

Evaluating temperature buffering capacity of floodplain side channels to promote refugia for salmonids in the Stillaguamish River basin

Ashley Bagley

A thesis

submitted in partial fulfillment of the
requirements for the degree of

Master of Marine Affairs

University of Washington

2019

Committee:

Cleo Woelfle-Erskine

Gordon Holtgrieve

Ryan Kelly

Program Authorized to Offer Degree:
School of Marine and Environmental Affairs

©Copyright 2019
Ashley Bagley

University of Washington

Abstract

Evaluating temperature buffering capacity of floodplain side channels to promote refugia for salmonids in the Stillaguamish River basin

Ashley Bagley

Chair of the Supervisory Committee:
Cleo Woelfle-Erskine
School of Marine and Environmental Affairs

In the Stillaguamish River basin, low streamflow and high stream temperatures during summer have been identified as barriers to Chinook (*Oncorhynchus tshawytscha*) and coho (*Oncorhynchus kisutch*) salmon recovery and will likely be exacerbated with climate change. Projections forecast higher stream temperatures, drier summers, more intense rain events, and less snowpack starting within the next 20 years. Groundwater seepage zones from side channels and tributaries are cooler than mainstems and can create cold-water refugia for spawning and rearing salmonids. Increasing groundwater storage potential of floodplains and the extent of side channel habitat through floodplain reconnection may buffer salmonids' vulnerability to high stream temperatures. A watershed characterization study done by Snohomish County between 2010 and 2015 determined that restoration of side channels and riparian areas along mainstem habitat would provide temperature benefits to mitigate climate change (Leonetti 2015). This project builds upon the Stillaguamish Tribe of Indian's knowledge and collaborations with Stillaguamish Watershed Council to identify variations in stream temperature, dissolved oxygen, stream type, cover type, and salmonid use of mainstem, side channel, and tributary habitats between five areas and 13 reaches within the Stillaguamish River basin. To help influence the Stillaguamish Tribe and Watershed Council's restoration planning efforts we conducted snorkel surveys in mainstem, side channel, and tributary habitats during August and September of 2018 to perform a reach-scale analysis. Results from a

Pearson's correlation test indicate air temperature and maximum stream temperature have a strong, positive correlation within our study reaches. In some mainstem reaches, stream temperatures will exceed salmonid thresholds (greater than 20 degrees Celsius) during the summer, but side channel and tributary inputs can create refugia within salmonid thresholds (10 to 17 degrees Celsius).

Dissolved oxygen concentrations ranged from 6 to 12 milligrams per liter in most habitats but dropped to about 3.0 milligrams per liter in some disconnected side channel habitat. We observed the highest counts of salmonids when wood (natural or man-made) and vegetation were present, which confirms previous research that salmonids aggregate near these cover types. We performed quasi-Poisson regression analyses to explain the relationship we observed between fish counts for adult Chinook and juvenile coho and potential predictors of fish count. Restoration strategies, such as engineered logjams (ELJs), designed to reconnect floodplain side channels will likely increase the extent of cold-water refugia, potentially mitigating climate change impacts. We created reach-scale maps to illustrate stream temperatures and dissolved oxygen concentrations and developed a model to explain our salmonid counts. In doing so, this research supports floodplain restoration planning efforts and documents pre-restoration conditions to support future adaptive management throughout the Stillaguamish River basin.

Introduction

Climate change is increasing summer stream temperatures and altering hydrologic regimes which in turn alters available instream salmonid habitat (Mantua et al. 2010; Justice et al. 2017). Higher stream temperatures and lower base streamflow during the summer lead to less groundwater storage and diminish upwelling of cool, oxygenated water (Mejia et al. 2016). A reduction in the extent of riparian forests along rivers for agricultural land contributes to less tree cover and groundwater retention within floodplains (Edwards 2003). In addition, levies disconnect floodplains from river channels thereby protecting infrastructure and residential floodplain property (The Nature Conservancy 2016). These changes cause shifts in the hydrologic cycle which affect the abundance of aquatic biota and ultimately the survival of salmonids (Mauger et al. 2015). Multiple climate related studies on the Stillaguamish River predict rain to intensify by 22 percent and peak annual winter streamflow volume to increase by 29 percent by the 2080s (Mauger et al. 2015; Mastin et al. 2016), increasing the likelihood for scouring and displacement of salmonid redds (nests). These climate predictions are essential in selecting appropriate habitat restoration strategies for Chinook salmon (*Oncorhynchus tshawytscha*), which are listed as threatened under the Federal Endangered Species Act (ESA). According to the Climate Change Adaptation Plan developed by the Stillaguamish Tribe and the University of Washington's Climate Impacts Group, declines in summer streamflow are expected to increasingly limit the access and availability of suitable spawning habitat areas for Chinook salmon (Whitely Binder 2017). Furthermore, the effects of declining summer streamflow will exacerbate rising stream temperatures leading to a reduction in spawning fecundity of Chinook.

As climate change intensifies, floodplain managers can prioritize floodplain acquisition and restoration to increase available salmonid habitat. Reconnecting and revegetating floodplains can decrease peak flows associated with spring rain-on-snow and rain events, protecting salmonid redds (nests) from scour; and can reduce flood damage to infrastructure by attenuating flows throughout the valley bottom (Mauger et al. 2015; Quinn 2018). Floodplain restoration benefits salmonids directly via increased food, cover, and protection from high flows and nutrient cycling (Thrush et al. 2000). Restoration within the floodplain also creates indirect benefits for salmonids, such as the increase in groundwater storage capacity and seepage, which creates a localized cooling effect on stream temperature. Increasing floodplain connectivity can create more side channel surface area, thereby increasing hyporheic exchange of cooler groundwater and the extent of cold-water salmonid rearing habitat during the hottest periods of the year (Bellmore et al. 2017). In the Stillaguamish

River basin, groundwater-fed floodplain side channels create temperature refugia up to 10 degrees Celsius cooler than adjacent habitat during peak summer temperatures and the lowest streamflows (Leonetti 2015). Groundwater seeps from floodplain recharge or tributary sources can cool mainstem habitats by 2 to 7 degrees Celsius, as evidenced by interpretation of infrared imagery (Leonetti et al. 2015; Fullerton et al. 2018).

Designed to primarily protect homes, property, and infrastructure, flood control measures create disconnection within the floodplain that reduces available salmonid habitat. Studies have shown that floodplain occupancy is a significant cause of increasing flood risk (Parker 1995). State and local agencies are primarily responsible for floodplain management and have the jurisdiction to limit development within the floodplain via zoning laws (Parker 1995; Olsen 2006). People have been living within floodplains for centuries because of the ecosystem services they provide, such as storage and conveyance of flood water, regulation of sediment and wood supplies in river networks, retention and transformation of nutrients and contaminants, support of forest ecosystems, and the creation of aquatic habitats (Konrad 2015; The Nature Conservancy 2016). Zoning laws can be utilized to deter additional development that strip the floodplain of ecosystem services. This would require floodplain managers to maintain and/or rebuild flood control measures. Floodplain managers are expected to balance flood risk and habitat restoration through the creation of floodplain management strategies. Managers increasingly focus on floodplain restoration to mimic natural or historic characteristics that provide an array of ecological functions (Beechie and Bolton 1999; Beechie et al. 2015), while also striving to reduce flood risk.

For restoration to be effective, it is essential for managers to have clear restoration goals identified to then select an appropriate restoration technique. Additionally, it is essential to collect pre- and post-project monitoring data as a way to evaluate river restoration success (Palmer 2005). Five general categories of restoration techniques include: (1) habitat reconnection, (2) road improvement, (3) riparian restoration, (4) instream habitat restoration, and (5) nutrient enrichment (Roni et al. 2002). For any technique, understanding the probable geomorphological and ecological outcome (e.g., shifts in channel form, groundwater-surface water exchange, vegetation, etc.) of a restoration action is necessary, in addition to having a specific location identified that will provide the greatest biological benefits from that action (Beechie and Bolton 1999; Roni et al. 2002).

Agencies are prioritizing floodplain reconnection to protect and restore cold-water refugia for salmonids throughout the Stillaguamish River basin. For example, the Stillaguamish Tribe of Indians and the Stillaguamish Watershed Council are working with other tribes, local governments,

state and federal agencies, and university partners to design, implement, and monitor floodplain restoration projects with the goal of restoring “healthy, viable populations of Chinook salmon to a level where natural population production is healthy enough to support recreational and commercial fisheries” (SIRC 2005). Groundwater recharge on reconnected floodplains has been identified by these managers as a promising but understudied mechanism to meet salmonid and habitat recovery objectives by absorbing and recharging peak flows into floodplain aquifers when they emerge months later as cold baseflow (Stillaguamish Tribe of Indians 2016). However, the Stillaguamish Tribe and Watershed Council lack a mandate and a specific funding stream to conduct field and spatial research to support their goal (Hall et al. 2014). Managers often lack technical guidance to evaluate how geomorphic processes respond to structural habitat restoration projects, as well as salmonids’ use of restored reaches (Stillaguamish Tribe of Indians 2016). Therefore, the Stillaguamish Tribe and Watershed Council have identified the need for pre- and post-project monitoring data on engineered logjam restoration sites throughout the basin.

To meet their needs for pre-engineered logjam monitoring data, we¹ conducted late summer snorkel surveys of five study areas and 13 select reaches within those areas. Our main research question is focused on how stream temperature, dissolved oxygen, stream type, and cover type vary among mainstem, side channel, and tributary habitats; and how those factors impact abundance of adult Chinook and juvenile coho salmon (*Oncorhynchus kisutch*). By gathering data through reach-scale surveys, we developed a model to explain the relationship we observed between counts of adult Chinook and juvenile coho and potential predictors of count within the Stillaguamish River basin. Our hypothesis was that groundwater-fed floodplain side channels will maintain cool (less than 16 degrees Celsius) temperatures throughout the summer, while mainstem temperatures will exceed salmonid thresholds. The null hypothesis is that floodplain side channels will exceed 16 degrees Celsius. We also hypothesized that adult Chinook salmon will preferentially spawn in cooler groundwater-fed side channels while coho salmon will preferentially rear in beaver pond habitats.

Study Watershed

The Stillaguamish River originates in the North Cascade Mountains and flows westward towards Puget Sound, Washington, U.S.A. The basin is approximately 1,126 square kilometers and is the fifth largest drainage basin in the Puget Sound region (SIRC 2005) (Figure 1). It is situated in Snohomish and Skagit counties and is made up of the North and South Forks, which meet to form

¹ Ashley Bagley and Cleo Woelfle-Erskine

the mainstem of the river near the town of Arlington at river mile 18 (SIRC 2005). The basin is the ancestral home of the Stoluck-wa-mish River Tribe (stuləg^wabs^ʃ), whose descendants are now known as the Stillaguamish Tribe of Indians (Stillaguamish Tribe of Indians 2016). The basin also provides spawning and rearing habitat to anadromous salmonids that continue to play a large role in the Tribe's traditional ways of life. Anadromous salmonids in the basin include Chinook salmon, coho salmon, chum salmon (*Oncorhynchus keta*), pink salmon (*Oncorhynchus gorbuscha*), sockeye salmon (*Oncorhynchus nerka*), steelhead (*Oncorhynchus mykiss*), and sea-run cutthroat trout (*Oncorhynchus clarkii*) (SIRC 2005).

In the late-1800s to mid-1900s, logging and agriculture removed essential floodplain forest and riparian areas, resulting in less complex salmonid habitat throughout the basin (Edwards 2003). Society has continued to degrade salmonid habitat as a direct result of floodplain development and as an indirect result of climate change. In 1990, the Stillaguamish Watershed Council, formerly known as the Stillaguamish Implementation Review Committee, was formed to manage the Stillaguamish Watershed Action Plan and eventually the 2005 Stillaguamish Chinook Recovery Plan (Washington State Conservation Commission 1999). The Stillaguamish Chinook Recovery Plan targets habitat, hatchery, and harvest management in order to protect and restore Chinook salmon populations (SIRC 2005). As part of the Plan, the Watershed Council adopted a 10-year watershed goal for enhancement projects which requires them to install over 50 engineered logjams or to use large woody debris² upstream of the confluence on the North and South Forks (Stillaguamish Tribe of Indians 2016). Engineered logjams and large woody debris were selected to increase Chinook salmon habitat through side channel enhancement, pool development, and in-channel cover; such as undercut banks and rootwad overhang (SIRC 2005). Engineered logjams cause the river to scour around the wood and to wander, which leads to anastomosing and the creation of side channels (Woelfle-Erskine et al. 2017). In addition, engineered logjams cause the river to avulse making the water spread out across the floodplain. This process is beneficial for salmonids because it results in groundwater recharge and seepage throughout the floodplain. See Table 1 for optimal, tolerable, and unsuitable salmonid conditions pertaining to stream temperatures and dissolved oxygen concentrations.

² Large woody debris (LWD) is considered to be wood that is greater than 10 centimeters in diameter. Engineered logjams are one example of LDW projects the Watershed Council is considering. Additional LDW projects the Watershed Council could incorporate include individual wood pieces, large wood revetments or smaller structures (SIRC 2005).

Interagency coordination is underway to research and restore degraded salmonid habitat throughout the basin. Since 1998, the Stillaguamish Tribe has constructed 23 engineered logjams in the mainstem of the middle North Fork at five restoration sites (Anchor QEA 2016). Additionally, with grant funding from the Washington State Department of Ecology, Snohomish County conducted a watershed characterization study between 2010 and 2015 to describe landscape-scale influences on water temperature. Their results determined that a large portion of the middle and upper North Fork shows signs of high watershed degradation despite being an important area for groundwater connectivity (Leonetti et al. 2015). This highlights a key concern for the basin because these areas are prime migration and spawning habitat for Chinook salmon (Whitely Binder et al. 2017). To build off Snohomish County's research and their own, the Stillaguamish Tribe is planning to install additional engineered logjams in the middle North Fork, as well as the South Fork to increase suitable summer salmonid habitat. However, detailed monitoring of engineered logjam restoration sites has not been yet completed.

Methods

For our snorkel surveys, we collected fish count data in each reach for Chinook and coho salmon and steelhead trout. When recording steelhead counts on our datasheets, we grouped them into the larger category of "trout" since sea-run cutthroat trout also occupy the basin. However, because of complications associated with differentiating each trout species from one another (Kennedy et al. 2008), steelhead are not included in our analysis.

