Validating Snoqualmie River Juvenile Salmonid Habitat Use and Associations

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King County

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Executive Summary

The Snoqualmie River provides important rearing habitat for juvenile salmonids, but habitats have been lost or degraded and remain a key limiting factor for juvenile abundance, growth, and survival. Understanding and validating juvenile salmonid habitat use and associations (i.e., habitat types and rearing conditions that juvenile salmonids prefer and need during early life stages) is fundamental to protecting and restoring the habitats and watershed processes that support juvenile salmonids. Snoqualmie River habitat restoration strategies are largely structured around these salmonid habitat associations; however, current understandings and assumptions are largely based on small-scale project monitoring or information from other rivers across Puget Sound.

To better understand and validate Snoqualmie River juvenile salmonid habitat use and associations, we conducted spatially extensive, randomized fish and habitat sampling across channel margin edge habitats in the lower Snoqualmie River from the confluence with the Raging River downstream to near the City of Duvall. We characterized and mapped mainstem edge habitats throughout the study extent and conducted fish and habitat sampling among randomly selected transects during late winter and spring (March–June) in 2022, late summer and early fall (September–October) in 2022, and the following winter (January) in 2023.

Our results validated prior Snoqualmie River project monitoring and research, showing that mainstem edge habitats throughout the lower Snoqualmie River are used by juvenile Chinook and coho salmon and trout (rainbow/steelhead and cutthroat) for early rearing. Snoqualmie River edge habitats support multiple life histories including sub-yearling fry and parr (recently emerged from redds) as well as yearling (born the prior year). In addition, our study further documented a cohort of late-emerging juvenile Chinook, which may contribute to the yearling life history.

Shallow and low-velocity edge habitats like bars and backwaters were preferred by sub-yearling Chinook and coho salmon, especially in late winter and spring. In addition, sub-yearling Chinook were more likely to be present and in greater abundance in edge habitats with smaller substrates like sand and gravel. Sub-yearling Chinook and coho were less frequent and less abundant in armored banks, which further validates that armored banks are unsuitable for sub-yearling salmon. As juvenile salmon grow, they transition to deeper and higher-velocity habitats such as armored and unarmored banks, which we observed, with yearling Chinook and coho salmon and trout more frequent and in greater abundance in bank habitats.

Our findings suggest that the availability and diversity of edge habitats are important for juvenile salmonids, which supports prior monitoring and research findings. Juvenile Chinook and coho salmon and trout were not only frequently observed using mainstem edge habitats but were observed across the full suite of available edge habitats. Edge habitats were used throughout the year with species and life histories displaying distinct seasonal shifts in edge habitat use. In addition, our findings reaffirm monitoring and

research observations, showing that sub-yearling salmonids are frequent and abundant in bars, likely due to shallow depth, wide low-velocity areas, and smaller substrates.

We observed that sub-yearling Chinook salmon were most abundant in reaches of the Snoqualmie River just downstream of the Tolt and Raging rivers. These Snoqualmie River reaches also had the greatest diversity of unarmored edge habitats, were near core Chinook spawning areas, and had the greatest extent of gravel and cobble bars. Our findings support that continued mainstem edge habitat restoration in these reaches will provide juvenile Chinook with more rearing opportunities that are both near the redds where they emerged and near important edge habitats.

This study and observations from Snoqualmie River project monitoring and research provide a collective basis to inform, validate, and refine habitat restoration strategies. Collective findings show that a continued focus on improving the extent, availability, and connectivity of low-velocity and shallow edge habitats will benefit juvenile salmonid rearing and increase abundance. Consistent and collective findings validate that removing bank armoring should remain a high priority for Snoqualmie River habitat restoration, because this action allows natural channel sediment, hydrologic, and migration processes to function, creating and maintaining mainstem habitats. Additionally, continued placement of large wood and restoration of riparian areas and related wood recruitment processes will benefit salmonid rearing conditions.

Habitat restoration actions that create and maintain a diversity of edge habitats will also benefit juvenile salmonids. A diversity of edge habitats provides the rearing habitats and conditions necessary to support various juvenile salmonid life histories, which in turn, may promote juvenile growth and survival and the productivity of Snoqualmie River salmonid populations. Habitat restoration project teams should ensure that a diversity of mainstem edge habitats is available across environmental conditions and seasons, especially for juvenile salmonids with extended freshwater rearing. Additionally, to fully support juvenile salmonid rearing, restoration project teams should consider how project actions create and maintain bar habitat and improve tributary confluence areas. Finally, Snoqualmie River reaches just downstream of the Tolt and Raging rivers should remain a high priority for salmonid habitat restoration and projects in these areas should maximize the extent, availability, and diversity of restored edge habitats.

1 Introduction

The Snoqualmie River provides critical rearing habitat for early life stages of several salmonids, including juvenile Chinook salmon (*Oncorhynchus tshawytscha*), which are listed as threatened under the Endangered Species Act. Channel edge habitats across the Snoqualmie River are especially important because channel margins are often used by juvenile salmonid for rearing during early life stages (Hillman et al. 1987; Bjornn and Reiser 1991; Beechie et al. 2005; King County 2021a, 2023). Edge habitats often have lower water velocities, shallower depths, and increased cover relative to mid-channel areas (Murphy et al. 1989; Tiffan et al. 2002; Beechie et al. 2005), all of which juvenile salmonids prefer for early rearing. Additionally, edge habitats can also be highly productive, supporting juvenile salmonid foraging and growth opportunities.

Across the Snoqualmie River, mainstem edge habitats have been lost or degraded due to several factors, including shoreline armoring from revetments and levees, construction of fish passage barriers, altered channel conditions, large wood removal, and widespread alteration and removal of riparian vegetation (Haring 2002; SBSRF 2005). Diminished and degraded rearing habitat are presumed to be key limiting factors impacting juvenile salmonid growth and survival (Haring 2002; SBSRF 2005; Beechie et al. 2023). Additionally, the productivity of Snoqualmie River salmonid populations, based on the number of offspring that successfully return to spawn for each spawning adult, is at only a small fraction of historical levels and currently well below salmonid recovery goals (SWF 2022).

Understanding juvenile salmonid habitat use and associations is fundamental to restoring and protecting the habitats and watershed processes that influence juvenile abundance, growth, and survival. Snoqualmie River habitat restoration strategies are largely structured around juvenile salmonid habitat associations; specifically, the habitat types and rearing conditions that juvenile salmonids are known to prefer or presumed to need during early life stages. However, current salmonid habitat associations, understandings, and assumptions are largely based on either small-scale project monitoring or information from other large rivers across the Puget Sound region.

Snoqualmie River project monitoring has generated valuable data on salmonid habitat use, but inferences remain limited because monitoring efforts only sample select seasons and small-scale, project-specific river reaches. As a result, restoration projects may be limited in how well they represent important habitats and habitat conditions that occur both throughout the Snoqualmie River and across seasons. Information from other river systems across the Puget Sound can also be useful; however, they may be limited in representing local salmonid adaptations and habitat requirements. Incorporating Snoqualmie-specific habitat use and associations can help ensure restoration strategies best support Snoqualmie River salmonid habitat needs and requirements. Generally, watershed-specific juvenile salmonid habitat associations are not detailed in the 2005 Snohomish River Basin Salmon Conservation Plan (Snohomish Salmon Plan), and several salmonid habitat associations are either assumed, inferred, or still need to be thoroughly evaluated (Kubo 2022a). A comprehensive evaluation of salmonid habitat associations would help refine restoration strategies, project designs,

and adaptive management approaches to best support Snoqualmie River salmonids. Additionally, validating salmonid habitat associations helps ensure that habitat types critical for different species and life stages are restored and protected.

To better understand and validate Snoqualmie River juvenile salmonid habitat use and associations, we conducted spatially extensive, randomized fish and habitat sampling along the lower Snoqualmie River. Our primary goal was to assess salmonid habitat use among mainstem edge habitats in spring, late-summer/early-fall, and winter. The primary questions and predictions of our study included:

1. Which juvenile salmonid life histories use mainstem edge habitats?
    - We predicted that the mainstem Snoqualmie River supports sub-yearling and yearling Chinook and coho salmon and trout.
2. How does the presence and relative abundances of juvenile salmonids vary among mainstem edge habitat types and do habitat associations differ among species and life histories?
    - We predicted that juvenile salmonid abundance would differ across edge habitats and that species and life histories would display distinct edge habitat preferences. Additionally, we predicted that sub-yearling salmonids do not prefer armored banks.
3. How do factors like water depth, low-velocity width, substrate, large wood, and cover vary among mainstem edge types?
    - We predicted that backwaters and bars would be shallow, have the greatest low-velocity widths, and the smallest substrates. Additionally, we predicted that large wood would be most frequent, and cover would be greatest in unarmored banks.
4. What is the distribution of mainstem edge habitats and juvenile salmonids throughout the lower Snoqualmie River?
    - We predicted that edge habitats and juvenile salmonids would not be evenly distributed across the lower Snoqualmie River.
5. What are the physical drivers of juvenile salmonid presence and abundance?
    - We predicted that edge type, water depth, low-velocity width, large wood, and substrate would be drivers of juvenile salmonid presence and abundance.

We compared results from our study with prior Snoqualmie River project monitoring and research to provide collective understandings to validate salmonid habitat associations, validate ongoing restoration strategies, and identify further considerations worth integrating into strategies moving forward. These collective findings will help ensure that restoration strategies and project designs best support the habitats and processes critical for juvenile salmonid rearing in the mainstem Snoqualmie River.

2 Methods

2.1 Survey Extent, Reaches, and Seasonal Periods

We surveyed mainstem edge habitats and salmonid presence, abundance, and distribution along the lower Snoqualmie River from river mile (RM) 34, at the confluence with the Raging River, downstream to RM 9, near the City of Duvall (Figure 1). We focused on this extent because it captured most of the Snoqualmie River reaches that are prioritized for mainstem habitat restoration. We characterized and mapped edge habitats throughout this extent, with edge habitat measurements and salmonid surveys conducted within four separate reaches, including the Raging River confluence downstream to the Neal Road boat launch (RM 34.3 to 31), Neal Road boat launch to the Tolt River boat launch (RM 31 to 23.9), Stossel Bridge to just upstream of the NE 124th Street bridge (RM 21.9 to 14.2), and NE 124th Street bridge to the Taylor Landing boat launch (RM 14.2 to 9). These reaches were chosen to ensure survey lengths were feasible for same day habitat and fish surveys (discussed in Subsection 2.2 and 2.3) The Snoqualmie River reach from the Tolt River to the Stossel Bridge was not included for edge habitat measurements and salmonid surveys because adding this additional length to either the upstream or downstream reach would be infeasible due to survey length and time. We included additional survey locations in the Raging River to Neal Road reach (RM 34.3 to 31) to provide concurrent project effectiveness monitoring for the Fall City Floodplain Restoration Project. We used the same habitat measurement and fish collection methods for all study and project monitoring survey locations, as described in Subsections 2.2 and 2.3. We sampled the four survey reaches for habitat and salmonids three times from late winter through spring (March–June) of 2022, once in late summer through early fall (September–October) of 2022, and once in winter (January) of 2023.

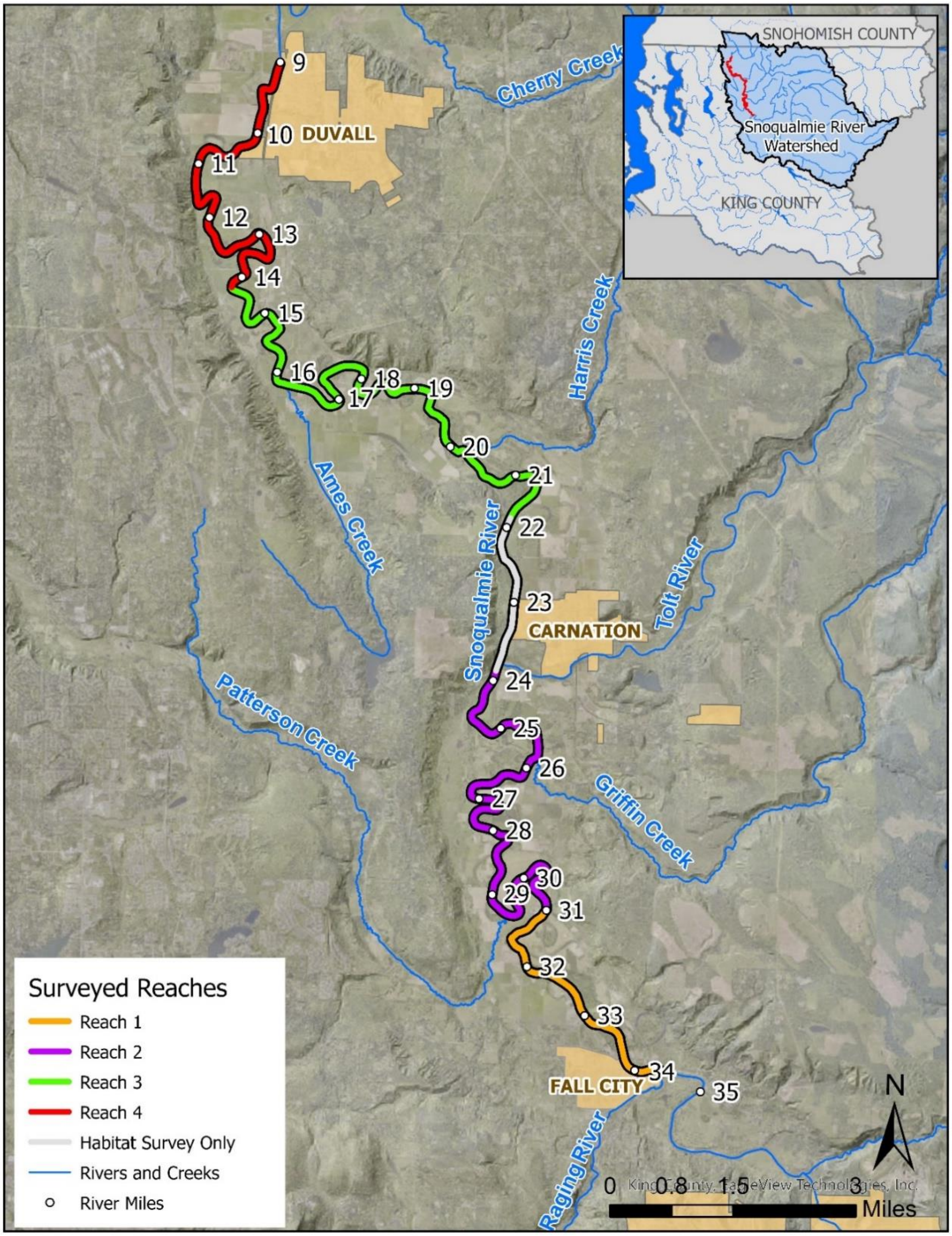

Figure 1. **Survey extent of fish and habitat sampling along the lower Snoquamie River. Reach 1 is from the Raging River confluence downstream to the Neal Road boat launch (RM 31–34.3), Reach 2 is from Neal Road boat launch to Tolt River boat launch (RM 23.9–31), Reach 3 is from Stossel Bridge to the NE 124th Street bridge (RM 14.2–21.9), and reach 4 is from NE 124th Street bridge to the Taylor Landing boat launch (RM 9–14.2).**

2.2 Edge Habitat Characterization and Mapping

Prior to all salmonid and habitat sampling, we identified, characterized, and mapped mainstem edge habitats throughout the surveyed extent. Across three days in January 2022, we floated the entire survey extent characterizing edge habitats and recording the GPS location of each edge habitat type's upstream and downstream extent. Edge habitats were characterized as either backwater, bar, unarmored bank, riprap armored bank, or confluence (Table 1; Appendix A for representative photos). From the combined inventory of all edge habitat types mapped across the survey extent, we randomized each edge habitat type/location with a random number generator, and then we drew a subset of edge habitat replicates for each of the four survey reaches. These randomly selected edge habitat replicates would be sampled for habitat and salmonids. Randomly selecting and sampling edge habitats helped ensure that we included a diversity of conditions within each habitat type and reduced the risk of repeatedly sampling a given area. Within each surveyed reach, we aimed to sample three to four edge habitat type replicates with a new set of edge habitat replicates selected for each survey occurrence. Some reaches had a small number of edge habitat type replicates, so in these circumstances all edge habitat replicates of that given edge type were surveyed. As previously highlighted, we included additional edge habitat replicates near the Fall City Floodplain Restoration Project to provide concurrent project effectiveness monitoring.

Table 1. Channel edge habitat types and descriptions.

Edge Habitat Type[1]	Description
Armored Bank	Riprap armored: Steep-gradient bank armored with placed riprap or large angular rock, designed to limit lateral channel migration.
Backwater	Partially enclosed slack-water area separated from the main river channel and often at the downstream/upstream end of a disconnected side channel or behind a flow-blocking feature (such as a gravel bar or wood jam). During most flows, backwater features are deposition zones for fine substrate, suspended sediments, and organic debris.
Confluence	Transition area between a defined tributary stream/creek channel or oxbow outlet and the main river channel. Generally containing eddies or a strong current shear line (i.e., velocity line between high and low velocity flows).
Bar	Low-gradient depositional areas generally consisting of sand, gravel, and small cobble.
Unarmored Bank	Steep-gradient bank where erosional lateral channel migration is occurring with no artificial hardening.

[1] Representative edge habitat photos are included in Appendix A.

2.3 Edge Habitat Measurements and Salmonid Surveys

Within each edge habitat type replicate, we surveyed a 25-meter-long transect for edge habitat characteristics and salmonid presence and abundance. We conducted these surveys by cataraft, with the habitat survey occurring during the daytime and the salmonid survey occurring the evening of the same day. We measured and estimated

edge habitat characteristics, including edge habitat low-velocity width, edge habitat depth, primary and secondary substrates, large wood presence, and the amount of overhanging cover.

We defined low-velocity width as the edge area having velocities that were less than approximately 1.5 feet-per-second (0.46 meters-per-second) (Beechie et al. 2005). We visually estimated the boundary between edge habitats and mid-channel areas by using the visible current shear line, where flows changed from low-velocity edge habitats to higher velocity mid-channel areas. Width measurements were taken from the channel wetted edge to the extent of the low-velocity area. We measured low-velocity width every 5 meters for a total of five measurements per transect. We did not measure low-velocity widths for confluence edge habitats because of difficulty in delineating low-velocity boundaries. We measured edge habitat depths 1.5 meters from the water's edge with measurements taken every 5 meters. We collected depth and width measurements to the tenths of a meter using a stadia rod and/or laser rangefinder.

We estimated primary and secondary substrates in edge habitats based on majority or minority substrate extents, including hardpan, fines, sand, fine gravel, coarse gravel, cobble, boulder, bedrock, or riprap. We based large wood presence on any large wood that was within the wetted area of an edge habitat and was at least 30 centimeters (12 inches) in diameter and at least 7.6 meters (25 feet) in length (USFS 2021). Wood smaller than these dimensions was only included if a rootwad greater than 1 meter (39 inches) in diameter was present. We assessed overhanging cover by visually estimating the combined percent cover provided by wood, vegetation, and/or banks within 1.5 meters of the water surface. Estimated overhanging cover was binned into six cover classes: None (0%), Low (0-20%), Low-Moderate (20-40%), Moderate (40-60%), Moderate-High (60-80%), or High (80-100%).

During the late-summer/early-fall sample period, backwater and confluence edge habitats became infrequent and were not sampled due to insufficient replicates. Low flows in the Snoqualmie River during the late-summer/early-fall of 2022 resulted in few wetted backwaters and many smaller confluences were either no longer wetted or had flows too low for adequate sampling. Flows during the late-summer/early-fall of 2022 were among the lowest across the last decade (discussed in Subsection 4.1).

Following the daytime habitat survey, we re-floated the survey reach and collected salmonids within each 25-meter-long transect using a cataraft-based electrofishing approach. The electrofishing cataraft was built by King County staff to specifically monitor juvenile salmonids in large rivers. The cataraft set-up consists of an aluminum rowing frame, 14-foot inflatable PVC tubes, flood lights, anode and cathode arrays, and Smith-Root 2.5 GPP electrofishing components. We used the electrofishing cataraft instead of snorkeling or net-seining because the cataraft is more effective due to conditions in the lower Snoqualmie River. Water visibility in the lower Snoqualmie River is poor during winter and spring due to high turbidity, which limits the utility of visual-based snorkel surveys. Additionally, steep banks and deep channels characteristic of the lower Snoqualmie River make bank-deployed net-seining ineffective.

We conducted the electrofishing surveys about 30 to 60 minutes after sunset. Salmonid sampling was done at night because juvenile salmonids often hide themselves during daylight and are more active at night (Roni and Fayram 2000; Bradford and Higgins 2001), likely to reduce risk from visual-based predators. Additionally, King County large river monitoring and observations indicated that cataraft-based electrofishing has greater capture efficiency during darkness. Along each 25-meter transect, we sampled salmonids by orienting the electrofishing cataraft toward the water’s edge with the anode arrays placed within the low-velocity area of each edge habitat. Electrofisher settings were generally set to the high voltage range (50-1000), direct current, 30 pulses-per-second, and 40-60 percent of power (output voltage and pulse width simultaneously). Once at the start (upstream extent) of the transect, two netters on the front of the boat began electrofishing, netting any stunned fish and placing them in a holding bucket as the pilot maneuvered the cataraft along the shore to the end of the transect (downstream extent). The pilot rowed along each transect and controlled the generator and electrofisher settings. After each transect, the pilot recorded the effort (seconds of electrofishing). We anesthetized captured fish using MS-222; identified them to species, genus, or family; measured them for fork length (tip of the head to the fork in the caudal fin); and then placed captured fish in a bucket of fresh water until they were fully recovered and could be released safely.

