Utilizing stream temperature in regional barrier removal planning does not substantially improve cool-water habitat restoration

J Kahn

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Committee:
Sunny Jardine
Robby Fonner
Mark Scheuerell

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J Kahn

University of Washington

Abstract

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J Kahn

Chair of the Supervisory Committee:
Sunny Jardine
School of Marine and Environmental Affairs

Mathematical optimization strategies which maximum quantity of restored habitat are a common approach to prioritize small fish passage barriers for removal. Despite the importance of cool summer stream habitat for adult migrating salmon, such approaches have not been evaluated for their efficacy at restoring thermally suitable habitat. In this study, I analyze how well a habitat-maximizing optimization strategy performs at increasing cool-water habitat access, based on mean August stream temperatures, for barrier removals in western Washington. I additionally evaluate whether recent historical stream temperatures can serve as an effective proxy for future stream temperatures in cool-water-focused restoration. I find for this region, there is little relationship between temperature and habitat value, and the habitat-maximizing strategy achieves 70% or better of possible cool-water habitat gains for most relevant summer stream temperatures, making it moderately effective at cool-

water restoration. Furthermore, when considering climate change, current stream temperature models indicate spatially homogeneous stream warming, making current temperatures an effective proxy for future temperatures. This study will help inform the utility of incorporating stream temperature information into fish passage planning strategy on regional scales.

1 Introduction

Pacific salmon (*Oncorhynchus* spp.) have keystone ecological importance and considerable economic and cultural value in Washington State. Unfortunately, many salmon populations have experienced declines and several are at risk of extinction (*2022 State of Salmon in Watersheds*, 2022). While multiple pressures have driven their decline, two primary issues are limited access to spawning grounds and the degradation of accessible habitat quality. As salmon migrate from the ocean to freshwater streams to spawn, they often encounter in-stream anthropogenic structures that block their migration to upstream waters. Additionally, in both accessible and obstructed stream habitat, salmon experience increased thermal stress due to warming waters. For salmon to thrive during the freshwater portion of their life cycle, they require both connected and cool habitat (Quinn, 2018).

Some of the "most recurrent and correctable obstacles" limiting migratory fish access to connected in-stream habitat are barrier culverts (Wagner & Sekulich, 1997). Culverts are the tube- or tunnel-shaped structures located underneath roadways at stream crossings, designed to facilitate streamflow beneath roads. They can become barriers to fish passage when poorly designed or deteriorated, such that fish cannot migrate through them. For instance, an undersized culvert can accelerate water flow beyond what salmon can overcome, creating a "velocity barrier" to migration (Reicher, 2024). In other cases, a culvert might erode the streambed below it, elevating the culvert outlet above the surface of the stream and requiring fish to leap a considerable height to continue their migrations (Lehrter et al., 2024). In either case, barrier culverts can severely restrict the amount of in-stream habitat that salmon can access.

Another limitation on freshwater habitat utilization for salmon are water temperatures: salmon require cool waters for successful migration and spawning, and increasing temperatures due to climate change restrict the availability of suitable habitat. While the severity of impacts may differ between species and populations, elevated temperatures stress fish and in severe cases cause mortality in fish (Zillig et al., 2021). Significant mortality events have been recorded during summer heat waves, in for example, sockeye and Chinook populations (Martins et al., 2011, Marcoli et al., 2023). These heat-induced mortality events will likely become more common, as stream temperatures are projected to continue to increase, with an average rise of 1.4 to 1.9 °C across Washington expected by the 2040s (Isaak et al., 2017, Mantua et al., 2010). Salmon may attempt to reduce or avoid heat stress by seeking out coldwater refuges, when and where available; however, these diversions can slow their migrations and increase the risk of pre-spawn mortality and unsuccessful migration (Goniea et al., 2006). As stream temperatures increasingly limit habitat suitability for salmon, it is important to consider how thermal suitability factors should be integrated into salmon habitat restoration efforts.

In Washington, replacing barrier culverts with alternatives that enable fish passage is both a priority management objective and a legal imperative (Neatherlin et al., 2021, United States v. Washington, 2017). Restoring access to habitat blocked by a barrier culvert typically requires a comprehensive construction project to remove the barrier culvert and replace it with a differently designed structure such as a bridge, bottomless culvert, or concrete box culvert (see Kanzler et al., 2024 for examples). Although culvert replacements are considered a relatively cost-effective habitat restoration option because of the considerable habitat benefits they produce relative to their costs (Roni et al., 2002), the total costs of a fish passage program can quickly accumulate in regions with a large number of roadway-stream crossings, such as western Washington. More than 18,000 barrier culverts have been identified in Washington (Kroman & Reicher, 2023). As of June 2024, expenditures to restore only 146 of the largest and most expensive barriers have exceeded $4 billion dollars (Kanzler et al., 2024, Reicher, 2024.) Given the sheer number of barrier culverts and the costs associated, repairing all barrier culverts is impossible, so restoration efforts must employ a strategy to prioritize barrier projects.

Fish passage restoration efforts should aim to increase the availability of high-quality habitat as much as possible. An effective prioritization scheme should take into account both the variable costs and expected benefits of potential culvert projects. Several formal methods exist to systematically prioritize fish passage barrier culverts for removal, but limited research has been conducted to evaluate how successful these methods at increasing access to high-quality habitat (e.g. Garcia de Leaniz and O'Hanley, 2022, O'Hanley and Tomberlin, 2005, McKay et al., 2020, see O'Hanley et al., 2013 for a method which incorporates a habitat suitability index).

While effective culvert prioritization is essential for enhancing salmon habitat, there is currently no literature which addresses the efficacy of these methods at increasing cool-water habitat. Given the critical importance of cool water to salmon and the threats posed by rising stream temperatures, it is essential to consider how available stream temperature data might best contribute to a prioritization strategy for barrier removal. In this thesis, I explore how effectively a culvert prioritization method that does not consider temperature can restore cool-water habitat compared to a method that does. I furthermore examine whether current stream temperatures can serve as a proxy for future stream temperatures when prioritizing culvert restoration for climate resilience in salmon habitat.

To answer these questions, I formulate two versions of a method for prioritizing culvert repair, which use optimization to produce barrier restoration portfolios that maximize increases in either total or cool-water habitat. I then solve the optimizations for barrier culverts in western Washington and evaluate the trade-off between the two objectives by comparing how the total habitat method restores habitat compared to the cool-water method. To evaluate the climate-resilient restoration, I compare the results of a cool-water prioritization based on recent historical temperatures to those of a prioritization based on anticipated 2040s temperatures.

2 Background

2.1 Ecological Context

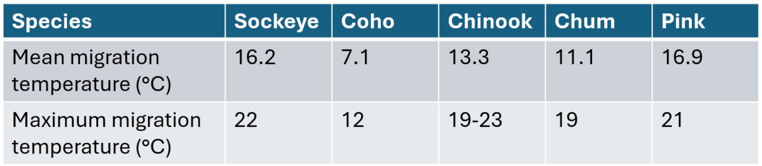
This research is concerned primarily with habitat access for migrating pre-spawning fish from five species of Pacific salmon (*Oncorhynchus*) found in Washington: pink (*O. gorbuscha*), chum (*O. keta*), coho (*O. kisutch*), Chinook (*O. tshawytscha*), sockeye (*O. nerka*) (*2022 State of Salmon in Watersheds*, 2022). The basic life cycle of almost all Pacific salmon is characterized by anadromy: their journey from natal rivers to the ocean and back again to spawn. Larval salmon hatch in freshwater streams, generally in the spring (Quinn, 2018). They spend a variable amount of time, depending on the species and individual, growing in their rivers before migrating to the ocean (Quinn & Myers, 2004). Juveniles grow and develop in the ocean for anywhere from a few months to 7 years (Crozier et al., 2008). In the summer and fall for most populations, the salmon migrate back to their natal streams to spawn, which marks the end of their lives (Quinn, 2018).

The spawning migration, necessary to reproduce the next generation, places high physiological stress on individuals and requires considerable energy expenditures to complete. As part of this journey, salmon undergo extensive morphological changes to adapt their bodies for survival in freshwater and reproduction (Quinn, 2018). During this migration, referred to as a "run," salmon completely stop eating and use only the energy stores in their bodies to complete upriver journeys that can span hundreds of miles (Crozier et al., 2020, Minke-Martin et al., 2018). As semelparous organisms, salmon expend all their physical resources into reproduction and die soon after spawning (Quinn & Myers, 2004). Among all fish, the reproductive stages, embryonic and spawning, have been found to be the most sensitive to changes in temperature (Dahlke et al., 2020). The pre-spawning migratory stage is therefore particularly important to consider because of its importance for propagating the species and because it is particularly vulnerable to negative impacts from stressors because of the high energetic pressures placed on individuals during this stage.

Thermal stress occurs when salmon encounter thermal conditions outside of their optimal range, which require physiological and behavioral adaptation to maintain homeostasis (Alfonso et al., 2021). As ectothermic organisms, salmon rely on environmental heat sources to maintain appropriate temperatures to carry out their physiological processes. Since they are unable to internally thermoregulate, they must use behavioral thermoregulation strategies, such as seeking out cooler water conditions (Goniea et al., 2006). When exposed to thermal stress, the bodies of salmon release stress hormones which provoke changes in tissues and re-allocate energy towards responding to the stressor, such as by seeking out cooler water (Alfonso et al., 2021). In the context of pre-spawning salmon, responding to this thermal stress requires transfering limited energetic resources away from migration and reproduction (Alfonso et al., 2021, Plumb, 2018).

