2023). As a result, restoration for freshwater anadromous habitat often fails to align with ecological needs, performing no better, and sometimes worse, than randomly chosen projects (Barnas et al., 2015). This is particularly true in small-scale restoration. The slow pace of restoration and changes in species population dynamics are, additionally, compounded by inadequate monitoring in small-scale projects. These shortcomings in post-restoration monitoring and evaluation present challenges to detecting population-level responses to restoration actions (Bilby et al., 2023; Stillaguamish Tribe, 2016).

We aimed to address these discrepancies by incorporating an economic lens to prioritizing areas for restoring PS Chinook spawning habitat. While our analyses do not entirely address concerns with monitoring and evaluation, they provide estimates on the costs and outcomes of restoration efforts based on location and restoration type (Beechie et al., 2023). Considering the urgency of SRKW recovery against restraints in time and funding needed to restore their prey's spawning habitat, there is a pressing need to advance prioritizing PS Chinook recovery projects by taking into consideration both effectiveness and costs. Our analyses aimed to identify cost-effective interventions in locations that have the highest potential to increase Chinook spawner abundance in the Stillaguamish River basin, and, thus, optimize funding decisions directed toward restoring PS Chinook spawning habitat.

Methods

Cost Model: A Primer on Habitat Restoration Costs

To estimate the costs of restoration projects in the Stillaguamish River basin, models for cost estimates were adapted from Puget Sound Shared Strategy (PSSS) (PSSS, 2003). The PSSS document was originally produced in 2003 to inform cost estimates for watershed restoration for managers in the Puget Sound region. The PSSS cost document provides cost estimates for common river restoration projects such as riparian planting, ELJs, and floodplain restoration. The cost estimates were produced via interviews with restoration experts in the Puget Sound area. Each section of the document describes major cost components by specific restoration method. In this study, the guidance within the cost models were applied to the Stillaguamish River basin for floodplain restoration, ELJs and riparian planting. The costs proposed in this document are presented as ranges to provide room for error.

Benefit Model: HARP Model

The HARP model was developed by NOAA's Northwest Fisheries Science Center to inform habitat restoration planning that targets salmonid species in Washington state (Jorgensen et al., 2021). The HARP model is species and site specific. To date, it has been applied to several basins across the state, including the Stillaguamish, the Snohomish, and the Chehalis River basins (Beechie et al., 2023; Fogel et al., 2022). Each implementation of the HARP model considers the life history of the salmonid species in a target basin and the weight that environmental variables have over species recovery. The HARP model analyzes how habitat-forming processes, habitats types, and salmon populations have changed from historical to current conditions. Diagnostic scenarios are used to determine the restoration potential for each restoration action type individually. The diagnostic scenarios use a spatial analysis, a habitat analysis, and life cycle models to isolate the effect of each restoration action. Raw data layers such as precipitation amounts, land cover, elevation and location of spawning streams are used for a spatial analysis.

The outputs of the spatial analysis are habitat data layers that delineate the major habitat types, such as floodplain habitat, spawning riffles, and the river itself. These layers are the inputs of the habitat analysis. The habitat analysis produces estimates of current and historical habitat conditions. The life cycle model is then used to determine each restoration actions' capacity to increase spawner abundance for each of the modeled species. The diagnostic scenarios were run deterministically, so there is no annual variation around the modeled spawner abundances. For Chinook in the Stillaguamish, estuary rearing and sub yearling rearing are sensitive parameters in the model, and they have the largest increases resulting from restoration actions that increase rearing habitat in large rivers and the delta's estuary. This study will primarily focus on the increased spawner abundance estimates for fall-run Chinook salmon in the Stillaguamish River basin, but the HARP model also produces estimates for coho salmon and winter- and summer-run steelhead trout (Beechie et al., 2023).

The primary limitation of using the HARP model is that the output values produced under each diagnostic scenario represent the increased number of spawners a subbasin could support if fully restored to historical conditions. For instance, the increased number of spawners resulting from the wood abundance scenario (Figure 7) are the number of spawners that would be produced if wood loading levels were restored to historic levels, but all environmental factors (shade, migration barriers, sediment loading, etc.) were unchanged. Additionally, the HARP model outputs we used fail to consider that the capacity of a particular subbasin may be higher than reported values if restoration efforts have been undertaken downstream from that subbasin. When restoration occurs downstream from a specific subbasin, it can elevate juvenile survival rates, which in turn positively impact spawner recruitment. Therefore, there exists a benefit in prioritizing the restoration of subbasins through which more salmon migrate, as they possess the potential to augment spawner abundance in upstream subbasins.

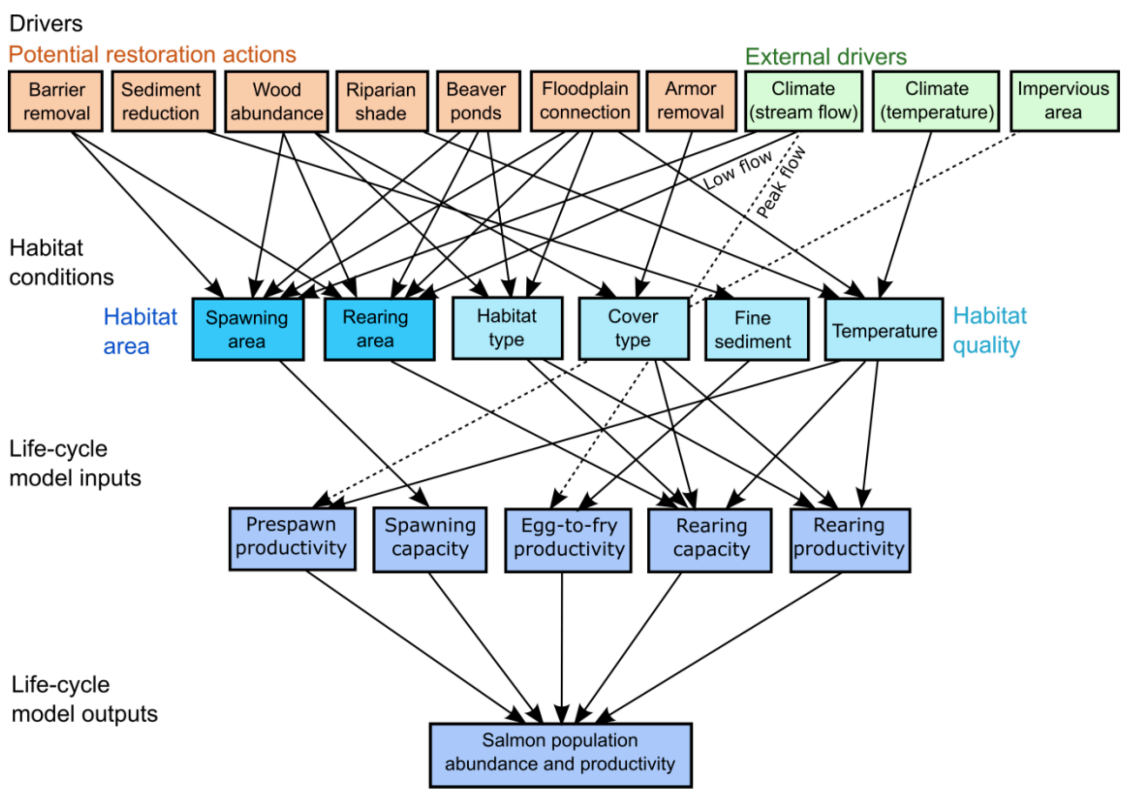

Figure 7. Structure of HARP model demonstrating the connections between drivers, habitat conditions, lifecycle model inputs and outputs (Beechie et al., 2023).

Our Approach

Costs were calculated for our chosen three restoration actions: floodplain restoration, riparian planting, and ELJs. All analyses were conducted in RStudio version 2023.9.0.463 (Posit team, 2023). Key environmental factors such as slope, river width, and proximity to the nearest road served as inputs for the cost models. We used models that were specified in the

Puget Sound Shared Strategy document. Costs were comprehensively estimated for each restoration type and covered construction, design, permitting, basic monitoring for 2 years, routine maintenance for 2 years, reestablishing the site to its baseline conditions (before 1900), and project management expenses that are typical of capital projects (PSSS, 2003). Costs were first calculated for each 500 meter stream reach, but then were added together to develop a cost estimate range for each restoration type per subbasin. After the costs were estimated, we applied the producer price index (PPI) for construction materials to calculate how the cost estimates would have increased since the document that produced these estimates in the spring of 2003 until November 2023 according to the following equation (U.S. Bureau of Labor Statistics, 2024):

$$Eq\ 1.\ \frac{ppi_{2023} - ppi_{2003}}{ppi_{2003}} = \frac{327.242 - 145.200}{145.200} = 2.254$$

The selection of these three restoration actions was informed by the HARP report, which highlighted that these actions had the greatest potential to enhance habitat capacity for Chinook in the Stillaguamish basin relative to other actions (Beechie et al., 2023). Costs were only calculated for Stillaguamish subbasins that have HARP modeled estimates for increased Chinook spawner abundance. Following the cost estimation, the HARP model was employed to calculate benefits, measured in terms of the increased salmon spawner abundance that a specific subbasin could sustain if restored to its historical conditions. A cost-effectiveness ratio was subsequently computed to determine increases in spawner abundance relative to a project's total cost. This ratio guided recommendations on prioritizing each restoration type per Stillaguamish subbasin.

Floodplain Restoration Costs

The estimated expenses related to floodplain restoration include all costs involved in reestablishing connections between a main stream and its tributaries, as well as the main streams' connection to floodplain areas (PSSS, 2003). It is important to note that it is very difficult to predict the costs associated with floodplain restoration due to the large scale and many variable costs of the projects. Since we targeted specific subbasins that are known to have degraded floodplain habitat, the estimated costs account for the price associated with restoration of all habitat fully to historic conditions.

Floodplain restoration was divided into two categories: floodplain tributary reconnection and side channel reconnections. Floodplain tributary reconnection is the process of restoring connections between the main channel of a river and other, nearby water bodies, including lakes and ponds, that are connected to the main channel by one primary point. Side channel reconnection is the process of restoring connections between the main channel of a river and side channel streams that connect to the main channel in two spots as well as marshes. Figure 8 shows a simplified version of our methodology:

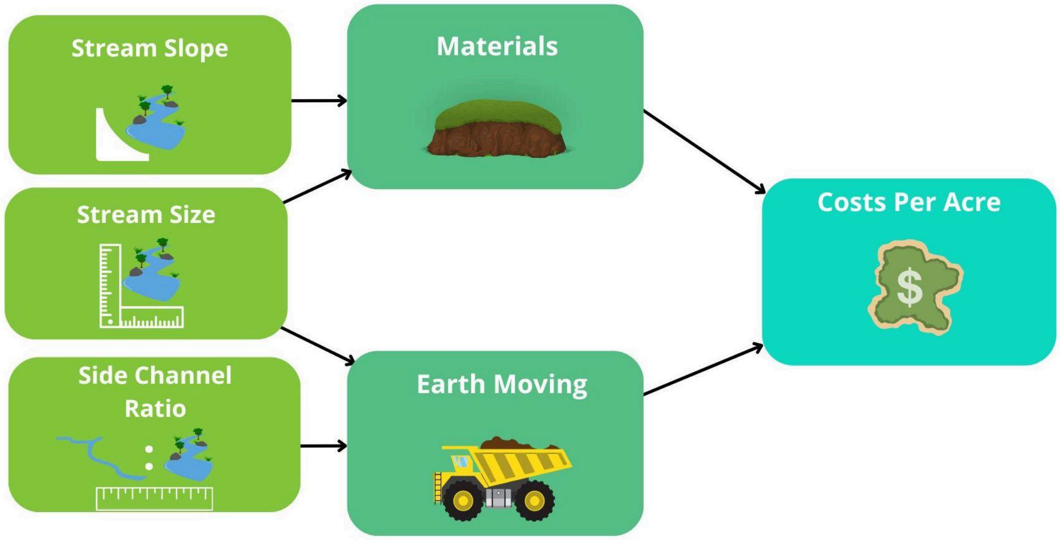

Figure 8. Flow chart describing how floodplain restoration cost estimates were produced.

Floodplain Tributary Reconnection

Two primary inputs were used to calculate the cost of floodplain tributary reconnection: earthmoving and material costs. Earthmoving includes the costs of moving rocks, land, or man-made structures that block water within the floodplain's natural flow. Projects that only require a few days of labor have lower costs than projects that take longer and require removal of larger items. Earthmoving costs tend to be higher for side channel reconnection projects than floodplain tributary reconnection since side channels need to be reconnected to the main channel at two points. We approximated the costs associated with earth moving using the ratio between the main channel length of a river and the side channel length of a river segment as well as river size. These two factors are assessed at the closest river segment to the pond or lake, as it is the probable site for reconnection, and thus provides the conditions for estimating costs.

The ratio of side-channel length divided by main-channel length is defined by the HARP model as the side channel multiplier. The side channel multiplier captures the relative amount of side channel habitat in a river segment. Values greater than one indicate that there is more side channel length in a given segment than main channel length, whereas values less than one indicate the inverse. We defined a low multiplier as less than 0.5, and a high multiplier as greater than or equal to 1.5. These values corresponded to breaks in the distribution of multiplier values. Subbasins with more habitat requiring restoration will cost more than subbasins with less degraded habitat.

For river size, the HARP model defined each stream reach as either small or large. We used the combination of the side channel multiplier and river size to approximate the energy and the amount of floodplain habitat to be restored in each reach which relates to the amount of earth that needs to be moved in order to restore a reach. We created a matrix that estimated the relative extent of earthmoving required based on these two conditions (Table 2).

Table 2. Impact of river slope and width on earthmoving costs.

		Side Channel Multiplier	
		Low (<0.1)	High (≥0.1)
Size	Small	low	medium
	Large	medium	high

Material costs capture the price of the rock, logs, stumps, plants, etc. to restore the stream to its natural condition. At the low range of material cost, most of the costs are from plants, and at the high end large quantities of stumps, large rocks and logs may be required. Waterway energy was used as a proxy to estimate the material cost of a given project, since materials for larger rivers cost more (Abbe et al., 2018). Table 3 describes the cost ranges of floodplain tributary reconnection projects without inflation.

Table 3. Cost of floodplain tributary reconnection projects ($/acre).

		Extent of Earthmoving		
		Minimal	Moderate	Substantial
Energy (Materials)	Low	$5k-10k	$10k-$20k	$30k-$40k
	Medium	$10k-$20k	$20k-$30k	$40k-$60k
	High	$30k-$40k	$40k-$60k	$60k-$80k

After applying the PPI to the cost ranges produced in Table 3, the cost per acre values were multiplied by the area of historical ponds and lakes in each subbasin. This area was derived from shapefiles supplied from the HARP model.

Side Channel Reconnection

The cost model for side channel reconnection was used to calculate the costs for two different habitat regions: marshes and side channel habitat adjacent to the main channel of the river. The area of the marsh habitat was derived from shapefiles supplied from the HARP model. The area of degraded side channel habitat for each stream reach was calculated by multiplying the length of the stream reach by a third of the bankfull width by the percent reduction of floodplain habitat by subbasin relative to historic conditions.

Two primary inputs were used to calculate the cost of side channel reconnection: earthmoving and waterway energy. Table 2 (from floodplain tributary reconnection above) was also used to calculate earthmoving for side channel reconnection projects.

Slope and river size were used as a proxy to bin the waterway energy of each stream segment (Table 4). To calculate the slope and river size for marsh habitat not directly adjacent to a stream reach, the slope and river size of the nearest stream segment was used. Slope was binned into three categories, with streams with slopes of less than 1 percent categorized as small, streams with slopes from 1 percent to 4 percent categorized as medium and streams with sloped greater than 4 percent categorized as high.

Table 4. Impact of river slope and size on waterway energy (low, medium or high).

		Slope		
		Low (<1%)	Medium (1% to 4%)	High (>4%)
River Size	Small	low	medium	medium
	Large	medium	high	high

Waterway energy considers the flow of the river; a side channel of a higher flow river will be subject to higher flow than a side channel of a low flow river. Higher material, construction, and permitting costs are associated with higher flow streams (PSSS, 2003). Together, the relative levels of waterway energy and extent of earthmoving were used to produce cost ranges for side channel reconnection projects in dollars per acre (Table 5).

Table 5. Cost of side channel reconnection projects ($/acre).

		Energy of Waterway		
		Low	Medium	High
Extent of Earthmoving	Minimal	$20k-40k	$40k-$70k	$60k-$90k
	Moderate	$40k-$60k	$70k-$100k	$100k-$200k
	Substantial	$60k-$100k	$130k-$200k	$200k-$300k

After applying the PPI to the cost ranges produced in Table 5, the cost per acre values were multiplied by the area of marshes and historical floodplain habitat adjacent to the stream reach in each subbasin.

Combining Floodplain Costs

The costs associated with floodplain tributary reconnection projects and side channel reconnection projects were added together, so that the final cost estimates by subbasin include the price of both types of floodplain restoration. The final product of this analysis contains the lower and upper range of costs for each subbasin in the Stillaguamish basin. Average values were taken for low and high cost estimate ranges.

Engineered Log Jams Costs

The costs of ELJ projects includes costs for projects that are often done on larger streams as well as large woody debris (LWD) projects that often occur on smaller streams. These restoration actions are characterized by their use of woody materials to increase spawning habitat suitability for Chinook. The costs associated with ELJ projects were estimated using the bankfull width of each stream, waterway energy (Table 4) and the distance to the nearest road. The distance to nearest road was calculated using the st_distance function in RStudio on a shapefile that was a combination of all of the roads in the regions and another shapefile of the stream. The material costs and transportation were combined to produce a value that indicates an intermediate cost value (Table 6). Energy was used as a proxy for material costs since higher energy streams require more materials. Figure 9 shows a simplified version of our methodology:

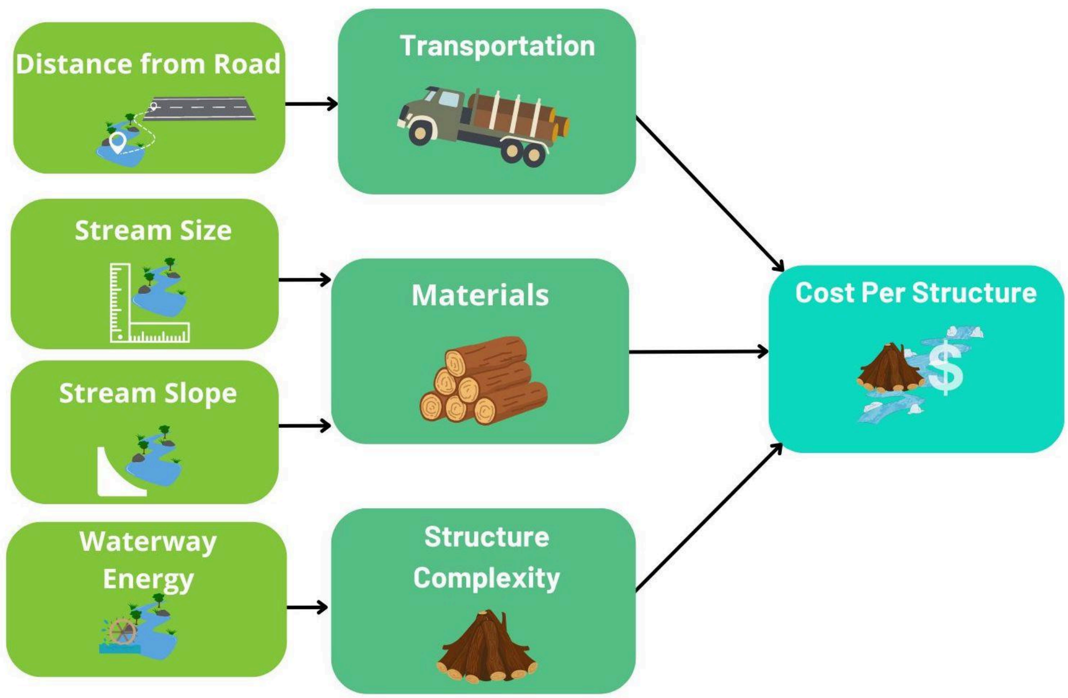

Figure 9. Flow chart describing how ELJ project cost estimates were produced.

