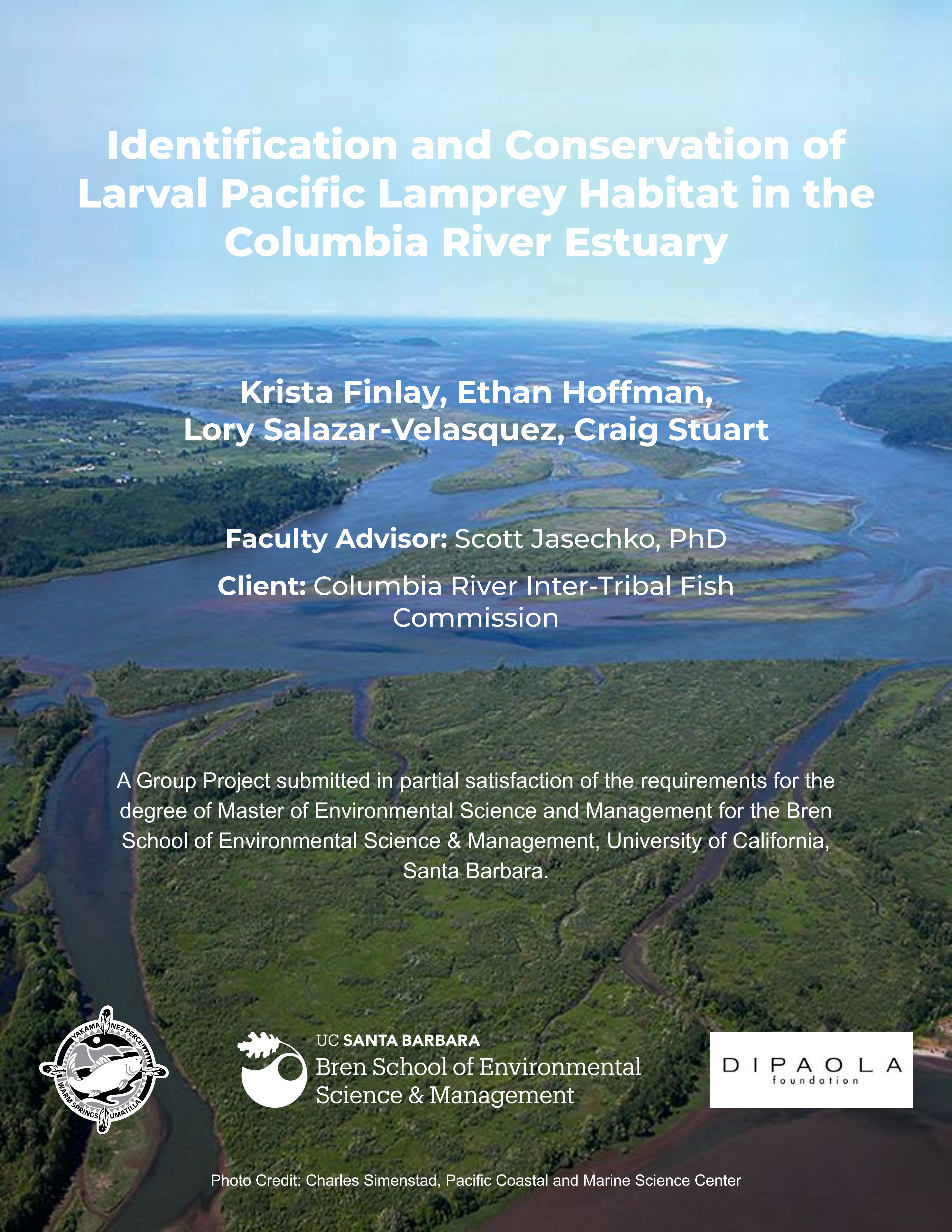

Identification and Conservation of Larval Pacific Lamprey Habitat in the Columbia River Estuary

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Client: Columbia River Inter-Tribal Fish Commission

A Group Project submitted in partial satisfaction of the requirements for the degree of Master of Environmental Science and Management for the Bren School of Environmental Science & Management, University of California, Santa Barbara.

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Signature Page

As authors of this Group Project report, we archive this report on the Bren School's website such that the results of our research are available for all to read. Our signatures on the document signify our joint responsibility to fulfill the archiving standards set by the Bren School of Environmental Science & Management.

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

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ABSTRACT

The Pacific lamprey (*Entosphenus tridentatus*) is an ancient, native species of fish whose range spans throughout the Columbia River Basin and the Pacific Coast. During the past 60 years, populations in the Columbia River have declined by 95% from their historic levels. The decline of lamprey has been concurrent with anthropogenic changes to the Columbia River Basin that have altered the river's habitat conditions. In their larval stage, Pacific lamprey burrow in fine sediment and are susceptible to elevated salinity levels and elevated temperatures within the river's ecosystems when they burrow for extended periods of time. Knowledge gaps that concern lamprey life stages create challenges in the identification of potentially suitable habitat and enactment of restoration operations to promote larval development. The development of a Habitat Suitability Analysis within the Columbia River Estuary provides potential regions of suitable habitat for larval lamprey using ideal salinity and temperature criteria. The analysis results display that less than 1% of the Columbia River Estuary met the required criteria for all 12 months of the year. The greatest amount of suitable larval lamprey habitat is identified during the spring and fall months, while the winter and summer months have the least amount of suitable habitat. Our results show that habitat conditions in the Columbia River Estuary are unable to support larval lamprey year-round due to spatial and temporal limitations within the Estuary. Future restoration strategies may need to assess habitat suitability within the region and implement conservation measures on a seasonal basis. These operations should consider anthropogenic impacts on the Columbia River, such as limited passageways and dredging, to reduce the number of threats that can displace or harm larval lamprey.

Keywords: Pacific lamprey, larvae, Columbia River, Columbia River Estuary, salinity, temperature, sediment, Habitat Suitability Analysis, restoration, dams, dredging

Table of Contents

Abstract 4

Table of Contents 5

List of Figures 8

List of Tables 9

Background 10

Project Location 10

Pacific Lamprey 13

Pacific Lamprey Life Cycle 13

Ecological Importance 16

Tribal Presence and History 17

Cultural Importance 18

Pacific Lamprey Decline 19

Climate Change Concerns 21

Pacific Lamprey Status 22

Project Areas of Focus 25

Focal Phase: Larvae 25

Larval Lamprey Habitat 25

Environmental Parameters 26

Environmental Parameters - Temperature 26

Environmental Parameters - Salinity 27
Environmental Parameters - Sediment 27
Environmental Parameters - Water Flow 29
Non-Environmental Parameters 29
Non-Environmental Parameters - Levees 30
Non-Environmental Parameters - Dredge Sites 31
Non-Environmental Parameters - Restoration Projects 31
Non-Environmental Parameters - Barriers 32
Non-Environmental Parameters - Contamination Sites 33
Knowledge Gaps 33
Project Objectives **35**
Methods **36**
General Approach 36
Temperature 36
Salinity 38
Geomorphology 39
Total Output 39
Summary Statistics 39
Results **42**
Total Available Habitat 42

Temporal Distribution of Primary Suitable Habitat 43

Temporal Distribution of Secondary Suitable Habitat 44

Spatial Distribution of Primary and Secondary Suitable Habitat 46

Discussion **52**

Temporal and Spatial Analysis 52

Climate Change Concerns 53

Non-Environmental Parameters 54

Non-Environmental Parameters - Levees 54

Non-Environmental Parameters - Dredge Sites 55

Non-Environmental Parameters - Restoration Projects 57

Non-Environmental Parameters - Barriers 58

Non-Environmental Parameters - Contamination Sites 59

Limitations 60

Conclusions and Recommendations **63**

References **67**

Appendix I: Data Obtained from the Columbia River Inter-Tribal Fish Commission 76

Appendix II: Model GeoTIFF Documentation from the Columbia River Inter-Tribal Fish Commission 79

Appendix III: Data Obtained from the Lower Columbia Estuary Partnership 80

Appendix IV: Schematic of Model Builder Workflow used in ArcGIS Pro to Identify Suitable Habitat 81

Appendix V: Table of Projects from the Pacific Lamprey Conservation Initiative- Lower Columbia/Willamette Regional Management Unit - Lower Columbia Sub-Unit 82

Appendix VI: Monthly Outputs of Habitat Suitability Analysis 86

List of Figures

Figure 1: The Columbia River Basin spans across seven U.S. states and a portion of southeastern British Columbia, Canada. 11

Figure 2: The region of interest for the project, the Columbia River Estuary, is from the Bonneville Dam to the mouth of the Columbia River at the Pacific Ocean. 12

Figure 3: The life cycle of Pacific Lamprey from larvae to adult in the Columbia River Estuary. 14

Figure 4: Adult Pacific Lamprey counts crossing Bonneville Dam from 1938 to 1969, and from 1998 to 2010. 20

Figure 5: Categorization system for sediment and habitat types used by Pacific lamprey in aquatic environments. 29

Figure 6: Workflow used to complete habitat suitability analysis. 36

Figure 7: Temperature raster for the month of January. 37

Figure 8: Salinity raster for the month of January. 38

Figure 9: Geomorphology of the Columbia River Estuary. 43

Figure 10: Temporal distribution of primary suitable habitat in the Columbia River Estuary. 44

Figure 11: Temporal distribution of secondary suitable habitat in the Columbia River Estuary. 45

Figure 12: Total amount of primary and secondary suitable habitat. 46

Figure 13: Spatial distribution of suitable habitat at the mouth of the Columbia River Estuary. 48

Figure 14: Average monthly temperature (℃) in the Columbia River Estuary. 49

Figure 15: Spatial distribution of suitable habitat in Columbia River Tributaries. 50

Figure 16: Spatial distribution of suitable habitat in the Portland Harbor Superfund area. 51

Figure 17: Levees in the Columbia River Estuary from the Pacific Ocean to Bonneville Dam. 55

List of Tables

Table 1: Geomorphology characteristics of the Columbia River Estuary 40

BACKGROUND

Project Location

Originating in Canada and flowing 1,253 miles to the Pacific Ocean, the Columbia River is the largest river system in the Pacific Northwest (Lower Columbia Estuary Partnership, 2022b). Our project area occurs within the Columbia River Basin (Figure 1), from Bonneville Dam to the mouth of the Columbia River Estuary which flows into the Pacific Ocean. The project area encompasses 146 miles of the lower portion of the Columbia River, and hereafter will be referred to as the Columbia River Estuary (Figure 2). The geological complexity of the Columbia River Estuary is a result of its unique sedimentary geology, physical oceanography, and biology (Sherwood & Creager, 1990). The boundary between Washington State and Oregon runs through the middle of the Columbia River Estuary, thus both states contribute to the jurisdiction of the Columbia River Estuary (Weaver, 1997). The Columbia River Estuary is an essential part of the Columbia River by providing wildlife refuges, recreational opportunities, a shipping channel, access to cities and towns, and a transition point for fish and wildlife from freshwater to saltwater ecosystems (Lower Columbia Estuary Partnership, 2022b). The Willamette River is the largest tributary by volume that is connected to the Columbia River Estuary (Lower Columbia Estuary Partnership, 2022b).

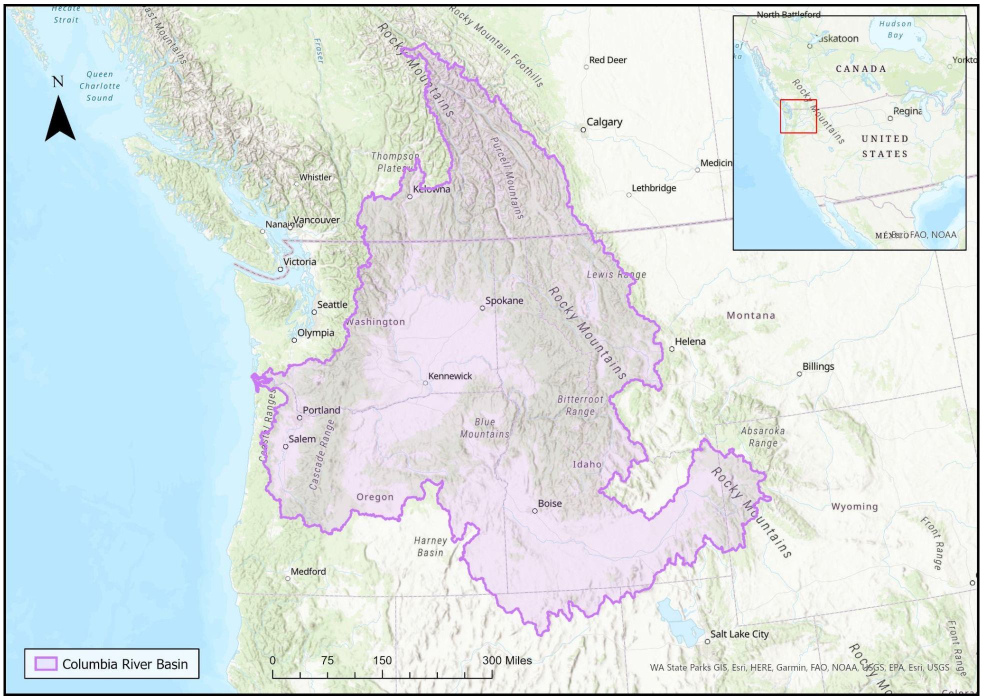

Figure 1: The Columbia River Basin spans across seven U.S. states and a portion of southeastern British Columbia, Canada. The states within the boundary and area of the Columbia River Basin include Washington, Oregon, Idaho, Montana, and small parts of Nevada, Utah, and Wyoming. The Columbia River Basin extends from the Rocky Mountains in the east through the Cascade Range on the west, and the Great Basin to the south. Major cities located within the Columbia River Basin are Portland, Oregon, Spokane, Washington, and Boise, Idaho. Data Source: Transboundary Freshwater Dispute Database.[1]

The Columbia River Estuary experiences warm, dry summers, and wet, cool winters (Lower Columbia Estuary Partnership, 2022b). Between November and March, winter rain can cause high flows in the Estuary, and snow melt can add freshwater flows to the Estuary during the spring (Lower Columbia Estuary Partnership, 2022b). The Columbia River Estuary has a quick flushing time, high stratification, and strong tidal influence, which result in large amounts of water that flow through the area (Kärnä et al., 2015). River discharge, tides, and coastal winds determine the amount of circulation in the Estuary, with the highest discharge events occurring in the spring from May to June (Kärnä et al., 2015). The Columbia River Estuary has two channels, a North Channel, and a South Channel. The North Channel is more tidally dependent and contains a developed salt wedge, while the South Channel is kept at an average depth of 13.1 meters; however, fluctuations occur from releases at Bonneville Dam, precipitation, and storm floods (Baptista et al., 2015). High flow rates from spring freshwater flows can reduce salinity intrusion and move salt wedges out of the Estuary's North Channel (Kärnä et al., 2015).

[1] "Product of the Transboundary Freshwater Dispute Database, College of Earth, Ocean, and Atmospheric Sciences, Oregon State University. Additional information about the Transboundary Freshwater Dispute Database can be found at: http://transboundarywaters.science.oregonstate.edu."

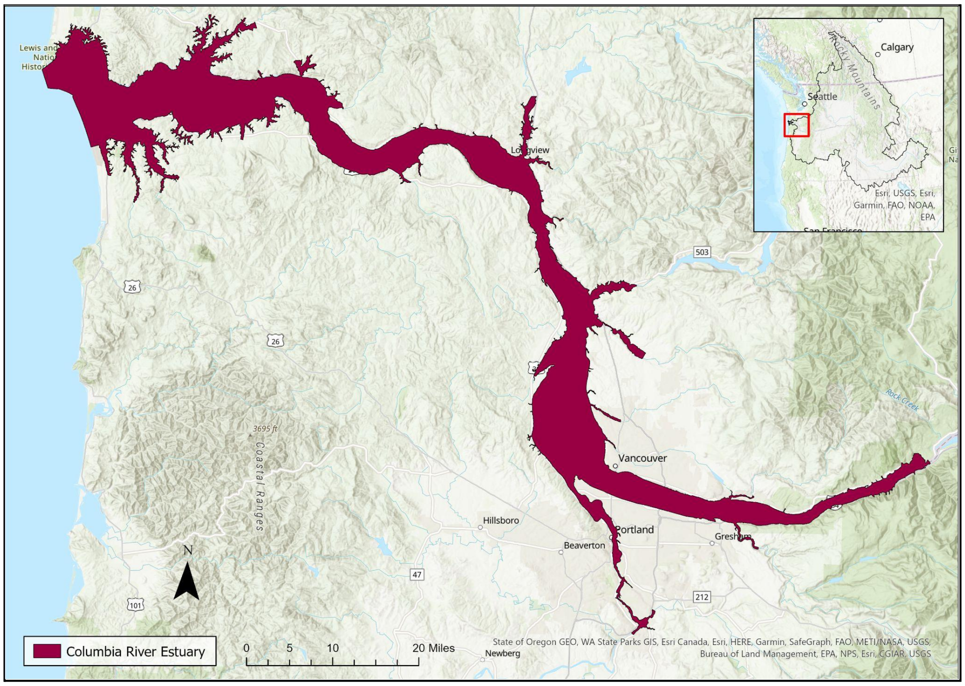

Figure 2: The region of interest for the project, the Columbia River Estuary, is from the Bonneville Dam to the mouth of the Columbia River at the Pacific Ocean. The area includes the Lower Columbia River, Willamette River in the southern section near Portland, a portion of the Cowlitz River north of Longview, and Youngs River south of the mouth of the Estuary. Major cities located along the Columbia River Estuary include Portland, Oregon, Vancouver, Washington, and Longview, Washington. Data Source: Lower Columbia Estuary Partnership.

The Columbia River Estuary has experienced several anthropogenic changes since the 1880s, including the construction of dams and dozens of smaller flow control structures throughout the area that are dedicated to hydropower, flood control, irrigation, and transportation (Lower Columbia Estuary Partnership, 2022b; Jolley et al., 2012a). The Columbia River Estuary is vulnerable to frequent changes in water levels from the Bonneville Dam's operations due to hydropower production and flood control (Poirier, 2020). The natural flow patterns and temperature of the Columbia River Estuary have been altered by the changes to flows in the Columbia River (Poirier, 2020). These alterations have resulted in the loss of wetlands, forested uplands, sediments, nutrients, decreased floods, and colder water that are vital for the survival of species that use the Estuary, such as salmon, steelhead, lamprey, American shad, frogs, and shorebirds (Lower Columbia Estuary Partnership, 2022d, Lower Columbia Estuary Partnership, 2022e, Lower Columbia Estuary Partnership, 2022f, Jolley et al., 2012a). Additional changes to water flow in the Estuary have included reductions in the annual flows and spring floods and altered the timing of flows (Lower Columbia Estuary Partnership, 2022b).