When thermal stress exceeds ability of salmon to respond, it can result in negative impacts such as reduced fertility, increased disease burden, or increased risk of migration failure (Hinch et al., 2021, Bradford et al., 2010, Martins et al., 2011). In severe cases, prolonged exposure to excessive temperatures causes mortality. Several mass mortality events in multiple salmon species have been recorded during recent heatwaves (Martins et al., 2011, Marcoli et al., 2023). Stream temperatures are anticipated to continue increasing with climate change, thermally stressful conditions are likely to become more common (Battin et al., 2007). These temperature changes present a risk of significant salmon population declines if preventative action is not taken (Ruesch et al., 2012). Since summer is both when the highest temperatures occur and when many migrating adult salmon begin to enter streams, studying how habitat restoration can be conducted to provide cool stream habitat for salmon in summer is essential.

In the context of this thesis, I am most concerned with the maximum temperatures that salmon can tolerate. The Environmental Protection Agency (EPA) guidance for the Pacific Northwest identifies temperatures at or above 21 – 22 °C as sufficient to cause thermal migration blockages, and prolonged exposure to temperatures greater than 17-18 °C as sufficient to cause overall reduction in migration fitness due to cumulative stress (*EPA Region 10 Guidance For Pacific Northwest State and Tribal Temperature Water Quality Standards*, 2003). These limits are relatively generous; another study recommends an upper thermal limit of 12.8 °C for pre-spawning salmon to prevent reductions in fertility (Richter & Kolmes, 2005). Sockeye and pink salmon experience average migration temperatures around 16 °C and maximum migration temperatures of 21 – 22 °C (Mayer et al., 2024). Chinook have been found to experience consistent migration blockages in the range of 19 – 23 °C (Richter & Kolmes, 2005). Of these species, coho appear to be the most thermally sensitive, with a maximum migration temperature around 12 °C. In this study, I use 15 °C as reference temperature, a relatively conservative limit which falls between several thermal limits (Fig 1).



Species	Sockeye	Coho	Chinook	Chum	Pink
Mean migration temperature (°C)	16.2	7.1	13.3	11.1	16.9
Maximum migration temperature (°C)	22	12	19-23	19	21

Adapted from Mayer et al. (2023) with Chinook data from Richter & Kolmes (2007)

Figure 1: Summary of thermal limits for migrating pre-spawning salmon

2.2 Restoration Context

The considerable effort, large number of participating organizations, and substantial financial investment in fish passage restoration highlight the need for effective culvert prioritization strategies to guide restoration programs. In this case study of western Washington, I focus on the Case Area region from the *United States v. Washington* "Culverts Case."

This landmark treaty rights case significantly increased investment in barrier culverts repairs in western Washington. The suit was initiated in 2001, when a group of twenty-one tribal nations filed suit against the State of Washington (United States v. Washington, 2017). The tribal nations argued that the State has a treaty obligation to protect fish habitat, and that the construction of culverts which prevent the movement of salmon are in violation of their treaty rights (Woods, 2019). The case was appealed up to the Supreme Court before finally being resolved in favor of the tribes in 2018 (United States v. Washington, 2017). To remedy the treaty violations, a permanent injunction was placed on Washington State, requiring the State to identify and inventory all barrier culverts under state-owned roads and correct enough culverts to restore 90% of the currently blocked potential salmon habitat within the Case Area by 2030 (United States v. Washington, 2017). The injunction has forced the state to accelerate their investment in fish barrier removal on state-owned roads. Furthermore, concerns that a focus only on injunction culverts would be insufficient for restoring aquatic connectivity have increased in coordinated restoration efforts, guided by systematic culvert prioritization strategies.

In complying with the injunction, the state has documented 2,074 fish passage barriers across the 4,037 state highway crossings of fish-bearing waters (Kanzler et al., 2024). The Washington Department of Transportation (WSDOT) has as of June 2024, repaired 146 of an intended 430 barrier culverts, restoring access to an estimated 919 kilometers of potential upstream habitat (Reicher, 2024, Kanzler et al., 2024). Expenditures from these injunction projects have totaled over $3.8 billion dollars so far (Reicher, 2024). The high price tag of these restoration has caused some public scrutiny of how culverts are being selected for repair (Reicher, 2024). Given the wide scope of these projects, a thoughtful approach to culvert prioritization is essential.

Local and regional investment in restoring aquatic connectivity has also been galvanized beyond what was mandated by the injunction. Cities, counties, tribes, and other state programs, while not bound by *United States v. Washington* or the injunction, have been active in fish barrier planning and removal (Washington Department of Fish and Wildlife, 2021). For example, the King County Fish Passage Restoration Program, in collaboration with several tribal nations and state partners, has identified 900 culverts under county-owned roads and, from those, has targeted 60 high-priority barriers. Repair of these high-priority culverts is expected to realize more than half of the possible habitat connectivity improvements for King County culverts ("Fish Passage Restoration Program", n.d.). As another example, the Cold Water Connection Campaign (CWCC), which brings together partners from all levels of government and non-governmental organizations, has identified over 4,000 barriers to fish passage in rivers along Washington's Outer Coast ("Coldwater Connection", 2019). To organize restoration efforts, the CWCC has developed a database and prioritization index to rank culverts across multiple watersheds for restoration (Peterson, 2024, Moore et al., 2019).

While these organizations have made important strides in restoring habitat connectivity, research suggests that restoration efficacy can be enhanced through larger scale coordination (Neeson et al., 2015).

To coordinate the disparate restoration efforts happening statewide and "maximize the salmon and orca recovery benefits from the public investment," the Washington state legislature has called for the creation of a "scientifically defensible and transparent and widely supported by the restoration community" strategy that could guide state recommendations for fish passage barrier funding ("Draft Statewide Barrier Prioritization Strategy." 2024). The statewide strategy is currently in development. A draft strategy, released in September 2024, recommends using an optimization approach to prioritize barriers on a statewide scale ("Draft Statewide Barrier Prioritization Strategy." 2024). The proposed objective function in the draft strategy maximizes increases in accessible upstream habitat, with additional weight given to habitat which benefits imperiled salmon species, particularly Chinook salmon. While the proposed optimization approach does not incorporate habitat quality criteria, the exact formulation of the objective is still being revised, so it is important to understand how well an approach which seeks to maximize increases in upstream habitat quantity does at restoring cool-water habitat.

2.3 Culvert Prioritization Strategies

There are several broad categories of culvert prioritization methods, but optimization is particularly suitable in this context. The two primary systematic methods for prioritizing barriers are mathematical optimization and score-and-rank (Garcia de Leaniz & O'Hanley, 2022). In mathematical optimization, a specific goal and a discrete set of actionable options are quantitatively defined and input into a mathematical program that identifies the set of actions that will most effectively achieve the designated goal (McKay et al., 2020). This approach produces a set of actions that are intended to be taken together (Garcia de Leaniz & O'Hanley, 2022). In contrast, the score-and-rank method involves individually scoring barriers based on a defined set of criteria and subsequently ranking them according to their scores, resulting in a prioritized list where barriers with the highest scores are considered highest priority (McKay et al., 2020).

While score-and-rank methodologies are commonly used in practical restoration contexts, optimization is considered the "gold standard for efficient barrier mitigation planning" because of its potential to find the most effective course of action within limited resources (Burch et al., 2024, McKay et al., 2020). Although score-and-rank is simpler to implement, requires less technical expertise and yields results that can be more easily adapted to practical constraints, in settings such as barrier culvert restoration, where many barriers often coexist within the same river system, it can underperform compared to optimization because it does not explicitly account for the interdependencies between barriers (McKay et al., 2020, Garcia de Leaniz and O'Hanley, 2022). In contrast, optimizations can be formulated to account for multiple barriers in series and, with a well-defined objective, will find the course of action which produces maximum benefits (Kemp & O'Hanley, J. R., 2010). The principal limitation of optimization is that it relies heavily on the availability of complete, accurate data to make its recommendations. In the case of barrier culverts, erroneous barrier coordinates or undocumented barriers can cause problems for an optimization approach (Garcia de Leaniz & O'Hanley, 2022). However, in western Washington this potential limitation is less significant; due to the extensive inventory efforts conducted in this region, the culvert inventory is unusually complete for such a large spatial area. As a result, optimization is a uniquely well-positioned methodology in this study system for comparing the trade-offs between habitat quality and quantity objectives.

3 Data

3.1 Overview

For the purposes of analyzing the outcomes of restoring barrier culverts with a focus on cool-water habitats, I utilize three primary datasets: the Washington Department of Fish and Wildlife's (WDFW) Fish Passage Barriers Inventory (culvert inventory), the United States Geological Survey (USGS) National Hydrography Dataset plus attributes in high resolution (NHDPlus HR), and stream temperature estimates from Siegel et al. (Siegel et al., 2023 and *unpublished data*).

3.2 Culvert Inventory

To identify the number, locations, and barrier status of the culverts in western Washington, I use the WDFW culvert inventory, a centralized repository that provides information on culverts, non-culvert road crossings, dams, natural barriers, and other stream obstructions throughout Washington (Barrett & Zweifel, 2019). As of January 7, 2025, the complete inventory contains data on approximately 60,000 features statewide ("Fish Passage Barrier Inventory", 2024). These data are contributed by trained personnel from both WDFW and partner organizations who conduct physical surveys of in-stream features following a standardized protocol (Barrett & Zweifel, 2019). The inventory is dynamically updated as new information becomes available (Barrett & Zweifel, 2019). During these surveys, each feature's type and barrier status are assessed and documented ("Fish Passage Barrier Inventory", 2024). The feature-type attribute differentiates between culverts, non-culvert crossings, dams, and natural barriers, while the barrier status indicates whether the culvert is fully passable, 33% passable, 66% passable, or completely impassable for fish migration across the barrier. Within the study region, 12,895 features from the inventory are classified as fish passage barrier culverts.