Table 6. Impact of materials and transportation on ELJ project cost (low, medium and high).

		Transportation		
		Near (<0.25 mi)	Average Distance (0.25 mi to 0.75 mi)	Far (>0.75 mi)
Energy	Low	low	medium	high
	Medium	low	medium	high
	High	medium	high	high

The relative effect of material cost and transportation on cost was then plugged into Table 7 to produce cost ranges given stream energy for various project types.

Table 7. Cost of ELJ projects ($/mile and $/structure). *Ranges given by per stream mile (assuming 100-400 pieces per stream mile) for LWD projects. All other cell ranges are given per structure for ELJ projects. All cost ranges assume purchased material.

		Transportation and Material Requirements		
		Low	Medium	High
Energy	Low	$10k-30k*	$20k-$50k*	$20k-$40k
	Medium	$20k-$50k*	$15k-$45k	$40k-$70k
	High	$10k-$20k	$40k-$60k	$60k-$80k

After applying the PPI to the cost ranges produced in Table 7, the costs were multiplied by the length of the stream reach in miles for LWD projects and by structure for ELJ projects. For estimated LWD project costs, we assume that 50 percent of a given sub basin requires LWD projects (Tim Beechie, personal communication, January 10 2024). For costs produced for ELJ projects, we assume one structure per 400 meters in low energy streams, one structure per 200 meters in medium energy streams and one structure per 100 meters in high energy streams. The costs per subbasin were then calculated by adding the costs for each stream reach within the subbasin. The final product of this analysis contains the lower and upper range of costs for ELJ projects in each subbasin in the Stillaguamish basin. Average values were taken for low and high cost estimate ranges.

Riparian Planting Costs

The riparian planting cost estimates include the cost ranges of restoring riparian habitat vegetation to historical levels. The three most important factors that determine the cost estimates for riparian planting include: 1) site accessibility, 2) materials, and 3) site preparation (PSSS, 2003). We used physical attributes of each stream reach such as distance to nearest road, stream slope and width, surrounding terrain slope, and current and historical canopy opening angle to best estimate the degree of these three factors. Figure 10 shows a simplified version of our methodology:

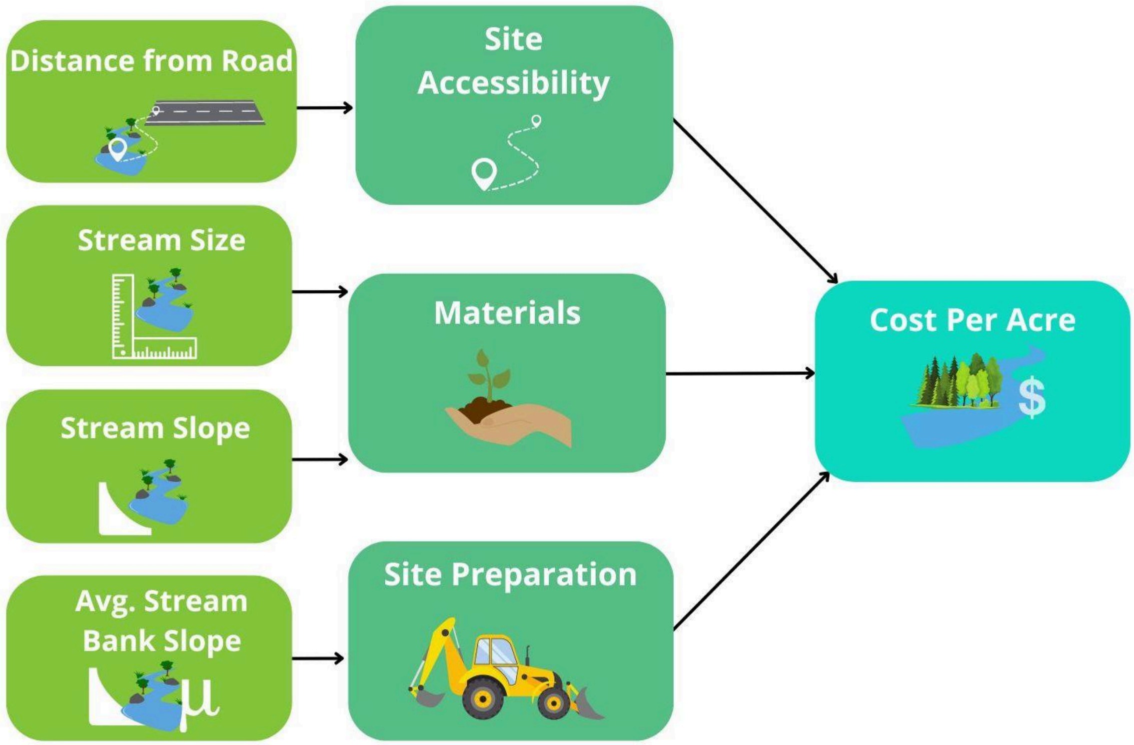

Figure 10. Flow chart describing how riparian planting cost estimates were produced.

Site accessibility refers to the ease of transporting personnel, equipment, vegetation, and other resources to the restoration site. We estimated site accessibility by calculating the distance to the nearest road for each stream reach using the same methods as above for ELJ projects.

Materials include the required vegetation (shrubs, trees, grasses, etc.) that will be planted to restore riparian areas alongside stream reaches. The PSSS document bins required materials as minimal, moderate, or substantial depending on the amount, size, and cost of required vegetation (PSSS, 2003). Projects using donated or inexpensive plants or small grasses and shrubs can be classified as “minimal” (primarily for smaller rivers or wetlands) whereas projects requiring expensive and/or large woody trees to be “substantial” with moderate somewhere in between. Due to the large scale of restoration in the Stillaguamish being estimated and necessity for larger shrubs, trees, and woody plants, we only classified stream reach materials as either needing moderate or substantial materials as smaller and/or donated vegetation was unrealistic for the proposed restoration.

We used the stream energy (refer to Table 4 for energy estimates) as a metric to estimate whether each stream would need moderate or substantial resources. We assume that higher energy streams require stronger root systems and larger plants to reinforce the banks from erosion and, therefore, require more expensive materials compared to low energy streams.

We, thus, classified low energy streams as minimal materials, medium energy as moderate materials, and high energy as substantial materials.

Once site accessibility and materials requirements were classified, we created an initial cost identification matrix using the results from both assessments (Table 8). This matrix produced intermediate costs as low, medium, or high depending on the combination of site accessibility and required materials. This matrix serves to identify the relative costs of just the site accessibility and required materials but not the site level preparation.

Table 8. Impact of Site Accessibility and Materials on Costs

		Site Accessibility		
		Easy	Moderate	Difficult
Materials	Minimal	low	low	medium
	Moderate	low	medium	high
	Substantial	medium	high	high

After identifying the initial relative costs, we then identified the level of site preparation necessary at each stream reach as one of three options according to the guidance document: flat slope and light clearing, average slope and average clearing, or steep slope and heavy clearing (PSSS, 2003). These refer to the level of work that is needed to prepare and restore the terrain based on the amount of vegetation to be cleared and/or the slope of the terrain. Because no data indicating the necessary vegetation clearing was available, we relied on the slope of the surrounding terrain to estimate necessary site preparation. These classifications were made based on the average slope within a 50 meter buffer on either side of each reach. 50 meters was used to ensure that all 30 meters of riparian buffer on either side of the reaches were accounted for plus an extra 20 meters from each reach to ensure personnel had enough distance to mobilize outside of the riparian restoration zone. Average slope was calculated from digital elevation/terrain raster files within the Stillaguamish basin at a 10 meter resolution[1]. Raster elevation data was then transformed to slope values using the “terra” package in R. Slope data was then cropped and masked to the 50 meter buffers around stream reaches, and the average slope was extracted for each reach. Stream reaches with an average 50 meters buffer zone of 0° to 10° were classified as flat/light clearing, 10° to 20° degrees as average slope/average clearing, and 20° to 30° degrees as steep/heavy clearing.

Both the combination of materials and site accessibility and level of site preparation results were then entered as inputs into a final cost estimation matrix (Table 9). Combinations of results from both assessments were used to estimate total cost of riparian planting projects ($/acre) for each stream reach, ranging from $5 thousand to $135 thousand depending on the required materials and necessary site preparation. Final cost estimate ranges were applied to

[1] https://gis.ess.washington.edu/data/raster/tenmeter/byquad/info.html

the total area of riparian vegetation surrounding each stream reach. First, we multiplied the length, in meters of each reach by 60 meters, including 30 meters of riparian buffer on each side of the stream, to find the total area, in meters squared, of riparian habitat.

Table 9. Cost of riparian planting projects ($/acre)

		Level of Site Preparation		
		Flat/light clearing	Avg. slope/ avg. clearing	Steep/heavy clearing
Materials/Site Accessibility	Low cost	$5k-25k	$20k-$50k	$60k-$100k
	Medium cost	$10k-$35k	$45k-$65k	$70k-$120k
	High cost	$30k-$50k	$55k-$80k	$100k-$135k

Calculating cost estimates for restoring the entire riparian area for each stream reach is not only misleading, but it would lead to overestimating costs as well. Therefore, we used the change in canopy cover from historic records to roughly gauge how much area of the riparian area would need to be restored.

$$Eq\ 2.\ \frac{current\ canopy\ angle - historical\ canopy\ angle}{historical\ canopy\ angle} = \Delta\ canopy\ angle$$

We multiplied this proportion by the total riparian area along each stream reach estimate the required restoration of riparian area by reach. This area was converted from meters squared to acres to put in common units with our cost range estimates from the matrix results. The final cost estimates for each stream reach (low and high range values in $/acre) were multiplied to the required restoration areas for each reach to get the final cost estimate range for the total area of the surrounding riparian area needing restoration. Lastly, the cost range estimates were multiplied by the calculated change in the PPI to compensate for the change in project/materials costs since the document was created in 2003. Final results yielded a low and high cost estimate for each reach. Average values were taken for low and high cost estimate ranges.

Benefits

To reiterate, the HARP model estimates the current number of Chinook salmon spawners as well as the numbers of spawners that would result from floodplain habitat, ELJs, and riparian planting restoration actions by subbasin in the Stillaguamish river basin (Beechie et al., 2023). We took the difference of the post-restoration spawner abundances and the current modeled spawner abundances for each of the three actions, which yielded the increased number of spawners for each action by subbasin. We refer to benefits as the increase in spawners resulting from restoration. For example, a subbasin may have modeled 30 current Chinook spawners, but 32.6 modeled Chinook spawners under a riparian planting restoration scenario. Restoring the riparian vegetation in that subbasin would, therefore, have an estimated benefit of 2.6 Chinook spawners. These changes in spawner abundances in the

HARP model assume a full restoration scenario to historical conditions for each action being considered. In the context of the previous example, this means that riparian vegetation would need to be restored fully to historical conditions to yield the benefits of the 2.6 spawners.

Not all subbasins have modeled increased Chinook spawner abundance resulting from restoration actions. These subbasins likely do not represent significant Chinook spawning areas. Some subbasins, additionally, have a fraction of a modeled spawner difference meaning the action would have a small, if not negligible effect on spawner abundance. We filtered out subbasins with Chinook spawner increases of less than one resulting from a given restoration action since a benefit of less than a whole fish is not realistic and would not be cost-effective.

Cost-Effectiveness

We estimated the average dollar cost per modeled increased spawner by restoration action and subbasin to identify sites with the best cost-effectiveness ratio. Since the benefits are in terms in increased spawners per year, we then annualized the costs using the following equation:

$$Eq\ 3.\ C = \sum_{t=0}^{\infty} a / (1+r)^t$$

In this equation, *C* is the total cost of the restoration action, *a* is the annual cost of restoration, *r* is the discount rate and *t* is years. After estimating costs per year, then the ratio of the annualized cost can be divided by the annualized benefits. This cost-effectiveness ratio ultimately resulted in a dollar per Chinook spawner value. For example, all floodplain restoration action in subbasin *X* costs $2 million, and the subbasin has a modeled increase in 11 spawners. We then divide $2 million by 11 spawners to get the total cost per spawner in subbasin *X* for floodplain habitat restoration.

It is important to note that benefits varied widely by restoration action and subbasin, and some showed very low increases to no increases. Some subbasins showed less than one fish modeled from one of the three restoration actions. Therefore, the dollar per Chinook spawner value is unusually high and appears to be prohibitively expensive. Annual return of Chinook salmon spawners in the Stillaguamish are quite variable and difficult to predict, and the predicted spawner increases are oftentimes considerably low. It is important to consider, however, that the benefits of these restoration actions go beyond increasing Chinook spawner abundance. Additional benefits include increases in spawner abundance for other salmonid species, cultural benefits such as recreational fishing access and ecotourism, among others. These additional benefits indicate that the cost-effectiveness ratios are an underestimate of total benefits to all aspects of restoring each subbasin, and our estimates focus specifically on benefits to SRKW recovery (ie, more prey).

Land Use and Costs

We calculated the primary land types in the Stillaguamish River basin using the st_area function in RStudio. Furthermore, we calculated the costs of agricultural land in the Stillaguamish basin that fell into our floodplain restoration areas since completing the restoration in most cases would require farmers to alter their land use practices. To estimate the costs associated with acquiring floodplain habitat that overlaps with agricultural land, we multiplied the acres of floodplain habitat with the estimated market value of land and buildings per acre. As of the 2022 census, this value was $22,374 per acre in Snohomish County, where the Stillaguamish occurs (2022 Census of Agriculture Washington State and County Data, 2024).

Demographics

We examined the population demographic trends in areas where habitat restoration would increase Chinook spawner abundance. The variables selected include the percentage of people of color, poverty and unemployment rates, and lands under tribal ownership. We considered using the White House's Climate Environmental Justice Screening Tool (CEJST) to access historic funding for disadvantaged communities through the Inflation Reduction Act (IRA) and Bipartisan Infrastructure Law (BIL), however, the federal government does not recognize any of the census tracts within the Stillaguamish River basin as disadvantaged.

We first filtered the Washington census tract data only to include census tracts that overlap with subbasins in which we identified the benefits of habitat restoration to Chinook salmon. Then, we compared the ranges of the percentages of people of color, people living under the poverty level, and unemployed people in a given census tract to the Washington state averages. Throughout the census tracts, the percentages of individuals residing below the poverty threshold and the unemployment rate closely mirrored the Washington state averages: 10 percent for poverty (Statista Research Department, 2023), and 4.2 percent for unemployment (U.S. Bureau of Labor Statistics, 2023), thus serving as our benchmark values. The percentage of people of color was below the Washington state average of 28 percent (Office of Financial Management, 2023) in most census tracts, so we used the median of the census tracts selected as the threshold.

To identify census tracts with a high proportion of people of color, unemployed individuals, and people living under the poverty line, we assigned a score of 1 to census tracts that had percentages higher than the reference values chosen for each variable and a score of 0 to census tracts that had percentages lower than the chosen threshold. Census tracts containing lands under tribal jurisdiction were also assigned a score of 1. Then, we calculated a total score for each census tract by adding the score for each variable of interest. A higher score indicates a census tract that meets more thresholds for people of color, unemployed individuals, impoverished people, and/or tribal lands.

Once each census tract was assigned a total score, we calculated the relative area of each census tract in a given subbasin. We multiplied this proportion by a census tract's total score when calculating the subbasin score. We used a weighted average since some subbasins contained multiple census tracts overlapping to varying degrees.

Results

Costs

Floodplain Restoration

Floodplain habitat restoration cost estimates were the highest of the three proposed interventions, with the Mainstem costing between $220 and $360 million (Figure 11). Besides the Mainstem Stillaguamish, the upper cost estimates for all other subbasins are under $100 million, with most under $20 million. Other subbasins with relatively high costs include the Mainstem North Fork 1, Mainstem South Fork 1, and Deer Creek. The Mainstem South Fork 4 was the least expensive subbasin, estimated to be between $6 million and $9 million.

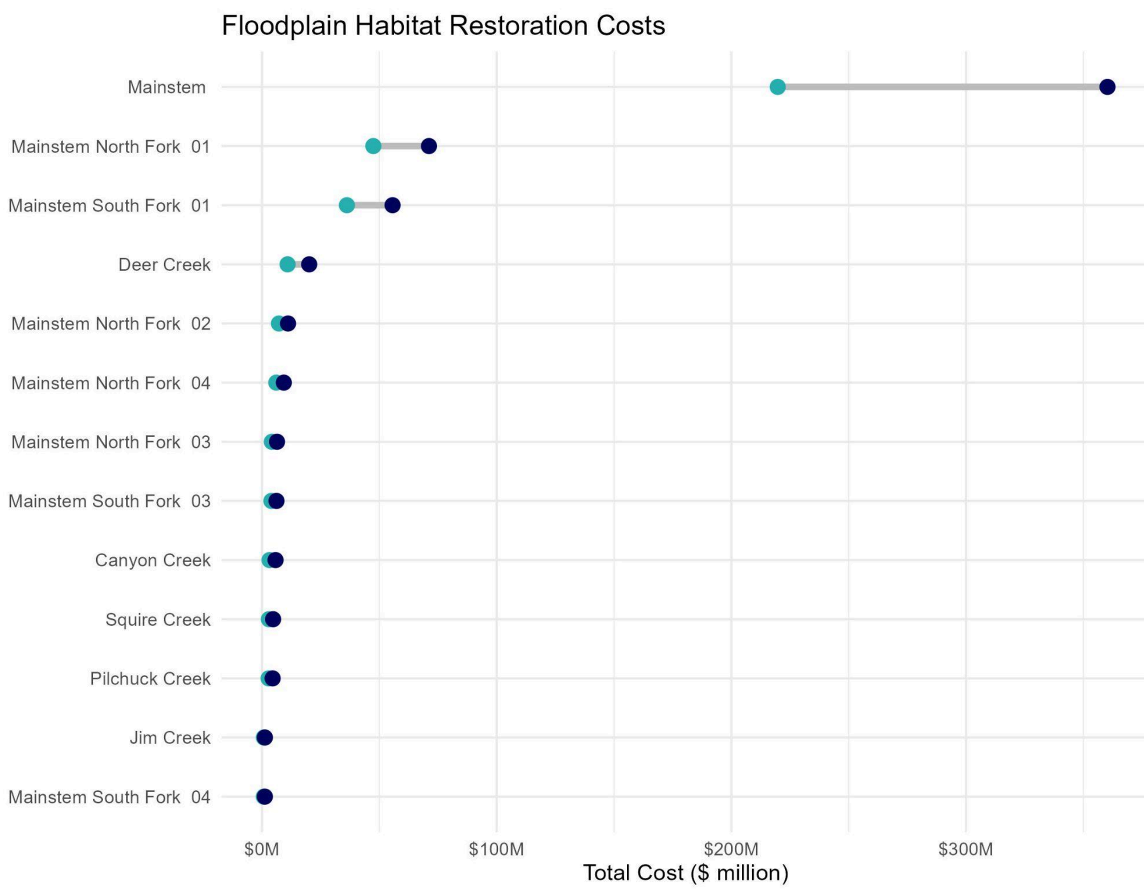

Figure 11. Estimated total upper and lower total costs for floodplain habitat restoration by subbasin.