The Columbia River Estuary provides essential habitat for several species, including migratory birds, and fish, wildlife, and plants listed under the Endangered Species Act (Lower Columbia Estuary Partnership, 2022b). One of the most important producers of Chinook salmon (*Oncorhynchus tshawytscha*) and steelhead (*Oncorhynchus mykiss)*, the Columbia River Basin still provides a substantial amount of stock for the salmon and steelhead fisheries of the West Coast (Lower Columbia Estuary Partnership, 2022b; National Oceanic and Atmospheric Administration Fisheries, 2020). Today, thirteen Pacific salmon (*Oncorhynchus spp.*) and steelhead species that use the Columbia River Estuary to migrate are listed as threatened or endangered under the Endangered Species Act (Lower Columbia Estuary Partnership, 2022b; National Oceanic and Atmospheric Administration Fisheries, 2020). Species who use the Columbia River Estuary to travel to and from their freshwater spawning grounds may struggle to survive as their environment changes in the Columbia River Basin. For example, a decrease in spring water flows may cause several fish species to become more susceptible to predation (Poirier, 2020). In addition, as spring freshwater flows shift to the early spring, this may lead to lower water levels for an extended period and could result in warmer water temperatures in the Columbia River Estuary that would affect salmon, lamprey, and other fish species that rely on the Columbia River Estuary (Poirier, 2020).

Pacific Lamprey

The Pacific lamprey (*Entosphenus tridentata*) is an ancient, native species of fish whose historical range spans throughout the Columbia River Basin and the Pacific Coast from California to Alaska (Columbia River Inter-Tribal Fish Commission, 2011; Luzier et al., 2011). Fossil evidence suggests that Pacific lamprey have existed for over 450 million years, that the Pacific lamprey is one of the foundational species of the Columbia River Basin, and that they play a vital role in the ecology of the basin's native freshwater community by providing ecosystem services (Columbia River Inter-Tribal Fish Commission, 2011). As an anadromous species that migrates from the ocean back to freshwater habitats to spawn, Pacific lamprey utilize a variety of freshwater and saltwater environments throughout their life (Silver, 2015). Pacific lamprey spend their larval phase and adult spawning phase in freshwater environments, and live their juvenile, parasitic phase in the ocean; once they return from the ocean, adult lamprey arrive in freshwater habitats to spawn and die (Clemens et al., 2019; Silver, 2015). The fact that Pacific lamprey migrate to and from the ocean indicates that marine, estuary, and freshwater habitats all play a vital role in their life history (Clemens et al., 2019).

Pacific Lamprey Life Cycle

Pacific lamprey have a complex life cycle (Figure 4), and limited knowledge about each of their life stages makes them a challenging species to monitor and protect (Clemens et al., 2017; Lamprey Technical Workgroup, 2020). Juvenile and adult Pacific lamprey use the Columbia River Estuary and mainstem Columbia River as their primary path to migrate between freshwater environments and the Pacific Ocean (Silver et al., 2007). Researchers estimate that adult lamprey return to freshwater systems between April and June, and that they finish migrating to upstream tributaries by September (Close et al., 2002). After spawning in the spring, larval lamprey drift downstream until they find suitable rearing habitat (Close et al., 2002). Larvae are commonly known to reside in freshwater tributaries, however researchers have yet to fully investigate if the Columbia River Estuary can provide suitable rearing habitat for larval lamprey (Silver et al., 2007).

Figure 3: The life cycle of Pacific Lamprey from larvae to adult in the Columbia River Estuary. Laid in freshwater tributaries, lamprey eggs hatch and larvae leave their rocky stream bottom nests to burrow in fine soft sediments. Larvae may stay in fine sediments of freshwater and last from 3 to 10 years until they begin to change into juveniles. During this change, lamprey undergo morphological and physiological changes as they travel through the Columbia River Estuary to the ocean. In the Pacific Ocean lamprey grow, mature, and feed on several species of fish. After maturation in the ocean, adult lamprey migrate back to freshwater tributaries to spawn and die. Pacific lamprey in the Columbia River may have an average life span of 8 to 12 years. Photo Credit: FISHBIO Fisheries Research, US Geological Survey Columbia River Research Lab, Ralph Lampman - Yakama Nation's Fisheries Resource Management Program, US Fish and Wildlife Service (Clockwise, beginning with larvae)

Pacific lamprey spawning occurs in freshwater tributaries, in shallow, gravel-bottom areas of streams with shallow, rocky stream bottoms to provide protection for their eggs (Moser & Close, 2003; McIlraith et al., 2017; Luzier et al., 2011). Lamprey eggs incubate in streams and hatch in about 30 days, though this can depend on water temperature (Columbia River Inter-Tribal Fish Commission, 2011; McIlraith et al., 2017). Within two to three weeks of hatching, new larval lamprey leave their nests and burrow in soft sediment composed of silt and sand (Close et al., 2002; Jolley et al., 2012a; Silver et al., 2007; Luzier et al., 2011). Larvae are known to burrow in sediment areas near the banks of streams and rivers that are associated with pools, alcoves, and side channels and in slow, backwater areas with substantial amounts of fine, silty sediments (Clemens et al., 2017; Lamprey Technical Workgroup, 2021). Habitats must provide enough substrate for burrowing up to a depth of 15 cm and a regular supply of suspended and/or benthic organic matter for feeding (Lamprey Technical Workgroup, 2021). The larval life stage of lamprey represents a large amount of biomass within streams where they filter feed on detritus, diatoms, and algae to promote nutrient cycling and improved water quality (Close et al., 2002; Moser & Close, 2003; Jolley et al., 2012b). Larval lamprey can be a food source to many fish species, including coho salmon fry and smallmouth bass (Close et al., 2002; Weitkamp et al., 2015; Lamprey Technical Workgroup, 2021; Silver et al., 2007). As larvae grow, preferences in sediment and habitat type can change from fine sediment in slow water to grainier material in habitats with faster water (Lamprey Technical Workgroup, 2021; Jolley et al., 2012a). Several factors can affect larval lamprey distribution in the Columbia River, such as the amount of suitable larval rearing habitat and their proximity to adult spawning areas (Silver et al., 2007). Prior to their migration to the ocean, larval lamprey can spend three to ten years in upstream habitat, burrowed in sediment (Clemens et al., 2020; Silver et al., 2007; Porter et al., 2021), however, the use of alternative habitat, such as larger river and estuarine habitats during the larval phase, is less known (Silver et al., 2007; Jolley et al., 2012a).

After burrowing in sediments for several years, larval lamprey undergo metamorphosis and begin their juvenile phase (Close et al., 2002). As juveniles, they experience several morphological and physiological changes before they travel to the ocean (Columbia River Inter-Tribal Fish Commission, 2011). These changes tend to occur between July and December, and juvenile lamprey begin to migrate downstream to the Pacific Ocean between the spring and fall during periods of high flow (Close et al., 2002; Jolley et al., 2012a). During the transition phase, lamprey develop eyes and a sucking disk mouth with teeth which they use to latch onto fish (Weitkamp et al., 2015; Columbia River Inter-Tribal Fish Commission, 2011). Juvenile lamprey feed on several species of fish in the lower Columbia River Estuary, including sub yearling Chinook salmon, American shad, and Pacific herring. (Weitkamp et al., 2015). The amount of time that juvenile lamprey spend in the Columbia River Estuary and how they use the Estuary's habitat is unknown (Columbia River Inter-Tribal Fish Commission, 2011).

Pacific lamprey grow and mature into their parasitic phase after entering the ocean (Clemens et al., 2019). Lamprey are parasitic on at least 23 species of fish, most commonly Walleye pollock and Pacific hake, along with marine mammals (Clemens et al., 2019). Estimates of the time parasitic Pacific lamprey stay in the ocean range from

18 to 40 months (Columbia River Inter-Tribal Fish Commission, 2011). In studies that included vertical and spatial sampling locations in the Bering Sea, many lamprey were found in pelagic areas (< 100 meters); however, the largest concentration of lamprey appeared in the benthic zones (< 500 meters) because of the large amount of prey available (Columbia River Inter-Tribal Fish Commission, 2011). Researchers found that lamprey length varies from 12 to 85 centimeters, which may suggest that lamprey spend many years in the ocean (Columbia River Inter-Tribal Fish Commission, 2011). After maturing in the ocean, lamprey return to freshwater tributaries where they spawn and die, which provides nutrients for larval lamprey and other species (Clemens et al., 2019). Lifespan estimates for Pacific lamprey vary (Columbia River Inter-Tribal Fish Commission, 2011). If larval lamprey live in freshwater from 3 to 10 years, then spend 3 to 4 years in the ocean as juveniles and return to freshwater ecosystems for another year before spawning, then the average life cycle of Pacific lamprey from the Columbia River may last between 8 and 12 years (Columbia River Inter-Tribal Fish Commission, 2011; Porter et al., 2021).

Ecological Importance

Pacific lamprey are ecologically important to the Columbia River Estuary because they provide several ecosystem services, such as nutrient processing and storage, and within local food webs where they are susceptible to predation from salmon and migratory birds (Weitkamp et al., 2015; Luzier et al., 2011). Pacific lamprey play a key role in cycling nutrients between freshwater and marine ecosystems and form a substantial portion of the biomass in freshwater streams as larvae and adults (Wang et al., 2020; Silver, 2015). As filter feeders, larval lamprey support nutrient cycling in aquatic ecosystems and improve water quality (Close et al., 2002; Moser & Close, 2003; Jolley et al., 2012b). Additionally, larval lamprey are deemed an important food resource for several fish species in the Columbia River (Close et al., 2002; Moser & Close, 2003; Jolley et al., 2012b). Juvenile lamprey are filter feeders that clean algae and sediment from rocks within streams and riparian areas, and they filter feed detritus and diatoms from the water (Columbia River Inter-Tribal Fish Commission, 2011; Close et al., 2002). After adult Pacific lamprey spawn and die, their bodies can provide nutrients to the Columbia River as a valuable food resource for other species in the Columbia River Basin (Columbia River Inter-Tribal Fish Commission, 2011; Close et al., 2002). In the ocean, lamprey are highly desired by many marine mammal predators, including seals and sea lions, because lamprey are high in fat and contain more calories than salmon (Close et al., 2002). The need to understand the biology of Pacific lamprey in the Columbia River Basin is essential to conserving the species and their cultural significance to the Indigenous Peoples of the basin (Hayes et al., 2013).

Tribal Presence and History

Our client is the Columbia River Inter-Tribal Fish Commission, whose member-tribes include the Nez Perce Tribe, the Confederated Tribes of the Umatilla Indian Reservation, the Confederated Tribes and Bands of the Yakama Nation, and the Confederated Tribes of the Warm Springs Reservation of Oregon. Within the Columbia River Basin, there are eight sovereign Tribes with histories that are tied to the environment and their homelands (Hobaish, 2019). In 1855, millions of acres of land from treaties with the United States government was surrendered from four of these tribes, the Nez Perce Tribe, the Confederated Tribes of the Umatilla Indian Reservation, the Confederated Tribes and Bands of the Yakama Nation, and the Confederated Tribes of the Warm Springs Reservation of Oregon (Columbia River Inter-Tribal Fish Commission, 2022b). The treaties included provisions that retained the tribes' rights to continue to fish both on their reservation and at their traditional fishing grounds (Columbia River Inter-Tribal Fish Commission, 2022b). Species within treaty-fishing rights include salmon, lamprey, and other aquatic species (Columbia River Inter-Tribal Fish Commission, 2022b). Over the next 100 years, federal, state, and local governments breached the 1855 treaty fishing rights, essential fishing habitats in the Columbia River Basin were lost to dams, and species such as salmon significantly decreased in number (Columbia River Inter-Tribal Fish Commission, 2022b).

In 1968, a federal court proceeding, *United States v. Oregon*, was brought by the four Tribes that signed treaties in 1855 with the U.S. government to enforce their reserved fishing rights (Columbia River Inter-Tribal Fish Commission, 2022b; National Oceanic and Atmospheric Administration Fisheries, 2020). The court ruled that the governing power of the states over Indigenous Peoples' fishing rights is restricted because of the treaties between the United States and the Tribes in 1855 (Columbia River Inter-Tribal Fish Commission, 2022b; National Oceanic and Atmospheric Administration Fisheries, 2020). The court also ruled that the treaties reserved up to 50% of the salmon harvest to the tribes and continued the right of Tribes to fish on their traditional lands (Columbia River Inter-Tribal Fish Commission, 2022b; National Oceanic and Atmospheric Administration Fisheries, 2020). The formation in 1977 of The Columbia River Inter-Tribal Fish Commission included the four treaty tribes: the Nez Perce Tribe, the Confederated Tribes of the Umatilla Indian Reservation, the Confederated Tribes and Bands of the Yakama Nation, and the Confederated Tribes of the Warm Springs Reservation (Columbia River Inter-Tribal Fish Commission, 2022b). The Columbia River Inter-Tribal Fish Commission's objectives are to coordinate common goals of fish resource management on the Columbia River and to make sure any issues about treaty fishing rights are settled to secure the maintenance and restoration of tribal fisheries (Columbia River Inter-Tribal Fish Commission, 2022; Columbia River Inter-Tribal Fish Commission, 2022a).

Cultural Importance

Pacific lamprey are of great significance to American Indian Tribes of the Pacific Northwest (Close et al., 1995). Lamprey have been harvested for multiple uses by Indigenous Peoples from the coast to the interior regions of the Columbia River (Close et al., 1995; Close et al., 2002). Our client's member tribes acknowledge the importance of Pacific lamprey as part of the ecosystem and the resource lamprey provide to the food web of the Columbia River Estuary (Columbia River Inter-Tribal Fish Commission, 2011). Pacific lamprey are spiritually, socially, ceremonially, medicinally, and culturally important, and have provided subsistence to Columbia River Basin tribal life for many generations (Close et al., 2002; Hayes et al., 2013; Columbia River Inter-Tribal Fish Commission, 2011). The Pacific lamprey is a "First Food" that is essential to the culture of the four sovereign Columbia River Treaty Tribes of the Columbia River Inter-Tribal Fish Commission (Columbia River Inter-Tribal Fish Commission, 2011). According to our client, the people of the Nez Perce, Umatilla, Yakama, and Warm Springs Tribes have depended on lamprey, salmon, roots, and berries for over 10,000 years. The harvest of lamprey for ceremonies and food have been essential to the client's four member tribes (Columbia River Inter-Tribal Fish Commission, 2011). Prior to dams being built on the Columbia River, the client member tribes traditionally harvested lamprey in the Columbia River mainstem, its tributaries, and Willamette Falls to sustain tribal families each year (Columbia River Inter-Tribal Fish Commission, 2011). Currently, Willamette Falls on the Willamette River in Oregon is the primary site of lamprey harvesting in the Columbia River Estuary (Luzier et al., 2011; Moser & Close, 2003) Tribes, such as the Nez Perce, Umatilla, Yakama, and Warm Springs, harvest lamprey at Willamette Falls pursuant to tribal self-regulation (Luzier et al., 2011; Wicks-Arshack et al., 2018). Harvests at Willamette Falls are extremely limited, restricted, and require a tribal permit (Luzier et al., 2011; Wicks-Arshack et al., 2018). The tribes continue to use lamprey for subsistence, as food and medicine, for ceremonial purposes, and pass down many stories and legends about lamprey from generation to generation (Columbia River Inter-Tribal Fish Commission, 2011). Lamprey are central to the cultural, economic, and sovereign benefit of the tribes (Columbia River Inter-Tribal Fish Commission, 2011). The tribes consider lamprey as their sacred elder and without the lamprey, they state that the circle of life is unbalanced (Columbia River Inter-Tribal Fish Commission, 2011).

The decrease in the number of Pacific lamprey in the Columbia River Basin and Estuary started to concern tribal members beginning in the 1970s (Columbia River Inter-Tribal Fish Commission, 2011). Currently, tribal members have limited opportunities to gather lamprey within the Columbia River Basin. In the client's Tribal Pacific Lamprey Restoration Plan, the decline of Pacific lamprey has been associated with several negative effects on tribal culture (Columbia River Inter-Tribal Fish Commission, 2011;

Close et al., 2002). These impacts include the loss of lamprey from “the ecological circle and tribal way of life,” the loss of a cultural heritage where young tribal members may not know how to fish and prepare lamprey for ceremonies, the loss of crucial legends associated with lamprey, and the loss of chances to fish in the historical fishing grounds (Columbia River Inter-Tribal Fish Commission, 2011; Close et al. 2002). Tribal members are concerned that the loss of lamprey will translate into the loss of historical fishing areas and a disappearance of ecological knowledge, resulting in a loss of essential culture for the Columbia River tribes (Columbia River Inter-Tribal Fish Commission, 2011; Close et al., 2002). Tribal elders are particularly concerned that with a decrease in lamprey to catch, prepare, and preserve, younger tribal members will lose a chance to obtain knowledge and cultural experiences, especially connections with the elder tribal members (Close et al. 2002; Columbia River Inter-Tribal Fish Commission, 2011). The Columbia River Inter-Tribal Fish Commission is currently working on an updated restoration plan to support their ongoing effort to protect and restore Pacific lamprey in their native habitat (Columbia River Inter-Tribal Fish Commission, 2011). The client states the need for lamprey populations to be restored to support the ecological health of the Columbia River, tributaries, habitats, species, and the culture of tribal communities (Columbia River Inter-Tribal Fish Commission, 2011).

Pacific Lamprey Decline

Commercial harvests of adult Pacific lamprey at Willamette Falls in the late 1800s recorded a range of 100,000 to 500,000 individuals (Columbia River Inter-Tribal Fish Commission, 2011). The number of adult Pacific lamprey were counted and recorded during the day beginning in 1938, which coincided with the completion of the first dam on the Columbia River, Bonneville Dam (Close et al., 1995; Columbia River Inter-Tribal Fish Commission, 2011). After Bonneville Dam was built, 17 additional dams were built on the mainstem Columbia River (Close et al., 2002). The number of lamprey were counted at Bonneville Dam from 1938 until 1969 (Figure 3), with 1969 providing the peak year of recordings of about 375,000 lamprey (Close et al., 1995). Between 1969 and 1993, counts of adult lamprey were not completed at Bonneville Dam (Close et al., 1995). When counts of adult lamprey resumed in 1994, there was a significant decline of lamprey numbers in comparison to the count in 1969 (Close et al., 1995; Luzier et al., 2011; Columbia River Inter-Tribal Fish Commission, 2011). From 2003 to 2010, adult populations of lamprey were recorded at Bonneville Dam and displayed a decline from 117,000 to 6,200 (Kostow, 2002; Columbia River Inter-Tribal Fish Commission, 2011). Since lamprey are nocturnal and counts were recorded during the day, the Confederated Tribes of the Umatilla Indian Reservation began night counts at Bonneville Dam in 1998 and 1999 to obtain more accurate population numbers (Close et al., 2002; Columbia River Inter-Tribal Fish Commission, 2011). Adult lamprey counts provide much of the information about Columbia River populations, and juvenile abundance and distribution data appear to parallel a decline in lamprey populations (Jolley et al., 2010). Demographic information about lamprey over the past thirty years has been associated with observations or been collected by accident while conducting studies on salmon, which means that many of the estimates are considered minimum population numbers (Poirier, 2020).