In addition to providing data on the number and type of barriers in Washington State, the inventory includes precise location information for each culvert, which facilitates the identification of culverts on the the stream network and the selection of candidate restoration projects. Latitude and longitude coordinates are collected during physical surveys using GPS devices (personal communication, Tim Young). For certain culverts, the stream name where the culvert is situated and the mainstem to which the stream is a tributary are also recorded.

Although the inventory is extensive and recognized as the most comprehensive source of culvert information, it does not encompass every barrier culvert in the region. Within the study area, WDFW inventory managers estimate the inventory to be over 90% complete for state-owned culverts, with variable completeness for locally owned culverts and the least completeness for privately owned culverts (Tim Young, personal communication, May 30, 2024). An underestimation of barrier numbers may affect prioritization for barrier removal (Garcia de Leaniz & O'Hanley, 2022). However, since this study's focus is on comparing the differences in culvert prioritization approaches rather than predicting specific outcomes from any individual approach, any incompleteness in the inventory should not impact the results.

3.3 Hydrography

I use the NHDplus HR hydrography model to construct a stream network capable of determining how potential barrier restoration projects would increase in-stream connectivity. This geospatial model, a collaborative product from the USGS and EPA, integrates a hydrography map, watershed boundary map, and a 10-meter digital elevation model ("Which NHD Product Do You Need and Which Do You Have?", 2021). The resulting model maps stream locations across the country and encodes network information, showing the flow directions of water between various stream reaches. The stream locations are based on a snapshot of the National Hydrography Dataset taken from 2015 – 2019, with a resolution of 1:24,000 ("Which NHD Product Do You Need and Which Do You Have?", 2021). For this study, I used data from the Oregon-Washington Coastal (1710) and Puget Sound (1711) hydrologic units.

The NHDPlus HR includes attributes that identify and characterize the network relationships and hydrological features of stream segments. These stream networks are categorized into discrete segments called "reaches," which can vary in lengths but exhibit relatively uniform hydrological characteristics ("What Is a Reach?", n.d.). Each stream reach is assigned a unique numeric identifier known as a COMID. Additionally, larger stream segments are identified with their official Geographic Names Information System (GNIS) names, such as "North Fork Nooksack River" (Moore et al., 2019). The hierarchical positions of stream segments within the stream network are represented by the attributes Stream Order (modified Stahler stream order) and Stream Calculator (further modified stream order). Steam Order is a numerical attribute assigned to each stream segment which indicates the hierarchical position of the segments within the overall network. Headwaters receive the number “1,” and segments increment in value the further downstream they are (Moore et al., 2019). Stream Calculator is almost identical to Stream Order, except divergences are assigned a value of “0,” and their downstream segments have correspondingly smaller values. Furthermore, descriptive attribute information related to the streams is encoded within a Feature Code, which assigns numeric codes that specify descriptions of the mapped water features (e.g., “canal/ditch,” “coastline,” “stream/river (intermittent)”) (Moore et al., 2019). Finally, the length in kilometers of each stream is specified, which is used to calculate the extent of habitat above each barrier culvert.

3.4 Stream Temperature Estimates

To select culvert portfolios based on temperature, stream temperature values are required for all reaches. However, we do not possess direct stream temperature logging data for all streams. Instead, we use a statistical model to estimate stream temperatures using geomorphological and climate data that are available across the entire region. Stream temperature predictions for both historical and future time periods were estimated by Siegal et al. (Siegel et al., 2023 and *unpublished data*). The model uses a generalized additive model structure which fits a series of splines (piecewise smooth functions) for temporally varying covariates and interactions and linear relationships for static covariates. The temporally varying predictors include antecedent air temperature, upstream snowpack size, time of year, and flow discharge. Static covariates include geomorphological and land use/cover characteristics such as slope and amount of riparian cover.

This model was created to address a need for dense stream temperature estimates across large spatial and temporal scales under dynamic climate conditions (Siegel et al., 2023). Published data predict daily stream temperature for reaches across the Pacific Northwest from 1990 – 2021 (Siegel et al., 2023). Additional, yet unpublished, projections of future stream temperatures extend the predictions both back and time and into the future, to the period of 1950 – 2099 (*unpublished data*). Approximately 5 million historical daily stream temperature data records, collected between 1993 – 2013 from 3,668 sensor sites, were used to fit the model (Isaak et al., 2017).

To effectively model the spatial and temporal autocorrelations in stream temperature response to air temperature, outperforming traditional statistical method, the authors introduce a moving-window metric over which antecedent air temperatures are averaged. To account for the variable rates at which streams warm in response to air temperatures, the authors define the "antecedent air temperature covariate" (Siegel et al., 2023). The authors argue that the autocorrelation in stream temperatures arises due to water's high specific heat capacity, which causes water to resist changes in temperature as it moves through a stream network (Siegel et al., 2023). Snowmelt-fed streams appear to be less sensitive to air temperatures than predominantly rain-fed streams, even after snowpack has melted, presumably because the snowmelt turned into groundwater, which continues feeding streams and buffering their temperature (Siegel et al., 2023).

The antecedent air temperature covariate is a variable-sized window which describes the time period over which prior air temperatures can inform stream temperature. The size of the window, which could vary from 1 to 60 days, is fit for each stream reach in each year based on its flow discharge and the dominant hydrology (snow-dominated, transitional, and rain-dominated) of its drainage area. Air temperatures averaged across the window period, and the averaged antecedent air temperature is used as a covariate to predict stream temperature.

Leave-one-out cross-validation on year and watershed found that the model had some difficulty expanding to new watersheds but did well predicting new time periods. The results of cross-validation found that prediction error was “higher at warmer air temperatures during the summer and during low flow and snowpack conditions” (Siegel et al., 2023). This last consideration is important to consider in relation to this research, as I am specifically using August air temperatures, which tend to be at the warm extreme.

4 Methods

4.1 Overview

To understand the trade-offs between total habitat and cool-water habitat in barrier prioritization and contemporary versus forward-looking cool-water habitat restoration, I model the expected habitat increases from these methods using mathematical optimization. I prepared the culvert, hydrography, and stream temperature data for use in the optimization; calculated expected habitat values for each culvert in each scenario; formulated and solved several versions of the optimization problem; and interpreted the results by calculating the quantity of habitat restored under different scenarios. All data processing and analysis were done in R (“R: A Language and Environment for Statistical Computing”, n.d.).

4.2 Data Processing

4.2.1 Stream temperature predictions

To get the formatting and spatial coverage of stream temperature estimates needed to be compatible with the culvert prioritization model, I summarized the raw stream temperature estimates and interpolated data for those stream reaches which did not have estimates. To use the stream temperatures, the optimization problem requires one stream temperature prediction for every reach in the NHDplus HR stream system for each studied time period. The stream temperature predictions, outputs from a statistical model which predicts stream temps based on physical attributes such as air temperature, elevation, glacier presence, were received as year-round stream temperature data for the Washington Coastal (HUC6 171001) and Puget Sound (HUC6 171100) regions (Siegel et al., 2023 and *(unpublished data, NOAA)*). I extracted and summarized August stream temperatures for both the recent historical (1993 — 2011) and near-future time period (2030 — 2059) to obtain a single decadal stream mean August stream temperature for each stream reach and time period. Since mean August stream temperatures are highly correlated with other metrics of summer stream temperatures, these can serve as a proxy for overall summer stream temperatures (Isaak et al., 2017).

Since the stream temperature predictions from the statistical model do not contain every NHDplus HR reach in the study region, and I lack the predictor information necessary to statistically predict temperatures for the missing reaches, I interpolated missing stream temperatures using inverse distance weighting (IDW) with 4 nearest neighbors (parameter value selected using *k*-fold cross-validation). This method interpolates stream temperatures exclusively based on the temperatures of the spatially nearest stream segments. I used the IDW implementation provided by the gstat package to predict a stream temperature measurement for the centroid of each reach in NHDPlus HR, resulting in a set of stream temperature estimates that I joined to the NHDPlus HR data to create a temperature-supplemented NHDPlus HR dataset (Graler et al., 2016).

4.2.2 Remove non-streams and divergences from hydrography

For the purposes of this study, only streams and rivers are considered to contribute to salmon habitat, so I set the habitat values of all other types of waterbodies to zero based on their FCODEs. The habitat value is equal to the length of rivers and streams (`FCODE in 46000, 46003, 46006, 46007`) and 0 for all other waterbody types. These features remain included in the network to allow accurate calculation later of the network relationships between barriers. Segments which indicate the locations of coastlines (`FCODE == 56600`) are filtered entirely from the dataset. I then removed divergences from the dataset to enforce a dendritic structure in the stream network. This was necessary for the connectivity constraint in the optimization, which requires that every culvert has a maximum of one directly downstream culvert, to function. Any stream whose Stream Order and Stream Calculator values differ was identified as a divergence and filtered from the dataset (Moore et al., 2019).

4.2.3 Filter culvert inventory

In this step, I reduce the inventory to only barrier culverts which are candidate projects for restoration and located the barrier culverts along the hydrography network. I removed features other than culverts (using the Feature Type Code) and culverts which were not identified as fish passage barriers (using the Fish Passage Status Code attribute). Natural barriers (such as. waterfalls) were also identified based on their Fish Passage Feature Type Code, and the culverts upstream of natural barriers were also removed, as they are not candidates for restoration. I used the sf package to identify the barriers that spatially intersect with the Case Area and removed those that do not (Pebesma, 2018). To locate culverts on the hydrography network, I used the culverts' latitude and longitude coordinates and the sf package to identify the spatially nearest points in NHDPlus HR to each culvert (Pebesma, 2018). The culverts were assumed to be located on the spatially nearest stream segment. I then removed culverts which are located on non-dendritic segments of the stream network as identified in the previous section.