Chinook Salmon

In Puget Sound, Chinook salmon are of cultural and economic importance to Pacific Northwest Tribes and surrounding communities. In the basin, 98 to 99 percent of Chinook salmon are ocean-type (Whitely Binder 2017), meaning they migrate to the sea within the first year of life and typically do not return until they are around three to five years-old to spawn (Quinn 2018). In addition, there are two genetically distinct seasonal runs of Chinook salmon in the basin: The North Fork summer run and the South Fork fall run (Whitely Binder 2017). However, the North Fork Chinook salmon are the predominant salmonid population within the basin (SIRC 2005). Chinook salmon tend to spawn in larger streams or the mainstem of a river (Quinn 2018). Degraded spawning habitat throughout the watershed currently limits the productivity of Chinook salmon in the basin (SIRC 2005).

According to 2017 survey efforts performed by the Stillaguamish Tribe and Washington State Department of Fish and Wildlife, the total number of returning adult Chinook salmon to the basin was approximately 1,212, with about 48 percent designated as hatchery-raised (personal communication, Kate Konoski, 29 May 2019). It is important to note the total number of adult Chinook we observed for all survey reaches was 28, which is much lower than we anticipated. The North Fork Chinook salmon start their migration to the Stillaguamish River in late May and continue entering through August. Spawning activity usually begins in late July and lasts through September (Whitely Binder et al. 2017). The South Fork Chinook historically enter the river in fall and spawn shortly after entering freshwater (Whitely Binder et al. 2017). Understanding the seasonality of Chinook salmon within the basin is important to ensure our survey data accurately represents adults returning to spawn. Comparing those seasons with our survey dates, snorkel surveys were performed at the middle to end of the spawning season which could be why we observed so few (Figure 2).

Coho Salmon

Puget Sound coho salmon are also an important cultural and economic resource to the Stillaguamish Tribe and to non-tribal fisheries. Coho are not currently listed under the ESA but face similar threats from a warming climate and increasing urbanization in the basin, as do other aquatic species. During late summer and early fall, adult coho salmon enter the Stillaguamish River and tend to spawn in small, low-gradient side channels or tributaries between November and February (Pollock et al. 2003). Juvenile coho salmon differ from Chinook salmon because they tend to spend one to two years rearing in freshwater before migrating to the sea as smolts (Quinn 2018). This makes coho salmon particularly vulnerable to increases in summer stream temperatures and decreases in streamflow, further emphasizing the need to restore and protect refugia throughout the Stillaguamish River basin.

Study Areas and Reaches

In mid-August and early September of 2018, we surveyed five areas and 13 reaches within the Stillaguamish River basin (see Appendix A for maps). The five main areas are Upper North Fork, Lower North Fork, Boulder River, Lower South Fork, and Jim Creek. The 13 reaches are named UNF Main1, UNF Main2, UNF Side1, UNF Side2, UNF Side3, LNF Main, LNF Trib, BR Trib, LSF Main, LSF Side, JC Trib1, JC Trib2, and JC Trib3, respectively.

The Upper North Fork is the longest and eastern-most area we surveyed and is located on the North Fork Stillaguamish River between the towns of Oso to the west and Darrington to the east. This area is of ecological and cultural importance to the Stillaguamish Tribe because it is historically known for providing important spawning habitat for Chinook salmon, and currently still does. Within this area there are a series of existing engineered logjams that were installed by the Stillaguamish Tribe between 1998 and 2015. Additionally, the Stillaguamish Tribe plans to install engineered logjams near the confluences of Fortson Creek and Boulder River in the near future. Within this area, we surveyed two mainstem reaches: UNF Main1 and UNF Main2. UNF Main1 is the furthest upstream reach on the North Fork beginning near Fortson Mill Pond and ending approximately 1,500 meters downstream. We did not survey the entirety of the reach but focused on gathering data upstream and downstream of the existing engineered logjams. UNF Main2 encompasses approximately 380 meters upstream and 500 meters downstream of the Boulder River confluence. We also surveyed three side channel reaches: UNF Side1, UNF Side2, and UNF Side3. UNF Side1 is the most upstream side channel surveyed; and is located downstream from the Washington Department of Fish and Wildlife's Whitehorse hatchery and upstream from Fortson Mill Pond. UNF Side2 is downstream from UNF Side1 and contains an engineered logjam. UNF Side3 is the most downstream side channel surveyed in the Upper North Fork area and had a series of beaver pools.

Boulder River is a tributary to the North Fork Stillaguamish River. The confluence of the two rivers is located between the Upper North Fork and Lower North Fork areas. Boulder River is important because it provides essential Chinook salmon spawning habitat. Near the confluence, where Boulder River enters the North Fork, there are two cold-water refuge areas that were identified by Snohomish County (Leonetti 2015). In these locations, the Stillaguamish Tribe has proposed installing engineered logjams to create local scour pools upstream and cross-stream. In addition, downstream of the confluence, four additional engineered logjams will be installed alternating on either bank every 200 feet to trigger avulsions in order to create side channels that will remain connected during low streamflow (Anchor QEA 2016). These proposed restoration actions aim to increase summer refugia throughout the North Fork and increase spawning and rearing habitat for salmonids. Within this area, we surveyed one tributary reach (BR Trib), which is located near the mouth of the confluence.

Lower North Fork is located west of the town of Oso near the Cicero Bridge in Cicero, Washington on the North Fork Stillaguamish River. We selected this area because it is downstream

of Oso with presumably more fine sediment and higher stream temperatures. Therefore, we were interested in whether cold-water inputs from a nearby tributary affected mainstem stream temperatures over summer. This section of river currently does not have any engineered logjams in place or in the planning phases; however, it is still vital habitat because adult Chinook salmon need to swim past this area to get to their desired spawning grounds farther upstream in the North Fork. Therefore, it is important to ensure there are refugia throughout this stretch of river where stream temperatures and dissolved oxygen levels do not reach lethal thresholds. Within this area, we surveyed one mainstem reach (LNF Main) and one tributary reach (LNF Trib).

Lower South Fork is located near River Meadows County Park in Arlington, Washington on the South Fork Stillaguamish River. Currently, this area does not have engineered logjams; however, the Stillaguamish Tribe is proposing to install a series of engineered logjams in the straight stretch of the mainstem, downstream from the mouth of Jim Creek to increase streamflow in side channels on the left and right banks year-round (Anchor QEA 2016). This area was designated as a cold-water refuge location. Cold-water inputs are important for lowering stream temperature in a localized area within the South Fork, which tends to have the warmest stream temperatures within the basin. Within this area, we surveyed one mainstem reach (LSF Main) and one side channel reach (LSF Side).

Lastly, Jim Creek is a tributary to the South Fork Stillaguamish River and provides suitable habitat for juvenile coho and steelhead and cutthroat trout. The mouth of Jim Creek was identified as a critical cold-water input spot and is a significant discharge point (Leonetti 2015) that benefits many fish species that reside in the South Fork. Jim Creek has some smaller engineered logjams farther upstream from the confluence. Additionally, Snohomish County is planning to install more engineered logjams within Jim Creek, but those plans have not yet been finalized. Within this area, we surveyed three tributary reaches: the most upstream reach is located near Vos Creek (JC Trib1), the middle reach runs through property owned by Washington Department of Natural Resources (JC Trib2), and the last reach is near the mouth of the confluence (JC Trib3).

Field Methods

We selected five target areas based on discussions with the Stillaguamish Tribe and Snohomish County. Factors that influenced our selected areas and corresponding reaches include accessibility, engineered logjam status (i.e., proposed location, existing location, or none), and location within the basin. Snohomish County is interested in acquiring data upstream and

downstream of the town of Oso, so we took that into consideration when making our selection. Within each selected area, we conducted surveys in mainstem, side channel, and/or tributary reaches. We are specifically interested in side channels and used Snohomish County's GIS data and consultation to identify areas with wetted side channels at low streamflows. Side channel reaches were also selected based on a variety of formation types (e.g., lateral scour-retreat, avulsion expansion, and wall-based) to get a diverse sample. We intentionally surveyed upstream and downstream of tributary junctions to assess the temperature effects of tributary inflow on the mainstem, as well as salmonids' use of the tributary junctions.

We surveyed 13 individual reaches within the five areas and broken down each reach into geomorphic units based on the geomorphology of the stream, such as a pool, riffle, run, and cascade (Montgomery and Buffington 1997). Through snorkel surveys we collected data on temperature, dissolved oxygen, habitat structure, and salmonids (specifically estimating species, age, and quantity) within each reach. Age was determined by the length of the fish and quantity was based on counts ($n < 20$) or estimations ($n > 20$). All the data was recorded by bank (left bank, center, right bank) for each geomorphic unit to capture the varying geomorphology within each reach (Appendix B). Each geomorphic unit was recorded using a global positioning system (GPS) device and was marked once the geomorphology of the stream changed. Therefore, the geomorphic units vary in length. It is important to state, we did not measure length, width, or depth of each geomorphic unit and therefore we cannot calculate fish density by volume or area. We measured stream temperature and dissolved oxygen using an EcoSense ODO200 meter and took most measurements about six inches below the surface so that the sensor was fully submerged. The habitat structure parameter is comprised of stream types and cover types (Appendix C). Streams were classified in a hierarchical approach based on geomorphic unit (Hawkins et al. 1993) and cover was assessed based on absence or presence. Therefore, cover types were recorded if they were observed within each geomorphic unit. We based cover types off the Stillaguamish Tribe's survey sheets to ensure our data is comparable with their annual spawner surveys. Our target salmonid species were adult Chinook and juvenile coho, but we also recorded counts for steelhead trout and mountain whitefish (*Prosopium williamsoni*).

Snorkel surveys were performed in mainstem, side channel, and tributary habitats. Reaches in the North Fork and South Fork primarily included mainstem and side channel habitats, whereas Boulder River and Jim Creek are considered tributary habitats (Figure 3). For mainstem habitats, we recorded whether the channel was single thread or multi-thread. For the North Fork and South Fork

areas most of the river that was surveyed consisted of mainstem habitat, either because side channels within those areas were challenging to access or because they were dry during surveys due to disconnection from the mainstem. For mainstem units surveys were conducted upstream to downstream with three to four snorkelers and one to two data recorders. For the Upper North Fork mainstem data recorders floated downstream in the Stillaguamish Tribe’s cata-raft while snorkelers floated down and made observations. For the Boulder River area surveys were conducted upstream to downstream with two snorkelers and one data recorder because streamflow was too high for us to snorkel up it. For side channel units and Jim Creek one to two people snorkeled and one person recorded data. These surveys were conducted downstream to upstream to preserve visibility in shallow water conditions. Even though Boulder River and Jim Creek are both tributaries, streamflow levels impacted the direction of our snorkel surveys.

We performed two quasi-Poisson regression analyses (Hoef and Boveng 2007) in R Studio (R Development Core Team 2008) to determine how stream temperature, dissolved oxygen, stream type, cover type, and habitat type impact adult Chinook spawning and late-summer juvenile coho survival. A quasi-Poisson regression (Hoef and Boveng 2007) was selected because we have relatively small fish count data, lots of zeros, and it adjusts for overdispersion in our data, meaning the variance is greater than the mean. Each analysis was broken down by species (adult Chinook or juvenile coho); therefore, we have two regression results. Since stream types and cover types were recorded by bank within each geomorphic unit, we used an interaction between “bank” and “stream type” and “bank” and “cover type” to associate specific characteristics with the bank it was observed along. Our hope with using an interaction was to get additional detail on whether a specific bank can inform fish count and if specific stream and cover types are more likely to occur on a specific bank due to the basin’s geomorphology. Our full quasi-Poisson regression equation is:

$$\text{Log(Fish Count)} = \beta_0 + \beta_1 X_{\text{Temperature}} + \beta_2 X_{\text{DO}} + \beta_3 X_{\text{StreamType}} + \beta_4 X_{\text{CoverType}} + \beta_5 X_{\text{HabitatType}} + \beta_6 X_{\text{StreamType:Bank}} + \beta_7 X_{\text{CoverType:Bank}} + \epsilon$$

To streamline our analyses, stream types were grouped into four categories based on the types we observed target species in: pool, riffle, run, and cascade pool. A pool is classified as a slow water stream and is created by scouring action of the water current or when water is impounded by a channel blockage, such as a beaver dam. Riffles and runs are classified as fast and shallow water habitats; however, riffles are considered turbulent water and runs are considered non-turbulent water. A cascade is classified as a fast water stream and is known for having a series of alternating

small falls and shallow pools. Although we did not observe any adult Chinook jumping over cascades, we wrote “cascade pool” when we observed adults in the pools just below a waterfall. Additionally, we grouped all the cover types into three categories: wood or vegetation, no wood or vegetation (e.g., cover provided by boulder or deep water), and no cover (see Appendix C for more details). The three cover types represent a scale of possible cover type categories based on preferred, mediocre, and bad cover for salmonids, respectively; and they indicate the decline of large wood and riparian cover within the basin. The three habitat types are mainstem, side channel, and tributary. We visualized data in R Studio (R Development Core Team 2008) to illustrate the percentage of each reach surveyed that was either mainstem, side channel, or tributary habitat; variations in temperature and dissolved oxygen for each reach; and to determine whether there is a relationship between stream type and cover type with our adult Chinook and juvenile coho observations.

Results

Quasi-Poisson Regression Results

Quasi-Poisson regression analyses were conducted to explain the relationship we observed between fish counts for each of the target salmonid species and potential predictors. Significant regression results suggest as stream temperature decreased by one unit, we observed a 62 percent increase in adult Chinook counts, and that as dissolved oxygen increased by one unit there was a 28 percent increase in in adult Chinook counts (Table 2). The model also confirms we observed 86 percent less adult Chinook in tributaries than mainstem habitat (Table 2). Significant regression results for juvenile coho reveal as dissolved oxygen increased by one unit, we observed a 62 percent increase in juvenile coho counts (Table 2). Similar to adult Chinook, when comparing tributary habitat to mainstem habitat, tributaries had 68 percent fewer juvenile coho (Table 2). Additional snorkel surveys and continuous stream temperature and dissolved oxygen measurements for the months of August and September are needed to strengthen our statistical power. The nonsignificant covariates, such as stream type, cover type, and bank suggest there are other factors most likely impacting adult Chinook and juvenile coho fish counts that are not being captured in our models.

