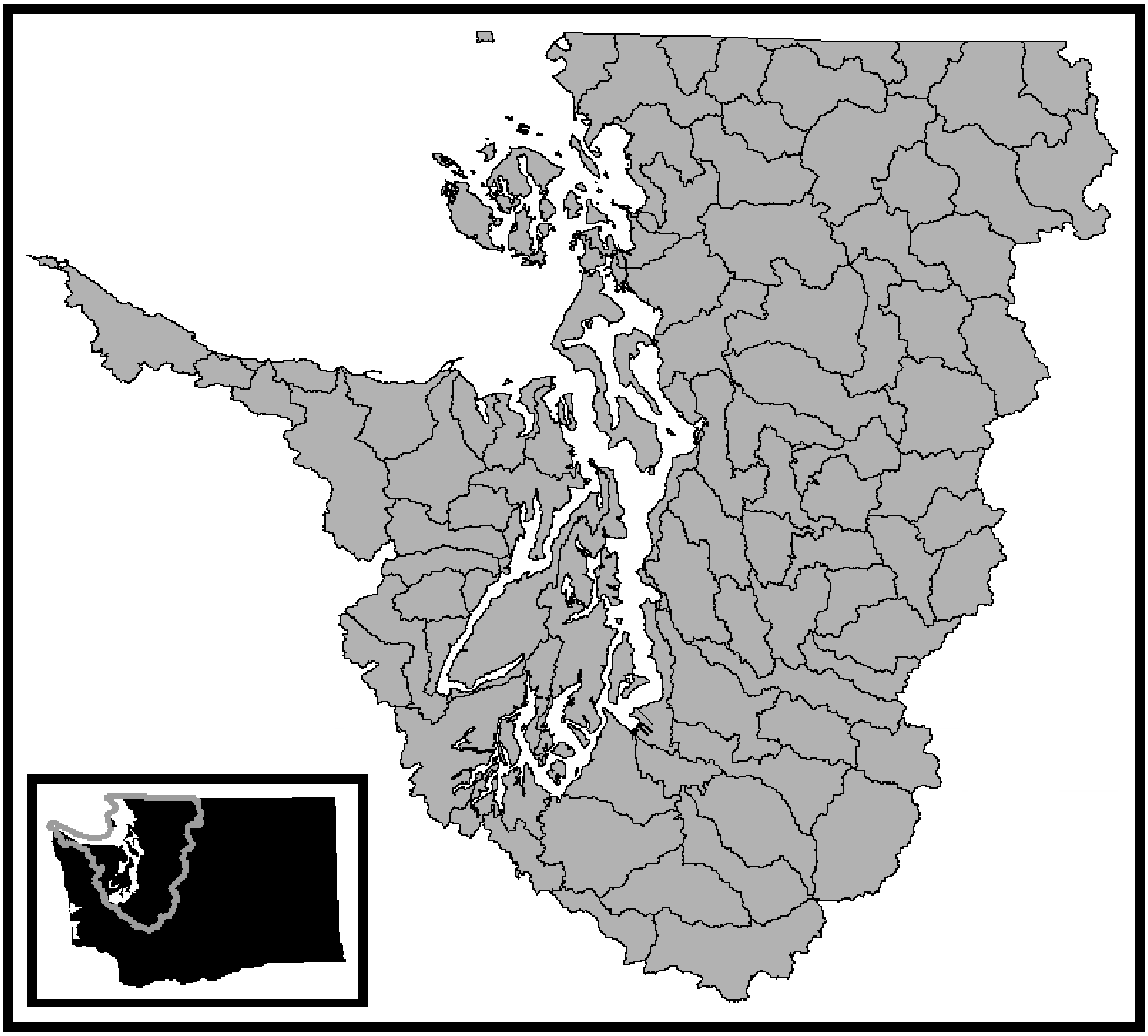
A landscape-scale watershed assessment method to support fish passage restoration in Puget Sound, Washington State:

An analysis for the Fish Barrier Removal Board



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A landscape-scale watershed assessment method to support fish passage restoration in Puget Sound, Washington State: An analysis for the Fish Barrier Removal Board

By

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ABSTRACT

In 2014, the Washington State Legislature directed the creation of the Fish Barrier Removal Board (FBRB), a multi-entity committee tasked with the development of a statewide strategy for removing anadromous fish barriers. The strategy shall identify watersheds with the greatest potential for salmon and steelhead recovery and implement the removal of multiple barriers within those watersheds. Prioritizing whole watersheds for barrier removal is a new and untested approach to fish passage restoration in Washington State. To inform the FBRB's watershed-based strategy, an analysis of aquatic habitat indicators was applied to a landscape-scale assessment of current and potential salmon and steelhead habitats in Puget Sound watersheds. Puget Sound watersheds were divided into 92 hydrologic units for a spatial analysis of 2 selected habitat indicators that correspond to habitat suitability and anthropogenic disturbance: potential for steelhead rearing and impervious land cover. Metrics of intrinsic potential for steelhead rearing and impervious surface land cover are presented in a decision support matrix for watershed prioritization of fish passage restoration.

Keywords – Fish Barrier Removal Board · fish passage · landscape scale assessment · Puget Sound · steelhead rearing intrinsic potential · impervious surface

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I am very fortunate. Thank you.

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INTRODUCTION

Puget Sound salmon and steelhead require a variety of complex habitats to support their anadromous life histories. Their reproductive success and survival is highly dependent on the ability to migrate freely between and through estuarine areas and the different freshwater habitats required for spawning and rearing. The expansion of roadway networks that support population growth in the Puget Sound lowlands has resulted in the installation of thousands of culverts and bridges that function as water crossing structures for transportation. Many of these structures have created hydraulic conditions that restrict access between the habitats that are critical for each stage of the salmon and steelhead life cycle.

While there has been a tremendous ongoing effort to correct these manmade in-stream barriers, a lack of project coordination and inconsistent funding has hindered the achievement of obtaining optimal fish passage conditions. Barrier correction projects that are completed upstream of remaining instream barriers diminish the effectiveness of recovery efforts and fail to efficiently capitalize on these investments. As an example, there have been thousands of barrier removals on forest roads in the upper watersheds of Washington State due to the road maintenance and abandonment requirements of Washington State's forest practices regulations (Washington Forest Protection Association, n.d.). For salmon and steelhead migrating upstream, the restored habitat connectivity in the upper watersheds is often completely inaccessible due to barriers that remain in the downstream portions of those watersheds.

There has also been a recent acceleration in the correction of State-owned barriers as a result of the permanent injunction issued by the United States District

Court in March 2013 (United States v. Washington, 2013). The ruling requires the correction of hundreds of anadromous fish barriers in Puget Sound and Washington Coast watersheds by four state agencies: Department of Transportation (WSDOT), Department of Fish and Wildlife (WDFW), Department of Natural Resources, and Washington State Parks. To come into compliance with this directive is expected to be very expensive for the State; WSDOT estimates that it will cost at least 150 million dollars annually through Year 2031, a total of 2.4 billion, for their barrier corrections alone (WSDOT, 2015).

The injunction does not adequately address the issue of habitat connectivity, as there is no requirement for the correction of adjacent non-state owned manmade blockages that may continue blocking the newly connected habitat. Supporting the need to identify potential solutions to this problem of inadequate barrier removal coordination, in 2014 the Washington State Legislature directed the creation of the Fish Barrier Removal Board (FBRB). The FBRB, a multi-entity panel composed of representatives from tribal governments and state and local natural resource and transportation agencies, has been tasked with developing a statewide strategy for removing anadromous fish barriers in the most efficient and cost effective manner that is practical (Revised Code of Washington [RCW] c 77.95 § 160, 2014). In accordance with the principles of this legislation, the strategy shall include the identification of high priority watersheds that have the greatest potential for salmon recovery and implement a coordinated, cross-jurisdictional approach to removing multiple barriers within a stream system. One of the primary intents of using a watershed-focused strategy is to optimize those recent fish passage investments that have resulted in minimal net benefit due to the continued existence of adjacent in-stream barriers. Within a priority watershed, the FBRB will select fish passage projects for funding, which will be administered through the fish barrier grant program established under RCW c 77.95 § 170 (2014).

Fish Barrier Removal Board Watershed Selection

Selecting watersheds across the state to provide funding recommendations to the legislature is a new and unfamiliar approach to restoring fish passage in Washington State. To facilitate this process, the FBRB relies heavily on the local knowledge and expertise of regional salmon recovery organizations and lead entities. These regional organizations, composed of tribes, private citizens, and federal, state, and local agencies, develop salmon and steelhead recovery plans and implement restoration projects that support the goals of those recovery plans (Washington State Recreation and Conservation Office [RCO], n.d.a; RCO, n.d.b). The solicitation of local input from these groups helps orient the FBRB toward reaching a final consensus on which watersheds throughout the state may be eligible for the fish barrier grant funding based on the principles of the legislation. This process also has the benefit of increasing communication and collaboration between government and non-institutional agencies, tribes, and interested stakeholders at the local level.

The watershed selection process is particularly challenging for the Puget Sound Partnership, the regional organization that develops and coordinates the implementation of regional recovery plans within the Puget Sound Salmon Recovery Region (Puget Sound Partnership, 2005). The Puget Sound Salmon Recovery Region (Figure 1, p.6), hereinafter 'PSR', is an administrative area defined by the RCO that is constituted of a complex human and hydrologic landscape. The PSR's high density of people, roadways, and waterways creates challenges to restoring stream habitat connectivity. Numerous conservation groups represent watershed areas across the entire PSR. Each of these groups has individual priorities and restoration goals based on the conditions and limiting factors of their local salmon and steelhead populations.

The PSR also contains the majority of the Culvert Case Area (Figure 2, p.7) which encompasses Water Resource Inventory Areas (WRIA) 1-23, as defined by the United States v. Washington, Case No. 70-9213 (2013). The potential of further litigation that targets other barrier owners, e.g., local governments and private entities, has increased general interest in fish passage-related issues in this area. The combination of these issues and the broad spectrum of the personal interests and values of local residents add to the cultural, political, economic and social factors that will be included in the FBRB's watershed selection process. A discussion of these elements is provided in the *Other Considerations* section (pp.57-66).

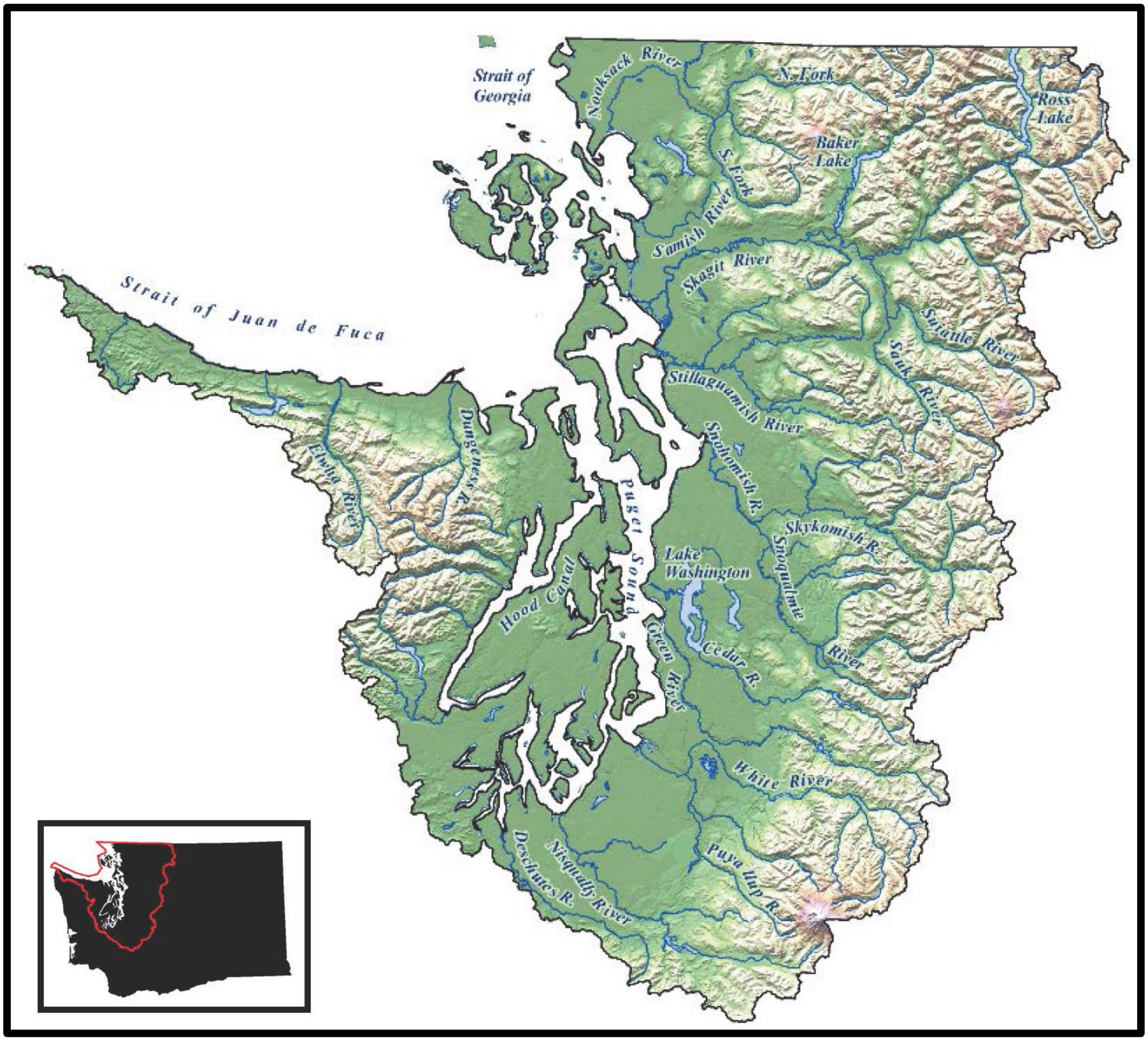

Figure 1. Puget Sound Region (PSR), Washington State (WDFW, 2011)

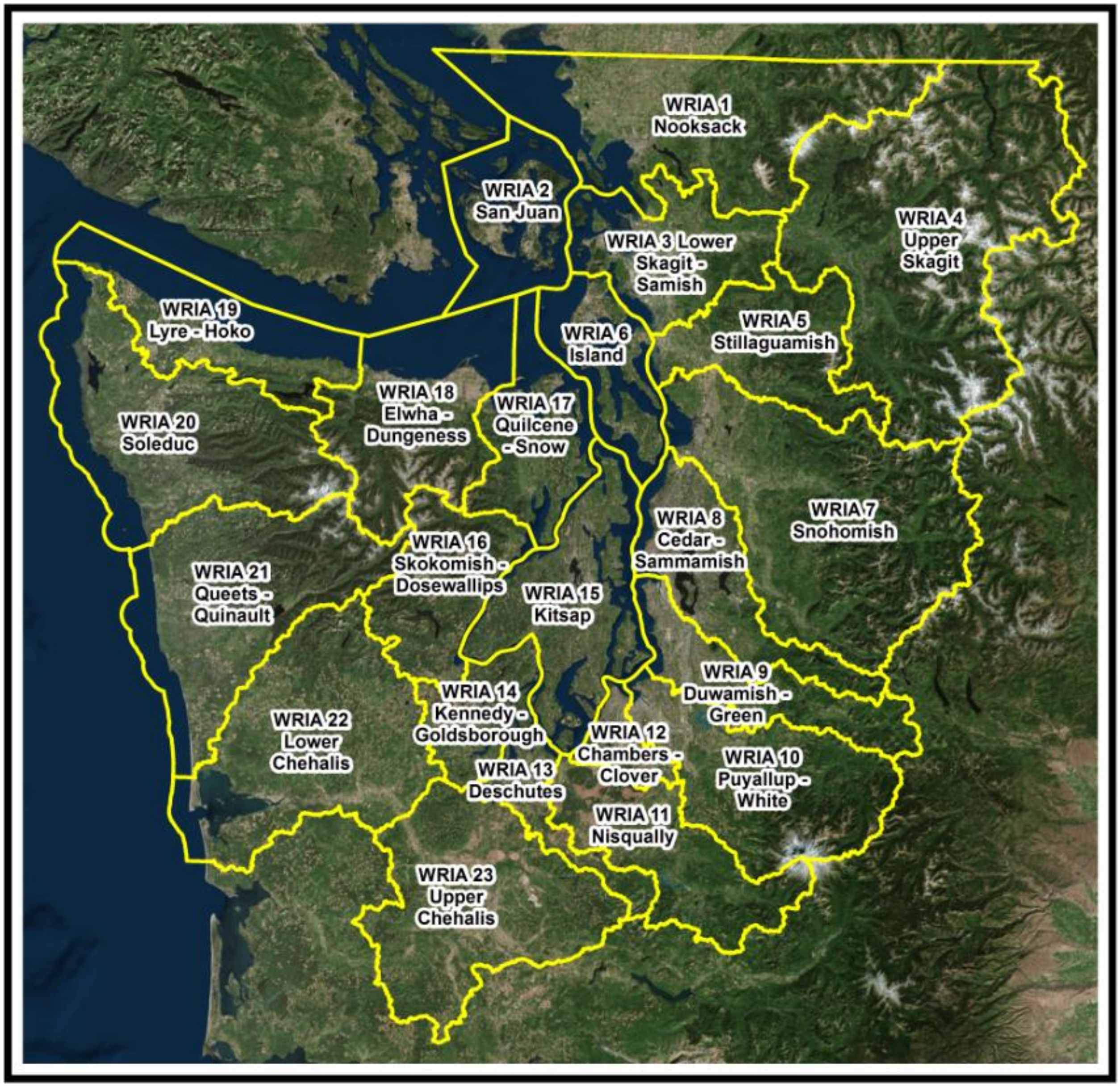

Figure 2. Culvert Court Case Area WRIAs 1-23 (Zweifel, 2015a)

Research Question

From a biological and ecological perspective, and in accordance with the principles described in RCW c 77.95 § 180 (2014), the FBRB must identify Puget Sound watersheds with the most potential to restore salmon and steelhead populations following the removal of migration barriers. This creates the need for an assessment mechanism for comparing Puget Sound watersheds that can assist in the selection of focus areas for fish passage restoration. Within this framework, the research and application of the recommended criteria described in this analysis will answer the question:

Using evaluation criteria that can help inform Puget Sound fish passage restoration strategies, how can a regional assessment be implemented to contrast the relative current and potential salmon and steelhead habitat conditions of Puget Sound watersheds?