Limitations exist with all methodologies used to assess relative fish abundance, including cataraft-based electrofishing. Electrofishing may have different capture probability across edge habitat types, which could influence respective abundance estimates. For example, cataraft-based electrofishing could have greater sampling efficiency among shallower edge habitats like bars and some backwaters because the electrical field and fleeing fish are constrained by habitat boundaries. Deeper channel areas may have lower electrofishing efficiency and capture probability because only a fraction of the water column is sampled. However, the depth of juvenile salmonid rearing tends to be skewed toward shallow waters in spring and then deeper waters in summer (Hillman et al. 1987; Allen 2000; Beecher et al. 2002; Holecek et al. 2009). Lower capture probability because of depth may be most relevant during summer but flows and depths are also generally lowest in summer. Thus, lower capture probability due to depth may be a limited constraint. Additionally, capture probability may be lower among complex wood structures and under dense overhanging vegetation because fleeing fish are harder to see and capture. Understanding sampling efficiency across edge habitats could help develop correction factors to adjust observed catches; however, there is currently limited information on efficiency estimates for cataraft-based electrofishing.

2.4 Analyses

We focused our analysis of salmonid presence and abundance on juvenile Chinook salmon, juvenile coho salmon, and juvenile and older trout (cutthroat and rainbow). We also focused our analysis on primary life histories, including sub-yearling (born within the same year) and yearling (born the prior year) Chinook and coho salmon as well as sub-yearling and yearling/older trout (some trout were more than a year old). We represented juvenile salmonid presence with frequency of occurrence (percent of transects where juveniles were observed) to show how widespread and often salmonids

were observed across edge habitats. We used juvenile salmonid abundance to show the comparative total number of juveniles observed across edge habitats. Collectively, both juvenile salmonid presence and abundance informs edge habitat use and are useful proxies of habitat preference and suitability.

The relative abundance of juvenile salmonids among edge habitats was represented by catch per seconds of electrofishing, known as catch per unit effort (CPUE). Relative abundance represented by CPUE as compared to a density or absolute abundance estimate can be beneficial for two reasons. First, CPUE is a semi-quantitative method that requires less time and fewer personnel to complete than methods used to estimate absolute abundance, such as complete census observations, mark/recapture, and removal methods (Crozier and Kennedy 1994; Van Den Avyle and Hayward 1999; Guy and Brown 2007). Second, large river environments are inherently difficult to sample, which makes it difficult to estimate absolute abundance and density.

We conducted all statistical analysis, data summarization, and data visualization using the R language for statistical computing (R Core Team 2023). We used random forest models (Breiman 2001; Strobl et al. 2009) implemented via the randomForest R package (Liaw and Wiener 2002) to evaluate the influence of explanatory variables on salmonid presence and relative abundance. Random forests are nonparametric, ensemble-based recursive partitioning algorithms that provide both relative measures of variable importance and an estimate of the overall error rate (categorical response) or proportion of variance accounted for (quantitative response) by the explanatory variables. We used random forests rather than generalized linear models because random forests can handle large numbers of potentially collinear explanatory variables better than generalized linear models.

We used random forest models to evaluate the influence of edge habitat type, low-velocity width, depth, wood presence, cover, primary substrate, secondary substrate, river flow, and time-of-year on salmonid presence and relative abundance. Specifically, we conducted random forest models for the presence and relative abundance of sub-yearling Chinook salmon, yearling Chinook salmon, sub-yearling coho salmon, yearling coho salmon, as well as sub-yearling, yearling, and older trout (both rainbow trout and cutthroat trout combined). Random forest models were run separately for late winter though spring (March–June) of 2022, late summer through early fall (September–October) of 2022, and winter (January) of 2023.

Means water depth and width of low-velocity areas were natural log-transformed for use as explanatory variables because we assumed fish use would be sensitive to the relative differences in the depth and/or width of edge habitat units. We used day-of-year to represent time of year in the models. River flow was represented by discharge at USGS gauge number 12149000 (Carnation, WA). Cover was converted from discrete qualitative cover classes to a quantitative scale where None = 0, Low = 1, Low-Moderate = 2, Moderate = 3, Moderate-High = 4, and High = 5. All continuous variables were standardized to a mean of zero and standard deviation of 1 prior to model fitting. Random forests were implemented with 1,000 individual trees and a random subset of four variables were considered at each split. We excluded confluence edge habitats

from the random forest models because edge habitat widths were not collected (see Subsection 2.3) and thus could not be correlated with juvenile salmonid presence or abundance. Once primary driving variables were determined from random forest models, we used partial dependence plots to provide a graphical depiction of the effect (variable effects based on the random forest models) of primary drivers on the probability of juvenile salmonid presence and relationship with relative abundances.

3 Results

Across the study extent, we surveyed fish and habitat across 204 randomly selected edge habitat transects, including 105 transects in spring (March–June), 46 transects in late-summer/early-fall (September–October), and 53 transects in winter (January). During the late-summer/early-fall sample period, backwater and confluence edge habitat became infrequent and were not sampled due to insufficient replicates. As discussed in Subsection 2.1, spring included three sample events per mainstem reach, while late-summer/early-fall and winter had one sample event per mainstem reach.

Table 2. Numbers of randomly selected mainstem Snoqualmie River edge habitat replicates across sample periods. Backwater and confluence edge habitats were not sampled in September and October.

Edge Habitat Type	March–June	September–October	January
Armored Bank	19	14	8
Backwater	18	NA	10
Confluence	19	NA	9
Bar	25	16	12
Unarmored Bank	24	16	14

3.1 Edge Habitat Characteristics and Extents

Transect measurements showed that backwaters and bars had wider low-velocity areas than other edge habitat types in both spring and winter (Figure 2). Armored and unarmored banks had narrower low-velocity areas than other edge habitat types in spring and winter. During late-summer/early-fall, much of the Snoqualmie River was low velocity and at base flow; thus, the widths of low-velocity areas were similar and often spanned the entire channel. Bars and backwaters had the shallowest depths in spring and winter. Armored banks were the deepest across seasonal periods, followed by unarmored banks.

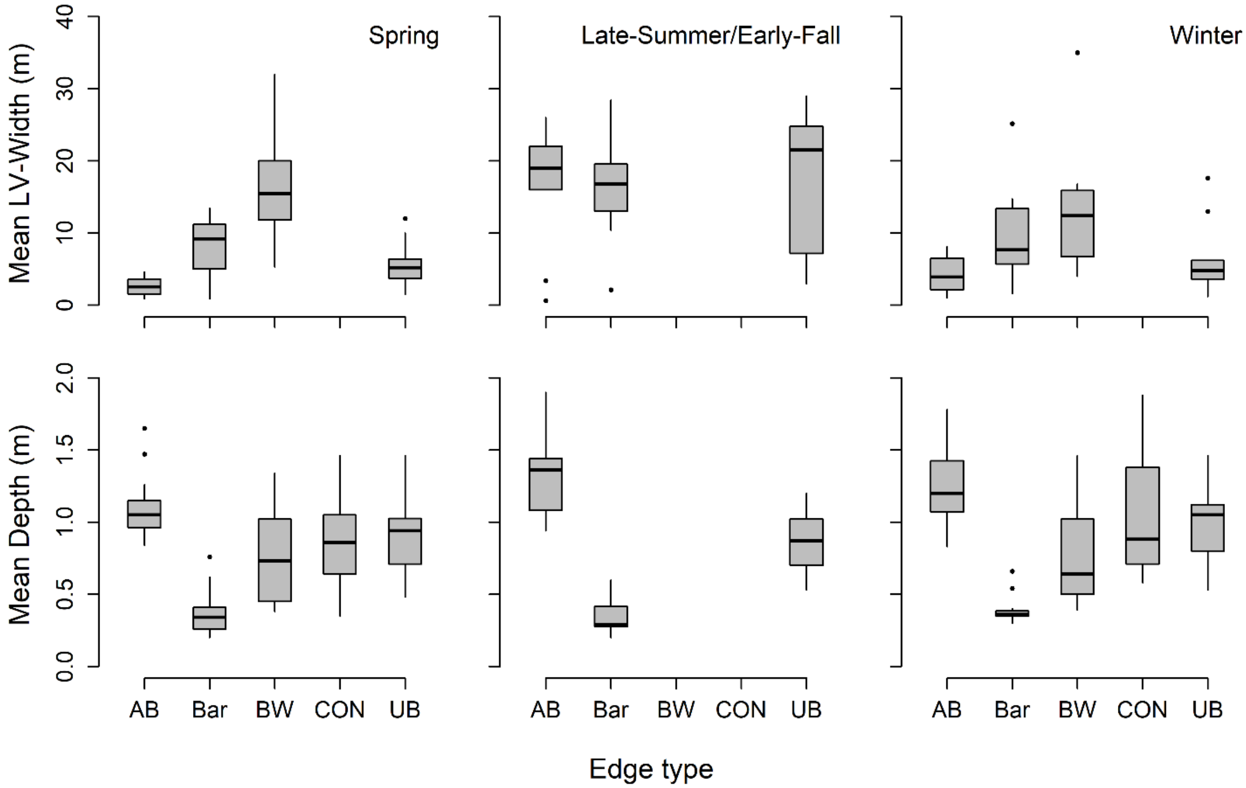

Figure 2. **Low-velocity (LV) width and water depths measured across edge types and seasons in the Snoqualmie River. Edge type codes: AB (armored bank), BW (backwater), CON (confluence), and UB (unarmored bank). Boxes indicate the first quartile, median, and third quartile. The whiskers indicate maximum and minimum values up to 1.5x the interquartile range and the points are values beyond 1.5x the interquartile range.**

Armored banks had primarily riprap and hardpan substrates, no overhanging cover, and large wood in only 8 percent of transects. Unarmored banks had primarily hardpan and sand substrates; either moderate or moderate-high overhanging cover; and large wood in 54 percent of transects. Backwaters had primarily sand and fines substrates; either none, low, or moderate-high overhanging cover; and large wood in 25 percent of transects. Bars had primarily sand and coarse gravel substrates, no cover, and no large wood. Confluences had primarily sand and hardpan substrates; either none, low, or moderate-high overhanging cover; and large wood in 31 percent of transects.

3.2 Salmonid Size Classes and Life Histories Across Monthly Periods

Juvenile Chinook and coho salmon as well as rainbow/steelhead and cutthroat trout used mainstem edge habitats for rearing, including multiple size classes and life histories. In March and April, juvenile Chinook salmon size classes primarily included smaller sub-yearling fry (35–50 mm) and medium-sized parr (50–70 mm), both of which had emerged from redds that year (Figure 3). A few larger juvenile Chinook (105–115 mm) were observed, which were yearlings that were born the prior year. As the spring progressed (May–June), fry continued to emerge (35–50 mm) and an increased frequency of medium-sized parr (50–75 mm) was observed. In late-summer/early-fall

(September–October), a cohort of larger juvenile Chinook (90–120 mm) remained in the system. These juveniles likely contribute to the yearling life history. In winter (January), there was a cohort of yearling Chinook (90–115 mm) as well as a cohort or recently emerged fry (35–45 mm).

Coho salmon size classes in March and April displayed two modes including smaller fry (30–45 mm) and a wide range in yearling sizes (65–130 mm) (Figure 4). In May and June, coho size classes primarily included fry and parr (30–70 mm), and by late-summer/early-fall a cohort of larger juvenile coho (65–110 mm) remained in the system. Similar to juvenile Chinook, this late-summer/early-fall cohort likely contribute to the yearling life history, which is the predominant juvenile life history for coho salmon. In winter, a broad range of larger juvenile coho (60–105 mm) was observed.

A broad range in trout size classes was observed in March and April (90–340 mm) (Figure 5). Relatively few trout were observed in May and June, ranging from 100–190 mm. In late-summer/early-fall, trout size classes displayed two modes including a relatively smaller-sized cohort (70–110 mm) and larger-sized cohort (160–240 mm). Like March and April, by January a broad range in trout size classes was observed, ranging from 70–280 mm.

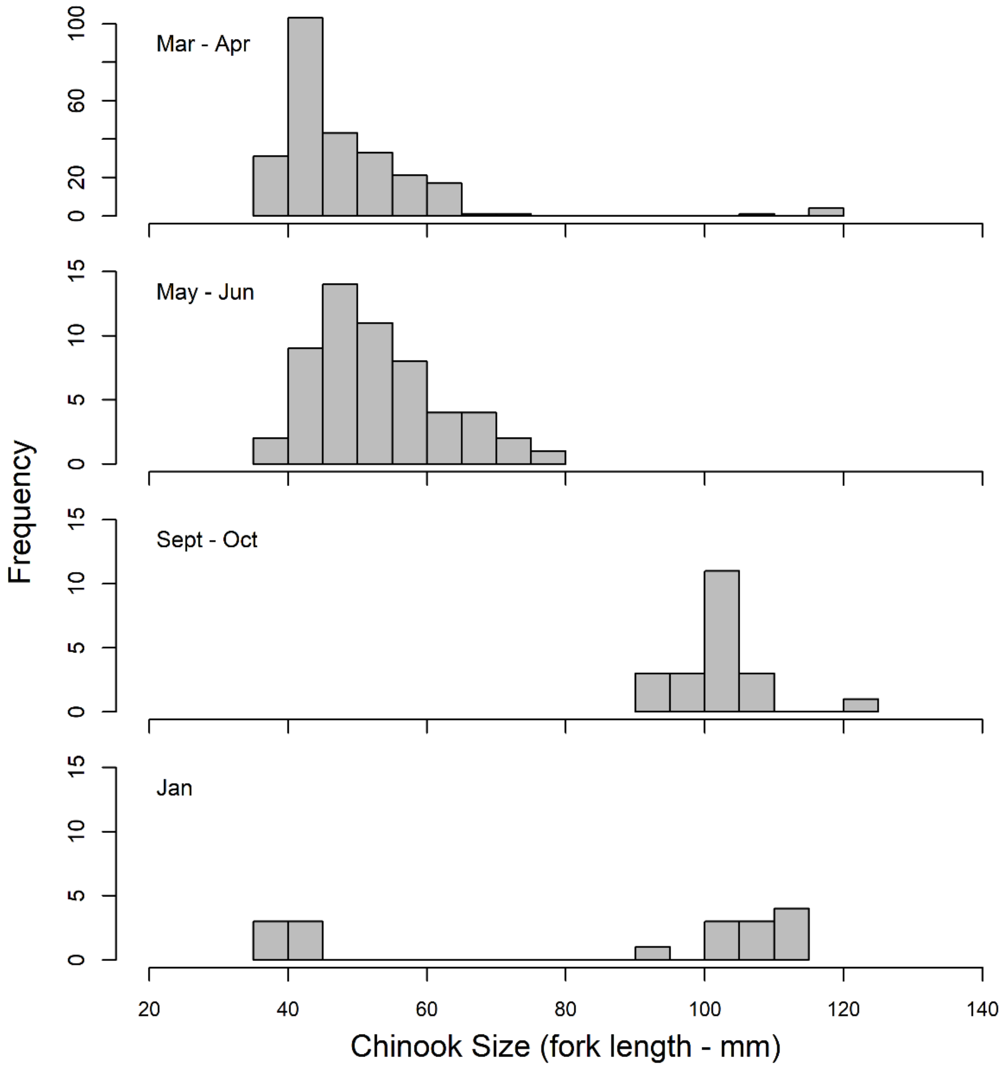

Figure 3. Juvenile Chinook salmon size frequencies across seasonal periods in the Snoqualmie River. Note different y-axis range for Mar–Apr due to greater frequencies.

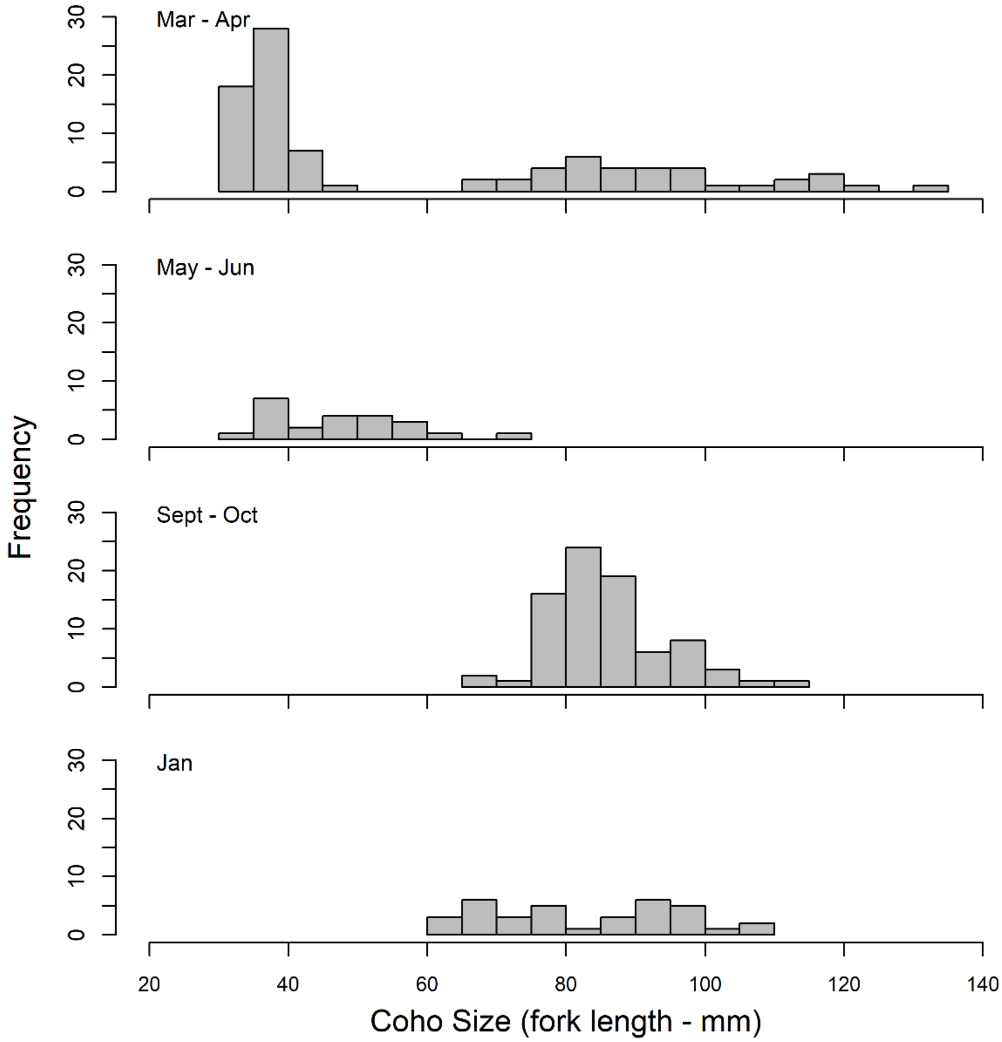

Figure 4. Juvenile coho salmon size frequencies across seasonal periods in the Snoqualmie River.

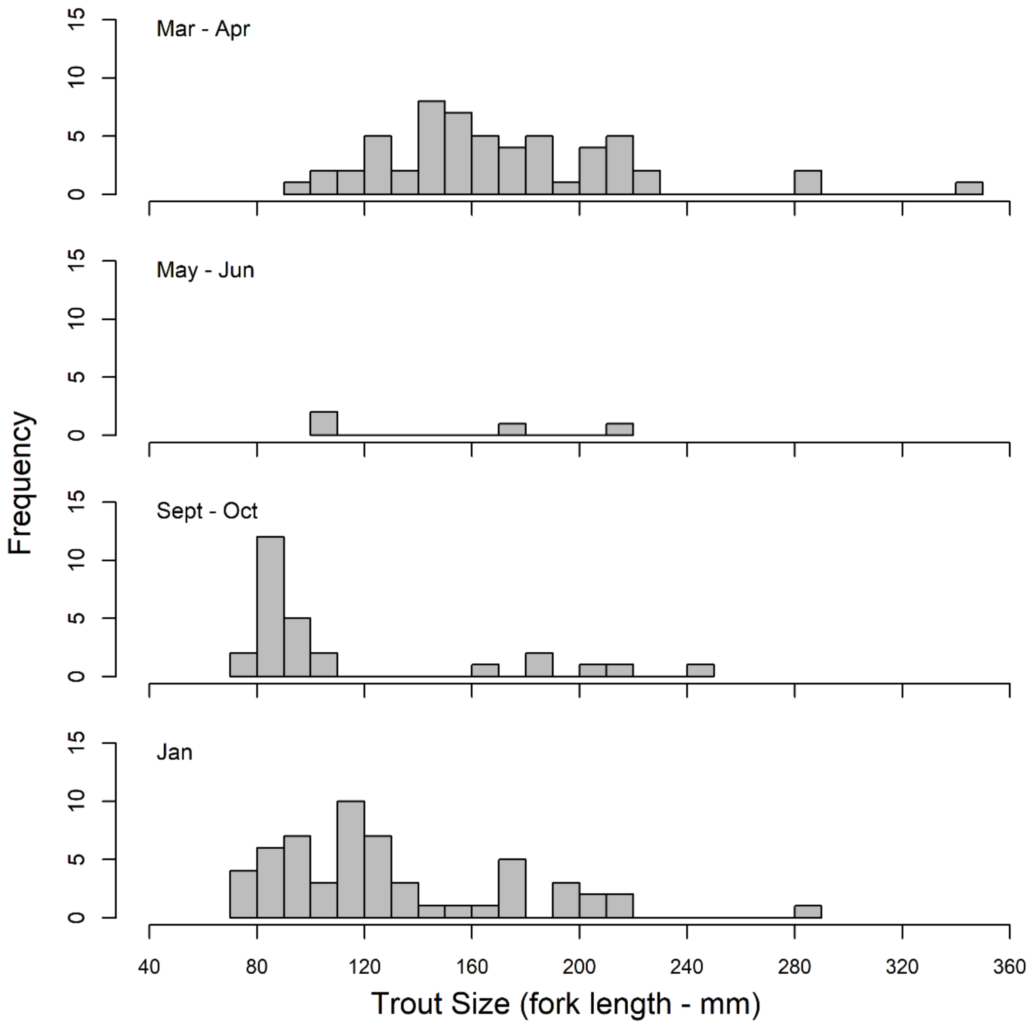

Figure 5. Trout (cutthroat and rainbow) size frequencies across seasonal periods in the Snoqualmie River.