Mainstem Habitat Results

Stream Temperature

We surveyed four mainstem reaches within the basin and found they have the warmest stream temperatures compared to the surveyed side channels and tributaries. The overall average stream temperature for surveyed mainstem habitat was 16.49 degrees Celsius (Table 3). LSF Main

had the warmest average mainstem temperature of 18.97 degrees Celsius (± 0.62) (Table 3). Whereas, the coolest average mainstem temperature was 14.88 degrees Celsius (± 1.14) in the upstream-most reach in the Upper North Fork, UNF Main1 (Table 3). The other Upper North Fork reach, UNF Main2, had an average temperature of 16.48 degrees Celsius (± 1.59) and the Lower North Fork reach, LNF Main, had an average temperature of 15.64 degrees Celsius (± 0.76) (Table 3).

Dissolved Oxygen

The overall average dissolved oxygen concentration for mainstem habitat was 9.76 milligrams per liter (Table 4). We measured the highest average dissolved oxygen concentration of mainstem habitat in the North Fork mainstem reach near the confluence of Boulder River, UNF Main2. This reach had an average concentration of 10.73 milligrams per liter (± 0.83) (Table 4). The lowest average mainstem dissolved oxygen concentration we measured was in UNF Main1 at 9.02 milligrams per liter (± 0.81) (Table 4). The two other mainstem reaches had the following average dissolved oxygen concentrations: LSF Main at 9.24 milligrams per liter (± 0.11) and LNF Main at 10.03 milligrams per liter (± 0.97) (Table 4).

Fish Counts, Stream Types, and Cover Types

We observed 24 adult Chinook in three different mainstem habitat reaches (Table 5). We made the most observations (13 total) in UNF Main2 (Table 5). The reach with the second highest observations (9 total) of adult Chinook was UNF Main1, followed by LSF Main with two observations (Table 5). We did not observe any adult Chinook in any other mainstem reach. When we made adult Chinook observations in mainstem habitat, the dominant stream type was run (12; 50 percent), followed by cascade pool (8; 34 percent), and then pool (2; 8 percent); we did not observe any adult Chinook in riffles³ (Figure 4). All the mainstem adult Chinook observations (24; 100 percent) we made were when wood and vegetation were present (Figure 4).

We observed 2,864 juvenile coho in mainstem habitat which calculates to a density of 0.78 based on total fish counts per total mainstem length surveyed in meters (Table 6). The most observations and highest densities were in the Upper North Fork, with 1,658 (1.78) in UNF Main1 and 944 (1.00) in UNF Main2 (Table 6). We made 245 observations (0.44) in LNF Main and 17 observations (0.01) in LSF Main (Table 6). When we made juvenile coho observations in mainstem habitat, the dominant stream type was pool (1,675; 58 percent), followed by run (533; 19 percent),

³ Adult Chinook observations were recorded when cover was not recorded (NA). These observations make up 8% of total mainstem adult Chinook observations.

then riffle (453; 16 percent), and lastly, cascade pool (98; 3 percent)⁴ (Figure 5). Most of the mainstem juvenile coho observations we made were when wood and vegetation were present (1,325; 46 percent); however, we made observations when there was no wood and vegetation⁵ (862; 30 percent)⁶ (Figure 5).

Side Channel Habitat Results

Stream Temperature

We surveyed four side channel reaches within the basin and their overall average stream temperature was 12.53 degrees Celsius (Table 3). The Lower South Fork, LSF Side, had the warmest average side channel temperature of 14.8 degrees Celsius (± 1.53) (Table 3). The coolest average side channel temperature we measured was 11.4 degrees Celsius (± 0.38) in the downstream-most side channel reach within the Upper North Fork area, UNF Side3 (Table 3). The two other side channel reaches, UNF Side2 and UNF Side1, had average stream temperatures of 11.77 (± 0.34) and 12.15 degrees Celsius (± 0.16), respectively (Table 3).

Dissolved Oxygen

The overall average dissolved oxygen concentration of the surveyed side channel reaches was 7.43 milligrams per liter (Table 4). In the upstream-most side channel reach in the North Fork, UNF Side1, we measured the highest average dissolved oxygen concentration at 9.85 milligrams per liter (± 0.33) for side channels (Table 4). The lowest average side channel dissolved oxygen concentration we measured was in UNF Side3 at 3.01 milligrams per liter (± 0.78) (Table 4). The two other side channel reaches had the following dissolved oxygen concentrations: UNF Side2 at 8.39 milligrams per liter (± 0.093) and LSF Side at 8.45 milligrams per liter (± 0.80) (Table 4).

Fish Counts, Stream Types, and Cover Types

We did not observe any adult Chinook in side channel reaches (Table 5). Side channels had the highest density (total fish count per meter length of surveyed habitat type) of juvenile coho at 1.04 and a total count of 834 (Table 6). We made the most observations in UNF Side1 (336; 1.68), followed by UNF Side2 (185; 0.93), LSF Side (171; 0.86), and then UNF Side3 (142; 0.71) (Table 6). When we made juvenile coho observations side channel habitat they were in runs (456; 55 percent) and pools (378; 45 percent) (Figure 5). Most of our juvenile coho observations in side channels were

⁴ Juvenile coho observations were recorded when stream type was not recorded (NA). These observations make up 4% of total mainstem juvenile coho observations.

⁵ This is different from no cover. See Appendix C for additional details on cover classification groups.

⁶ Juvenile coho observations were recorded when cover was not recorded (NA). These observations make up 24% of total mainstem juvenile coho observations.

made when wood and vegetation were present (692; 83 percent); however, we made observations when no wood and vegetation were present (82; 10 percent), as well as no cover (26; 3 percent)⁷ (Figure 5).

Tributary Habitat Results

Stream Temperature

We surveyed five tributary reaches to the Stillaguamish River basin and their overall average stream temperature was 14.95 degrees Celsius (Table 3). The middle reach of Jim Creek, JC Trib2, had the warmest average tributary temperature of 16.63 degrees Celsius (± 0.18) (Table 3). The coolest average tributary temperature was 12.33 degrees Celsius (± 0.32) in LNF Trib (Table 3). The three other tributary reaches, Boulder River, JC Trib3, and JC Trib1, had average temperatures of 13.78 (± 0.45), 15.74 (± 0.48), and 16.25 degrees Celsius (± 0.49), respectively (Table 3).

Dissolved Oxygen

The overall average dissolved oxygen concentration for tributary habitat was 9.54 milligrams per liter (Table 4). We measured the highest average dissolved oxygen concentration for tributary habitat in JC Trib2 at 10.62 milligrams per liter (± 0.13) (Table 4). The lowest average dissolved oxygen concentration we measured for tributaries was in LNF Trib at 6.45 milligrams per liter (± 0.42) (Table 4). The three other tributary reaches had the following dissolved oxygen concentrations: JC Trib3 at 9.95 milligrams per liter (± 0.18), BR Trib at 10.19 milligrams per liter (± 0.073), and JC Trib1 at 10.51 milligrams per liter (± 0.21) (Table 4).

Fish Counts, Stream Types, and Cover Types

We observed four adult Chinook in tributary habitat, with the only observations made in Boulder River (Table 5). We made the four observations in pools when wood and vegetation were present (4; 100 percent) (Figure 4). On average, tributaries were the least dense habitat type with a juvenile coho density of 0.72 and a total of 869 observations (Table 6). However, on a reach-scale, JC Trib1 had the highest density (1.89) of juvenile coho of all reaches surveyed (Table 6). The most observations of juvenile coho in tributary habitat were in pools (536; 62 percent), followed by runs (148; 17 percent), cascade pools (99; 11 percent), and then riffles (10; 1 percent)⁸ (Figure 5). Most of the juvenile coho observations we made in tributaries were when wood and vegetation were present

⁷ Juvenile coho observations were recorded when cover was not recorded (NA). These observations make up 4% of total side channel juvenile coho observations.

⁸ Juvenile coho observations were recorded when stream type was not recorded (NA). These observations make up 9% of total tributary juvenile coho observations.

(550; 63 percent); however, we made observations when there was no wood and vegetation present (198; 23 percent), as well as no cover (73; 8 percent)⁹ (Figure 5).

Discussion

Stream Temperatures

Our field data supports studies done by Snohomish County (Leonetti 2015) which have identified the warmest stream temperatures to be in the South Fork Stillaguamish River. Overall, mean mainstem and side channel temperatures in the South Fork exceeded those of the North Fork (Table 3). Within the Lower South Fork area, stream temperatures in the mainstem were warmer but more consistent compared to side channel temperatures which were cooler but more variable (Table 3). Furthermore, side channel reaches throughout the basin tended to be cooler than their adjacent mainstem and tributary habitats because the majority of geomorphic units never exceeded 16 degrees Celsius. This rejects our null hypothesis that floodplain side channels will not maintain cool (less than 16 degrees Celsius) temperatures throughout the summer. However, our results are most likely not generalizable because of our small sample size (n=4). Additional surveys of side channels throughout the North and South Forks should be conducted to confirm side channels that are groundwater-fed are cooler during the summer than mainstem and tributary habitats.

The only side channel that exceeded 16 degrees Celsius was in the Lower South Fork, LSF Side. This side channel is right next to Jordan Road, a known source of floodplain disconnection in the South Fork. LSF Side had the greatest temperature variability within one reach most likely because of differences in stream depth, and subsequently the availability of groundwater seepage. The downstream end of LSF Side was relatively shallow (approximately 0.08 meters) and required us to drag ourselves upstream because flows were so low (Appendix D.1). However, as we surveyed further upstream, we came upon a beaver pool. The beaver pool was deeper by approximately 0.22 meters than the downstream segment and required us to climb over the beaver dam to survey (Appendix D.2). Therefore, it is possible the groundwater recharge associated with the beaver pool caused stream temperatures to be lower upstream than the shallower sections of that reach downstream.

⁹ Juvenile coho observations were recorded when cover was not recorded (NA). These observations make up 5% of total tributary juvenile coho observations.

The Upper North Fork area displayed the greatest temperature heterogeneity, with temperature anomalies above and below median mainstem temperatures (Figure 6). Despite the warmest mean stream temperature in the mainstem of the Lower South Fork, the warmest temperature we measured of all the reaches surveyed was located in UNF Main2 at 20.3 degrees Celsius (UNF Main2 outlier; Figure 6). This geomorphic unit was on the river's right bank and was located upstream and across from the Boulder River confluence. Conversely, within UNF Main1 we encountered the coldest water for this area in two geomorphic units. The first geomorphic unit was on the river's left and upstream of an engineered logjam which we inferred to be cool (11.6 degrees Celsius) because of groundwater upwelling. The second geomorphic unit was near the Fortson Creek confluence which indicates the tributary input might have created a localized cooling effect (12.8 degrees Celsius) further downstream in the mainstem. Compared to mainstem reaches, tributaries had relatively similar or cooler stream temperatures; however, they were generally not as cold as side channels (Figure 6).

Climate Change Makes Many Reaches Inhospitable for Chinook and Coho

We have illustrated variations in stream temperature, dissolved oxygen, stream types, and cover types between the five areas and among mainstem, side channel, and tributary reaches in the Stillaguamish River; and how those factors may be impacting adult Chinook and juvenile coho salmon's use of the basin. Results from a Pearson's correlation test indicate there is a strong, positive correlation (Pearson's $r = 0.75$) between air temperature and maximum stream temperature within our study reaches (Figure 7). This suggests stream temperatures within the Stillaguamish River basin will be directly affected by increasing air temperatures, especially during the summer. Increasing air temperatures are likely to increase already warming stream temperatures if instream restoration and riparian planting are not continued on a basin-wide scale. National climate trends are predicting the ratio of record high to record low temperatures to continually increase (Meehl et al. 2016), with climate models predicting a 1.5 to 3.2 degree Celsius increase in average annual air temperature by the middle of the 21st century (Battin et al. 2007). Projections also indicate a decline in summer baseflows (Mauger et al. 2015). This is problematic because lower streamflow can increase floodplain disconnection and result in increased summer stream temperatures. Furthermore, climate change will exacerbate areas within the basin that are already exhibiting extreme conditions that are not optimal for salmonids. Our data reveals there are already reaches within the basin that are exceeding adult and juvenile salmonid thresholds and creating unsuitable conditions (Table 1). For example, thermal conditions were either on the very high end of tolerable or were unsuitable in the

UNF Main2 and LSF Main reaches. As a result, salmonid populations within the basin will likely be exposed to summer conditions outside of their thresholds for spawning and rearing. Salmonids' ability to adapt to increased stream temperatures will be crucial for them to survive and reproduce successfully (Fullerton et al. 2018). Adaptation may include adjusting migration and spawning seasons, as well as physiologically adapting to slight changes in stream temperature and dissolved oxygen.

Dissolved Oxygen Concentrations

Overall, dissolved oxygen does not seem to be a limiting factor in summer salmonid survival in the reaches we surveyed since most mean concentrations were above 7 milligrams per liter, with the exception of two reaches: UNF Side3 and LNF Trib (Figure 8). The only reach with lethal levels of dissolved oxygen was UNF Side3, with concentrations ranging between 2.03 and 3.89 milligrams per liter (Figure 8). This reach was dominated by a series of beaver pools on the downstream end and was disconnected to the mainstem at the upstream end (Appendix D.3 and D.4). Therefore, we believe the low levels of dissolved oxygen are most likely attributed to the reach's disconnection from the mainstem, thereby limiting the flow of oxygenated groundwater. Disconnection and dammed pools result in little to no streamflow and aeration (Woelfle-Erskine et al. 2017). However, this reach was relatively cold compared to adjacent mainstem habitat, suggesting groundwater with low dissolved oxygen may be upwelling within this reach. LNF Trib, the smaller tributary off the Lower North Fork, had tolerable dissolved oxygen conditions with a mean of 6.45 milligrams per liter (Table 4). LNF Trib is located between the North Fork on the river's right and Highway 530, which is contributing to floodplain disconnection. Furthermore, disconnection is most likely contributing to lower levels of dissolved oxygen within LNF Trib. Restoration via in-stream habitat enhancement projects upstream of these reaches could mitigate floodplain disconnection and potentially increase the dissolved oxygen concentrations.