LITERATURE REVIEW

Fish Passage Prioritization Methods

There have been numerous attempts to prioritize fish passage barriers using various methods and strategies. Prioritization schemes range from informal ad-hoc processes that rely almost exclusively on professional judgment to more formal methods that use a defined set of criteria to prioritize barriers based on a formula that outputs a score for each barrier. Some of the more advanced methods rely on modeling software and implement mixed integer linear programming algorithms to select barrier correction projects based on the maximization of a net benefit within a user-defined budget. Typically referred to as optimization models, these programs assess the spatial relationship of barriers throughout a watershed in combination with the interactive effects of fish passage improvements on longitudinal connectivity (O’Hanley, 2015).

The most common assessment criteria used in many of these prioritization methods include the barrier’s position in the stream network, severity of barrier, amount and quality of habitat, estimated cost of the barrier correction, and species use. Most prioritization formulas support the integration of additional criteria or the use of coefficients to weight specific variables to help formulate an output that aligns with project-specific goals.

Prioritization methods continue to improve as new information becomes available. For example, in 2015, Rachel Reagan of Oregon State University presented a stream crossing life-cycle cost model that uses an estimated annual maintenance cost throughout the lifespan of a crossing structure with a calculation of failure risk resulting from the potential hydrological impacts of climate change (Reagan, 2015). Models like these build on other proven models and are adaptable to different regional conditions.

Barrier prioritization strategies are often developed for ranking projects in a single watershed, or to compare barriers in disconnected watersheds. Many of the prioritization methods are scalable and adaptable to area-specific project needs. However, to effectively optimize fish passage barrier removals, you must have a complete and accurate barrier dataset within your focus area. This includes, at a minimum, knowledge of all barrier locations (manmade and natural barriers), the severity of the barriers, and quantity of adjacent stream habitat. Without a complete dataset, some barriers may be mistakenly prioritized and corrected upstream of existing barriers. This required baseline information is incomplete in the Puget Sound and it is impractical to meet these data requirements at this scale. Therefore, the geographic range must be narrowed to an area that is feasible for effectively identifying and assessing the data gaps.

Puget Sound Watershed Prioritization

Throughout the years, there have been many assessments of Puget Sound watersheds to prioritize restoration areas. These prioritization efforts use different sets of assessment criteria and data analyses to meet specific objectives. For example, there are multiple recovery plans that have been produced and implemented throughout the PSR by local salmon and watershed recovery organizations. These plans serve an important role in developing and advancing project lists to grant program administrators for potential funding opportunities.

RCW c 77.85 (2013) directs the organization and implementation of regional recovery plans to help identify local actions that are essential for the recovery of Endangered Species Act (ESA)-listed, or proposed to be listed, salmon and steelhead populations. This statute originated the Puget Sound Salmon Recovery Plan that outlines the shared strategy and vision for regional recovery planning (Puget Sound Partnership, 2005). The intent of the document is to narrate the overall salmon recovery strategy for the PSR, while also providing specific numerical recovery targets and criteria for abundance and escapement goals for each watershed. However, it was not in the scope of the Puget Sound Salmon Recovery Plan to prioritize watersheds for restoration.

To identify key actions necessary for making progress toward the abundance and escapement goals, 14 individual watershed recovery plans have been appended to the

Puget Sound Salmon Recovery Plan (Puget Sound Partnership, 2005). These watershed plans are site-specific, but maintain the goal of identifying actions that increase local salmon populations and support the recovery of other Puget Sound salmon populations. The plans detail the management needs for salmon recovery within each watershed but do not facilitate the comparison of information between watersheds. Additionally, the plans were created before the 2007 ESA listing of Puget Sound steelhead and will need to be updated to include management recommendations for this now federally listed threatened species.

Habitat limiting factors analysis reports have also been developed, as described in RCW c 77.85 (2013), that identify watershed issues including, but not limited to, fish passage barriers, water quality and quantity, riparian areas, floodplains, and hatchery management. Fish passage barriers are one of the highest priority limiting factors in nearly all of these analyses. Therefore, a cross-basin comparison of limiting factors reports does not provide much guidance for selecting a watershed to focus barrier correction efforts in the Puget Sound.

The Volume 2 Puget Sound Characterization Project is a recently completed regional assessment that provides a tool for comparing the relative values of freshwater, marine, and terrestrial habitats in small drainage areas throughout the Puget Sound (Wilhere, Quinn, Gombert, Jacobson, Weiss, 2013). This coarse-level assessment evaluates the relative value of ‘assessment units’ (AU) within the Puget Sound basin; these AUs have an average area of 12.2 square kilometers (Wilhere et al., 2013). Habitat metrics were measured within the AUs, and in areas with an upstream or downstream connection, to create indices that classify hydrogeomorphic features and reflect the relative conditions and capacity of salmon and steelhead habitats (Wilhere et al., 2013). The variables that were used in the characterization project have been demonstrated to correlate with freshwater lotic habitat conditions that affect salmon and steelhead (Wilhere et al., 2013).

The Volume 2 Puget Sound Characterization Project is one of the most comprehensive and thorough spatial analyses of the relative conservation value of fish and wildlife habitats throughout the Puget Sound basin. However, similar to other basin-wide prioritization studies, the analysis of data was conducted in a specific way for a particular purpose; the results of this characterization project are intended to assist users with local land use planning and zoning at the scale of one hundred to thousands of acres (Wilhere et al., 2013). In the final assignment of a relative habitat value, each AU was compared only with other AUs contained within the spatial extent of a WRIA and the final indices for each variable were categorized by deciles using a frequency distribution within a WRIA boundary (Wilhere et al., 2013). Therefore, the published results are not scalable to compare watersheds across the PSR without a recalculation of the data.

The absence of an available regional watershed prioritization tool to guide fish passage efforts supports the need for creating a new Puget Sound watershed assessment. The use of measurable habitat evaluation criteria can help estimate the relative potential for a watershed area to support salmon and steelhead recovery.

Available Watershed Habitat Condition Indicator Data

To provide an objective comparison of the relative conditions of Puget Sound watersheds for fish passage restoration, complete and quantifiable data must be applied consistently across the region. Several biological and ecological datasets were reviewed for use as indicators of watershed habitat conditions within the framework of the research question.

Salmonids are sensitive to changes in water quality and physical habitat conditions and therefore the presence of salmonid species can be an indicator of usable stream habitats (Glass, 2004). To compare salmonid use and distribution information for each watershed, I reviewed the utility of the Statewide Washington Integrated Fish Distribution database (SWIFD). The SWIFD dataset was created in 2014 by combining the WDFW and the Northwest Indian Fisheries Commission's (NWIFC) existing fish use data (WDFW, 2014); the merge created the most comprehensive fish distribution database available in Washington State. This data repository is actively maintained, and WDFW and NWIFC are continuously working to improve the fish distribution information as it becomes available.

SWIFD contains attributes for species presence in four main categories: documented, presumed, potential, and modeled use. Subcategories include information regarding artificial, transported, and historic use. Although there are many useful applications of SWIFD for multiple species throughout the Puget Sound, the data does not include values, e.g., population abundance or escapement estimates that can be used in a quantitative analysis.

Water temperature is a key component of water quality and can have ecological and biological implications for salmonid streams (Steel et al., 2012). The Washington State Department of Ecology (DOE), in compliance with the federal Clean Water Act Section 303(d), maintains a Category 5 list of state waters that exceed a temperature standard (DOE, 2015). Stream temperature data collection occurs in the field and is spatially sporadic. Temperature data is limited by the resources that are required to sample all waterways throughout the PSR, including restrictions in access to many remote areas. Due to the shortage of available basin-wide water temperature data, Category 5 listings are not suitable for this analysis.

Several other datasets were also considered for use in the development of this regional assessment including riparian conditions, hatchery impacts, genetic viability of salmon populations, production potential, and quantity and spatial structure of spawning habitat and manmade barriers. Each of these were found to have critical data gaps, inconsistent data collection methods, or were simply too complex to analyze within the scope of this analysis.

There is no perfect spatial data and the limited availability of comprehensive region-wide stream data creates restrictions to the assessment of relative watershed conditions. For this assessment, it is important to use data that was collected systematically throughout the entire region that also allows for repeatable and transparent data analysis. To be applicable to the evaluation of watershed conditions for fish passage restoration, the data must also indicate the relative potential for an area to support salmon and steelhead recovery following the successful implementation of fish barrier corrections. In agreement with these specifications, two indicators were evaluated and applied to a landscape-scale assessment of the relative habitat conditions of Puget Sound watersheds: the intrinsic potential for steelhead rearing and impervious land cover.

Intrinsic Potential

Due to the incompleteness and limited availability of population data, and the restriction of migratory species' spatial distribution imposed by instream barriers, an estimate of habitat suitability was used as a surrogate for actual salmon and steelhead occurrence data Suitable habitat conditions are a fundamental requirement of sustaining fish populations. Over a large geographic extent, the spatial distribution of stream reaches with the potential to provide usable habitats for salmonids has a bearing on the actual conditions of the habitat and status of populations (Burnett et al., 2007). In the absence of available, complete habitat data for watersheds, models can be a useful research tool for estimating habitat conditions. The use of Intrinsic Potential models is a common method for conducting large-scale valuations of habitat.

Intrinsic Potential (IP) is a concept that emanated from the exploration of the relationships between habitat characteristics and species use; the result was the creation of habitat suitability models (US Fish and Wildlife Service [USFWS], 1981). In the aquatic environment, IP is an indicator of habitat suitability based on the channel morphology resulting from a watershed's landform and hydrology. Because these geomorphic and hydrologic characteristics are not significantly affected by anthropogenic disturbances, IP is considered a reliable indicator of a stream's historic condition as well as a predictor of its potential condition if anthropogenic factors were removed and natural processes were able to be restored (Sheer et al., 2009). IP models have also been used as a spatial surrogate for production estimates when actual population abundance and distribution information is unavailable (Puget Sound Steelhead Technical Recovery Team [PSSTRT], 2013a; Myers et al., 2015).

The importance of this information and its adaptability from stream reach to watershed scales has prompted the creation of several IP models. Habitat preferences differ between salmonid species, and therefore IP models estimate species-specific habitat values based on the stream reach characteristics that are most readily used by each species (Sheer et al., 2009). The availability of more than one IP model creates the need to determine which one to use and which species to consider.

Steelhead as an Indicator of Fish Passage Conditions

Steelhead use a wide range of habitats throughout their life cycle. They exhibit natural life history characteristics that can include spending several years in freshwater, spawning multiple times, and even migrating more than once between inland freshwater streams and saltwater (Withler, 1966). Steelhead spawn in small to large mainstem rivers and medium to large tributaries. Steelhead have the ability to ascend steep stream gradients and, although there is not full agreement in the upper gradient limit that can be utilized by steelhead, it is generally agreed that their threshold is higher than any species of Puget Sound anadromous salmon (Sheer et al., 2009).

Due to the extended amount of time that steelhead spend in freshwater and because they can be found year-round throughout most Puget Sound freshwater streams, steelhead are typically considered to be a rearing-limited species. The habitat preferences and life history patterns of steelhead contribute to their spatial structure throughout their geographic range in the Puget Sound.

In the Puget Sound basin, steelhead, Chinook, and summer-run chum are all ESA-listed threatened species (USFWS, 2015). The migratory patterns of steelhead and their utilization of a wide range of habitats makes them the most ubiquitous of these ESA-listed species. Their pervasiveness and preference for rearing in small to medium streams where the majority of stream crossings are culverts, many of which are barriers to fish migration, supports the use of steelhead presence as an indicator of a watershed's fish passage conditions. Due to their spatially broad resource requirements, I used steelhead as an umbrella species and my analysis of intrinsic potential has the underlying assumption that correcting barriers to steelhead migration will benefit the other Puget Sound salmonids.

There is a limited amount of available occurrence data for steelhead in the PSR. Only 19 of the 32 Puget Sound steelhead Distinct Population Segments have escapement data that has been collected for at least 3 years since 1980 and still has ongoing data collection (WDFW, 2015a). The data gaps in escapement estimates restrict the ability to create meaningful trend analyses for these populations.

Historical harvest records have been reviewed to estimate population abundance, which represent one of the only available data sources for population estimates. The combination of harvest records and usable data from ongoing collection efforts have allowed abundance estimates to be made for 21 of the 32 populations; the remaining populations have very limited or no related data (WDFW, 2015a).

Steelhead Intrinsic Potential Models

Steelhead intrinsic potential models have been developed along the Pacific Coast and other areas in the Northwest that incorporate various geomorphic and hydrologic characteristics to assess historic or potential conditions for rearing and spawning life stages (Burnett et al., 2007; Agrawal, Schick, Bjorkstedt, Szerlong, & Goslin, 2005; Boughton, & Goslin, 2006; Olympic Natural Resources Center, 2012). Based primarily on expert opinion and the life stage of interest, specific variables are used to create habitat suitability values. The habitat suitability values are combined and processed by spatial models to output an estimate of a stream reach's potential to provide suitable habitat. The estimated potential to provide suitable habitat is not intended to be used to determine the actual 'quality' of habitat, which is typically measured through a demographic response, e.g., population abundance (Wilhere et al., 2013).

Due to the rearing-limited production potential of steelhead, and the juvenile habitat preferences and distribution that can extend into high gradient headwater streams, an intrinsic potential model that assesses steelhead rearing habitat is used in this analysis. I carefully evaluated two IP models for functionality and applicability to the research question: the Puget Sound Steelhead Threshold Intrinsic Potential Model and the Burnett et al. (2007) Intrinsic Potential Model for Steelhead.

Puget Sound Steelhead Threshold Intrinsic Potential Model

In 2013, the Puget Sound Steelhead Technical Recovery Team (PSSTRT, 2013a) developed a stream habitat-rating matrix. Stream segments were broadly categorized as high, moderate, low or extremely low in a simplified matrix that is based primarily on stream width and gradient (Figure 3, p.19). These basin characteristics, adapted from an IP model developed for the Interior Columbia River basin, were established to determine whether a Puget Sound watershed could support a sustainable steelhead population based on expert opinion and a literature review of the total annual escapement necessary to meet a minimum required effective population size (PSSTRT, 2013a). The IP values were derived from a calculation of the average parr production per meter squared based on the results of a 1985 steelhead spawning escapement study (Gibbons, Hahn, & Johnson, 1985).

Stream Habitat Rating Thresholds (intrinsic habitat potential below natural barriers)				
		Stream width (bankfull)		
		0 - 3 m	**3 - 50 m**	**> 50 m**
Stream gradient	**0 - 4%**	**low**	**high**	**moderate**
	>4%	**low**	**low**	**low**
Lakes and Tidal Zones		**Extremely Low**		

Figure 3. Steelhead Habitat Rating Matrix (PSSTRT, 2013a)

The primary benefit of using the stream habitat rating matrix for Puget Sound steelhead is that it represents the only IP model developed specifically for the PSR. Although the model is new and still being validated, it is a functional tool that is currently being applied in a Puget Sound steelhead life-cycle modeling project that helps predict plausible population abundance trajectories, establish recovery goals, and evaluate potential resource management actions (Phil Sandstrom pers. comm., October 2015; Ann Marshall, email correspondence, October 2015). However, the classification of habitats into binned high, moderate, low, and extremely low categories makes it challenging to complete a quantitative analysis of the data. The use of such a small number of habitat value categories causes a loss of data precision and makes the assumption the relationship between the predictor and response is equal within each interval (Harrell, 2013).

Burnett et al. (2007) Intrinsic Potential Model for Steelhead

The Burnett et al. (2007) Intrinsic Potential model for steelhead in the Coastal Province of Oregon is one of the most recognized and frequently cited intrinsic potential models available. This peer-reviewed model uses habitat suitability curves that are based on the relationship between juvenile steelhead use and three stream attributes: mean annual stream flow, calibrated valley-width index, and channel gradient (Figure 4, p.21). As described in Burnett et al. 2007, the index score for each stream attribute is based on empirical evidence from published studies that confirm the relationship between the value of each stream attribute and steelhead rearing; the numerous supporting references are described and cited in Burnett et al. (2007).

Congruent with the Puget Sound Characterization Project, I have chosen to use the Burnett et al. (2007) IP index model for the Puget Sound steelhead IP habitat analysis. Although this model was developed for the Oregon Coast Range, it has been applied in the PSR after review and general agreement by regional experts that the habitat relationships defined by Burnett et al. (2007) are likely to be very similar for Puget Sound steelhead populations (Wilhere et al., 2013).