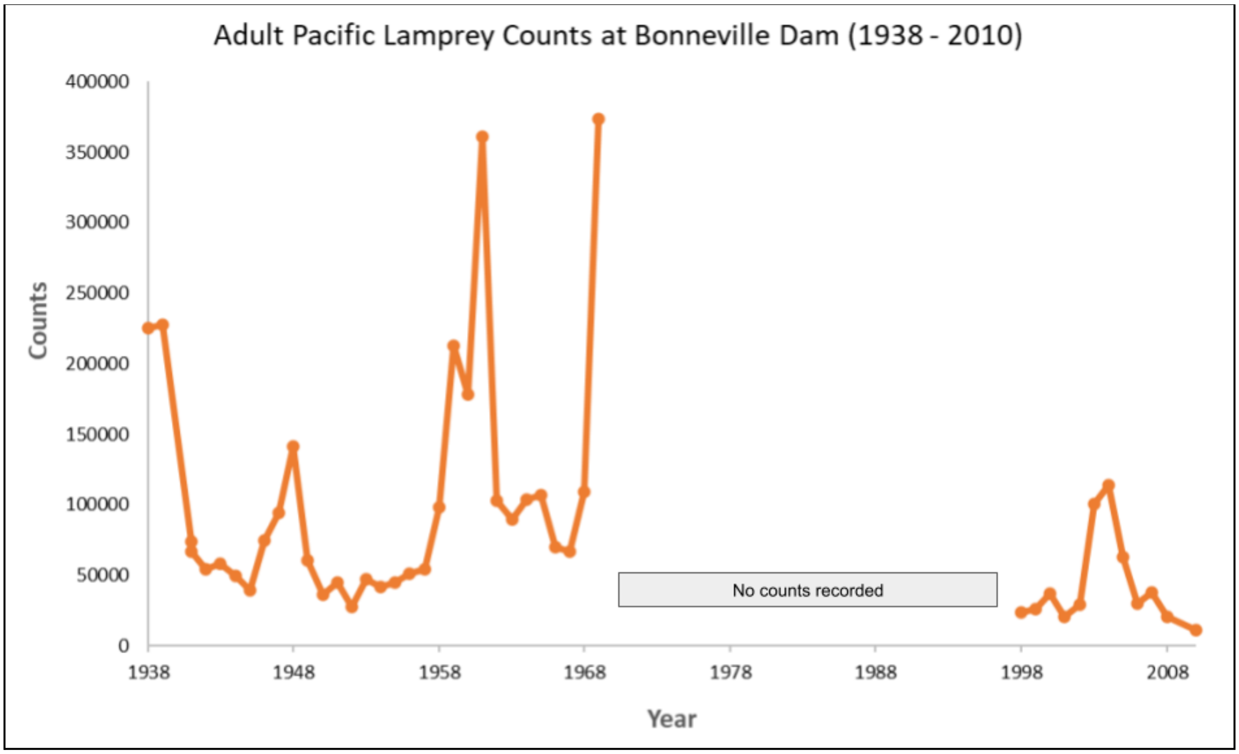

Figure 4: Adult Pacific Lamprey counts crossing Bonneville Dam from 1938 to 1969, and from 1998 to 2010. Records of adult Pacific lamprey began at Bonneville Dam in 1938, after the dam was completed, and continued to 1969. Counts of lamprey were not conducted between 1969 and 1998 at Bonneville Dam, however, counts continued at dams further up the Columbia River. Adult Pacific lamprey counts returned to Bonneville Dam in 1998, and population numbers were notably lower than counts during the earlier years of records, specifically in comparison to counts from 1969. Data Source: Columbia River Inter-Tribal Fish Commission Restoration Plan, 2011.

The Pacific lamprey population in the Columbia River has declined by 95% over the past 60 years, in comparison to historical observations of population numbers from tribal members (Columbia River Inter-Tribal Fish Commission, 2011; Close et al., 2002; Luzier et al., 2011). Pacific lamprey populations entering the Columbia River have decreased concurrently with anthropogenic changes to the Columbia River that include the construction of hydroelectric and flood control dams, irrigation and municipal water diversions, habitat degradation and loss, and poor water quality (Close et al., 2002; Wang & Schaller, 2015; Columbia River Inter-Tribal Fish Commission, 2011). Obstacles including mainstem and tributary dams may have blocked access to much of the Columbia River Basin's historic spawning and freshwater rearing habitat for Pacific lamprey (Wang & Schaller, 2015; Poirier, 2020). Destruction of spawning and rearing areas, loss of migrating juveniles to turbine structures at dams and non-native predators, and a decrease in access to spawning habitats has made lamprey more susceptible and impeded their ability to increase population numbers (Moser & Close, 2003).

Anthropogenic disturbances, such as dams, levees, dikes, and habitat destruction methods, have resulted in changes to water flow, reduced transport of sediments, and habitat loss in the Columbia River Estuary (Close et al., 2002, Luzier et al., 2011, Jolley et al., 2012a). The Bonneville Dam is the first major challenge that adult Pacific lamprey face as they return to spawn and an estimated 50 percent of adult lamprey are unable to migrate above the dam (Jolley et al. 2012a, Columbia River Inter-Tribal Fish Commission, 2011). Dams have implemented fish by-pass structures specifically designed for salmon passage; however, Pacific lamprey cannot use these structures to cross dams, and this may contribute to the loss of thousands of lamprey (Columbia River Inter-Tribal Fish Commission, 2011). As a result, Pacific lamprey may have been extirpated from the upper reaches of the Columbia River Basin (Wang & Schaller, 2015) and may try to locate habitat to spawn below the Bonneville Dam. Dams, irrigation diversions, levees, and habitat destruction may contribute to the decline of lamprey by delaying or slowing migration, and by increasing opportunities for predators to obtain lamprey (Poirier, 2020). Bonneville Dam may be an area where the mortality of Pacific lamprey may increase because of the gathering of predators (Poirier, 2020). Juvenile lamprey travel along the river and estuary as they migrate to the ocean and can become caught in dam turbines and screens, or hunted by predators (Moser & Close, 2003; Columbia River Inter-Tribal Fish Commission, 2011). A study by Moser and Close (2003) stated that the absence of larval lamprey in upper areas of sampled tributaries indicate that recruitment may be failing to occur in upper locations of the Columbia River Basin, and they speculate that this may be due to hydropower dams that restrict access to spawning areas by adult lamprey. Additionally, the operations at Bonneville Dam may be affecting the movement of larval lamprey, causing the return of fewer spawning adults, which may result in fewer larvae produced and prevent the recovery of lamprey populations (Jolley et al., 2012a).

Climate Change Concerns

Climate change in the Columbia River Estuary may exacerbate many of the threats to Pacific lamprey that were listed in the previous section, especially changes in water flow, ocean conditions, water quality, predation, and stream conditions (Luzier et al., 2011). In addition, there may be a reduction in sediment transport, and the degradation and loss of essential lamprey habitat in the Columbia River Estuary (Luzier et al., 2011). Any alterations to the environment due to climate change may negatively affect Pacific lamprey's ability to move through the Columbia River Estuary and/or locate habitats for spawning and rearing (Luzier et al., 2011; Close et al., 2002). Increases in the Columbia

River Estuary's water temperatures are also a factor of concern for the survivability of Pacific lamprey (Poirier, 2020). Warmer water temperatures are likely a cumulative result of an increase in air temperatures, and synergistic effects of water withdrawal along with land use activities in tributary and main stem areas of the Columbia River Estuary (Poirier, 2020). Temperatures of water located below Bonneville Dam can frequently surpass 19°C from late June to early September (Poirier, 202). The warmer water temperatures models of the Columbia River Estuary are concerning due to the impact that temperatures may have on Pacific lamprey, their spawning potential, and larval lamprey (Poirier, 2020). In addition, climate change models that predict temperature increases may expand the territory of warmwater predators into streams, putting further stress on native fish communities and Pacific lamprey populations (Poirier, 2020). Water quantity may also become a more prevalent issue as climate change leads to less available water in the Columbia River Estuary (Clemens et al., 2020). Due to the issue with water quality, water quantity, and climate change, the Oregon Department of Fish and Wildlife Service's Water Quality and Quantity Program plans to continue to identify areas where lamprey do not have instream flow protections, determine the specific instream flow protection needs for lamprey, and partner with other organizations to protect instream flows. (Clemens et al., 2020).

Pacific Lamprey Status

Pacific lamprey are designated as a species of concern by the U.S. Fish and Wildlife Service (Poirier, 2020; Luzier et al., 2011; Wicks-Arshack et al., 2018). In Oregon, Pacific lamprey are designated as a vulnerable and sensitive species, and in Washington State, Pacific lamprey are a state-monitored species (Luzier et al., 2011). States within the Columbia River Estuary have afforded Pacific lamprey several degrees of protection. In Washington State, it is illegal for any person to harvest Pacific lamprey (Moser & Close, 2003). Under Oregon law, except for Willamette Falls, "it is unlawful for any person to hunt, trap, pursue, kill, take, catch, angle for, or have in possession, either dead or alive, whole or in part" Pacific lamprey (Moser & Close, 2003). However, these state laws do not generally apply to tribal members who exercise their treaty rights (Moser & Close, 2003). Willamette Falls is the primary site of lamprey harvesting in the Columbia River Estuary (Luzier et al., 2011; Moser & Close, 2003). The U.S. Fish and Wildlife Service acknowledged in its Pacific Lamprey Conservation Assessment that this type of harvest is not a significant factor in the decline of Pacific lamprey (Luzier et al. 2011). In terms of the Endangered Species Act, Pacific lamprey fall under the jurisdiction of the U.S. Fish and Wildlife Service (Wicks-Arshack et al., 2018). The U.S. Fish and Wildlife Service have federal jurisdiction and authority to review petitions for listing lamprey under the Endangered Species Act, implement conservation initiatives, and issue rules or policy (Luzier et al., 2011; Wicks-Arshack et al., 2018).

Concerns about the survival of Pacific lamprey led to a petition to the U.S. Fish and Wildlife Service in 2003 for Pacific lamprey to be listed under the Federal Endangered Species Act (Hayes et al., 2013). In January 2003, eleven environmental groups, led by the Siskiyou Regional Education Project, petitioned the U.S. Fish and Wildlife Service to list lamprey under the Endangered Species Act as threatened or endangered and designate critical habitat for four lamprey species (Luzier et al., 2011; Wicks-Arshack et al., 2018). These species included Pacific lamprey, river lamprey, western brook lamprey, and kern brook lamprey, all found in California, Oregon, Washington, and Idaho (Luzier et al., 2011; Wicks-Arshack et al., 2018). The petition for listing was due to the dramatic declines in lamprey populations and an increased understanding of ecological and cultural values of lamprey (Luzier et al., 2011; Wicks-Arshack et al., 2018). The petitioners claimed the listing of these four species was warranted under each of the five factors set forth in Section 4 of the Endangered Species Act (Luzier et al., 2011; Wicks-Arshack et al., 2018). However, most of the petition focused on two of the listing factors: the “present or threatened destruction, modification or curtailment of its habitat or range” and the “inadequacy of existing regulatory mechanisms” (Luzier et al., 2011; Wicks-Arshack et al., 2018).

The petition presented to U.S. Fish and Wildlife Service referred to Pacific lamprey population declines, the impact of dams and other artificial barriers on upstream and downstream migration, dewatering of streams, and habitat degradation as among the threats that justified listing (Luzier et al., 2011; Wicks-Arshack et al., 2018). The petition identified a lack of monitoring data or a lack of information regarding the three other listing factors (Luzier et al., 2011; Wicks-Arshack et al., 2018). In December 2004, the U.S. Fish and Wildlife Service published their finding, in which they stated that “neither the information provided in the petition nor otherwise available in service files presents substantial scientific or commercial information to demonstrate that the petition to list Pacific lamprey located in the lower 48 states may be warranted” and that “accordingly, we are unable to define a listable entity of the Pacific lamprey” (Luzier et al., 2011; Wicks-Arshack et al., 2018). U.S. Fish and Wildlife Service determined that listing Pacific lamprey under the Endangered Species Act was not justifiable because of a lack of information and unique life history, and that Pacific lamprey were not a “listable entity” meaning that lamprey in the U.S. did not constitute a sufficient subset of the overall Pacific lamprey population (Luzier et al., 2011; Wicks-Arshack et al., 2018).

The U.S. Fish and Wildlife Service findings did not prompt a formal status review, however, the U.S. Fish and Wildlife Service pledged to continue to work with tribe co-managers to further research and gather information related to lamprey conservation measures (Poirier, 2020; Luzier et al., 2011; Wicks-Arshack et al., 2018). Specifically, the U.S. Fish and Wildlife Service encouraged additional information gathering and research to increase understanding of lamprey species (Luzier et al., 2011). The implementation of conservation actions in a coordinated manner can be viewed by the U.S. Fish and Wildlife Services' effort to create the Pacific Lamprey Conservation Agreement and Conservation Initiative (Luzier et al., 2011; Wicks-Arshack et al., 2018). The Pacific Lamprey Conservation Initiative and projects focused on threats to lamprey existence and were the result of the continued work and rejection of endangered species status for Pacific lamprey (Poirier, 2020; Luzier et al., 2011; Wicks-Arshack et al., 2018). The petition's rejection and the decision by the U.S. Fish and Wildlife Service were also a mechanism for tribes along with state and federal agencies to conduct further research to increase understanding of these species, and to plan lamprey restoration measures (Wicks-Arshack et al., 2018). Suggestions for the survival of Pacific lamprey include placing importance on coordinated conservation efforts coupled with legal protections that recognize Pacific lamprey's unique life history and importance to Columbia River Basin tribes and First Nations (Wicks-Arshack et al., 2018).

The Pacific Lamprey Conservation Agreement and Initiative built upon recommendations in the Tribal Pacific Lamprey Restoration Plan put forward by the member tribes of the Columbia River Basin ecosystem and tribes in the Columbia River Inter-Tribal Fish Commission (Luzier et al., 2011). The Pacific Lamprey Conservation Initiative establishes regional implementation plans by collaborating with tribal, federal, state, watershed councils, and other local partners (Clemens et al., 2017). The Pacific Lamprey Conservation Initiative develops implementation plans for each regional management unit by identifying threats, knowledge gaps, and developing conservation actions (Hayes et al., 2013; Wang & Schaller, 2015). These voluntary agreements and project proposals serve as the primary method to implement conservation actions within the Columbia River Basin specific to the Pacific lamprey (Poirier, 2020). The initiative states that additional research, monitoring, and evaluation including lamprey specific surveys and lamprey identification are necessary to provide more information on lamprey (Luzier et al., 2011). In addition, a lamprey technical workgroup acts as an advisory group to the conservation team of the Conservation Agreement and consists of several subgroups in areas such as tagging, passage metrics, and genetics and environmental DNA (Poirier, 2020; Luzier et al., 2011). Other conservation plans include the U.S. Army Corps of Engineers collaborating with tribes and the U.S. Fish and Wildlife Service to develop a 10-year passage improvement plan for Pacific lamprey on the Columbia and Snake Rivers (Clemens et al., 2017).

PROJECT AREAS OF FOCUS

Focal Phase: Larvae

For our project, we focused on the larval stage of Pacific lamprey in the Columbia River and Estuary. Complex life histories contribute to the susceptibility of Pacific lamprey to environmental and anthropogenic change (Lamprey Technical Workgroup, 2021). The decline in lamprey may be due to recruitment failures that stem from the reduction of spawning or rearing habitats in streams, which may then lead to a decline in larval lamprey populations (Moser & Close 2003). There may be many challenges for the larval phase of Pacific lamprey which include anthropogenic disturbances, such as levees and dredging, changes in hydrologic stream flow regimes (Elsner et al., 2010), habitat loss (Rostaminia, 2017), and water quality conditions, such as contamination (Nilsen et al., 2015). Therefore, it is important to understand how both physical and chemical changes in habitat conditions affect larval lamprey survival. The larval stage is significant because larvae can stay in this specific life phase for a substantial amount of time, ranging from three to ten years (Clemens et al., 2020; Silver et al., 2007; Luzier et al., 2011; Porter et al., 2021). The many years in the larval stage makes them more vulnerable to changes that could impact their survival to adulthood such as temperature changes, dredging, and pollutants (Blanchard et al., 2021; Gonzalez et al., 2017). Any significant changes to the larval environment have the potential to eliminate several generations and age classes of larvae at once, especially if larvae occur in high densities, and could result in the decline of the Pacific lamprey population (Luzier et al., 2011; Columbia River Inter-Tribal Fish Commission, 2011). Shifts in the conditions in the Columbia River Estuary due to climate changes may cause a survival-related bottleneck for the larvae phase due to the extended period in the larvae phase and the potential for exposure to extreme alterations in the environment (Wang et al., 2020; Elsner et al., 2010). The lack of knowledge about the movement of larvae and their preferred habitats in the Columbia River Estuary has added to the challenge of understanding larvae and was another factor in our choice of the larvae stage (Silver et al., 2007; Jolley et al., 2012a).

Larval Lamprey Habitat

Larval lamprey spend their larval phase in fine sand or silt sediment habitats (Clemens et al., 2020; Close et al., 2002; Porter et al., 2021). Environments necessary for the survival of larval lamprey must include a consistent amount of food sources and enough sediment to allow for burrowing (Lamprey Technical Workgroup, 2021). Habitats where larval lamprey have been observed include shallow depositional areas, mainstem dredged habitats in deep water (> 16 m), and the Portland Harbor area (Jolley et al., 2012b). However, the extent of additional habitat used by lamprey during the larval phase is unknown (Silver et al., 2007).

Pacific lamprey rely on the Columbia River Estuary as the primarily migratory corridors for juvenile and adult Pacific lamprey to and from freshwater environments (Silver et al., 2007). Still, the use of the Columbia River Estuary by larval and adult lamprey as an environment that could support suitable spawning and rearing locations has yet to be fully investigated (Silver et al., 2007). Other potential factors beyond sediment that may influence larval lamprey habitat selectivity could include land cover, or shoreline characteristics, in the identification of suitable larval habitat. Locations along the main-channel or in shallow off-channel pools, where water flow can be slower and microhabitats are shallower, are critical for larval survival (Vadas, 2017). Within the desired off-channel microhabitats, it is important to consider the habitats that line the water's edge. Because of the protection and promotion of algae and detritus growth (Kelly & King, 2001; Stone & Barndt, 2005), forested or shrubby wooded shoreline sites are the most optimal for habitat selection (Vadas, 2000). Through the comparison of locations of potentially suitable habitat with the shoreline features identified in the Columbia River Estuary, we may be able to determine which habitats and areas would be better for future projects in the conservation of larval lamprey.

Environmental Parameters

The identification of limiting factors for Pacific lamprey in their early life stages is essential to the project and recovery efforts, due to these early life stages being essential for recruitment (Meeuwig et al., 2003). Limiting factors such as water temperature, salinity levels, flow of water, and sediments are essential to assessing suitability of available habitats (Meeuwig et al., 2003).

Environmental Parameters - Temperature

Thermal conditions can greatly influence the quantity and quality of habitat available to Pacific lamprey and aquatic organisms in the Columbia River Estuary (Meeuwig et al., 2005). Recent alterations to the thermal regime of the Columbia River Estuary, such as increases in spring and summer temperatures, have prompted interest in the habitat requirements and thermal ecology of aquatic species within the Estuary (Meeuwig et al., 2005). Since temperature is of great importance to aquatic life, knowledge about how temperature affects Pacific lamprey, their larvae, and other species, is essential to understanding the basic ecology of the species (Meeuwig et al., 2005). Water temperature can impact how communities form and interact with the environment, habitat selection and separation, physiological rates, reproductive timing, and survival and fitness of individuals (Meeuwig et al., 2005). As cold-blooded species, lampreys can directly be affected by the temperature of their environment (Meeuwig et al., 2005). Due to changes in weather and conditions in the Columbia River Estuary, Pacific lamprey may be exposed to a broad range of thermal conditions (Meeuwig et al., 2005). Discharge water from dams, storms, and stream temperatures can affect the physiological processes of Pacific lamprey, regardless of life stage (e.g., respiration rates) (Wang et al., 2020).