3.3 Salmonid Presence and Abundance

We report results for both juvenile salmonid presence and abundance to show how widespread and often juveniles were observed across edge habitats and to show the comparative number of juveniles observed across edge habitats. Salmonid presence and abundance collectively inform juvenile salmonid edge habitat use and are useful proxies of habitat preference and suitability. During spring, juvenile sub-yearling Chinook salmon frequency of occurrence (percent of transects where juveniles were observed) was highest in bars (88 percent), unarmored banks (83 percent), confluences (74 percent), and backwaters (67 percent), with occurrence lowest in armored banks (17 percent) (Figure 6). In spring, only five yearling Chinook were observed and were thus not included in analyses. In late-summer/early-fall, juvenile Chinook occurred most frequently in bars (50 percent), less frequently in unarmored banks (25 percent), and were not observed in armored banks. By winter, yearling juvenile Chinook were most frequent in armored banks (50 percent) and were less frequent in backwaters (20 percent), bars (17 percent), and unarmored banks (14 percent). During winter, juvenile Chinook were not observed in confluences.

During spring, the relative abundance (catch per seconds electrofished) of juvenile sub-yearling Chinook salmon was greatest in bars, backwaters, unarmored banks, and confluences and was lowest in armored banks (Figure 7). Sub-yearling Chinook used all edge habitats in spring with backwaters primarily used in early- to mid-spring and bars, confluences, and unarmored banks used throughout spring with increasing use in late spring (Appendix B). Sub-yearling Chinook were considerably less abundant in late-summer/early-fall than in spring with relative abundance greatest in bars and unarmored banks. In winter, yearling Chinook were most abundant in armored banks.

In spring, juvenile sub-yearling coho salmon were most frequent in unarmored banks (61 percent), backwaters (56 percent), and confluences (42 percent) and less frequent in armored banks (22 percent) (Figure 6). Yearling coho were most frequent in unarmored banks (40 percent) and were less frequent in armored banks (22 percent), confluences (21 percent), and backwaters (17 percent). In late-summer/early-fall, sub-yearling coho were most frequent in unarmored banks (100 percent) and bars (58 percent) and least frequent in armored banks (44 percent). Yearling coho were not observed in the late-summer/early-fall because they had out-migrated. By winter, yearling coho were most frequent in armored banks (50 percent) and less frequent in unarmored banks (36 percent), confluences (33 percent), backwaters (30 percent), and bars (8 percent). Sub-yearling coho were not observed in winter because they had not yet emerged from redds.

During spring, the relative abundance (catch per seconds electrofished) of sub-yearling coho salmon was greatest in backwaters, unarmored banks, and confluences and lowest in armored banks and bars (Figure 7). Yearling coho were most abundant in unarmored banks. In late-summer/early-fall, sub-yearling coho were most abundant in unarmored banks and bars and least abundant in armored banks. By winter, yearling coho were most abundant in armored banks. Sub-yearling coho used backwaters throughout spring, bars primarily in late-summer/early-fall, and increasingly used unarmored banks from spring to late-summer/early-fall (Appendix B). Confluences and armored banks were used similarly throughout the year.

In spring, trout (yearling and older cutthroat and rainbow) were most frequent in armored banks (67 percent) and less frequent in unarmored banks (35 percent), bars (24 percent), backwaters (17 percent), and confluences (16 percent) (Figure 6). Sub-yearling trout were not observed in spring. In late-summer/early-fall, sub-yearling trout were most frequent in bars (50 percent) and less frequent in unarmored banks (25 percent) and armored banks (11 percent). Yearling and older trout were most frequent in unarmored banks (50 percent) and bars (50 percent) and less frequent in armored banks (11 percent). By winter, yearling and older trout were most frequent in armored banks (88 percent) and less frequent in unarmored banks (43 percent), bars (42 percent), backwaters (30 percent), and confluences (20 percent).

During spring, the relative abundance (catch per seconds electrofished) of trout was greatest in armored and unarmored banks and lowest in bars, backwaters, and confluences (Figure 7; Appendix B). In late-summer/early-fall, sub-yearling trout were

more abundant in bars and unarmored banks and were less abundant in armored banks. Yearling and older trout were most abundant in unarmored banks and bars. In winter, yearling and older trout were most abundant in armored banks.

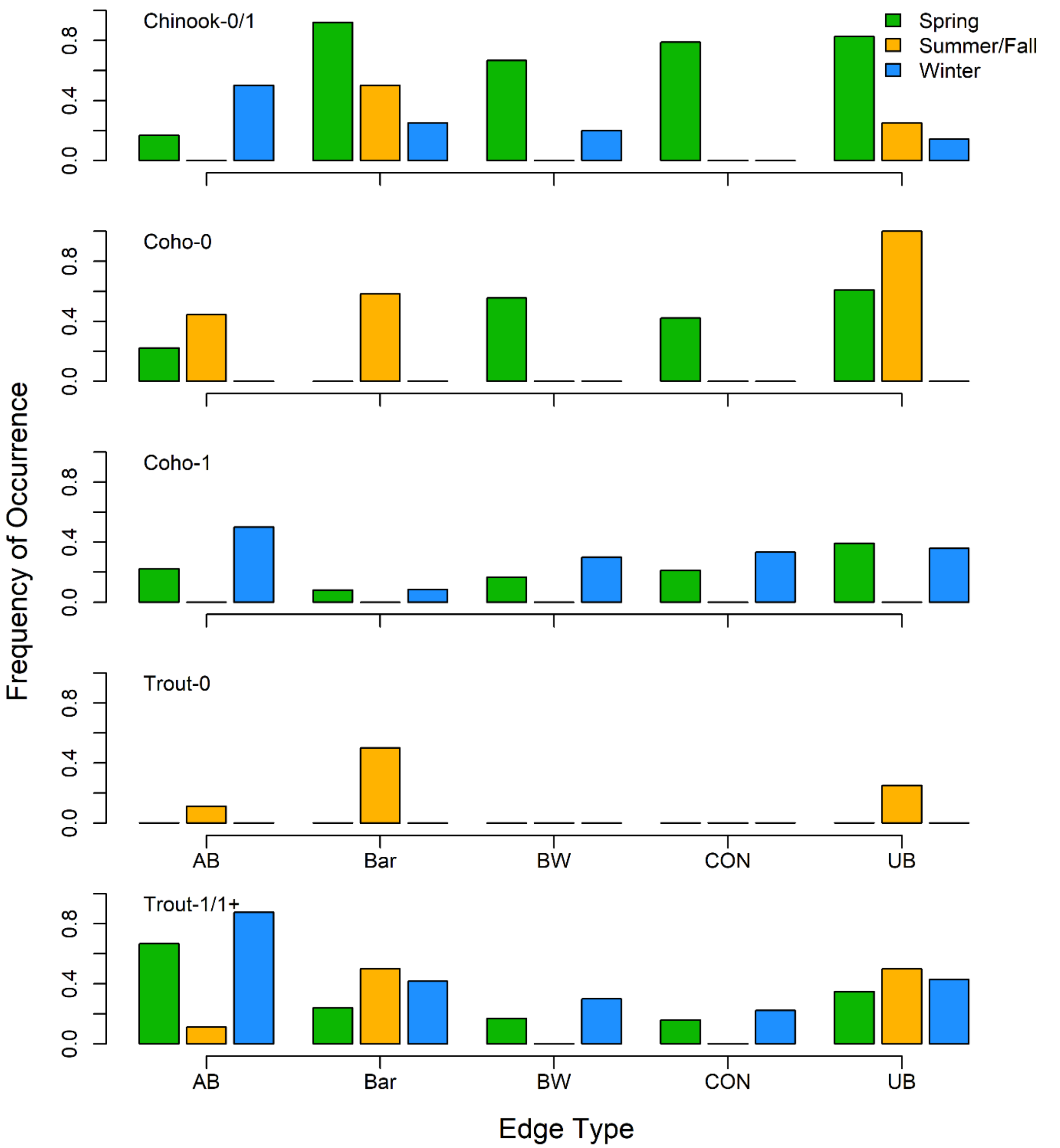

Figure 6. Frequency of occurrence (percent of transects where fish were observed) of sub-yearling (0) and yearling (1) Chinook and coho salmon and trout across edge habitats and periods in the Snoqualmie River. Only 5 yearling Chinook were observed in spring and thus were not included for analysis. All coho observed in late-summer/early-fall were sub-yearling and all trout observed in spring and winter were yearling or older. Edge type codes: AB (armored bank), BW (backwater), CON (confluence), and UB (unarmored bank).

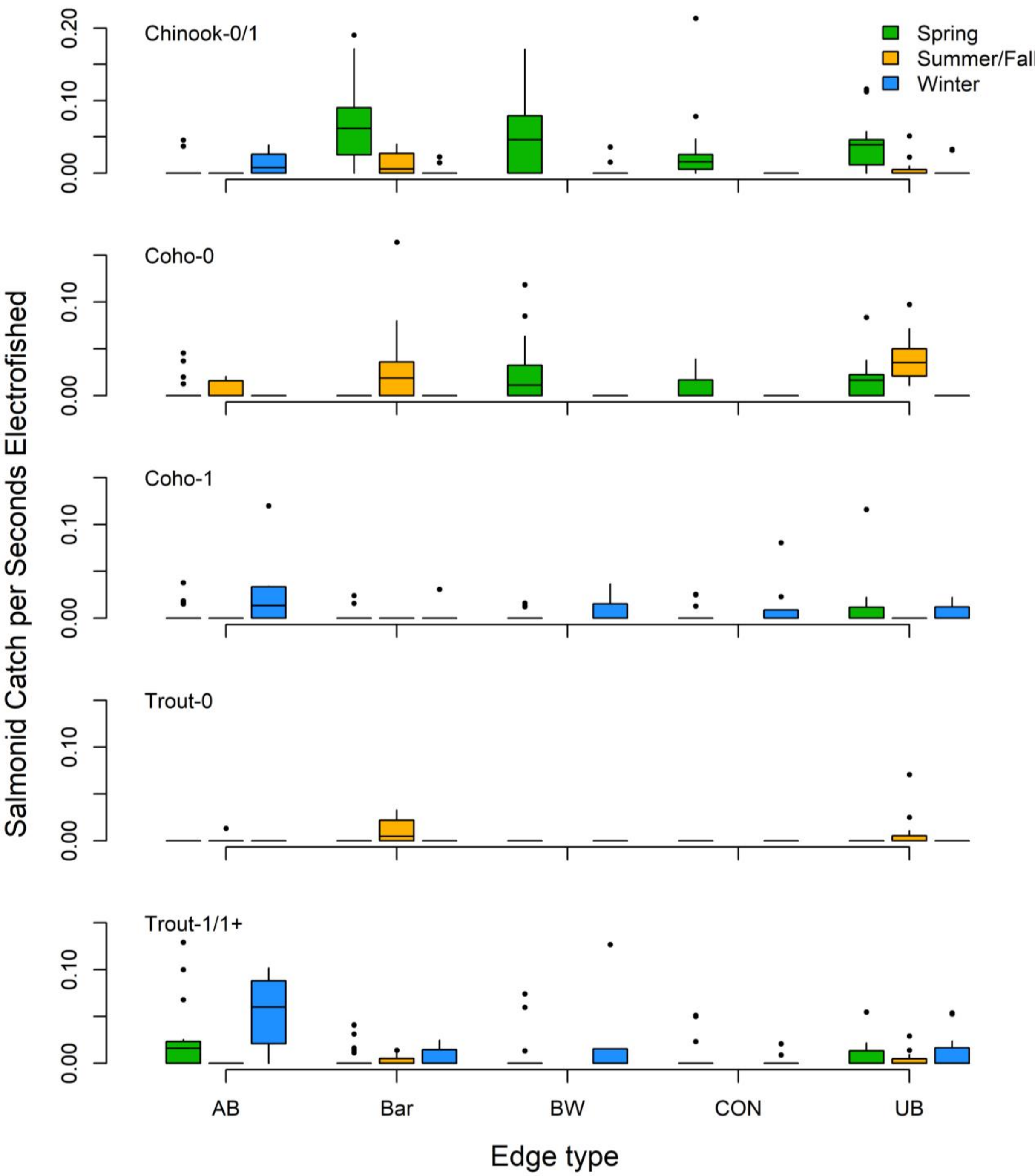

Figure 7. Relative abundance (catch per seconds electrofished) of sub-yearling (0) and yearling (1) Chinook and coho salmon and trout across edge habitats and periods. Only 5 yearling Chinook were observed in spring and thus were not included for analysis. All coho observed in late-summer/early-fall were sub-yearling and all trout observed in spring and winter were yearling and older. Edge type codes: AB (armored bank), BW (backwater), CON (confluence), and UB (unarmored bank). Boxes indicate the first quartile, median, and third quartile. The whiskers indicate maximum and minimum values up to 1.5x the interquartile range and the points are values beyond 1.5x the interquartile range.

3.4 Longitudinal Distribution of Edge Habitats and Juvenile Salmonids

Across the surveyed extent (RM 9 to 34), areas with the greatest extent of armored edge habitat included RM 16, 23, 28 to 30, and 33 to 34 (Figure 8). Areas that had the greatest diversity of unarmored edge habitats (i.e., greatest extent and variety of edge habitats) included RM 19 to 21, RM 26, and RM 31 to 34.

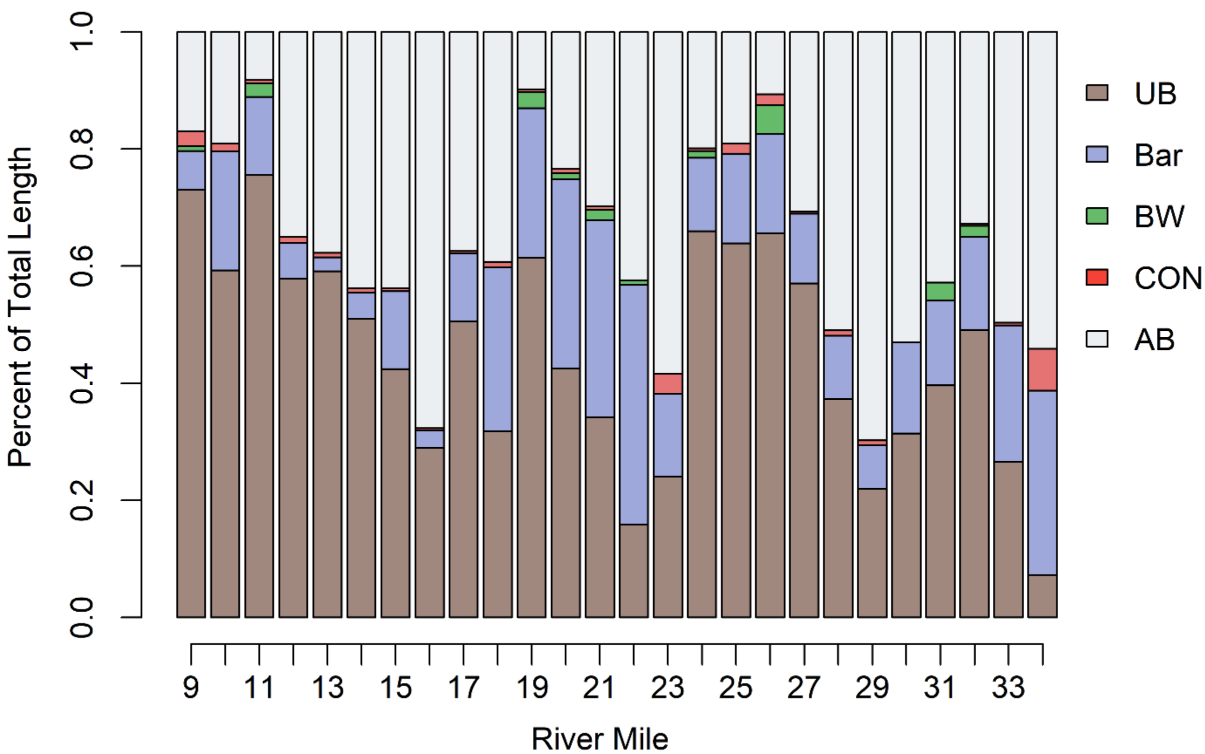

Figure 8. Percentage of edge habitats across river miles in the Snoqualmie River. Only a third of RM 34 was surveyed. Edge type codes: UB (unarmored bank), BW (backwater), CON (confluence), and AB (armored bank).

Across the surveyed extent, the relative abundance of juvenile Chinook salmon was greatest from RM 16 to 21 and 30 to 34 (Figure 9). Chinook relative abundance was lowest within RM 9 to 15 and RM 24 to 29. Coho salmon abundance was slightly greater within RM 19 to 21 and 30 to 32; however, coho abundance was relativity similar across RM 19 to 32. Trout abundance was greatest in RM 30 to 32.

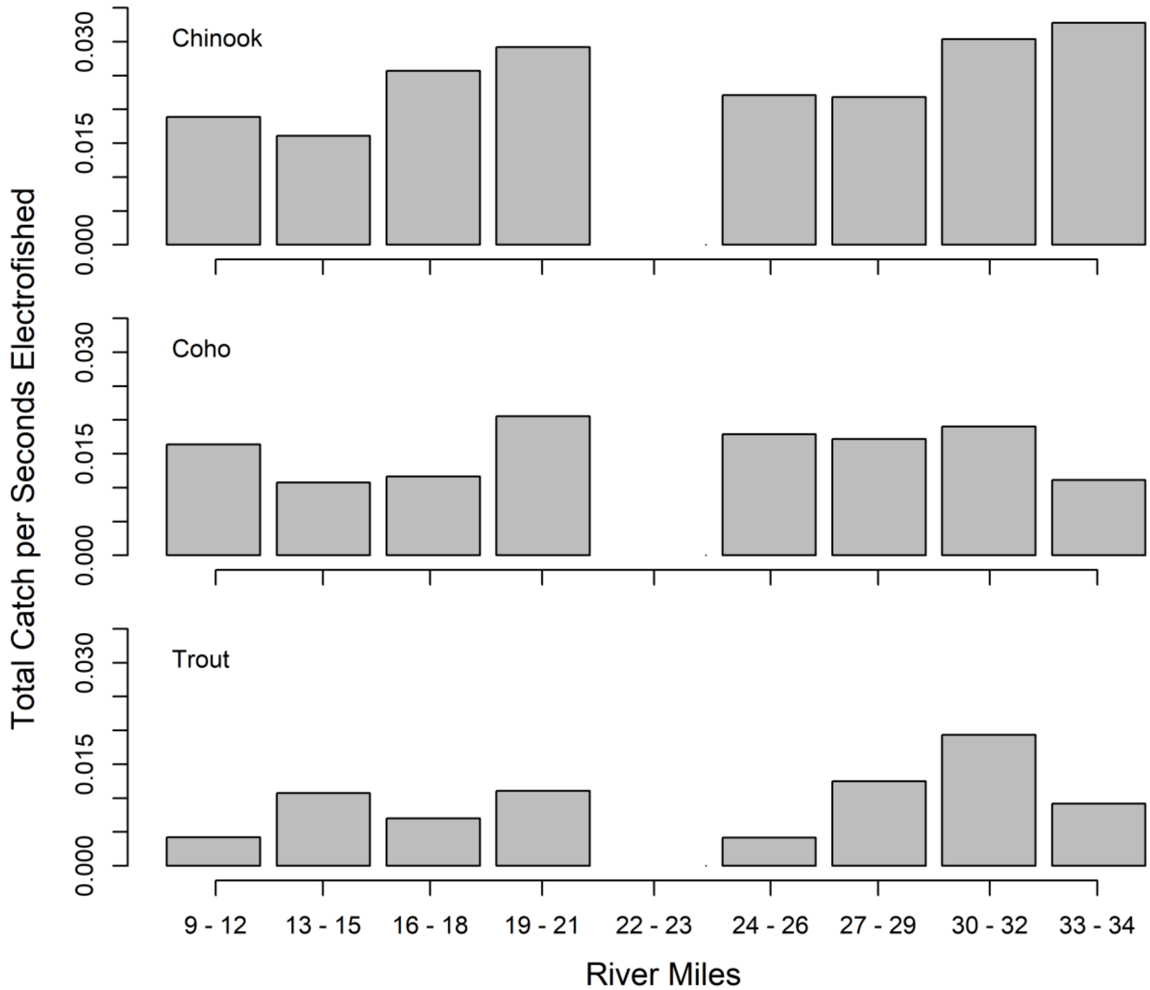

Figure 9. Relative abundance (catch per seconds electrofished) of Chinook and coho salmon and trout across river mile bins in the Snoqualmie River. RM 22 and 23 were not sampled for salmonids and only a third of RM 34 was sampled.