Tributaries had more consistent and higher concentrations of dissolved oxygen compared to side channel habitat (Figure 8). This might be attributed to engineered logjams or large wood accumulation we found in Boulder River and Jim Creek as a result of strong streamflow leading to increased levels of aeration. Although, mainstem habitat also had suitable dissolved oxygen concentrations with the highest measurements observed in UNF Main2. Within UNF Main2, and within the same geomorphic unit we observed the highest stream temperature (20.3 degrees Celsius), we also observed the highest dissolved oxygen concentration measurement out of all the survey reaches. This geomorphic unit had a maximum concentration of 11.83 milligrams per liter (Figure 8).

We are not sure why this might be, but it signifies that other geomorphological factors may be at play for creating these varying conditions.

Fish Counts, Stream Types, and Cover Types

Most of our adult Chinook observations were made in mainstem habitat; therefore, we fail to reject the null hypothesis that adult Chinook salmon will not preferentially spawn in cooler groundwater-fed side channels. This suggests that if conditions are suitable, adult Chinook will spawn in mainstem habitat, and to a lesser degree, tributary habitat. Additionally, our cover type data supports the literature in stating that adult Chinook prefer reaches with large woody debris and vegetation (Figure 4). Since the mainstem of the Upper North Fork and Boulder River had the greatest quantity of large woody debris of all the reaches based on our observations, it is therefore intuitive that we only observed adult Chinook in these areas. Lastly, our Chinook observations are not representative of the actual number of adults that returned to spawn within the basin. It is possible that the 2018 summer run Chinook salmon migrated and spawned earlier as a result of temperature changes associated with climate change, which would make our survey dates even more skewed with Chinook migration and spawning seasons. The time of day we were conducting surveys might also be contributing to low observation counts. During the day, and especially in the summer, when temperatures are at their hottest and streamflows are at their lowest, adult Chinook tend to take refuge in deeper pools. When we surveyed in deep pools, we made reasonable estimates despite the depth; however, we most likely did not count all adult Chinook present due to poor visibility.

Stream classification results suggest the rejection of the null hypothesis that juvenile coho will not preferentially rear in beaver pond habitat. However, our decision to classify the stream types into four general categories limits our ability to quantify whether more juvenile coho were actually in beaver ponds compared to other types of pools. Based on our count data, mainstem habitat had the highest number of observed juvenile coho salmon. However, side channels had the highest density of juvenile coho salmon based on fish count per meter length of each reach habitat surveyed. Examining juvenile coho density on a reach-scale, JC Trib1 had the highest density overall (1.89). This reach had a lot of slow-water habitat along the banks as a result of lateral scour-retreat from large woody debris, both natural and man-made, as well as suitable stream temperatures and optimal dissolved oxygen concentrations, demonstrating ideal summer rearing habitat.

Wood Accumulation Initiates Channel-Forming Hydrological Processes

Recognizing the need for thermal refugia throughout the basin, the Stillaguamish Tribe and Watershed Council have made floodplain acquisition and restoration a priority of theirs to aid in

salmonid recovery. A study done on Washington watersheds indicates wood jam densities are positively correlated with the ratio of side channel to mainstem length most likely because of the wood initiating hydrological processes within the river (Hall et al. 2018). In relation to wood, hydrological processes can include but are not limited to avulsion, scour, and groundwater recharge and seepage. As such, our stream temperature measurements revealed side channel reaches tended to be cooler most likely because of groundwater seepage as result of floodplain connection. Due to their cooler temperatures, groundwater-fed floodplain side channels are an example of salmonid thermal refugia that already exists within the basin. Other studies done in the Stillaguamish River basin have determined the North Fork to have the highest number of side channels compared to the South Fork and Mainstem, with lateral scour-retreat (wood-formed) as the dominant formation type (Leonetti 2019). This is most likely because the South Fork and Mainstem have less large woody debris overall, which could be attributed to the fact that both have larger bankfull widths (greater than 20 meters) (Leonetti 2019). Additionally, the Mainstem is constrained by floodplain modifications whereas the South Fork has limited floodplain area (Leonetti 2019). As a result, this limits the pool-riffle complex (Montgomery and Buffington 1997) that leads to greater sinuosity and wood accumulation.

Through the installation of engineered logjams, the Stillaguamish Tribe and Watershed Council are increasing floodplain connection by restoring hydrological processes that result in increased thermal heterogeneity and slow-water stream habitats which are beneficial for spawning and rearing salmonids. Juvenile coho salmon benefit from wood accumulation because of the scour pool habitat it creates. Our observations support this claim because juvenile coho were predominantly observed in woody and vegetated pool reaches. Additionally, adult Chinook were only observed in mainstem and tributary reaches when wood and vegetation were present most likely because of the shade and shelter the wood creates. Fish tend to use large woody debris because it provides shelter from aerial predators and can create a localized cooling effect because of the shade. This indicates wood and vegetation are essential attributes to alluvial river systems where salmonids are present because of the habitat conditions they provide. In the Cedar River watershed, habitat created through restoration projects resulted in measurable changes to habitat complexity (Hall et al. 2018). By continually monitoring proposed and existing restoration sites, the Stillaguamish Tribe and Watershed Council are able to evaluate their efforts and adapt their strategies accordingly. Connecting habitat changes with salmonid biological impacts is necessary for

natural resource managers to evaluate the potential benefits of restoration actions and adapt management decisions as needed (Justice et al. 2017).

Need for Floodplain Restoration

The need for floodplain restoration on a basin-wide scale highlights the fact that restoration managers should prioritize recovery strategies that protect “riverscapes of high social value and high ecological vulnerability” (Hand et al. 2018) which tend to be lower-elevation habitats because of the increased human interaction in those regions. It is through human interaction in low-lying areas that increases social value and can simultaneously lead to increased ecological vulnerability via land use changes. Studies done on the Snohomish River basin have suggested recovery plans that focus on enhancing low elevation habitats are more likely to be successful within the next 50 years than those that target higher elevation habitats where restoration action is more limited and challenging (Battin et al. 2007). Therefore, low-lying floodplain is prime habitat to target restoration efforts because of its diverse uses. Floodplains have high social value because people live and recreate within them which subsequently makes them ecologically vulnerable. This emphasizes the need for reach-scale studies within the Stillaguamish River’s low-lying floodplain to assess existing salmonid habitat conditions and identify target restoration areas based on their importance to salmonid migration, spawning, and rearing habitat. Floodplains have the potential to increase salmonid populations via increased habitat quantity and improved habitat quality through strategic restoration actions. Utilizing the relationships Snohomish Conservation District has established in working with private property owners to create conservation easements for riparian planting will be strategic in limiting additional floodplain development as the Stillaguamish Tribe continues to acquire floodplain property throughout the basin.

Additional Monitoring Data is Necessary

Our research assists in the Stillaguamish Tribe and Watershed Council’s identification and prioritization of opportunistic restoration locations by illustrating the variations in stream temperature, dissolved oxygen, stream type, cover type, and salmonid observations in the five study areas and 13 reaches. To build upon the snorkel surveys that were done in the summer of 2018, our next steps are to develop a habitat capacity model in ArcMap 10.6.1. Our model will be based off prior studies done on the Columbia River basin (Bond et al. 2018) and Trinity River (Beechie et al. 2015) to quantify Chinook abundance if floodplain restoration was done at specific locations within the basin. This will bolster our analysis since our data is from snorkel surveys that were conducted at a single point in time and might not be representative of the basin and average summer conditions.

Additional and repeated snorkel surveys will be conducted in the summer of 2019 to increase our statistical power in analyzing how engineered logjams create suitable salmonid habitat via increased hydrological processes. Continuous stream temperature measurements will be gathered in the summer of 2019 to strengthen our correlation and provide greater insight into the effectiveness of engineered logjams as a mitigation tool. Survey reaches will most likely be refined to allow for more detailed data collection. Reaches and survey methodology will be determined through correspondence with the Stillaguamish Tribe and Watershed Council.

Conclusions

The results of our visual and statistical analyses showcase side channel habitat within the basin were primarily cooler than mainstem and tributary habitats. Tributary reaches were either cooler or approximately similar to mainstem stream temperatures. The cool anomalous locations we observed within the mainstem of the Upper North Fork suggest tributary sources may lower mainstem stream temperatures locally. Dissolved oxygen concentrations across survey reaches ranged between 7 and 12 milligrams per liter with some exceptions, suggesting it may not be a limiting factor within our survey reaches. However, our quasi-Poisson regression results indicate it is significantly impacting salmonid counts. The Stillaguamish Tribe and Snohomish County have been using engineered logjams as a mitigation tool because they increase groundwater storage which can cause upwelling of cool, oxygenated groundwater during the summer when stream temperatures are at their warmest. This restoration strategy strives to keep stream temperatures within optimal salmonid conditions and supports year-round streamflow. Our approach is amenable to meet the Stillaguamish Tribe and Watershed Council's needs to effectively track and monitor water quality and salmonid habitat conditions over summer to inform salmonid recovery at reach and watershed scales. This research emphasizes the need for continuous monitoring of engineered logjam sites to effectively capture how they influence groundwater recharge and upwelling within the floodplain in order to create complex, suitable summer salmonid habitat. As the climate continues to change, identifying and prioritizing restoration sites around the preservation and restoration of cold-water inputs will be critical to ensure there is suitable summer salmonid habitat throughout the Stillaguamish River basin.

Acknowledgements

I would like to acknowledge the Stillaguamish Tribe of Indians and Stillaguamish Watershed Council for their consultation and resources during the onset of this research project. Thanks to my thesis committee and the FRESH Water Relations Lab at the University of Washington for their input, feedback, and continued support. A very special thanks to the volunteers who assisted on the snorkel surveys – I could not have done it without you! Last, but certainly not least, thank you to my family for supporting me mentally and emotionally throughout this whole process – I appreciate you deeply. Funding for this work was provided through a Department of the Interior Northwest Climate Adaptation Science Center graduate fellowship.

Tables

Adult Salmonid Conditions	Temperature	Dissolved Oxygen
Optimal	< 15 degrees Celsius	> 7 mg/L
Tolerable	15 to 20 degrees Celsius	4.5 to 7 mg/L
Unsuitable	> 20 degrees Celsius	< 4.5 mg/L
Juvenile Salmonid Conditions	Temperature	Dissolved Oxygen
Optimal	5 to 11 degrees Celsius	> 8 mg/L
Tolerable	11 to 16 degrees Celsius	5 to 8 mg/L
Unsuitable	> 17 degrees Celsius	< 5 mg/L

Table 1. Temperature ranges broken into three zones based on adult and juvenile salmonid thresholds. Temperature thresholds are adopted from Fullerton et al. (2018) and are based on EPA's criteria for the 7-day average of daily maximum temperature. Dissolved oxygen thresholds are based on Whitmore et al. (1960) and Carter (2005). Temperature and dissolved oxygen thresholds may vary based on species, age, and basin.

Covariate	Dependent Variable: Adult Chinook Count	Dependent Variable: Juvenile Coho Count
Temperature	-0.889 ** (0.282)	-0.076 (0.093)
Dissolved oxygen	0.485 . (0.249)	0.484 ** (0.152)
Pool	-0.467 (25,643.630)	-0.202 (1.175)
Riffle	0.401 (27,386.400)	0.386 (1.146)
Run	0.208 (25,184.270)	-1.803 (1.305)
Left bank (LB)	-18.828 (32,421.210)	0.154 (2.293)
Right bank (RB)	2.694 (29,447.710)	-3.228 (3.711)
No wood/veg. (NWV)	-0.422 (12,413.290)	0.835 (1.264)
Wood/veg. (WV)	-0.660 (13,195.970)	0.281 (1.316)
Side channel	-22.059 (4,651.325)	0.738 (0.580)
Tributary	-1.955 * (0.904)	-1.126 ** (0.379)
Pool:LB	16.384 (30,263.340)	0.023 (1.527)
Riffle:LB	-0.258 (33,003.500)	-1.543 (1.660)
Run:LB	19.557 (29,875.100)	-0.984 (1.843)
Pool:RB	-2.062 (25,643.630)	1.364 (1.868)
Riffle:RB	-20.674 (28,959.850)	-2.934 (4.637)
Run:RB	-3.536 (25,184.270)	1.667 (2.000)
NWV:LB	0.495 (16,185.650)	0.370 (1.883)
WV:LB	21.203 (15,883.060)	1.370 (1.887)
NWV:RB	-0.005 (18,272.550)	1.902 (3.327)
WV:RB	20.810 (18,027.560)	2.915 (3.307)
Constant	-12.051 (26,763.940)	-1.246 (2.475)
Observations	305	305

Table 2. Quasi-Poisson regression results for adult Chinook and juvenile coho salmon.

Mean Stream Temperature (°C)			
Reach	Mainstem	Side Channel	Tributary
Upper NF Main1 (UNF Main1)	14.88 ± 1.14	-	-
Upper NF Main2 (UNF Main2)	16.48 ± 1.59	-	-
Upper NF Side1 (UNF Side1)	-	12.15 ± 0.16	-
Upper NF Side2 (UNF Side2)	-	11.77 ± 0.34	-
Upper NF Side3 (UNF Side3)	-	11.4 ± 0.38	-
Boulder River (BR Trib)	-	-	13.78 ± 0.45
Lower NF Main (LNF Main)	15.64 ± 0.76	-	-
Lower NF Trib (LNF Trib)	-	-	12.33 ± 0.32
Lower SF Main (LSF Main)	18.97 ± 0.62	-	-
Lower SF Side (LSF Side)	-	14.8 ± 1.53	-
Jim Creek 1 (JC Trib1)	-	-	16.25 ± 0.49
Jim Creek 2 (JC Trib2)	-	-	16.63 ± 0.18
Jim Creek 3 (JC Trib3)	-	-	15.74 ± 0.48
Grand Average	16.49	12.53	14.95

Table 3. Mean stream temperatures for each survey reach, categorized by habitat type. Side channel habitat had the coolest mean stream temperatures compared to tributary and mainstem habitat.