Studies completed on tributaries with larval lamprey recorded water temperatures that varied from 13.7 degrees Celsius to 23.8 degrees Celsius (Moser & Close, 2003; Meeuwig et al., 2005; Clemens et al., 2020). From laboratory experiments on early life stages of larval lamprey, optimal temperature ranges were noted from 10 to 18 degrees Celsius (Goertler et al., 2020; Vadas, 2017). Additional laboratory experiments on early life stages of Pacific lamprey focused on the response to temperature as measured by the proportion of individuals that survive to hatch and survive to the larval stage (Meeuwig et al., 2005). Survival was greatest at 18 degrees Celsius, followed by 14, 10 and 22 degrees (Meeuwig et al., 2005). The studies generated information and evidence that will offer researchers a reference to refer to with temperature conditions for early life stage Pacific lamprey and will support the assessment and prediction of suitable spawning and rearing habitats for lamprey in the Columbia River Estuary.

Environmental Parameters - Salinity

Salinity levels can impact Pacific lamprey and vary in the Columbia River Estuary from releases of freshwater from Bonneville Dam, freshwater runoff from storms, and great tidal and wave activity from the Pacific Ocean (Lower Columbia Estuary Partnership, 2022b). Laboratory experiments that transferred larval lamprey from freshwater into media with fixed salinity indicated that lamprey species are obligate freshwater species and are only able to tolerate a narrow range of salinity (Silver, 2015). During the experiments, larval Pacific lamprey had a 50% mortality rate at 12.2 parts per thousand (Silver, 2015). In the fixed salinity experiments, higher salinity concentrations resulted in lower larval survival rates (Silver, 2015). A 100 percent survival rate occurred for up to 96 hours in tests at 0 parts per thousand, 6 parts per thousand, 8 parts per thousand, and 10 parts per thousand experiments (Silver, 2015). Additional studies documented larval lamprey having trouble with tolerating salinities greater than 12 parts per thousand (Goertler et al., 2020). As larval Pacific lamprey survive and move through the Columbia River Estuary, the transition in salinity is likely to be less abrupt, and more salinity mixture may be possible (Goertler et al., 2020). Therefore, estuarine rearing may be limited by future changes in salinity and salinity intrusion (Goertler et al., 2020).

Environmental Parameters - Sediment

Pacific lamprey spend their larval stage burrowed in fine sand or silt sediment habitats where they filter feed; therefore, sediments have an essential role in their life cycle and distribution in the Columbia River Estuary (Clemens et al., 2020; Close et al., 2002). The Columbia River Estuary has fine silt and sediment, which are regarded as prime habitat for larval lamprey rearing (Poirier, 2020; Jolley et al., 2012a). As larval lamprey continue to grow in the larval stage, they move from fine sediment habitats in slow water, towards areas with coarser sediments and faster moving water (Lamprey Technical Workgroup, 2021). The Columbia River Estuary Data Development Program initiated an extensive bottom sampling program to provide data on sediment size and to characterize grain-size distributions in the Columbia River Estuary (Sherwood & Creager, 1990). They observed seasonal and spatial variations in sediment distribution from samples collected throughout the Estuary (Sherwood & Creager, 1990). Columbia River Estuary sediments are documented to be mostly sand, with a narrow range of size distributions (Sherwood & Creager, 1990). New loads of sediments and nutrients flow into the Columbia River Estuary usually between late autumn and the early spring and coincide with an increase in freshwater from storms and snowpacks (Baptista et al., 2015).

John Crandall and Eric Wittenbach of the Methow Salmon Recovery Foundation developed a classification system for larval lamprey and sediments to systematize sediment presence and identify the distribution of habitat types (Crandall & Wittenbach, 2015). The authors categorized sediment and larval lamprey habitat into three distinct types: Type I, Type II, and Type III (Figure 5) (Crandall & Wittenbach, 2015). Type I habitats can have fine sediment including silt, sand, and detritus, along with medium-high organic matter and are frequently used by larval lamprey (Crandall & Wittenbach, 2015). Type I habitat can usually be found in specific areas and can either remain in these same locations from year to year or move and develop in new sites depending on yearly speeds in the buildup of sediment (Crandall & Wittenbach, 2015). Type II habitat can include variable coarse sand, small gravel, low organic matter, and are somewhat used by larval lamprey (Crandall & Wittenbach, 2015). Type III habitat can contain large gravel, including bedrock, boulders, cobble with low or no organic matter, and larval lamprey are rarely found in this type of habitat (Crandall & Wittenbach, 2015). Due to their presence of fine sediment, Type I habitats should be the focus of consideration when identifying habitats and sediments for larval lamprey in the Columbia River Estuary.

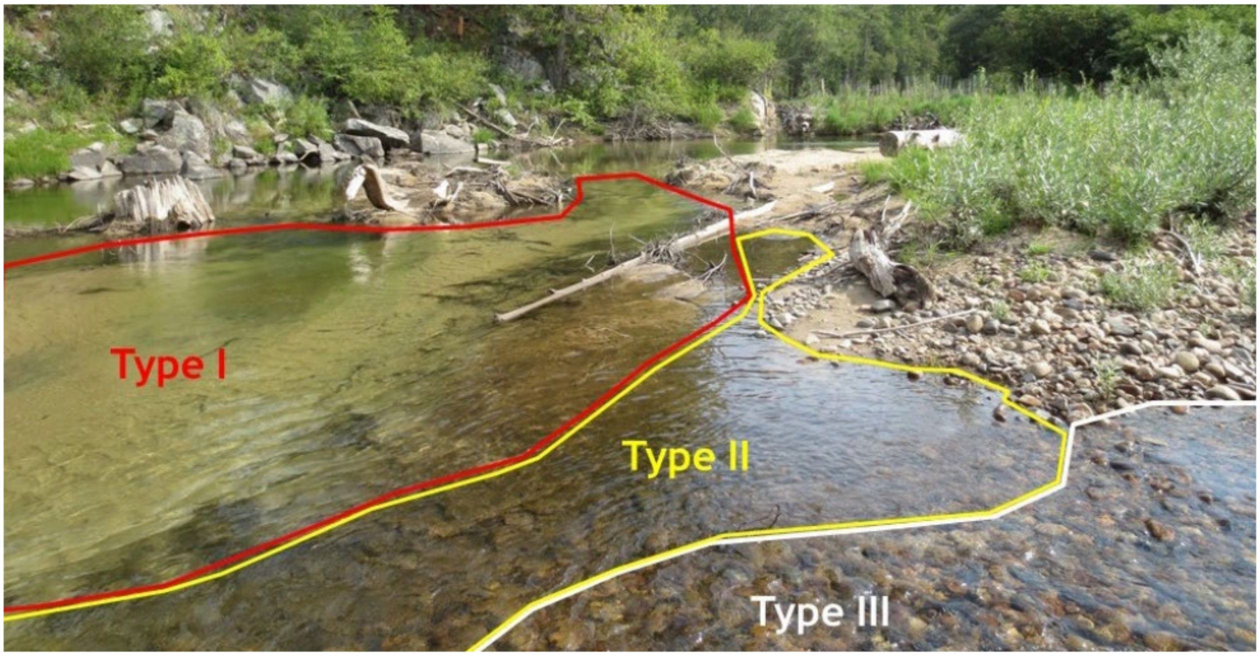

Figure 5: Categorization system for sediment and habitat types used by Pacific lamprey in aquatic environments. John Crandall and Eric Wittenbach of the Method Salmon Recovery Foundation determined three distinct types of sediment in their 2015 Pacific Lamprey Habitat Restoration Guide. Type I consists of fine sediment of sand, silt, and organic matter. Type II contains coarse sediment, small gravel, and low organic matter. Type III involves bedrock, boulders, and no to low organic matter. Type I is documented as being most consistently used by lamprey, Type II is slightly used by lamprey, and Type III is the least used by lamprey. Larval lamprey will more likely be found in Type I habitat and sediments. Data Source: Crandall & Wittenbach, 2015. Photo Credit: Ralph Lampman.

Environmental Parameters - Water Flow

The larval lamprey phase occurs in habitats and streambanks with slow water movement that include pools, alcoves, and side channels (Clemens et al., 2017). As larvae begin to undergo metamorphosis and the juvenile phase, they migrate towards habitats with faster flowing water (Jolley et al., 2012a). Larval occurrence corresponds with low water velocity, pool habitats, and the availability of suitable burrowing habitat (Luzier et al., 2011). Notable information about the Columbia River Estuary includes average daily discharges at Bonneville Dam that range from 2,000 $m^{3}*s^{-1}$ in the early fall to 15,000 $m^{3}*s^{-1}$ during spring freshets (Baptista et al., 2015). Tides, discharge from Bonneville Dam, and runoff from storms and snow melt add water to the Columbia River Estuary and affect the rate of flow (Karna et al., 2015). Changes to the habitat from dredging, vegetation removal, and sediment amounts will cause water flow to fluctuate in different regions of the Columbia River Estuary and may impact larval lamprey burrowing locations (Marcoe & Pilson, 2022; Jolley et al., 2012b).

Non-Environmental Parameters

The Columbia River Estuary has been changed by anthropogenic disturbances, such as levees, dikes, and dams, which have resulted in changes to water flow regimes, reduced sedimentation transport, and habitat loss, and may impact Pacific lamprey (Close et al., 2002, Luzier et al., 2011, Jolley et al., 2012a). Additionally, the Columbia River Estuary has experienced the loss of side channels and native vegetation removal (Luzier et al., 2011). Changes such as channelization and the conversion of land for agriculture, grazing, and development (rural, urban, commercial, industrial) have reduced or eliminated a substantial amount of side channel and wetland habitat (Luzier et al., 2011). The Columbia River Estuary is the region found below Bonneville Dam that has been channeled and limited by major railroad and transportation passageways that are located parallel to the Columbia River (Luzier et al., 2011). The shoreline of the Columbia River Estuary has levees along edges armored with riprap and tributaries have been modified from the addition of culverts and bridges (Luzier et al., 2011). Many anthropogenic impacts have been implicated in the decline of lamprey populations and their struggle to increase in numbers (Jolley et al., 2012a; Close et al., 2002). Passage barriers (including culverts, dams, and bypass screens) can harm or kill lamprey, or prevent lamprey from spawning or depositing marine-derived nutrients to watersheds (Clemens et al., 2017). Researchers believe that larval lamprey may have historically used the Estuary and tributary habitats more evenly in the Columbia River where natural rearing habitats occurred (e.g., natural depositional areas, side channels) (Jolley et al., 2012a). However, more studies on larval lamprey movement, passageways and survival rates at Columbia River dams would significantly improve the understanding of the relative importance and potential impacts on larval lamprey populations (Jolley et al., 2012a).

Non-Environmental Parameters - Levees

Levees are one of several anthropogenic factors that have altered the flow of the Columbia River, and many are in the Columbia River Estuary (Poirier, 2020). Vegetation in the Columbia River Estuary has been eliminated and constrained by extensive levees throughout the Estuary (Luzier et al., 2011). Levees have had a negative impact on larval Pacific lamprey by separating the Columbia River from floodplains and estuary habitat (e.g., tidal swamp, marsh, wetlands) (Poirier, 2020). These actions have reduced the Columbia River to one main channel and can separate larval lamprey from suitable habitat that they may need for spawning and rearing (Goodman & Reid, 2012). The Army Corps of Engineers maintains many of the levees in the Columbia River Estuary, and the levees are located around or near agricultural lands (Poirier, 2020). Research on larval lamprey usage in the Columbia River Estuary would need to take into consideration the continued impact of levees on estuary habitats and potential spawning and rearing locations.

Non-Environmental Parameters - Dredge Sites

Efforts in the Columbia River Estuary to maintain the shipping channel (such as jetties and pile dikes) have altered flow patterns and increased sediment accumulation that requires dredging to remove (Poirier, 2020; Clemens et al., 2020). Lampreys of various age classes are present in freshwater year-round, therefore in-water work windows for dredging can impact all life stages of lamprey (Lamprey Technical Workgroup, 2021). Dredging is deemed a threat and may contribute to the decrease in the number of Pacific lamprey in the Columbia River Estuary and Basin (Lamprey Technical Workgroup, 2021). The dredging of the Columbia River Estuary could eliminate or disrupt sediments where larval lamprey could live (Crandall & Wittenbach, 2015). Dredged substrates (spoils) are removed from the water and disposed of on land, potentially leaving larval and juvenile lampreys susceptible to undesirable conditions (Lamprey Technical Working Group, 2021). Generally completed using heavy machinery, dredging may harm lamprey by crushing and drying out soil, when sediment that contains lamprey is taken from the water and placed on the shorelines surrounding the Columbia River Estuary (Crandall & Wittenbach, 2015). Road construction, ditch and shipping channel maintenance, irrigation, and stream restoration projects could include dredging operations (Crandall & Wittenbach, 2015). Dredging can remove larval lamprey from the fine sediment they burrow in and kill larval Pacific lamprey by placing them on the land, which dries them out or makes them susceptible to predation. (Clemens et al., 2017). The impacts of dredging on larval lamprey and their potential spawning and rearing habitats may be a critical issue to focus on for future studies, since effects from dredging and the channel maintenance on species in the Columbia River Estuary have not been fully documented (Poirier, 2020).

Non-Environmental Parameters - Restoration Projects

Although many habitat restoration projects have been and continue to be implemented for salmonid populations, few studies and data exist on if lamprey populations could benefit from these restoration projects and techniques (Roni et al., 2015; Gonzalez et al., 2017). Efforts in the Columbia River and Estuary have focused on the restoration of habitats for salmonid species, such as the establishment of wooden structures and riparian vegetation to improve salmon habitat (Poirier, 2019, Gonzalez et al., 2017). However, there are very few studies on how salmon restoration projects can impact Pacific lamprey and larval lamprey populations (Poirier, 2019, Gonzalez et al., 2017). Large wood is frequently used for stream restoration in the Pacific Northwest and the benefits of such restoration to fish are being studied (Stewart et al., 2009). However, studies on non-salmonid species, such as lamprey, and restoration strategies and projects are limited (Stewart et al., 2009). Lamprey and other species could have vastly different habitat requirements when compared to salmonid species, and less is known about how lamprey respond to large wood (Stewart et al., 2009; Clemens et al., 2017).

Differences in restoration projects take place due to variations in design, locations, and the size of restoration projects, along with the availability of biological information used to determine their effectiveness (Stewart et al., 2009). Another factor is the possibility that a variety of species or life stages may have different responses when restoration projects implement large wood in a river (Stewart et al., 2006; Roni, 2003).

Habitat restoration is needed to address issues with water quality, water quantity, and habitat access for larval lamprey in the Columbia River Estuary (Clemens et al., 2020). Habitat restoration can be addressed by restoring natural river processes, promoting the connection between ground and surface waters, improving riparian vegetation, and inhibiting expansion of non-native predatory species (Clemens et al., 2020). Recent studies have been completed to evaluate salmon restoration methods and wooden structures on larval Pacific lamprey (Gonzalez et al., 2017; Poirier, 2019). Large woody structures can benefit streams by affecting the structural complexity of the channel by creating pools, increasing the accumulation of fine soil material and organic matter for larval lamprey (Gonzalez et al., 2017). Results show a link between large wood and habitat used by larval lamprey (Gonzalez et al., 2017). Larval lampreys were found to be more prevalent in pools with greater surface area of fine sediment and greater sediment depth regardless of sediment type, and each of these habitat conditions was positively associated with instream large woody structures (Gonzalez et al., 2017). Studies should provide important insights into restoration, lamprey, and a much broader perspective of opportunities and future projects that protect and restore larval lamprey habitat in the Columbia River Estuary (Clemens et al., 2017; Gonzalez et al., 2017).

Non-Environmental Parameters - Barriers

Interest in passage and barriers for Pacific lamprey on tributaries in the Columbia River Estuary are due to their impact on the larval and adult life stages (Poirier, 2020). Irrigation and municipal screens, as well as dams in tributaries prevent lamprey from reaching their spawning ground and migratory habitat, thus reducing spawning and rearing opportunities, and larval populations (Columbia River Inter-Tribal Fish Commission, 2011). There is a lack of information about the movement of lamprey around barriers in the Columbia River Estuary and tributaries (Poirier, 2020). Road crossing tunnel structures are common in the Columbia River Estuary and may fragment aquatic habitats and prevent the migration of lampreys upstream (Poirier, 2020). Tide gates are found in tidal influenced streams in the Columbia River Estuary; they do not allow tidal backflow and provide few chances for fish to pass them (Poirier, 2020). Many culverts near stream mouths in the Columbia River Estuary are considered impassable and prevent access to miles of potential habitats for adult lampreys to move upstream and spawn (Poirier, 2020). Barrier removal projects have occurred in the Columbia River Estuary, however more work is necessary to focus on the passage needs of adult and larval Pacific lamprey (Poirier, 2020). Currently, a project by the Lower Columbia River Watershed Council (through the Pacific Lamprey Conservation Initiative) is focusing on the issue of barriers in the Columbia River Estuary (Poirier, 2020). The aim of the project is to inventory and assess potential barriers for lamprey and recommend passage solutions in high priority sites for Pacific lamprey (Poirier, 2020). Since habitat access is a limiting factor for adult and larval lamprey, future projects are encouraged to focus on identifying and eliminating barriers to Pacific lamprey habitats of the Columbia River Estuary (Clemens et al., 2020).

Non-Environmental Parameters - Contamination Sites

Studies have found adult lamprey avoid contaminated sediments, and larval and adult lamprey do not attempt to burrow in highly contaminated sediments (McIlraith et al., 2017). Pesticides, flame retardants, mercury, and dichloro-diphenyl-trichloroethane (DDT) are among the common contaminants of concern found throughout the Columbia River Estuary (McIlraith et al., 2017). In the Portland Harbor Superfund Site on the Willamette River, habitat restoration actions have been implemented and focus on the recovery of juvenile Chinook salmon (Blanchard et al., 2021). The methods utilized in the habitat restoration of the Superfund areas may also affect Pacific lamprey (Blanchard et al., 2021). In 2000, a section of the mainstem of the lower Willamette River was declared a Superfund site by the U.S. Environmental Protection Agency, and larval Pacific and Western Brook lamprey have been documented in the area (Blanchard et al., 2021). The use of restored habitats by lamprey, specifically the larval life stage, has not been widely studied (Blanchard et al., 2021). The U.S. Fish and Wildlife Service determined that monitoring the impact of habitat restoration efforts on larval Pacific lamprey and within areas previously contaminated may provide information on the effectiveness of the restoration methods (Blanchard et al., 2021). Larval lamprey can spend many years burrowed in sediments; therefore, sediment contamination could have a major influence on the physiological processes and population dynamics of the larval life stage (McIlraith et al., 2017). Since larval lamprey can be more susceptible to contaminants because of their burrowing behavior in riverine sediment for several years, future projects should evaluate habitat regions with a high potential of contamination (Close et al., 2002).