I then performed a data quality step to identify which culvert-stream pairs are most likely incorrectly matched and remove them from the data set. Inaccurate culvert-stream pairs cause inaccurate habitat calculations for the mismatched culvert, but also lead to incorrect understandings of the connectivity relationships between culverts so that other culverts' habitat values are incorrectly calculated. Suspected "bad matches" were first screened using a random forest machine learning (ML) model (Cooke et al., 2024). The bad match model was trained on a manually labeled subset of 301 randomly selected culverts (3.9% of the total dataset). 10% of the labeled data (30 culverts) were withheld from the training data set to use for validation. The culverts were examined on both the NHDPlus HR stream network and a separate, lidar-based stream network. Culvert distances from these streams, azimuth (angle), culvert distance from NHD/road intersection, stream similarity, culvert sizes, and stream flow were all tested as possible predictors for the ML model. The final predictors and their weights were chosen based on the model which performed the best at classifying the training data. While data-driven approaches are often quite effective at prediction, the relatively small amount of available training data likely limits the efficacy of this particular model. Out of 22,265 structures in the pre-processed inventory, 5,906 (27%) were identified as possible bad matches.

I then refined the bad match predictions from the ML model by examining whether the recorded stream or mainstem name of the culvert is the same as the name of the matched segment from the hydrography dataset. In the culvert inventory, the name of the stream in which the culvert is located and the mainstem that the stream is a tributary to are recorded. Since this information is based on physical surveys, it is likely reliable. Additionally, major streams in the NHDPlus HR network are labeled with their GNIS Name. While many streams in both data sets are unnamed, if the stream name from the culvert inventory is the same as the stream name from its matched NHDPlus HR segment, we can be confident that the culvert and stream are correctly matched. Using a similar logic, if the mainstem that the culvert is *not* located on has the same name as the matched NHDPlus HR segment, we can be confident that a mismatch has occurred. Using the fedmatch package, I converted the names from both datasets to lowercase and expanded abbreviations (Friedrichs et al., 2004). I then classified any pair of names which had a string distance of less than or equal to 1 as having the same name using the stringdist package (van der Loo, 2014). I updated the ML model's bad match classifications if there was either a stream name or mainstem name match between the culvert and NHDPlus HR data and left the ML model's predictions unchanged if not.

This method did not catch all minor misspellings and differences in naming styles. For example, it did not catch that "Samammish River" and "Sammamish River" are matches. However, more permissive string-matching criteria introduced the possibility of false positive matches, which I wanted to avoid. To remove the most problematic uncaught bad matches, at the end of data processing, I manually examined every culvert purportedly worth at least 25 km of habitat value and removed uncaught bad matches based on the tributary to name. Following this filtering process, the culvert inventory used in the analysis contains 6,765 barrier culverts.

4.2.4 Add cost estimates to culverts

Predicted costs for each culvert project, c_i, were generated using an ML model and data from previously completed culvert restoration projects (Van Deynze et al., 2022). Predictors used in the ML model include hydrologic and road characteristics, land cover, nearby land ownership, local economic conditions, and project size and complexity (Van Deynze et al., 2022). I multiplied these cost estimates by an inflation adjustment to account for the increase in construction costs since 2019, when they were generated. The inflation adjustment was calculated as the ratio between the current consumer price index (CPI) and the CPI in 2019, using data from the US Bureau of Labor Statistics. For culverts added to the inventory after these cost estimates were generated, I used IDW interpolation to roughly estimate the predicted costs based on the cost estimates for nearby culverts.

4.2.5 Create connectivity matrix

The optimization problem requires a description of the connectivity relationships between culverts, i.e. which culverts are upstream or downstream of each other within the same river system. I defined the D matrix such that D_{ij} is 1 if barrier i is immediately downstream of barrier j with no intermediate barriers and 0 otherwise.

I located the barriers immediately upstream of barrier i in one of two different ways. If there was another barrier on the same stream segment as i (identified by checking for other culverts matched to the same COMID as i), then I ordered the barriers along the segment and identified the next barrier upstream of i. I ordered the barriers by calculating the "partial length" of each barrier on the segment, which gives the length of the stream segment upstream of each barrier (Blodgett & Johnson, n.d.). This allows me to sort the barriers along the stream segment. Whichever barrier is immediately upstream of i is its only marginally upstream barrier.

If i is the most upstream barrier on the segment or there are no other barriers on its segment, I find its upstream barriers using the second method. - identifying the tributaries upstream of the segment; filtering to just the marginally upstream tributaries; and getting the barriers on those tributaries. I find the upstream tributaries of the segment that i is located on with the `getUT` function in nhdplusTools. I then check whether any of those segments contain a barrier culvert, which produces the full set of barriers upstream of i. To reduce this set to only the barriers immediately upstream of i, I repeat the process on the upstream barriers to find the set of upstream barriers for each barrier upstream of i. If a barrier is upstream of both i

and one of the upstream barriers, then it is not immediately upstream of i and is removed from the set.

4.3 Habitat value calculation

Next I calculate the habitat value metrics for each barrier culvert to quantify how much restoration would increase habitat connectivity. Two habitat value metrics are calculated: habitat length and cool-water habitat length. Habitat length is defined as the length of habitat upstream of the barrier that would become connected with downstream sections if the barrier is removed. Cool-water habitat is defined similarly, except only reaches whose mean August temperature is at or below a threshold temperature T_{max} during the defined time period are counted as contributing to habitat value. Reaches whose predicted temperature is above the threshold are considered to have no habitat value. Since cool-water habitat value is defined relative to a threshold temperature and time period, multiple cool-water habitat values are calculated for a range of T_{max}s between 9 to 25 °C, for both historical and 2040s stream temperatures.

Habitat length, h_i is calculated for each barrier i by navigating the NHDplus HR network and adding up the stream distance between i and either the immediately upstream barriers or the upstream termini of the river. To find the marginal habitat value of barrier i, I first calculate the habitat value on the same reach. If there is another barrier upstream on the same reach, then the habitat value is simply the length between barrier i and the next upstream barrier. If there are no upstream barriers on the same reach, then the length of the stream segment above barrier i is added to a running habitat value calculation (Fig 2, (1)). I then identify the reaches upstream of i which contain no barriers, and the full length of each of these stream segments is added to the running habitat value calculation (Fig 2, (2)). Finally, for any barriers immediately upstream of i, I add the partial downstream length of their reaches to the habitat value calculation (Fig 2, (3)). The sum of all these lengths is the habitat length value. Cool-water habitat value is calculated in the same manner, except the temperature of each stream segment is checked and the reach is only added to the habitat calculation if its temperature is below T_{max}.

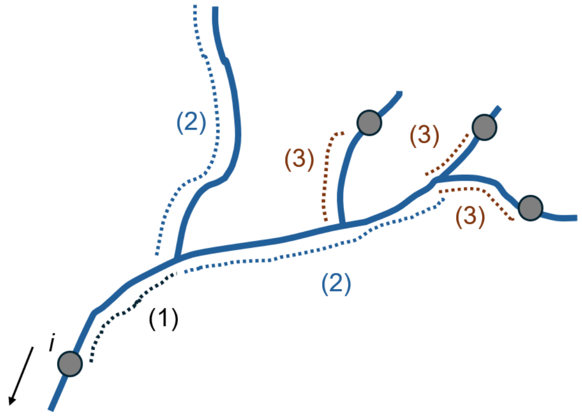


Figure 2: Schematic diagram of habitat value calculation for barrier i. The marginal upstream habitat value is the sum of the partial upstream habitat on the same segment as i (1), the length of the upstream segments without barriers (2), and the partial downstream length of upstream segments with barriers (3). The direction of flow is indicated by the black arrow.

4.4 Culvert Prioritization Model

In this thesis, I use an optimization approach to examine the trade-offs between two management objectives: restoring habitat length and restoring cool-water habitat. When using mathematical optimization, it requires a two-step process of formulating and then solving a problem. Formulating the problem, or mathematically specifying what we want, is where the research design choices happen, and then formulated problem is in a form that can be solved using standard techniques. To formulate an optimization, we define three statements: an objective function, a set of decision variables, and a set of constraints. The objective function is a function which defines the quantity that we wish to maximize or minimize (Williams, 2013). Its value changes depending on the value of the decision variables, which represent the set of actions that we can take or control to achieve the objective (Williams, 2013). Finally, the constraints limit the values that the decision variables can take. In the culvert removal problem, the objective is to maximize instream habitat access, and the decision variables are which culverts we choose to restore. The constraints include the available budget and the requirement that culverts be repaired from downstream up.

The culvert selection problem imagines a restoration scenario across the entire western Washington region north of the Columbia River basin. The goal is to maximize habitat gains within a defined budget. Culverts are assumed to be either fully impassable for migrating salmon or fully passable and be fully passable after restoration. Barriers are assumed to impede fish migrating upstream from the ocean and not pose a migration barrier for fish migrating downstream.

To compare the trade-offs between the maximum habitat and cool-water habitat objectives, I formulate two versions of the optimization problem: one which seeks to maximize total accessible habitat length and one which maximizes cool-water habitat length.

To mathematically formulate the problem, consider the following definitions.