Mean Dissolved Oxygen (mg/L)			
Reach	Mainstem	Side Channel	Tributary
Upper NF Main1 (UNF Main1)	9.02 ± 0.81	-	-
Upper NF Main2 (UNF Main2)	10.73 ± 0.83	-	-
Upper NF Side1 (UNF Side1)	-	9.85 ± 0.33	-
Upper NF Side2 (UNF Side2)	-	8.39 ± 0.093	-
Upper NF Side3 (UNF Side3)	-	3.01 ± 0.78	-
Boulder River (BR Trib)	-	-	10.19 ± 0.073
Lower NF Main (LNF Main)	10.03 ± 0.97	-	-
Lower NF Trib (LNF Trib)	-	-	6.45 ± 0.42
Lower SF Main (LSF Main)	9.24 ± 0.11	-	-
Lower SF Side (LSF Side)	-	8.45 ± 0.80	-
Jim Creek 1 (JC Trib1)	-	-	10.51 ± 0.21
Jim Creek 2 (JC Trib2)	-	-	10.62 ± 0.13
Jim Creek 3 (JC Trib3)	-	-	9.95 ± 0.18
Grand Average	9.76	7.43	9.54

Table 4. Mean dissolved oxygen concentrations for each survey reach, categorized by habitat type. Mainstem habitat had the highest mean dissolved oxygen concentrations.

Adult Chinook Counts			
Reach	Mainstem	Side Channel	Tributary
Upper NF Main1 (UNF Main1)	9	-	-
Upper NF Main2 (UNF Main2)	13	-	-
Upper NF Side1 (UNF Side1)	-	0	-
Upper NF Side2 (UNF Side2)	-	0	-
Upper NF Side3 (UNF Side3)	-	0	-
Boulder River (BR Trib)	-	-	4
Lower NF Main (LNF Main)	0	-	-
Lower NF Trib (LNF Trib)	-	-	0
Lower SF Main (LSF Main)	2	-	-
Lower SF Side (LSF Side)	-	0	-
Jim Creek 1 (JC Trib1)	-	-	0
Jim Creek 2 (JC Trib2)	-	-	0
Jim Creek 3 (JC Trib3)	-	-	0
Total	24	0	4

Table 5. Adult Chinook observations for each survey reach, categorized by habitat type.

Juvenile Coho Counts (Densities)			
Reach	Mainstem	Side Channel	Tributary
Upper NF Main1 (UNF Main1)	1,658 (1.78)	-	-
Upper NF Main2 (UNF Main2)	944 (1.00)	-	-
Upper NF Side1 (UNF Side1)	-	336 (1.68)	-
Upper NF Side2 (UNF Side2)	-	185 (0.93)	-
Upper NF Side3 (UNF Side3)	-	142 (0.71)	-
Boulder River (BR Trib)	-	-	52 (0.26)
Lower NF Main (LNF Main)	245 (0.44)	-	-
Lower NF Trib (LNF Trib)	-	-	32 (0.16)
Lower SF Main (LSF Main)	17 (0.01)	-	-
Lower SF Side (LSF Side)	-	171 (0.86)	-
Jim Creek 1 (JC Trib1)	-	-	581 (1.89)
Jim Creek 2 (JC Trib2)	-	-	203 (1.02)
Jim Creek 3 (JC Trib3)	-	-	1 (0.00)
Total	2,864 (0.78)	834 (1.04)	869 (0.72)

Table 6. Juvenile coho observations and densities for each survey reach, categorized by habitat type.

Figures

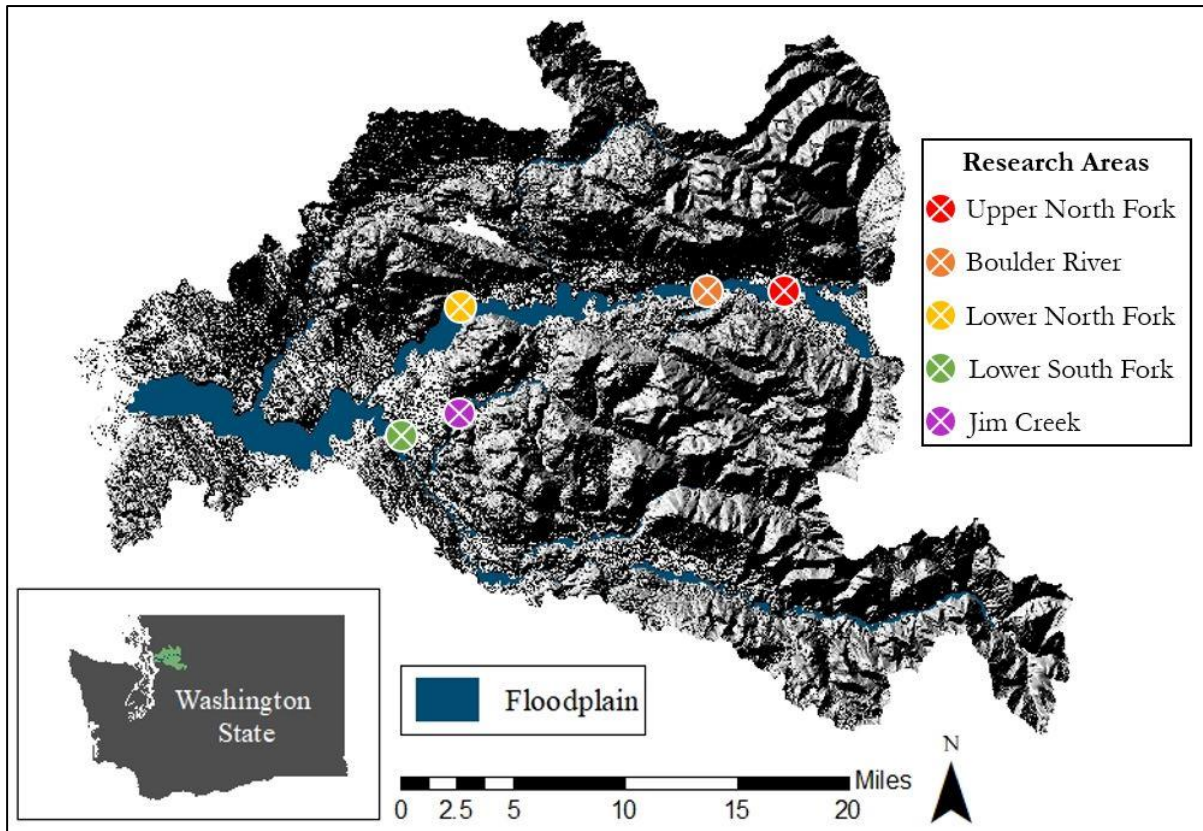


Figure 1. Location of the Stillaguamish River basin, Washington. The blue shading delineates the extent of the floodplain within the basin and the colored dots represent approximate locations of the research areas.

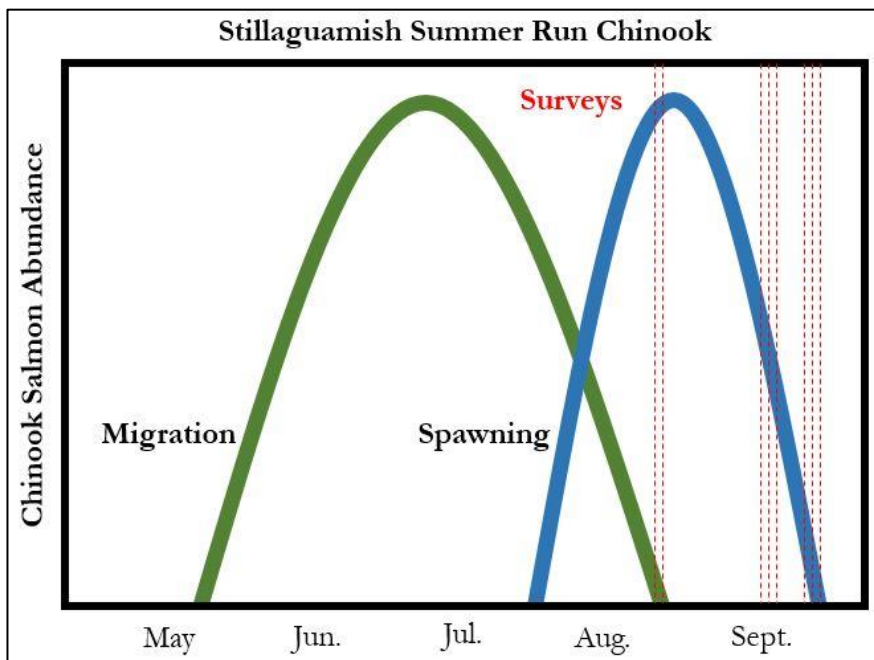


Figure 2. Migration and spawning seasons for North Fork summer run Chinook salmon in comparison to our survey dates. Surveys were done in the middle to end of their spawning season. Spawning data is from Whitely Binder et al. 2017.

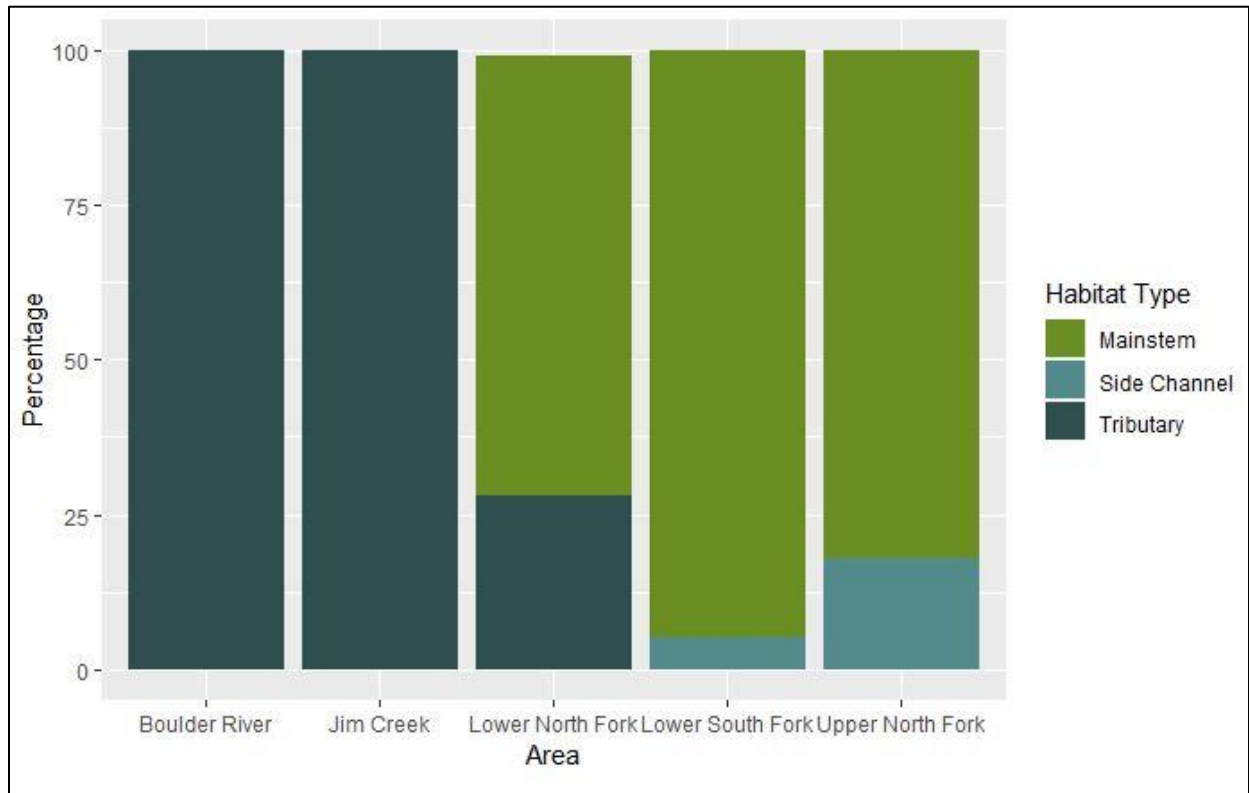


Figure 3. Bar graph illustrating the percentage of each area surveyed that was either mainstem, side channel, or tributary habitat.

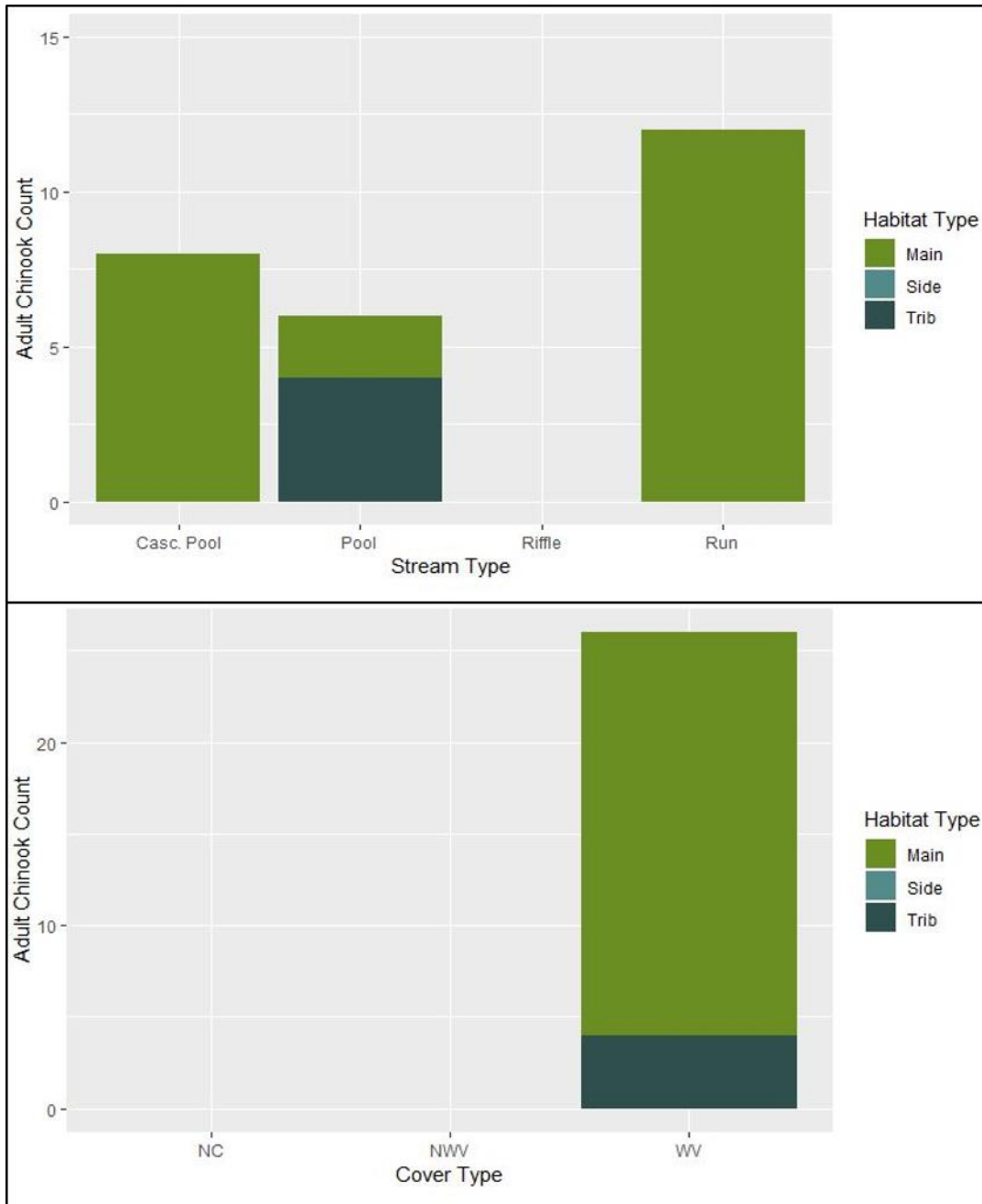


Figure 4. Bar graphs categorized by habitat type illustrating adult Chinook observations by stream type (top) and cover type (bottom). Cover types include no cover (NC), no wood or vegetation present (NWV), and wood and vegetation present (WV).