Knowledge Gaps

Knowledge gaps have hindered Pacific lamprey conservation and management in the Columbia River Basin (Wang & Schaller, 2015). These knowledge gaps stem in part from a lack of studies on Pacific lamprey, along with a lack of demographic, biological, and ecological information about lampreys in the Columbia River Basin (Wang & Schaller, 2015). The client’s Tribal Pacific Lamprey Restoration Plan and a federally led conservation initiative aim to reverse Pacific lamprey population declines and restore them to their historical range by addressing threats to lamprey and knowledge gaps about the species (Clemens et al., 2017). The act of quantifying habitat variability can provide a baseline to address the range of potential changes and habitats available in the Columbia River Estuary (Rostaminia, 2017). Several major river mouths located below Bonneville Dam and in the Columbia River Estuary are considered suitable fine sediment habitats and have detected larval lamprey within their range (Jolley et al., 2012a). Besides being in the larval stage for three to ten years, there is less information known about the use of additional habitat by larval lamprey, such as larger river and estuarine habitats during the larval phase (Silver et al., 2007; Jolley et al., 2012a; Porter et al., 2021). In addition, the lack of knowledge about the movement of larvae, their preferred locations in the Columbia River Estuary, and their population dynamics have added to the challenges of understanding larvae (Silver et al., 2007; Jolley et al., 2012a). The presence of baseline detection information with further investigation into downstream habitat variability may provide insight into potentially unknown larval lamprey habitat. Evidence obtained may fill the knowledge gap and provide information for the implementation of management actions to increase Pacific lamprey abundance in the Columbia River Estuary and throughout their historical range. It will be essential for restoration projects to understand the larval lamprey phase, determine environmental parameters associated with larval lamprey, and identify habitats that support adult and larval lamprey to protect Pacific lamprey in the Columbia River Estuary.

PROJECT OBJECTIVES

The goal of this project is to determine where preferred larval Pacific lamprey habitat exists to aid restoration efforts in the Columbia River Estuary. To achieve this goal, we identified the following objectives:

1. Identify the spatial and temporal distribution of suitable habitat for larval Pacific lamprey in the Columbia River Estuary.

2. Provide recommendations for future studies and projects based on factors that may impact the survival and recovery of Pacific lamprey in the Columbia River Estuary.

Deliverables coinciding with our objectives include a selection of maps of larval Pacific lamprey suitable habitat and a set of recommendations for future research and restoration approaches.

METHODS

General Approach

To address our objective of identifying where there are regions of suitable habitat for larval Pacific lamprey in the Columbia River Estuary, we chose to 1) complete a Habitat Suitability Analysis and 2) assess summary statistics to better understand the distribution of suitable habitat. The purpose of this methodology was to identify spatial and temporal trends in suitable habitat as well as to aid in our recommendations for Pacific lamprey habitat restoration in the Columbia River Estuary.

We built our Habitat Suitability Analysis in ArcGIS's Model Builder. The model uses geospatial datasets for temperature, salinity, and geomorphology provided through the Center for Coastal Margin Observation & Prediction and the Lower Columbia Estuary Partnership. The following workflow was used to wrangle and process data:

1. Input the geospatial datasets in the proper coordinate reference system.
2. Clip datasets to the region of interest.
3. Classify values to meet the habitat suitability criteria.
4. Combine monthly outputs to visualize suitable habitat throughout the year.

Figure 6: Workflow used to complete Habitat Suitability Analysis. Temperature, salinity, and geomorphology were inputted and reprojected to be in the same coordinate reference system. The outputs were then clipped to our region of interest, the Columbia River Estuary. Temperature, salinity, and geomorphology were then classified using a binary classification approach, so that only values meeting our suitability criteria were retained. Temperature, salinity, and geomorphology were then summed per month. The total outputs for each month, January through December, were then summed to visualize the amount of suitable habitat available throughout the year.

The criteria chosen for suitable habitat and spatial analyst tools used to process the data inputs are discussed in detail in the following sections.

Temperature

The temperature data, sourced from the Center for Coastal Margin Observation & Prediction, was received as GeoTIFF raster data files (Appendix I). The files contain temperatures from the bottom of the Columbia River, averaged for every calendar month of each year and ranging from 1999-2018 (Figure 7) for a total of 12 files. We constrained the temperature data using a vector layer of the Columbia River Estuary to remove points from outside our region of interest. We then developed two sets of criteria for temperature, based on ranges of larval Pacific lamprey thermal tolerance, to define suitable habitat. *Primary* suitable habitat was defined as habitat with ideal conditions for larval Pacific lamprey, based on both observations and laboratory settings; for temperature, research suggests 10 - 18 °C is the ideal range of temperature to best support larval Pacific lamprey and thus was used for the *primary* suitable habitat criteria (Goertler et al., 2020; Vadas, 2017). Conversations with our client and recent studies suggest a broader range of temperature may still support larval Pacific lamprey. We broadened our suitable habitat range to 8 - 22 °C to reflect this new research and defined it as our criteria for *secondary* suitable habitat. For both *primary* and *secondary* habitat criteria, we used a binary classification approach, categorizing the temperature values as “1,” meaning the values meet the suitable habitat criteria, or “0,” meaning the values do not meet the suitable habitat criteria. The results of the binary classifications produced temperature layers highlighting the areas that met the suitable habitat criteria. This procedure was repeated for each month.

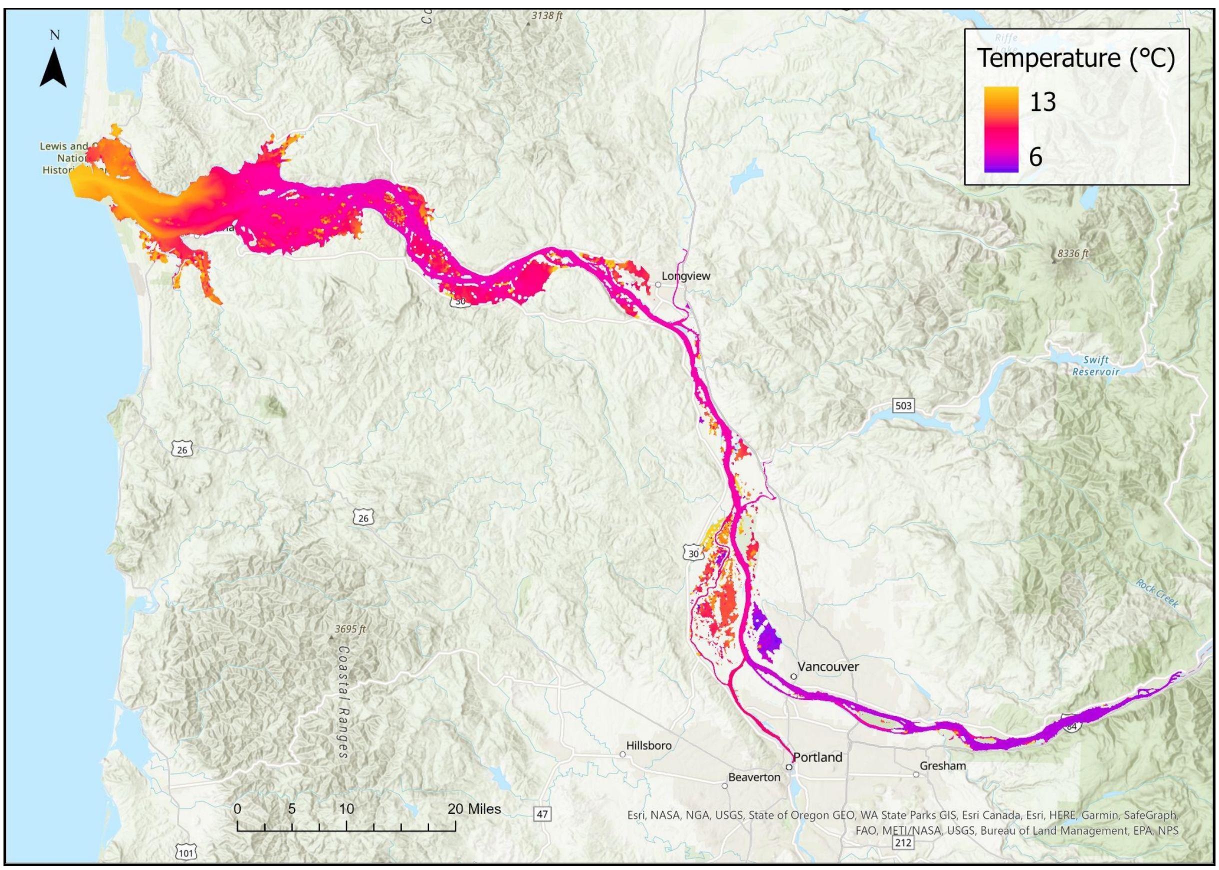

Figure 7. Temperature raster for the month of January. The raster consists of temperature data from the bottom of the Columbia River, summarized for every January between 1999 and 2018. Maximum temperature averages were used and provided in degrees Celsius. Colored regions indicate areas within our project’s region of interest. Purple indicates low temperatures, and orange indicates high temperatures. Equivalent rasters for every month of the year were used in our Habitat Suitability Analysis. Data Source: Center for Coastal Margin Observation & Prediction.

Salinity

The salinity data, sourced from the Center for Coastal Margin Observation & Prediction, was received as GeoTIFF raster data files (Appendix I). The files contain salinity from the bottom of the Columbia River, averaged for every calendar month of each year and ranging from 1999-2018 (Figure 8) for a total of 12 files. We constrained the salinity data using a vector layer of the Columbia River Estuary to remove points from outside our region of interest. We then used a binary classification approach to the salinity values to categorize them as “1,” meaning the values meet the suitable habitat criteria, or “0,” meaning the values do not meet the suitable habitat criteria. Research indicates larval Pacific lamprey have difficulty tolerating salinities greater than 12 parts per thousand (ppt) (Goertler et al., 2020), so we selected a range from 0 - 12 ppt as the *primary* suitable habitat criteria. A broader range of salinity tolerance was not apparent, with research showing larval mortality beginning with a salinity level of 12.2 ppt under experimental conditions (Silver, 2015). Therefore, for *secondary* suitable habitat, the same 0 - 12 ppt criteria range was applied. The results of the binary classifications produced salinity layers highlighting the areas that met the suitable habitat criteria. This procedure was repeated for each month.

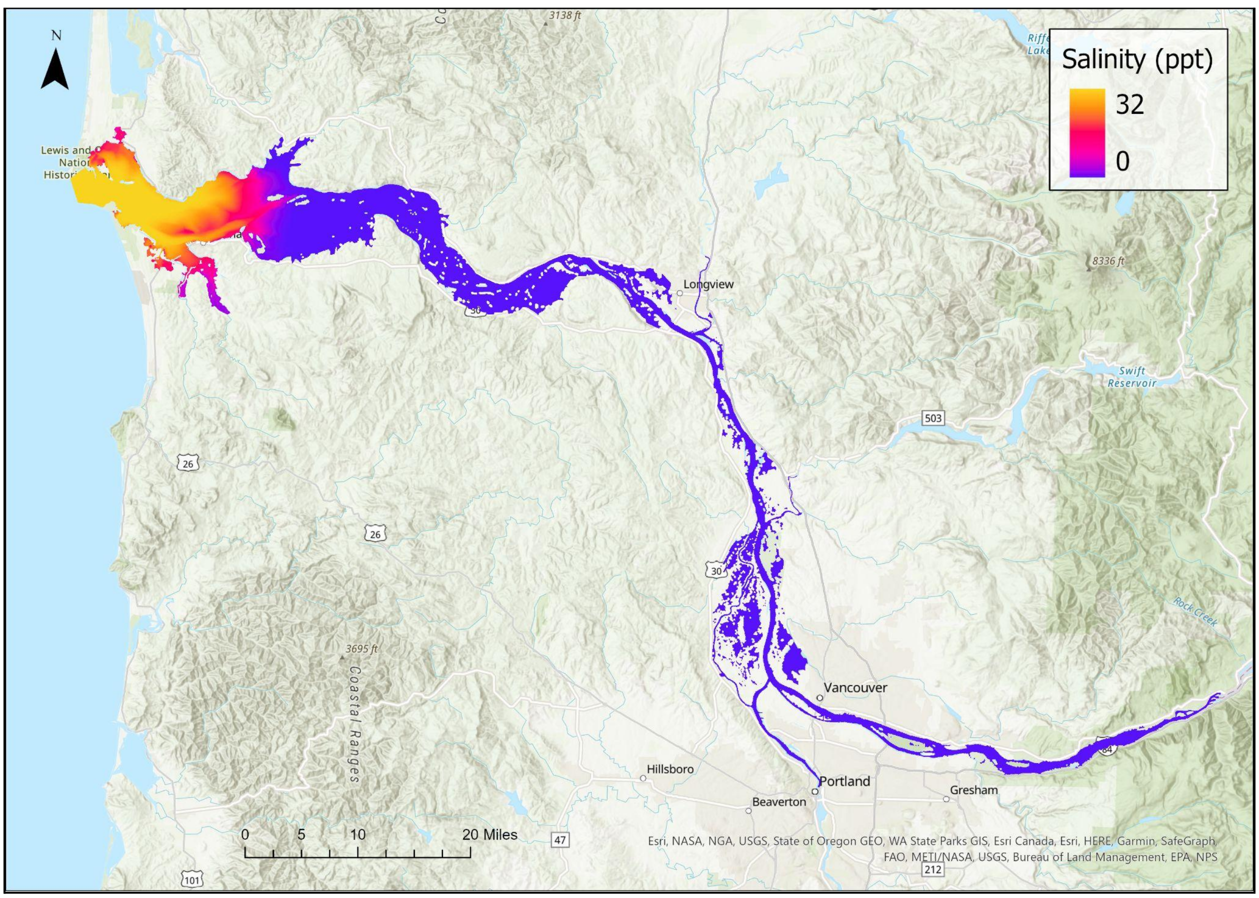

Figure 8: Salinity raster for the month of January. The raster consists of salinity data from the bottom of the Columbia River, summarized for every January between 1999 and 2018. Maximum salinity

averages were used and provided in parts per thousand. Colored regions indicate areas within our project's region of interest. Purple indicates low salinity, and orange indicates high salinity. Equivalent rasters for every month of the year were used in our Habitat Suitability Analysis. Data Source: Center for Coastal Margin Observation & Prediction.

Geomorphology

The geomorphology data were obtained from the Lower Columbia Estuary Partnership as a shapefile containing geomorphic catena layers, defined as individual landforms within the Columbia River's ecosystem complexes that were created during the past 2,000 years and represented natural changes in the ecosystem (Simenstad et al., 2011). The geomorphology layer was contained within a larger geodatabase of the Columbia River Estuary Ecosystem Classification. We applied a binary classification to the geomorphology and divided the aquatic regions, to which we applied a "1," from the non-aquatic regions, to which we applied a "0" (Table 1). We then converted the shapefile to a raster, resulting in a raster layer in which aquatic regions with the value of 1 were considered suitable for both *primary* and *secondary* suitable habitat. The raster was used to define suitable geomorphology for all months.

Total Output

For each month, we combined the output layers of suitable temperature, salinity, and geomorphology to produce final layers in which only regions that met the suitability criteria were included. Areas considered unsuitable for temperature, salinity, or geomorphology were excluded. This process was repeated for both the *primary* and *secondary* suitable habitat criteria. To assess the overall number of months where suitable habitat is met, we summed all 12 of the total monthly layers for *primary* and *secondary* habitat, respectively. The resulting layers displayed regions with values between 0 and 12, with a value of 12 indicating suitable habitat exists in that region for 12 months of the year.

Summary Statistics

We completed summary statistics to better understand the distribution of suitable habitat. For each month, we calculated the total area of suitable habitat and divided it by the total area of the region of interest. We repeated this for both *primary* and *secondary* habitat. The output indicated the percentage of habitat that either met the *primary* or *secondary* habitat criteria for each month of the year.

Table 1: Geomorphology characteristics of the Columbia River Estuary. Geomorphology describes the landforms within the Columbia River Estuary and is categorized as either aquatic or non-aquatic. Aquatic geomorphology layers are ranked “1,” indicating it is suitable habitat for larval Pacific lamprey. Non-aquatic geomorphology layers are ranked “0.” Data Source: Lower Columbia River Estuary Partnership.

Geomorphology	Rank	Type
Artificial beach/bar	0	Non-aquatic
Artificial water body	0	Non-aquatic
Bedrock	0	Non-aquatic
Channel bar	0	Non-aquatic
Deep channel	1	Aquatic
Developed floodplain	0	Non-aquatic
Dredge spoils	0	Non-aquatic
Dune deposit	0	Non-aquatic
Filled areas	0	Non-aquatic
Floodplain	0	Non-aquatic
Floodplain channel	0	Non-aquatic
Intermittently exposed	1	Aquatic
Intermittently exposed bedrock	0	Non-aquatic
Lake or wetland	0	Non-aquatic
Lake/pond	0	Non-aquatic
Landslide deposit	0	Non-aquatic
Lower flooded	0	Non-aquatic
Natural levee	0	Non-aquatic
Permanently flooded	1	Aquatic
Side channel	1	Aquatic
Terrace	0	Non-aquatic
Tertiary channel, intermittently exposed	1	Aquatic
Tertiary channel, permanently flooded	1	Aquatic
Tidal channel	1	Aquatic
Tie channel	0	Non-aquatic
Tributary (minor)	0	Non-aquatic
Tributary delta	0	Non-aquatic
Tributary fan	0	Non-aquatic
Tributary valley (outside floodplain)	0	Non-aquatic
Undifferentiated flooded	0	Non-aquatic
Unknown	0	Non-aquatic
Unknown depth	1	Aquatic
Upper flooded	0	Non-aquatic
Volcanogenic delta	0	Non-aquatic

Volcanogenic delta affected by Columbia River floods	0	Non-aquatic
Wetland	0	Non-aquatic

RESULTS

The Habitat Suitability Analysis identified the spatial and temporal distribution of regions within the Columbia River Estuary that were most suitable for larval Pacific lamprey survival. The criteria for suitable habitat was based on three parameters: temperature, salinity, and geomorphology. In ArcGIS Pro's Model Builder feature, we created a workflow to visualize the iterative process used to identify suitable habitat (Appendix IV). The initial intention of the Habitat Suitability Analysis was to identify regions of suitable habitat where the criteria for *primary* and *secondary* habitat were met spatially and temporally for all 12 months of the year. The spatial assessment was used to identify where suitable habitat was limited by environmental parameters throughout the Columbia River Estuary. The temporal assessment of suitable habitat determined the number of months a particular region in the Columbia River Estuary met the suitable habitat criteria and which months contributed most to the suitable habitat availability throughout the Columbia River Estuary.

Total Available Habitat

The Habitat Suitability Analysis used the boundary of the Columbia River Estuary to define the spatial extent of the total potential habitat available to larval Pacific lamprey. Within this region, we used geomorphic characteristics to identify habitat that was predominantly influenced by aquatic or terrestrial conditions. Of the total potential habitat within the Columbia River Estuary, less than half (43%) met the criteria for aquatic geomorphology used to identify suitable habitat for larval Pacific lamprey (Figure 9).