Let I be the set of n barrier culverts available for restoration, indexed by i and j. Then, the decision variables are given by,

$$x_i = \begin{cases} 1 & \text{if culvert } i \text{ selected for restoration} \\ 0 & \text{otherwise} \end{cases} \tag{1}$$

The marginal habitat value of culvert i, or the kilometers of habitat between a barrier and the next upstream barriers(s) is defined as h_i. For the total habitat model, h_i is the entire length of marginal habitat. For the cool-water model, h_i is defined as the length of habitat whose predicted temperature is below a threshold temperature, T_{max}. I chose to use a binary threshold to represent cool-water habitat to make the cool-water objective function as directly comparable to the total-habitat function as possible.

The objective of the optimization is to maximize the quantity of habitat restored, given by,

$$\sum_i h_i x_i \tag{2}$$

subject to the constraints:

$$\sum_i c_i x_i \leq B \tag{3}$$

$$x_i - \sum_j d_{ij} x_j \leq 1 - \sum_j d_{ij} \quad \forall i \in I \tag{4}$$

The budget constraint (Equation 3) ensures that the total cost of the prioritized culvert projects is less than or equal to the total budget, B.

The connectivity constraint set enforces that restoration occurs starting with the most downstream barriers and moves upward (Equation 3). This constraint ensures that restored stream reaches are fully connected with downstream waters, so that salmon migrating from the ocean have access to the maximum possible habitat. The connectivity between barriers in the system is defined such that $d_{ij} = 1$ if culvert i is immediately upstream of culvert j and 0 otherwise. Mathematically, the constraint works by enforcing that if culvert i is selected ($x_i = 1$), then all culverts downstream of culvert i ($d_{ij} = 1$) must also be selected ($x_j = 1$) to satisfy the inequality.

The optimization is constrained to only allow full restoration; restoring culverts to partially passability is not permitted. This is in line with realistic design requirements; Washington State rules require that any construction done on culverts result in a structure which does not impede fish passage ("Water Crossing Structures", 2015). For state-owned, post-construction monitoring and further corrections are required to ensure full fish passage after repair (Kanzler et al., 2024).

The formulation defined about was input into the R interface to the Gurobi Optimizer, a mixed linear integer optimization solver and solved using the branch-and-cut algorithm ("Gurobi Optimizer Reference Manual", 2023). Solutions are returned as a set of culverts selected for restoration. Since the constraints are formulated as linear combinations of the decision variables, the solver is guaranteed to find the optimal solution (Arora, 2004).

Both the total habitat problem and the cool-water problem were solved repeatedly across a range of budgets, from \$0 up to the cost of restoring every culvert in the system. The cool-water problem was solved across every combination of budgets and a range of T_{max} values from 7 ° C to 29 ° C for both baseline and 2040s stream temperatures. This allows us to see how sensitive the performance of the cool-water problem is to the choice of threshold for defining cool-water.

5 Results

5.1 Culvert Attributes

The majority of culverts in the inventory obstruct very little habitat, although some significantly hinder habitat connectivity. The culverts that block substantial habitat are particularly important, as their repair can disproportionately improve habitat connectivity. Following pre-processing, the inventory of candidate barrier culverts contains a total of 6,765 culverts. Among these, 1,423 culverts have zero habitat value due to their locations on and downstream of non-stream/river hydrologic features. These culverts remain in the inventory because they may be viable restoration candidates to restore connectivity to upstream habitats that are affected by additional barrier culverts.

For the culverts with non-zero habitat potential, marginal habitat length values range from less than one meter to a maximum of 306 km. The distribution of calculated habitat values is highly skewed; while the majority of culverts block minimal amounts of habitat, a small number of culverts obstruct significantly more habitat (Fig 3). Specifically, 3,365 (63%) of the culverts with non-zero habitat values block 1 km or less of marginal habitat value, whereas only 109 (2%) block 15 km or more. This finding aligns with previous research which found that fish passage barriers are generally distributed such that a small proportion of barriers have a disproportionately high impact on habitat fragmentation (Garcia de Leaniz & O'Hanley, 2022).

Cool-water habitat values follow a similarly skewed distribution. For barriers with non-zero marginal habitat values, cool-water values for a 15 °C threshold temperature range from 0.004 km to 211 km, with a median value of 0.58 km. For the majority of culverts (97.5%), at this threshold, the culvert's cool-water habitat value is either zero, because all marginally upstream habitat is warmer than 15°C or equal to its marginal habitat, because all marginally upstream habitat is below the threshold temperature. There is no theoretic reason why cool-water values must bifurcate like this, and the split is likely due to a high level of autocorrelation in the estimated stream temperatures.

There is little relationship between cool-water habitat and marginal habitat value in the candidate barrier culverts. In other words, the culverts which have non-zero cool-water habitat value do not on average have higher or lower marginal habitat values on average than those that do not. Conditional on having a non-zero value of marginal habitat, there was not a significant difference in the mean marginal habitat value for culverts with and without cool-water habitat (unpaired t-test, $t = -0.046$, $p = 0.96$). This lack of relationship is also visually apparent, as at each marginal habitat value there are a mix of both cool-water and non-cool water culverts (Fig 4A).

While there is some variability in estimated restoration costs for the candidate culverts, for the most part, the costs vary by less than an order of magnitude, with 95% of candidate projects estimated to cost between \$21,627 and \$165,393. Furthermore, there is no correlation between marginal habitat value and cost (Pearson's correlation = -0.008), nor is a relationship visually evident between the two variables (Fig 4B). From these relationships, it is likely that while cost has some influence in differentiating the prioritization of culvert projects, its impact is limited.

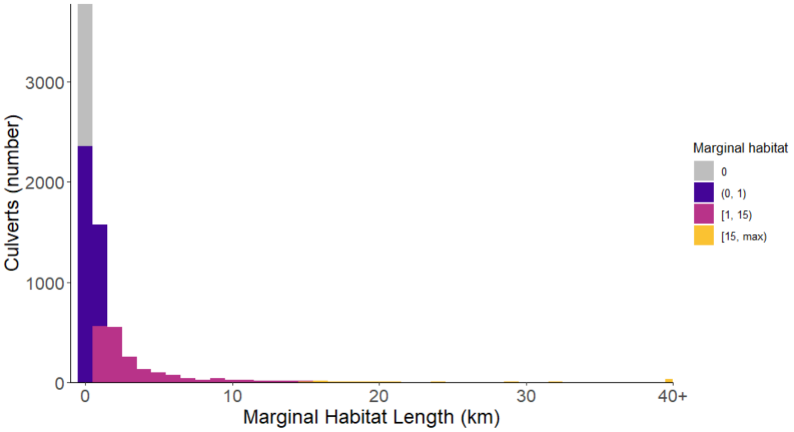


Figure 3: The distribution of marginal habitat values across all culverts is highly skewed. The majority of culverts have 0 habitat value or less than a kilometer of habitat value. Only a small number of culverts are worth more than 15 km of habitat.

There is limited interconnectivity between barriers in the region; many barrier culverts have few or no downstream barriers, and the culverts with the highest habitat potential, which would be first targeted for restoration, do not systematically have more downstream barriers. The optimization problem is formulated to require that, if barrier a is selected for restoration, all downstream barriers on the same stream network must also be selected for restoration. This constraint could, theoretically, significantly influence the sequence in which culverts are prioritized for restoration. For example, if a culvert with considerable habitat value is upstream of several other barriers, restoring that high-impact culvert would entail restoring all downstream culverts as well, thereby increasing the effective cost of its restoration. However, in this inventory, most culverts have few or no downstream barriers. In

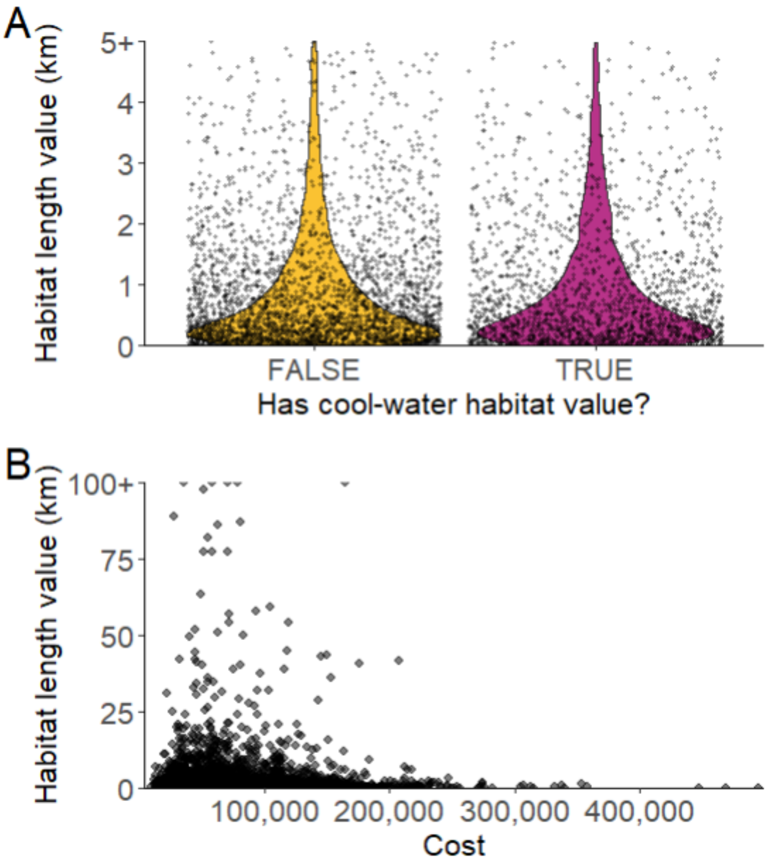


Figure 4: Habitat length value versus whether or not the culvert has cool-water habitat value, for all candidate culverts with non-zero habitat lengths (A) and habitat length value versus restoration cost for all candidate restoration culverts (B). There is no strong relationship between habitat value and whether the culvert has upstream cool-water habitat or between habitat value and cost.

fact, 3,183 (47%) of the candidate culverts have no inventoried downstream barriers, and a further 1,559 (23%) have only a single downstream barrier. This leaves 2,023 (30%) of culverts that have two or more downstream barriers (Fig 5). The maximum number of downstream barriers seen in the inventory is a single culvert with 16 downstream barriers (Fig 5). Furthermore, there is little relationship between the number of downstream barriers and marginal habitat value (Pearson's correlation = -0.05), and the culverts with greatest habitat value are not obstructed by many downstream barriers. The 11 culverts which block 75 km or more of habitat are all blocked by at most one downstream barrier. Even considering more high-impact culverts, the 73 culverts worth 25 or more km all have five or fewer downstream barriers (Fig 5). The fact that most culverts and, in particular, the most impactful culverts, have few downstream barriers indicates that the connectivity constraint likely does not play a critical role in influencing the prioritization of culverts in optimization.