3.5 Primary Drivers of Salmonid Presence and Relative Abundance

Primary drivers of salmonid presence and relative abundance across seasons is summarized in Table 3 and Table 4. Subsections 3.5.1 and 3.5.2 detail these primary drivers as well as their effects on salmonid presence and abundance. Plots of variable importance from random forest models and related partial dependence plots displaying the effects of primary drivers on salmonid presence and abundance are included in Appendix C and D.

Table 3. **Primary drivers of salmonid presence in the Snoqualmie River across seasons and life histories. Column codes include LV for low velocity and Sub. for substrate. Rows with light grey shading indicate seasons with no species/life history observations or too few observations for analysis.**

Species and Life History	Season	Primary Driving Variable								
		Edge Type	LV-Width	Depth	Primary Sub.	Second Sub.	Cover	Wood	Day-of-Year	Flow
Sub-yearling Chinook	Spring	X			X					
	Summer - Fall			X					X	
	Winter	X	X							
Yearling Chinook	Spring									
	Summer - Fall									
	Winter	X			X					
Sub-yearling Coho	Spring	X								
	Summer - Fall	X		X						
	Winter									
Yearling Coho	Spring	X	X		X				X	X
	Summer - Fall									
	Winter	X					X			
Sub-yearling Trout	Spring									
	Summer - Fall			X	X	X	X			
	Winter									
Yearling and older Trout	Spring			X						X
	Summer - Fall				X					
	Winter				X					

Table 4. Primary drivers of salmonid relative abundance (catch per seconds electrofishing) in the Snoqualmie River across seasons and life histories. Column codes include LV for low velocity and Sub. for substrate. Rows with light grey shading indicate seasons with no species/life history observations or too few observations for analysis.

Species and Life History	Season	Primary Driving Variable								
		Edge Type	LV-Width	Depth	Primary Sub.	Second Sub.	Cover	Wood	Day-of-Year	Flow
Sub-yearling Chinook	Spring			X	X					
	Summer - Fall			X					X	
	Winter	X	X		X					
Yearling Chinook	Spring									
	Summer - Fall									
	Winter	X		X						
Sub-yearling Coho	Spring	X								
	Summer - Fall				X					
	Winter									
Yearling Coho	Spring				X				X	
	Summer - Fall									
	Winter	X			X					
Sub-yearling Trout	Spring									
	Summer - Fall			X	X					
	Winter									
Yearling and older Trout	Spring			X	X				X	X
	Summer - Fall				X		X		X	
	Winter	X			X					

3.5.1 Salmonid Presence

The primary drivers of sub-yearling Chinook salmon presence in spring included edge type and substrate (Table 3; Appendix C). Sub-yearling Chinook presence was more likely in bars, backwaters, and unarmored banks and in edge habitats with sand, fine gravel, and cobble substrates. It's worth noting that substrate and edge type may be collinear such that substrate is a characteristic of edge type rather than an independent driver. While several model results for salmonid abundance found substrate a primary driver without concurrently edge type (discussed below), it's likely that edge type and

substrate are at least partially dependent. Yearling Chinook were too infrequent in spring for analysis. In late-summer/early-fall, drivers of sub-yearling Chinook presence included depth and day-of-year, with presence more likely in depths between 0.2 and 0.8 meter and more likely in late summer than in early fall. By winter, primary drivers of sub-yearling Chinook presence included low-velocity width and edge type, with presence more likely in habitats with low-velocity widths between 11-15 meters and 18-20 meters, and more likely in backwaters. In winter, drivers of yearling Chinook presence included edge type and substrate, with presence most likely in armored banks and in habitats with hardpan and riprap substrates.

The primary drivers of sub-yearling coho salmon presence in spring included edge type, with presence more likely in backwaters and unarmored banks (Table 3; Appendix C). In spring, drivers of yearling coho presence included edge type, day-of-year, primary substrate, and low-velocity width. In March through April, yearling coho presence was more likely in unarmored and armored banks; in habitats with cobble, hardpan, and sand substrates; and in habitats with low-velocity widths between 3.5 and 4.5 meters. In late-summer/early-fall, drivers of sub-yearling coho presence included edge type and depth, with presence most likely in unarmored banks and in depths between 0.6 and 1.5 meters. In winter, drivers of yearling coho presence included edge type, cover, and depth, with presence more likely in armored and unarmored banks, in habitats with less cover, and in habitats with depths greater than 0.8 meter.

Drivers of yearling and older trout presence in spring included depth and river flow, with presence more likely in depths greater than 0.8 meter and less likely with flows greater than 3200 cfs (Table 3; Appendix C). In late-summer/early-fall, drivers of sub-yearling trout presence included cover and substrate, with presence more likely in depths less than 0.5 meter, in habitats with less cover, and in habitats with coarse gravel substrates. In late-summer/early-fall, the driver of yearling and older trout presence was substrate, with presence more likely in habitats with coarse gravel and hardpan substrates. In winter, the driver of yearling and older trout presence was primarily substrate, with presence more likely in habitats with coarse gravel and riprap substrates.

3.5.2 Salmonid Abundance

Primary drivers of sub-yearling Chinook salmon relative abundance (catch per seconds of electrofishing) in spring were depth and substrate, with abundance greatest in depths less than 0.5 meter and in habitats with sand substrate (Table 4; Appendix D). In late-summer/early-fall, primary drivers of sub-yearling Chinook abundance included day-of-year and depth, with abundance greater in late summer than early fall and in depths less than 0.8 meter. By winter, primary drivers of sub-yearling Chinook abundance included edge type, substrate, and low-velocity width, with abundance greatest in backwaters with hardpan substrates and low-velocity widths between 11-15 m and 18-20 meters. In winter, drivers of yearling Chinook abundance included depth and edge type, with abundance greatest in depths greater than 1.0 meter and in armored banks.

In spring, the primary driver of sub-yearling coho salmon abundance was edge type, with abundance greatest in backwaters and unarmored banks (Table 4; Appendix D). Primary drivers of yearling coho abundance in spring included substrate and day-of-

year, with abundance greatest in habitats with hardpan substrate and during early spring. In late-summer/early-fall, the driver of sub-yearling coho abundance was substrate, with abundance greatest in habitats with fine gravel substrate. In winter, drivers of yearling coho abundance included substrate and edge type, with abundance greatest in armored banks with riprap substrates.

Yearling and older trout abundance in spring was primarily driven by flow, day-of-year, substrate, and depth, with abundance greater in flows less than 3000 cfs, earlier in spring, in habitats with riprap substrate, and in depths greater than 0.8 meter (Table 4; Appendix D). In late-summer/early-fall, drivers of sub-yearling trout included substrate and depth, with abundance greatest in habitats with coarse gravel and in depths less than 0.6 meter. In late-summer/early-fall, drivers of yearling and older trout abundance included cover, day-of-year, and substrate, with abundance greater in early fall than late summer and greatest in habitats with more cover and with hardpan substrates. In winter, primary drivers of yearling and older trout abundance included substrate and edge type, with abundance greatest in armored banks with riprap substrate.

4 Discussion

The following subsections reflect the main findings of our study and the management implications of observed juvenile salmonid habitat use and associations.

4.1 Snoqualmie River supports multiple salmonid life histories, including juvenile Chinook with extended freshwater rearing.

Edge habitats along the mainstem Snoqualmie River support multiple salmonid species and life histories. Observations from this study and other project monitoring and research efforts indicate that juvenile Chinook and coho salmon as well as rainbow/steelhead and cutthroat trout use mainstem edge habitats (David and Kubo 2020; King County 2021a, 2021b; Kubo 2022b). Our findings validate predictions of our first research question, that multiple juvenile Chinook and coho life histories use mainstem edge habitats, including sub-yearling fry and parr (recently emerged from redds) as well as yearling (born the prior year). Multiple trout life histories also use mainstem edge habitats, including sub-yearling, yearling, and older juveniles and adults.

Mainstem edge habitats are particularly important for juvenile Chinook salmon (Hillman et al. 1987; Bjornn and Reiser 1991; Levings and Lauzier 1991; Beechie et al. 2005); however, our findings and observations from Snoqualmie River monitoring and research suggest that mainstem edge habitats are also important for juvenile coho salmon. While juvenile coho tend to be associated more often with off-channel habitats such as side channels, wetlands, ponds, oxbows, and tributaries (Swales et al. 1986; Murphy et al. 1989; Swales and Levings 1989; Bjornn and Reiser 1991; Nickelson et al. 1992), they were consistently observed in Snoqualmie River mainstem edge habitats.

Snoqualmie River Chinook salmon predominantly display a sub-yearling juvenile life history, with juveniles rearing and out-migrating the year they are born. However, a small cohort of Snoqualmie Chinook display extended freshwater rearing typical of the yearling life history (Kubo et al. 2013; King County 2021b; Keith et al. 2023). Further research is needed to better understand the drivers of yearling Chinook salmon expression and persistence in the Snoqualmie River. We hypothesize that a cohort of late-emerging juvenile Chinook may contribute to the yearling life history (King County 2021b). We observed smaller juvenile Chinook (i.e., fry <50 mm) into June, which is consistent with observations from project monitoring and life history studies (David and Kubo 2020; King County 2021a, 2021b; Kubo 2022b). The smaller size classes in late spring suggest a relatively late emergence, which could be a result of late-spawning adult Chinook and/or spawning in colder tributaries or reaches. We hypothesize that these late-emerging juveniles contribute to the yearling life history because late emergence may require juveniles to remain in freshwater areas to attain the necessary size and condition prior to out-migration (King County 2021b).

The yearling Chinook salmon life history has been consistently observed in the Snoqualmie River across project monitoring efforts (David and Kubo 2020; King County 2021a; Kubo 2021) and prior research shows widespread yearling Chinook distribution and abundance in late-summer, fall, and winter (King County 2021b). However, the abundance of yearling Chinook observed in this study was considerably lower than in

prior years, especially in late-summer/early-fall and winter. Fewer yearling Chinook observations may be the result of inter-annual variability in life-history expression, possibly due to late-summer/early-fall conditions in 2022, or other reasons. During the late-summer/early-fall survey period (Sept. 19th–Oct. 3rd), the Snoqualmie River had lower flow (555 cfs) than the prior 10 years for that same period (630–4226 cfs; avg.1558 cfs) (USGS Carnation 12149000). In addition, during this period, the Snoqualmie River was warmer (14.3°C) than the prior 10 years (12.1–13.8°C; avg. 13.1°C). We speculate that late-summer/early-fall low flows and warmer temperatures may have resulted in juvenile Chinook either out-migrating from the Snoqualmie River or moving into tributaries.

4.2 Availability, quantity, and diversity of mainstem edge habitats are important for juvenile salmonids.

Our results continue to support that Snoqualmie River mainstem edge habitats are important for juvenile salmon rearing. Snoqualmie River project monitoring efforts and research studies have shown that mainstem edge habitats are frequently used by juvenile Chinook and coho salmon in late winter and spring and also throughout the year (David and Kubo 2020; King County 2021a, 2021b; Kubo 2022b). Channel margins are often used by juvenile salmon for rearing during early life stages (Hillman et al. 1987; Bjornn and Reiser 1991; Beechie et al. 2005). Our study builds on these collective understandings and validates predictions of our first and second research questions, emphasizing that mainstem edge habitats are not only used for rearing by juvenile salmonids but that species and life histories display unique variation in edge habitat use and seasonal preferences. In addition to mainstem edge habitat, habitats throughout the Snoqualmie watershed support salmonid species and life histories, including off-channel areas like side-channels and oxbows, seasonally inundated floodplain areas, tributaries, wetlands, headwaters, etc. However, these habitats and their relative importance were not evaluated in this study.

Bars appear to provide important early rearing habitat for sub-yearling salmonids, especially in spring for sub-yearling Chinook salmon and in late-summer/early-fall for sub-yearling coho salmon and trout. Juvenile salmonid use of bar habitat was previously assumed to be relatively minimal based on observations from other large river systems (Beamer and Henderson 1998; Beechie et al. 2023). However, our results and observations from other Snoqualmie River project monitoring and research studies indicate that bars are not only used by juvenile salmonids but can support some of the greatest abundances across all edge habitats (David and Kubo 2020; King County 2021a, 2021b; Kubo 2022b). Bars were generally shallow in depth with wide low-velocity areas, especially during spring and winter, which is consistent with juvenile salmon rearing habitat preferences (Murphy et al. 1989; Beechie et al. 2005; Tiffan et al. 2006; Hellmair et al. 2018). In addition, bars were characteristic of relatively smaller substrates, which are preferred by sub-yearling salmon (discussed in Subsection 4.3).

Chinook salmon, coho salmon, and trout were observed across the full suite of available edge habitats, with species and life histories displaying unique shifts in habitat use across seasons. Our findings are consistent with observations from Snoqualmie River project monitoring and research, which have documented juvenile salmonid use of the

full suite of available edge habitats, shifts in habitat use among species and life histories, and edge habitat use across seasons (David and Kubo 2020; King County 2021a, 2021b; Kubo 2022b). As juvenile salmonids grow, they typically move from shallow and slow habitats to deeper and faster habitats (Everest and Chapman 1972; Hillman et al. 1987; Beechie et al. 2005; Holecek et al. 2009). Our findings support these understandings and validate predictions of our second research question, with sub-yearling Chinook and coho abundant in shallow, low-velocity backwaters and bars in spring and late-summer/early-fall, and then by winter, when juveniles are largest in size prior to outmigration, they were most abundant in deeper and higher-velocity bank habitats.

During winter, yearling salmonids were abundant in armored banks, likely due the large riprap rocks providing holding spaces for overwintering (discussed in Subsection 4.4). While this suggests that armored banks provide winter habitat for yearling salmonids, unarmored banks with abundant large wood, exposed roots, and aquatic vegetation provide similar overwintering areas while also providing a myriad of other benefits for salmonid habitats (discussed in Subsection 4.3). However, large wood and wood jams are relatively sparse across the lower Snoqualmie River and many reaches have extensive bank armoring (King County 2018). Bank armoring can impair natural channel sediment, hydrologic, and migration processes, limit the availability and accessibility of off-channel habitats and floodplain areas, and reduce mainstem edge habitat complexity and cover (Spence et al. 1996, Beamer and Henderson 1998, Ward and Wiens 2001). Subsequently, while armored banks may provide near-term overwintering habitat, the benefits of unarmored banks, especially in the long term, are considerably greater for salmonid habitats conditions.

Collective finding from our study and Snoqualmie River monitoring and research highlights the importance of edge habitat availability, quantity, and diversity across seasons and environmental conditions. As juvenile salmonids grow and transition through life stages, a diverse mosaic of edge habitats across mainstem reaches, seasons, and environmental conditions is important for juvenile salmonid rearing.

4.3 Edge habitat type and characteristics influence juvenile salmon presence and abundance.

Winter and spring are critical rearing periods for sub-yearling salmon, when juveniles tend to prefer shallow and low-velocity habitats (Murphy et al. 1989; Allen 2000; Beechie et al. 2005; Tiffan et al. 2006; Hellmair et al. 2018). In the Snoqualmie River, backwaters and bars had the greatest low-velocity widths and shallowest depths in both winter and spring, which supports predictions of our third research question and is consistent with measurements from various Snoqualmie River project monitoring efforts (David and Kubo 2020; King County 2021a; Kubo 2022b, King County in prep). Our results validate collective monitoring and research findings that sub-yearling salmon prefer low-velocity and shallow edge habitats, especially in winter and spring, with juvenile sub-yearling Chinook salmon abundance greatest in backwaters and bars and juvenile sub-yearling coho salmon frequently present in backwaters. Results from our study emphasize the importance of edge habitat characteristics and validate predictions of our fifth research question, showing that edge type, depth, and low-velocity width

were some of the primary drivers of sub-yearling Chinook presence and abundance in spring and winter. In spring, sub-yearling Chinook were more likely to be present and in greater abundance in depths less than 1.0 meter and in winter were more likely to be present and in greater abundance in depths less than 0.5 meter and in edge habitats with relatively greater low-velocity widths.

Large wood was generally infrequent across all edge habitats, aside from unarmored banks, which supports predictions of our third research question and prior assessments showing that the mainstem Snoqualmie River lacks large wood and wood jams (King County 2002, 2018). The importance of large wood in creating and maintaining salmon habitat is well recognized as it creates complex edge habitats, increases hydraulic heterogeneity that promotes habitat diversity, provides high quality cover, and dissipates hydraulic energy during peak flows (Bilby 1984; Harmon et al. 1986; Bilby and Ward 1991). Our study did not find wood presence a primary driver of salmonid abundance, refuting predictions of our fifth research question; however, sub-yearling Chinook, sub-yearling coho, and yearling coho were frequently observed along unarmored banks where large wood was most prevalent.

Sub-yearling Chinook salmon are also known to avoid large angular rock substrates (McLain and Castillo 2009; Hellmair et al. 2018). During spring in the Snoqualmie River, substrate was a primary driver for sub-yearling Chinook presence and abundance, which validates predictions of our fifth research question. Our analysis indicated that sub-yearling Chinook were less likely to be present and in lower abundance in habitats with riprap rock and were more likely to be present and in greater abundance in edge habitats with sand and gravel. Furthermore, in spring, sub-yearling Chinook abundance was lowest in armored banks, which were dominated by large angular riprap rock, and greatest in backwaters and bars, which were dominated by sand and gravel. Collectively, our findings suggest that sub-yearling Chinook prefer unarmored edge habitats with relatively smaller substrates for early rearing. As discussed in Subsection 3.5.1, it's likely that edge type and substrate are at least partially dependent.

Additional factors that were not characterized or measured in this study likely influence habitat use, abundance, and distribution. Additional habitat-scale factors may include variation in the availability and quality of food resources, temperature regimes, competitive interactions, and predator pressures. Broader riverine- and watershed-scale factors may include channel and floodplain complexity, juvenile salmonid density dependence, subbasin hydrology, and salmonid and fish population abundance as well as other factors.

4.4 Armored banks are unsuitable for juvenile sub-yearling salmon but can support yearling salmonids.

Throughout late winter and spring, juvenile sub-yearling Chinook and coho salmon were less frequent and less abundant in armored banks, which supports predictions of our second research question and is consistent with Snoqualmie River project monitoring evaluations (David and Kubo 2020; King County 2021a; Kubo 2022b), project monitoring in other King County large rivers (David 2022; King County 2023), and observations from other west coast river systems (Knudsen and Dilley 1987; Beamer

and Henderson 1998; Quigley and Harper 2004; Hellmair et al. 2018). Limited use of armored banks by sub-yearling salmon may be due to several factors, including higher water velocities, low habitat variability, predator presence, and reduced prey availability and production (Hellmair et al. 2018).

During spring and winter, armored banks had the least amount of low velocity habitat, the greatest depths, the lowest wood frequency, and were dominated with large riprap rock substrate. As highlighted in Subsection 4.3, sub-yearling Chinook and coho salmon tend to prefer shallow and low-velocity habitats for winter and spring rearing, which likely indicates why sub-yearling salmon were infrequent and less abundant in armored banks. Additionally, the large riprap rock in armored banks likely limited sub-yearling salmon use because they prefer relatively smaller substrates.

As highlighted by Hellmair et al. (2018), predator presence may be a contributing factor deterring sub-yearling salmon from using armored banks. In the Snoqualmie River, yearling and older trout, sculpin, sunfishes, and others are likely to prey on sub-yearling salmon. Throughout spring, trout and sculpin were frequent and abundant in armored banks, suggesting that predator presence may have deterred sub-yearlings. Shallow edge habitats like bars and backwaters as well as unarmored banks with large wood may provide areas for sub-yearlings to hide and avoid predators.

During spring and winter, yearling and older Chinook and coho salmon and trout were frequent and abundant in armored banks, which was similarly observed by King County (2021b). As discussed in Subsection 4.2 and 4.3, as juvenile salmonids grow, they transition from using shallow and low-velocity habitats to using deeper and faster habitats. In the Snoqualmie River, both armored and unarmored banks were typically deeper and faster than other edge habitats and supported yearling salmonids. Our analysis supports that yearling salmonids generally preferred deeper habitats, with yearling and older trout in spring more likely present and in greater abundance in depths greater than 0.8 meter, and yearling Chinook and coho in winter more likely present in depths greater than 1.0 meter and 0.8 meter, respectively.

Armored banks may provide opportunities for yearlings to maximize prey capture while reducing swimming expenditures by providing lower-velocity holding areas (spaces between large rocks) directly adjacent to faster currents where prey drift and capture is greatest (Donofrio et al. 2018; Hellmair et al. 2018). Sub-yearling salmon may have difficulty accessing and holding in these higher-velocity areas due to limited swimming abilities and may be less likely to use armored banks due to predator presence. Bank habitats are also known to support overwintering, where salmonids use the microhabitats among coarse substrates, aquatic vegetation, roots, and large wood as shelter to minimize swimming energy expenditures, reduce predation risks, and maintain foraging (Rosberg and Associates 1987; Muhlfeld et al. 2001, 2003). Our results showed that armored banks rarely had large wood and aquatic vegetation cover; however, the spaces within large riprap rocks likely provide overwintering shelter. Large wood, exposed roots, and vegetation provide similar shelter, but large wood is infrequent across the Snoqualmie River and wood recruitment from adjacent riparian areas is limited due to degraded riparian conditions (King County 2002, 2018). We

hypothesize that yearling salmonids are abundant in armored banks because the availability of riprap banks is greater than unarmored banks with abundant large wood, exposed roots, and aquatic vegetation. While there are many long reaches of the Snoqualmie River with unarmored banks, the lack of large wood and related holding areas likely makes these areas less suitable for overwintering by yearling salmonids.

4.5 Distribution of juvenile sub-yearling Chinook salmon aligns with habitat extents, adult spawning, and priority salmon recovery reaches.