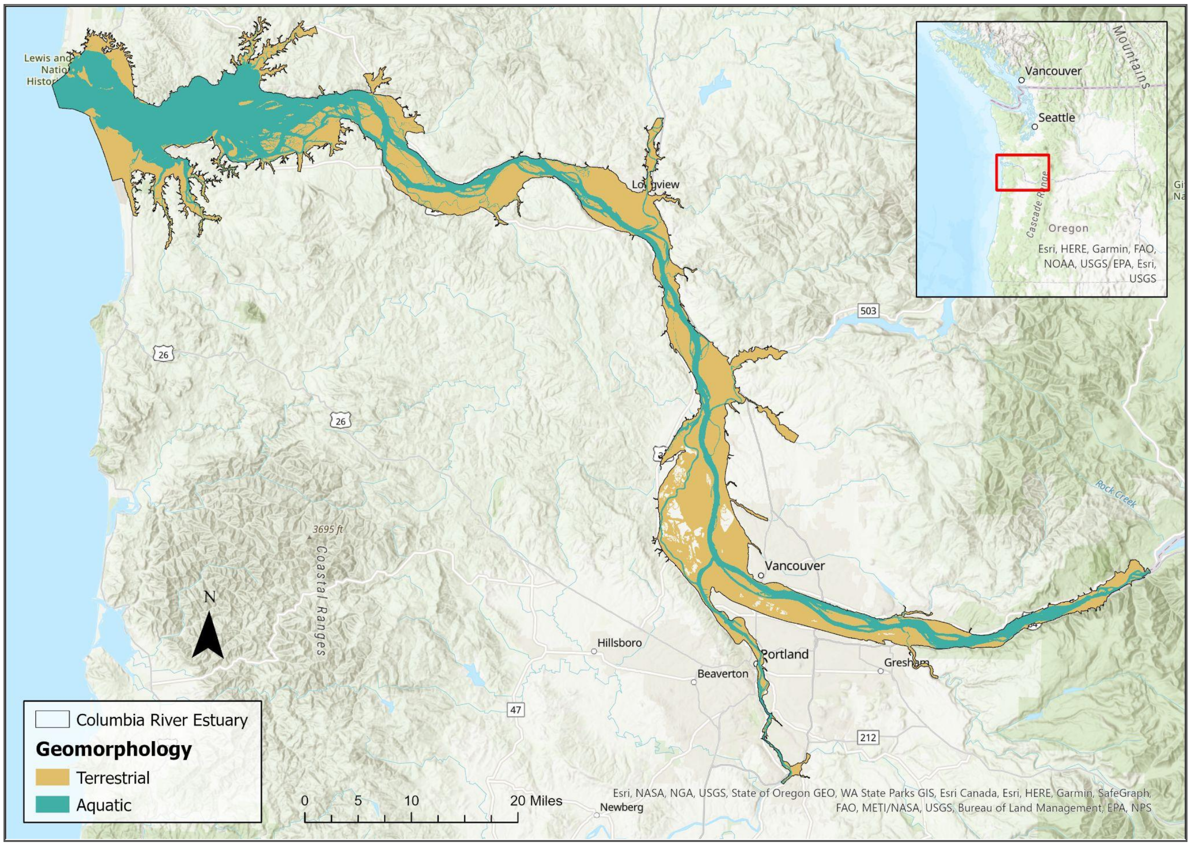

Figure 9: Geomorphology of the Columbia River Estuary. The geomorphic reclassification shows the distribution of aquatic and terrestrial habitat within the region of interest. Aquatic regions (teal) meet the suitable habitat criteria and are predominantly influenced by aquatic environments. Terrestrial regions (brown) consisted mostly of terrestrially influenced habitats and were excluded from the suitable habitat criteria. The total available habitat for larval Pacific lamprey was restricted to aquatic geomorphology only. Aquatic features include deep channel, intermittently exposed, permanently flooded, side channel, tertiary channel (intermittently flooded), tertiary channel (permanently flooded), tidal channel, and unknown depth. Terrestrial features include: artificial beach/bar, artificial water body, bedrock, channel bar, developed floodplain, dredge spoils, dune deposit, filled areas, floodplain, floodplain channel, intermittently exposed bedrock, lake or wetland, lake/pond, landslide deposit, lower flooded, natural levee, terrace, tie channel, tributary (minor), tributary delta, tributary fan, tributary valley (outside floodplain), undifferentiated flooded, unknown, upper flooded, volcanogenic delta, volcanogenic delta affected by Columbia River floods, and wetland. Data Source: Lower Columbia Estuary Partnership (Geomorphic Catena).

Temporal Distribution of Primary Suitable Habitat

The results of the Habitat Suitability Analysis for *primary* suitable habitat revealed that minimal habitat (< 1%) met the criteria for all 12 months of the year (Figure 10). In addition, less than 1% of *primary* suitable habitat was not present in the Estuary for more than six months of the year. Of the regions that did meet the *primary* suitable habitat criteria, the greatest proportion (36%) of *primary* suitable habitat occurred during just three months of the year. Summary statistics reveal that March, April, and November made up the greatest proportion of *primary* suitable habitat (Figure 12). Collectively, the months of January, February, May, and December made up about 16% of the total *primary* suitable habitat, whereas June, July, August, September, and

October comprised only 1% of the total *primary* suitable habitat. The general trend in the temporal distribution of *primary* suitable habitat followed seasonal patterns of water temperature, with warmer, summer months (June, July, August, and September) offering the least suitable habitat and cooler, spring and fall months (March, April, November) offering more suitable habitat.

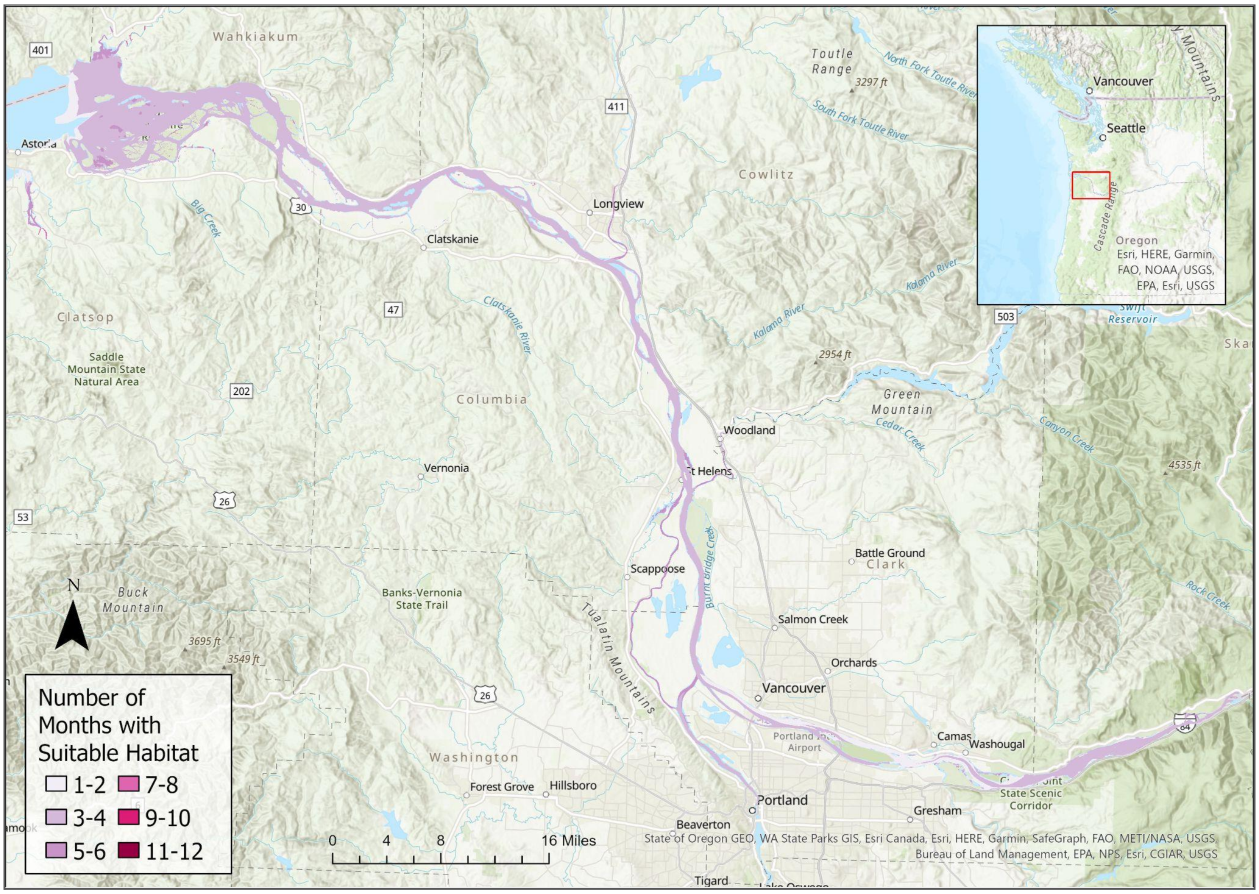

Figure 10: Temporal distribution of primary suitable habitat in the Columbia River Estuary. The Habitat Suitability Analysis displays the number of months where regions in the Estuary fulfill the *primary* suitable habitat criteria. Regions labeled with darker shades of pink represent a greater number of months meeting habitat criteria and lighter shades of pink represent the least number of months meeting habitat criteria over a 12 month period. Each color shade defines a two-month range (i.e., 9-10 months of the year). Regions that failed to meet the *primary* suitable habitat criteria for at least one month were excluded. The following criteria were used to identify *primary* suitable habitat: temperature (10-18℃); salinity (0-12pt); geomorphology (deep channel, intermittently exposed, permanently flooded, tidal channel, and unknown depth). Data Sources: Center for Coastal Margin Observation & Prediction; Lower Columbia Estuary Partnership.

Temporal Distribution of Secondary Suitable Habitat

The Habitat Suitability Analysis for the *secondary* suitable habitat revealed that little to no habitat (< 1%) persisted for all 12 months of the year (Figure 11). Furthermore, less than 1% of *secondary* suitable habitat was not present in the Estuary for more than eight months of the year. The greatest proportion (46%) of *secondary* suitable habitat occurred six months of the year. Summary statistics reveal that the greatest proportion of *secondary* suitable habitat was distributed between the spring months of March, April, and May, and fall months of October, November, and December (Figure 12). January and February also displayed *secondary* suitable habitat, however, it only contributed to a fraction (19% and 15%, respectively) of the total available habitat. June, July, August, and September show an insignificant amount (< 1%) of *secondary* suitable habitat, similar to the *primary* habitat results. While the trends of *secondary* suitable habitat also reflect seasonal patterns in water temperature, we observed an overall greater occurrence of *secondary* suitable habitat compared to *primary* suitable habitat.

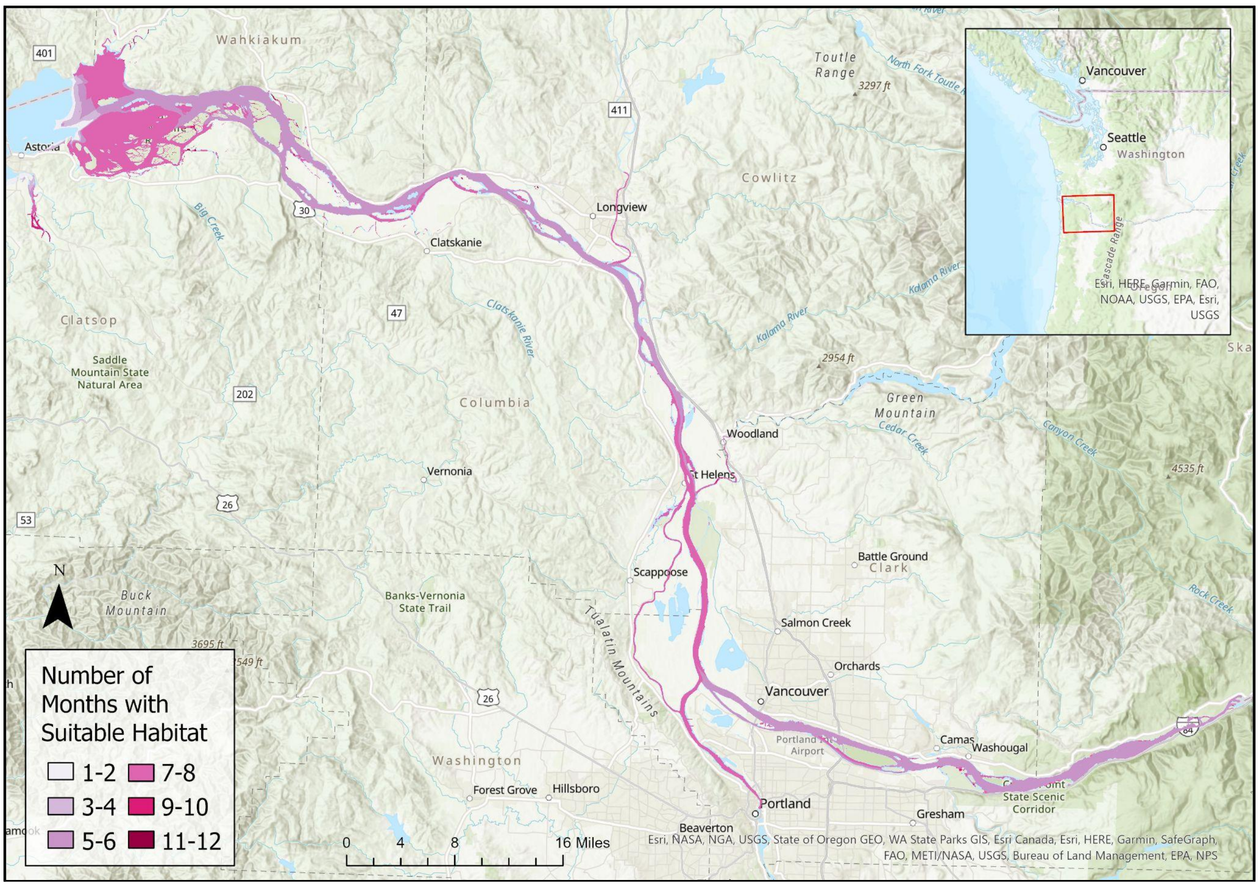

Figure 11: Temporal distribution of secondary suitable habitat in the Columbia River Estuary. The temporal analysis showed the number of months where regions in the Estuary satisfy the *secondary* suitable habitat criteria. Darker shades of pink represent a greater number of months meeting habitat criteria and lighter shades of pink represent the least number of months meeting habitat criteria over a 12 month period. Each color shade defines a two-month range (i.e., 9-10 months of the year). Regions where *secondary* suitable habitat failed to meet the criteria for any month were excluded. The following criteria were used to identify *secondary* suitable habitat: temperature (8-22℃); salinity (0-12 ppt); geomorphology (deep channel, intermittently exposed, permanently flooded, tidal channel, and unknown depth). Data Sources: Center for Coastal Margin Observation & Prediction; Lower Columbia Estuary Partnership.

Spatial Distribution of Primary and Secondary Suitable Habitat

The spatial distribution of *primary* and *secondary* suitable habitat varied similarly throughout the Columbia River Estuary. Most notably, the spatial distribution was limited by salinity and temperature in different regions of the Estuary. At the mouth of the Estuary, between river mile 0 and around river mile 20, no *primary* or *secondary* suitable habitat was observed during any month of the year (Figure 13). Salinity in this region exceeded the 12 parts per thousand (ppt) criteria for larval Pacific lamprey suitable habitat. Beyond river mile 20, salinity measurements were consistently 0 ppt, and therefore did not limit suitable habitat availability. Between river mile 20 and river mile 146 (Bonneville Dam), the fluctuations in temperature primarily limited the spatial distribution of *primary* and *secondary* suitable habitat. The average monthly temperature throughout the Estuary ranged from 9.1℃ to 24.2℃ and followed seasonal patterns with warmer temperatures in the summer and cooler temperatures in the winter (Figure 14).

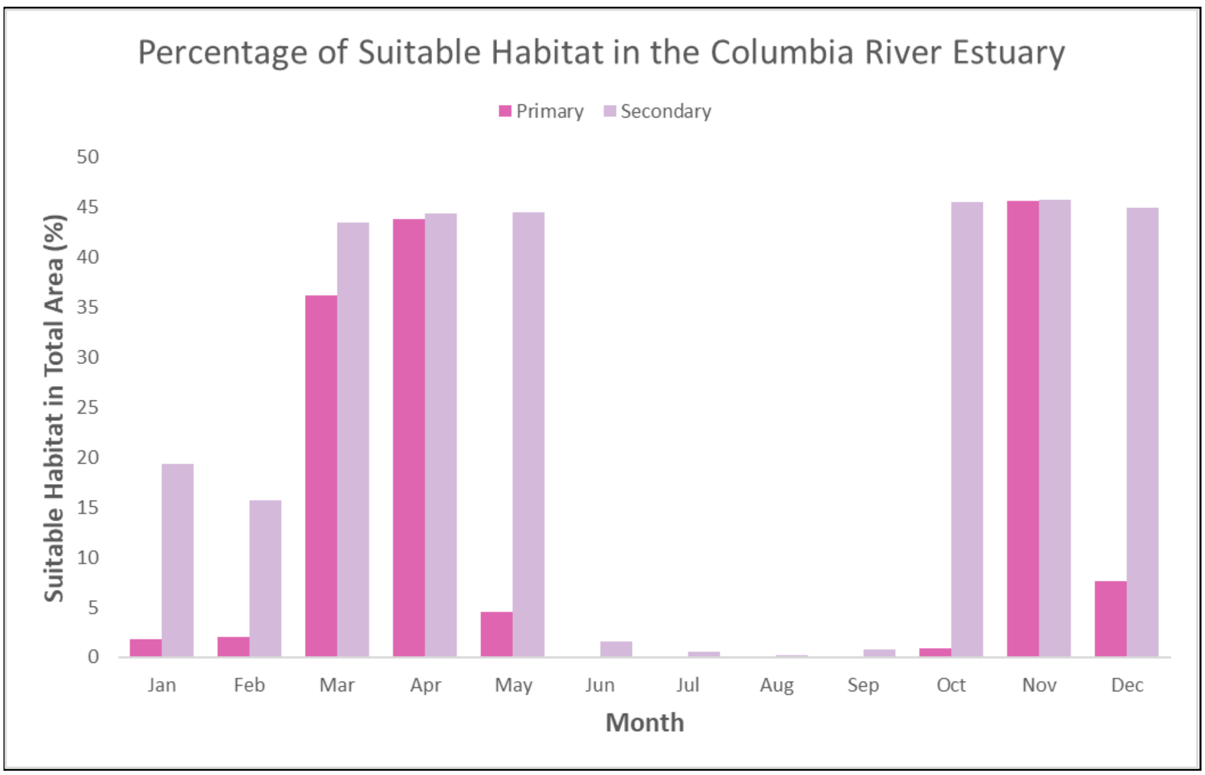

Figure 12: Total amount of primary and secondary suitable habitat. The percentage of *primary* (dark pink) and *secondary* (light pink) suitable habitat for each month shows variations between suitable conditions in the Columbia River Estuary throughout the year. *Primary* and *secondary* suitable habitat were calculated relative to the total available habitat (Estuary boundary) for each suitable habitat criteria (i.e., In May, less than 5% of total available habitat meets the criteria for *primary* suitable habitat; about 45% of total available habitat meets the criteria for *secondary* suitable habitat). See Appendix VI for monthly Habitat Suitability Analysis results. Data Source: Center for Coastal Margin Observation & Prediction.