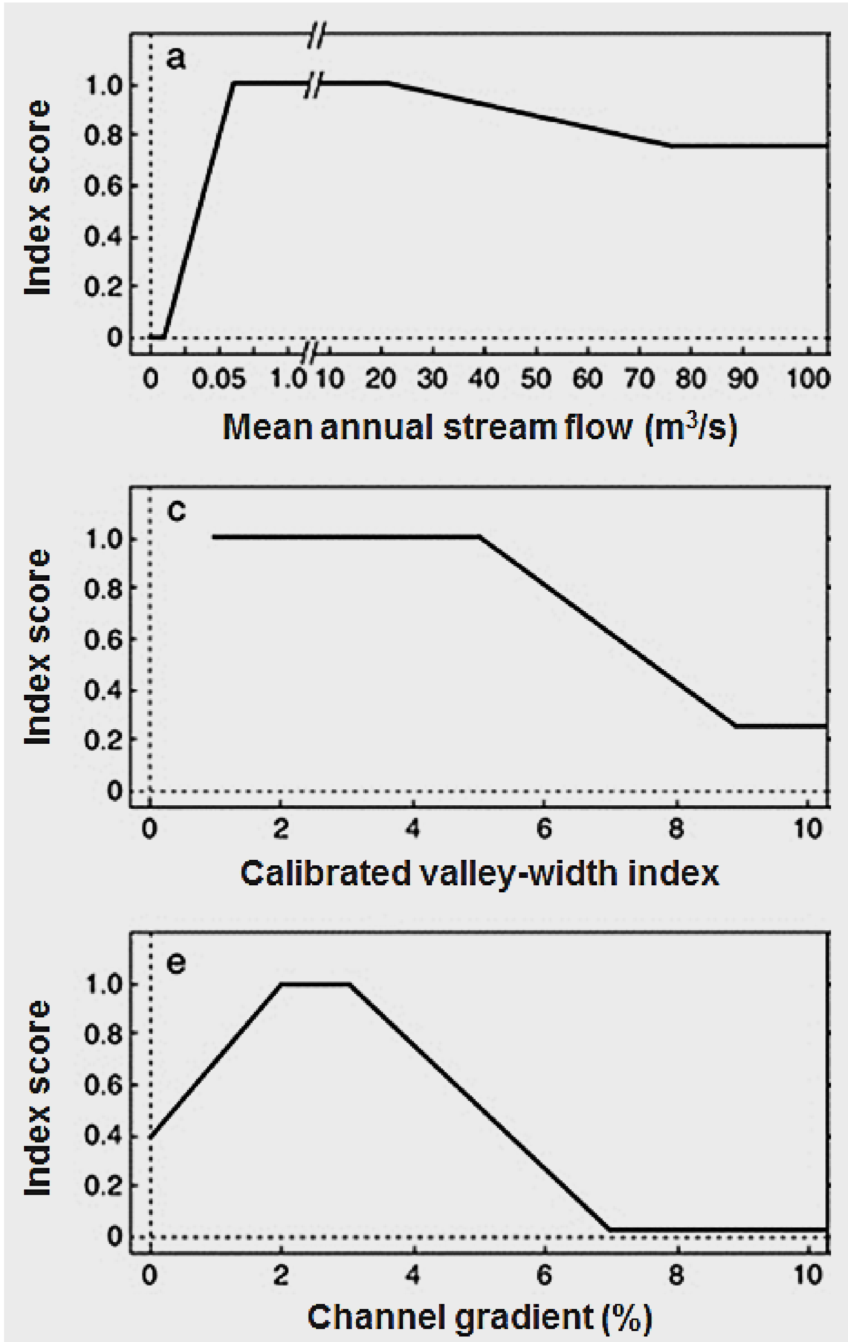

Figure 4. Steelhead Habitat Suitability Curves (Burnett et al., 2007)

Impervious Surface Land Cover

An estimation of impervious surfaces can be used as an indicator of a watershed's ecological conditions. Significant amounts of impervious surfaces can signal a multitude of disturbances throughout a watershed. Impervious surface land cover data is often collected through satellite imagery, using standardized methods over a large geographic extent. The scale and consistency of this data collection allows for an objective broad range analysis of the density of impervious surfaces and an inference of the level of disturbance to watershed conditions.

Much research has concluded that there are strong linear relationships between the amount of impervious surface land cover and predictors of biological, hydrologic, physical, and chemical conditions of aquatic systems (Schueler, 2003). Disturbances that trigger significant changes in watershed conditions often lead to biological responses including decreases in sensitive fish species and invertebrate species diversity (Paul & Meyer, 2001).

Urban areas typically have a high density of impervious surfaces. Urbanization is arguably the most intensive land use that affects watershed processes, primarily as a result of the increase in impervious surface land cover (Paul & Meyer, 2001). The development of new impervious surfaces is a nearly complete, semi-permanent transformation of a watershed's land surface. Several studies have shown that increases in urbanization can cause changes in a stream's hydrology, geomorphology, and temperature (Paul & Meyer, 2001).

There are several effects of urbanization, and the subsequent increases in imperviousness, that create stream conditions that negatively impact salmon and steelhead populations. For instance, salmon and steelhead require cool water temperatures for survival; impervious surfaces in urban areas can warm stormwater runoff, which then contributes to warmer stream temperatures (Pluhowski, 1970). A literature review of salmon and steelhead thermal tolerances and behavioral responses verified that increased stream temperatures could inhibit migration and spawning (Peery, 2010).

Urbanization can also contribute pollutants to nearby waterways via stormwater runoff. A 2011 study in the Puget Sound lowlands confirmed that salmon mortality was positively correlated with roadways that were contributing toxic stormwater runoff to streams (Feist, Buhle, Arnold, Davis, Scholz, 2011).

Impervious surfaces can cause greater flood magnitude and frequency (Leopold, 1968). Unstable stream banks and erosion often result from the increase in flood events. Erosion and bank failure contribute to sedimentation of spawning areas and, in more extreme cases, can cause a landslide that affects an entire watershed (Randolph, 2004). Climate change is expected to alter flow regimes and may amplify these impacts to watershed conditions and ecological functions (Blair et al., 2010).

A 1997 study of the effects of urbanization on Puget Sound lowland streams demonstrated a positive linear relationship between road density and the percentage of a watershed's total impervious area (May, Horner, Karr, Mar, & Welch). These findings aligned with a previous impervious surface coverage evaluation completed by the City of Olympia that reported over 60% of watershed imperviousness in suburban areas is transportation-related (City of Olympia, 1994).

An increase in road density, consequently, correlates with an increase in the number of transportation-related stream crossings (Wheeler, Angermeier, & Rosenberger, 2005). In November 2015, a query of WDFW's fish passage database revealed that 46% of transportation-related stream crossings in the PSR are confirmed barriers to fish migration (WDFW, 2015b). With such a high percentage of barriers caused by roadways, a measure of impervious surfaces may be an indicator of barrier density and a valuable tool in a cost-benefit analysis to estimate the net habitat gain per barrier correction.

Impervious surfaces can be assessed using a variety of methods. The most common methods are measurements of total impervious area and effective impervious area (May, Horner, Karr, Mar, & Welch, 1997). Total imperviousness simply refers to the sum of the areas covered by impervious surfaces and effective imperviousness is only the surfaces hydraulically connected to a stream (Booth & Jackson, 1997).

Effective impervious area, sometimes referred to as 'directly connected impervious', has been shown in some studies to have a more defined relationship with indicators of ecological conditions (Walsh, Fletcher, & Ladson, 2005). There have been multiple attempts to define the relationship between effective impervious and total impervious, often as a ratio, but the results have varied considerably based on local factors, including site-specific urban drainage practices and geography (Jacobson, 2011; Roy & Shuster, 2009). Effective impervious area is difficult to estimate due to the amount of data required at the local watershed level and therefore total impervious area, typically expressed as a percentage, has been widely accepted as a predictor of watershed conditions for many studies (Chowdhury et al., 2005).

Use of Intrinsic Potential Model with Impervious Surface Land Cover

The IP model is based on watershed characteristics that are not significantly affected by anthropogenic disturbances, and therefore this model does not reflect the actual quality of habitat, which is highly affected by human actions on the landscape. A measurement of impervious surface land cover can serve as a proxy for the actual, current biological and ecological conditions of a watershed. Even though there is no known relationship between the IP model and imperviousness, it would be counteractive to restore fish passage to a watershed that has a high intrinsic potential for usable habitat that is also highly affected by impervious surfaces, thus creating stream conditions that may not be able to support fish life. Therefore, this joint assessment provides a more balanced and effective evaluation of a watershed's habitat conditions than using only a single indicator.

DATA AND METHODS

Study Area Description

The PSR (Figure 1, p.6) includes several inlets and straits from the south end of the Puget Sound and Hood Canal, northward to the Strait of Georgia, and westward to the Strait of Juan de Fuca for nearly 5,000 kilometers of shoreline (Natural Resources Conservation Service [NRCS], 2015). Over 10,000 streams and rivers flow into these interconnected marine waterways ranging from unnamed streams with drainage areas that are just a fraction of a square mile up to the much larger Skagit River with a drainage area of over 7,700 square kilometers (NRCS, 2006).

To assess and compare the relative habitat conditions of PSR watershed areas for potential fish passage restoration, I isolated watershed areas using the US Geological Survey's fifth level hydrologic units (HUC 10). The HUC 10 scale was selected based on feasibility considerations following a preliminary review of the WDFW's fish passage database to visually assess Puget Sound barrier density. The HUC 10 spatial scale was approved as the unit of assessment by the FBRB in April 2015. There are 92 HUC 10s (Figure 5, p.27; Table 1, p.28) in the PSR combining for a total area of 35,550 square kilometers; the average area of these HUC 10s is 386 square kilometers (NRCS, 2015).

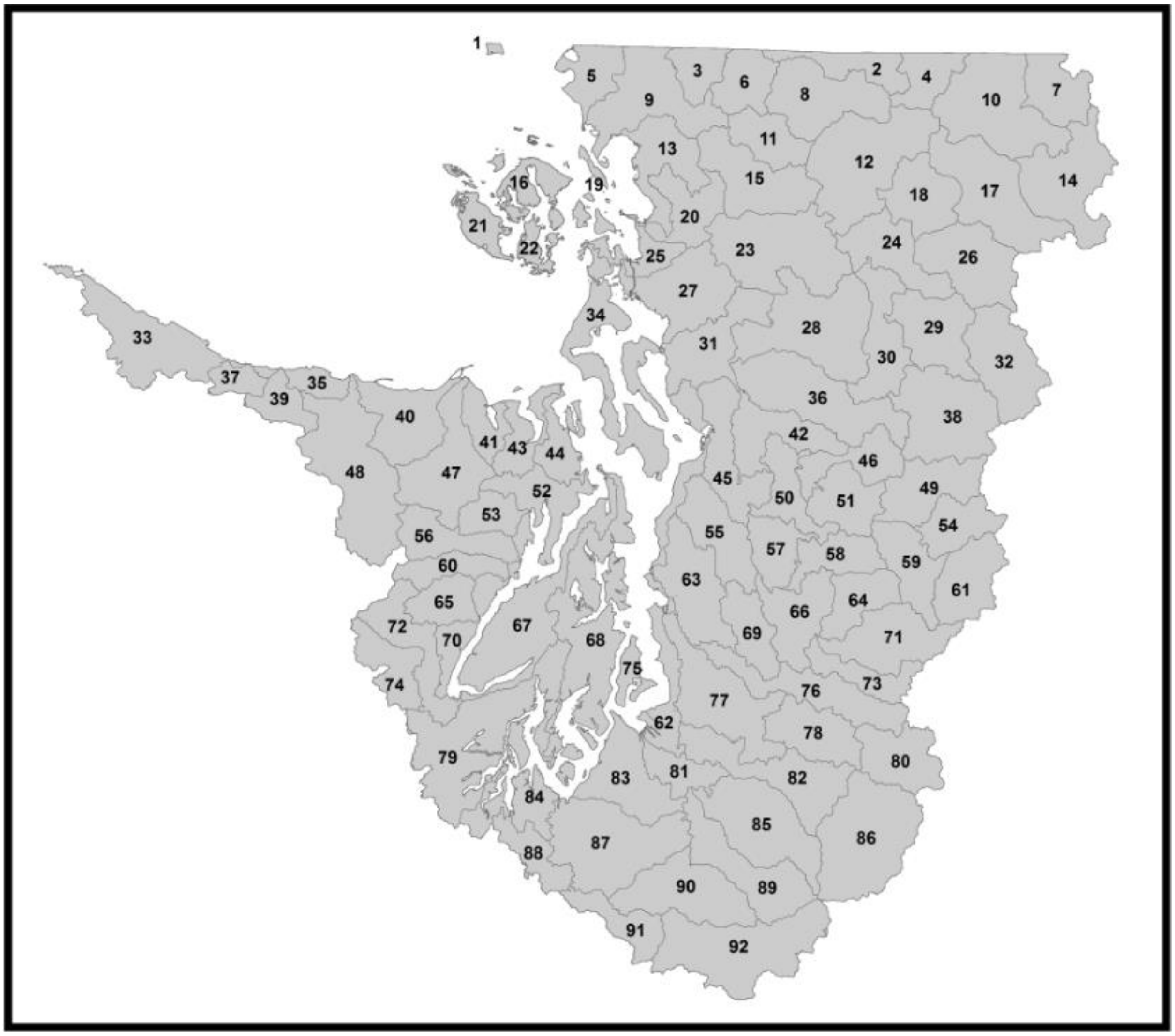

Figure 5. Puget Sound Region's 92 HUC 10 Boundaries (Zweifel, 2015b). HUC Names in Table 1.

Table 1. HUC 10 Names (see Figure 5, p.27)

HUC ID		HUC 10 Name
1		Point Roberts-Frontal Strait of Georgia
2		Middle Chilliwack River
3		Lower Chilliwack River
4		Upper Chilliwack River
5		California Creek-Frontal Semiahmoo Bay
6		Lower North Fork Nooksack River
7		Three Fools Creek-Lightning Creek
8		Upper North Fork Nooksack River
9		Nooksack River
10		Ross Lake-Skagit River
11		Middle Fork Nooksack River
12		Baker River
13		Whatcom Creek-Frontal Bellingham Bay
14		Ruby Creek
15		South Fork Nooksack River
16		Orcas Island
17		Gorge Lake-Skagit River
18		Diobsud Creek-Skagit River
19		Bellingham Bay Islands
20		Samish River
21		San Juan Island
22		Lopez Island
23		Finney Creek-Skagit River
24		Illabot Creek-Skagit River
25		Telegraph Slough-Frontal Padilla Bay
26		Cascade River
27		Skagit River-Frontal Skagit Bay
28		North Fork Stillaguamish River
29		Lower Suiattle River
30		Lower Sauk River
31		Stillaguamish River
32		Upper Suiattle River
33		Pysht River-Frontal Strait of Juan De Fuca
34		Whidbey Island
35		Salt Creek-Frontal Strait of Juan De Fuca
36		South Fork Stillaguamish River
37		Lyre River-Frontal Strait of Juan De Fuca
38		Upper Sauk River
39		Lyre River
40		Morse Creek-Frontal Port Angeles Harbor
41		Jimmycomelately Creek-Sequim Bay
42		Pilchuck River
43		Snow Creek-Frontal Discovery Bay
44		Chimacum Creek-Frontal Port Ludlow
45		Quilceda Creek-Frontal Possession Sound
46		Sultan River
47		Dungeness River
48		Elwha River
49		North Fork Skykomish River
50		Woods Creek-Skykomish River
51		Wallace River-Skykomish River
52		Little Quilcene River-Frontal Hood Canal
53		Big Quilcene River
54		Beckler River
55		Middle Sammamish River
56		Dosewallips River
57		Lower Snoqualmie River
58		Tolt River
59		South Fork Skykomish River
60		Duckabush River
61		Tye River
62		Lunds Gulch-Frontal Puget Sound
63		Lower Sammamish River
64		North Fork Snoqualmie River
65		Jefferson Creek-Hamma Hamma River
66		Upper Snoqualmie River
67		Tahuya River-Frontal Hood Canal
68		Ollala Valley-Frontal Puget Sound
69		Lake Sammamish
70		Lilliwaup Creek-Frontal Hood Canal
71		Middle Fork Snoqualmie River
72		North Fork Skokomish River-Skokomish River
73		South Fork Snoqualmie River
74		South Fork Skokomish River
75		Anderson Island-Hartstene Island
76		Cedar River
77		Lower Green River
78		Middle Green River
79		Goldsborough Creek-Frontal Puget Sound
80		Upper Green River
81		Lower Puyallup River
82		Lower White River
83		Chambers Creek-Frontal Puget Sound
84		McLane Creek-Frontal Puget Sound
85		Carbon River
86		Upper White River
87		Lower Nisqually River-Frontal Puget Sound
88		Lower Deschutes River
89		Upper Puyallup River
90		Middle Nisqually River
91		Upper Deschutes River
92		Upper Nisqually River

Intrinsic Potential for Steelhead Rearing Habitat Dataset

Intrinsic potential index values were generated by uploading a 10-meter Digital Elevation Model (DEM) to Terrain Works' NetMap tool (Terrain Works, 2016) and using Burnett et al. (2007) habitat suitability curves for juvenile steelhead (Figure 4, p.21). Following the approaches adopted from earlier studies (Morrison, Marcot, & Mannan, 2012; Vadas & Orth, 2001) by Burnett et al. 2007, the IP index value for a stream reach was calculated by first multiplying the unweighted species-specific index scores from each of the three stream attributes in Figure 4: mean annual flow, calibrated valley-width index, and channel gradient (Burnett et al., 2007). The geometric mean of this product represents the final IP index value for a stream reach (Burnett et al., 2007). The IP index values range from 0-1, where an IP value of zero represents no potential rearing habitat value and an IP value of one represents the highest potential rearing habitat value.