These costs account for the restoration of 667 hectares of marsh land, 6 hectares of ponds, and 5,415 hectares of side channel habitat across the Stillaguamish basin. There were two ponds that required restoration in this study, both in the Mainstem North Fork Stillaguamish

1. Marsh habitat was spread across four subbasins, with the majority in the Mainstem Stillaguamish and the Mainstem North Fork 1 (Figure 12). Side channel floodplain habitat was spread across 13 different subbasins, with the highest amount in the Mainstem Stillaguamish and the Mainstem North Fork 1 (Figure 12).

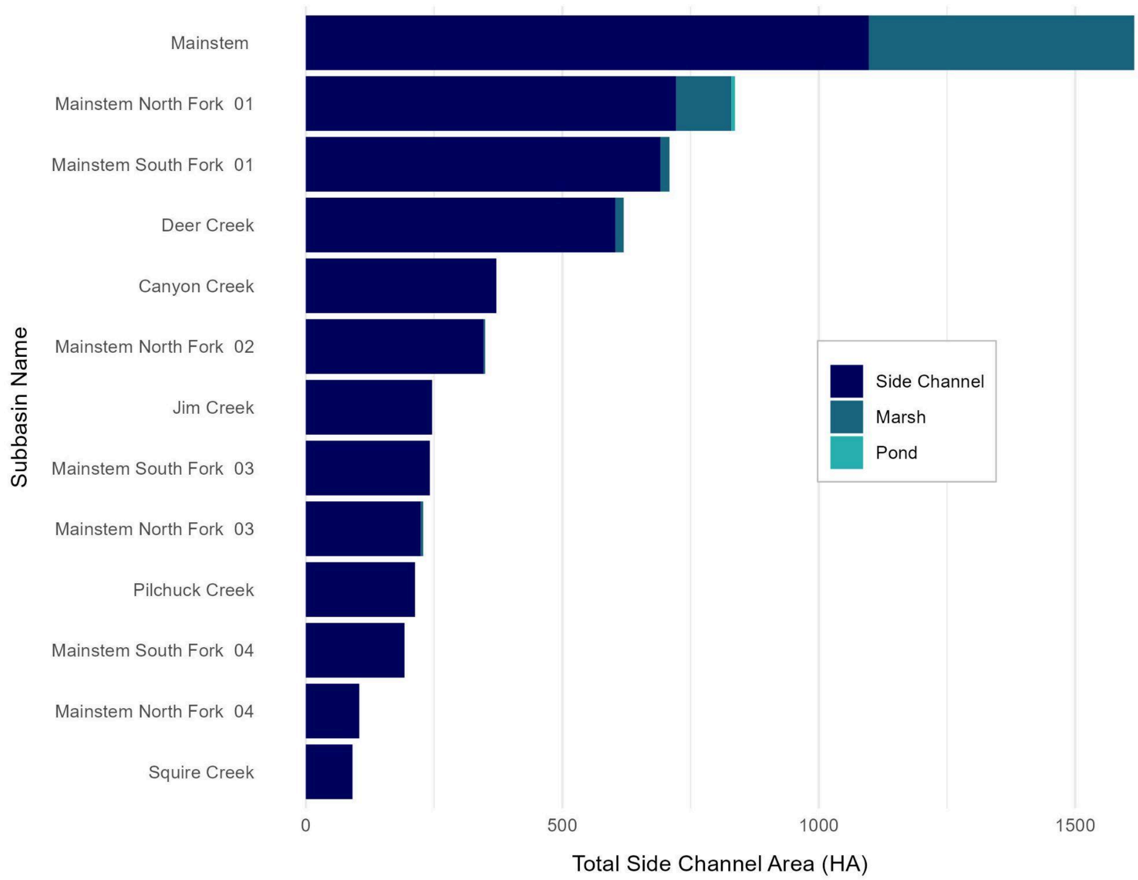

Figure 12. Area of floodplain habitat types and area to be restored by subbasin.

Average low and high floodplain habitat restoration cost estimates per acre for marsh, pond, and side channel habitats were calculated for each subbasin (Table 10). These estimates provide the average costs per acre of all habitat in each subbasin identified. These values do not represent the total costs as they do not account for the total area. The lowest average estimates by habitat type were $90,149 per acre of marsh in the Deer Creek, Mainstem North Fork 1 and 3 subbasins, $90,149 per acre of pond in the Mainstem North Fork 1, and $98,057 per acre of side channel in Pilchuck Creek. The highest average estimates by habitat type were $450,747 per acre of marsh in the Mainstem North Fork 2 and South Fork 1 subbasins, $135,224 per acre of pond in the Mainstem North Fork 1, and $424,742 per acre of side channel in the Mainstem South Fork 4 subbasin.

Table 10. Average low and high cost per acre estimates of floodplain habitat restoration by habitat type and subbasin.

Subbasin	Restoration	Metric	Lower Average Cost	Upper Average Cost
Canyon Creek	Side Channel	Per Acre	$ 128,203	$ 230,314
Deer Creek	Marsh	Per Acre	$ 90,149	$ 157,761
Deer Creek	Side Channel	Per Acre	$ 153,961	$ 286,282
Jim Creek	Side Channel	Per Acre	$ 106,797	$ 178,315
Pilchuck Creek	Side Channel	Per Acre	$ 98,057	$ 166,460
Squire Creek	Side Channel	Per Acre	$ 118,260	$ 194,112
Upland Lower North Fk	Marsh	Per Acre	$ 123,955	$ 180,299
Upland Lower South Fk	Marsh	Per Acre	$ 157,761	$ 225,373
Upland Lower	Marsh	Per Acre	$ 157,761	$ 225,373
Upland Middle North Fk	Marsh	Per Acre	$ 45,075	$ 90,149
Mainstem North Fork 01	Pond	Per Acre	$ 90,149	$ 135,224
Mainstem North Fork 01	Marsh	Per Acre	$ 90,149	$ 135,224
Mainstem North Fork 01	Side Channel	Per Acre	$ 196,136	$ 298,641
Mainstem North Fork 02	Marsh	Per Acre	$ 292,985	$ 450,747
Mainstem North Fork 02	Side Channel	Per Acre	$ 219,050	$ 332,385
Mainstem North Fork 03	Marsh	Per Acre	$ 90,149	$ 135,224
Mainstem North Fork 03	Side Channel	Per Acre	$ 212,550	$ 322,517
Mainstem North Fork 04	Side Channel	Per Acre	$ 279,550	$ 424,742
Mainstem South Fork 01	Marsh	Per Acre	$ 292,985	$ 450,747
Mainstem South Fork 01	Side Channel	Per Acre	$ 261,461	$ 400,694
Mainstem South Fork 03	Side Channel	Per Acre	$ 128,338	$ 205,549
Mainstem South Fork 04	Side Channel	Per Acre	$ 159,264	$ 264,137
Mainstem	Marsh	Per Acre	$ 187,811	$ 300,498
Mainstem	Side Channel	Per Acre	$ 198,260	$ 315,424

Engineered Log Jams

ELJs generally had the lowest cost estimates out of the three interventions. Most average subbasin cost estimates for ELJs were well under $10 million, with some subbasins approaching $30 million on the high end (Figure 13). Deer Creek was estimated to have the highest and most variable cost estimates ($17 to $30 million), followed by Jim Creek, Canyon Creek, Pilchuck Creek, and Mainstem North Fork 1. The Mainstem South Fork 4 subbasin had the lowest cost estimates for ELJ restoration, ranging from $0.82 to $1.4 million.

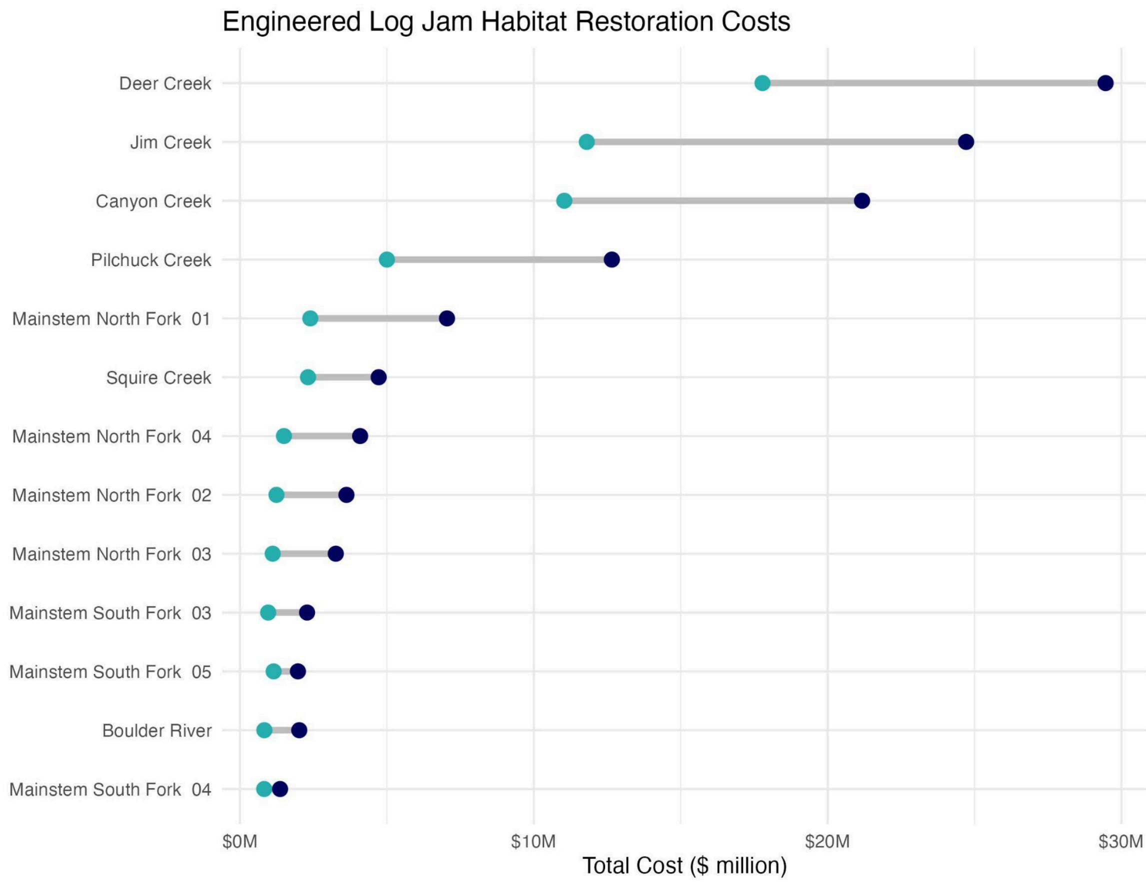

Figure 13. Estimated total upper and lower costs for ELJ habitat restoration by subbasin.

Average low and high ELJ habitat restoration cost estimates per stream mile and per structure were calculated for each subbasin (Table 11). These estimates provide the average costs per acre of all restorable habitat in each subbasin. The lowest average estimate per stream mile was $31,782 in the mainstem, and the lowest per structure estimate was $33,806 in the Mainstem, Mainstem South Fork 1, Mainstem North Fork 1, and Mainstem North Fork 3 subbasins. The highest estimate per stream mile was $112,687 in Boulder River, Mainstem North Fork 4, and Mainstem South Fork 2 subbasins. The highest per structure estimate was $155,187 in the Deer Creek subbasin.

Table 11. Average low and high cost per stream mile and structure estimates of ELJ habitat restoration.

Subbasin	Restoration	Metric	Lower Average Cost	Upper Average Cost
Boulder River	ELJ	Per Mile	$ 45,075	$ 112,687
Boulder River	ELJ	Per Structure	$ 52,758	$ 117,297
Canyon Creek	ELJ	Per Mile	$ 43,132	$ 108,801
Canyon Creek	ELJ	Per Structure	$ 75,478	$ 133,941
Deer Creek	ELJ	Per Mile	$ 41,318	$ 105,174
Deer Creek	ELJ	Per Structure	$ 99,880	$ 155,187
Jim Creek	ELJ	Per Mile	$ 42,571	$ 107,678
Jim Creek	ELJ	Per Structure	$ 61,094	$ 125,060
Pilchuck Creek	ELJ	Per Mile	$ 37,970	$ 98,478
Pilchuck Creek	ELJ	Per Structure	$ 49,014	$ 113,145
Squire Creek	ELJ	Per Mile	$ 36,796	$ 96,129
Squire Creek	ELJ	Per Structure	$ 67,356	$ 129,846
Upland French-Segelsen	ELJ	Per Mile	$ 40,747	$ 104,032
Upland French-Segelsen	ELJ	Per Structure	$ 48,267	$ 115,128
Upland Gold Basin	ELJ	Per Mile	$ 43,749	$ 110,035
Upland Gold Basin	ELJ	Per Structure	$ 67,773	$ 128,624
Upland Lower North Fk	ELJ	Per Mile	$ 42,021	$ 106,580
Upland Lower North Fk	ELJ	Per Structure	$ 51,335	$ 118,321
Upland Middle North Fk	ELJ	Per Mile	$ 41,050	$ 104,638
Upland Middle North Fk	ELJ	Per Structure	$ 68,494	$ 135,322
Mainstem North Fork 01	ELJ	Per Mile	$ 36,317	$ 95,171
Mainstem North Fork 01	ELJ	Per Structure	$ 33,806	$ 101,418
Mainstem North Fork 02	ELJ	Per Mile	$ 39,874	$ 102,285
Mainstem North Fork 02	ELJ	Per Structure	$ 33,806	$ 101,418
Mainstem North Fork 03	ELJ	Per Mile	$ 40,302	$ 103,141
Mainstem North Fork 03	ELJ	Per Structure	$ 33,806	$ 101,418
Mainstem North Fork 04	ELJ	Per Mile	$ 45,075	$ 112,687
Mainstem North Fork 04	ELJ	Per Structure	$ 43,431	$ 108,696
Mainstem South Fork 01	ELJ	Per Mile	$ 42,334	$ 107,205
Mainstem South Fork 01	ELJ	Per Structure	$ 33,806	$ 101,418
Mainstem South Fork 02	ELJ	Per Mile	$ 45,075	$ 112,687
Mainstem South Fork 02	ELJ	Per Structure	$ 99,164	$ 154,483
Mainstem South Fork 03	ELJ	Per Mile	$ 40,127	$ 102,792
Mainstem South Fork 03	ELJ	Per Structure	$ 55,476	$ 114,420
Mainstem South Fork 04	ELJ	Per Mile	$ 44,284	$ 111,105
Mainstem South Fork 04	ELJ	Per Structure	$ 90,149	$ 135,224
Mainstem South Fork 05	ELJ	Per Mile	$ 44,819	$ 112,174
Mainstem South Fork 05	ELJ	Per Structure	$ 85,815	$ 132,624
Mainstem	ELJ	Per Mile	$ 31,782	$ 86,101
Mainstem	ELJ	Per Structure	$ 33,806	$ 101,418

Riparian Planting

Riparian planting estimates were much more variable than ELJs but less so than floodplain estimates. Most subbasins' cost estimates were under $15 million, and the top 4 basins ranged from $30 to $100 million (Figure 14). Deer Creek was estimated to have the highest and most variable cost estimates of $70 to $110 million, followed by Jim Creek, Canyon Creek, Pilchuck Creek, and Mainstem North Fork 01. The Mainstem South Fork 04 received the lowest cost, estimated at $1.0 to $2.9 million.

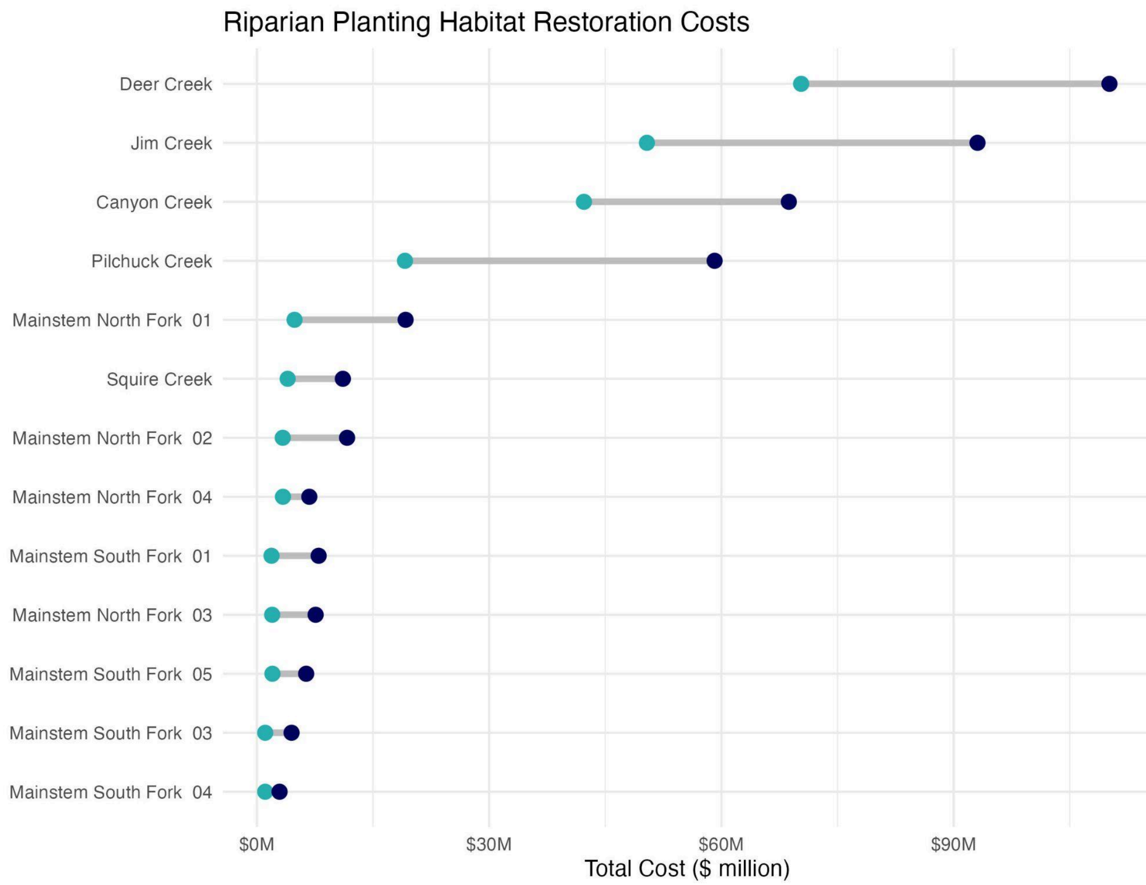

Figure 14. Estimated total upper and lower costs for riparian planting habitat restoration by subbasin.

Average low and high riparian planting habitat restoration cost estimates per acre were calculated for each subbasin with restorable riparian habitat (Table 12). These estimates provide the average costs per acre of all restorable habitat in each subbasin. The lowest cost estimate was $5,364 per acre in the Mainstem South Fork 1 subbasin, and the highest was $159,129 per acre in the Upland Gold Basin subbasin.

Table 12. Average low and high cost per acre estimates of riparian planting habitat restoration by subbasin.