In general, most suitable habitat occurs in upstream tributaries, along shorelines of main-stem and side channel habitats, and near bays. Although our study was limited by the extent of the Columbia River Estuary's boundaries, we observed several regions that met *primary* and *secondary* suitable habitat within the lower regions of tributaries connected to the Columbia River mainstem. For example, the Youngs River and the Lewis and Clark River are two tributaries in Oregon near the mouth of the Estuary that experience varying degrees of *primary* and *secondary* suitable habitat conditions (Figure 15). Additionally, suitable habitat was observed within the Portland Harbor Superfund area, along the Willamette River in Oregon where restoration projects currently focus on habitat restoration efforts that may benefit larval Pacific lamprey (Figure 16).

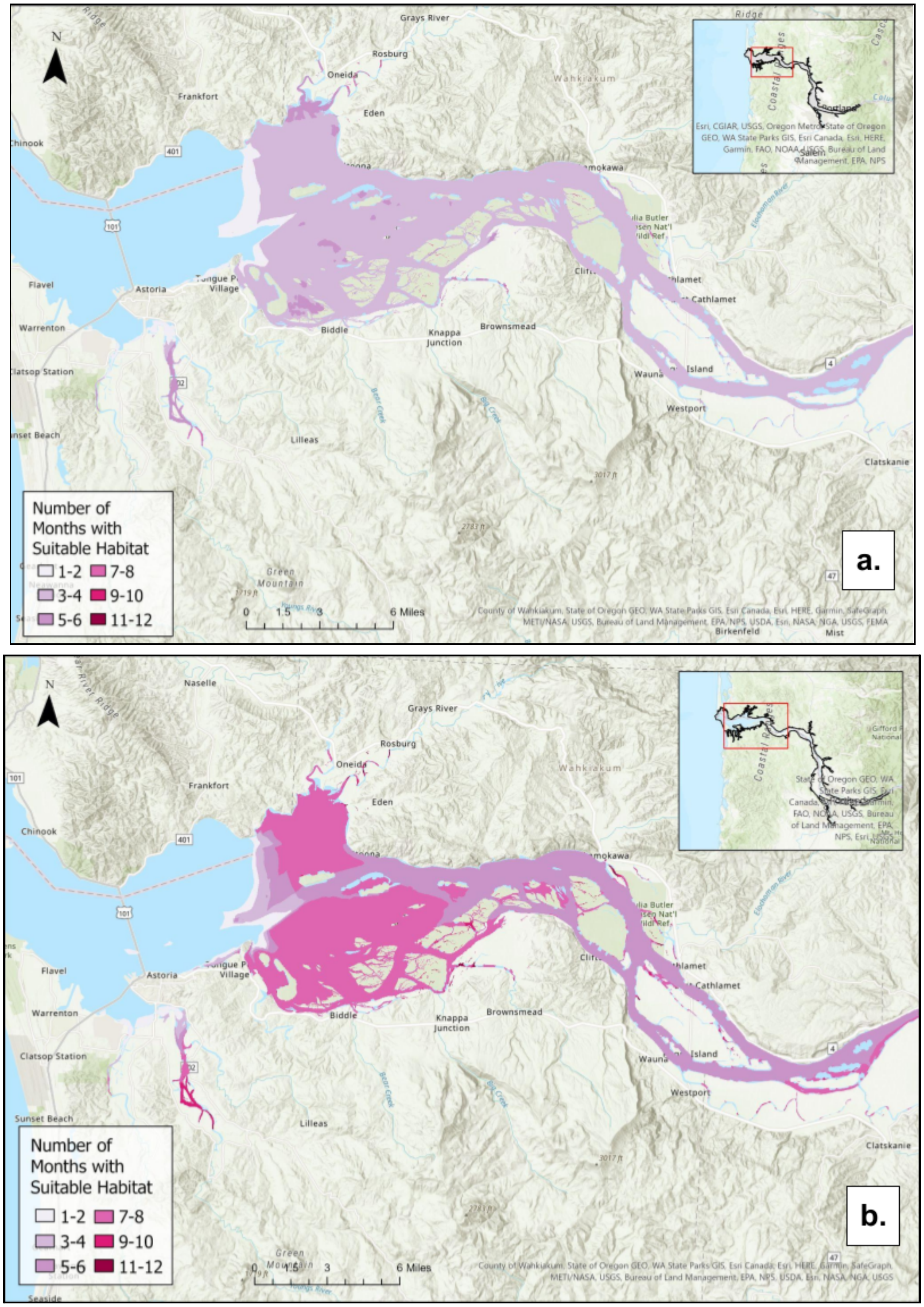

Figure 13: Spatial distribution of suitable habitat at the mouth of the Columbia River Estuary. The spatial distribution of *primary* (a) and *secondary* (b) suitable habitat at the mouth of the Estuary. Regions between river mile 0 and river mile 20 show limitations by salinity intrusion greater than 12 ppt. Regions beyond river mile 20 are most limited by temperature. Labels with darker shades of pink represent a greater number of months meeting habitat criteria and lighter shades of pink represent the least number of months meeting habitat criteria over a 12 month period. Each color shade defines a two-month range (i.e., 9-10 months of the year). Data Sources: Center for Coastal Margin Observation & Prediction; Lower Columbia Estuary Partnership.

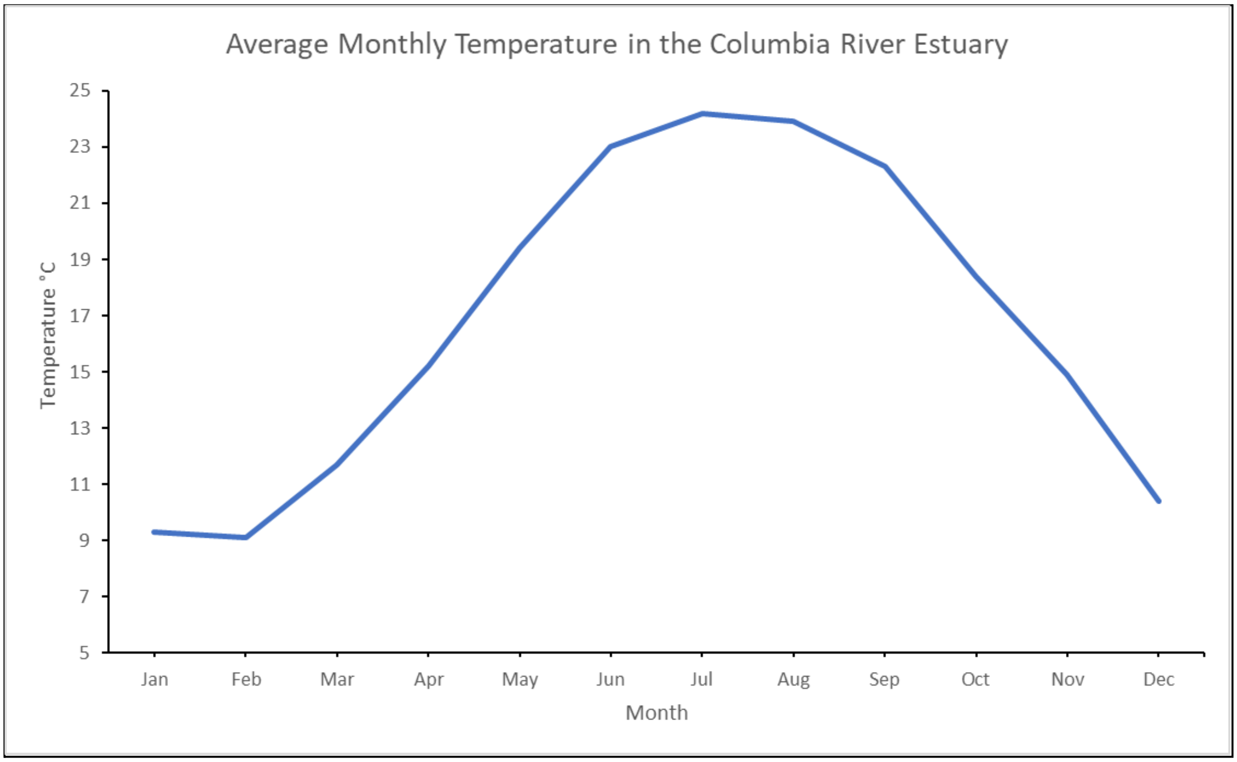

Figure 14: Average monthly temperature (℃) in the Columbia River Estuary. The average monthly temperature observed over a 20-year period from 1998 - 2018. The month of February experienced the lowest average temperatures at around 9.1℃, whereas July experienced the greatest average temperatures close to 24.2℃. Data Source: Center for Coastal Margin Observation & Prediction.

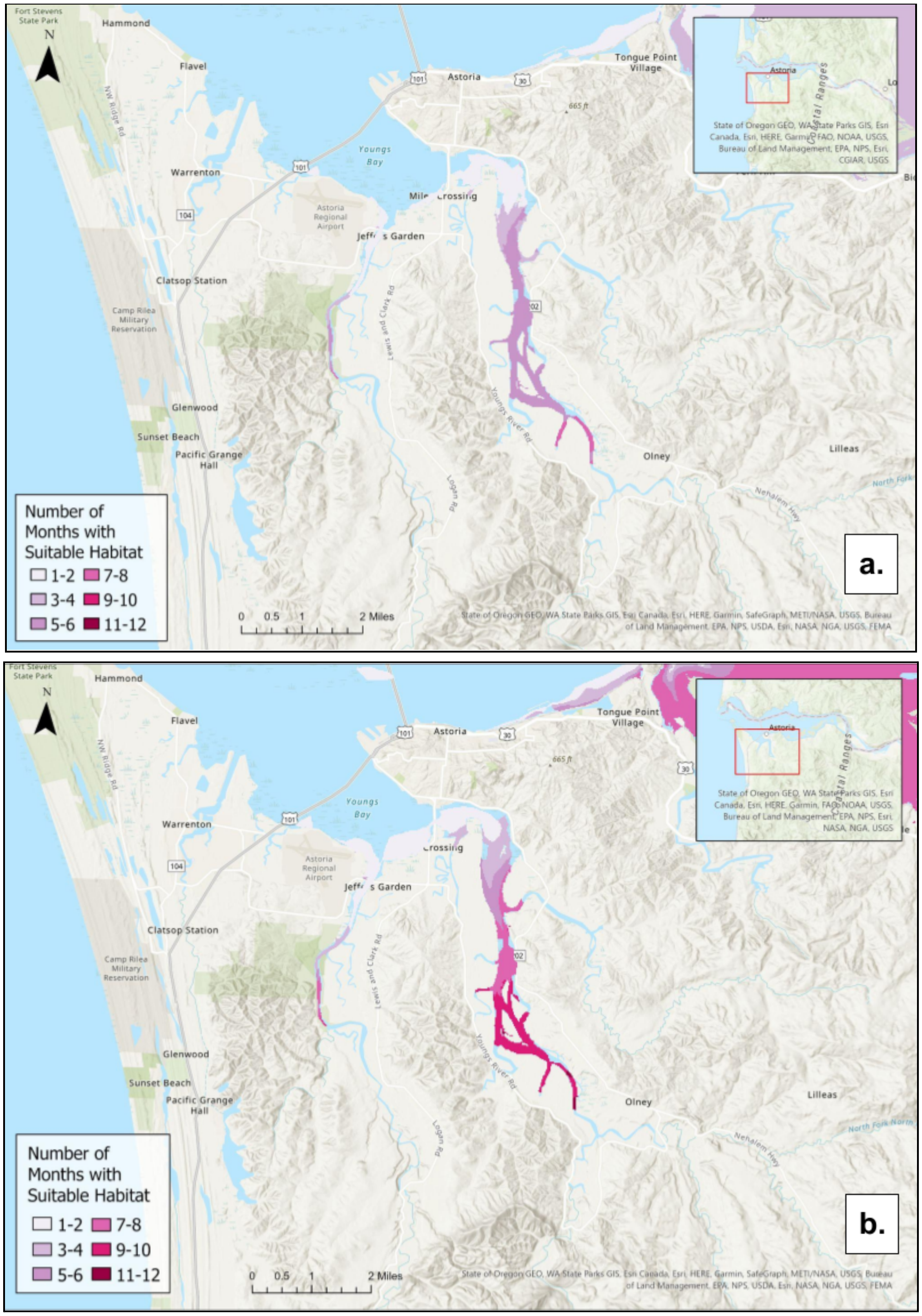

Figure 15: Spatial distribution of suitable habitat in Columbia River Tributaries. The Habitat Suitability Analysis showed *primary* (a) and *secondary* (b) suitable habitat for Columbia River tributaries, including Youngs River (right) and the Lewis and Clark River (left). The shaded regions represent the number of months that the region meets the criteria for *primary* and *secondary* suitable habitat over a 12 month period. Each color shade defines a two-month range (i.e., 9-10 months of the year). Tributaries may provide suitable habitat conditions for the larval Pacific lamprey. However, tributaries were not included within the scope of the Habitat Suitability Analysis, which only examined the mainstem Columbia River. Data Sources: Center for Coastal Margin Observation & Prediction; Lower Columbia Estuary Partnership.

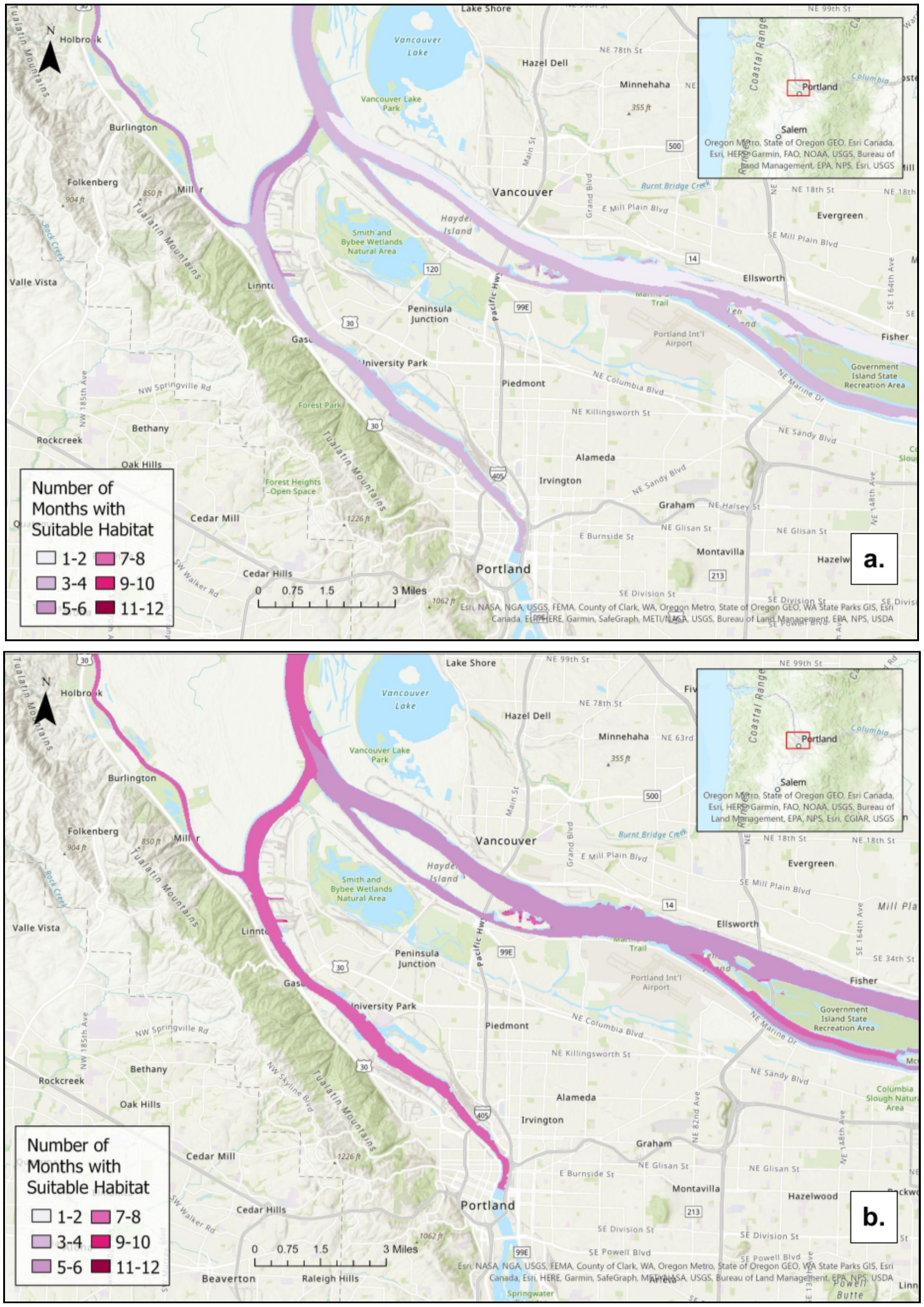

Figure 16: Spatial distribution of suitable habitat in the Portland Harbor Superfund area. The Habitat Suitability Analysis showed *primary* (a) and *secondary* (b) suitable habitat in the Portland Harbor Superfund area, on the lower Willamette River near Portland, OR. This area has been subject to various habitat restoration projects since it was declared a Superfund Site in 2000 by the U.S. Environmental Protection Agency and is currently a focus area for larval Pacific lamprey habitat restoration (Blanchard et al., 2021). The shaded regions represent the number of months that the region meets the criteria for *primary* and *secondary* suitable habitat over a 12 month period. Each color shade defines a two-month range (i.e., 9-10 months of the year). Data Sources: Center for Coastal Margin Observation & Prediction; Lower Columbia Estuary Partnership.

DISCUSSION

Temporal and Spatial Analysis

The Habitat Suitability Analysis results indicate that the region of interest does not meet *primary* or *secondary* suitable habitat criteria for larval Pacific lamprey year-round. An extremely small amount of the Columbia River Estuary was able to fulfill *primary* suitable habitat criteria for a maximum of 10 months and *secondary* suitable habitat criteria for a maximum of 8 months. Since larval lamprey may burrow in sediment for three to ten years, the results make it difficult to establish long-term restoration efforts within the region of interest and limit where larvae would thrive for several consecutive months.

Salinity and temperature levels did not meet the *primary* or *secondary* suitable habitat ranges for every month of the year, and they limited the areas that can support larval populations, both spatially and temporally. This was likely due to monthly variations within both habitat parameters. Salinity limited potential lamprey habitat at the mouth of the Columbia River Estuary, where summer months experienced greater instances of salinity intrusion within the region of interest than the winter months. Future restoration efforts should not focus on the mouth of the Estuary because larval lamprey mortality begins to occur when salinity levels exceed 12.2 parts per thousand (ppt) (Silver, 2015). Temperature became the primary limiting factor in areas east of river mile 20, and summer temperatures tended to exceed the *primary* and *secondary* suitable habitat criteria, reducing the availability of suitable habitat. These temperature limits extended all the way to the Bonneville Dam. Both the salinity and temperature values limited the amount of potentially suitable habitat within the Columbia River Estuary and the number of months that produced ideal habitat conditions.