Candidate culverts are distributed across the study region, with some variation in concentration between watersheds (Fig 6). Notably, there are higher concentrations of candidate culverts in lower elevation regions and in proximity to the coast. However, large numbers of inventoried culverts are also present in more inland regions, such as the Chehalis River basin. The increased concentration of culverts in relatively downstream waters may be partially due to greater road development in low-elevation than in mountainous regions, resulting in a higher concentration of roadways crossing streams. The higher concentration is likely also partially attributable to culverts being more likely to fall upstream of a natural barrier, such as a waterfall, and be removed from consideration the further upstream they are. The

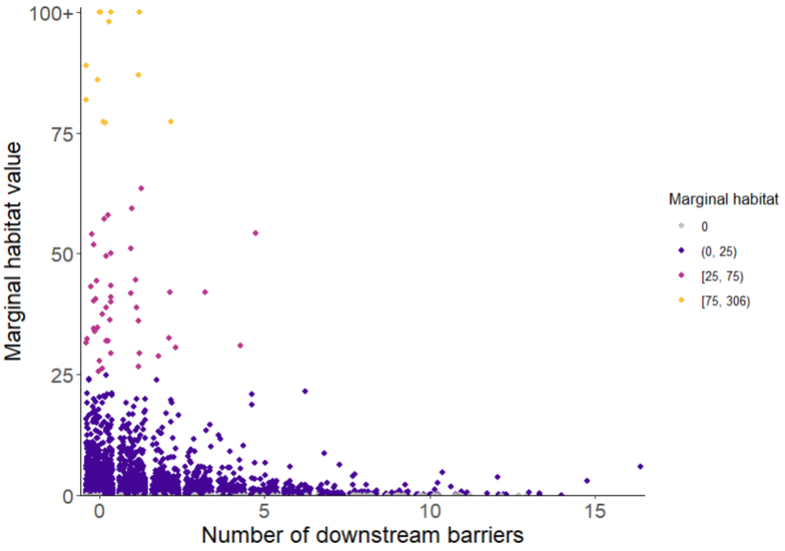


Figure 5: Number of downstream barriers versus marginal habitat value for each candidate culvert project. Downstream barriers must also be selected for a culvert to be selected for restoration, while marginal habitat value describes how much in-stream habitat would be made accessible if the culvert was repaired. Most culverts have few or no downstream barriers, and little upstream habitat is obstructed by long strings of barrier culverts.

variable density of culverts between regions is also probably due in part to varied regional inventorying effort.

5.2 Baseline Stream Temperatures

Estimated mean August stream temperatures in the study region for the baseline period (1993 - 2011) vary from levels comfortably within the thermal limits for salmonids to those exceeding acute lethal thresholds. After interpolation, the mean stream temperature, weighted by length, is 15.3 °C. The regional minimum and maximum temperatures are recorded at 2.98 °C and 34.5 °C, respectively. For streams currently obstructed by barrier culverts, which could be made accessible through restoration efforts, the weighted mean temperature is 16.4 °C, with mini-

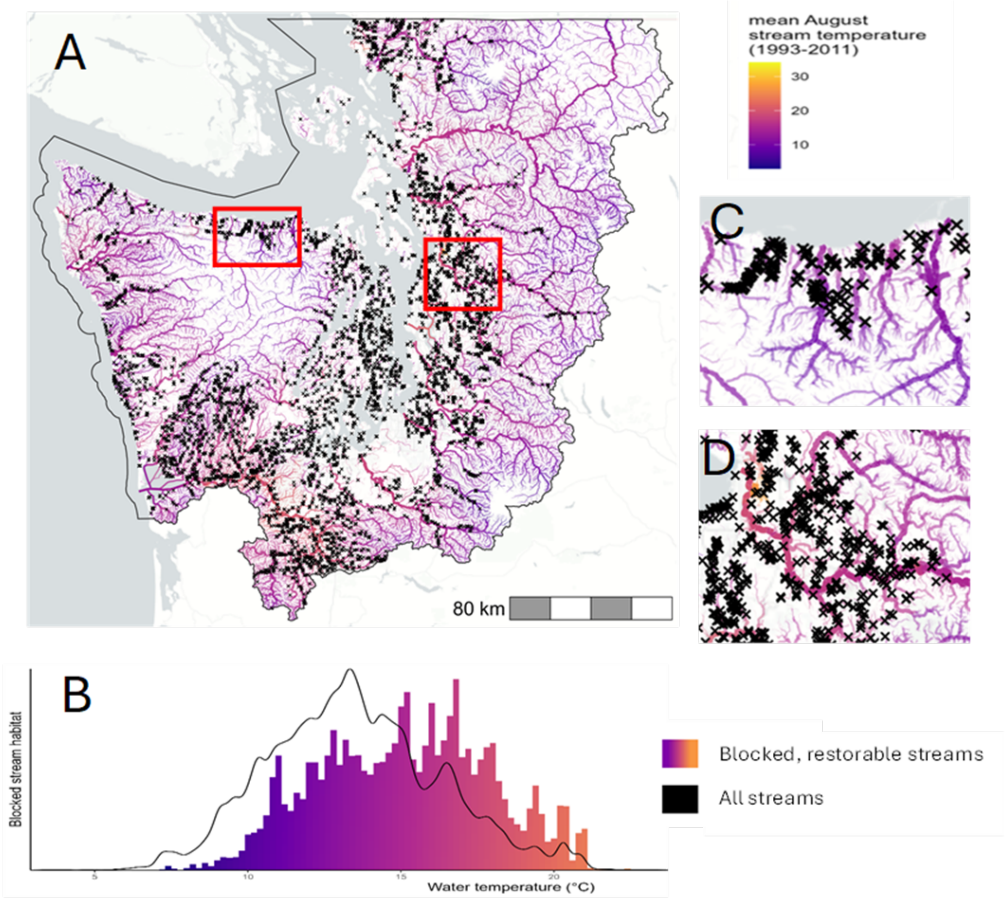


Figure 6: The study region of western Washington State and estimated mean August stream temperatures for 1993-2011. Major streams are colored by temperature and candidate barrier culverts are marked with Xs (A). The temperature distribution of stream habitat for the entire region (black outline) is on average 1 °C cooler than that of the obstructed habitat that might be made accessible by culvert repair (colored histogram) (B). Inset maps show a closer view of several creeks surrounding Port Angeles and the Snohomish River (C and D, respectively).

mum and maximum temperatures at 6.94 °C and 28.1 °C, respectively. Thus, on average, the currently blocked habitats exhibit temperatures approximately one degree higher than the overall stream temperatures for the region (Fig. 6).

5.3 Comparison of the total habitat portfolio to the cool-water portfolio

The goal of this study is to evaluate whether a culvert prioritization method that does not consider temperature can secure cool-water habitat effectively compared to a method that does. To further motivate this research question, consider two example river systems (Fig 6, C and D). Panel C, which zooms in on Port Angeles, shows several culvert-blocked creek systems with cool water and short stream lengths. The lower inset plot shows a downstream portion of the Snohomish River. In contrast with the creeks in the first system, this river system is much longer, potentially providing more habitat access but is warmer, especially near its mouth. When imagining a barrier prioritization strategy to restore habitat across these two systems, there is a potential trade-off between barrier prioritization to maximize accessible habitat length and accessible cool-water; the creeks outside Port Angeles have less but cooler habitat to offer compared to the Snohomish River. To what extent does this potential trade-off between habitat length and cool-water habitat persist when examining the full region? I address this question by comparing the performance of a culvert prioritization approach that seeks to maximize total habitat increases against a strategy which performs optimally for increasing cool-water habitat and observing the differences in cool-water habitat increases.

In comparison to the optimal cool-water strategy, for a cool-water threshold of 15 °C, the total habitat method achieves most of potential cool-water habitat increases at all budget levels (Fig 7A). The optimal cool-water strategy restores a maximum of 3,420 km of cool-water habitat at a budget level equal to 35% of the cost of restoring all culverts. In contrast, the total habitat method requires a 80% budget to do so, at which point it is also selecting every habitat-increasing culvert in the system. (Because a portion of candidate culvert projects have zero habitat value and do not unblock upstream barriers, the optimization does not select all possible projects, even with a full budget. This is why the total habitat restoration portfolios only continue increasing until the 80% budget.) At smaller budgets, the total-habitat portfolio suffers relatively minor cool-water losses. For example, at a 15% budget, the total habitat portfolio restores 79% of the optimal cool-water habitat for that budget (Fig 7A).