Subbasin	Restoration	Metric	Lower Average Cost	Upper Average Cost
Boulder River	RP	Per Acre	$ 10,225	$ 29,424
Canyon Creek	RP	Per Acre	$ 66,851	$ 109,335
Deer Creek	RP	Per Acre	$ 80,345	$ 126,758
Jim Creek	RP	Per Acre	$ 49,705	$ 92,749
Pilchuck Creek	RP	Per Acre	$ 18,312	$ 56,986
Squire Creek	RP	Per Acre	$ 16,600	$ 47,135
Upland French-Segelsen	RP	Per Acre	$ 41,450	$ 89,464
Upland Gold Basin	RP	Per Acre	$ 98,738	$ 159,129
Upland Lower North Fk	RP	Per Acre	$ 41,539	$ 91,232
Upland Middle North Fk	RP	Per Acre	$ 87,312	$ 142,178
Mainstem North Fork 01	RP	Per Acre	$ 9,573	$ 36,212
Mainstem North Fork 02	RP	Per Acre	$ 10,240	$ 36,355
Mainstem North Fork 03	RP	Per Acre	$ 7,811	$ 30,195
Mainstem North Fork 04	RP	Per Acre	$ 28,960	$ 56,512
Mainstem South Fork 01	RP	Per Acre	$ 5,634	$ 23,818
Mainstem South Fork 02	RP	Per Acre	$ 43,103	$ 63,105
Mainstem South Fork 03	RP	Per Acre	$ 6,366	$ 27,074
Mainstem South Fork 04	RP	Per Acre	$ 10,740	$ 30,989
Mainstem South Fork 05	RP	Per Acre	$ 9,278	$ 29,856
Mainstem	RP	Per Acre	$ 9,685	$ 43,384

Benefits

The potential increase in Chinook spawners resulting from restoration varied across the subbasins within the Stillaguamish (Figure 15). The greatest total benefits were in the Jim Creek subbasin.

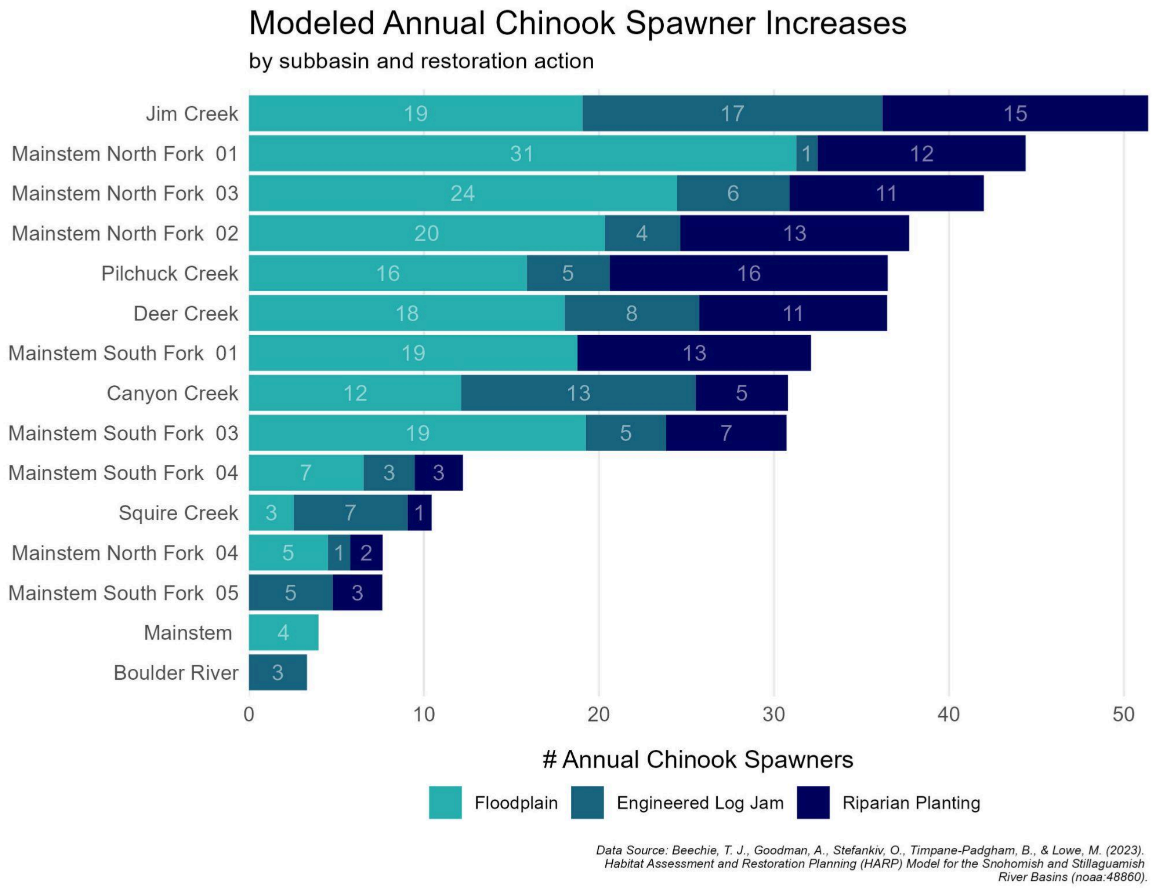

Figure 15. Increase in Chinook spawner abundance in Stillaguamish River subbasins by restoration type.

Floodplain Restoration

The HARP model estimated the total benefits, or increased capacity of the annual number of Chinook spawners, for floodplain restoration in the Stillaguamish River basin to be 211. These values may differ slightly from those predicted from the HARP model as we only included subbasins that received a potential increase of at least one spawner. These benefits were spread across many subbasins, with the most shown in the Mainstem North Fork 1 (~31 spawners) and the Mainstem North Fork 3 (~24 spawners, Table 13). Subbasins with the lowest benefits from floodplain restoration are the Boulder River (~1 spawner) and Squire Creek (~3 spawners, Table 13).

Table 13. Summary table containing total cost ranges, number of Chinook salmon spawners resulting from restoring floodplain, and the cost-effectiveness ratio by subbasin.

Subbasin Name	Lower Cost	Upper Cost	Average Cost	Spawners	CB Ratio
Mainstem	$ 219,753,849	$ 360,255,616	$ 290,004,733	3.98	$ 2,186,927.77
Mainstem North Fork 01	$ 47,437,092	$ 71,143,478	$ 59,290,285	31.27	$ 56,874.42
Mainstem South Fork 01	$ 36,167,954	$ 55,640,384	$ 45,904,169	18.77	$ 73,361.07
Deer Creek	$ 10,899,219	$ 20,106,774	$ 15,502,997	18.06	$ 25,756.87
Mainstem North Fork 02	$ 7,215,309	$ 11,089,818	$ 9,152,563	20.33	$ 13,503.75
Mainstem North Fork 04	$ 6,085,413	$ 9,298,642	$ 7,692,028	4.51	$ 51,140.86
Mainstem North Fork 03	$ 4,189,519	$ 6,395,071	$ 5,292,295	24.46	$ 6,489.75
Mainstem South Fork 03	$ 4,011,217	$ 6,171,731	$ 5,091,474	19.26	$ 7,932.35
Canyon Creek	$ 3,208,240	$ 5,770,549	$ 4,489,395	12.13	$ 11,105.09
Squire Creek	$ 2,936,232	$ 4,736,162	$ 3,836,197	2.56	$ 44,954.84
Pilchuck Creek	$ 2,833,558	$ 4,531,828	$ 3,682,693	15.88	$ 6,957.98
Jim Creek	$ 772,060	$ 1,227,225	$ 999,642	19.05	$ 1,573.99
Mainstem South Fork 04	$ 745,492	$ 1,217,043	$ 981,267	6.55	$ 4,494.68

Engineered Log Jams

Total benefits, or increased capacity of the annual number of Chinook spawners, for ELJs was estimated to be 78. These values may differ slightly from those predicted from the HARP model as we only included subbasins that received a potential increase of at least one spawner. The increase in spawner abundance resulting from the ELJs ranged from 1 to 17 across the subbasins (Table 14). The Mainstem North Fork 1 and Mainstem North Fork 4 both only have the potential to increase annual spawner abundance by 1 Chinook. The top two subbasins with the highest potential benefits from ELJs are Jim Creek and Canyon Creek, which have the potential to increase spawner abundance by 17 and 13 spawners, respectively.

Table 14. Summary table containing total cost ranges, number of Chinook salmon spawners resulting from restoring levels of woody debris to historical conditions via ELJs and LWD, and the cost-effectiveness ratio by subbasin.

Subbasin Name	Lower Cost	Upper Cost	Average Cost	Spawners	CB Ratio
Deer Creek	$ 17,784,070	$ 29,462,565	$ 23,623,318	7.68	$ 92,320.57
Jim Creek	$ 11,802,594	$ 24,715,398	$ 18,258,996	17.14	$ 31,951.07
Canyon Creek	$ 11,037,528	$ 21,172,669	$ 16,105,099	13.40	$ 36,064.40
Pilchuck Creek	$ 5,000,331	$ 12,656,482	$ 8,828,407	4.74	$ 55,842.46
Mainstem North Fork 01	$ 2,392,744	$ 7,045,315	$ 4,719,029	1.22	$ 116,421.78
Squire Creek	$ 2,314,802	$ 4,719,434	$ 3,517,118	6.51	$ 16,219.85
Mainstem North Fork 04	$ 1,494,528	$ 4,088,842	$ 2,791,685	1.28	$ 65,363.69
Mainstem North Fork 02	$ 1,240,265	$ 3,622,732	$ 2,431,498	4.31	$ 16,930.49
Mainstem North Fork 03	$ 1,112,454	$ 3,259,755	$ 2,186,105	6.43	$ 10,199.61
Mainstem South Fork 03	$ 958,455	$ 2,283,127	$ 1,620,791	4.59	$ 10,596.46
Mainstem South Fork 05	$ 1,144,144	$ 1,970,720	$ 1,557,432	4.79	$ 9,751.08
Boulder River	$ 828,165	$ 2,016,774	$ 1,422,470	3.32	$ 12,849.96
Mainstem South Fork 04	$ 823,120	$ 1,364,048	$ 1,093,584	2.93	$ 11,209.96

Riparian Planting

The HARP Model estimated the total benefits, or increased capacity of the annual number of Chinook spawners, for riparian planting to be 112. These values may also differ slightly from those predicted by the HARP model as we only included subbasins that received a potential increase in at least one spawner. Across subbasins, the potential increase in Chinook spawners is highest in Pilchuck Creek at 16 Chinook and lowest in Squire Creek at 1 (Table 14).

Table 15. Summary table containing total cost ranges, number of Chinook salmon spawners resulting from restoring levels of shade to historical conditions via riparian planting, and the cost-effectiveness ratio by subbasin.

Subbasin Name	Lower Cost	Upper Cost	Average Cost	Spawners	CB Ratio
Deer Creek	$ 70,302,284	$ 110,123,094	$ 90,212,689	10.73	$ 252,174.91
Jim Creek	$ 50,379,310	$ 93,082,852	$ 71,731,081	15.18	$ 141,733.70
Canyon Creek	$ 42,245,813	$ 68,711,311	$ 55,478,562	5.28	$ 315,438.61
Pilchuck Creek	$ 19,128,034	$ 59,126,735	$ 39,127,384	15.88	$ 73,924.25
Mainstem North Fork 01	$ 4,863,880	$ 19,211,717	$ 12,037,799	11.89	$ 30,380.81
Squire Creek	$ 3,975,865	$ 11,107,504	$ 7,541,684	1.38	$ 164,437.35
Mainstem North Fork 02	$ 3,342,720	$ 11,651,914	$ 7,497,317	13.08	$ 17,189.49
Mainstem North Fork 04	$ 3,369,754	$ 6,772,933	$ 5,071,344	1.85	$ 82,222.79
Mainstem South Fork 01	$ 1,889,532	$ 7,977,152	$ 4,933,342	13.35	$ 11,088.96
Mainstem North Fork 03	$ 1,977,095	$ 7,587,586	$ 4,782,340	11.10	$ 12,929.05
Mainstem South Fork 05	$ 2,010,399	$ 6,367,179	$ 4,188,789	2.83	$ 44,357.73
Mainstem South Fork 03	$ 1,074,114	$ 4,479,265	$ 2,776,690	6.88	$ 12,113.47
Mainstem South Fork 04	$ 1,073,927	$ 2,928,600	$ 2,001,263	2.76	$ 21,789.03

Cost-Effectiveness

Of the three restoration types we analyzed, generally floodplain restoration has the lowest cost-effectiveness ratios. Low ratios indicate that a given restoration type in a subbasin has a better "bang for its buck" than a higher ratio. After floodplain restoration, ELJs have the next lowest effectiveness ratios. Finally, riparian planting projects generally have the highest cost-effectiveness ratios (Table 16). But given the small benefits in some subbasins, some subbasins can have relatively low costs but have a high cost-effectiveness ratio (Figure 16). For instance, ELJ restoration has relatively low cost-effectiveness ratios, but generally does not produce a relatively high number of spawners. Riparian planting has high cost-effectiveness ratios and also generally low potential to increase spawner abundance. Finally, floodplain restoration generally has lower ratios than both ELJs and riparian planting and also produces more spawners.

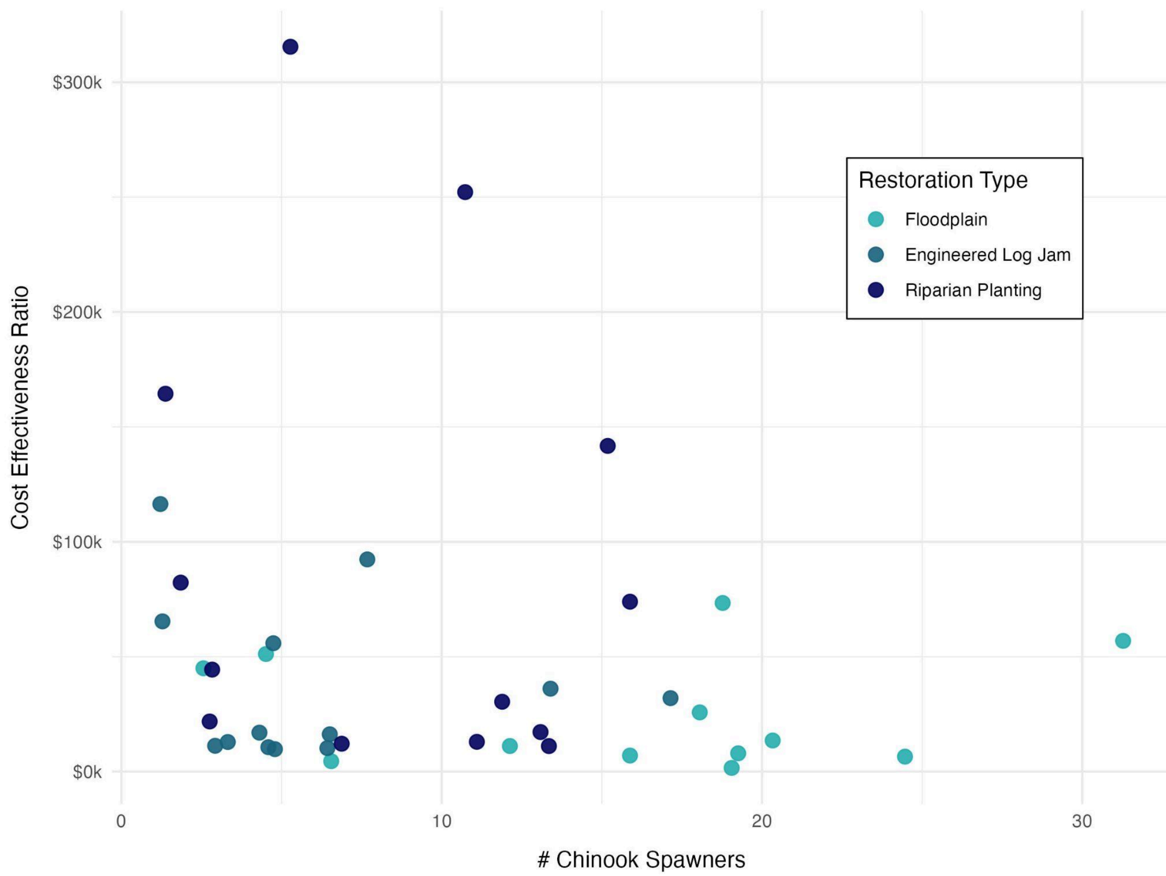

Figure 16. Cost-effectiveness ratio as a function of the increased number of spawners by restoration type.

Table 16. Top 20 areas with the greatest cost-effectiveness ratios (CB Ratio), total cost ranges, and increased spawner abundance.

Subbasin Name	Restoration Type	Lower Cost	Upper Cost	Average Cost	Spawners	CB Ratio
Jim Creek	floodplain	$ 772,060	$ 1,227,225	$ 999,642	19.05	$ 1,573.99
Mainstem South Fork 04	floodplain	$ 745,492	$ 1,217,043	$ 981,267	6.55	$ 4,494.68
Mainstem North Fork 03	floodplain	$ 4,189,519	$ 6,395,071	$ 5,292,295	24.46	$ 6,489.75
Pilchuck Creek	floodplain	$ 2,833,558	$ 4,531,828	$ 3,682,693	15.88	$ 6,957.98
Mainstem South Fork 03	floodplain	$ 4,011,217	$ 6,171,731	$ 5,091,474	19.26	$ 7,932.35
Mainstem South Fork 05	elj	$ 1,144,144	$ 1,970,720	$ 1,557,432	4.79	$ 9,751.08
Mainstem North Fork 03	elj	$ 1,112,454	$ 3,259,755	$ 2,186,105	6.43	$ 10,199.61
Mainstem South Fork 03	elj	$ 958,455	$ 2,283,127	$ 1,620,791	4.59	$ 10,596.46
Mainstem South Fork 01	rp	$ 1,889,532	$ 7,977,152	$ 4,933,342	13.35	$ 11,088.96
Canyon Creek	floodplain	$ 3,208,240	$ 5,770,549	$ 4,489,395	12.13	$ 11,105.09
Mainstem South Fork 04	elj	$ 823,120	$ 1,364,048	$ 1,093,584	2.93	$ 11,209.96
Mainstem South Fork 03	rp	$ 1,074,114	$ 4,479,265	$ 2,776,690	6.88	$ 12,113.47
Boulder River	elj	$ 828,165	$ 2,016,774	$ 1,422,470	3.32	$ 12,849.96
Mainstem North Fork 03	rp	$ 1,977,095	$ 7,587,586	$ 4,782,340	11.10	$ 12,929.05
Mainstem North Fork 02	floodplain	$ 7,215,309	$ 11,089,818	$ 9,152,563	20.33	$ 13,503.75
Squire Creek	elj	$ 2,314,802	$ 4,719,434	$ 3,517,118	6.51	$ 16,219.85
Mainstem North Fork 02	elj	$ 1,240,265	$ 3,622,732	$ 2,431,498	4.31	$ 16,930.49
Mainstem North Fork 02	rp	$ 3,342,720	$ 11,651,914	$ 7,497,317	13.08	$ 17,189.49
Mainstem South Fork 04	rp	$ 1,073,927	$ 2,928,600	$ 2,001,263	2.76	$ 21,789.03
Deer Creek	floodplain	$ 10,899,219	$ 20,106,774	$ 15,502,997	18.06	$ 25,756.87

Floodplain Restoration

Cost-effectiveness ranged from about $1,500 per spawner to over $2.1 million per spawner. These values varied considerably between subbasins, and some of the subbasins with the highest or least cost-effective ratios had minimal benefits associated with restoring floodplain. Specifically, the Mainstem Stillaguamish had a cost-effectiveness ratio of over $2.1 million more per spawner than the following highest cost-effectiveness ratio (Table 13, Figure 17). Taking out the Mainstem Stillaguamish, the average cost-effectiveness ratio for floodplain restoration was $25,345 per spawner.