To more accurately represent the potential distribution extent of steelhead within the modeled stream network, stream reaches upstream of steelhead-specific gradient barriers were not included in the computation. Various steelhead maximum gradient thresholds have been used for different purposes along the Pacific Coast and other areas in the Northwest. In Washington State, a 20% gradient for a distance of 160 meters is the uppermost limit that has been applied as a steelhead barrier. This gradient cutoff has been used by the WDFW since 1998 and has been adopted for use in other Puget Sound and Washington Coast steelhead IP analyses (Olympic Natural Resources Center, 2012; Cooney & Holzer, 2006; WDFW, 2009).

The average Puget Sound IP stream segment (Geographical Information System [GIS] polyline) length is approximately 97 meters. Formulas were created in Microsoft Excel to identify gradient barriers based on contiguous stream reaches that exceed the gradient and length threshold. These stream reaches were flagged for review and error checking in ArcGIS before removal from the calculations.

Modeled stream reaches were also excluded above natural point barriers, i.e., waterfalls, without fishways. Only waterfalls classified as total barriers, according to the 3.7-meter vertical height threshold described in WDFW 2009, were used in the analysis. This maximum leaping threshold was derived from a 1984 Washington State University study (Powers & Orsborn, 1984) that investigated the physical and biological conditions that affect fish passage at waterfalls.

Natural point barrier data was reviewed from WDFW's fish passage database and supplemented with a natural barrier dataset received from NOAA fisheries; both datasets represented current records as of September 10, 2015. The datasets were combined and filtered to only include waterfall barriers categorized as a total blockage. Natural barrier records created through the digitization of WRIA maps were excluded due to uncertainties stemming from multiple recent field verifications that revealed no barrier at the record location or a misclassification of barrier severity. Duplicates records were removed, resulting in a final list of 1,222 natural point barriers from eight different data sources.

Within each HUC 10 the length (meters) of each stream reach located downstream of a natural barrier was multiplied by its IP index value (no defined units) to produce a reach score. The sum of these reach scores, commonly referred to as intrinsic potential meters (IPm, or equivalent), is commonly used to compare the relative intrinsic potential value of watersheds (Fullerton et al., 2011; Spence & Williams, 2001). However, calculations of the total IPm are highly affected by the size (area) of the watershed. The PSR HUC 10s vary greatly in size, ranging from 11.7 to 872.3 square kilometers (NRCS, 2015). To normalize the output and limit the weight of watershed size in the calculations, IPm was divided by the area of the HUC 10 to generate a final metric of IP density. IP density, also used in the Puget Sound Watershed Characterization Project and peer-reviewed by a panel of expert scientists with the appropriate professional expertise (Wilhere et al., 2013), is a better representation of the abundance and frequency of usable steelhead rearing habitat within a HUC 10. There are no units of measure associated with IP density, and therefore the final values were normalized from zero to one.

Intrinsic Potential Score Definitions

IP Index Value**:** Steelhead IP index value of stream segment

Stream Segment Length: Length (meters) of stream segment

Area of HUC 10: Area of HUC 10 (square meters)

Intrinsic Potential Score Formula

IP Index Value * Stream Segment Length = IP Meters

∑ [IP Meters] / Area of HUC 10 = IP Density

Final HUC 10 steelhead IP score is IP Density (normalized 0 to 1)

Impervious Surface Land Cover Dataset

Impervious surface areas were calculated using the National Oceanic and Atmospheric Administration's (NOAA) 2011 Coastal Change Analysis Program (C-CAP) dataset for Regional Land Cover and Change. C-CAP land cover data is collected systematically every 5 years through aerial surveys, but is typically not available until 2 years after the completed surveys: the 2011 data was published in 2013, and the 2016 data may not release until 2018 (pers. comm. Dr. Ken Pierce, October 2015). Each 30-meter cell is categorized into one of 24 land cover classes that are identified as important indicators of coastal ecosystems that can be consistently derived through remote-sensing (NOAA, n.d.a).

Developed lands with areas of constructed materials, i.e., anthropogenic impervious surfaces, were divided into 4 classes based on defined ranges of the percent of imperviousness: open space and low, medium, and high intensity (NOAA, n.d.a). Within each HUC 10, the area of imperviousness for each developed cell was scaled by its class specific Impervious Coverage (IC) Coefficient (Figure 6, p.33). The sum of the scaled impervious areas was divided by the area of the HUC 10 to generate the final percentage of impervious surface land cover.

Impervious Surface Score Definitions

Cell Area: 30 square meter pixel

IC Coefficient: Class-specific impervious coverage coefficient

Area of HUC 10: Area of HUC 10 (square meters)

Impervious Surface Score Formula

Cell Area * IC Coefficient = Area of Impervious Surface

∑ [Area of Impervious Surface] / Area of HUC 10 = Percentage of Impervious Surfaces

Final HUC 10 impervious surface score is Percentage of Impervious Surfaces

C-CAP Class Name	IC Coefficient
Developed, High Intensity – contains significant land area that is covered by concrete, asphalt, and other constructed materials. Vegetation, if present, occupies less than 20 percent of the landscape. Constructed materials account for 80 to 100 percent of the total cover. This class includes heavily built-up urban centers and large constructed surfaces in suburban and rural areas with a variety of land uses.	0.8503
Developed, Medium Intensity – contains areas with a mixture of constructed materials and vegetation and other cover. Constructed materials account for 50 to 79 percent of the total area. This class commonly includes multi- and single-family housing areas, especially in suburban neighborhoods, but may all types of land use.	0.5768
Developed, Low Intensity – contains areas with a mixture of constructed materials and substantial amounts of vegetation and other cover. Constructed materials account for 21 to 49 percent of the total area. This subclass commonly includes single-family housing areas, especially in rural neighborhoods, but may all types of land use.	0.2929
Developed, Open Space – contains a mixture of some constructed materials, but mostly managed grasses or low-lying vegetation planted in developed areas for recreation, erosion control, or aesthetic purposes. These areas are maintained by human activity such as fertilization and irrigation, are distinguished by enhanced biomass productivity, and can be recognized through vegetative indices based on spectral characteristics. Constructed surfaces account for less than 20 percent of the total cover.	0.0941

Figure 6. NOAA C-CAP Classes for Developed Land Cover. IC coefficient represents average percentage of impervious land cover per cell (30 meter pixel) (NOAA, n.d.a)

Using IP and Impervious Surfaces to Compare HUC 10s

The purpose of this analysis is to develop a method for evaluating the relative current and potential habitat conditions of Puget Sound watersheds. The results provide a decision support tool that can be used by the FBRB in the process of determining which watersheds to focus fish passage efforts in consideration of the relative potential for the recovery of salmon and steelhead populations after barrier removal. There are multiple ways to integrate the calculated steelhead IP and impervious surface values. Various mathematical expressions could be used if a single numerical output is preferred for ranking purposes. These range from a simple arithmetical formula to a more complex scoring matrix that bins or weights one or both values.

There is some logic in discretizing, or ‘binning’, the intrinsic potential and impervious surface values into a limited number of classes. Intrinsic potential index values have been classified in different ways in various reports. Studies using the Burnett et al. (2007) habitat suitability curves have applied thresholds of ‘high quality’ steelhead rearing habitat at index values of 0.70, 0.75, and 0.80 (Burnett, Reeves, Miller, Clarke, Christiansen, & Vance-Borland, 2003; Burnett et al., 2007; Bjorkstedt et al., 2005). Cutoffs that demarcate the IP index values into categories of high, medium, and low are useful for a visual display of the information, e.g., in the creation of geospatial products, as it allows end users to quickly identify stream reaches that have the highest potential for usable habitat. However, these breakpoints have not been tested using a sophisticated statistical analysis that relates fish use to steelhead IP values (Burnett, email correspondence Oct 26, 2015). Similarly, the data presented in the results of many impervious surface studies is often categorized based on an interpretation of the severity of impacts to aquatic systems (Schueler, 2003). However, depending on the methods employed, characteristics of the study area, indicators of aquatic condition, and other factors, the results vary and there is no universal agreement in the optimal division of the range of impervious surface values.

Weighting one of the outputs is an easy way to emphasize the importance of one variable over the other. The use of coefficients provides a common method of weighting a variable. However, due to the absence of information relating intrinsic potential to impervious surfaces, weighting one of the variables based on its significance would be completely subjective.

In the absence of unanimity or empirical support for biological breakpoints, the integration of the two variables is based on the actual calculated outputs. This approach prevents the introduction of additional assumptions and helps discern the area-specific habitat conditions between each HUC 10, i.e., the relative IP density and impervious surface values.

RESULTS

The calculated steelhead IP density (before normalization) and impervious surface percentage values are tabulated for each of the 92 HUC 10s (Table 2, p.36). The values for impervious surface area, HUC area, and IP-weighted stream length are in Appendix A.

Table 2. HUC 10 Steelhead IP Density and Impervious Surface Scores. HUC ID corresponds with Figure 5.

HUC ID	HUC 10 Name	IP Density (x 10^4)	Imp. Surf. (%)	HUC ID	HUC 10 Name	IP Density (x 10^4)	Imp. Surf. (%)
1	Point Roberts-Frontal Strait of Georgia	0.81	8.34	47	Dungeness River	1.30	1.28
2*	Middle Chilliwack River	UNK	0.02	48	Elwha River	1.45	0.09
3*	Lower Chilliwack River	UNK	2.20	49	North Fork Skykomish River	1.37	0.11
4*	Upper Chilliwack River	UNK	0.00	50	Woods Creek-Skykomish River	4.14	2.06
5	California Creek-Frontal Semiahmoo Bay	3.89	5.63	51	Wallace River-Skykomish River	3.11	1.20
6	Lower North Fork Nooksack River	3.35	0.45	52	Little Quillcene River-Frontal Hood Canal	2.13	0.51
7*	Three Fools Creek-Lightning Creek	0.00	0.00	53	Big Quilcene River	0.83	0.17
8	Upper North Fork Nooksack River	1.07	0.26	54	Beckler River	1.61	0.48
9	Nooksack River	4.27	4.22	55	Middle Sammamish River	4.08	21.84
10*	Ross Lake-Skagit River	0.00	0.00	56	Dosewallips River	0.68	0.06
11	Middle Fork Nooksack River	2.19	0.12	57	Lower Snoqualmie River	4.92	2.98
12	Baker River	0.99	0.17	58	Tolt River	2.40	0.39
13	Whatcom Creek-Frontal Bellingham Bay	2.07	7.02	59	South Fork Skykomish River	2.07	0.34
14*	Ruby Creek	0.00	0.27	60	Duckabush River	0.83	0.08
15	South Fork Nooksack River	2.64	0.25	61	Tye River	0.60	0.39
16	Orcas Island	0.71	1.57	62	Lunds Gulch-Frontal Puget Sound	2.88	29.42
17	Gorge Lake-Skagit River	1.26	0.12	63	Lower Sammamish River	2.55	27.41
18	Diobsud Creek-Skagit River	1.61	0.14	64*	North Fork Snoqualmie River	0.00	0.53
19	Bellingham Bay Islands	0.23	0.86	65	Jefferson Creek-Hamma Hamma River	0.25	0.09
20	Samish River	4.62	2.19	66	Upper Snoqualmie River	3.13	2.19
21	San Juan Island	1.72	2.73	67	Tahuya River-Frontal Hood Canal	4.34	1.92
22	Lopez Island	0.65	1.72	68	Ollala Valley-Frontal Puget Sound	3.59	8.66
23	Finney Creek-Skagit River	5.04	0.71	69	Lake Sammamish	3.99	10.10
24	Illabot Creek-Skagit River	2.88	0.40	70	Lilliwaup Creek-Frontal Hood Canal	1.78	0.41
25	Telegraph Slough-Frontal Padilla Bay	3.81	9.53	71*	Middle Fork Snoqualmie River	0.00	0.13
26	Cascade River	1.18	0.15	72	North Fork Skokomish River-Skokomish River	3.47	0.31
27	Skagit River-Frontal Skagit Bay	6.50	5.44	73*	South Fork Snoqualmie River	0.00	2.38
28	North Fork Stillaguamish River	3.27	0.33	74	South Fork Skokomish River	3.29	0.21
29	Lower Suiattle River	1.76	0.09	75	Anderson Island-Hartstene Island	1.75	3.19
30	Lower Sauk River	2.57	0.52	76	Cedar River	3.96	4.19
31	Stillaguamish River	4.22	3.47	77	Lower Green River	4.29	20.24
32	Upper Suiattle River	1.46	0.00	78	Middle Green River	3.60	0.54
33	Pysht River-Frontal Strait of Juan De Fuca	4.66	0.28	79	Goldsborough Creek-Frontal Puget Sound	4.76	1.93
34	Whidbey Island	1.21	6.17	80	Upper Green River	2.24	0.26
35	Salt Creek-Frontal Strait of Juan De Fuca	3.33	0.54	81	Lower Puyallup River	3.65	23.11
36	South Fork Stillaguamish River	4.18	0.59	82	Lower White River	3.03	5.04
37	Lyre River-Frontal Strait of Juan De Fuca	3.97	0.64	83	Chambers Creek-Frontal Puget Sound	3.57	27.39
38	Upper Sauk River	1.28	0.05	84	McLane Creek-Frontal Puget Sound	2.79	10.82
39	Lyre River	0.73	0.15	85	Carbon River	2.09	1.16
40	Morse Creek-Frontal Port Angeles Harbor	2.18	3.98	86	Upper White River	2.13	0.20
41	Jimmycomelately Creek-Sequim Bay	1.55	6.10	87	Lower Nisqually River-Frontal Puget Sound	3.51	3.80
42	Pilchuck River	5.35	3.94	88	Lower Deschutes River	4.06	9.83
43	Snow Creek-Frontal Discovery Bay	1.79	1.74	89	Upper Puyallup River	3.20	1.22
44	Chimacum Creek-Frontal Port Ludlow	2.29	3.50	90	Middle Nisqually River	3.26	0.80
45	Quilceda Creek-Frontal Possession Sound	5.25	13.69	91	Upper Deschutes River	2.44	0.58
46	Sultan River	3.23	0.32	92*	Upper Nisqually River	0.00	0.27

*not included in matrix (Figure 7, p.38); see *HUC 10s Omitted from Matrix* subsection (pp.39-40)
UNK = unknown

Intrinsic Potential x Impervious Surface Matrix

To provide a graphical representation of the relative scores in Table 2, the IP density and impervious surface values were divided into quartiles and organized in a matrix for 82 of the HUC 10s (Figure 7, p.38); the 10 hydrologic units that were omitted from the matrix are described in the next subsection. The horizontal axis represents the normalized IP density and the vertical axis represents the impervious surface percentage. Each coordinate is labeled by its HUC ID, provided in Table 2.

The matrix (Figure 7, p.38) serves as a decision support tool that is easy to understand and explain during the review of the 82 qualified Puget Sound HUC 10s. The bottom right cell of the matrix represents the highest relative steelhead IP density and the lowest percentage of impervious surfaces. This configuration of the data allows users to visualize the influence of each habitat indicator on an individual HUC 10's final position in the matrix. It also facilitates adaptation to shifting priorities and objectives. From the bottom right cell, users may move horizontally or vertically to other cells if interested in deemphasizing one of the variables or applying a user-defined threshold to either or both variables. It is important to note that the empirical relationship of these two independently derived variables has not been validated, and must be examined at a finer spatial scale.

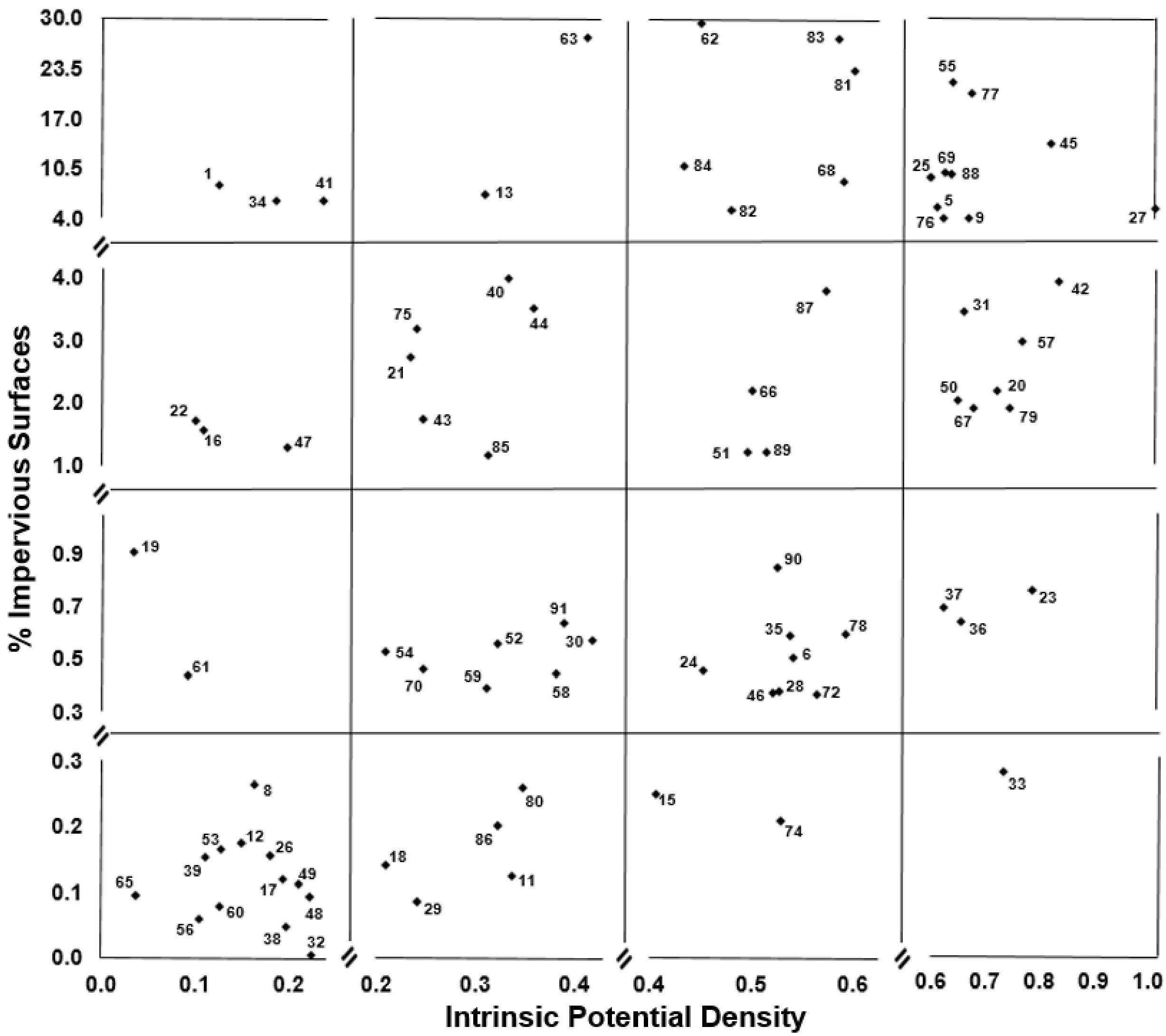

Figure 7. Puget Sound HUC 10 Intrinsic Potential x Impervious Surface Matrix. This figure depicts the relative HUC 10 IP Density and Impervious Surface scores for 82 HUC 10s. HUC 10s are labeled by HUC ID (Table 2, p.36). IP Density (x-axis) is normalized 0 to 1. Axes are broken into quartiles at irregular intervals.