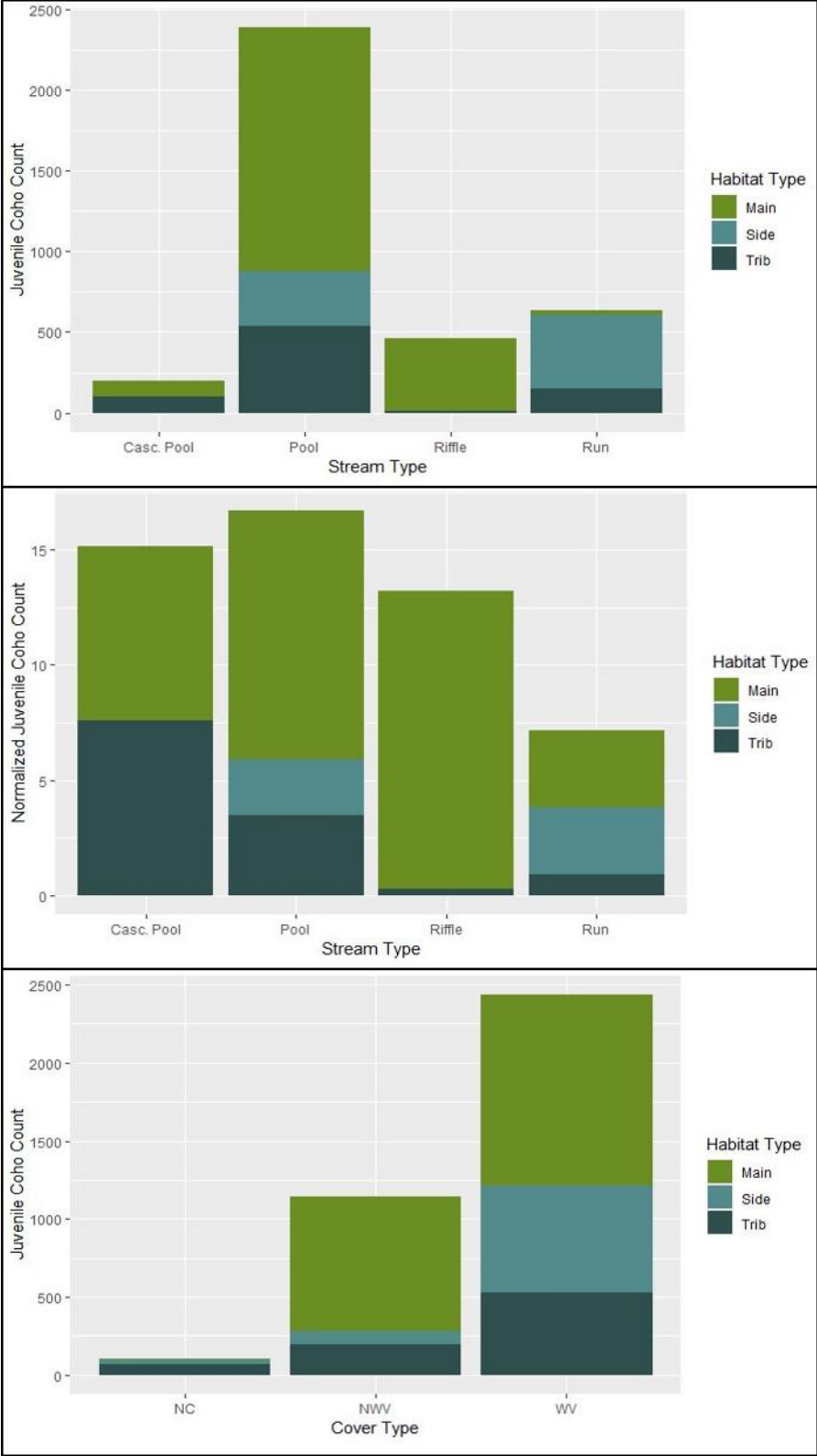


Figure 5. Bar graphs categorized by habitat type illustrating juvenile coho observations by stream type (top & middle) and cover type (bottom). The middle graph shows normalized juvenile coho counts by stream type (total fish counts in each stream type divided by the number of times we surveyed that particular stream type). Cover types include no cover (NC), no wood or vegetation present (NWV), and wood and vegetation present (WV).

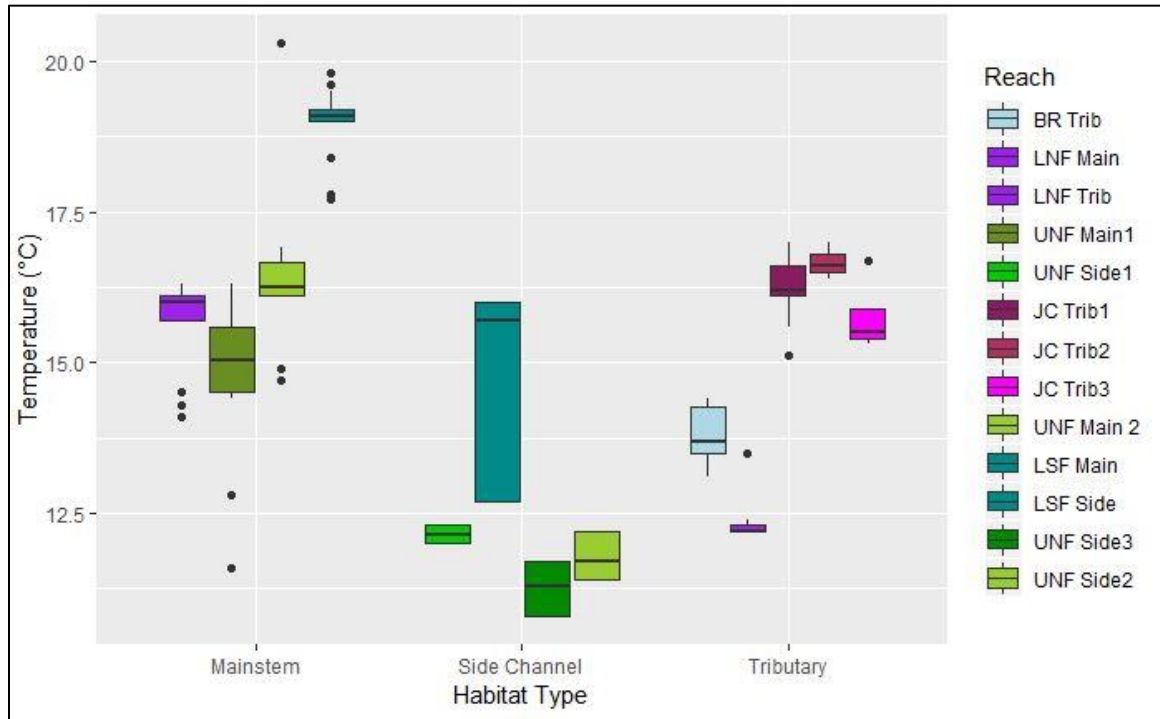


Figure 6. Boxplot illustrating stream temperature variability for each reach by habitat type.

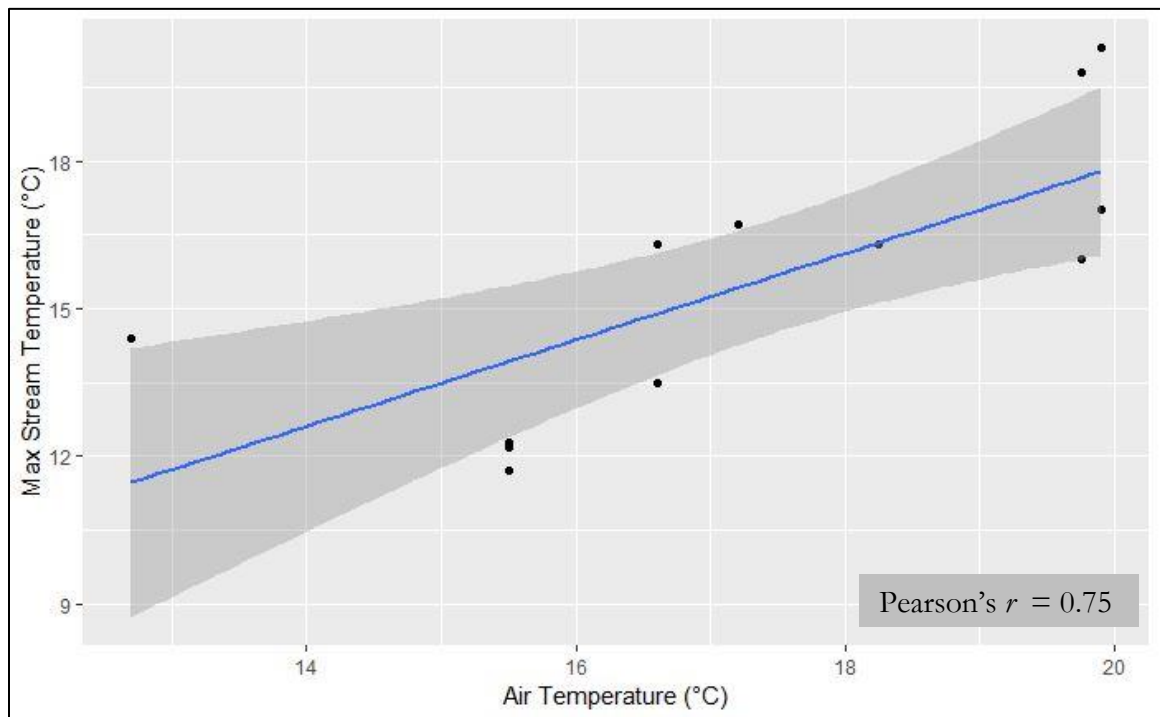


Figure 7. Scatterplot displaying a strong, positive relationship between air and max stream temperatures for the 13 reaches on the various survey dates.

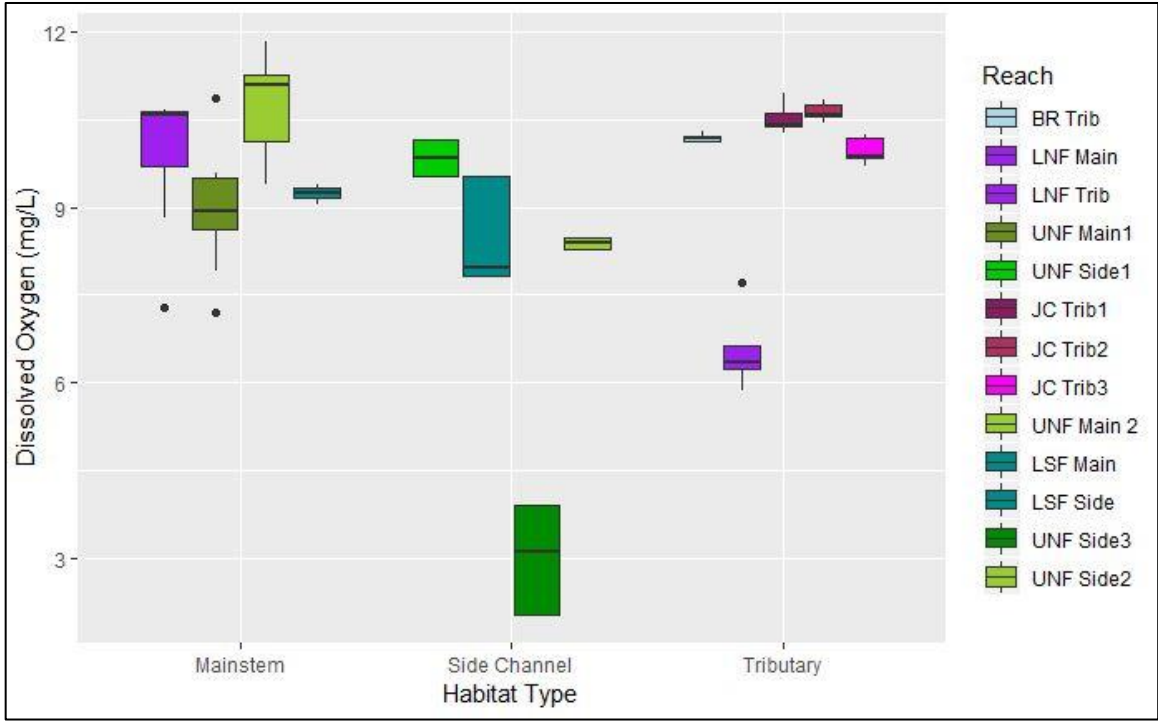


Figure 8. Boxplot illustrating dissolved oxygen variability for each reach by habitat type.