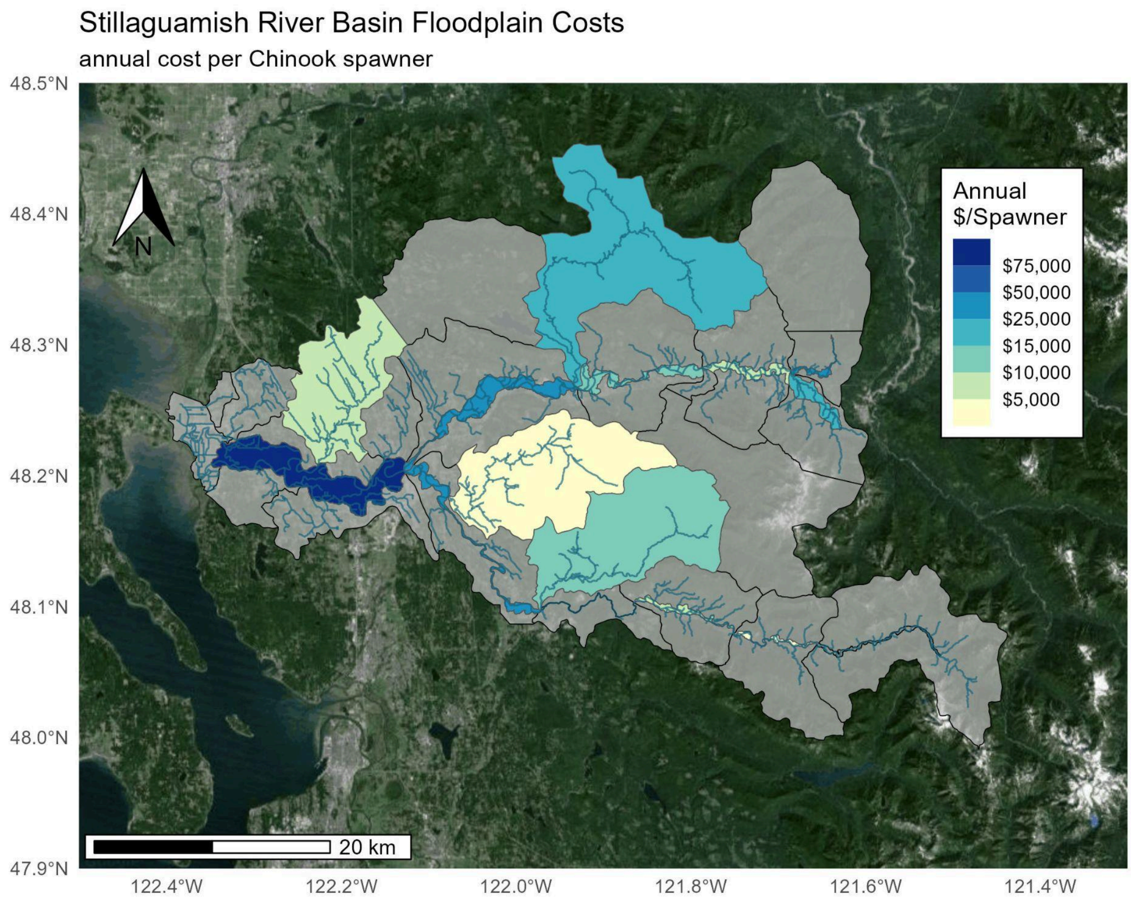

Figure 17. Cost-effectiveness ratio calculated for floodplain restoration by subbasin.

Engineered Log Jams

Cost-effectiveness ranged from about $9,800 per spawner to over $116,000 per spawner, with an average cost-effectiveness ratio of $37,363.18 per spawner. These values varied considerably between subbasins, and some subbasins with the highest or least cost-effective ratios had minimal benefits associated with ELJs (Table 14). The highest cost-effectiveness ratio was in the Mainstem North Fork 1, and the lowest was in the Mainstem South Fork 5 (Figure 18).

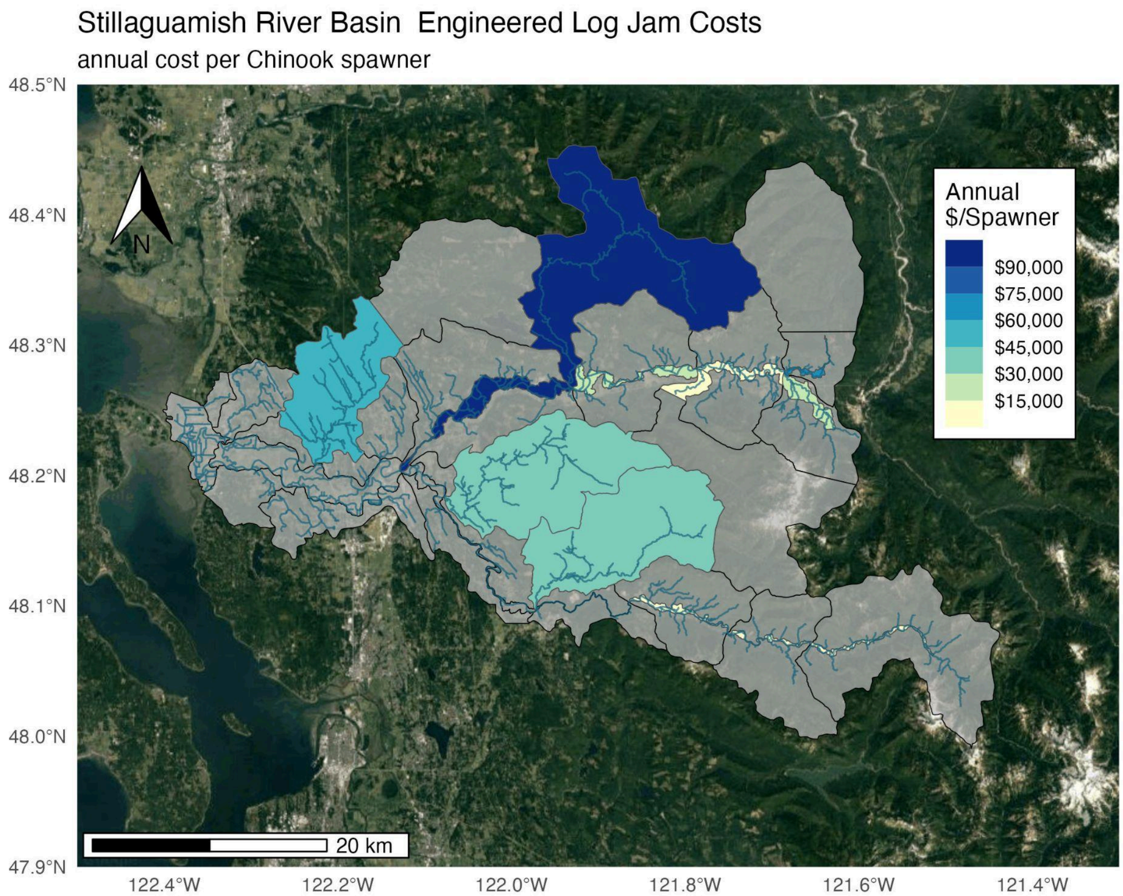

Figure 18. Cost-effectiveness ratio calculated for ELJ restoration by subbasin.

Riparian Planting

Cost-effectiveness ranged from about $11,100 per spawner to over $315,000 per spawner, with an average cost-effectiveness ratio of $9,0752.32 per spawner. These values varied considerably between subbasins, and some subbasins with the highest or least cost-effective ratios had minimal benefits associated with riparian (Table 15). For instance, Canyon Creek had the highest cost-effectiveness ratio and only would benefit about five spawners. The lowest cost-effectiveness ratio was in the Mainstem South Fork 1 (Figure 19).

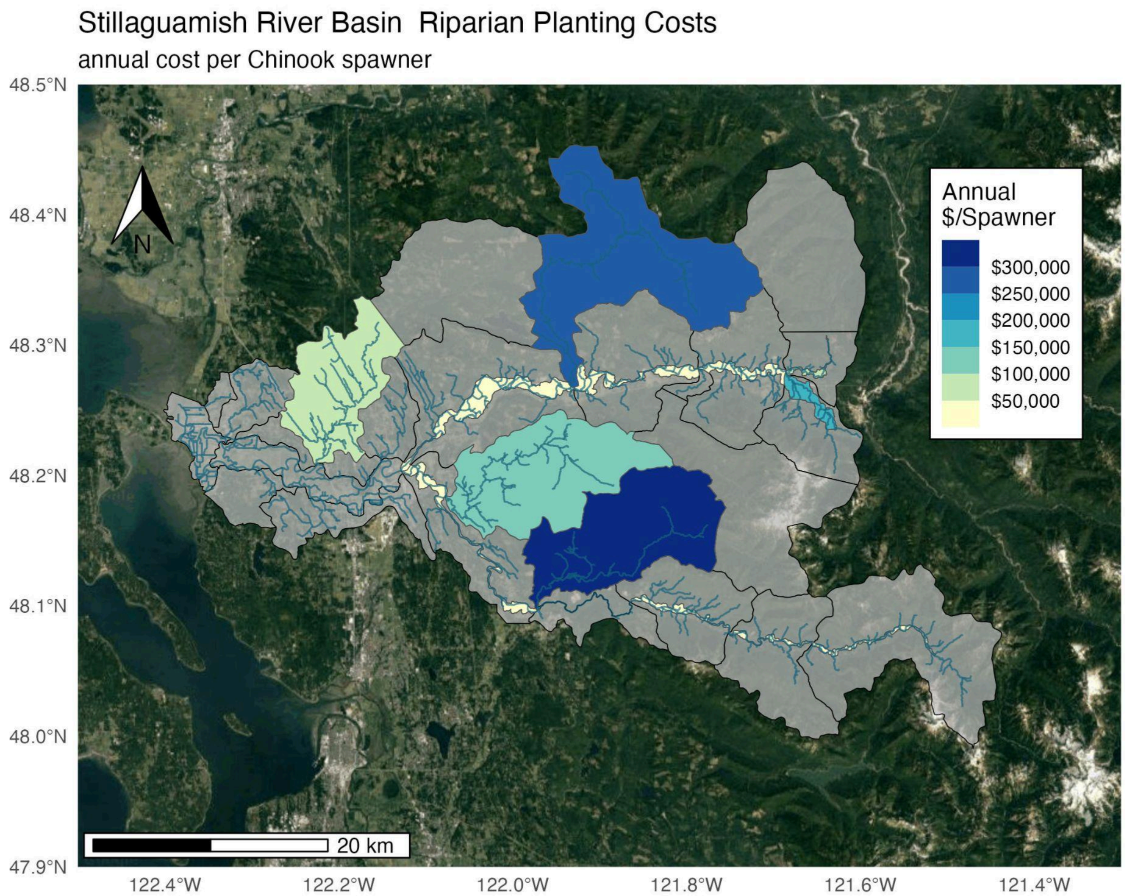

Figure 19. Cost-effectiveness ratio calculated for riparian planting restoration by subbasin.

Land Use and Costs

The primary land types in the Stillaguamish River basin include forested lands (43,944 ha), rural character residential (8,526 ha), and agricultural area (5,469 ha) (Figure 20). Although the breakdown across subbasins varies, forest lands make up the majority of Deer Creek, Jim Creek and Canyon Creek. Whereas, rural character residential also make up Jim Creek and Pilchuck Creek. The mainstem Stillaguamish and the mainstem North Fork 1 have large amounts of agricultural land relative to other areas.

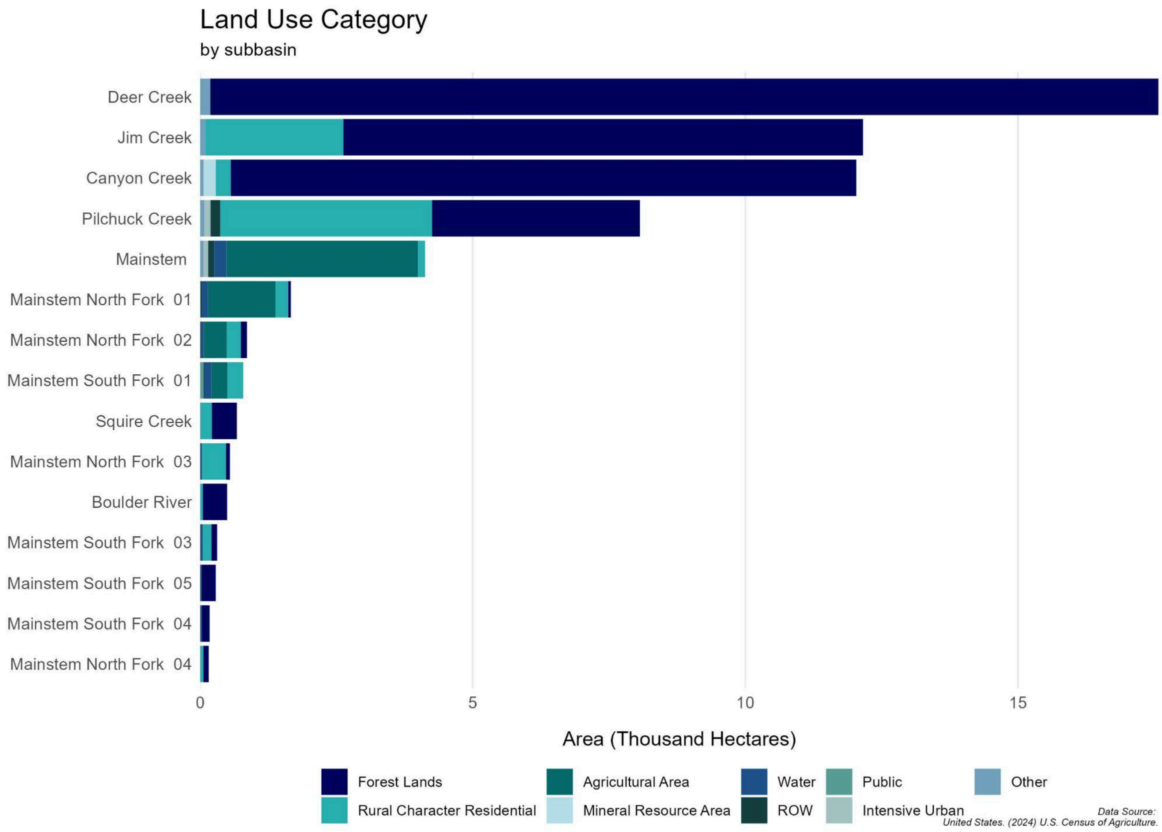

Figure 20. Subbasin land use area categorized by land type.

Additionally, we calculated the costs of agricultural land in the Stillaguamish that fell into our floodplain restoration areas since completing the restoration in most cases would require landowners to adjust their land use practices. Six subbasins that have benefits from floodplain restoration also contained agricultural land that overlapped with potential restoration areas (Figure 21). Costs for these subbasins are highest in the Mainstem Stillaguamish at over $45 million. The next most costly subbasin is the Mainstem North Fork 1 at over $12 million. We estimated that the total costs for acquiring agricultural land that contains floodplain habitat are roughly $67 million. These estimates do not include the costs of restoration.

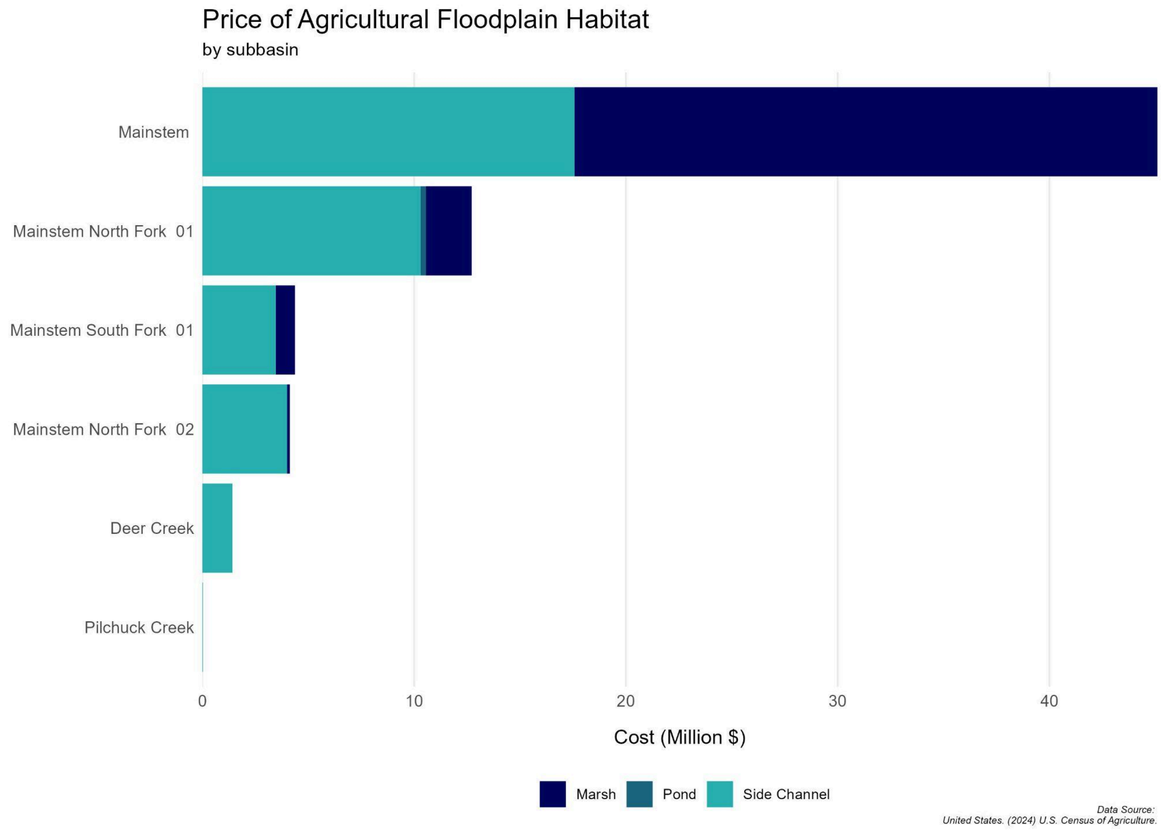

Figure 21. Cost of agricultural land overlapping with historical floodplain habitat by subbasin.

Co-Benefits to Other Salmonids

The HARP model quantifies benefits for coho salmon and steelhead trout in addition to Chinook. While the focus of our analyses was the costs and benefits of restoring Chinook habitat, the benefits of these restoration actions for other salmonids in the basin are important to consider. Restoration actions for Chinook will result in increases in spawner abundance for other salmonids with similar habitat requirements. For instance, if all subbasins in our analyses were restored to historic levels of available floodplain habitat, log jams, and shade from vegetation, then spawner abundance increases for coho would be over 13,000 spawners per year (Figure 22). Similar to Chinook, the greatest benefits to coho result from floodplain restoration. Additionally, the benefits from these restoration actions for steelhead trout can potentially result in an increase of over 600 spawners per year (Figure 23). The greatest benefits to steelhead spawners are from floodplain restoration and ELJs.