HUC 10s Omitted from Matrix

One of the goals of this analysis is to provide a decision support tool that aligns with the duties and objectives of the FBRB, as described in RCW c 77.95 § 160 (2014). During the course of the analysis, it was determined that 10 of the 92 HUC 10s had major conflicts with the fundamental principles of the legislation. Consequently, these HUC 10s were omitted from the matrix (Figure 7, p.38) for the reasons described in the following paragraphs.

In this assessment, natural barriers without fishways were not assumed to provide future fish passage conditions. A natural barrier without a fishway precludes anadromous access. The duty of the FBRB is to prioritize human-made impediments to anadromous fish passage (RCW c 77.95 § 160, 2014). Therefore, the North, Middle, and South Fork Snoqualmie River HUC 10s were omitted due to a natural barrier, Snoqualmie Falls, located in the Upper Snoqualmie River HUC 10 that blocks all upstream migration to these three subwatersheds.

The Skagit River Hydroelectric Project (Skagit Hydro Project) consists of a series of three major dams in the upper Skagit River watershed that do not have fish passage facilities. Manmade barriers, e.g., dams, were not reviewed in the IP analysis based on the assumption that fish passage will be provided at these structures in the future. However, historical records indicate that a natural barrier existed in the vicinity of the most downstream of these Skagit dams before construction, and therefore fish passage has never been required through the Skagit Hydro Project (Smith & Anderson, 1921). With consideration of this historic natural barrier and an absence of any documented anadromous fish use above the Skagit Hydro Project area, the Ross Lake-Skagit River, Three Fools Creek-Lightning Creek, and the Ruby Creek HUC 10s upstream of the Skagit Hydro Project were omitted.

Similar to the Skagit Hydro Project, the Nisqually River Project includes two major dams that were constructed just upstream of a natural barrier on the Nisqually River. These dams were also not required to provide fish passage due to the historic presence of a natural barrier that is widely believed to have blocked the Upper Nisqually River (Kerwin 1999). In 1997, the dams were relicensed without fish passage after consultations between the Nisqually Tribe and state and federal resource agencies (Low Impact Hydropower Institute, n.d.). With no known historical records of anadromous species use above the most downstream Nisqually dam, the Upper Nisqually River HUC 10 was also omitted.

Three of the 92 HUC 10s contain streams that only flow northward into Canada: Lower, Middle, and Upper Chilliwack River. The legislation requires that those barriers located furthest downstream in a system must be corrected first (RCW c 77.95 § 160 & 180, 2014). The Chilliwack HUCs may contain manmade barriers in the lower reaches flowing through Canada and therefore it may be difficult to adhere to this principle and the FBRB is not likely to spend Washington State funds to correct barriers outside of the state. Additionally, the natural point barrier dataset that was used to adjust the modeled stream length in the intrinsic potential analysis was limited to barrier locations in Washington State, making it challenging to determine if any natural barriers existed downstream of the international border. Therefore, the Lower, Middle, and Upper Chilliwack HUC 10s were omitted.

DISCUSSION

A landscape-scale assessment of the current and potential salmon and steelhead habitat conditions of Puget Sound watersheds is fundamental to the development of a regional fish passage restoration strategy. The methods described in this analysis use two key evaluation criteria to produce a decision support tool that is useful for understanding the relative habitat conditions of Puget Sound HUC 10s from a fish passage restoration perspective. The IP analysis reflects historic and predicts potential conditions as a result of the applied stream attributes that are minimally affected by anthropogenic disturbances, such as urban development. However, the impervious surface land cover analysis reflects anthropogenic disturbances and helps balance the use of the IP model. The combination of these habitat indicators is particularly useful when there is a limited number of biological datasets that are complete throughout an entire region.

HUC Boundary Delineation

The spatial structure of HUC 10s and instream barriers must be assessed to ensure compliance with the legislative requirement of prioritizing the correction of barriers located furthest downstream (RCW c 77.95 § 180, 2014). A standard hydrologic unit boundary is delineated by starting at a designated outlet, i.e., the point on a single stream channel that drains an area, continuing to the highest elevation of land that divides the direction of water flow, and connecting back to the designated outlet where it crosses perpendicular to the stream channel (USGS, 2013). Reservoirs and natural lakes are delineated to avoid interruption of the natural drainage network (USGS, 2013).

The PSR also has several coastal streams that form nonstandard hydrologic units. These frontal HUC 10s may encompass several adjacent systems that are not hydrologically connected and drain to individual points along the coastline. Some islands in the PSR are large enough to be considered individual HUC 10s (Figure 5, p.27).

The federal standard for delineating hydrologic units creates spatial boundaries that typically encompass entire subwatersheds. Therefore, adjacent HUC 10s are generally only connected by a major waterway: the mainstem of a large river. Due to the volumetric flow rates of the mainstem rivers that transect hydrologic units in the PSR, it is unlikely that a manmade barrier, other than a major dam, would impede migration between HUC 10s. It was not within the scope of this project to determine the variable timing and conditions of fish passage facilities at dams, including trap and haul operations, fish ladders, and other factors that contribute to the degree of passability. Therefore, any potential manmade barriers that may exist on a mainstem river need to be reviewed to ensure access to a HUC 10 that flows through another HUC 10 before reaching the marine shoreline.

While HUC boundaries are typically created from topographic and hydrologic features, nine PSR HUC 10s have a portion of the HUC boundary defined by the international border with Canada. Of these, as previously described, the three Chilliwack HUC 10s only contain streams that flow northward and were consequently removed from the matrix. Ross Lake and Three Fools-Lightning Creek HUC 10s also have an international border and were removed from the matrix due to a historic downstream natural barrier.

The other four HUC 10s that are partially delineated by the international border are Point Roberts – Frontal Strait of Georgia, California Creek – Frontal Semiahmoo Bay, Lower North Fork Nooksack River, and Nooksack River HUC 10. All four of these contained modeled streams that are the uppermost headwaters of small tributary streams that flow northward into Canada; these headwater stream reaches that incidentally extend into Washington State were removed from the IP calculations. The Nooksack River HUC 10 is the only one of these four with streams that originates in Canada and flow southward into Washington State; one hundred twenty-seven square kilometers of the Nooksack watershed is in Canada (NWIFC, 2012).

Application of the Matrix at a Watershed Scale

As described in the previous subsection, some larger watersheds may contain multiple HUC 10s. Within those larger systems, in the absence of a barrier on the mainstem, migratory fish can move freely between HUC 10s. Therefore, a review of the intrinsic potential and impervious surface scores of adjacent, connected HUCs can provide a more complete watershed-scale assessment of the habitat conditions throughout a watershed of interest. Figure 8 provides a color-coded reference for each axis of the matrix that relates to the symbology used in Figures 9 and 10. Figures 9 and 10 use the Green-Duwamish River Watershed as an example of three HUC 10s that are hydrologically connected and may be reviewed at the larger watershed scale.

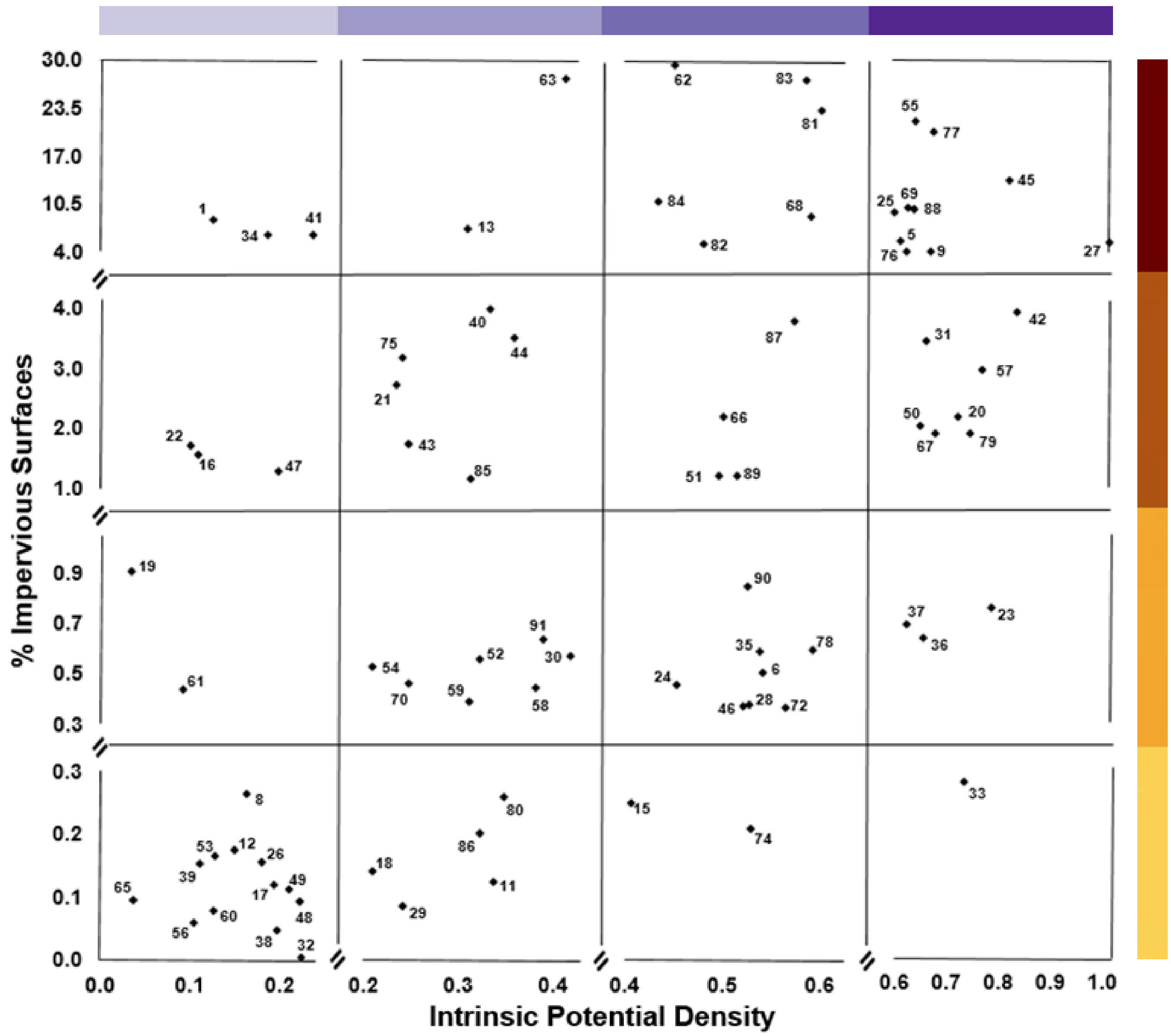

Figure 8. Puget Sound Matrix for Reviewing HUC 10s at a Watershed-Scale. Each quartile of each axis is color-coded to create a symbology reference for Figures 9 and 10.

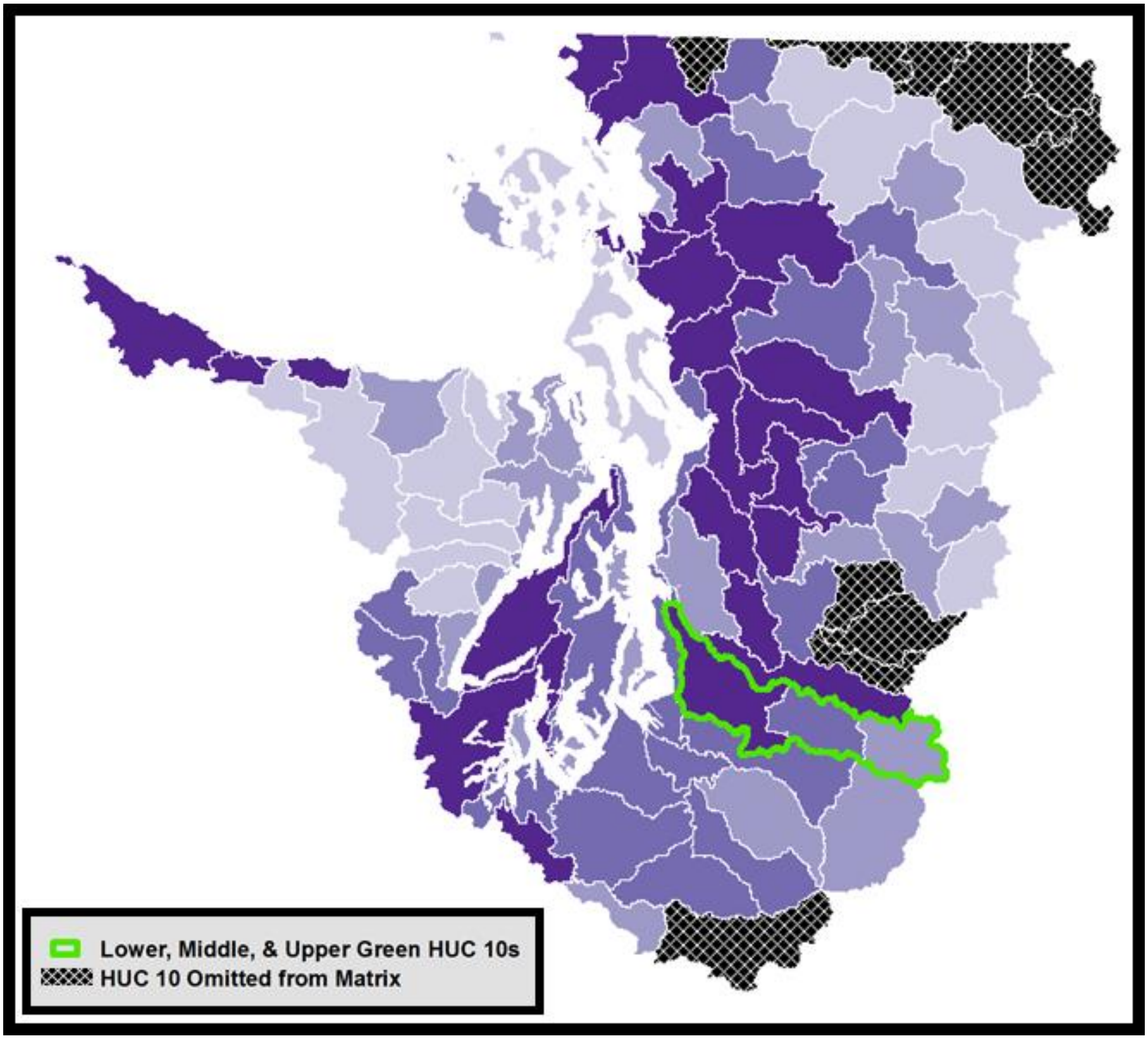

Figure 9. Color-Coded Intrinsic Potential Scores of Puget Sound HUC 10s (Zweifel, 2016a). Refer to Figure 8 for the symbology of this figure. The Green-Duwamish River Watershed is an example of a watershed containing multiple HUC 10s.