Our results support predictions of our fourth research question, showing a greater diversity of unarmored edge habitats in RM 19 to 21, RM 26, and RM 31 to 34, and the greatest juvenile Chinook abundance in RM 16 to 21 and 30 to 34. Generally, Snoqualmie River reaches with a greater diversity of unarmored edge habitats aligned with areas of greatest juvenile Chinook salmon abundance. While not directly correlated as part of our analysis, these findings suggest that areas which have both a greater extent of unarmored edge habitats and a greater variety of edge habitats support more juvenile Chinook rearing opportunities and abundance. Juvenile Chinook distribution patterns may also be the result of proximity to core Chinook spawning areas and primary tributaries. Core Chinook spawning in the mainstem Snoqualmie River occurs from RM 20 to 24, RM 30 to 34, and RM 35 to 37 (Pete Verhey, WDFW spawner data). The two core spawning areas that fall within the study extent align well with areas of greater juvenile Chinook abundance, suggesting that proximity to spawning areas may be a driver of edge habitat use and early rearing. Additionally, the areas of highest juvenile Chinook abundance also align with reaches just downstream of the Tolt River (RM 23.8) and the Raging River (RM 34.3), which are the primary tributaries for Chinook spawning in the Snoqualmie River watershed.

The greatest extent of gravel and cobble bars were RM 18 to 22 and RM 33, below the confluences with the Tolt and Raging rivers (RM 23.8 and 34.3, respectively). These tributaries, as well as sediment coming over Snoqualmie Falls, provide the majority of coarse sediments in the lower Snoqualmie River (Booth et al. 1991). Sediments coming from these tributaries help create and maintain bar habitat, which as discussed in Subsection 4.2, supports an abundance of juvenile salmonids. Additionally, the coarse sediment coming from these tributaries provide key spawning substrates for adult Chinook, which primarily occurs in Snoqualmie River reaches below both the Tolt and Raging rivers.

As a result of core Chinook salmon spawning, restoration potential, and presumed juvenile salmon rearing, the reaches below the Tolt and Raging rivers are the highest priority for mainstem Snoqualmie River habitat restoration, specifically RM 20.8 to 24.9 and RM 31.2 to 35 (Table 11.6.6, SBSRF 2005). These priority reaches are supported by our observations, with RM 19 to 21 and RM 30 to 34 showing the greatest juvenile Chinook abundance (fish surveys were not conducted from RM 22 to 23). Our findings suggest that a continued focus on these priority reaches, as well as reaches downstream of other major tributary confluences, will provide juvenile Chinook with more rearing opportunities that are both near the redds where they emerged as well as near important edge habitats.

4.6 Management implications of juvenile salmon habitat use and associations.

The Snohomish Salmon Plan and related habitat restoration strategies in the Snoqualmie River are structured around understandings and assumptions of juvenile salmonid habitat use and associations, specifically, the habitat types and rearing conditions that juvenile salmonids prefer and need during early life stages (SBSRF 2005; SWF 2022). Results from this study and collective observations from Snoqualmie River project monitoring and research provide a broad basis to help inform assumptions and validate or refine ongoing restoration strategies. Additionally, these collective efforts help to identify further considerations worth integrating into restoration strategies moving forward.

4.6.1 Restore low velocity mainstem edge habitats.

Our results build on prior project monitoring and research observations showing that juvenile sub-yearling Chinook and coho salmon prefer low-velocity and shallow habitat for early rearing. Increasing the extent, availability, and connectivity of these habitats and other low-velocity habitats like side channels and inundated floodplain areas will best support rearing for sub-yearling salmon. The Snohomish Salmon Plan prioritized the restoration of low-velocity, off-channel, and floodplain habitats (SBSRF 2005). Collective Snoqualmie River monitoring and research observations validate that increasing the area and connectivity of low-velocity and off-channel habitats will greatly benefit juvenile salmon.

Restoration strategies and project designs may need to further consider and integrate bar habitats. Consistent and collective Snoqualmie River observations indicate that bar habitats are generally shallow with wide low-velocity areas and support some of the greatest juvenile Chinook and coho salmon abundances across edge types. However, bar habitat is not directly addressed in the Snohomish Salmon Plan but rather assumed through the restoration of hydrologic, large wood, and sediment transport processes. As restoration project teams evaluate how project actions restore critical rearing habitats, they should consider how bar habitat is created and maintained in a project reach. Project teams should consider how project actions support bar formation through unconfined channel migration, adequate sediment sources, hydrologic conditions that promote sediment deposition, and large wood to create heterogeneity and promote sediment deposition. Consideration of bars in addition to other edge habitats will ensure that restoration strategies support the full suite of mainstem edge habitats important for juvenile salmonid rearing.

4.6.2 Support mainstem edge habitat diversity and availability across seasons.

A diversity of mainstem edge habitats is important to support juvenile salmonids as they grow and transition through early life stages. As shown by our study and other Snoqualmie River monitoring and research efforts, juvenile salmonids not only use the full suite of available edge habitats, but species and life histories display distinct seasonal shifts in habitat use. Restoration strategies that support edge habitat diversity, availability, and connectivity will therefore greatly benefit juvenile salmonid rearing throughout the mainstem Snoqualmie River. Snoqualmie River habitat restoration efforts are focused on restoring watershed- and reach-scale processes to create and

maintain a diversity of salmonid habitats (SBSRF 2005). Our findings and collective Snoqualmie River monitoring and research observations validate the benefits of this approach. Moving forward, further consideration may be needed to ensure that a diversity of edge habitats is available across seasons and environmental conditions (e.g., flow ranges and temperature regimes) to best support juvenile salmonid rearing.

Currently, project designs are primarily structured around sub-yearling juvenile salmon habitat requirements during late winter and spring, with project design elements and hydrologic modelling focused on flows and habitat conditions during these periods. However, our findings and other Snoqualmie River monitoring and research observations indicate that projects should consider mainstem edge habitats and environmental conditions throughout the year. Consideration of edge habitats across seasonal periods and varying environmental conditions could include ensuring habitat availability and connectivity across a broader range of flows in spring, providing temperature refuge during summer, and providing overwintering habitat in confluences, tributaries, and large wood jams along unarmored banks. Ensuring edge habitats are available and connected throughout the year will help maintain Snoqualmie River life history diversity by providing habitats important to life histories that display extended freshwater rearing.

Increasing edge habitat diversity may require a shift in project designs and approaches to increase certain edge habitat types that are generally underrepresented in habitat restoration projects and strategies. As discussed in Subsections 4.2 and 4.6.1, bar habitat is important and should be incorporated into restoration strategies and project designs, especially when process-based restoration influences hydrologic and sediment transport processes. Confluence areas may be another habitat type to integrate and worthy of more attention. Confluences are locations of dynamic physical and biological processes (Rice et al. 2008), many of which influence juvenile salmon rearing, foraging, and growth. In addition, confluences provide overwintering habitat for juveniles with extended freshwater rearing (Rosberg and Associates 1987; Levings and Lauzier 1991). Our findings as well as prior Snoqualmie River observations (King County 2021b; Kubo 2021) indicate that juvenile Chinook salmon can be abundant in confluence areas. Integrating confluences into reach-scale restoration may include improved confluence connectivity, increased confluence large wood abundance, and reduced confluence bank armoring.

4.6.3 Continue removing bank armoring.

Improving and increasing the extent of mainstem edge habitats, especially through the removal of riprap armoring, will benefit juvenile salmon rearing opportunities and conditions. Our findings as well as Snoqualmie River project monitoring and research efforts support that armored banks do not provide suitable habitat conditions for sub-yearling Chinook and coho salmon. In addition, removing bank armoring can allow natural channel sediment, hydrologic, and migration processes to function, creating and maintaining mainstem habitats. Our findings suggest that armored banks do provide near-term overwintering habitat for yearling salmonids (discussed in Subsections 4.2 and 4.4); however, the long-term benefits of unarmored banks with abundant large

wood, exposed roots, and aquatic vegetation are considerably greater for salmonid habitat conditions.

Removing bank armoring and improving mainstem edge habitats has been a fundamental habitat restoration strategy in the Snohomish Salmon Plan (SBSRF 2005; SWF 2022). In addition, Snohomish River Basin life cycle modelling indicates that improving bank conditions as well as increasing large wood loading and floodplain connectivity directly benefit juvenile Chinook and provide significant lift for returning adult spawner abundance (Beechie et al. 2023). The life cycle model also indicated that wood loading is especially important for juvenile coho. Despite the importance of improved bank conditions, considerable lengths of the lower Snoqualmie River continue to have bank armoring, especially in key spawning and rearing reaches (King County 2018). Collective Snoqualmie River monitoring and research findings support that the removal of bank armoring should remain a high priority for habitat restoration and salmon recovery.

4.6.4 Increase the abundance of mainstem large wood.

The presence and abundance of large wood along the mainstem Snoqualmie River is important for juvenile salmonid rearing. As noted in Subsection 4.3, the importance of large wood in creating and maintaining salmon habitat is well recognized. Subsequently, habitat restoration strategies in the Snoqualmie River include placement of large wood in restored habitats and restoring riparian large wood recruitment processes, such as through riparian restoration and the removal of bank armoring, which encourages channel migration and subsequent wood recruitment (SBSRF 2005; SWF 2022). The latter approach is process-based where natural wood recruitment and retention is assumed to support large wood presence; however, riparian areas throughout the lower Snoqualmie River have been historically cleared (Haas and Collins 2001) with current riparian areas generally narrow, lacking mature large trees, and dominated by invasive vegetation. Thus, large wood recruitment and retention in the lower Snoqualmie River remains impaired. The placement of large wood is a primary strategy in the Snohomish Salmon Plan to provide near-term functions while restored riparian areas mature (SBSRF 2005; SWF 2022).

While our study did not find large wood a primary driver of salmonid presence or abundance, likely because large wood was absent in most edge habitat transects, evidence from the broader published literature affirms that large wood is considerably important for salmonid habitat. Restoration of riparian areas, wood recruitment processes, and continued placement of large wood along mainstem edge habitats and throughout adjacent riparian areas should remain a high priority.

4.6.5 Maximize habitat restoration in priority reaches.

In the Snoqualmie River watershed, the Snohomish Salmon Plan identified “Mainstem Primary” priority reaches for habitat restoration across the Snoqualmie, Tolt, and Raging rivers. In the mainstem Snoqualmie River, priority reaches include areas adjacent and downstream of the Tolt and Raging rivers (RM 20.8 to 24.9 and RM 31.2 to 35; Table 11.6.6, SBSRF 2005). These mainstem Snoqualmie River priority reaches not only align

with primary Chinook salmon spawning areas, but as shown by our findings, also align with areas of relatively greater juvenile Chinook abundance and rearing. Additionally, these reaches include some of the greatest extent of bar habitat, which as previously discussed, provide important rearing habitat. Our findings support that restoration efforts should continue to prioritize these reaches and projects should focus on maximizing the extent, availability, and diversity of restored edge habitats, including across environmental conditions and seasons. Improving edge habitats in these priority reaches and near core spawning areas where juveniles emerge and are abundant will best support juvenile salmonid rearing opportunities during early life stages.

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6 References

Allen, M.A. 2000. Seasonal microhabitat use by juvenile spring Chinook salmon in the Yakima River basin, Washington. Rivers 7(4): 314–332.

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

Beecher, H.A., Caldwell, B.A., and DeMond, S.B. 2002. Evaluation of depth and velocity preferences of juvenile coho salmon in Washington streams. North American Journal of Fisheries Management 22(3): 785–795. Taylor & Francis.

Beechie, T.J., Goodman, A., Stefankiv, O., Timpane-Padgham, B., and Lowe, M. 2023. Habitat Assessment and Restoration Planning (HARP) Model for the Snohomish and Stillaguamish River Basins. U.S. Department of Commerce, NOAA Contract Report NMFS-NWFSC-CR-2023-02.

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

Bilby, R.E. 1984. Characteristics and frequency of cool-water areas in a western Washington stream. Journal of Freshwater Ecology 2(6): 593–602. Taylor & Francis.

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

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

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

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

Breiman, L. 2001. Random forests. Machine learning 45: 5–32. Springer.

Crozier, W.W., and Kennedy, G.J.A. 1994. Application of semi-quantitative electrofishing to juvenile salmonid stock surveys. Journal of Fish Biology 45(1): 159–164. Wiley Online Library.

David, A. 2022. Porter Reach Restoration Project: Pre- and Post-Implementation Fish and Aquatic Habitat Monitoring. King County Department of Natural Resources and Parks, Water Land and Resources Division, Seattle, WA.

David, A., and Kubo, J. 2020. Upper Carlson Floodplain Restoration Project: Fish and Aquatic Habitat Monitoring. Technical Memorandum to the Snoqualmie Watershed Forum, Seattle, WA.

Donofrio, E., Simon, T., Neuswanger, J.R., and Grossman, G.D. 2018. Velocity and dominance affect prey capture and microhabitat selection in juvenile Chinook (*Oncorhynchus tshawytscha*). Environmental Biology of Fishes 101: 609–622. Springer.

Everest, F.H., and Chapman, D.W. 1972. Habitat selection and spatial interaction by juvenile chinook salmon and steelhead trout in two Idaho streams. Journal of the Fisheries Board of Canada 29(1): 91–100.

Guy, C.S., and Brown, M.L. 2007. Analysis and interpretation of freshwater fisheries data. American Fisheries Society.

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

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

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

Hellmair, M., Peterson, M., Mulvey, B., Young, K., Montgomery, J., and Fuller, A. 2018. Physical characteristics influencing nearshore habitat use by juvenile Chinook salmon in the Sacramento River, California. North American Journal of Fisheries Management 38(4): 959–970.

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

Holecek, D.E., Cromwell, K.J., and Kennedy, B.P. 2009. Juvenile Chinook Salmon Summer Microhabitat Availability, Use, and Selection in a Central Idaho Wilderness Stream. Transactions of the American Fisheries Society 138(3): 633–644.

Keith, J., Grindall, J., and Holmgren, D. 2023. 2000-2022 Skykomish and Snoqualmie Rivers Chinook and Coho Salmon Out-migration Study. Tulalip Tribes Natural Resources Department.

King County. 2002. Snoqualmie Watershed Aquatic Habitat Conditions Report: Summary of 1999-2001 Data. Prepared by Fran Solomon and Melissa Boles, Water and Land Resources Division. Seattle, WA.

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

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

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

King County. 2023. Enhancing knowledge of juvenile salmon habitat use in the mainstem Green River. Prepared by Aaron David, Water and Land Resources Division. Seattle, WA.

King County. In Preparation. Chinook Bend Floodplain Reconnection Project - Year 10 (2019) Monitoring and Maintenance Report. Prepared by Jo Wilhelm, Josh

Latterell, Dan Eastman, and Ashley Gould, Water and Land Resources Division. Seattle, WA.
Knudsen, E.E., and Dilley, S.J. 1987. Effects of riprap bank reinforcement on juvenile salmonids in four western Washington streams. North American Journal of Fisheries Management 7(3): 351–356.
Kubo, J. 2021. Tolt Pipeline Protection/Winkelman Revetment Reconstruction Project: Year 3 Post-Project Aquatic Habitat and Juvenile Salmonid Monitoring Results. King County Department of Natural Resources and Parks, Water Land and Resources Division.
Kubo, J. 2022a. Snoqualmie River Chinook Salmon Conceptual Model. Technical Memorandum, Prepared by King County Water and Land Resources Division for the Snoqualmie Watershed Forum, Seattle, WA.
Kubo, J. 2022b. Fall City Floodplain Restoration Project: Fish and Aquatic Habitat Pre-Project Monitoring. Technical Memorandum to King County Ecological Restoration and Engineering Services Unit, Seattle, WA.
Kubo, J., Finley, K., Nelson, K., Sheldon, M., Chairman, T., Parker, D., James, C., Fryberg Jr, M., Sheldon, T., and Gobin, G. 2013. 2000-2012 Skykomish and Snoqualmie Rivers Chinook and Coho Salmon Out-migration Study.
Levings, C.D., and Lauzier, R.B. 1991. Extensive use of the Fraser River basin as winter habitat by juvenile chinook salmon (*Oncorhynchus tshawytscha*). Canadian Journal of Zoology 69(7): 1759–1767. NRC Research Press Ottawa, Canada.
Liaw, A., and Wiener, M. 2002. Classification and regression by randomForest. R news 2(3): 18–22.
McLain, J., and Castillo, G. 2009. Nearshore areas used by fry Chinook Salmon, *Oncorhynchus tshawytscha*, in the northwestern Sacramento–San Joaquin Delta, California. San Francisco Estuary and Watershed Science 7(2).
Muhlfeld, C.C., Bennett, D.H., and Marotz, B. 2001. Fall and winter habitat use and movement by Columbia River redband trout in a small stream in Montana. North American Journal of Fisheries Management 21(1): 170–177.
Muhlfeld, C.C., Glutting, S., Hunt, R., Daniels, D., and Marotz, B. 2003. Winter diel habitat use and movement by subadult bull trout in the upper Flathead River, Montana. North American Journal of Fisheries Management 23(1): 163–171.
Murphy, M.L., Heifetz, J., Thedinga, J.F., Johnson, S.W., and Koski, K.V. 1989. Habitat utilization by juvenile Pacific salmon (*Onchorynchus*) in the glacial Taku River, southeast Alaska. Canadian Journal of Fisheries and Aquatic Sciences 46(10): 1677–1685. NRC Research Press Ottawa, Canada.
Nickelson, T.E., Rodgers, J.D., Johnson, S.L., and Solazzi, M.F. 1992. Seasonal changes in habitat use by juvenile coho salmon (*Oncorhynchus kisutch*) in Oregon coastal streams. Canadian Journal of Fisheries and Aquatic Sciences 49(4): 783–789. NRC Research Press Ottawa, Canada.
Quigley, J.T., and Harper, D.J. 2004. Streambank protection with rip-rap: an evaluation of the effects on fish and fish habitat. Canadian Manuscript Report of Fisheries and Aquatic Sciences 2701. Fisheries and Oceans Canada.
Rice, S., Roy, A., and Rhoads, B. 2008. River confluences, tributaries and the fluvial network. John Wiley & Sons.

Roni, P., and Fayram, A. 2000. Estimating winter salmonid abundance in small western Washington streams: a comparison of three techniques. North American Journal of Fisheries Management 20(3): 683–692.
Rosberg, G.E., and Associates. 1987. Sampling of Juvenile Salmonids in the Frasier River Mainstem Over the Winter of 1986–1987. Data report prepared for Fisheries and Oceans Canada, Vancouver, B. C.
Snohomish Basin Salmon Recovery Forum (SBSRF). 2005. Snohomish River Basin Salmon Conservation Plan. Snohomish County Department of Public Works, Surface Water Management Division. Everett, WA.
Snohomish Basin Salmonid Recovery Technical Committee (SBSRTC). 2004. Snohomish River Basin Ecological Analysis for Salmonid Conservation. Snohomish County Surface Water Management Division.
Snoqualmie Watershed Forum (SWF). 2022. 15-Year Status Report Snoqualmie & South Fork Skykomish Watersheds 2005 - 2020. Prepared by Cory Zyla, Elissa Ostergaard and Emily Davis, Snoqualmie Watershed Forum, King County, Seattle, WA.
Spence, B.C., Lomnicky, G.A., Hughes, R.M., and Novitzki, R.P. 1996. An Ecosystem Approach to Salmonid Conservation. TR-4501-96-6057. ManTech Environmental Research Services Corporation, Corvallis, OR.
Strobl, C., Malley, J., and Tutz, G. 2009. An introduction to recursive partitioning: rationale, application, and characteristics of classification and regression trees, bagging, and random forests. Psychological methods 14(4): 323. American Psychological Association.
Swales, S., Lauzier, R.B., and Levings, C.D. 1986. Winter habitat preferences of juvenile salmonids in two interior rivers in British Columbia. Canadian Journal of Zoology 64(7): 1506–1514. NRC Research Press Ottawa, Canada.
Swales, S., and Levings, C.D. 1989. Role of off-channel ponds in the life cycle of coho salmon (*Oncorhynchus kisutch*) and other juvenile salmonids in the Coldwater River, British Columbia. Canadian Journal of Fisheries and Aquatic Sciences 46(2): 232–242. NRC Research Press Ottawa, Canada.
Tiffan, K.F., Clark, L.O., Garland, R.D., and Rondorf, D.W. 2006. Variables Influencing the Presence of Subyearling Fall Chinook Salmon in Shoreline Habitats of the Hanford Reach, Columbia River. North American Journal of Fisheries Management 26(2): 351–360.
Tiffan, K.F., Garland, R.D., and Rondorf, D.W. 2002. Quantifying flow-dependent changes in subyearling fall Chinook salmon rearing habitat using two-dimensional spatially explicit modeling. North American Journal of Fisheries Management 22(3): 713–726.
United States Forest Service (USFS). 2021. Stream Inventory Handbook Level I & II Pacific Northwest Region. Version 2.21. United States Department of Agriculture.
Van Den Avyle, M.J., and Hayward, R.S. 1999. Dynamics of exploited fish populations. Inland fisheries management in North America, 2nd edition. American Fisheries Society, Bethesda, Maryland 5: 127–166.
Ward, J. V., and Wiens, J. A. 2001. Ecotones of Riverine Ecosystems: Role and Typology, Spatio-Temporal Dynamics, and River Regulation. Ecohydrology & Hydrobiology 1(1-2):25-36.

Appendix A: Mainstem Snoqualmie River Edge Habitat Types

Figure A-1: Armored bank (riprap rock armoring).

Figure A-2: Backwater.

Figure A-3: Bar.