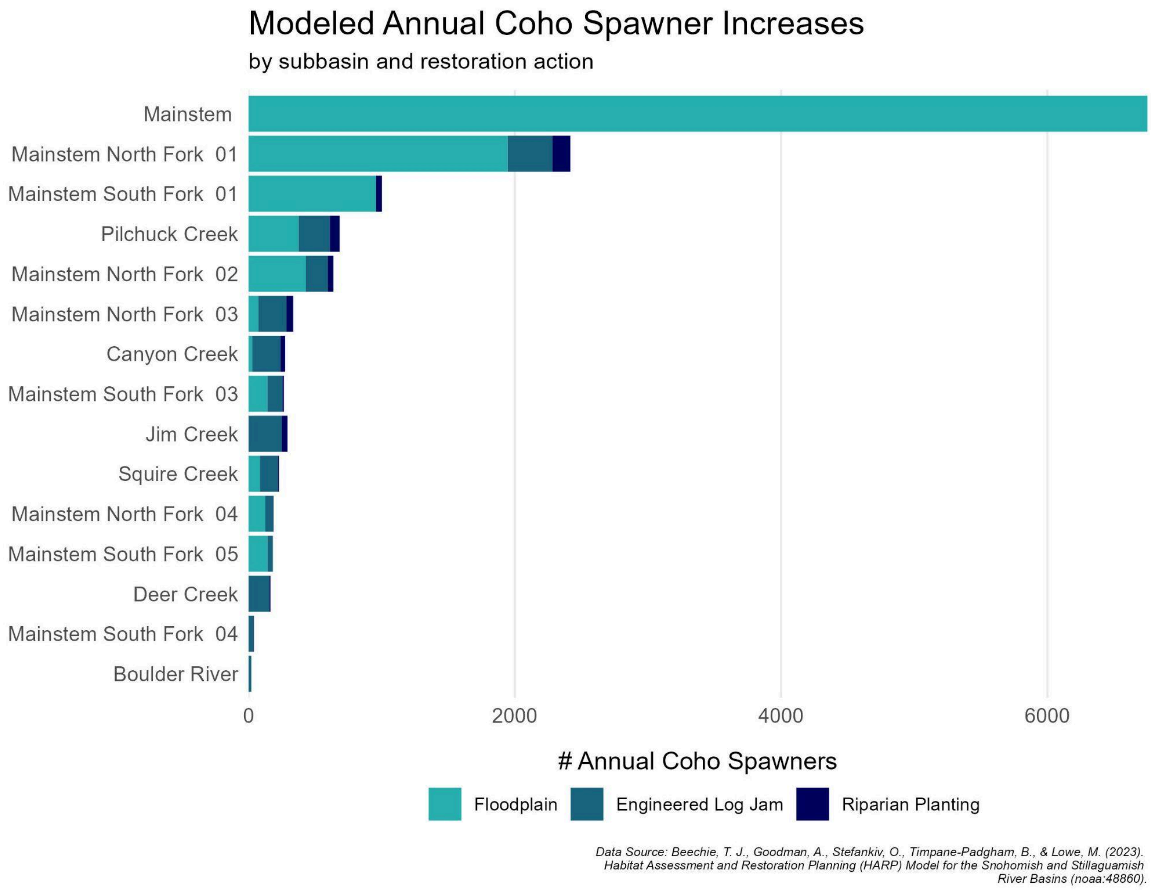

Figure 22. Increase in coho spawner abundance in Stillaguamish River subbasins by restoration type.

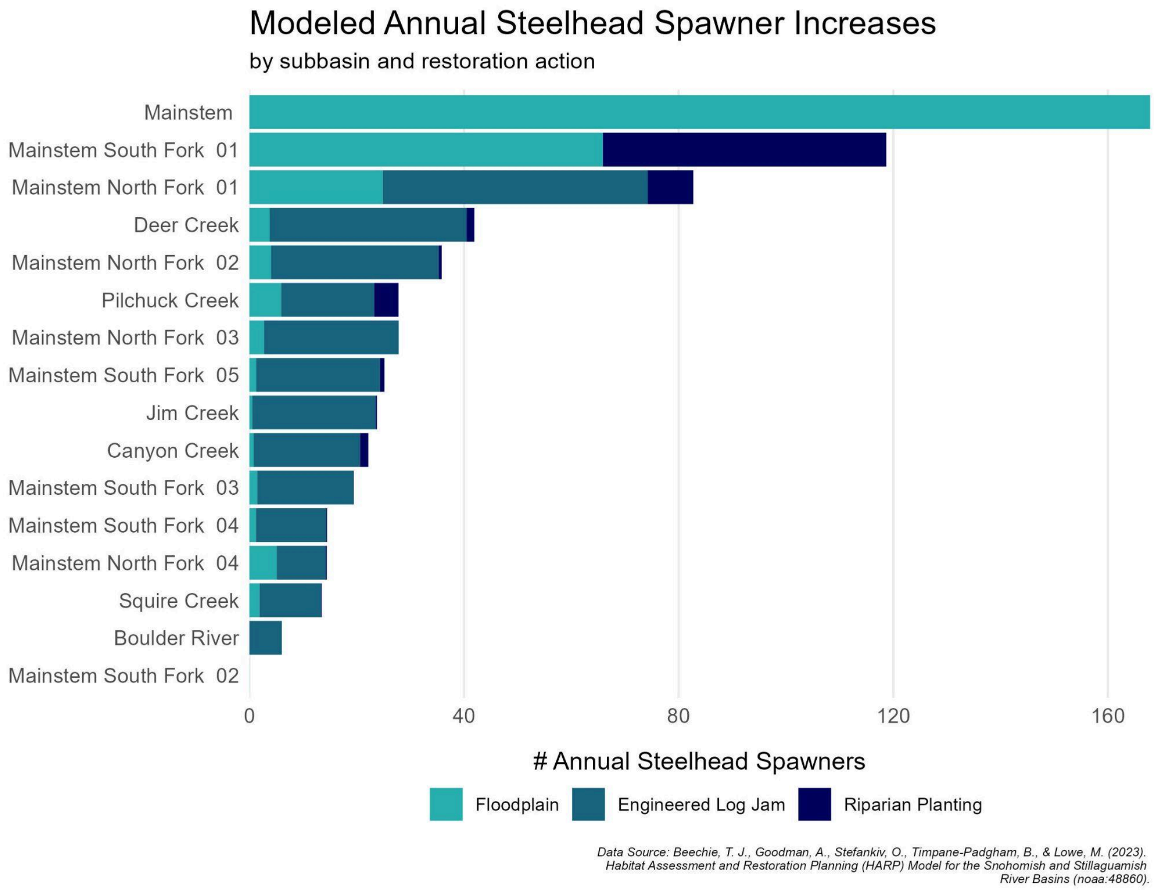

Figure 23. Increase in steelhead trout spawner abundance in Stillaguamish River subbasins by restoration type.

Demographics

The Mainstem South Fork Stillaguamish 1 has the highest demographic score of 3.13 out of the subbasins that we identified as having potential benefits from Chinook spawning habitat restoration (Figure 24). The Mainstem South Fork Stillaguamish 3 and the Mainstem North Fork Stillaguamish 1 both have the lowest demographic score of 2. None of the subbasins had a score below 2 since every subbasin contains lands under tribal ownership.

At the census tract level, all of the census tracts that overlap with the Mainstem South Fork Stillaguamish 1 had poverty rates higher than the Washington state average. Only some of the census tracts had higher unemployment rates than the Washington state average. Similarly, some of the census tracts in this subbasin had a higher percentage of people of color relative to the other subbasins in the Stillaguamish. Finally, the Mainstem South Fork Stillaguamish 1 contains lands under tribal ownership.

We set the threshold as the mean for the census tracts included in the analyses since all but one census tract had lower percentages of people of color than the Washington state average. The census tracts that overlap with Stillaguamish River subbasins were overall above both the state average unemployment and poverty. All census tracts in the area contained land under tribal ownership. Many census tracts in the Stillaguamish basin had a higher percentage of people of color than the mean for the census tracts that overlapped with restoration subbasins.

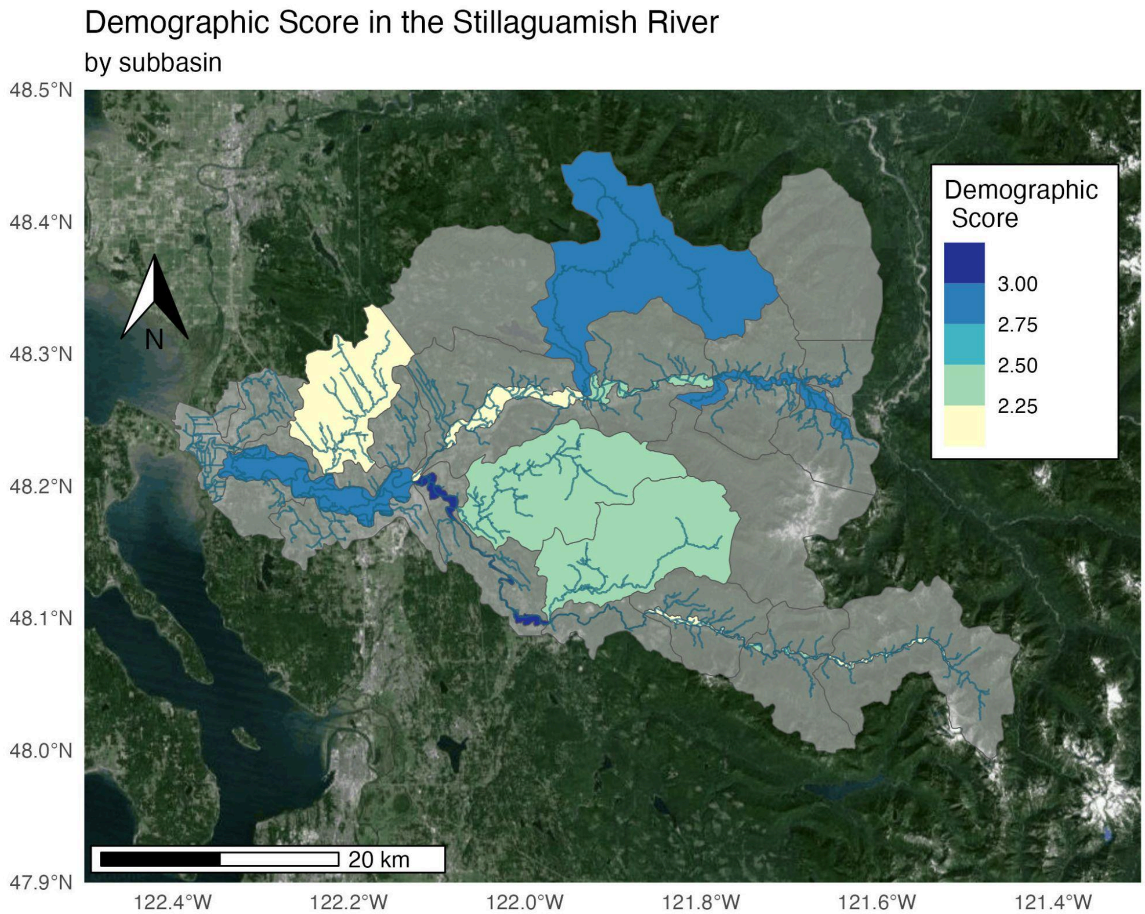

Figure 24. Demographic scores in Stillaguamish River subbasins where restoration actions are predicted to result in increased Chinook spawner abundance. Higher scores indicate census-tract-averaged subbasins that meet higher thresholds for percentage of people of color, poverty, and unemployment rates and/or lands under tribal ownership.

Discussion

Interpretation Of Results

Costs and Cost-Effectiveness

The total costs of area restored per Stillaguamish River subbasin, along with the cost-effectiveness of increasing spawner abundance, vary considerably between the three interventions that this study considers.

Floodplain restoration had the highest total costs per Chinook spawner increase, followed by riparian planting, and ELJs with the lowest total costs. Floodplain restoration costs ranged dramatically, with lower ranges between $750 thousand to $12 thousand per acre restored, and upper ranges between $220 million to $360 million. The average costs per Chinook spawner in response to floodplain restoration ranged from $28 thousand to $2.6 million per additional spawner depending on the subbasin. The average cost-effectiveness, or cost per spawner, resulting from floodplain restoration was $25,345. These cost ranges depend on location and amount of subbasin area that requires restoration. Estimates for floodplain restoration in the Stillaguamish Mainstem, for instance, range between $220 million to $360 million. When assessing the cost-effectiveness of the Mainstem Stillaguamish, it significantly surpasses that of all the other subbasins due to its high land costs and the limited outcome of restoring only four spawners. In calculating the average cost-effectiveness of floodplain restoration, this particular value was treated as an outlier and was omitted.

The costs for ELJs varied less dramatically, with lower ranges estimated at $0.82 million to $1.4 million and upper ranges from $17 million to $30 million. These estimates depend on the individual reach being restored and the complexity of the log structure that are required. Larger river sections with greater stream energy demand larger amounts of materials and more complex log structures to create the slow moving pools required for Chinook spawning habitat. Smaller streams require smaller log jams with less materials and simpler designs. Larger stream reaches with higher streamflow energy were, therefore, estimated to be more expensive than smaller ones.

Riparian planting had the second highest total costs, with lower range estimates from $1 million to $2.9 million and upper range estimates from $70 million to $110 million. Average cost-effectiveness was $9,0752.32 per spawner, ranging between $1.6 thousand and $73.4 thousand per spawner. Riparian planting restoration cost estimates were highest in Deer Creek, Jim Creek, Canyon Creek, and Pilchuck creek. These basins also received poor cost-effectiveness ratios, given that they require immense financial investment for restoration that would yield few benefits. Mainstem North Fork 3 and Mainstem South Fork 3 received the best cost-effectiveness ratios of $12.9 thousand and $12.1 thousand per spawner, indicating that they are priority sites for riparian planting restoration. It is also important to note that the number of annual increase of spawners in these subbasins remains low, with an increase of 11 spawners in Mainstem North Fork 3 and seven in Mainstem South Fork 3.

A common driver of costs for all three intervention types was location, in that it drives the other contributing factors such as stream size and velocity, or a restoration site's distance from the nearest road. The Stillaguamish subbasins that consistently represent highest costs across all three intervention types Deer Creek, Jim Creek, and Mainstem North Fork 1 (Table 7). Higher cost ranges occurred at higher, more remote elevations on the river's North and South Forks consistently across all restoration types. This consistency in cost ranges indicates how factors such as terrain and accessibility drive restoration costs. Conversely, highest costs for floodplain restoration occurred along the river's Mainstem closer to its delta. This finding represents the value of the land in that area as well as the level to which it has been degraded.

Benefits

Between the three restoration actions we considered in our analyses, floodplain restoration had the highest estimated annual increase in Chinook spawners, followed by riparian planting, and ELJs with the lowest spawner increases. If all three interventions were implemented to restore all Stillaguamish subbasins to historical conditions, the interventions would result in an increase of 401 Chinook spawners. Floodplain restoration is estimated to increase the annual Chinook spawner abundance by 211 individuals, representing 53 percent of full restoration benefits. Riparian planting would increase spawner abundance by 28 percent, representing 112 annual spawners. ELJs would increase spawner abundance by 19 percent, representing 78 additional spawners annually.

A critical consideration for restoring the Stillaguamish River basin is that restoration in the estuaries in the deltas closer to the river's mouth will yield cascading effects for increasing spawner abundance in subsequent generations. Restoration in estuarine deltas offers additional habitat for juvenile Chinook that hatch in upstream subbasins. Increasing rearing habitat for juvenile Chinook will enable more individuals to enter their adult life stage, yielding more prey for SRKW. The implications of the restoration outcomes that were not considered by our analyses, such as increasing juvenile rearing habitat, warrant deeper consideration for the benefits of Chinook habitat restoration to SRKW recovery.

Despite the challenges of connecting localized increases in Chinook spawner abundance to SRKW recovery, we can contextualize the benefits of restoring spawning habitat to the whales' recovery. In 2019, an estimated 2,167 Chinook spawners returned to the Stillaguamish river basin (Shaw, 2020). If we combine the benefits of the chosen three restoration interventions, and restore the Stillaguamish River basin to historic conditions, these efforts would potentially yield an annual increase in Chinook spawner abundance by 401. This marks a yearly 5.4 percent increase in Stillaguamish Chinook from the 2019 estimates. Each Chinook that successfully spawns, represents immense reproductive potential that would contribute to the SRKWs' prey base. The prey base can be expected to increase over time, given each spawner's contribution to the overall PS Chinook ESU.

Land Use and Costs

Land type and use are important considerations for the feasibility of successfully completing any restoration project. The three primary land types in the Stillaguamish River basin are mixed composition forests (43,944 ha), rural character residential (8,526 ha), and agricultural lands (5,469 ha). In many instances, completing large-scale restoration projects in residential areas is not viable because it would necessitate residents to relocate.

However, potential exists to collaborate with property owners for restoring habitat on their land. The restoration of Johnson Creek in Portland, OR is an example of collaborative restoration with landowners. The Johnson Creek project is aimed at mitigating flood risks while restoring freshwater salmon habitat (C. Jordan, NOAA NWFSC, personal communication, March 11, 2024).

Additionally, wide scale floodplain restoration projects have been implemented across the PNW region, primarily at large scales on National Forest Service land (Flitcroft et al., 2022). Several floodplain and other freshwater restoration projects have already been completed or are underway within Mt. Baker-Snoqualmie National Forest, where most of the forested land in the Stillaguamish River basin occurs (USDA Forest Service, 2024). We assume that restoration feasibility and permitting costs on Forest Service land will be negligible and do not include those costs in this study.

Twenty-two percent of the privately owned agricultural land in the Stillaguamish River basin overlaps with historical marsh, pond, and side channel floodplain habitat. This poses an additional cost for floodplain habitat restoration as this land would either have to be purchased, leased, or land owners would have to be compensated for the restoration of this land back into floodplain habitat. We estimated that this level of land acquisition would add approximately $67 million to the initial restoration costs (Figure 21). Collaboration with landowners can be considered a more cost-effective alternative in the event that landowners are unwilling to sell their land or relocate.

Demographics

Considerations for how restoration actions benefit or impact the lives of the people living in restoration areas is as important to the process as assessing costs and benefits to SRKW. Recovering salmon fisheries through habitat restoration has the potential to increase industries such as tourism or recreational and commercial fishing in the area. However, short term impacts for local residents may include restricted access to restoration areas and the recreation opportunities those areas might provide.

Many large restoration grants are specifically aimed at advancing the welfare and climate resilience of underserved communities (NMFS, 2024). These include grants from non-government organizations, local governments, and federal agencies like NOAA, who provide Coastal Habitat Restoration and Resilience Grants for Tribes and Underserved Communities. In 2023, for example, the State of Washington Department of Ecology awarded the Stillaguamish Tribe of Indians $8.8 million from the Floodplains by Design grant. These funds are directed toward improving the quality of life for individuals living within the Stillaguamish River basin through floodplain restoration that supports both Chinook salmon recovery and stormwater retention for tribal members living in the area (Washington State Department of Ecology, 2024).

In our analysis of how restoration projects in the Stillaguamish River basin might overlap with underserved communities we found the Mainstem South Fork 1 has the highest demographic score in addition to the subbasin's high cost-effectiveness for floodplain restoration and riparian planting.. ELJs were not projected to increase the number of Chinook spawners in this subbasin. In terms of overall restoration costs, the Mainstem South Fork 1 had the third highest cost range compared to other subbasins, at $36 million to $56 million for floodplain restoration. The cost range for riparian planting was on the lower end of the range, with estimates ranging from $2 million to $8 million. The increased number of Chinook spawners resulting from the restoration of South Fork Stillaguamish 1 for all three restoration types is 32 spawners. The relatively high cost-effectiveness, varying costs, average benefits and high demographic score demonstrate how decision makers might distribute restoration funding to the best benefit of people living in restoration areas.