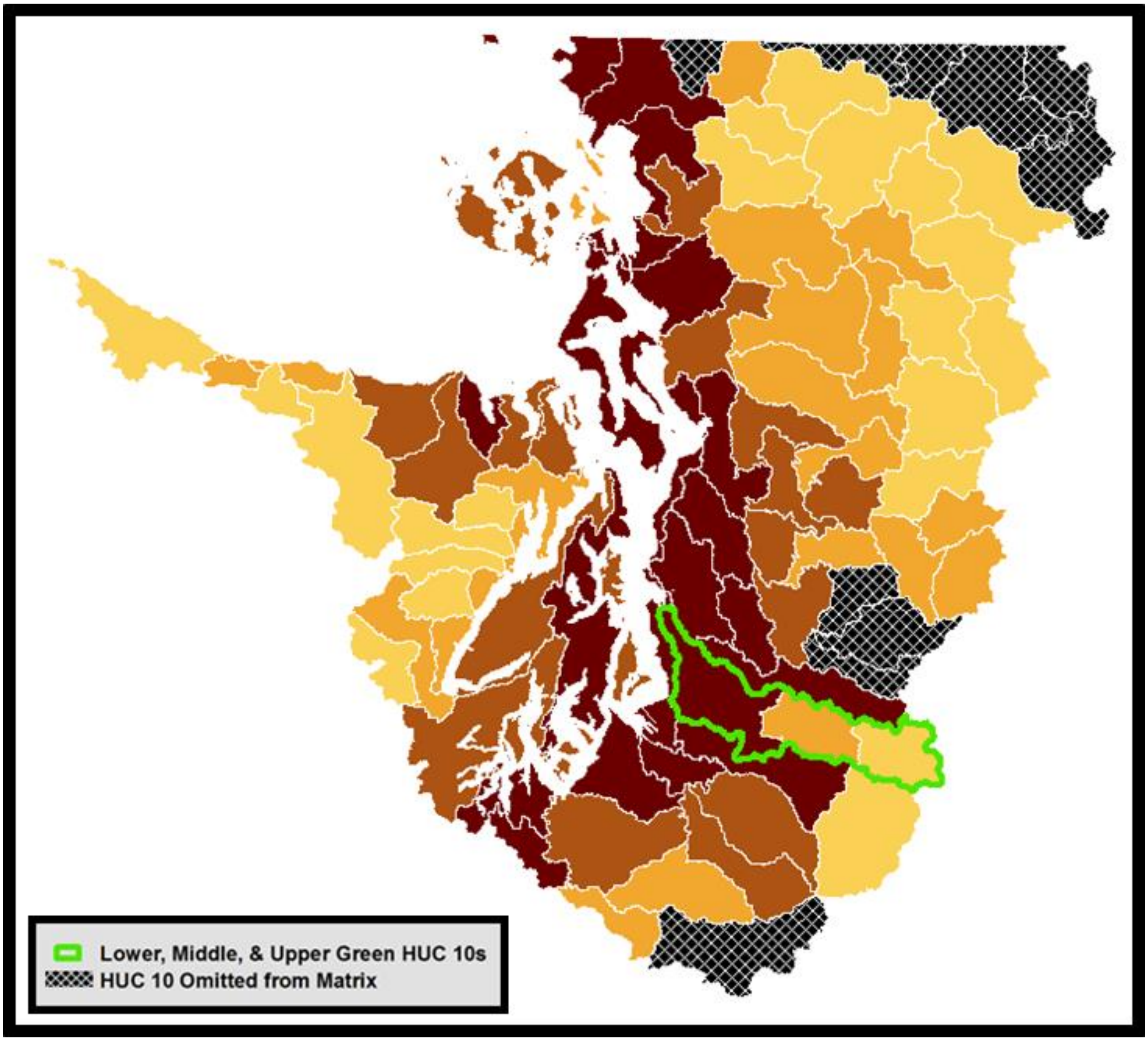

Figure 10. Color-Coded Impervious Surface Scores of Puget Sound HUC 10s (Zweifel, 2016b). Refer to Figure 8 for the symbology of this figure. The Green-Duwamish River Watershed is an example of a watershed containing multiple HUC 10s.

Intrinsic Potential for Steelhead Rearing Habitat

The steelhead rearing IP values were created from the published 2007 Burnett et al. habitat suitability curves (Figure 4, p.21) and spatial data analysis tools available in NetMap, a landscape analysis computational platform that contains a geospatial data structure for use in a GIS to support natural resource management planning (TerrainWorks, 2016). NetMap was used to compute topographic and watershed attributes over a 10-meter DEM traced channel network to create 100-meter stream segments with a calculated steelhead IP score.

A final IP score for a stream reach is created by taking the geometric mean of the product of the un-weighted index scores of three stream attributes: mean annual flow, calibrated valley-width index, and channel gradient (Burnett et al., 2007). This approach works on the assumption that each of these stream attributes are approximately equal in importance and the one with the lowest index score has the greatest influence on the final IP score for that stream reach (Burnett et al., 2007).

Juvenile steelhead are able to ascend steep stream gradients and have been found rearing in reaches with a 16% gradient (Bryant, Zymonas, & Wright, 2004). However, they generally rear in the lower gradient areas of those high gradient stream reaches (Engle, 2002). As shown in Figure 4, the gradient index score remains constant for reaches above 7%, and is 'zero' for reaches with a gradient above 10%.

Juvenile steelhead tend to use stream reaches with hill slopes that constrict the channel and limit interaction with the floodplain (Hicks, 1990; Reeves, Bisson, & Dambacher, 1998). This preference for confined channels is reflected in the calibrated valley-width index (Figure 4, p.21).

Juveniles can rear in a wide range of flows, from large mainstem rivers up to small headwater tributaries (Meehan & Bjornn, 1991). With the exception of those stream reaches with very little to no mean annual flow, the mean annual flow index is fairly high across a very large range of flows (Figure 4, p.21). However, there has been considerable deliberation on the actual productivity of large mainstem rivers, over 50 meters wide, as much of the channel area is typically not used by juveniles in the absence of instream cover (PSSTRT, 2013b).

Impervious Surface Land Cover

As expected, the HUC 10s with the most impervious surface land cover were those in the Puget Sound lowlands. These areas have the highest rates of urban development in the PSR. The intensity of development can be viewed spatially in Figure 11 and referenced to the location of Puget Sound cities in Figure 12.

Studies in the Puget Sound have shown that increases in imperviousness correspond with increases in road density (City of Olympia, 1994; May et al., 1997). A high road density typically indicates the presence of many transportation-related water crossing structures, and therefore could indicate a high fish barrier density. In consideration of the density of barriers and stream conditions of urban watersheds, a cost-benefit analysis may be used to help decide whether to restore highly disturbed habitat or protect less disturbed habitat. The relative priority of restoration and protection actions often depends on cost and the length of time that is required to realize results.

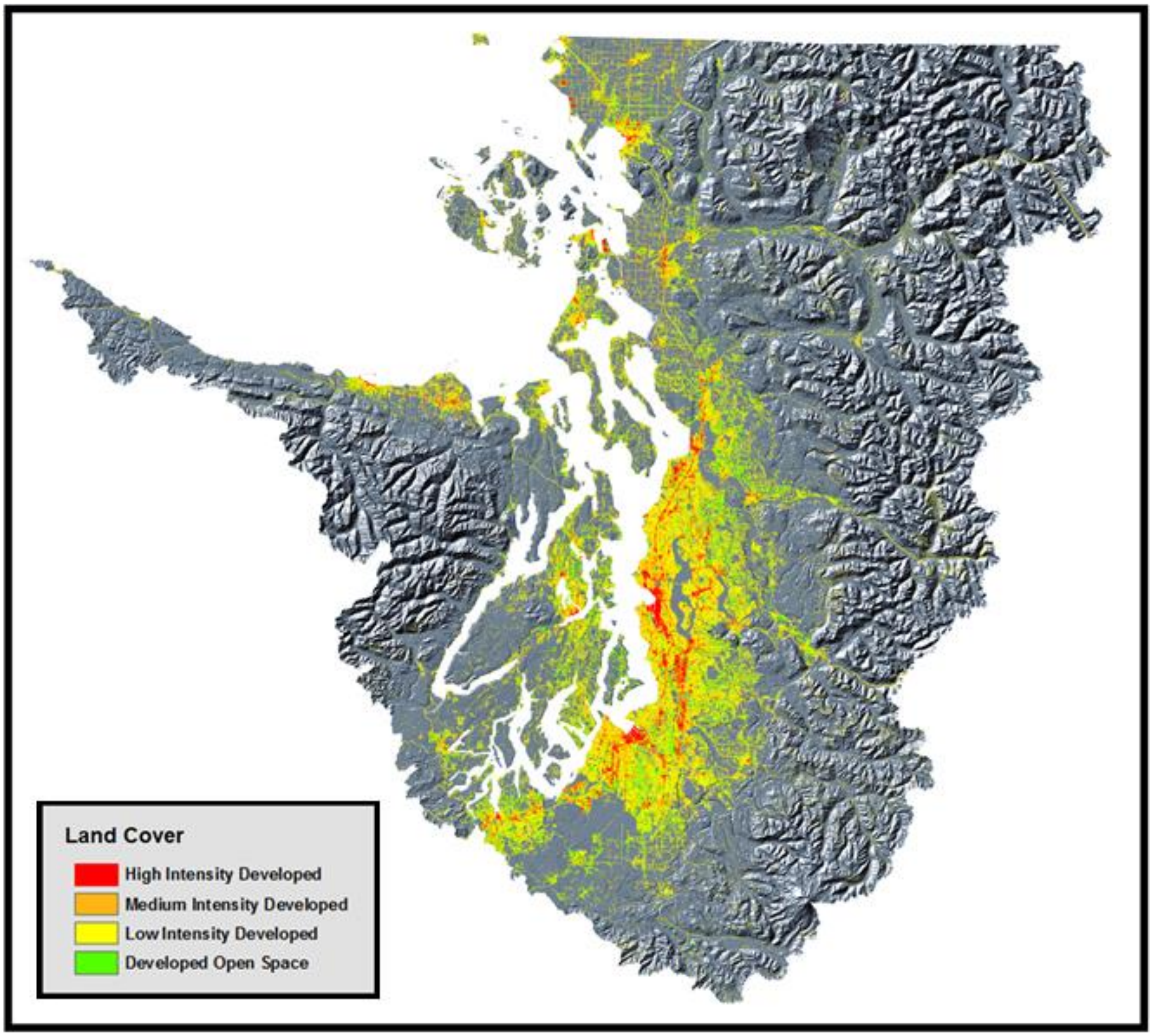

Figure 11. Puget Sound Region Impervious Surfaces (Zweifel, 2015c)

Distinct Population Segments

A Distinct Population Segment (DPS), as determined by the USFWS, is a discrete population of a species that is considered biologically and ecologically significant (Fay & Nammack, 1996). A DPS is partially defined by the geographic boundaries within the range of a subspecies (Fay & Nammack, 1996). Within that range, the designation is based on a review of physiological, morphological, genetic, and several other factors for the purpose of managing the protection and conservation of a population and its habitats (Fay & Nammack, 1996). This combination of geographic and biological factors creates a taxonomic descriptor, a DPS, which represents the smallest unit that may be protected by the ESA (Fay & Nammack, 1996).

The PSR, primarily an administrative boundary, extends westward beyond the Elwha River - the geographic boundary of ESA-protected Puget Sound steelhead populations (NMFS, 2010). This PSR assessment included 4 HUC 10s that are actually part of the non ESA-listed Olympic Peninsula steelhead DPS: Pysht River-Frontal Strait of Juan De Fuca, Salt Creek-Frontal Strait of Juan De Fuca, Lyre River-Frontal Strait of Juan De Fuca, and Lyre River HUC 10. The Pysht River-Frontal Strait of Juan De Fuca HUC 10 was the only of all 82 qualified HUC 10s to score in the top 25% of both impervious surface (low impervious surface land cover percentage) and IP density (high IP density value) categories. The Lyre River-Frontal Strait of Juan De Fuca was also in the top 25% for IP density. The steelhead DPS is an important factor if the goal is to focus on ESA-listed steelhead only.

HUC 10s Without Documented Reproducing Salmonid Populations

At the time of this assessment, four of the 82 qualified HUC 10s had no record of anadromous fish use in the SWIFD database: Point Roberts-Frontal Strait of Georgia, San Juan Island, Lopez Island, and Bellingham Bay Islands. Although these HUC 10s do not have known naturally reproducing salmonid populations, they do provide streams that can be used for rearing by juvenile salmonids that migrate from other watersheds. None of these four HUC 10s have a particularly favorable position in the matrix.

Non Transportation-Related Manmade Barriers

The FBRB may consider funding the correction of high priority manmade barriers that are not transportation-related, e.g., dams, flumes, weirs, etc. The decision to pursue the correction of these other barrier types will likely be based on a number of considerations including feasibility and cost-benefit analyses, compliance with the principles of the legislation, and other requisite criteria to be determined by the FBRB.

The assessment presented in this analysis assumes that all manmade barriers to anadromous migration, including major dams, will eventually provide fish passage. Therefore, in the absence of a historic natural barrier, IP modeled stream reaches upstream of manmade barriers were included in the calculations. Users of the matrix need to examine the location and fish passage conditions of potential manmade barriers within or downstream of any HUC 10 that is being considered for fish passage restoration to ensure access to that HUC 10. For example, there is a well-known diversion dam on the mainstem of the Middle Fork Nooksack River HUC 10 that operates to supplement the City of Bellingham's water supply. This structure currently does not have fish passage facilities. The potential restoration of fish passage at this diversion dam would need to be reviewed by the FBRB for feasibility and funding eligibility if the Middle Fork Nooksack HUC 10 or any connected subwatershed is being discussed during the decision-making process. If it is discovered that there are existing plans to provide fish passage at this dam in the near future, or a similar structure in another system, then there may be an opportunity to coordinate efforts and maximize these planned investments.

Limitations

There are always uncertainties and inherent limitations when using models and a GIS approach to addressing natural resource management issues. While the best available complete and consistent datasets were applied in the watershed assessments, the primary limitations to the results were those imposed by the datasets themselves. There are functional limitations in data that are produced from remote sensing techniques and these are best described by the individual data sources.

Natural barriers

There is a difference in the steelhead IP assessment results of this analysis, compared to those from similar studies, primarily due to the evaluation methods of natural barriers. The gradient barriers included in this analysis were derived from 10 meter DEMs. However, natural point barriers, i.e., waterfalls, were only considered if they were field verified as total barriers. Burnett et al. (2007) also only considered natural point barriers that were field verified. This method does introduce a bias against streams that have more physical survey information. This approach differs from the IP assessments that also incorporate datasets with natural point barriers and cascade barriers digitized from WRIA maps. It has been my professional experience that these digitized natural barrier locations are highly inaccurate upon field review. The significance of the effects of using different natural barrier datasets depends on the location and accuracy of the digitized barriers in the stream network.

As described in the *Data and Methods* section (pp.25-35), over 1,200 natural point barriers from eight data sources were reviewed. To help validate passage conditions at these points, the SWIFD database was used to review the spatial distribution of documented anadromous fish use. The natural barrier data and the documented fish distribution had several conflicts, i.e., there were streams that contained documented anadromous use upstream of natural point barriers that were categorized as total blockages. Therefore, I developed a hierarchy of evidence to assist with the determination of data integrity when there were disagreements between anadromous fish distribution and presence of a natural barrier.

Natural point barriers that were field verified by WDFW staff with photos and measurements were always assumed to be accurate. I reviewed limiting factors reports, published habitat assessments, and similar documents from trusted sources including tribes, WDFW, and various watershed restoration groups; if these had photos or/and descriptions consistent with the point record, these were assumed to be accurate. If supporting documentation for the natural barrier could not be located and the SWIFD database had a record of documented anadromous use extending upstream, then other resources such as recovery plans and other credible publications were reviewed to determine if the natural barrier information was accurate. If a natural point barrier was determined to not be a total barrier, then it was completely disregarded and the IP calculations continued to the next natural point barrier, gradient barrier, or end of fish use.

One of the likely causes of discrepancies between natural point barriers and anadromous distribution is the inconsistency and incompleteness in the documentation for both datasets. For example, the SWIFD database currently includes records of documented fall Chinook extending a very long distance upstream of the 3 Upper Skagit River dams that have no fish passage facilities. Although the SWIFD database is maintained by the WDFW and NWIFC, both the WDFW and tribes have agreed with the 1921 survey that found no historical record of anadromous fish use above the current location of the most downstream dam (Smith & Anderson, 1921).

Another example supporting the need to carefully review natural barriers involves WDFW's fish passage database record of Granite Falls on the South Fork Stillaguamish River. This waterfall was appended to the database as a total barrier without a fishway in 2004. However, it is widely known that there is a fish ladder, constructed in 1954, that allows upstream migration to several miles of habitat above Granite Falls.

Natural barriers are species-specific and the blocked species information is missing from most of the feature records used in this analysis. A natural feature that is a complete barrier to the weaker swimming and leaping chum salmon is not necessarily a complete barrier to the stronger swimming and leaping steelhead, however most of the records did not contain information about which species were blocked. Further investigation was required, as previously described, if these records were also missing a measurement of the vertical height of the natural point barrier.

As these data gaps are filled and as better natural barrier information becomes available, the IP assessment results presented in this analysis must be reviewed and possibly recalculated.

Data resolution

It is highly recommended that the impervious surface and IP outputs be recalculated as more accurate, higher resolution data becomes available. The steelhead IP indices were derived from a 10-meter DEM. Elevation rasters produced from higher resolution Light Detection and Ranging (LiDAR) would provide better accuracy. Higher resolution DEMs are not readily available for the entire PSR, but could be obtained through multiple sources. Data from multiple sources would need to be checked for consistency, which was not within the scope of this analysis.

The 2011 C-CAP dataset includes Landsat data that is captured at a 30-meter resolution (NOAA, 2012). Dr. Kenneth Pierce (2011) conducted a feasibility study, referred to as the High Resolution Change Detection Project, to assess land cover changes in three Puget Sound WRIAs using 1-meter resolution. The use of the higher resolution imagery resulted in land cover class changes of 0.057 - 0.105% from undeveloped classes to developed classes within the three WRIAs; these were the results of omission errors from the use of medium resolution imagery (Pierce, 2011). A higher resolution dataset would allow a more accurate estimate of impervious surfaces. However, a comprehensive analysis of land cover in the PSR at a 1-meter resolution has not yet been completed.