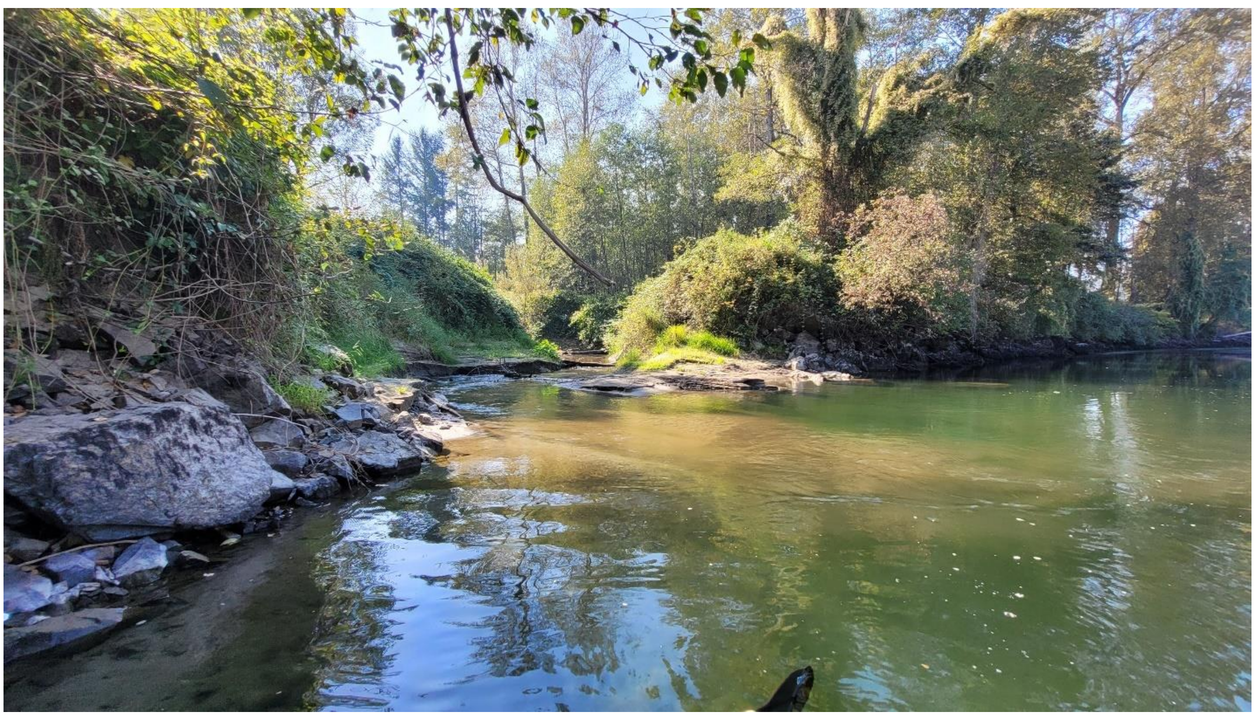

Figure A-4: Confluence.

Figure A-5: Unarmored bank.

Appendix B: Salmonid Abundance Across Edge Habitats and Months

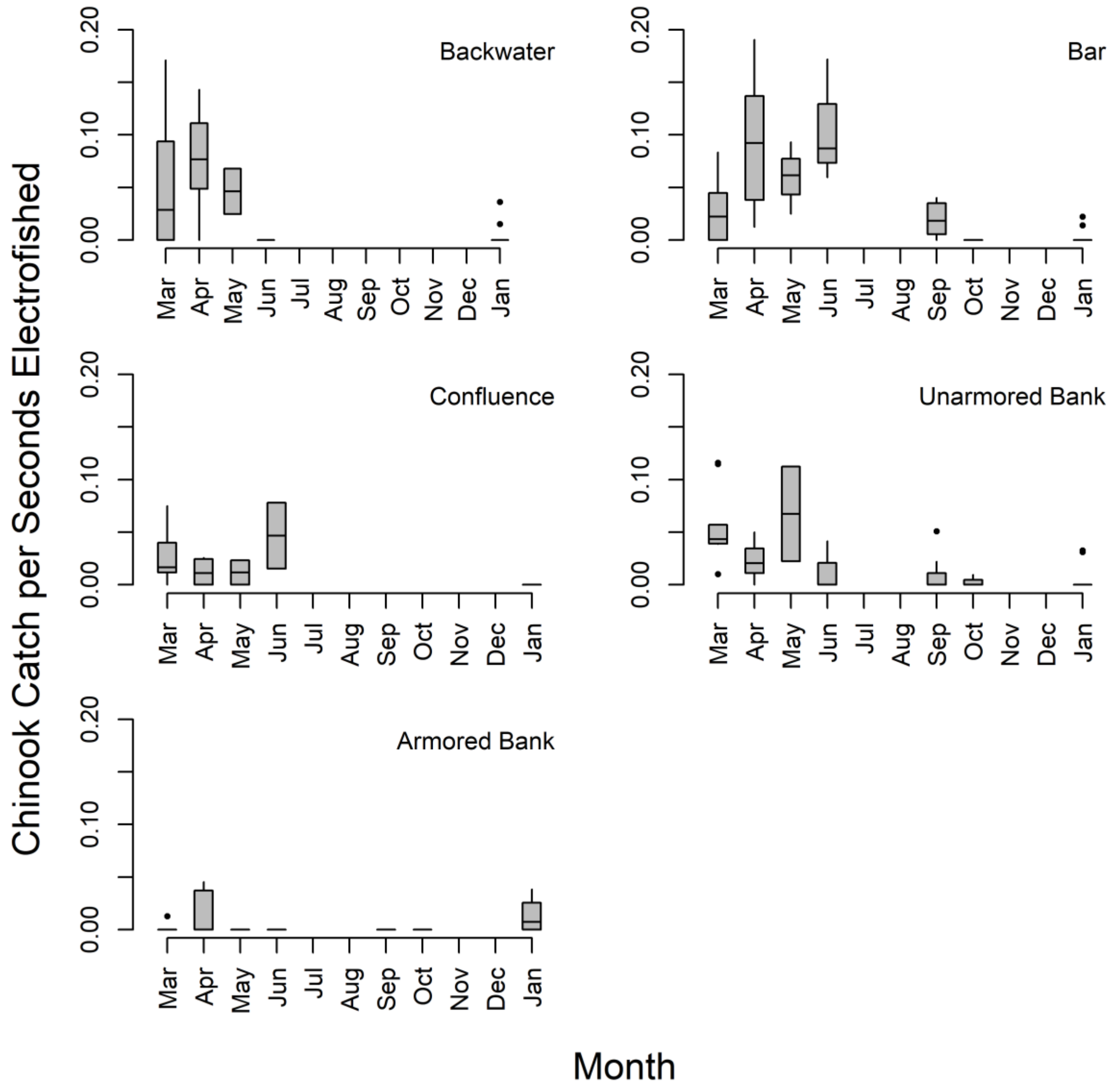

Figure B-1: Juvenile Chinook salmon relative abundance (catch per seconds electrofished) across edge habitats and months.

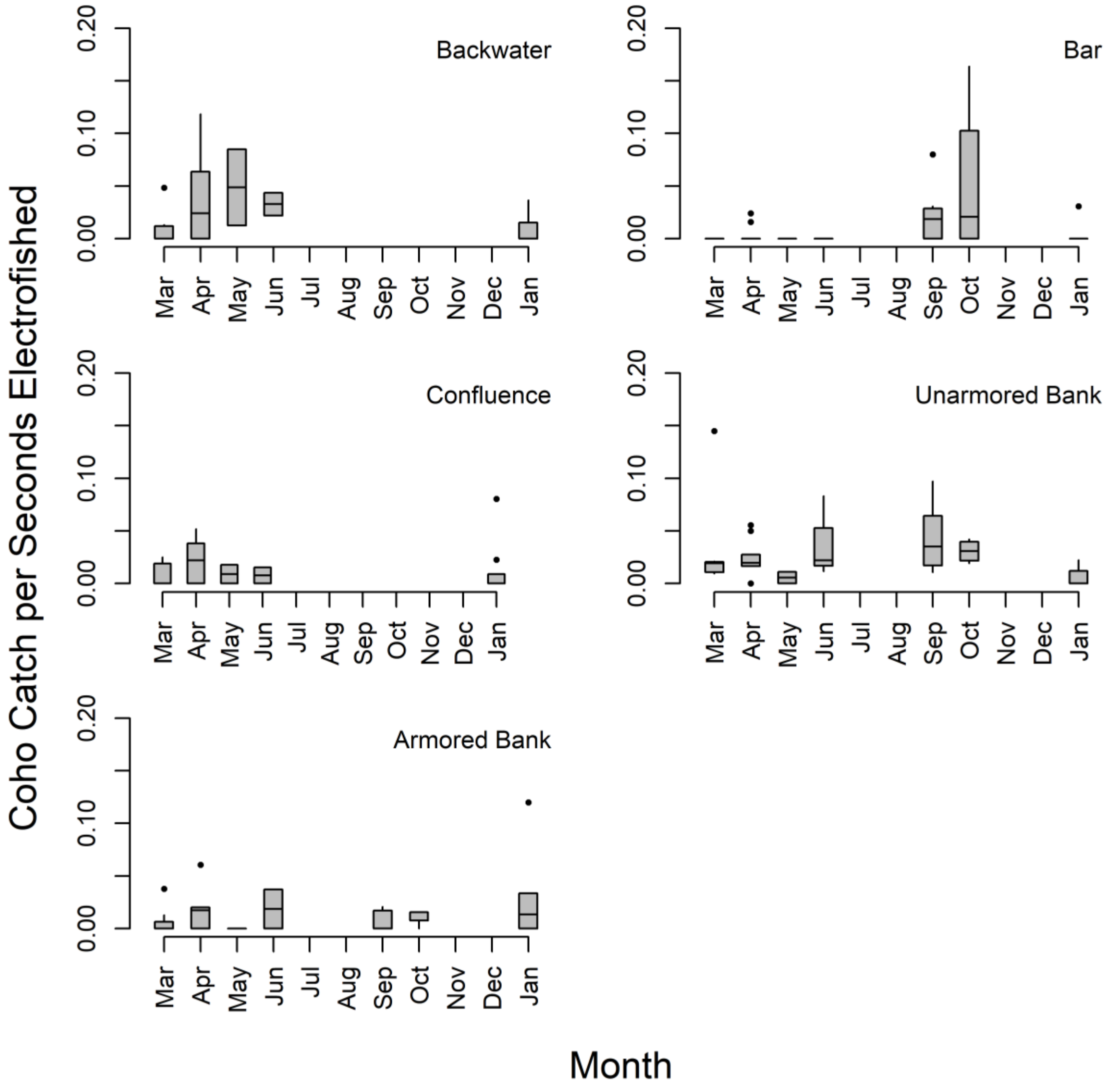

Figure B-2: Juvenile coho salmon relative abundance (catch per seconds electrofished) across edge habitats and months.

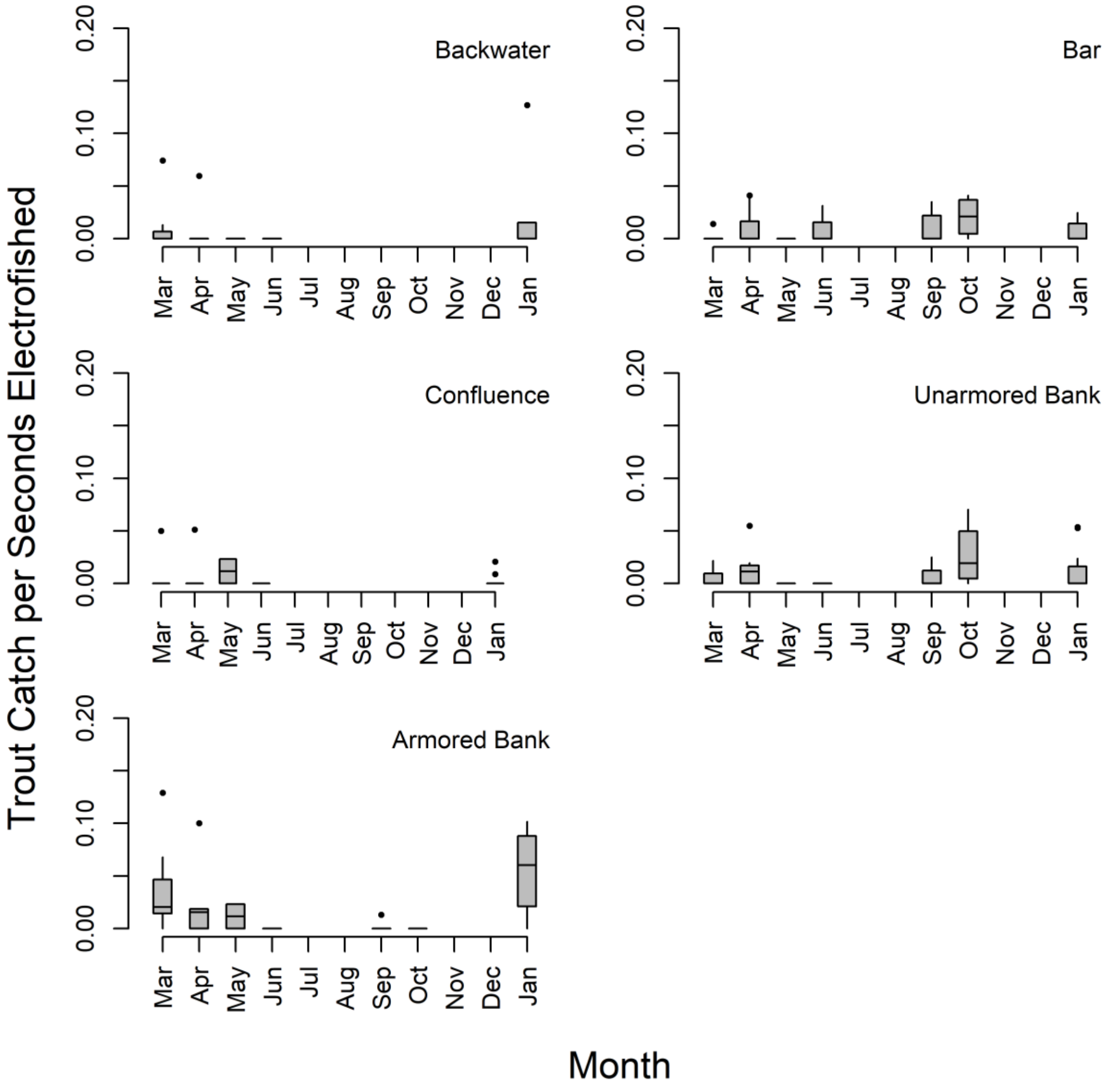

Figure B-3: Trout (rainbow and cutthroat) relative abundance (catch per seconds electrofished) across edge habitats and months.

Appendix C: Random Forest Plots of Variable Importance and Partial Dependence Plots of Variable Effects for Salmonid Presence

Random forest plots in Appendix C and D indicate the relative importance of each variable for juvenile salmonid presence and abundance, with primary driving variables having the greatest positive importance values and the greatest relative difference in importance values compared to other variables. The primary and most influential variables are displayed on the left side of the plotted area.

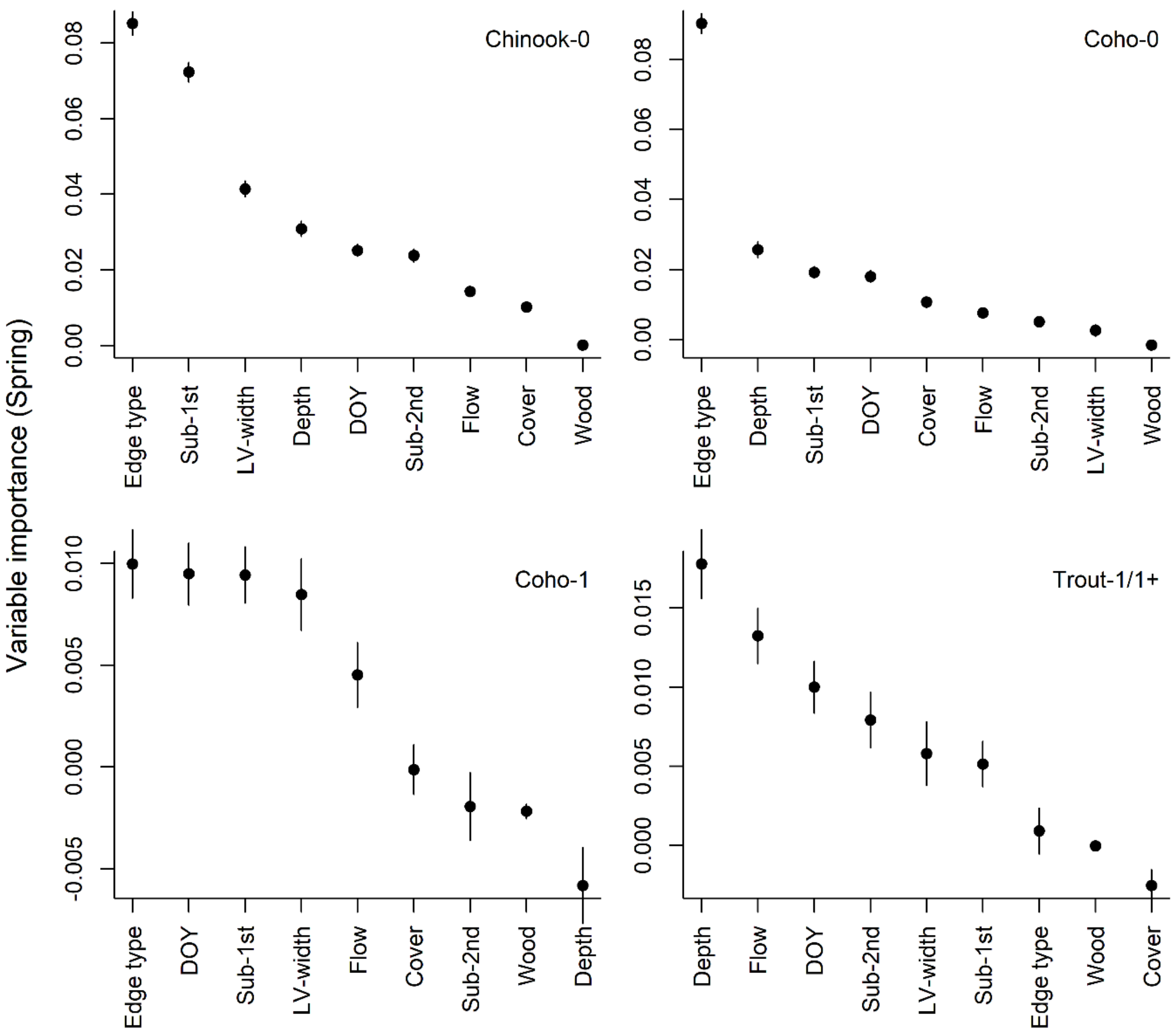

Figure C-1: Random forest plots of variable importance for salmonid presence in spring. Variable codes: LV (low velocity), DOY (day of year), Sub-1 (primary substrate), Sub-2 (secondary substrate). Whiskers indicate standard deviation or variable importance.

Partial dependence plots in Appendix C and D show how the presence or abundance of juvenile salmonids varies based on the primary driving variables identified from the related random forest Models. Categorical variables indicate comparative differences across categories (e.g., presence more/less likely or abundance greater/less, based on edge type) and continuous variables show how presence and abundance changes with an increase in the primary driving variable (e.g., presence more/less likely or abundance greater/less with increasing variable value).

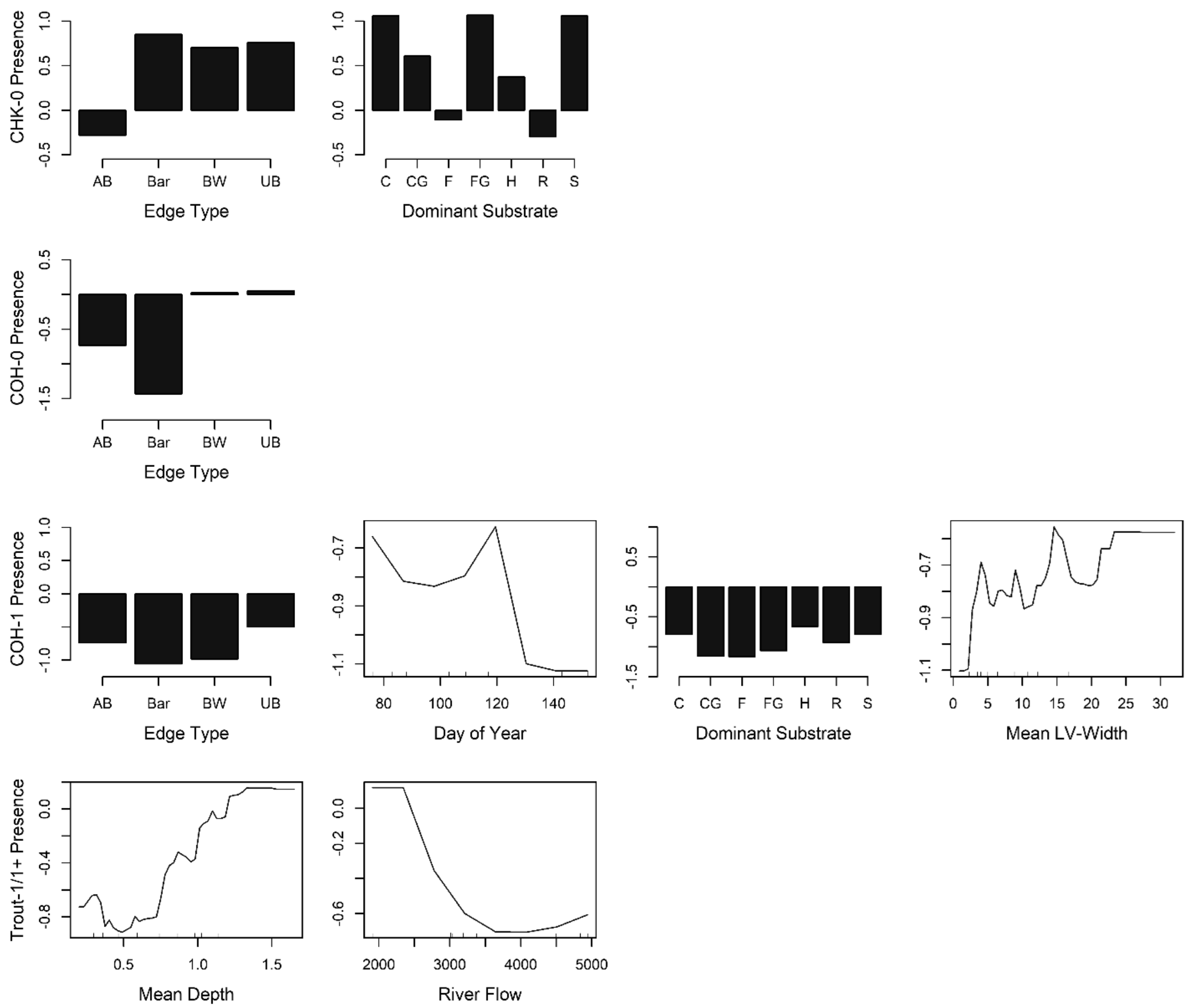

Figure C-2: Partial dependence plots of primary variable effects on salmonid presence in spring. Variable effect codes: armored bank (AB), backwater (BW), unarmored bank (UAB), cobble (C), coarse gravel (CG), fines (F), fine gravel (FG), hardpan (H), riprap (R), sand (S), low-velocity (LV).