References

- Anchor QEA (2016) North Fork Stillaguamish River 2016 restoration assessment and conceptual design. Final memorandum for the Stillaguamish Tribe of Indians, Arlington, Washington
- Battin J, Wiley MW, Ruckelshaus MH, Palmer RN, Korb E, Bartz KK, Imaki H (2007) Projected impacts of climate change on salmon habitat restoration. *PNAS* 104(16):6720 – 6725
- Beechie TJ, Bolton S (1999) An approach to restoring salmonid habitat-forming processes in Pacific Northwest watersheds. *Fisheries* 24:6 – 15
- Beechie TJ, Imaki H, Greene J, Wade A, Wu H, Pess G, Roni P, Kimball J, Stanford J, Kiffney P, Mantua N (2013) Restoring salmon habitat in a changing climate. *River Research Application* 29:939 – 960
- Beechi TJ, Pess GR, Imaki H, Martin A, Alvarez J, Goodman DH (2015) Comparison of potential increases in juvenile salmonid rearing habitat capacity among alternative restoration scenarios, Trinity River, California. *Restoration Ecology* 23(1):75 – 84
- Bellmore JR, Benjamin JR, Newsom M, Bountry JA, Dombroski A (2017) Incorporating food web dynamics into ecological restoration: a modeling approach for river ecosystems. *Ecological Applications* 27(3):814 – 832
- Bond MH, Nodine TG, Beechi TJ, Zabel RW (2018) Estimating the benefits of widespread floodplain reconnection for Columbia River Chinook salmon. *Canadian Journal of Fisheries and Aquatic Sciences* 00:1 – 15
- Brown C and Hallock D (2009) Washington State dissolved oxygen standard: A review and discussion of freshwater intragravel criteria development. Washington State Department of Ecology (publication number 09-03-039)
- Carter K (2005) The effects of dissolved oxygen on steelhead trout, coho salmon, and chinook salmon biology and function by life stage. Prepared for the California Regional Water Quality Control Board, North Coast Region. Retrieved from <http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.640.8406&rep=rep1&type=pdf>
- Climate Impacts Group (2015) How will climate change affect the Stillaguamish Watershed? Prepared for Floodplains by Design, Seattle, Washington
- Edwards SL (2003) Forestry policy analysis for salmon recovery planning in the Stillaguamish Watershed (WRIA 5). Final report prepared for the Stillaguamish Implementation Review Committee, Arlington, Washington

- Fullerton AH, Torgersen CE, Lawler JJ, Steel EA, Ebersole JL, Lee SY (2018) Longitudinal thermal heterogeneity in rivers and refugia for coldwater species: effects of scale and climate change. *Aquatic Sciences* 80:3
- Hall JE, Beechie TJ, Pess GR (2014) Influence of climate and land cover on river discharge in the North Fork Stillaguamish River. Final report prepared for the Stillaguamish Tribe of Indians, Arlington, Washington
- Hand et al. (2018) A social-ecological perspective for riverscape management in the Columbia River Basin. *Front Ecol Environ* 16(S1):S23 – S33
- Hawkins et al. (1993) A Hierarchical approach to classifying stream habitat features. *American Fisheries Society* 18(2):3 – 12
- Justice C, White SM, McCullough DA, Graves DS, Blanchard MR (2017) Can stream and riparian restoration offset climate change impacts to salmon populations? *Journal of Environmental Management* 188:212 – 227
- Kennedy BM, Baumsteiger J, Gale WL, Ardren WR, Ostrand KG (2008) Morphological, physiological, and genetic techniques for improving field identification of steelhead, coastal cutthroat trout, and hybrid smolts. *Marine and Coastal Fisheries: Dynamics, Management, and Ecosystem Science* 1(1):45 – 56
- Konrad KP (2015) Geospatial assessment of ecological functions and flood-related risks on floodplains along major rivers in the Puget Sound Basin, Washington. U.S. Department of the Interior and U.S. Geological Survey. Prepared in cooperation with The Nature Conservancy, Washington State Department of Ecology, and U.S. Environmental Protection Agency, Scientific Investigations Report 2015-5033
- Krosby M, Morgan HC, Whitely Binder L (2016) Stillaguamish Tribe natural resources climate change vulnerability assessment. Climate Impacts Group, University of Washington
- Lake Stewards of Maine (2019) Maximum dissolved oxygen concentration saturation table. Accessed 25 March 2019. Retrieved from <https://lakestewardsofmaine.org/wp-content/uploads/2014/01/Maximum-Dissolved-Oxygen-Concentration-Saturation-Table.pdf>
- Leonetti FE (2019) Stillaguamish floodplain channel monitoring. Snohomish County Public Works, Surface Water Management. Everett, WA. Prepared for the Stillaguamish Technical Advisory Group. Retrieved from

[http://www.stillaguamishwatershed.org/TAG%20Meetings/2019%20TAG%20Meetings/04-%20April/StillySideChannelMon_TAG_2019%20\(reduced\).pdf](http://www.stillaguamishwatershed.org/TAG%20Meetings/2019%20TAG%20Meetings/04-%20April/StillySideChannelMon_TAG_2019%20(reduced).pdf)

- Leonetti FE (2015) Summer temperature monitoring among channel and habitat types in the Stillaguamish watershed, 2008-2012. Snohomish County Public Works, Surface Water Management. Everett, WA. Prepared for the Washington State Department of Ecology (grant agreement G1000349), Bellevue, Washington
- Leonetti FE, Terpstra KJ, Dittbrenner B (2015) Temperature anomalies in the Stillaguamish River mapped from 2001 infrared aerial imagery. Snohomish County Public Works, Surface Water Management. Everett, WA. Prepared for the Washington State Department of Ecology (grant agreement G1000349), Bellevue, Washington
- Leonetti FE, Bylin A, Hagen S (2015) Stillaguamish watershed characterization: An application of Washington Department of Ecology's water flow process results to describe landscape-scale influence on water temperature. Snohomish County Public Works, Surface Water Management. Everett, WA. Prepared for the Washington State Department of Ecology (grant agreement G1000349), Bellevue, Washington
- Lytle DA and Poff NL (2004) Adaptation to natural flow regimes. *Trends in Ecology and Evolution* 19(2): 94-100
- Mantua N, Tohver I, Hamlet A (2009) Climate change impacts on streamflow extremes and summertime stream temperature and their possible consequences for freshwater salmon habitat in Washington State. *Climate Change* 10:187 – 223
- Mastin MC, Konrad CP, Veilleux AG, Tecca AE (2016) Magnitude, frequency, and trends of floods at gaged and ungaged sites in Washington, based on data through water year 2014. (ver1.1, November 2017) U.S. Geological Survey Scientific Investigations Report 2016-5118: 70. Available at <http://dx.doi.org/10.3133/sir20165118>
- Mauger GS, Casola JH, Morgan HA, Strauch RL, Jones B, Curry B, Busch Isaksen TM, Whitely Binder L, Krosby MB, Snover AK (2015) State of knowledge: Climate change in Puget Sound. Report prepared for the Puget Sound Partnership and the National Oceanic and Atmospheric Administration. Climate Impacts Group, University of Washington, Seattle. doi:10.7915/ CIG93777D. Available at <https://cig.uw.edu/resources/special-reports/ps-sok/>

- Meehl GA, Tebaldi C, Adams-Smith D (2016) US daily temperature records past, present, future. Proceedings of the National Academy of Sciences. Retrieved from <https://news.ucar.edu/124082/days-record-breaking-heat-ahead>
- Mejia FH, Baxter CV, Berntsen EK, Fremier AK (2016) Linking groundwater – surface water exchange to food production and salmon growth. Canadian Journal of Fisheries and Aquatic Sciences 73:1650 – 1660
- Montgomery DR and Buffington JM (1997) Channel-reach morphology in mountain drainage basins. Geological Society of America Bulletin 109: 596 – 611
- Parker DJ (1995) Floodplain development policy in England and Wales. Applied Geography 15(4):341 – 363
- Palmer et al. (2005) Standards for ecologically successful river restoration. Journal of Applied Ecology 42:208 – 217
- Pollock MM, Pess GR, Beechie TJ and Montgomery DR (2003) The importance of beaver ponds to coho salmon production in the Stillaguamish River Basin, Washington, USA. North American Journal of Fisheries Management 24:749 – 760
- R Development Core Team (2008) R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna. ISBN: 3-900051-07-0, <http://www.R-project.org/>
- Roni P, Beechie TJ, Bilby RE, Leonetti FE, Pollock MM, Pess GR (2002) A review of stream restoration techniques and a hierarchical strategy for prioritizing restoration in Pacific Northwest watershed. North American Journal of Fisheries Management 22:1 – 20
- Stillaguamish Tribe of Indians (2016) State of our watersheds – Stillaguamish River Basin. Final report prepared for the NW Treaty Tribes, Arlington, Washington
- The Nature Conservancy (2016) Floodplains by design: Vision, strategies and actions for Puget Sound major river floodplains. Final report prepared for Puget Sound Partnership and Washington State’s Department of Ecology
- Torgersen CE, Ebersole JL, Keenan DM (2012) Primer for identifying cold-water refuges to protect and restore thermal diversity in riverine landscapes. Report number EPA 910-C-12-001. U.S. Environmental Protection Agency, Region 10, Seattle, Washington under EPA Interagency Agreement No. DW-14-95755001-0

- Trush WJ, McBain SM, Leopold LB (2000) Attributes of an alluvial river and their relation to water policy and management. *Proceedings of the National Academy of Sciences* 97:11858 – 11863
- Ver Hoef JM, Boveng PL (2007) Quasi-Poisson vs. negative binomial regression: How should we model overdispersed count data? *Ecology Society of America* 88(11):2766 – 2772
- Whitely Binder L, Morgan H, Krosby M, Sevigny J, Summers A, Neuffer T (2017) Stillaguamish Tribe of Indians natural resources climate change adaptation plan. A collaboration of the Stillaguamish Natural Resources Department and the University of Washington Climate Impacts Group, Seattle, Washington
- Whitmore CM, Warren CE, Doudoroff P (1960) Avoidance reactions of salmonid and centrarchid fishes to low oxygen concentrations. *Trans Am Fish Soc* 89:17 – 26
- Woelfle-Erskine C, Larsen LG, Carlson SM (2017) Abiotic habitat thresholds for salmonids over-summer survival in intermittent streams. *Ecosphere* 8(2): e01645.10.1002/ecs2.1645
- Washington State Conservation Commission (1999) Salmon habitat limiting factors final report. Prepared for the Water Resource Inventory Area (WRIA) 5 Stillaguamish Watershed. Retrieved from <https://snohomishcountywa.gov/Archive/ViewFile/Item/2137>. Accessed on 20 December 2018
- Quinn TP (2018) *The behavior and ecology of Pacific salmon and trout*. University of Washington Press, Seattle

Appendix A: Reach-scale Maps

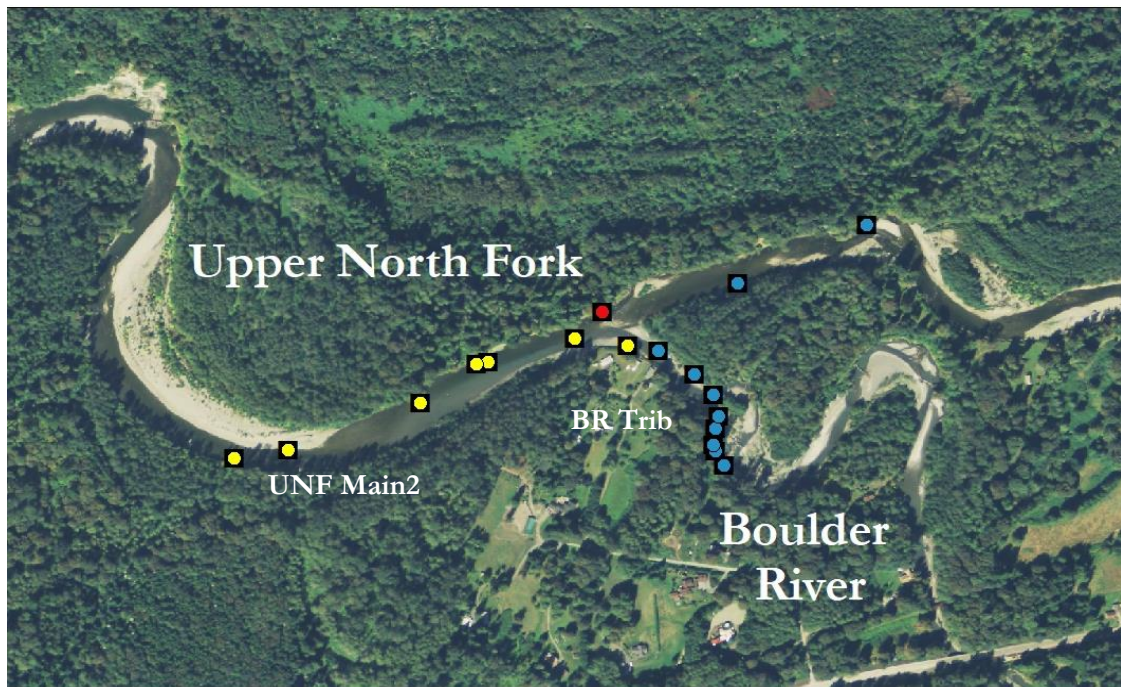
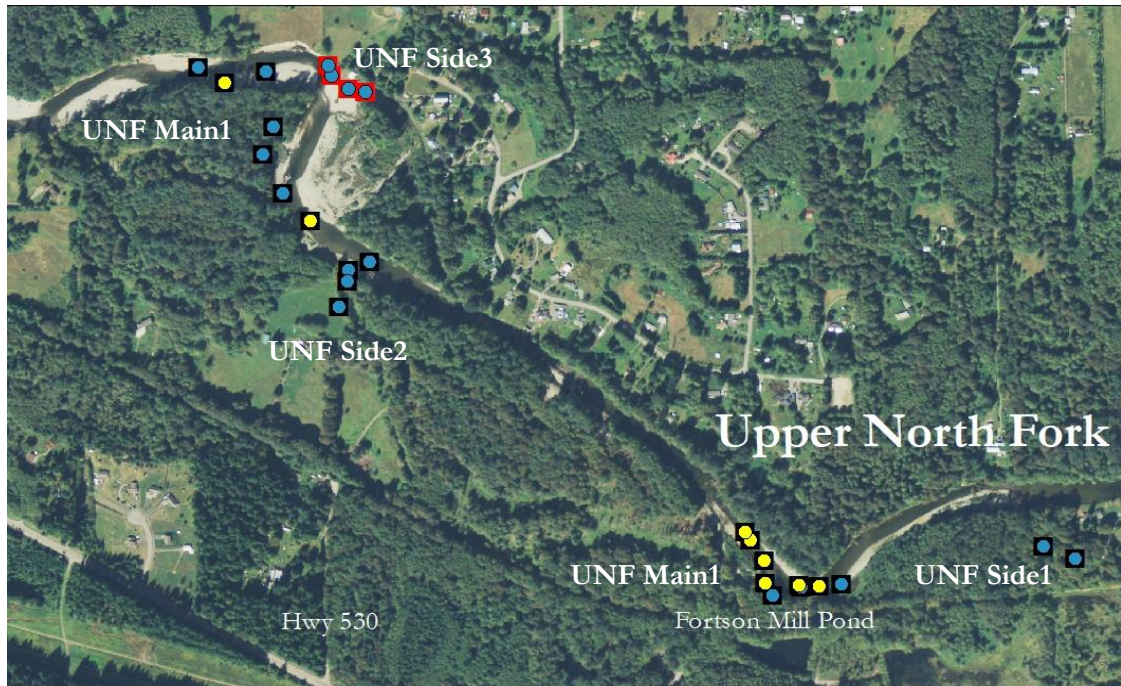


Figure 1. Reach-scale maps of the Upper North Fork and Boulder River areas displaying stream temperature and dissolved oxygen measurements. Top: UNF Main1, UNF Side1, UNF Side2, UNF Side3. Bottom: UNF Main2 and BR Trib.