This assessment uses impervious surface estimates from 2011 (Figure 11, p.49). The amount of impervious surface areas is expected to increase with population growth and urbanization. From 2006 to 2011, there was an increase of 9,457 acres of impervious surface land cover in the PSR (NOAA, 2012). The 2016 C-CAP data is expected to be available in 1-3 years, allowing this assessment to be repeated to reflect post-2011 development.

Further Research Needs

In addition to recalculating the intrinsic potential and impervious surface values as new data becomes available, further research may be undertaken to support the results of this analysis. As described in the *Literature Review* section (pp.8-25), the available biological datasets in the PSR contain many data gaps and inconsistencies that make them difficult to use in a comparative analysis of watersheds. Furthermore, the actual distribution of salmon and steelhead throughout the PSR is directly affected by the presence of manmade barriers.

A comparison of barrier density and steelhead population trends within a watershed could prove useful for estimating the impacts of barriers on Puget Sound steelhead. The available steelhead occurrence data would likely need to be standardized to create population estimates across multiple years for a meaningful trend analysis throughout Puget Sound watersheds. If a relationship between steelhead population trends and barrier density is discovered, that information may help discern thresholds for the intrinsic potential and impervious surface values, i.e., score breaks that represent positive, negative, or no correlation to population trends. This information would help further demonstrate how the matrix can and should be used.

OTHER CONSIDERATIONS

The limited availability of landscape-scale spatial datasets that have reasonable implications for fish passage restoration strategies contributed to the restriction of the watershed evaluations to a spatial analysis of just 2 indicators of current and potential habitat conditions for salmon and steelhead. Although the habitat assessment criteria are supported by peer-reviewed sources and expert opinion, the results will not be the determinant of which HUC 10s receive fish passage funding.

Using the impervious surface and IP matrix to narrow the list of priority HUC 10s facilitates the investigation of other important information within the geographically smaller focus areas. Some factors that may be considered include the status of other restoration projects, the number of recently completed barrier corrections, hatchery impacts, landowner willingness to provide fish passage, invasive species and other relevant information about environmental and human-landscape interactions that are often difficult to quantify.

In the following sections, I review the principles of the RCW that defined the duties of the FBRB and discuss the social, economic, political, and cultural considerations that are pertinent to the FBRB's mission. The selection of watersheds for fish passage barrier removal will involve these elements, and their interaction with conservation and human values that are immeasurable, to complete the conceptual framework for the implementation of a strategy that aligns with the intent of the legislation.

Principles of RCW Title 77 Chapter 95

The FBRB must develop and implement a statewide fish barrier removal strategy that adheres to the principles described in RCW c 77.95 § 180 (2014). Accordingly, the strategy must determine the appropriate pathways to prioritizing fish passage restoration opportunities that maximize habitat recovery. The RCW describes this framework through the formulation of a watershed-based approach that corrects barriers throughout whole streams, rather than continuing with traditional methods of prioritizing individual, isolated projects.

There is also much emphasis on facilitating coordination between government agencies and other entities in order to help reduce spending by all parties involved in the implementation of cost effective projects. Process efficiencies and improvements include streamlined permitting and assistance with engineering and technical services. The FBRB will also strive to capitalize on recent habitat recovery investments and leverage existing fish barrier removal programs.

Cultural Considerations

In the Pacific Northwest, salmon have a significant role in traditional and modern culture. Salmon are a cultural centerpiece to Native Americans, including those tribes who ceded much of the PSR to the federal government in exchange for protected fishing rights. As a symbol of cultural tradition and religious belief, salmon are often celebrated at tribal ceremonies.

The harvest of salmon and steelhead are of great economic importance to the Native Americans and the welfare of their tribes and communities. Cultural impacts can be defined as the effects that change the norms, values, and beliefs of a group and their society (National Marine Fisheries Service [NMFS], 1994). Indisputably, the decline of Puget Sound salmon and steelhead populations has had a tremendous impact on tribal culture and commercial fisheries.

The FBRB has tribal representation, per the requirements of membership and duties described in RCW c 77.95 § 160 (2014), with voting authority to help ensure FBRB recommendations to the legislature are aligned with tribal interests. These delegates serve treaty and non-treaty tribes throughout the state, including federally-recognized tribes with reservations within the PSR (Figure 12, p.60). Each Puget Sound tribe has ‘usual and accustomed harvest areas’ that represent their traditional fishing areas; in these areas, tribes have federally-protected rights to harvest salmon (NOAA, n.d.b). Barrier removals that have a high potential to directly contribute to salmon populations in these tribal areas may be given priority consideration by the FBRB for funding.

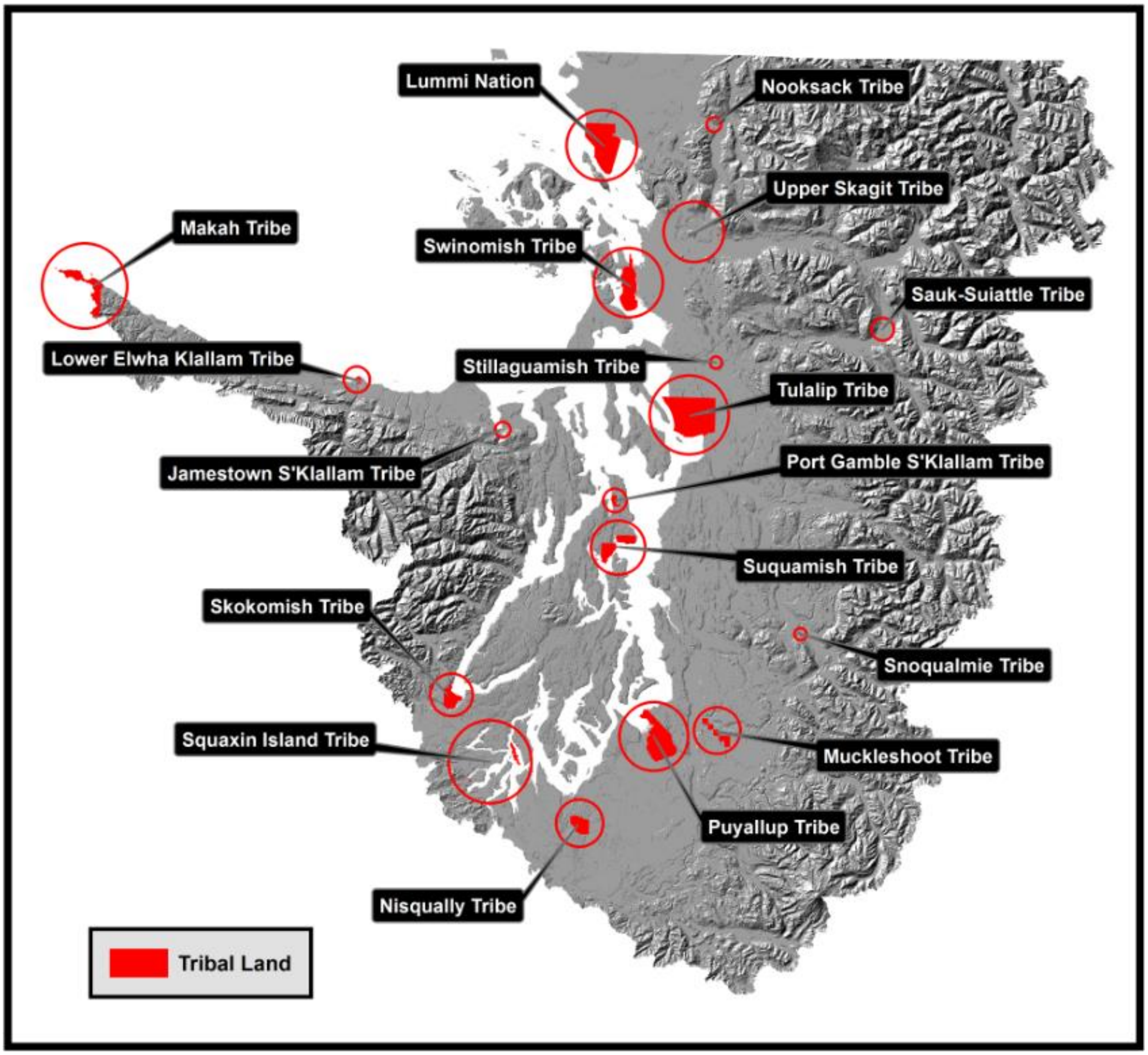

Figure 12. Puget Sound Region Tribes (Zweifel, 2015d)

Economic Importance

The economic importance of salmon and steelhead is vast. The most familiar economic impacts are those from the commercial and recreational fisheries. The NOAA Fisheries Economics and Social Analysis Division estimated that commercial salmon fisheries provided the Washington State seafood industry with over 28 million dollars in revenue and supported thousands of jobs in 2012 (NMFS, 2014). That same year, the state's recreational fishery generated over 494 million dollars in revenue and supported nearly 4,000 jobs for a combined income of over 183 million dollars (NMFS, 2014). Commercial and recreational fisheries are major economic drivers for coastal communities and the Puget Sound and NOAA economists interpret these reports as evidence of the importance of managing fisheries sustainably for the good of the environment and the economy (NMFS, 2014).

The economic drivers of these two fisheries differ as a result of their associated business transactions. The economics of commercial fisheries are based on multiple transactions occurring between the initial harvest by fishermen and the final consumption by the end user (Southwick Associates, 2013). Within this market, sales and purchases occur repeatedly through a chain of processors, wholesalers, distributors and vendors (Southwick Associates, 2013). The economics of recreational fishing, in contrast, are primarily driven by angler expenditures that are directly related to the recreational activity, e.g., the purchase of fishing gear and any travel expenses, including fuel and lodging (Southwick Associates, 2013). Although the transactions differ between these markets, many local businesses can benefit from the economic stimulation created by both commercial and recreational fishing operations.

At a smaller scale, the fish passage barrier removal projects that are selected for construction will help strengthen local economies through the creation of construction and environmental planning jobs. Project managers may also purchase goods and labor from local businesses, including construction-related materials and field equipment, traffic control supplies and services, and design work for the new water crossing and associated structures. A study conducted at the University of Oregon estimated that 1.52 local jobs are created for every $100,000 spent on fish passage restoration projects (Pincus & Moseley, 2010). It is evident that the economic importance of Puget Sound salmon and steelhead is extended to many different industries.

Social Factors

There are many social benefits that result from salmon and steelhead recovery efforts in the PSR. At the local level, habitat restoration projects frequently bring together special-purpose districts, private landowners, and citizen volunteers, which helps build a strong sense of community. In addition to these local partners, large-scale watershed-based restoration strategies often require the coordination of tribal, federal, state, and local governments to be successful. In addition, throughout the PSR, various salmon and watershed restoration and conservation groups are actively involved in salmon recovery activities at all levels. The coordinated efforts of these communities, agencies, and organizations help create partnerships that can provide new environmental education and recreation opportunities to local schools and families and bring in outside dollars to local communities.

The experience of joining in locally organized activities that contribute to fish and wildlife conservation provides many participants with a feeling of accomplishment. Restoration projects that improve fish passage conditions can very quickly create new salmon viewing opportunities, as it is common for salmonids to begin migrating through reconnected stream reaches to spawn and rear in the newly available habitat almost immediately after barrier removal. In the longer term, an improvement in spawning escapement and juvenile to adult survival would increase population abundance, which could support future recreational fishing opportunities.

Other societal benefits to replacing undersized transportation-related water crossing structures include improvements to public safety, local flood and erosion control, better water quality, and countless ecosystem services. The combination of all these factors provides significant social benefits to families and communities that overlap and extend beyond the economic benefits of salmon and steelhead recovery efforts.

Political Drivers

Urban development in response to population growth has created challenges to fish passage restoration in the PSR. The Puget Sound lowlands have the highest density of roadways and waterways in the state and is home to roughly 2/3 of the state's population (Washington State Office of Financial Management [OFM], 2015). This region also has the most rapid population growth in Washington State; from April 2014 to April 2015, there was an increase of over 70,000 people residing in the 12 counties bordering the Puget Sound shoreline (OFM, 2015). The Washington Legislature identified the need for coordinated and planned growth and passed the Growth Management Act (GMA) in 1990 (RCW c 36.70A, 2015). The GMA requires state and local governments to work together to strategically plan for sustainable growth. The resulting city and county-specific growth management plans address how the key elements listed in RCW c 36.70A § 070 (2010), including land use and transportation, will be managed in a way that supports environmental protection.

It can be financially challenging for rapidly growing cities and counties to meet new development needs and maintain existing infrastructure while also minimizing impacts to the environment. Even without providing fish passage, water crossing structures associated with public roadways can be costly to install and maintain. These crossings have a lifespan that can vary based on many factors such as the type, size, and material of the structure as well as the hydrologic characteristics of the stream. A culvert life-cycle cost model that calculates the estimated replacement costs, expected life span, and probability of structural failure due to potential climate change-related impacts, such as flooding, was presented in 2015 (Reagan, 2015). The output of the model can be used to assist local governments with their evaluation of the financial significance of proposed culvert replacement projects (Reagan, 2015). Reliable models that are able to assist with the prioritization of transportation projects based on culvert life cycle costs and fish passage requirements can provide a decision support tool that maximizes investments by improving local infrastructure and public safety, reducing annual maintenance costs, and restoring habitat and aquatic ecosystems. The use of these models and support tools also helps local governments be proactive in addressing barriers, which could lead to more flexible and strategic solutions. However, the effectiveness of these prioritization tools is often limited when the optimal solutions cannot be achieved due to insufficient funds.

It is now common for representatives of local governments to lobby for transportation improvement funds for projects that have the added benefit of restoring fish passage to support their funding request. Local governments are eligible to apply for funding to correct transportation-related fish passage barriers through grant programs administered by the Salmon Recovery Funding Board and the Transportation Improvement Board. However, these grant programs operate on a limited budget and can be very competitive. The FBRB grant program will help by providing a new funding source that can contribute some much-needed financial assistance.

As the FBRB begins funding projects that support a watershed-based fish passage restoration strategy, they will inevitably be selecting projects with variable ownership types, i.e., state, county, city, private, etc. In addition to selecting projects that provide the most benefit to salmon and steelhead, the FBRB will be working within the principle of the legislation that directs financial assistance to cities and counties with limited resources (RCW c 77.95 § 180, 2014). The PSR encompasses 114 cities across 12 counties (Figure 13, p.66).

Because the FBRB is comprised of a diverse group of representatives from multiple agencies and tribes, each serving individual organizations, members, and jurisdictions, attempting to evenly distribute funds and meet other program goals may introduce political conflicts to the decision-making process. To be successful, it will be important to ensure that the political drivers of the FBRB's barrier correction strategy are considered, but not misdirecting the actions necessary to meet the habitat restoration goals of the legislation.

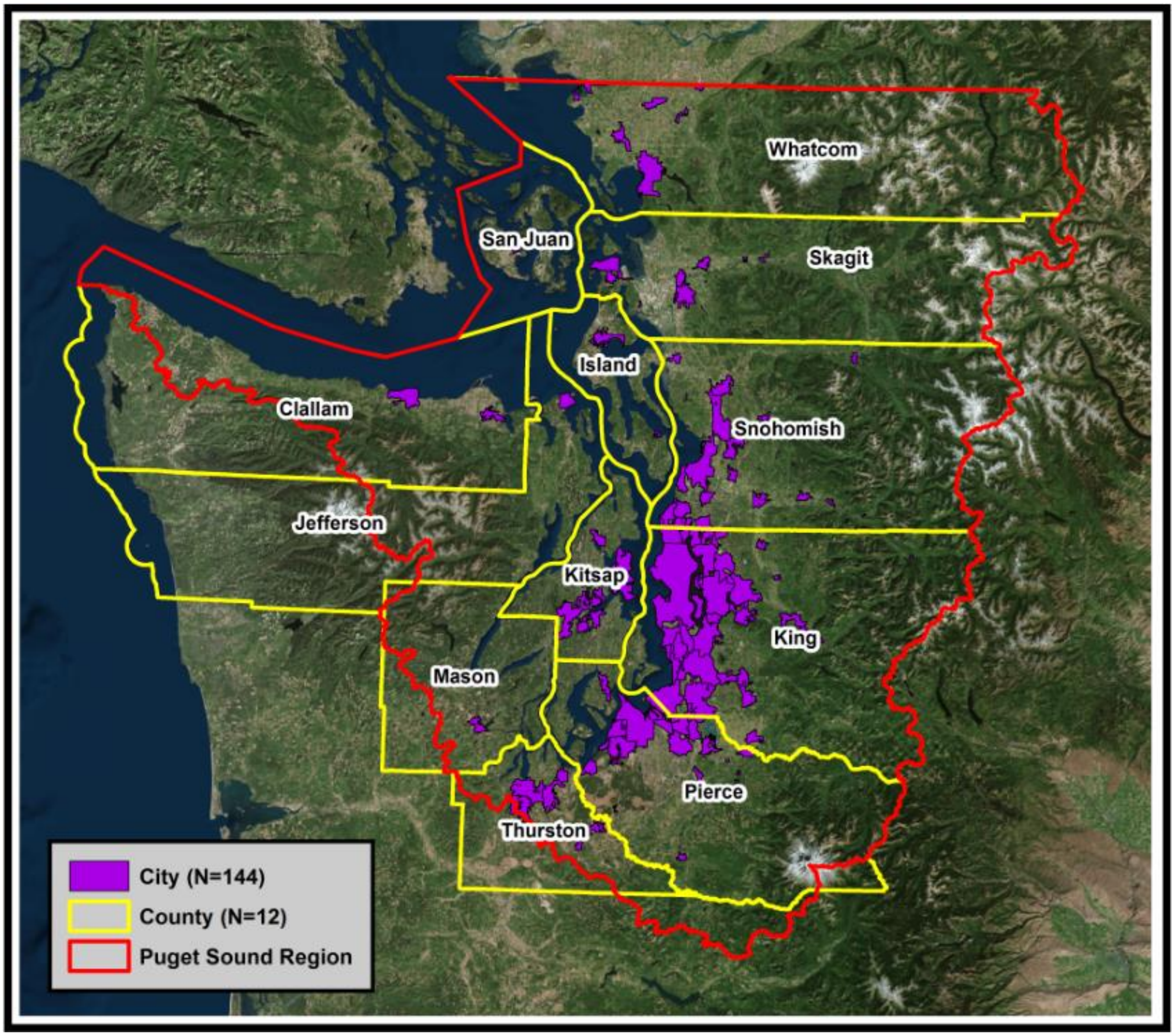

Figure 13. Puget Sound Cities and Counties (Zweifel, 2015e)

CONCLUSION

This analysis combines an assessment of aquatic habitat conditions with a discussion of the important cultural, economic, social, and political factors that will be considered during the selection of a Puget Sound watershed for fish passage restoration funding. The matrix (Figure 7, p.38) created by this assessment provides an objective analysis tool to contrast the relative current and potential salmon and steelhead habitat conditions of Puget Sound watersheds and can be used by the FBRB during the selection of a watershed. Although watershed boundaries are defined by topographic and hydrologic features, rather than political, tribal, or other administrative boundaries, the removal of political and institutional barriers will also be important to the successful implementation of a watershed-scale fish passage barrier removal program.