Implications

Costs

While the total cost estimates by subbasin appear high, it is important to consider that these costs represent each subbasin returning to its historical conditions. However, restoration of the entire basin is a costly and extensive process that is often not possible or needed at that extent to reasonably increase abundance. Restoration on this scale would potentially take decades to complete and would not immediately yield significant increases in Chinook spawner abundance (NMFS, 2020).

The high costs of restoration become more manageable when considering the actual scale of localized restoration projects. Restoration practitioners can utilize the varying cost per acre for floodplain restoration (Table 10) and riparian planting (Figure 14), as well as the cost per mile or structure for ELJs (Figure 13), to gain a clearer understanding of the project costs beyond the scope of restoring the entire subbasin. Additionally, most of the historic floodplain habitat in the Mainstem Stillaguamish overlaps with residential and agricultural land, making restoration difficult and prohibitively expensive in this subbasin.

Since costs are discounted over time, long term benefits may outweigh short term investments in restoration. In conducting our analyses, we relied on cost estimates generated in 2003. It is essential to acknowledge that while we adjusted these figures using the producer price index to align with 2023 values, historical costs may not fully capture current expenses. Nevertheless, our thorough investigation revealed no compelling evidence indicating significant alterations in the primary cost drivers since the initial estimation.

Additional costs that were not unaccounted for in our analyses may include long-term maintenance of restoration sites, initial disturbances to and resistance from community members living in restoration areas, and economic opportunities that are lost from agriculture, timber harvest, and residential development.

Cost-Effectiveness

Cost-effectiveness ratios provide insights into the success of a restoration action, indicating the investment that is required to increase spawner abundance by a single individual. Producing cost-effectiveness ratios is important for informing funding distribution, given the high variability of costs per restoration action, location, and increased spawner abundance. The cost-effectiveness estimates from our analyses are generally low, indicating high costs that are required to increase spawner abundance by one individual. This low cost-effectiveness is due in part to our estimates for annual increase in Chinook spawner abundance are solely based on the estimates for the first year following a restoration action's completion. We used the value for the first year's spawner abundance increase as a conservative estimate of the future increases. This estimate does not account for how spawner abundance will continue to increase in subsequent years.

The HARP model outputs, moreover, do not account for fluctuations in population dynamics such as stochastic events, or future changes in environmental conditions and restoration costs, or population changes in other subsets of the PS Chinook ESU. They also do not account for implications of climate change such as rising stream temperature, or peak streamflow fluctuations resulting from flooding or reduced snowpack. These factors may affect spawner abundance following restoration, which in turn, may impact cost-effectiveness.

Benefits

Annual increases in spawner abundance are predictions and not guaranteed results of restoration. While the estimated increase in spawner abundance estimates presented only reflect one year, we recognize that benefits accumulate exponentially as initial spawners reproduce, leading to a continual rise in spawner abundance in subsequent years.

Across the restoration actions analyzed, floodplain restoration had the greatest potential to increase Chinook spawner abundance. Further, HARP model outputs estimate that floodplain restoration would also yield substantial benefits for coho salmon and steelhead trout spawner abundance. Additionally, 86 percent of common terrestrial and freshwater wildlife species in the Pacific Northwest utilize riparian areas, wetlands, and streams seasonally or for part of their life cycle, highlighting the broader benefits of restoring salmonid freshwater habitat (Shared Strategy Development Committee, 2007). This restoration not only supports commercial and recreational fisheries but also enhances the landscape's climate resilience. Given the limited fisheries stocks in the Stillaguamish River basin, increasing the Chinook population may contribute to higher catch limits in Washington. Floodplain habitat restoration can also increase species richness of terrestrial plants, leading to benefits such as bank stability, decreased erosion, and more diverse ecological communities (Mouw et al., 2009). These additional restoration benefits underscore the importance of considering the holistic impacts when implementing floodplain habitat restoration, distinct from benefits associated with ELJs or riparian planting, both of which are encompassed by floodplain restoration's broader co-benefits.

Moreover, within the spectrum of floodplain restoration strategies, Stage 0 restoration, coined by Cluer and Thorne, represents a comprehensive approach aimed at restoring entire floodplain habitats (2014). Stage 0 restoration is a process-based, valley-wide restoration approach that targets restoring an entire floodplain habitat as opposed to approaching restoration through smaller projects that focus on portions of a floodplain. Stage 0 restoration includes restoring floodplains to a "predisturb[ed], dynamically meta-stable network of anabranching channels and floodplain with vegetated islands supporting wet woodland or grassland." Stage 0 restoration essentially involves restoring a habitat, often a valley within a river basin, in its entirety to its historical condition. The proposed outcome aims to provide more ecological benefits than traditional, piecemeal restoration actions (Cluer & Thorne, 2014; Flitcroft et al., 2022). While this strategy has not been implemented on a broadscale, where it has been applied has shown improvement in processes like introducing fine sediment, wood loading, and regulating water temperature to varying degrees in select areas (Flitcroft et al., 2022).

As our analyses suggest, it is important to note that a complete Stage 0 restoration of a floodplain like the Stillaguamish Mainstem is likely infeasible due to the levels of development and private property that occur along that river segment. This conclusion, however, does not rule out the effectiveness of piecemeal floodplain restoration in the Stillaguamish Mainstem.

Additionally, it is crucial to acknowledge the time frame involved in riparian planting initiatives, as the benefits, such as increased shade and habitat enhancement, emerge gradually over decades, contrasting with the relatively faster impacts of floodplain restoration and ELJs. Trees that are planted take years to reach their full height and provide the river with shade. This means spawners are unlikely to respond right away. Existing estimates suggest that the effects of shading may take approximately 25 years following revegetation. This estimate accounts for the time that planted trees require to reach heights that provide the necessary shade to regulate stream temperature (Justice et al., 2017). Most shading benefits, however, typically manifest around 75 years post-planting (Justice et al., 2017). Considering the urgency of SRKW recovery, and recognizing that the impacts of floodplain restoration and ELJs materialize relatively quickly, we do not advocate prioritizing riparian planting to address SRKW recovery.

Limitations

Cost-Effectiveness

When calculating the cost-effectiveness ratio for each restoration action, we assumed that the interventions would have infinite life spans while discounting, but this is not the case for ELJs. ELJs have wide ranging lifespans that depend on river conditions such as structure type and channel morphology (Roni et al., 2015). Long term ELJ monitoring is, furthermore, not robust enough to draw conclusions about their average lifespan, with some cases lasting only one year and others persisting for over 60 years (Roni et al., 2015).

Benefits

Our results interpretation is constrained by our use of the HARP model. It is crucial to acknowledge that the HARP model was not built to estimate increases in spawner abundance of less than 10 individuals within fine spatial resolutions. Given this design focus, many of the estimates generated for individual restoration actions within specific subbasins fall below the model's intended threshold. Consequently, determining the precise number of increased spawners becomes challenging, leading to inherent imprecision in our findings. Additionally, the HARP model considers floodplain restoration, ELJs, and riparian planting interventions independently; the impacts are not cumulative or multiplicative (Beechie et al., 2023).

Furthermore, our ability to apply the results is hampered by the temporal limitations of the HARP model. Specifically, the outputs we used in our analyses were designed to estimate increased spawner abundance only within the initial year following spawning habitat restoration. An important consideration, however, is that the effects of floodplain restoration, ELJs, and riparian planting unfold over distinct timeframes. Floodplain restoration and ELJs typically yield immediate improvements, leading to an increase in spawner abundance shortly after completion (Tabor et al., 2022). Conversely, the benefits associated with riparian planting take much longer to materialize. These variations in temporal dynamics underscore the complexity of accurately assessing restoration impacts on spawner abundance.

In sum, the HARP model outputs we produced lack the capability to quantitatively account for temporal variability. While the estimates account for initial increase in spawner abundance that recur annually, the benefits of increasing spawner abundance will likely compound over time, yielding further increases in spawner abundance. The HARP model's outputs, instead, primarily focus on assessing the effects of restoring specific environmental conditions within a river basin. Our methodology operates under the assumption that spawner abundance will follow a similar trajectory in subsequent years as observed in the initial period. Although stochastic fluctuations may introduce variations in population dynamics, our approach enables us to provide a conservative estimate of the enhanced spawner abundance that is attributable to restoration interventions.

This assumption also means that our analyses do not consider the impacts that initial spawning events have on the abundance of future generations of Chinook. While some adult Chinook will survive the open ocean and complete their lifecycle, others will contribute to the SRKW prey base, as well as commercial fisheries harvest. These predictions do not account for the fate of offspring in years following spawning events. These caveats prevent us from predicting the number of Chinook that will become available to SRKW as a result of spawning restoration action.

Application Of Findings

Analyses from the HARP model and the findings of our report are intended to inform funding distribution for Chinook habitat restoration in the Stillaguamish River basin. The HARP model's outputs ultimately provide insights as to where restoration spending will result in increased spawner abundance. With the appropriate available data, the model may be applied to other watersheds in the Puget Sound to more accurately assess how to prioritize restoration funding (Beechie et al., 2023). These analyses can be incorporated into funding decisions directed toward SRKW recovery. Insights from the HARP model may be applied to the numerous entities that fund PS Chinook recovery.

Our cost-effectiveness analyses can be incorporated into essential fish habitat (EFH) consultations that are mandated by the Magnuson-Stevens Fisheries and Conservation Act (16 U.S.C. §§ 1801 et seq.). Under the Magnuson-Stevens Act (MSA), government agencies must consult with the NMFS to assess how fisheries management practices, including restoration and government funding distributions, impact EFH. If an intervention or management strategy influences EFH, then NMFS is responsible for recommending conservation actions. Our insights may be used to make targeted EFH conservation recommendations under the MSA mandate that optimize costs, cost-effectiveness, and increased spawner abundance.

NOAA's Pacific Coastal Salmon Recovery Fund (PCSRF), directs $106 million from the Bipartisan Infrastructure Law (BIL) and the Inflation Reduction Act (IRA) for a diversity of pacific salmonid recovery projects (NMFS, 2023). NOAA's Coastal Habitat Restoration and Resilience Grants for Tribes and Underserved Communities similarly directs $45 million from the Bipartisan Infrastructure Law and Inflation Reduction Act for coastal and floodplain restoration, which can be utilized by peoples like the Stillaguamish Tribe to restore Chinook habitat. Our analyses can assist NOAA in strategizing how these funds are disbursed to optimize Chinook recovery.

Recommendations

The predicted increases in Chinook spawner abundance in the Stillaguamish are low relative to the nutritional needs of SRKW. Therefore, it is not recommended to focus Chinook habitat restoration efforts in the Stillaguamish river basin if the sole goal is to increase prey availability for the SRKW, and NMFS should consider prioritizing restoration in other basins in which the increased spawner abundance from restoration would be higher to optimize the number of Chinook for SRKW. This entails directing attention towards Chinook populations with larger run sizes, ensuring that restoration efforts yield a significant increase in the number of individuals, even if the impact is a relatively small percentage rise in relation to the total population. However, this does not denounce the necessity to restore habitat in the Stillaguamish river basin when considering the poor conditions of Chinook and other salmonid populations.

Restoration efforts aimed at Stillaguamish Chinook salmon alone may not significantly benefit SRKW. However, habitat restoration will still play a crucial role in restoring the most depleted Puget Sound ESU population and sustaining hatchery populations, among other co-benefits such as increased ecosystem function and services. Restoration interventions must be chosen strategically to ensure higher prey availability for lower costs as time and resources are both limited. Furthermore, restoration types should first consider the ecological needs of the subbasin when comparing interventions to ensure underlying issues are addressed. While project costs and spawner recruitment varied by restoration action and location, floodplain restoration would relatively be the most cost-effective intervention.

Floodplain habitat restoration is predicted to be the most cost-effective strategy to increase Chinook spawner abundances within the Stillaguamish and should be prioritized. Specifically, floodplain restoration in the subbasins in the mainstem of the Stillaguamish have high potential to act as rearing habitat for out-migrating juveniles from all upstream subbasins. When juveniles have more rearing habitat, then more of them survive to become spawners in the next generation. This effectively increases the benefits in the next year.

Both the Mainstem North Fork 1 and Mainstem South Fork 1 are prime candidates for floodplain restoration due to the significant advantages associated with restoring floodplains in subbasins that serve as pathways for juvenile salmon en route to the ocean. Despite the low cost-effectiveness of these subbasins relative to others, they also offer some of the most substantial benefits immediately following restoration completion for Chinook and other species of salmonids. Moreover, the Mainstem South Fork 1 yielded the highest demographic score among all Stillaguamish subbasins, suggesting it could be an ideal target for grants aimed at serving marginalized communities. It is crucial to engage in collaborative efforts with tribes and local conservation organizations familiar with the area's social and ecological dynamics. Given that floodplain habitats in both subbasins coincide with agricultural land, we suggest collaborating with landowners to facilitate restoration without the necessity of purchasing their land, which would entail significant costs.

Prioritizing restoration actions such as implementing ELJs or riparian planting is likely a short term or incomplete solution to a much longer term problem. Unlike floodplain restoration, these actions typically yield lower benefits and are also less cost-effective on average. ELJs represent temporary solutions that necessitate significant long term maintenance to maintain structures. They degrade over time and do not contribute to a mechanism that invests in long term rehabilitation of habitat such as floodplain restoration. Additionally, the increase in spawner abundance resulting from riparian planting would be delayed due to the long time frames required for trees to reach heights that significantly impact water temperature, thus making the habitat more favorable for spawners. Floodplain habitat not only is estimated to have the highest impact on Chinook spawners, but it also contributes to a more permanent, long term solution compared to the other two options.

Conclusion

Prioritizing economic cost-effectiveness and predicted population growth can be a beneficial tool in the planning stage of prey recovery projects. As life cycle models become more common for determining which habitat scenarios would best aid salmon recruitment, it is important to combine these ecological considerations with restoration costs, land use, and population demographics to comprehensively weigh intervention scenarios. It is also important to note that the way that we defined benefits highly influenced the recommendations we made.

Here, we have provided a framework for identifying cost-effective interventions for Chinook salmon in the Stillaguamish river basin. Habitat restoration in the Stillaguamish river basin is demonstrated to increase Chinook stocks and support multi-agency efforts for SRKW population recovery. However, increasing Chinook salmon populations is a lengthy and expensive process. Many projects are unsuccessful partially due to inadequate monitoring, which records changes in population growth and sustains progress over time (Bilby et al. 2023). In a similar aspect, it may take over a decade to observe meaningful responses to restoration. Therefore, we recommend long-term monitoring of implemented projects to better understand population outputs over time.

We emphasize economic costs and benefits to the focal species to help restorationists prioritize and justify restoration costs for funding opportunities. However, there are additional costs and benefits unaccounted for in the final cost-effectiveness estimates including increases in other salmonid populations, restored ecosystem function, and additional ecosystem services. Considering indirect outcomes and mitigating negative impacts could strengthen project justifications for federal funders, the Stillaguamish river basin community, and other stakeholders, especially with federal grants increasingly requiring environmental justice considerations.

Promoting prey availability through habitat restoration alone is not enough to revive the SRKW population. For Chinook salmon, strategies that sustain Chinook populations in the marine life stage, in other key regions, and against other stressors should also be maintained. For SRKW, NMFS should continue to minimize vessel disturbances and contamination, along with research, outreach, and community coordination. With opportunities to implement our framework for consultations and grants, these considerations should improve project output success and move SRKW recovery forward.

Citations

Abbe, T. B., Hrachovec, M., & Winter, S. (2018). *Engineered Log Jams: Recent Developments in Their Design and Placement, with examples from the Pacific Northwest, U.S.A.* https://api.semanticscholar.org/CorpusID:133785425

Alava, J. J., Ross, P. S., & Gobas, F. A. P. C. (2016). Food Web Bioaccumulation Model for Resident Killer Whales from the Northeastern Pacific Ocean as a Tool for the Derivation of PBDE-Sediment Quality Guidelines. *Archives of Environmental Contamination and Toxicology*, *70*(1), 155–168. https://doi.org/10.1007/s00244-015-0215-y

Ayres, K. L., Booth, R. K., Hempelmann, J. A., Koski, K. L., Emmons, C. K., Baird, R. W., Balcomb-Bartok, K., Hanson, M. B., Ford, M. J., & Wasser, S. K. (2012). Distinguishing the Impacts of Inadequate Prey and Vessel Traffic on an Endangered Killer Whale (Orcinus orca) Population. *PLoS ONE*, *7*(6), e36842. https://doi.org/10.1371/journal.pone.0036842

Barnas, K. A., Katz, S. L., Hamm, D., & Diaz, M. C. (2015). Is habitat restoration targeting relevant ecological needs for endangered species? Using Pacific Salmon as a case study. *Wiley*. https://doi.org/10.1890/ES14-00466.1

Beechie, T. J., Goodman, A., Stefankiv, O., Timpane-Padgham, B., & Lowe, M. (2023). *Habitat Assessment and Restoration Planning (HARP) Model for the Snohomish and Stillaguamish River Basins* (noaa:48860). https://doi.org/10.25923/v2mt-nj66

Bigg, M. A., Olesiuk, P., Ellis, G. M., Ford, J., & III, K. C. (1990). Organization and genealogy of resident killer whales (Orcinus orca) in the coastal waters of British Columbia and Washington State. *Report - International Whaling Commission, Special Issue*, *12*, 383–405.