The differences in cool-water habitat gains between the two methods are driven by the differences in the culverts they prioritize. The total habitat method must select all barriers prioritized by the cool-water restoration strategy, as these are the barriers that must be restored to maximize cool-water habitat gains. At lower budget levels where the total habitat method does not restore maximal cool-water habitat, roughly half of the culverts selected with the total habitat method selects are also selected by the cool-water method. At the 15% budget, 38% of the culverts selected by the total habitat method are also selected by the cool-water method. At the 35% budget, 41% of the culverts the total habitat method selects are shared with the cool-water method, which at that point stops adding culverts to its optimal portfolio. The total habitat method eventually collects all of the culverts in the optimal cool-water portfolio as the budget increases (Fig 7B). At an 80% budget, the total habitat method restores all culverts with positive marginal habitat values, and the cool-water portfolio becomes a subset of the total habitat portfolio (Fig 7B).

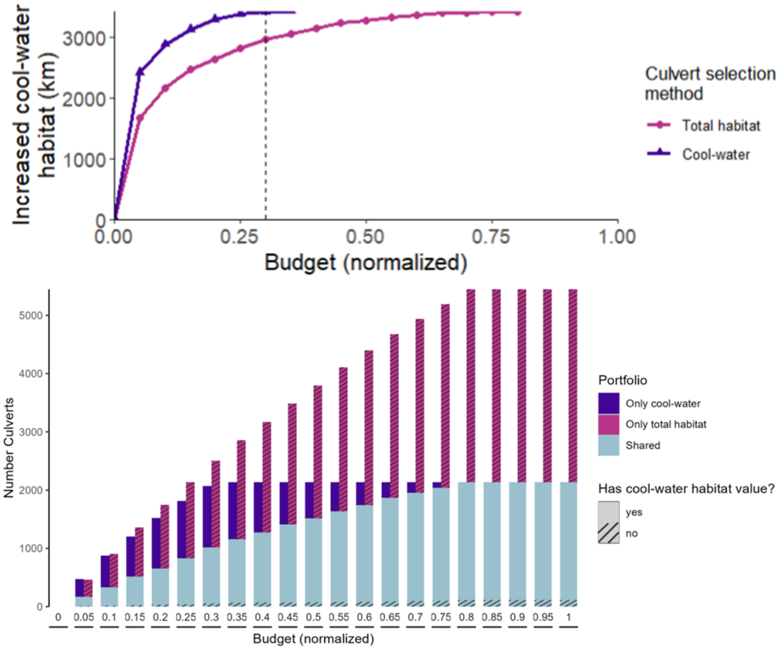


Figure 7: Efficacy of a total habitat culvert prioritization approach at increasing access to cool-water habitat, compared to the optimal cool-water approach. The top panel shows the habitat increases achieved by the total habitat approach (magenta) compared to the cool-water approach (purple). The bottom panel shows the number of distinct and shared culverts between the two approaches, with cross-hatch shading applied to the culverts which do not contribute cool-water habitat. Even at low budget levels, the total habitat method chooses many of the same culverts as the cool-water method (light blue). As the budget grows sufficiently large, selects all of the culverts in the optimal cool-water approach. The total habitat model additionally selects many culverts which do not contribute cool-water habitat (cross-hatched magenta bars). Cool-water is here defined as 15 °C or cooler. Budgets are normalized so that 1 is equal to the cost of restoring every culvert in the system and smaller values are fractions thereof.

5.3.1 Sensitivity Analysis

Recommended upper thermal limits of migrating salmon can range from 12 °C to 22 °C depending on the species and impacts being considered, so understanding how these results change with the choice of the cool-water threshold temperature is important (Mayer et al., 2024, *EPA Region 10 Guidance For Pacific Northwest State and Tribal Temperature Water Quality Standards*, 2003). In this section, I explore the robustness of my main results to alternative temperature thresholds, ranging from 9 to 25 °C. The total habitat method selects the same portfolios regardless of threshold temperature, but the cool-water value of these portfolios varies depending on the choice of threshold temperature. I evaluate the cool-water habitat access created with the total habitat method for several budgets across the range of threshold temperatures.

I find that at all thresholds, with a budget of 30% or greater, the cool-water gains of the total habitat method closely tracked those of the optimal strategy (Fig 8A). The quantity of potentially restorable cool-water habitat varies considerably with threshold temperature (Fig 8B). At nearly all thresholds, the total habitat method restores 75% or more of the available cool-water habitat with a 30% budget. Proportionally, the total habitat method lags more behind the cool-water method at lower threshold temperatures, particularly at lower budgets, when the objectives between the two are the most dissimilar (Fig 8). As expected, when the budget increases to 100%, regardless of the temperature threshold, the total habitat method restores access to all cool-water habitat because all culverts are restored. Similarly, as the threshold temperature increases, more stream segments are considered cool-water habit (Fig 6), and the total habitat method behaves increasingly similarly to the cool-water method. For thresholds of 20 °C and warmer, nearly all potential stream habitat are considered cool water, so the two methods select identical restoration portfolios (Fig 8A). Thus, a significant trade-off between total habitat length and cool-water habitat only exists when both the threshold temperature is set relatively low (< 14°C) and budget is small enough ($<= 10\%$) that only a small portion of culverts can be restored.

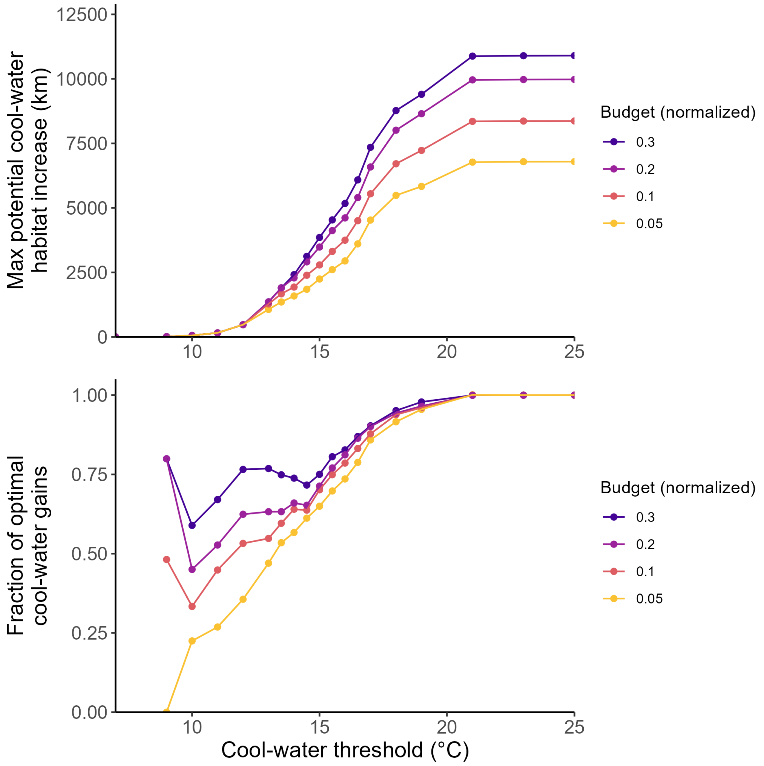


Figure 8: The cool-water habitat increases achieved by the total habitat method relative to the optimal strategy, for several budgets across a range of cool-water thresholds (top panel) and the absolute cool-water habitat increases of the optimal strategy (bottom panel). With a 30% budget, the total habitat method restores 75% or more of the potential cool-water habitat at nearly all threshold temperatures. With smaller budgets, the fractional cool-water habitat increases achieved by the total habitat model decrease for thresholds below 15 °C (top panel). The top panel shows the quantity of cool-water habitat available for several budgets across a range of temperature thresholds. Very little cool-water habitat is potentially restorable below 13 °C.

5.4 Current vs future temperature prioritization

In this section, I evaluate how well a cool-water barrier prioritization approach based on recent historical temperatures does at restoring cool-water habitat into the 2040s. The stream temperatures used in this study predict some heterogeneity in warming patterns, with already warm streams predicted to warm slightly more than cool streams (Fig 9B). For the interpolated stream temperatures, the mean is expected to increase from 15.8 °C in the 2000s to 16.6 °C by the 2040s.

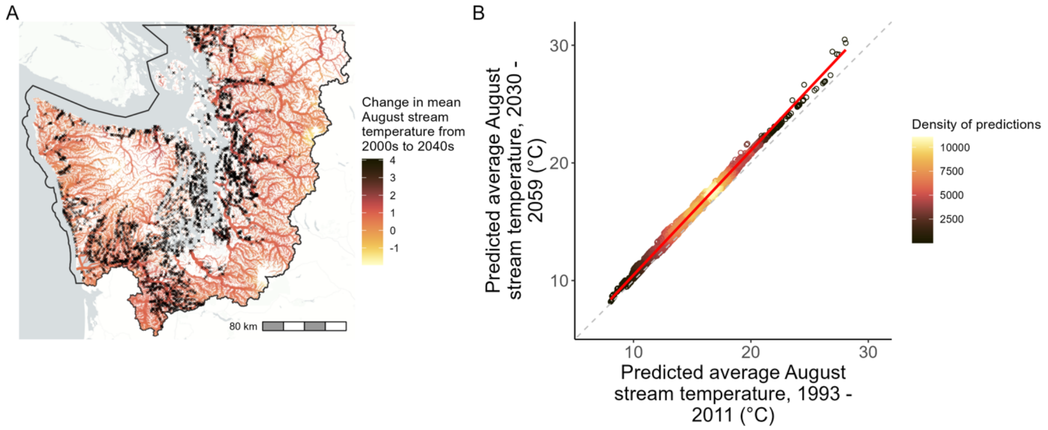


Figure 9: Projected stream temperature warming by region from 2000s to 2040s, compared to the locations of culverts (A) and projected change in temperature for individual reaches, colored by density of predictions (B). Each point represents a reach, and the red line shows the linear trend.