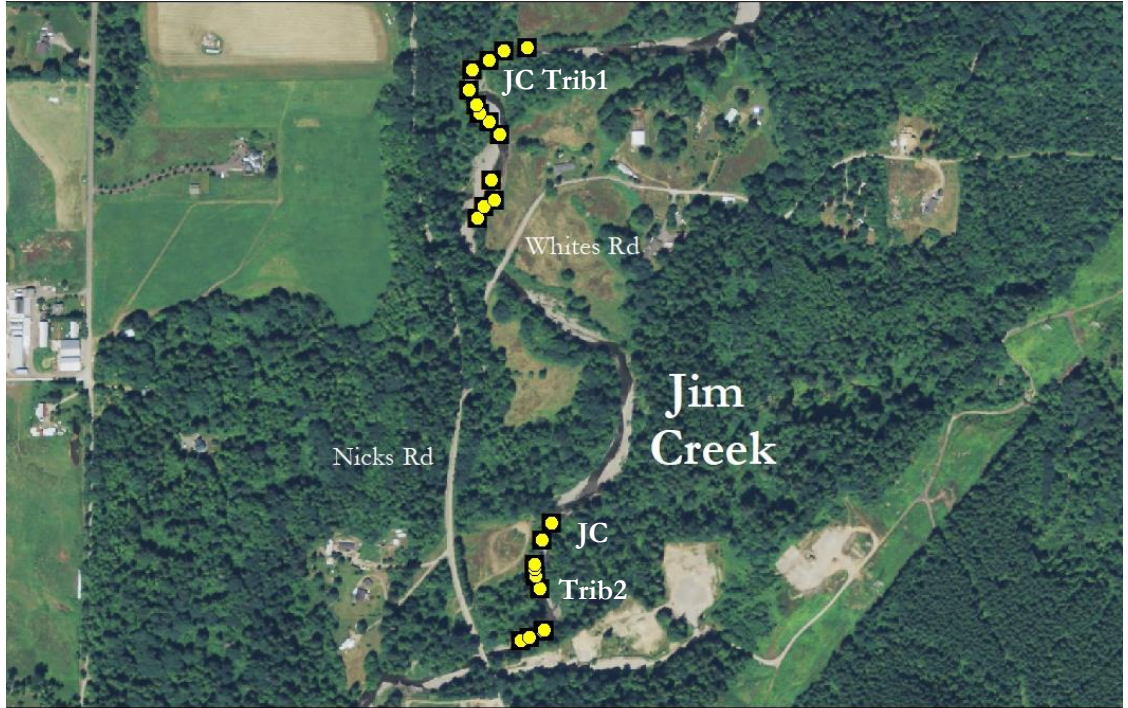
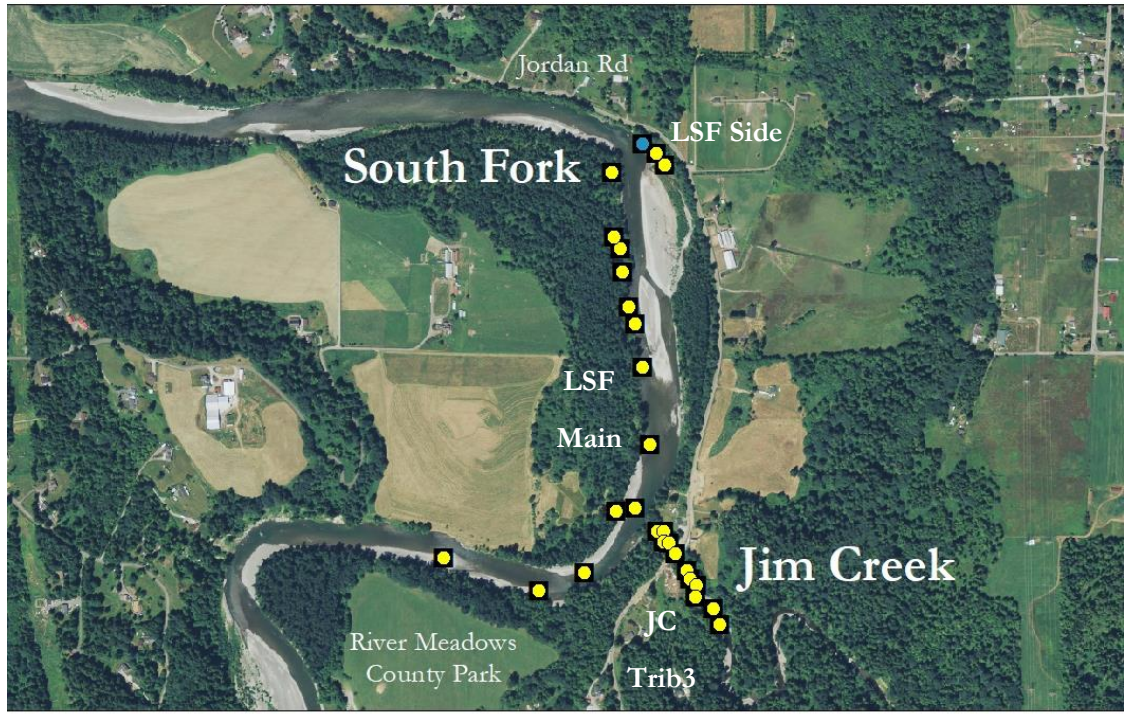


Figure 2. Reach-scale maps of the Lower South Fork and Jim Creek areas displaying stream temperature and dissolved oxygen measurements. Top: LSF Main, LSF Side, JC Trib1. Bottom: JC Trib1 and JC Trib2.

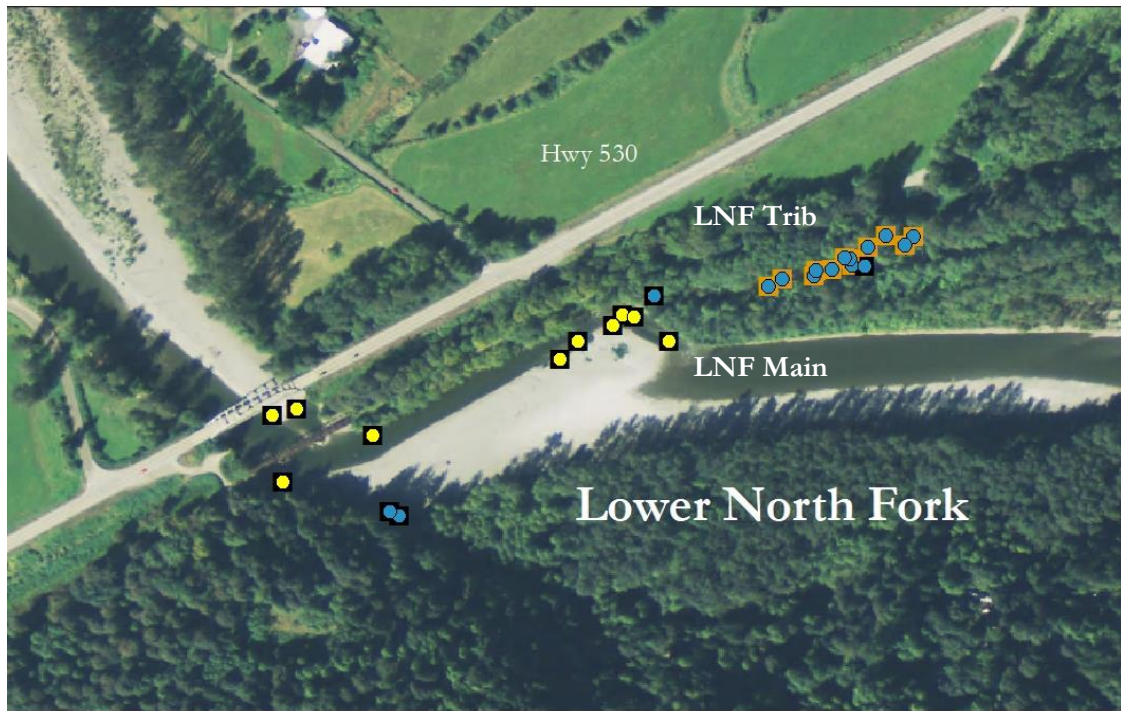


Figure 3. Reach-scale map of the Lower North Fork area near the town of Cicero displaying stream temperature and dissolved oxygen measurements. Reaches within this area include LNF Main and LNF Trib.

Appendix C: Cover and Stream Classifications

All Cover Types		
Abbreviation	Type	Description
BL	Boulder	Rocks ≥ 256 mm
BD	Bedrock	Exposed Solid Rock
CB	Cobble	Rounded rocks 64-256 mm
DW	Deep Water	Water depths > 1 m (other cover takes precedence)
VG	Vegetation	Live, terrestrial vegetation
APL	Aquatic Plants	Live, non-woody aquatic vegetation
RR	Riprap	Angular boulder sized rock placed for bank protection
UB	Undercut Banks	Submerged area underneath an overhanging bank
BH	Branch	Woody debris < 20 cm in diameter, not accumulated in debris pile
BR	Bank Roots	Roots of live trees and shrubs in the water
DP	Debris Piles	Numerous or single types of wood cover accumulated in a pile or jam
SL	Single Log	Woody debris > 20 cm in diameter, not accumulated in a pile or jam
RW	Rootwad	Roots and lower trunk of non-growing trees
NC	No Cover	Substrate $<$ cobble size, depth < 1.0 m, and none of the above present

Refined Cover Types		
Wood/Vegetation (WV)	No Wood/Vegetation (NWV)	No Cover (NC)
VG APL UB BH BR DP SL RW DW	BL BD CB RR DW	NC
<i>*Banks within a geomorphic unit were labelled WV if any of these cover types were present.</i>	<i>*Banks within a geomorphic unit were labelled NWV if any of these cover types were present without wood or vegetation.</i>	<i>*Banks within a geomorphic unit were labelled NC if there was no cover.</i>

Stream Classifications			
Level 1	Abbreviation	Habitat Type	Description
	MC	Main Channel	Mainstem River
	BC	Braided Main Channel	Two or more channels separated by bar(s) with little to no vegetation
	SC	Side Channel	A channel separated from the main by well vegetated riparian woodland
	OC	Overflow Channel	Small channels that inter-connect a side channel to the main channel.
	TM	Tributary Mouth	Mouth of a tributary stream entering the main channel.
	SL	Slough	Slough formed when sediment/organic debris block head of a braid or branch of a mainstem (slow water velocity)
Level 2	Level 3	Level 4	Description
FW (Fast Water)			Riffles; rapid, shallow stream sections with steep water surface gradient
	TUR (Turbulent)		Channel units having swift currents, high channel roughness, steep gradient, nonlaminar flow
		FA (Fall)	Steep vertical drop in water surface elevation
		CD (Cascade)	Series of alternating small falls and shallow pools
		RP (Rapid)	Deeper section with considerable surface agitation and swift current, standing waves often present
		RI (Riffle)	Shallow, lower gradient channel units with moderate current velocity and some partially exposed substrate
		CH (Chute)	Narrow, confined channel with rapid, relatively unobstructed flow and bedrock substrate
	NT (Non Turbulent)		Channel units having low channel roughness, moderate gradient, laminar flow, and lack of surface turbulence
		SH (Sheet)	Shallow water flowing over smooth bedrock
		RN (Run)	Shallow water flowing over a variety of substrates
SW (Slow Water)			slow velocity; low water surface gradient
	SP (Scour Pool)		Formed by scouring action of current
		ED (Eddy)	Formed by circular current pattern created by bank obstruction, usually occur along the bank
		TR (Trench)	Formed by scouring of bedrock, usually located in the main channel
		MC (Mid-Channel)	Form in the main channel by channel constriction at head of a pool.
		CV (Convergence)	Form in the main channel by converging streams
		LT (Lateral)	Formed in mainstem where flow is deflected by partial channel obstruction; usually outside bends of meandering streams, deeper on one side than the other and form as a result of a deflector at the head of the pool
		PL (Plunge)	Form in main channel, deeper upstream, and are formed by water dropping vertically over a channel obstruction
		DE (Deposition)	Depositional area within a scour pool. Usually along the point bar of a lateral scour pool.
	DP (Dammed Pool)		Water impounded by channel blockage
		DS (Debris)	Formed by rootwad and logs
		BR (Beaver)	Formed by beaver
		LS (Landslide)	Formed by large boulders
		BW (Backwater)	Formed by obstructions along banks
		AC (Abandoned Ch.)	Formed alongside main channel, usually associated w/gravel bars.

Appendix D: Photos



D.1: Downstream end of LSF Side with very low streamflow.



D.2: Upstream end of LSF Side with dammed pool created by beaver.



D.3: Downstream end of UNF Side3 dammed up by beaver.



D.4: Upstream end of UNF Side3 dried up and disconnected from the mainstem.



D.5: Snorkel surveying UNF Side2 that had an engineered logjam in place.



D.6: An adult Chinook salmon using a rootwad from an engineered logjam as shelter in UNF Main2.