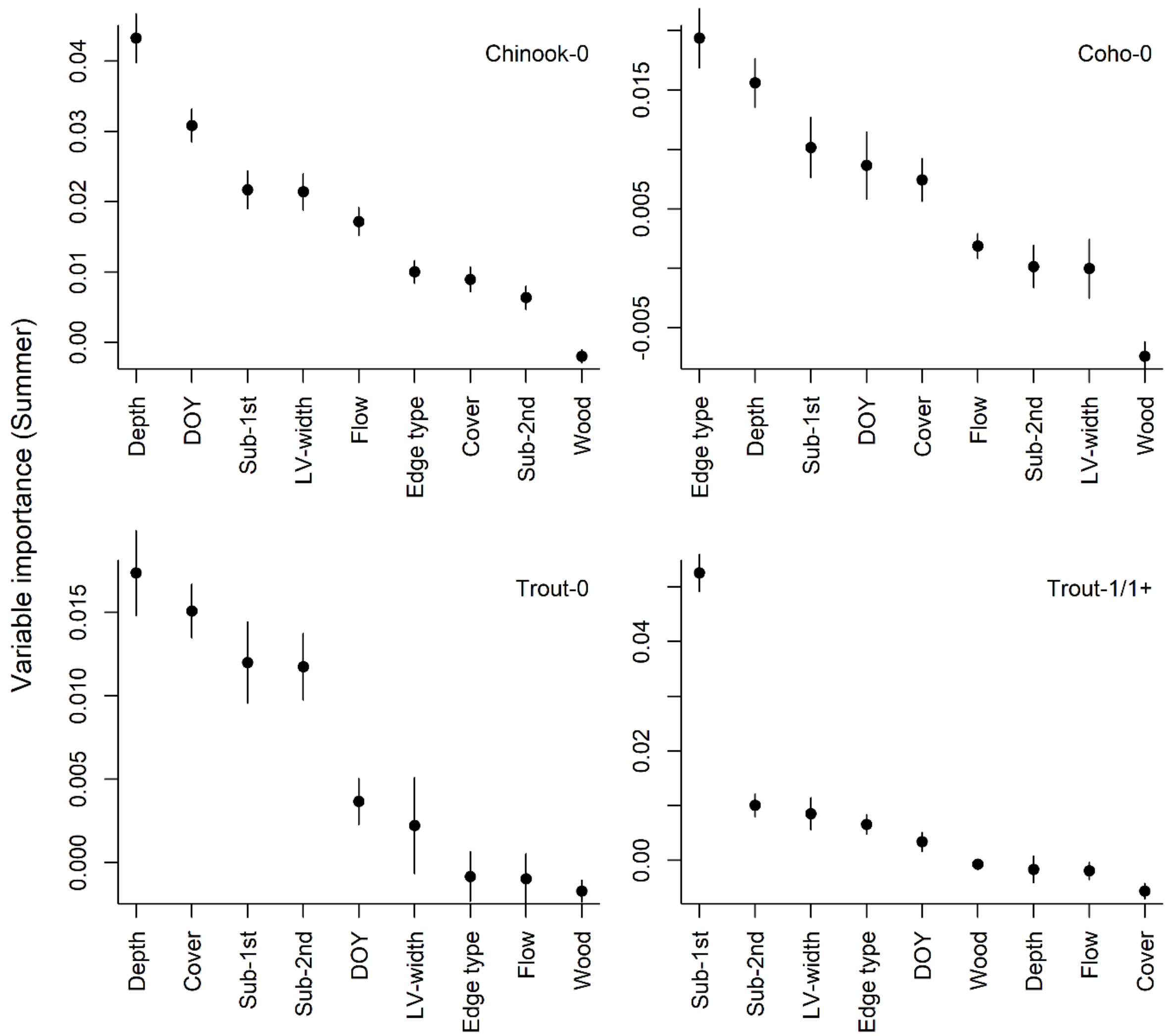

Figure C-3: Random forest plots of variable importance for salmonid presence in late-summer/early-fall. Variable codes: LV (low velocity), DOY (day of year), Sub-1 (primary substrate), Sub-2 (secondary substrate). Whiskers indicate standard deviation or variable importance.

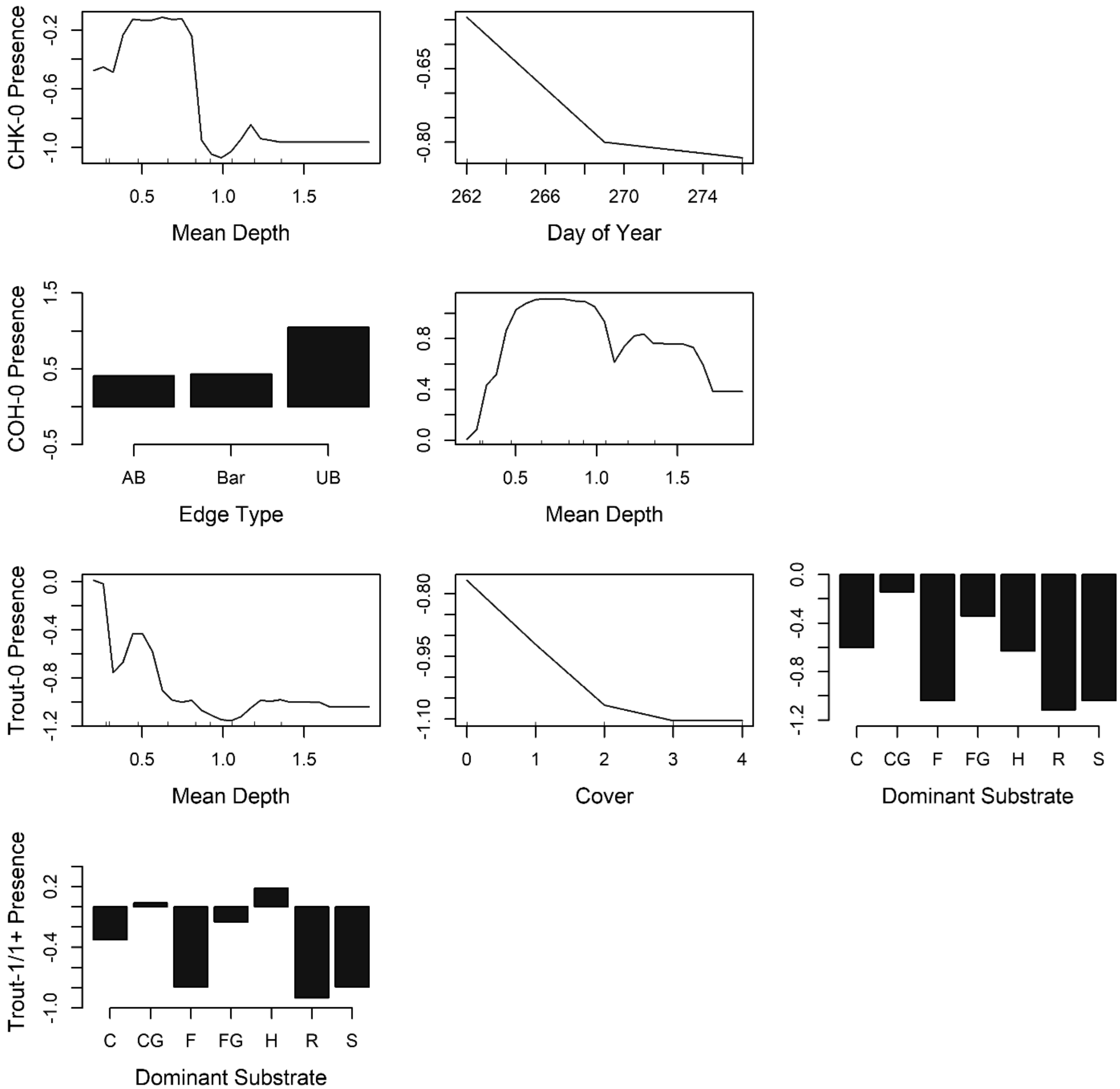

Figure C-4: Partial dependence plots of primary variable effects on salmonid presence in late-summer/early-fall. Variable effect codes: armored bank (AB), unarmored bank (UAB), no cover (0) low cover (1), low-moderate cover (2), moderate cover (3), moderate-high cover (4), high cover (5), cobble (C), coarse gravel (CG), fines (F), fine gravel (FG), hardpan (H), riprap (R), sand (S), low-velocity (LV).

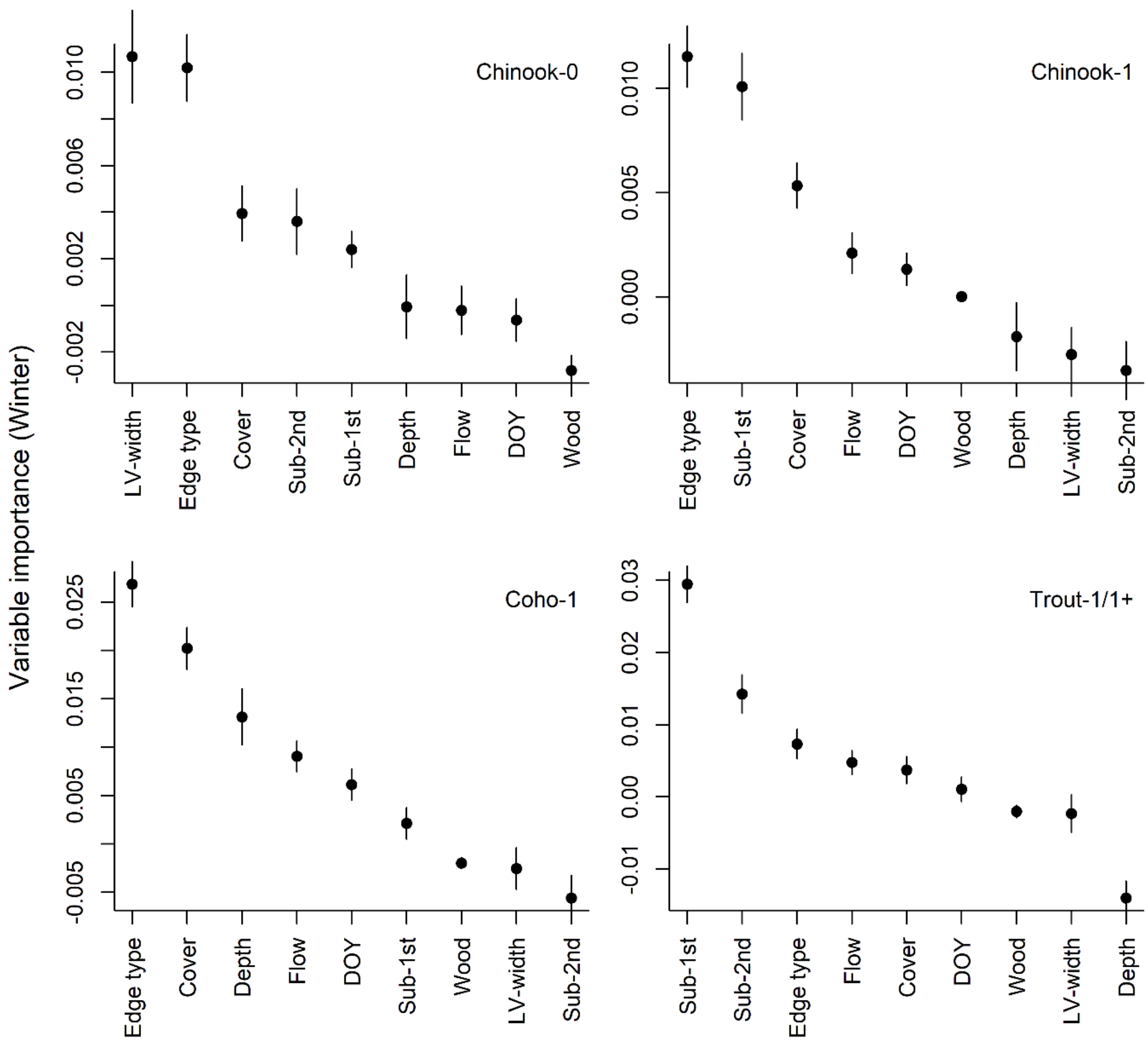

Figure C-5: Random forest plots of variable importance for salmonid presence in winter. Variable codes: LV (low velocity), DOY (day of year), Sub-1 (primary substrate), Sub-2 (secondary substrate). Whiskers indicate standard deviation or variable importance.

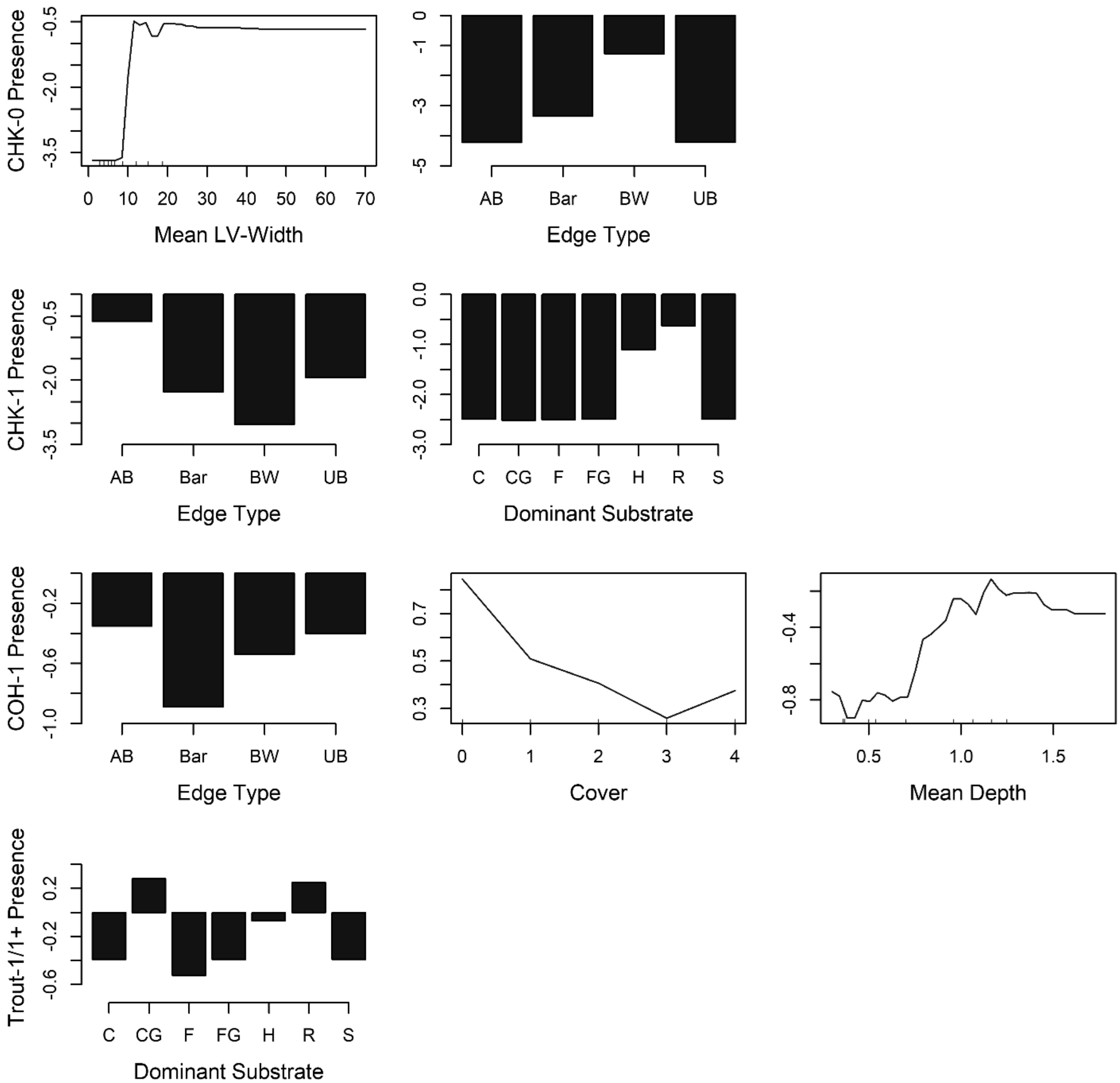

Figure C-6: Partial dependence plots of primary variable effects on salmonid presence in winter. Variable effect codes: low velocity (LV), armored bank (AB), backwater (BW), unarmored bank (UAB), cobble (C), coarse gravel (CG), fines (F), fine gravel (FG), hardpan (H), riprap (R), sand (S), no cover (0) low cover (1), low-moderate cover (2), moderate cover (3), moderate-high cover (4), high cover (5).

Appendix D: Random Forest Plots of Variable Importance and Partial Dependence Plots of Variable Effects for Salmonid Abundance

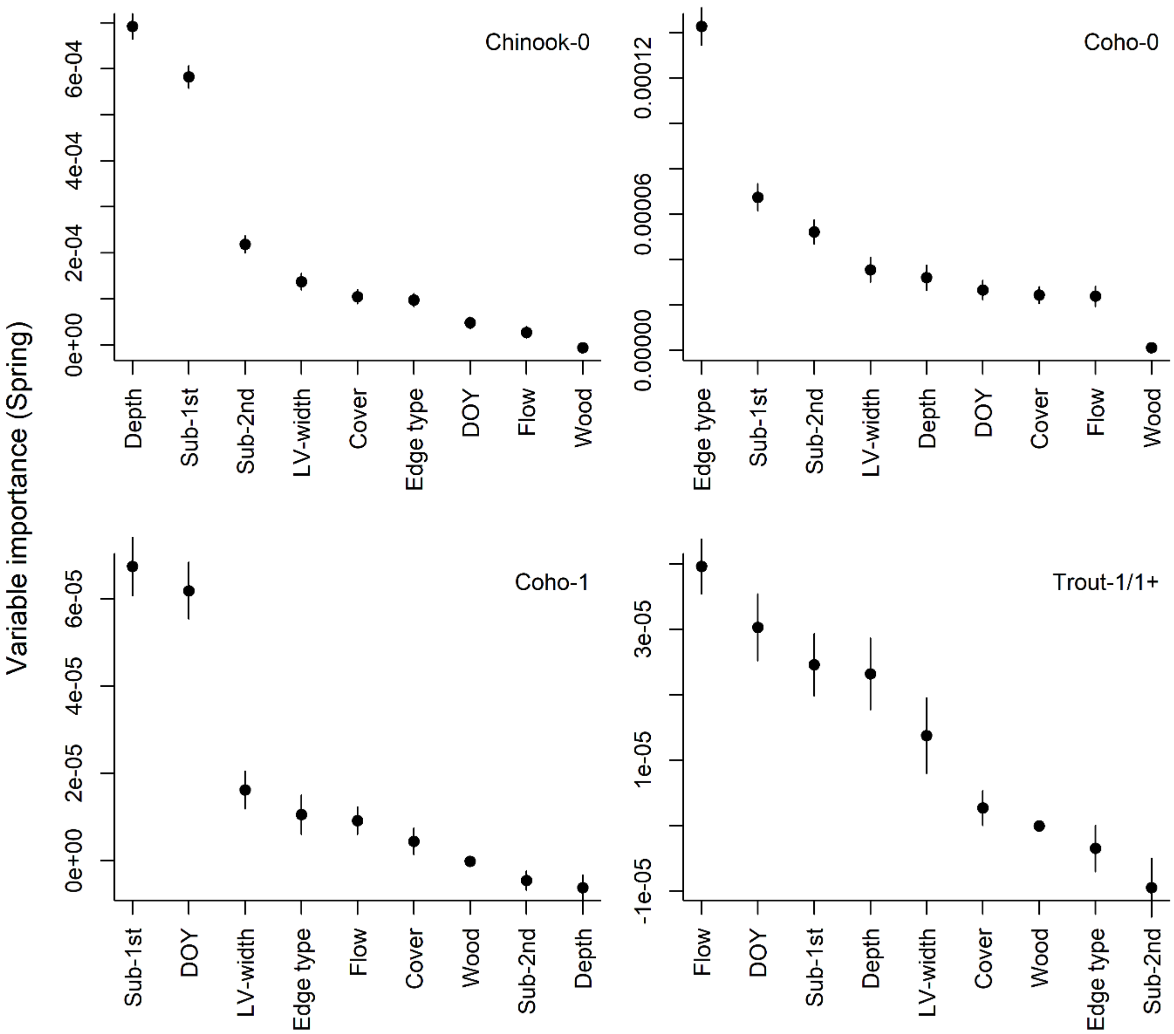

Figure D-1: Random forest plots of variable importance for salmonid relative abundance (catch per seconds electrofished) in spring. Variable codes: LV (low velocity), DOY (day of year), Sub-1 (primary substrate), Sub-2 (secondary substrate). Whiskers indicate standard deviation or variable importance.