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Appendix A. Raw data tables

HUC 10 Code	HUC 10 Name	Total IP Meters	Tot. Imp. Surf.Area (m²)	Area of HUC 10 (m²)
1711001904	Anderson Island-Hartstene Island	47593.87	8668666.44	271337526.34
1711000507	Baker River	76032.61	1329785.01	771647550.34
1711000902	Beckler River	42046.17	1242789.75	261233164.27
1711000206	Bellingham Bay Islands	1784.91	655182.63	76459078.00
1711001806	Big Quilcene River	14744.63	292240.44	177091861.86
1711000202	California Creek-Frontal Semiahmoo Bay	90129.67	13036838.40	231741739.64
1711001401	Carbon River	123686.71	6884009.82	592964975.99
1711000506	Cascade River	56589.18	740447.91	479914603.65
1711001201	Cedar River	180706.92	19134025.56	456817259.04
1711001903	Chambers Creek-Frontal Puget Sound	153492.92	117771421.32	430011379.17
1711001908	Chimacum Creek-Frontal Port Ludlow	47692.59	7274028.96	207848557.47
1711000505	Diobsud Creek-Skagit River	55896.19	487486.62	347781670.49
1711001805	Dosewallips River	20330.68	179359.29	298725515.44
1711001804	Duckabush River	16388.49	154996.92	197928851.38
1711002003	Dungeness River	66609.04	6577621.02	514297326.44
1711002005	Elwha River	120740.08	754844.04	832808635.10
1711000701	Finney Creek-Skagit River	360366.85	5051358.00	715149351.27
1711001906	Goldsborough Creek-Frontal Puget Sound	414859.63	16798153.32	872322530.56
1711000504	Gorge Lake-Skagit River	79945.07	756010.89	632694597.48
1711000508	Illabot Creek-Skagit River	106154.00	1484523.54	367964401.55
1711001802	Jefferson Creek-Hamma Hamma River	5409.58	202954.14	217538423.54
1711002002	Jimmycomelately Creek-Sequim Bay	27308.09	10758841.83	176238304.39
1711001202	Lake Sammamish	104187.26	26387665.65	261353817.90
1711001803	Lilliwaup Creek-Frontal Hood Canal	35758.72	826020.27	200470377.07
1711001807	Little Quillcene River-Frontal Hood Canal	72694.97	1736644.50	341907917.63
1711000302	Lopez Island	6937.26	1819133.46	105955992.18
1711000103	Lower Chilliwack River*	0.00	4005096.57	182019646.77
1711001602	Lower Deschutes River	83884.71	20322690.84	206832715.78
1711001303	Lower Green River	250626.27	118125109.17	583610166.94
1711001503	Lower Nisqually River-Frontal Puget Sound	255997.89	27731478.06	729819706.65
1711000402	Lower North Fork Nooksack River	84451.79	1136727.72	252383108.69
1711001405	Lower Puyallup River	72583.10	45900196.38	198605186.77
1711001204	Lower Sammamish River	117381.17	126431926.92	461180912.25
1711000604	Lower Sauk River	99197.55	1994241.24	385793165.47
1711001006	Lower Snoqualmie River	120046.31	7261581.69	243806040.39
1711000603	Lower Suiattle River	72717.30	354006.45	414156015.16
1711001404	Lower White River	159826.56	26599431.87	528115838.54
1711001902	Lunds Gulch-Frontal Puget Sound	128461.15	131379781.32	446576572.83
1711002101	Lyre River	12623.02	265474.62	173850202.29
1711002102	Lyre River-Frontal Strait of Juan De Fuca	45067.90	729816.84	113601870.90
1711001905	McLane Creek-Frontal Puget Sound	77613.00	30103071.93	278329409.54
1711000102	Middle Chilliwack River*	0.00	46151.10	227703307.30
1711000403	Middle Fork Nooksack River	56489.76	318706.11	257724757.13
1711001002	Middle Fork Snoqualmie River*	0.00	595927.80	443054773.07
1711001302	Middle Green River	125890.91	1896966.63	349459453.08
1711001502	Middle Nisqually River	167592.38	4092298.29	513511497.04

Within the hydrologic unit's boundaries:
Total IP Meters is the sum of all stream segment lengths multiplied by their IP index value
Impervious Surface Area is the sum of all cell areas multiplied by their IC Coefficient (Figure 6)

*removed from matrix (Figure 7) for reasons described in Results section

HUC 10 Code	HUC 10 Name	Total IP Meters	Tot. Imp. Surf.Area (m²)	Area of HUC 10 (m²)
1711001203	Middle Sammamish River	149768.69	80105024.70	366823511.89
1711002004	Morse Creek-Frontal Port Angeles Harbor	90763.67	16590499.47	416621422.20
1711000405	Nooksack River	236504.72	23403387.51	554222910.88
1711001702	North Fork Skokomish River-Skokomish River	126888.54	1149165.90	366179347.99
1711000904	North Fork Skykomish River	52161.56	426306.87	380198384.07
1711001001	North Fork Snoqualmie River*	0.00	1401541.29	266759654.82
1711000801	North Fork Stillaguamish River	241531.73	2413045.08	738117997.50
1711001907	Ollala Valley-Frontal Puget Sound	268340.17	64719623.43	746949923.39
1711000301	Orcas Island	13330.95	2964390.48	188540262.31
1711001101	Pilchuck River	190243.19	14013224.37	355351382.20
1711000201	Point Roberts-Frontal Strait of Georgia	948.67	971705.88	11648169.79
1711002103	Pysht River-Frontal Strait of Juan De Fuca	265406.29	1585462.95	570022012.33
1711001102	Quilceda Creek-Frontal Possession Sound	209921.27	54716084.64	399661286.45
1711000503	Ross Lake-Skagit River*	0.00	13164.30	698721187.04
1711000502	Ruby Creek*	0.00	1541053.44	560853275.68
1711002102	Salt Creek-Frontal Strait of Juan De Fuca	44993.37	729816.84	135222597.30
1711000203	Samish River	138482.78	6568665.21	299753834.11
1711000303	San Juan Island	27572.13	4366208.07	159895004.96
1711000702	Skagit River-Frontal Skagit Bay	300528.30	25134111.45	462422000.60
1711002001	Snow Creek-Frontal Discovery Bay	37571.63	3663719.01	210348398.41
1711000404	South Fork Nooksack River	126987.51	1202691.96	481188716.61
1711001701	South Fork Skokomish River	87945.66	553423.32	267593051.13
1711000903	South Fork Skykomish River	66790.57	1098729.45	322042026.20
1711001003	South Fork Snoqualmie River*	0.00	5339684.16	224146000.21
1711000802	South Fork Stillaguamish River	275095.81	3858875.55	657342359.18
1711000803	Stillaguamish River	178867.85	14724044.73	424144796.31
1711000905	Sultan River	87945.53	866640.69	271892590.66
1711001801	Tahuya River-Frontal Hood Canal	276155.50	12235300.02	636813374.41
1711000205	Telegraph Slough-Frontal Padilla Bay	60818.10	15195470.31	159521909.52
1711000501	Three Fools Creek-Lightning Creek*	0.00	0.00	293567820.96
1711001005	Tolt River	60771.81	986821.65	253423236.76
1711000901	Tye River	21081.06	1371638.97	351485742.94
1711000101	Upper Chilliwack River*	0.00	1573.56	217807352.55
1711001601	Upper Deschutes River	56638.61	1354227.48	232252659.37
1711001301	Upper Green River	78645.64	900396.45	350393944.16
1711001501	Upper Nisqually River*	0.00	1995718.23	749567430.44
1711000401	Upper North Fork Nooksack River	53508.06	1312634.70	500713835.30
1711001402	Upper Puyallup River	151929.01	5771445.30	474165481.69
1711000601	Upper Sauk River	79594.77	286623.27	619928407.38
1711001004	Upper Snoqualmie River	114675.40	8025063.30	365975709.85
1711000602	Upper Suiattle River	69806.15	12389.67	477247790.46
1711001403	Upper White River	161129.00	1515750.03	756167028.05
1711000906	Wallace River-Skykomish River	94468.26	3647433.42	303948416.73
1711000204	Whatcom Creek-Frontal Bellingham Bay	75123.42	25442549.37	362645268.50
1711001901	Whidbey Island	73781.99	37509293.97	607858971.90
1711000907	Woods Creek-Skykomish River	112222.58	5576971.77	270851165.79

Within the hydrologic unit's boundaries:
Total IP Meters is the sum of all stream segment lengths multiplied by their IP index value
Impervious Surface Area is the sum of all cell areas multiplied by their IC Coefficient (Figure 6)

*removed from matrix (Figure 7) for reasons described in Results section

Appendix B. Washington State Legislature Revised Code of Washington Title 77 Chapter 95 Sections 160-180

RCW 77.95.160

Fish passage barrier removal board—Membership—Duties.

(1) The department shall maintain a fish passage barrier removal board. The board must be composed of a representative from the department, the department of transportation, cities, counties, the governor's salmon recovery office, tribal governments, and the department of natural resources. The representative of the department must serve as chair of the board and may expand the membership of the board to representatives of other governments, stakeholders, and interested entities.

(2)(a) The duty of the board is to identify and expedite the removal of human-made or caused impediments to anadromous fish passage in the most efficient manner practical through the development of a coordinated approach and schedule that identifies and prioritizes the projects necessary to eliminate fish passage barriers caused by state and local roads and highways and barriers owned by private parties.

(b) The coordinated approach must address fish passage barrier removals in all areas of the state in a manner that is consistent with a recognition that scheduling and prioritization is necessary.

(c) The board must coordinate and mutually share information, when appropriate, with:

(i) Other fish passage correction programs, including local salmon recovery plan implementation efforts through the governor's salmon recovery office;

(ii) The applicable conservation districts when developing schedules and priorities within set geographic areas or counties; and

(iii) The recreation and conservation office to ensure that barrier removal methodologies are consistent with, and maximizing the value of, other salmon recovery efforts and habitat improvements that are not primarily based on the removal of barriers.

(d) Recommendations must include proposed funding mechanisms and other necessary mechanisms and methodologies to coordinate state, tribal, local, and volunteer barrier removal efforts within each water resource inventory area and satisfy the principles of RCW 77.95.180. To the degree practicable, the board must utilize the database created in RCW 77.95.170 and information on fish barriers developed by conservation districts to guide methodology development. The board may consider recommendations by interested entities from the private sector and regional fisheries enhancement groups.

(e) When developing a prioritization methodology under this section, the board shall consider:

(i) Projects benefiting depressed, threatened, and endangered stocks;

(ii) Projects providing access to available and high quality spawning and rearing habitat;

(iii) Correcting the lowest barriers within the stream first;

(iv) Whether an existing culvert is a full or partial barrier;

(v) Projects that are coordinated with other adjacent barrier removal projects; and

(vi) Projects that address replacement of infrastructure associated with flooding, erosion, or other environmental damage. (f) The board may not make decisions on fish passage standards or categorize as impassible culverts or other infrastructure developments that have been deemed passable by the department.

[2014 c 120 § 4; 2000 c 107 § 110; 1997 c 389 § 6; 1995 c 367 § 2. Formerly RCW 75.50.160.]

NOTES:

Findings—1997 c 389: See note following RCW 77.95.100.

Severability—Effective date—1995 c 367: See notes following RCW 77.95.150.

RCW 77.95.170

Salmonid fish passage—Removing impediments—Grant program—Administration—Database directory.

(1) The department may coordinate with the recreation and conservation office in the administration of all state grant programs specifically designed to assist state agencies, private landowners, tribes, organizations, and volunteer groups in identifying and removing impediments to salmonid fish passage. The transportation improvement board may administer all grant programs specifically designed to assist cities, counties, and other units of local governments with fish passage barrier corrections associated with transportation projects. All grant programs must be administered and be consistent with the following:

(a) Salmonid-related corrective projects, inventory, assessment, and prioritization efforts;

(b) Salmonid projects subject to a competitive application process; and

(c) A minimum dollar match rate that is consistent with the funding authority's criteria. If no funding match is specified, a match amount of at least twenty-five percent per project is required. For local, private, and volunteer projects, in-kind contributions may be counted toward the match requirement.

(2) Priority shall be given to projects that match the principles provided in RCW 77.95.180.

(3) All projects subject to this section shall be reviewed and approved by the fish passage barrier removal board created in RCW 77.95.160 or an alternative oversight committee designated by the state legislature.

(4) Other agencies that administer natural resource-based grant programs shall use fish passage selection criteria that are consistent with this section when those programs are addressing fish passage barrier removal projects.

(5)(a) The department shall establish a centralized database directory of all fish passage barrier information. The database directory must include, but is not limited to, existing fish passage inventories, fish passage projects, grant program applications, and other databases. These data must be used to coordinate and assist in habitat recovery and project mitigation projects.

(b) The department must develop a barrier inventory training program that qualifies participants to perform barrier inventories and develop data that enhance the centralized database. The department may decide the qualifications for participation. However, employees and volunteers of conservation districts and regional salmon recovery groups must be given priority consideration.
[2014 c 120 § 3; 1999 c 242 § 4; 1998 c 249 § 16. Formerly RCW 75.50.165.]

NOTES:

Findings—Purpose—Report—Effective date—1998 c 249: See notes following RCW 77.55.181.

RCW 77.95.180

Fish passage barrier removal program.

(1)(a) To maximize available state resources, the department and the department of transportation must work in partnership to identify and complete projects to eliminate fish passage barriers caused by state roads and highways.

(b) The partnership between the department and the department of transportation must be based on the principle of maximizing habitat recovery through a coordinated investment strategy that, to the maximum extent practical and allowable, prioritizes opportunities: To correct multiple fish barriers in whole streams rather than through individual, isolated projects; to coordinate with other entities sponsoring barrier removals, such as regional fisheries enhancement groups incorporated under this chapter, in a manner that achieves the greatest cost savings to all parties; and to correct barriers located furthest downstream in a stream system. Examples of this principle include:

(i) Coordinating with all relevant state agencies and local governments to maximize the habitat recovery value of the investments made by the state to correct fish passage barriers;

(ii) Maximizing the habitat recovery value of investments made by public and private forest landowners through the road maintenance and abandonment planning process outlined in the forest practices rules, as that term is defined in RCW 76.09.020;

(iii) Recognizing that many of the barriers owned by the state are located in the same stream systems as barriers that are owned by cities and counties with limited financial resources for correction and that state-local partnership opportunities should be sought to address these barriers; and

(iv) Recognizing the need to continue investments in the family forest fish passage program created pursuant to RCW 76.13.150 and other efforts to address fish passage barriers owned by private parties that are in the same stream systems as barriers owned by public entities.

(2) The department shall also provide engineering and other technical services to assist nonstate barrier owners with fish passage barrier removal projects, provided that the barrier removal projects have been identified as a priority by the department and the

department has received an appropriation to continue that component of a fish barrier removal program.

(3) Nothing in this section is intended to:

(a) Alter the process and prioritization methods used in the implementation of the forest practices rules, as that term is defined in RCW 76.09.020, or the family forest fish passage program, created pursuant to RCW 76.13.150, that provides public cost assistance to small forest landowners associated with the road maintenance and abandonment processes; or

(b) Prohibit or delay fish barrier projects undertaken by the department of transportation or another state agency that are a component of an overall transportation improvement project or that are being undertaken as a direct result of state law, federal law, or a court order. However, the department of transportation or another state agency is required to work in partnership with the fish passage barrier removal board created in RCW 77.95.160 to ensure that the scheduling, staging, and implementation of these projects are, to [the] maximum extent practicable, consistent with the coordinated and prioritized approach adopted by the fish passage barrier removal board.

[2014 c 120 § 2; 2010 1st sp.s. c 7 § 83; 1995 c 367 § 3. Formerly RCW 75.50.170.]

NOTES:

Effective date—2010 1st sp.s. c 26; 2010 1st sp.s. c 7: See note following RCW 43.03.027.

Severability—Effective date—1995 c 367: See notes following RCW 77.95.150.