I find that historical cool-water restoration based does nearly as well at restoring future cool-water habitat as the future cool-water method (Fig 10). The future cool-water method achieves 2,871 km, the available quantity of future cool-water habitat, of habitat increases with 25% budget. The historical cool-water method achieves the same soon after, with a 35% budget. At all budgets, the historical method secures 90% or better of the habitat increases of the future method. The similar performance of the two strategies is explained by their similar portfolios: at every budget, a majority of culverts selected by the two methods are shared (Fig 10). These results indicate that the two make similar restoration choices, and that current temperatures likely are an effective proxy for future temperatures, based on available stream temperature estimates.

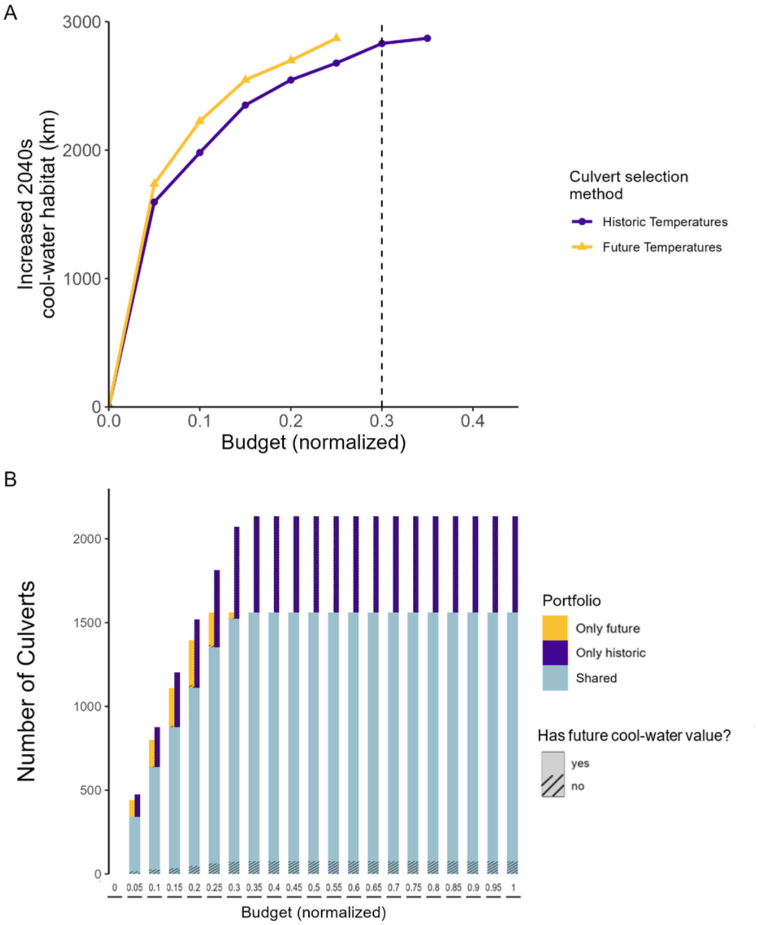


Figure 10: Efficacy of cool-water culvert prioritization using historical temperatures to restore future cool-water habitat, in comparison with an optimal future cool-water approach. The future cool-water habitat increases for the historical (purple) and future (golden) approaches are very similar at all budgets (A), as are the culverts selected between the two methods (B). The distinct (golden and purple) and shared culverts (light blue) at each budget are shown, with cross-hatch shading applied to the culverts which do not contribute future cool-water habitat. Cool-water is here defined as 15 °C or cooler. Budgets are normalized so that 1 is equal to the cost of restoring every culvert in the system and smaller values are fractions thereof.

6 Discussion and Conclusion

The total habitat culvert prioritization method, which does not explicitly prioritize cool-water habitat, is nevertheless effective at increasing access to cool-water habitat, as it yields comparable habitat improvements and selects similar portfolios to an alternative approach that specifically focuses on prioritizing cool-water habitat, for ecologically relevant thresholds for cool-water. At most budget levels and with most temperature thresholds, the total habitat method experiences only small to moderate decreases in cool-habitat compared to the optimal cool-water strategy. For moderate temperature thresholds, around 15 °C, the total habitat method is effective at restoring cool-water habitat for moderate to large budgets. For definitions of cool-water at and above 17 °C, the total habitat method restores 80% of possible cool water habitat, even at low budgets. The total habitat method is less effective when cool water is defined below 14 °C and the restoration budget is low (less than or equal to 10% of the cost to restore all barriers in the system). Consequently, the total habitat method may be less suitable if only restoring a small fraction of barriers in the system. Upper thermal limits for most species of migrating salmon are defined in the range of 19 – 22 °C, well within the range of effective cool-water restoration for the total habitat method (Fig 1). The result implies that the total habitat method does well at restoring cool-water habitat defined within reasonable upper thermal limits for salmon, indicating limited value from explicitly accounting for thermal stress in project prioritization even if cool-water habitat is a restoration priority.

The total habitat method is able to restore significant amounts of cool-water habitat even at low budgets, when it does not restore all the same culverts as the optimal cool-water strategy, because of the skewed distribution of habitat values and the lack of relationship between cool-water and overall habitat value among the barrier culverts. Because of this highly skewed marginal habitat value distribution, at a 15% budget, even though only 38% of the culverts selected with the total habitat method contribute to cool-water habitat, the total habitat method still achieves 79% of the potential cool-water habitat gains for that budget (Fig 7). Because there is apparently no relationship between marginal habitat value and the presence of cool water, culverts with cool-water habitat value are present for all marginal habitat values. Thus, when the total habitat method selects the culverts which contribute the most marginal habitat value, it also selects the culverts which contribute the most cool-water habitat. In this system, downstream barriers and cost both exert relatively little impact on culvert prioritization strategy, so much of the prioritization order is driven by habitat value. Together these features of the study system drive a relatively good performance at restoring cool-water habitat for a prioritization strategy which ignores stream temperature.

One caveat to this conclusion is that the future stream temperature predictions used here reflect broad anticipated trends in stream temperatures across the region and likely do not accurately reflect reach-level warming patterns. Stream temperatures are locally influenced by groundwater inputs, riparian vegetation, confluences between tributaries, and other factors which are not reflected in the stream temperature model (Fullerton et al., 2015). Previous studies have found these small-scale cold patches are used extensively by salmon to alleviate thermal stress, and these thermal refuges will likely be critical to salmon population resilience as temperatures continue to warm (Wang et al., 2020, Battin et al., 2007, Fullerton et al., 2018).

Despite their ecological importance, the stream temperature predictions used in my study do not predict where these small-scale refuges occur, so they do not factor into prioritization decisions.

Previous work has found that detecting these cold patches requires spatially dense ($<$1 km apart) temperature measurements (Fullerton et al., 2018). Consequently, Fullerton and colleagues' predictions are unlikely to represent the fine-grained thermal heterogeneity in rivers that provides cool-water refuge to salmon. In the future, improvements in technology for data collection may facilitate the dense temperature measurements necessary to model cool-water refuges across large regions. With developments in remote sensing technology, detailed thermal profiles have been created for some stream systems (e.g. Fullerton et al., 2015). Although such detailed data is not currently available on the scale required for regional planning, as remotely sensed data becomes more widely available and stream temperature models continue to develop, it may become possible in the future to incorporate these cold spots in stream temperature prediction models.

Replicating this analysis at a more localized scale, such as an individual watershed, where detailed thermal profiles are available, would be interesting to determine how much these results are tied to the scale of the data and analysis. Above, I found that incorporating temperature does not substantially improve habitat outcomes for regional-scale restoration planning. If, at the scale of individual watersheds, with more detailed temperature estimates, a cool-water strategy is substantially more effective at restoring cool-water habitat, then that would indicate that enhanced temperature data is valuable for restoration decision-making and might motivate improvements in the ability to collect and share stream temperature monitoring data. At present, Washington State does not maintain a centralized repository for stream temperature monitoring data that researchers can access, despite the fact that many local jurisdictions do have stream temperature monitoring programs (e.g. King County ("Streams Monitoring", n.d.)).

Additionally, this analysis only uses mean August stream temperatures as a metric of habitat suitability for salmon. This aggregated temperature metric likely obscures relevant diel fluctuations in temperature. Beyond temperature, effective climate-resilient habitat restoration requires considering the multitude of ways that climate will change salmon habitat quality. In addition to warming streams, climate change is projected to alter the timing of precipitation and streamflow, the frequency of extreme weather events, and hydrologic regimes (Battin et al., 2007). Future analysis of habitat suitability in barrier prioritization metrics could incorporate more complex representations of habitat quality in order to better understand the trade-offs between prioritizing habitat quantity and quality in restoring aquatic connectivity.

Despite the relevance of stream temperatures for population health in salmon and widespread fish passage barrier correction efforts in Washington, the intersection between temperature and barrier restorations has not previously been considered. This study is the first to evaluate the efficacy of a culvert prioritization approach at restoring cool-water habitat. The results from this work provide insights that can inform culvert prioritization strategies in Washington and fish passage restoration efforts more broadly.

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