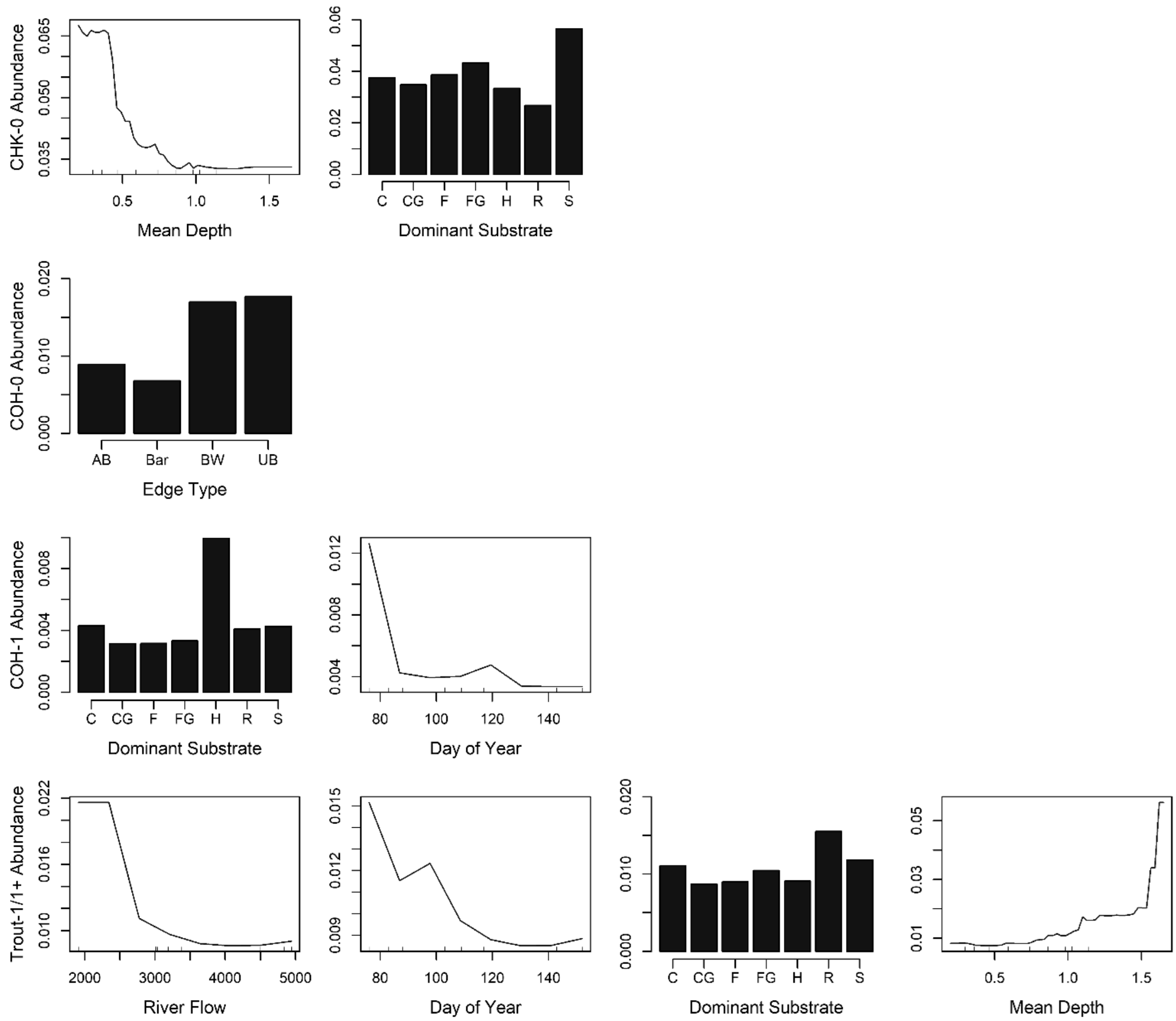

Figure D-2: Partial dependence plots of primary variable effects on salmonid relative abundance (catch per seconds electrofished) in spring. Variable effect codes: cobble (C), coarse gravel (CG), fines (F), fine gravel (FG), hardpan (H), riprap (R), sand (S), armored bank (AB), backwater (BW), unarmored bank (UAB).

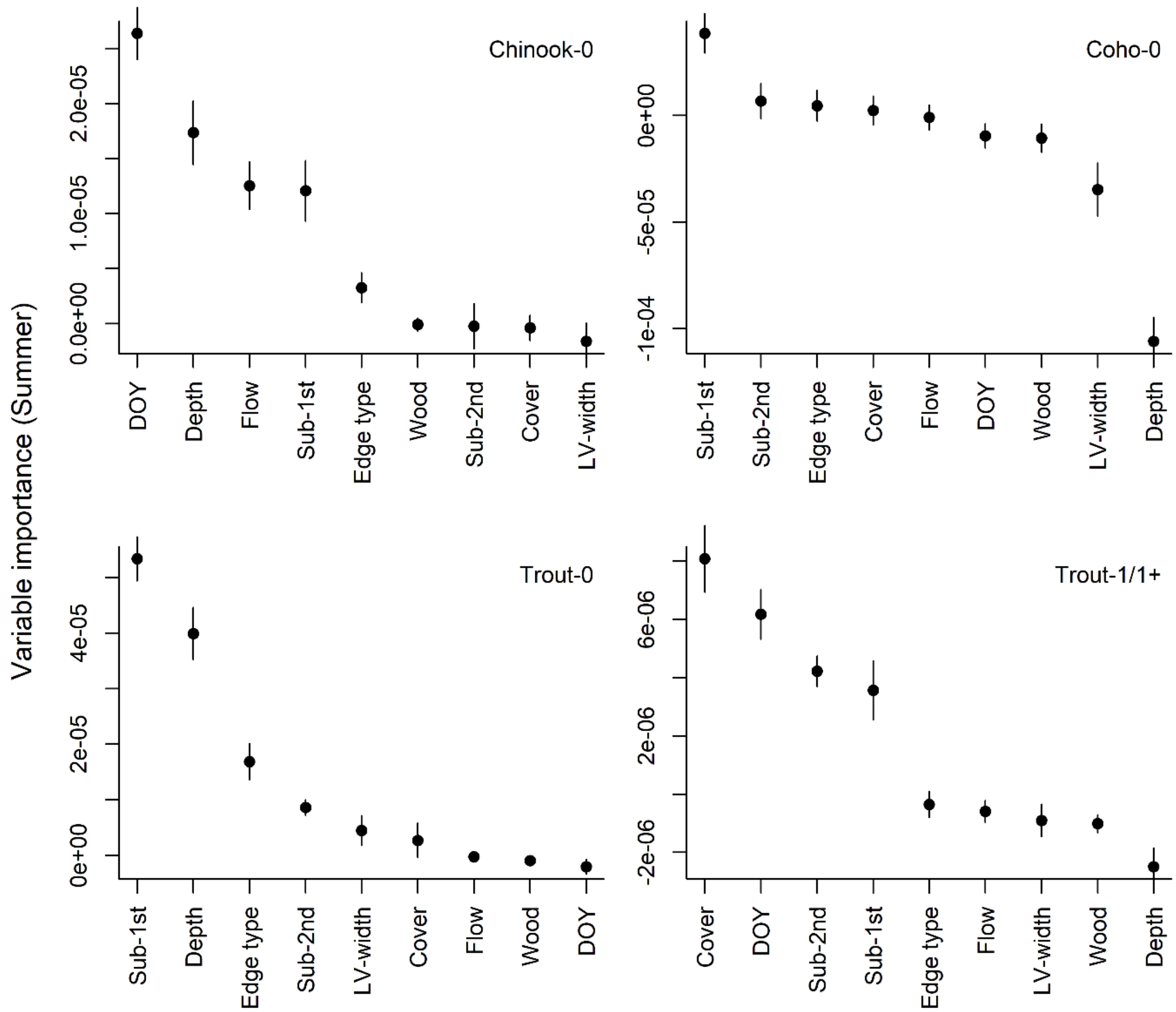

Figure D-3: Random forest plots of variable importance for salmonid relative abundance (catch per seconds electrofished) in late-summer/early-fall. Variable codes: LV (low velocity), DOY (day of year), Sub-1 (primary substrate), Sub-2 (secondary substrate). Whiskers indicate standard deviation or variable importance.

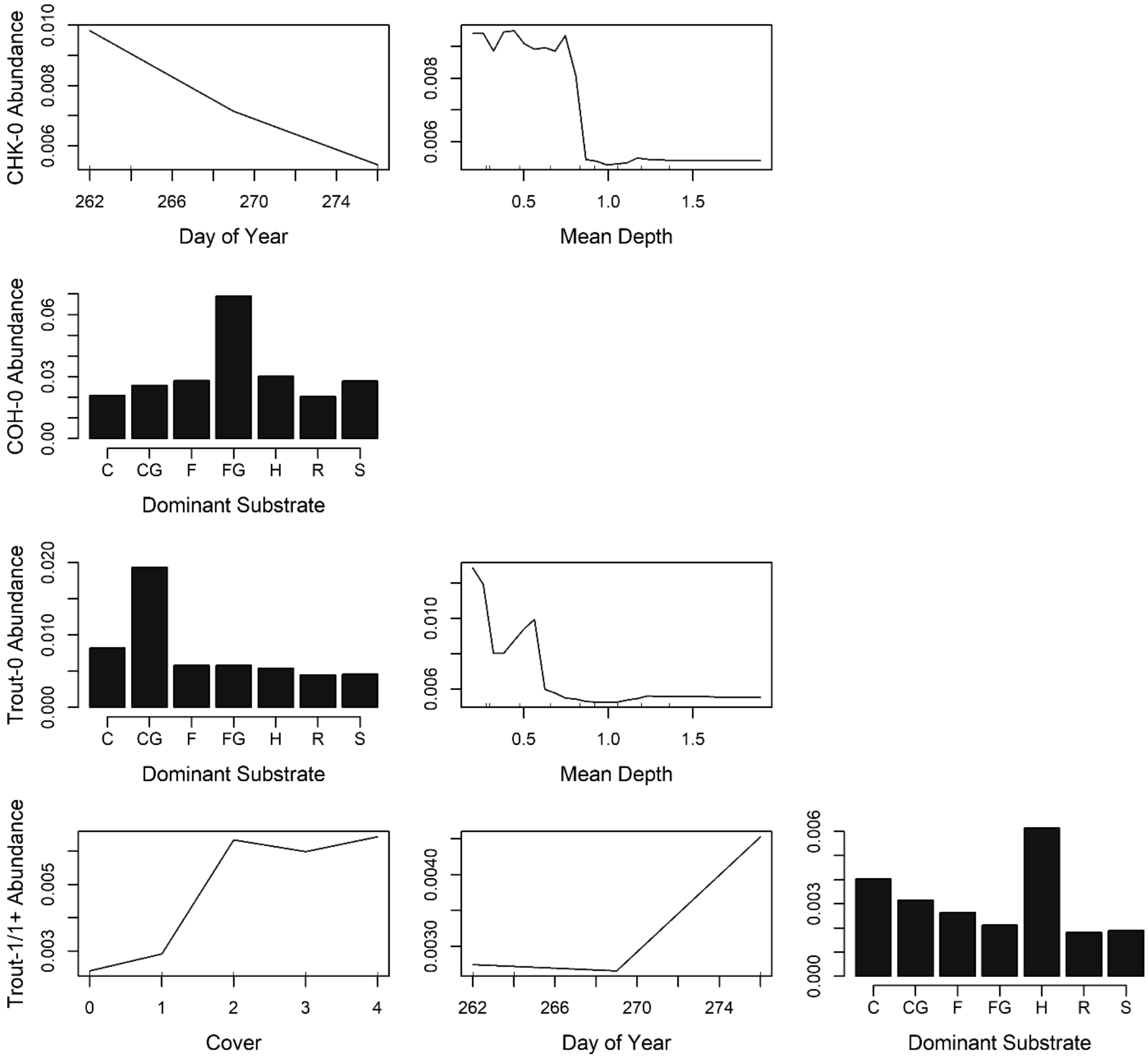

Figure D-4: Partial dependence plots of primary variable effects on salmonid relative abundance (catch per seconds electrofished) in late-summer/early-fall. Variable effect codes: cobble (C), coarse gravel (CG), fines (F), fine gravel (FG), hardpan (H), riprap (R), sand (S), no cover (0) low cover (1), low-moderate cover (2), moderate cover (3), moderate-high cover (4), high cover (5).

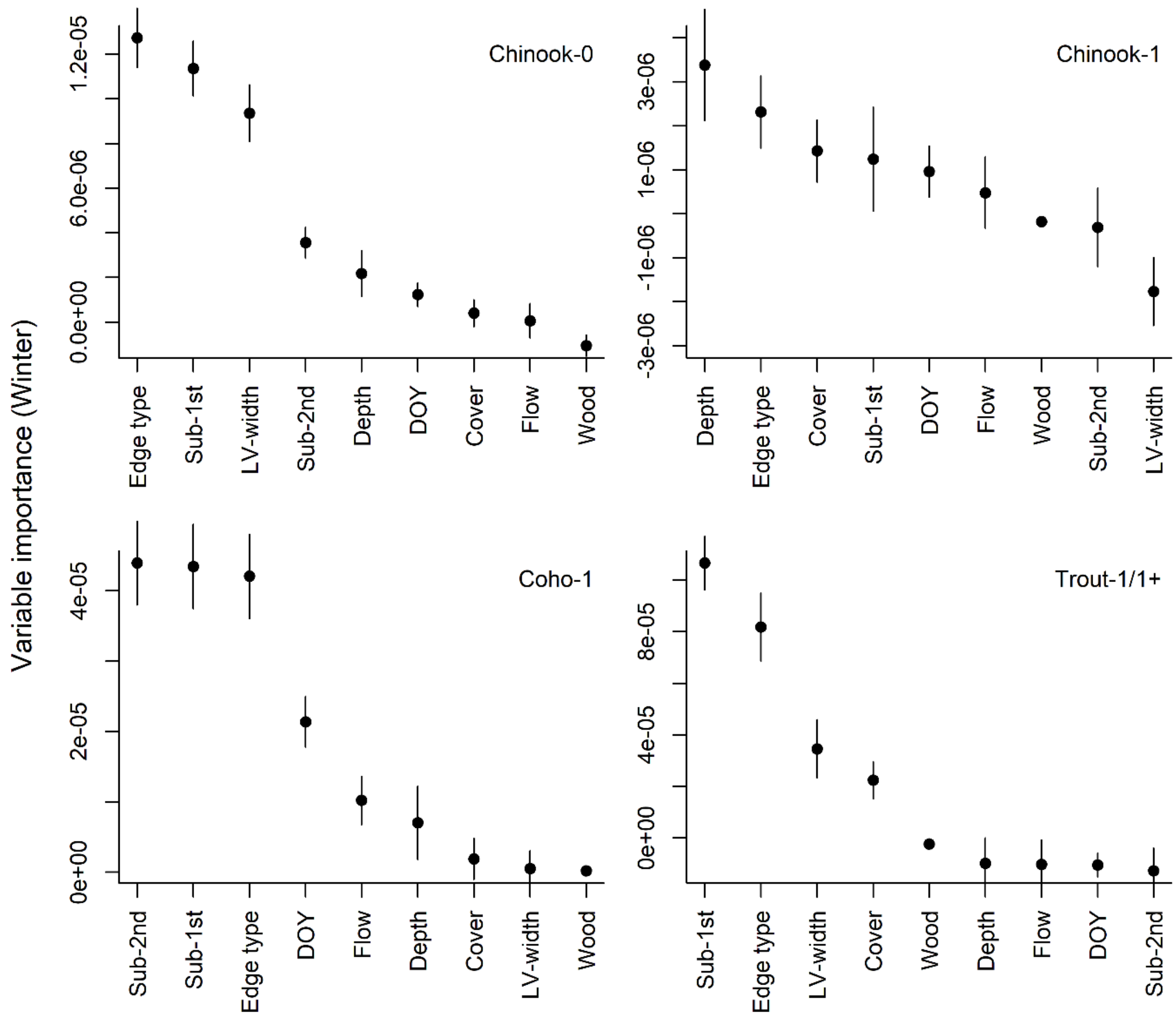

Figure D-5: Random forest plots of variable importance for salmonid relative abundance (catch per seconds electrofished) in winter. Variable codes: LV (low velocity), DOY (day of year), Sub-1 (primary substrate), Sub-2 (secondary substrate). Whiskers indicate standard deviation or variable importance.

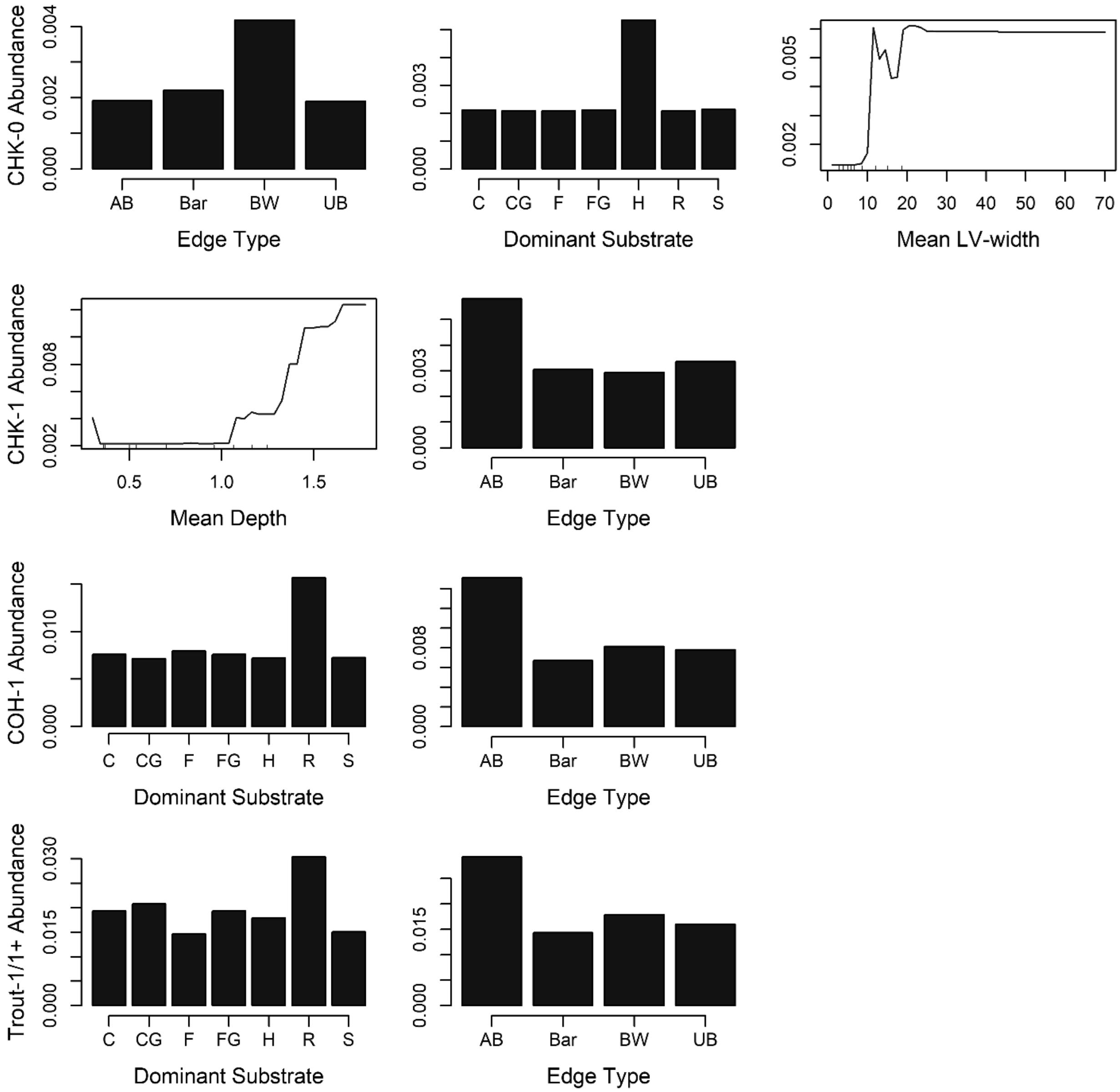

Figure D-6: Partial dependence plots of primary variable effects on salmonid relative abundance (catch per seconds electrofished) in winter. Variable effect codes: armored bank (AB), backwater (BW), unarmored bank (UAB), cobble (C), coarse gravel (CG), fines (F), fine gravel (FG), hardpan (H), riprap (R), sand (S), low velocity (LV).