Bilby, R. E., Currents, K. P., Fresh, K. L., Booth, D. B., Fuerstenberg, R. R., & Lucchetti, G. L. (2023). Why Aren't Salmon Responding to Habitat Restoration in the Pacific Northwest? *American Fisheries Society*. https://doi.org/10.1002/fsh.10991

Cauvel, K. (2023, October 13). *Restoration effort is decolonizing the Stillaguamish delta*. Northwest Treaty Tribes. https://nwtreatytribes.org/restoration-effort-is-decolonizing-the-stillaguamish-delta/

Center for Whale Research. (2023, September). *Southern Resident Orca (SRKW) Population*. https://www.whaleresearch.com/orca-population

Cluer, B., & Thorne, C. (2014). A Stream Evolution Model Integrating Habitat and Ecosystem Benefits. *River Research and Applications*, *30*(2), 135–154. https://doi.org/10.1002/rra.2631

Columbia River Inter-Tribal Fish Commission. (2021). *We are all Salmon People*. https://critfc.org/salmon-culture/we-are-all-salmon-people/

Couture, F., Oldford, G., Christensen, V., Barrett-Lennard, L., & Walters, C. (2022). Requirements and availability of prey for northeastern pacific southern resident killer whales. *PLOS ONE*, *17*(6), e0270523. https://doi.org/10.1371/journal.pone.0270523

Duda, J. J., Torgersen, C. E., Brenkman, S. J., Peters, R. J., Sutton, K. T., Connor, H. A., Kennedy, P., Corbett, S. C., Welty, E. Z., Geffre, A., Geffre, J., Crain, P., Shreffler, D., McMillan, J. R., McHenry, M., & Pess, G. R. (2021). Reconnecting the Elwha River: Spatial Patterns of Fish Response to Dam Removal. *Frontiers in Ecology and Evolution*, *9*, 765488. https://doi.org/10.3389/fevo.2021.765488

Flitcroft, R. L., Brignon, W. R., Staab, B., Bellmore, J. R., Burnett, J., Burns, P., Cluer, B., Giannico, G., Helstab, J. M., Jennings, J., Mayes, C., Mazzacano, C., Mork, L., Meyer, K., Munyon, J., Penaluna, B. E., Powers, P., Scott, D. N., & Wondzell, S. M. (2022). Rehabilitating Valley Floors to a Stage 0 Condition: A Synthesis of Opening Outcomes. *Frontiers in Environmental Science*, *10*. https://doi.org/10.3389/fenvs.2022.892268

Fogel, C. B., Nicol, C. L., Jorgensen, J. C., Beechie, T. J., Timpane-Padgham, B., Kiffney, P., Seixas, G., & Winkowski, J. (2022). How riparian and floodplain restoration modify the effects of increasing temperature on adult salmon spawner abundance in the Chehalis River, WA. *PLOS ONE*, *17*(6), e0268813. https://doi.org/10.1371/journal.pone.0268813

Ford, J. K. B., Ellis, G. M., & Olesiuk, P. F. (2005). *Disponibilité des proies et dynamique des populations: Est-ce que la limitation des ressources alimentaires a pu causer les diminutions récentes des épaulards « résidants » (Orcinus orca) en Colombie-Britannique?*

Hall, J. E., Greene, C. M., Stefankiv, O., Anderson, J. H., Timpane-Padgham, B., Beechie, T. J., & Pess, G. R. (2018). *Large river habitat complexity and productivity of Puget Sound Chinook salmon*. https://doi.org/10.1371/journal.pone.0205127

Hanson, M. B., Emmons, C. K., Ford, M. J., Everett, M., Parsons, K., Park, L. K., Hempelmann, J., Doornik, D. M. V., Schorr, G. S., Jacobsen, J. K., Sears, M. F., Sears, M. S., Sneva, J. G., Baird, R. W., & Barre, L. (2021). Endangered predators and endangered prey: Seasonal diet of Southern Resident killer whales. *PLOS ONE*, *16*(3), e0247031. https://doi.org/10.1371/journal.pone.0247031

Haraguchi, K., Hisamichi, Y., & Endo, T. (2009). Accumulation and mother-to-calf transfer of anthropogenic and natural organohalogens in killer whales (Orcinus orca) stranded on the Pacific coast of Japan. *Science of The Total Environment*, *407*(8), 2853–2859. https://doi.org/10.1016/j.scitotenv.2009.01.003

Hauser, D., Logsdon, M., Holmes, E., VanBlaricom, G., & Osborne, R. (2007). Summer distribution patterns of southern resident killer whales Orcinus orca: Core areas and spatial segregation of social groups. *Marine Ecology Progress Series*, *351*, 301–310. https://doi.org/10.3354/meps07117

Healey, M. C. (1991). Life history of chinook salmon (Oncorhynchus tshawytscha). *Pacific*

Salmon Life Histories, 311–394.

Honea, J. M., Jorgensen, J. C., McCLURE, M. M., Cooney, T. D., Engie, K., Holzer, D. M., & Hilborn, R. (2009). Evaluating habitat effects on population status: Influence of habitat restoration on spring-run Chinook salmon. *Freshwater Biology*, *54*(7), 1576–1592. https://doi.org/10.1111/j.1365-2427.2009.02208.x

Jorgensen, J. C., Nicol, C., Fogel, C., & Beechie, T. J. (2021). Identifying the potential of anadromous salmonid habitat restoration with life cycle models. *PLOS ONE*, *16*(9), e0256792. https://doi.org/10.1371/journal.pone.0256792

Justice, C., White, S. M., McCullough, D. A., Graves, D. S., & Blanchard, M. R. (2017). Can stream and riparian restoration offset climate change impacts to salmon populations? *Journal of Environmental Management*, *188*, 212–227. https://doi.org/10.1016/j.jenvman.2016.12.005

Krahn, M. M., Wade, P. R., Kalinowski, S. T., Dahlheim, M. E., Taylor, B. L., Hanson, M. B., Ylitalo, G. M., Angliss, R. P., Stein, J. E., & Waples, R. S. (2022). *Status Review of Southern Resident Killer Whales (Orcinus orca) under the Endangered Species Act*.

Lacy, R. C., Williams, R., Ashe, E., Balcomb Iii, K. C., Brent, L. J. N., Clark, C. W., Croft, D. P., Giles, D. A., MacDuffee, M., & Paquet, P. C. (2017). Evaluating anthropogenic threats to endangered killer whales to inform effective recovery plans. *Scientific Reports*, *7*(1), 14119. https://doi.org/10.1038/s41598-017-14471-0

Mongillo, T., Holmes, E., Noren, D., VanBlaricom, G., Punt, A., O'Neill, S., Ylitalo, G., Hanson, M., & Ross, P. (2012). Predicted polybrominated diphenyl ether (PBDE) and polychlorinated biphenyl (PCB) accumulation in southern resident killer whales. *Marine Ecology Progress Series*, *453*, 263–277. https://doi.org/10.3354/meps09658

Mouw, J. E. B., Stanford, J. A., & Alaback, P. B. (2009). Influences of flooding and hyporheic exchange on floodplain plant richness and productivity. *River Research and Applications*, *25*(8), 929.

National Park Service. (2022). *Riparian Zones—It's all about the Water*.

Nelson, B. W., Shelton, A. O., Anderson, J. H., Ford, M. J., & Ward, E. J. (2019). Ecological implications of changing hatchery practices for Chinook salmon in the Salish Sea. *Ecosphere*, *10*(11), e02922. https://doi.org/10.1002/ecs2.2922

Nisqually River Council. (2016). *Yil-Me-Hu Winter 2015/2016*. https://www.slideshare.net/Nisqually/yilmehu-winter-20152016

NMFS. (2008). *Recovery plan for southern resident killer whales (Orcinus orca)*. https://repository.library.noaa.gov/view/noaa/15975

NMFS. (2017). *2016 5-Year Review: Summary & Evaluation of Puget Sound Chinook Salmon Hood Canal Summer-run Chum Salmon Puget Sound Steelhead*. https://repository.library.noaa.gov/view/noaa/17015

NMFS. (2020, February 14). *Southern Resident Killer Whale Priority Chinook Salmon Stocks—Questions and Answers*. https://www.fisheries.noaa.gov/west-coast/endangered-species-conservation/southern-resident-killer-whale-priority-chinook-salmon#q:-why-is-this-list-of-priority-chinook-salmon-stocks-important?

NMFS. (2021a). *Southern Resident Killer Whales (Orcinus orca) 5-Year Review: Summary and Evaluation*. https://media.fisheries.noaa.gov/2022-01/srkw-5-year-review-2021.pdf

NMFS. (2021b). *Species in the Spotlight Priority Actions 2021-2025—Southern Resident Killer Whale*.

NMFS. (2023). *NOAA Fisheries Recommends $106.1 Million in NOAA Pacific Coastal Salmon Recovery Funding to Protect and Restore West Coast Salmon and Steelhead*. https://www.fisheries.noaa.gov/feature-story/noaa-fisheries-recommends-1061-million-noaa-pacific-coastal-salmon-recovery-funding#:~:text=In%20fiscal%20year%202023%2C%20we,salmon%20recovery%20programs%20and%20projects.

NMFS, N. (2024, February 26). *Coastal Habitat Restoration and Resilience Grants for Underserved Communities Selected for Funding | NOAA Fisheries* (National). NOAA. https://www.fisheries.noaa.gov/national/habitat-conservation/coastal-habitat-restoration-and-resilience-grants-underserved

NMFS, & WDFW. (2018). *Southern Resident Killer Whale Priority Chinook Stocks Report*. https://media.fisheries.noaa.gov/dam-migration/srkw_priority_chinook_stocks_conceptual_model_report___list_22june2018.pdf

Office of Financial Management. (2023). *Washington State Population by race*. https://ofm.wa.gov/washington-data-research/statewide-data/washington-trends/population-changes/population-race

Olesiuk, P., Ellis, G., & Ford, J. (2005). *Life History and Population Dynamics of Northern Resident Killer Whales (Orcinus orca) in British Columbia*.

Pacific Fishery Management Council. (2024). *Preseason Report I: Stock Abundance Analysis and Environmental Assessment Part 1 for 2024 Ocean Salmon Fishery Regulations*. https://www.pcouncil.org/documents/2024/03/agenda-item-c-2-supplemental-attachment-3-preseason-report-i-electronic-only.pdf/

Posit team. (2023). *RStudio: Integrated Development Environment for R* (2023.9.0.463) [Computer software]. Posit Software, PBC. http://www.posit.co/

PSSS. (2003). *A Primer on Habitat Project Costs*. Evergreen Funding Consultants. https://www.psp.wa.gov/shared-salmon-strategy/files/PrimeronHabitatProjectCosts_wLetter.pdf

Raverty, S., St. Leger, J., Noren, D. P., Burek Huntington, K., Rotstein, D. S., Gulland, F. M.

D., Ford, J. K. B., Hanson, M. B., Lambourn, D. M., Huggins, J., Delaney, M. A., Spaven, L., Rowles, T., Barre, L., Cottrell, P., Ellis, G., Goldstein, T., Terio, K., Duffield, D., … Gaydos, J. K. (2020). Pathology findings and correlation with body condition index in stranded killer whales (Orcinus orca) in the northeastern Pacific and Hawaii from 2004 to 2013. *PLOS ONE*, *15*(12), e0242505. https://doi.org/10.1371/journal.pone.0242505

Richter, A., & Kolmes, S. A. (2005). Maximum Temperature Limits for Chinook, Coho, and Chum Salmon, and Steelhead Trout in the Pacific Northwest. *Reviews in Fisheries Science*, *13*(1), 23–49. https://doi.org/10.1080/10641260590885861

Roni, P., Beechie, T., Pess, G., & Hanson, K. (2015). Wood placement in river restoration: Fact, fiction, and future direction. *Canadian Journal of Fisheries and Aquatic Sciences*, *72*(3), 466–478. https://doi.org/10.1139/cjfas-2014-0344

Scofield, C. (2013). *Stillaguamish Watershed Steelhead Habitat Management Plan*.

Shared Strategy Development Committee. (2007). *Puget Sound Salmon Recovery Plan (Volume 1)*.

Shared Strategy for Puget Sound. (2024). *Maps*. https://www.psp.wa.gov/shared-salmon-strategy/resources.htm#maps

SIRC. (2005). *Stillaguamish Watershed Chinook Salmon Recovery Plan*. Stillaguamish Implementation Review Committee (SIRC). https://www.stillaguamishwatershed.org/Documents/Stillaguamish%20Watershed%20Salmon%20Recovery%20Plan%20--%20Jun.pdf

Southern Resident Orca Task Force. (2019). *Final Report and Recommendations*. https://www.governor.wa.gov/sites/default/files/OrcaTaskForce_FinalReportandRecommendations_11.07.19.pdf

STAG. (2000). *Technical Assessment and Recommendations for Chinook Salmon Recovery in the Stillaguamish Watershed*. Stillaguamish Technical Advisory Group (STAG). https://snohomishcountywa.gov/Archive/ViewFile/Item/2165

Statista Research Department. (2023, November 3). *Poverty Rate Washington U.S. 2022*. Statista. https://www.statista.com/statistics/205715/poverty-rate-in-washington/

Stewart, J. D., Durban, J. W., Fearnbach, H., Barrett-Lennard, L. G., Casler, P. K., Ward, E. J., & Dapp, D. R. (2021). Survival of the fattest: Linking body condition to prey availability and survivorship of killer whales. *Ecosphere*, *12*(8), e03660. https://doi.org/10.1002/ecs2.3660

Stillaguamish Tribe. (2016). *2016 State of Our Watersheds Report—Stillaguamish River Basin*.

Stillaguamish Tribe of Indians. (2022). Environmental Program. *Stillaguamish Tribe*. https://www.stillaguamish.com/natural-resources/environmental-program/

Swan, G. A. (1989). Chinook salmon spawning surveys in deep waters of a large, regulated river. *Regulated Rivers: Research & Management*, *4*(4), 355–370. https://doi.org/10.1002/rrr.3450040404

Tabor, R. A., Liermann, M. C., Gearns, H. A., Moore, Z. J., Lynch, K. D., Kurko, K., Crittenden, J., & Shoemaker, M. E. (2022). Effectiveness monitoring of juvenile Chinook salmon restoration projects in south Lake Washington, Washington State. *Lake and Reservoir Management*, *38*(2), 180–196. https://doi.org/10.1080/10402381.2022.2027054

Tennessen, J. B., Holt, M. M., Wright, B. M., Hanson, M. B., Emmons, C. K., Giles, D. A., Hogan, J. T., Thornton, S. J., & Deecke, V. B. (2023). Divergent foraging strategies between populations of sympatric matrilineal killer whales. *Behavioral Ecology*, arad002. https://doi.org/10.1093/beheco/arad002

Thornton, S. J. (2022). *Southern resident killer whale (Orcinus orca) summer distribution and habitat use in the southern Salish Sea and the Swiftsure Bank area (2009 to 2020)*. Canadian Science Advisory Secretariat (CSAS).

U.S. Bureau of Labor Statistics. (2023, December). *Local Areas Unemployment Statistics: Washington*. https://www.bls.gov/lau/

U.S. Bureau of Labor Statistics. (2024). *Producer Price Index by Commodity: Special Indexes: Construction Materials [WPUSI012011]* [dataset]. https://fred.stlouisfed.org/series/WPUSI012011

US EPA, R. 10. (2021a). *Chinook Salmon* (Canada, Puget Sound) [Reports and Assessments]. https://www.epa.gov/salish-sea/chinook-salmon

US EPA, R. 10. (2021b). *Southern Resident Killer Whales* (Canada, Puget Sound) [Reports and Assessments]. https://www.epa.gov/salish-sea/southern-resident-killer-whales

USDA Forest Service. (2024). *Mt. Baker-Snoqualmie National Forest—Projects*. https://www.fs.usda.gov/projects/mbs/landmanagement/projects

Walters, D. M., Fritz, K. M., Johnson, B. R., Lazorchak, J. M., & McCormick, F. H. (2008). Influence of Trophic Position and Spatial Location on Polychlorinated Biphenyl (PCB) Bioaccumulation in a Stream Food Web. *Environmental Science & Technology*, *42*(7), 2316–2322. https://doi.org/10.1021/es0715849

Ward, E. J., Holmes, E. E., & Balcomb, K. C. (2009). Quantifying the effects of prey abundance on killer whale reproduction. *Journal of Applied Ecology*, *46*(3), 632–640. https://doi.org/10.1111/j.1365-2664.2009.01647.x

Washington Forest Protection Association. (n.d.). *Fish Habitat –*. Retrieved March 10, 2024, from https://www.wfpa.org/aquatic-habitat/fish-habitat/

Washington State Department of Ecology. (2024). *Floodplains by Design*. https://ecology.wa.gov/water-shorelines/shoreline-coastal-management/hazards/floods-floodplain-planning/floodplains-by-design

Washington State Recreation and Conservation Office. (2024). *Salmon Recovery Portal*. https://srp.rco.wa.gov/projectmap?mlayer=projects

Wasser, S. K., Lundin, J. I., Ayres, K., Seely, E., Balcomb Iii, K. C., Hempelmann, J., Parsons, K., & Booth, R. (2017). Population growth is limited by nutritional impacts on pregnancy success in endangered Southern Resident killer whales (Orcinus orca). *PLoS One*, *12*(6). https://doi.org/10.1371/journal.pone.0179824

WDFW. (2023a). *Chinook salmon (Puget Sound ESU)*. https://wdfw.wa.gov/species-habitats/species/oncorhynchus-tshawytscha-pop-15

WDFW. (2023b). *Stillaguamish Restoration and Recovery*. https://wdfw.wa.gov/species-habitats/habitat-recovery/stillaguamish-restoration, https://wdfw.wa.gov/species-habitats/habitat-recovery/stillaguamish-restoration

WDFW. (2023c, November 20). *Salmonid Population Indicators (SPI)*. Data.WA.Gov. https://data.wa.gov/Natural-Resources-Environment/WDFW-Salmonid-Population-Indicators-SPI-Population/ncqh-ypvf

WDFW, Washington State Department of Transportation, & Brian Abbott Fish Barrier Removal Board. (2021). *Biennial Report on the Development of a Statewide Fish Passage Barrier Removal Strategy*.

Weiss, M. N., Ellis, S., Franks, D. W., Nielsen, M. L. K., Cant, M. A., Johnstone, R. A., Ellifrit, D. K., Balcomb, K. C., & Croft, D. P. (2023). Costly lifetime maternal investment in killer whales. *Current Biology*, *33*(4), 744-748.e3. https://doi.org/10.1016/j.cub.2022.12.057

Worley II, A. (2023, November 5). *Southern resident orca reportedly missing from K-pod since July*. https://komonews.com/news/local/southern-resident-orca-reportedly-missing-from-group-since-july-k34-k-pod-killer-whale-western-washington-center-for-whale-research-encounters-k13-k25-poor-condition-skinny-population-demographic-changed

WSDOT. (2023a). *Federal court injunction for fish passage*. https://wsdot.wa.gov/construction-planning/protecting-environment/fish-passage/federal-court-injunction-fish-passage

WSDOT. (2023b). *WSDOT Fish Passage Performance Report*. https://wsdot.wa.gov/sites/default/files/2022-07/Env-StrRest-FishPassageAnnualReport.pdf

Glossary

Term	Definition
Cost-effectiveness ratio	Cost per increase in spawner abundance. Both costs and spawner abundance are annual rates.
Earth moving	Excavating large quantities of earth or rubble for building purposes.
Ecotype	A genetically distinct geographic variety of a species that is adapted to local ecological conditions, but can interbreed with other ecotypes.
Endangered	Any species which is in danger of extinction throughout all or a significant portion of its range (defined by the ESA).
Endangered Species Act (ESA)	A framework to conserve and protect endangered and threatened species and their habitats both domestically and abroad.
Engineered log jam (ELJ)	Strategically placed large woody debris, meant to slow streamflow analogous to natural conditions.
Evolutionarily significant unit (ESU)	A population of organisms that is considered distinct for purposes of conservation.
Fecundity	An individuals' probability of giving birth multiplied by the probability of the offsprings' survival.
Floodplain Restoration	Actions that restore the river and/or surrounding river basin to pre-industrial conditions and repair ecosystem function.
Habitat Assessment and Restoration Planning (HARP) model	A model produced by NOAA scientists to estimate the impact of restoration actions on salmon populations in specific river basins in the Pacific Northwest.
Natal	Relating to the place or time of one's birth
National Marine Fisheries Service (NMFS)	A federal agency within the US Department of Commerce's National Oceanic and Atmospheric Administration that is responsible for the stewardship of U.S. national marine resources.
National Oceanic and Atmospheric Administration (NOAA)	A federal agency within the US Department of Commerce tasked with understanding and predicting changes in climate, weather, ocean, and coasts, and conserving and managing coastal and marine ecosystems and resources.

Producer Price Index (PPI)	A measure of the change in prices that domestic producers receive for their goods and services.
Salmonid	A fish of the salmon family (*Salmonidae*) (e.g. Chinook salmon, coho salmon, steelhead trout, mountain whitefish, bull trout).
Southern Resident Killer Whale (SRKW)	A distinct population segment of killer whales that exclusively eat fish and live in the Northeast Pacific Ocean.
Spawner	A salmon life stage at which sexually mature adults return to their natal stream to lay eggs and die.
Stochastic	The property of being well-described by a random probability distribution.
Threatened	Any species which is likely to become an endangered species within the foreseeable future throughout all or a significant portion of its range (defined by the ESA).