Since the results of the Habitat Suitability Analysis were unable to meet either category of suitable habitat criteria during every month of the year, restoration efforts may need to assess habitat suitability on a seasonal basis. Seasonal restoration efforts should utilize habitat conditions during the spring months between March and May and the fall months between October and December. The spring and fall months were found to provide the greatest percentage of *primary* and *secondary* habitat in the region of interest. These results pose some uncertainty concerning lamprey restoration efforts during the winter months between January and February and the summer months between June and September, when salinity and temperature conditions fail to meet *primary* and *secondary* habitat suitability criteria. Although it is still possible for larval Pacific lamprey to survive during these periods of unsuitable conditions, it is important to consider how long-term exposure to these conditions impacts larval lamprey survival. Future restoration work should evaluate how seasonality affects larval lamprey burrowing habits during each season and develop strategies to protect larvae year-round.

Climate Change Concerns

Climate change can potentially affect larval Pacific lamprey and their habitat in the Columbia River Estuary. Pacific lamprey that hatch at warm incubation temperatures that are greater than 18 degrees Celsius can result in larval abnormalities (Wang et al., 2021). When studying the thermal tolerance of Pacific lamprey, they can survive at temperatures as high as 27 to 28 degrees Celsius and can begin to exhibit reduced survival in settings of 28 degrees Celsius; lamprey were estimated to experience mortality if water temperatures reach 29 to 30 degrees Celsius (Wang et al., 2021). While the Habitat Suitability Analysis set its maximum temperature threshold at 22 degrees Celsius, the results from Wang et al. (2021) show that Pacific lamprey can survive in water temperatures as high as 27-28 degrees Celsius. However, there is some uncertainty about the amount of time in which lamprey can remain in these elevated temperatures. A study by Wang et al. (2020) evaluated the risks associated with a changing climate in 15 rivers in the Western United States. The authors applied two Representative Conservation Pathways (4.5 and 8.5) to a mid-century time period and an end-of-century time period (Wang et al., 2020). Among the authors' main findings, they determined that Representative Conservation Pathways that contain a higher greenhouse gas emission (such as the 8.5 scenario) makes species more vulnerable to climate change and that Pacific lamprey are more vulnerable to the impacts of climate change if they are in highly altered rivers (Wang et al., 2020). An increase in water temperature is expected to affect lamprey survivability and vulnerability to the impacts of climate change. There is uncertainty about how specific aspects of climate change may affect lamprey because some of these aspects are difficult to predict, such as altered hydrology (Wang et al., 2021). Future research should utilize available data to estimate how climate change aspects, such as salinity and temperature, may individually affect larval Pacific lamprey.

As climate change is expected to worsen, it could result in greater temperature variation that may impact ecosystems. A strong heat dome that was driven by a high-pressure system and easterly winds which further compressed and warmed the air resulted in temperatures in the Pacific Northwest surpassing 100 degrees in June 2021 (Cappucci & Samenow, 2021). The heat dome's record-breaking temperatures have been attributed in part to climate change which has caused average temperatures in the region to be three degrees warmer than they were half a century ago (Cappucci & Samenow, 2021). An increase in the region's average temperature is likely to increase the risk and frequency of stronger heat waves, which can be exacerbated by an increasing variation in overall temperature (Cappucci & Samenow, 2021). These variations could potentially affect Pacific lamprey in the Columbia River by causing the river's temperature to exceed their maximum temperature threshold and highlight the importance of incorporating climate variation and multiple climate change scenarios into studies on Pacific lamprey.

Non-Environmental Parameters

Anthropogenic actions have altered the Columbia River's complex river network, flow dynamics, and environmental health. Several of these impacts can affect larval Pacific lamprey populations, either directly, such as restricting their access to sedimentary habitats (Poirier, 2020), or indirectly, such as contaminating the river with heavy metals and legacy pollutants (Columbia River Inter-Tribal Fish Commission, 2011). Pacific lamprey habitat can be restored through habitat restoration, though there are several ongoing knowledge gaps about the lamprey life cycle that hinder restoration efforts (Luzier et al., 2011; Wang & Schaller, 2015). Several of the anthropogenic impacts discussed previously in the Project Areas of Focus section of this report do not strictly relate to the environmental conditions that were used in the Habitat Suitability Analysis. While the non-environmental parameters weren't part of the overall analysis, researchers should account for each of the following parameters and their associated knowledge gaps when developing and implementing lamprey conservation measures.

Non-Environmental Parameters - Levees

Levees have had a profound impact on the Columbia River Estuary. They have altered the Columbia River's flow by cutting off the river's mainstem from floodplain and estuary habitats (Poirier, 2020). This can separate lamprey from floodplains and estuaries even though these areas may provide more ideal habitat conditions for the larval life stage than the river's mainstem. However, it is possible to restore the connections between the mainstem and floodplains by removing levees (Beechie et al., 2013). Levee removal has been shown to help salmon migrate through floodplains and can reduce water temperatures by increasing the length of stream flow paths (Beechie et al., 2013). It may be possible to get rid of levees to promote *primary* or *secondary* habitat conditions for larval Pacific lamprey, and it may require collaboration with organizations that maintain levees. Figure 17 shows the distribution of levees throughout the Columbia River Estuary. Areas that have a greater concentration of levees could increase streamflow paths and reduce water temperatures. By removing levees in these areas, this could improve overall streamflow conditions and habitat conditions in the Columbia River Estuary. Conservation organizations can advocate for the removal of levees to improve habitat connectivity for larval lamprey. However, this process may require them to collaborate with several stakeholders that maintain levees and could start a regulatory process that may take several years to complete.

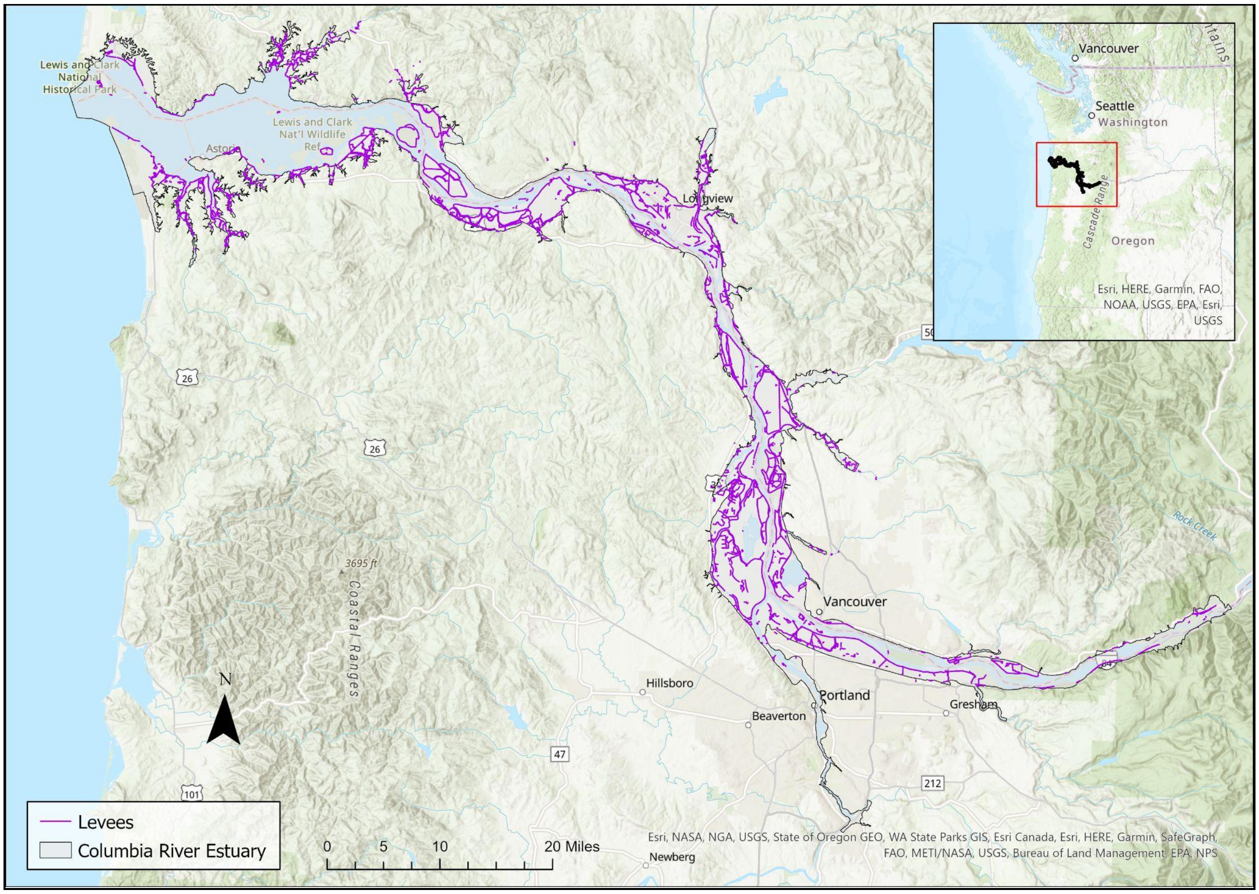

Figure 17: Levees in the Columbia River Estuary from the Pacific Ocean to Bonneville Dam. Levees are distributed throughout the mainstem Columbia River and its tributaries. The shaded region represents the Columbia River Estuary, and the purple lines represent the levees situated along the Columbia River and its tributaries. Levees have cut off the river's mainstem from nearby floodplains (Poirier, 2020) and could inhibit larval lamprey's access to floodplains and side channels for spawning. Data Source: Lower Columbia Estuary Partnership.

Non-Environmental Parameters - Dredge Sites

Dredging can affect larval Pacific lamprey by physically removing them from their environment or by preventing them from reaching the Pacific Ocean. These operations can displace or injure larval lamprey or make larvae susceptible to predation by removing them from their fine sediment habitats (Clemens et al., 2020; Clemens et al., 2017) and by disposing of dredged material on land or in areas that cannot support larval populations (Lamprey Technical Workgroup, 2021). Alternatively, these operations can bury lamprey under several layers of dredged material and contribute to larval mortality by preventing them from reaching the water column (Lamprey Technical Workgroup, 2021; J. Skalicky, personal communication, November 16, 2021). Luzier et al. (2011) noted that dredging studies rarely include Pacific lamprey due to knowledge gaps about the species, which include a lack of information about their presence and distribution. These knowledge gaps make it difficult to determine the full extent of dredging's impacts on Pacific lamprey. An additional source of uncertainty is that researchers don't know the amount of sediment that would prevent larval lamprey from entering the water column (J. Skalicky, personal communication, November 16, 2021). There is a lack of information about dredging disposal sites and about the connections between the disposal of dredged material and lamprey mortality. Dredging presents challenges for lamprey conservation because of its ability to displace or harm larvae. Since larval lamprey burrow in fine sediment for three to seven years (Columbia River Inter-Tribal Fish Commission, 2011), dredging may harm several generations of lamprey at once by relocating them, burying them, or creating a combination of these factors. Any studies on the impacts of dredging on larval Pacific lamprey should collaborate with the Army Corps of Engineers, which oversees dredging operations in the Columbia River.

While conservation organizations can work to remove levees from the Columbia River, they won't be able to easily reverse the effects of dredging. Sediment accumulates within the Columbia River's shipping channel and requires periodic dredging to clear the channel for ships that travel upriver (Poirier, 2020). In addition to harming larval lamprey, dredging can destroy their habitat and cause contaminants to disperse within the river's ecosystem (Poirier, 2020). In an interview with Joe Skalicky from the U.S. Fish and Wildlife Service, he noted that the cheapest methods to dispose of dredged sediment are to relocate sediment to a different part of the river or by creating man-made islands (J. Skalicky, personal communication, November 16, 2021). He estimated that 80% of dredged material goes back into the Columbia River. However, most of this sediment ends up within the river's side channels and is unable to accumulate in the shipping channel (J. Skalicky, personal communication, November 16, 2021). Larval lamprey may be relocated to side channels and may be unable to reach the shipping channel to burrow in fine sediment until they mature. If levees have separated the river's side channels from the main shipping channel, relocated lamprey may be entirely cut off from the mainstem Columbia River and the Pacific Ocean.

The Lamprey Technical Workgroup (2021) provides recommendations to address dredging's impact on larval lampreys. A main recommendation is that dredging operations should relocate sediment to areas of the Columbia River that have fast currents to separate larvae from dredged material (Lamprey Technical Workgroup, 2021). Alternatively, these operations can salvage larvae before or during the dredging process to prevent them from being displaced or buried under several layers of sediment (Lamprey Technical Workgroup, 2021). The workgroup recommends that future studies should evaluate dredging's impact on lamprey life stages and their behavior (Lamprey Technical Workgroup, 2021). None of these recommendations can permanently reverse the effects of dredging. Because of this, conservation organizations should consider efforts to routinely mitigate dredging's impact on larval lamprey.

Non-Environmental Parameters - Restoration Projects

While anthropogenic factors such as levees and dredging have harmed larval Pacific lamprey habitat, habitat restoration projects may provide opportunities for lamprey to burrow and develop within the Columbia River. One option to restore river and stream habitats is to add wooden structures into natural habitats by modifying flow conditions and stabilizing rivers and streambanks (Gonzalez et al., 2017; Roni, 2003; Roni et al., 2015; Stewart et al., 2009). Restoration groups can combine wooden structures with additional restoration operations including riparian buffering zones to improve river and stream ecosystems (Stewart et al., 2009). Researchers have debated whether wooden structures are less effective in large streams, though there are a lack of studies that evaluate their effectiveness in aquatic environments. (Stewart et al., 2009). This presents uncertainty about their ability to support larval Pacific lamprey or their habitat conditions.

The scientific community has debated whether wooden structures play a role in habitat restoration. While landowners have been installing wooden structures to improve fish habitat since the 1890s, Roni et al. (2015) noted a lack of scientific consensus on their success rates, whether they could improve physical habitats, and whether they could benefit aquatic populations. They reviewed several studies and found that wood structures tend to remain stable for more than a decade, that wood placement improves physical habitats overall, and that wood structures can support salmonid species. However, they note that few studies focus on wooden structures' impact on non-salmonid species (Roni et al., 2015). Roni et al. (2015) did not evaluate the role that wood structures play in restoring larval lamprey habitat, and their paper acknowledges existing knowledge gaps concerning habitat restoration and non-salmonid species. These knowledge gaps result in a lack of information about whether larval lamprey directly benefit from habitat restoration, specifically wooden structures.

There is uncertainty about the exact impact of wooden structures on larval Pacific lamprey. However, it is possible that wooden structures may provide habitat conditions that benefit larvae. Gonzalez et al. (2017) evaluated whether large wood would affect juvenile coho salmon and larval lamprey populations (including Pacific lamprey). They defined large wood as pieces of wood that were greater than 15 centimeters in diameter and were 3 meters long (Gonzalez et al., 2017). The study included 281 pieces of large wood that were installed within Little Wolf Creek, a tributary of the Umpqua River in southwestern Oregon, between 2008 and 2009 (Gonzalez et al., 2017). In addition, the study accounted for salmon and lamprey presence in pools during summer low flows (Gonzalez et al., 2017). Larval lamprey were found to be more prevalent in pools that had copious amounts of fine sediment and were composed of sediment with depths greater than 10 centimeters; these areas were most likely to contain large wood (Gonzalez et al., 2017). When evaluating sediment depth, the authors did not consider sediment composition in their analysis (Gonzalez et al., 2017). The authors determined that pools with large wood had a greater surface area when compared to pools without large wood (Gonzalez et al., 2017). They identified a correlation between larval lamprey presence in pools and large wood, where pools with large wood tended to contain fine sediment where larval lamprey burrow until they mature. Researchers should continue to study the restoration potential of wooden structures as one strategy to support larval Pacific lamprey populations.

Non-Environmental Parameters - Barriers

Anthropogenic barriers such as dams and culverts can affect Pacific lamprey within the Columbia River and its tributaries. Barriers prevent adult Pacific lamprey from migrating upstream and accessing spawning and rearing habitat (Poirier, 2019; Columbia River Inter-Tribal Fish Commission, 2011). The Columbia River Inter-Tribal Fish Commission (2011) notes that only 50% of adult lamprey can successfully pass through one dam, and that dam passage systems have been installed for salmon use; lamprey are unable to utilize these systems. In addition, screens at irrigation and municipal diversions as well as culverts and dams act as barriers that prevent adult lamprey from passing through tributaries and they can result in lamprey mortality (Columbia River Inter-Tribal Fish Commission, 2011, A. Whiting, personal communication, January 7, 2022). Future research on how barriers impact larval lamprey passage will need to account for several types of barriers and their location within historical lamprey habitat.

Organizations such as the Lower Columbia River Watershed Council have assessed barriers to Pacific lamprey migration within the lower Columbia River. Led by Allan Whiting, the Lower Columbia River Watershed Council is currently identifying barriers that exist within historical Pacific lamprey habitat and evaluating their impact on Pacific lamprey passage within their historical range (A. Whiting, personal communication, January 7, 2022; Lower Columbia River Watershed Council, 2022). The Columbia River Inter-Tribal Fish Commission (2011) recommends that restoration programs should incorporate lamprey passage structures within tributaries to prevent lamprey from becoming trapped within irrigation canals and water diversions. They suggest that lampreys be tagged to track their ability to navigate through tributaries (Columbia River Inter-Tribal Fish Commission, 2011). Removing barriers can improve passage within the Columbia River and its tributaries and provide additional opportunities for adult lampreys to spawn. Similar to levees, conservation organizations can advocate for the removal of barriers, though they may need to collaborate with several stakeholders that oversee the barriers.

Non-Environmental Parameters - Contamination Sites

Environmental contamination can affect Pacific lamprey and tribal members who eat lamprey. Pacific lamprey can be susceptible to several contaminants and can accumulate contaminants within their tissues (Columbia River Inter-Tribal Fish Commission, 2011). Larval lamprey have been found to contain large concentrations of toxins that may affect their survival, though the Columbia River Inter-Tribal Fish Commission notes that future studies need to evaluate toxins' effects on lamprey life histories (Columbia River Inter-Tribal Fish Commission, 2011). A study of Pacific lamprey collected at Willamette Falls found that lamprey samples contained several pollutants, including mercury, DDT, chlordane, dieldrin, and polychlorinated biphenyls. Contaminants pose a series of health risks to tribal members who eat lamprey, especially pregnant women, and children (Columbia River Inter-Tribal Fish Commission, 2011). Larvae contain higher levels of contaminants than salmon due to their high lipid content and their extended period of exposure from burrowing in sediment during their larval life stage (Columbia River Inter-Tribal Fish Commission, 2011). Researchers should work with the Columbia River Inter-Tribal Fish Commission to study contaminant bioaccumulation in lamprey and restore lamprey habitat to reduce the risk of contamination.

The Columbia River Inter-Tribal Fish Commission has worked with the U.S. Environmental Protection Agency, the Oregon Department of Environmental Quality, and the Oregon Department of Human Services to study how contaminants affect Pacific lamprey and how contaminants may affect tribal members who consume lamprey (Columbia River Inter-Tribal Fish Commission, 2011). In addition, the Columbia River Inter-Tribal Fish Commission has worked with the U.S. Geological Survey to evaluate legacy and emerging contaminants in Pacific lamprey, including exposure to contaminants and bioaccumulation in larval tissue (Columbia River Inter-Tribal Fish Commission, 2011). The commission is collaborating with government agencies and university researchers to increase water quality monitoring efforts within the mainstem Columbia River and the Columbia River Estuary (Columbia River Inter-Tribal Fish Commission, 2011). Water quality monitoring would not only focus on contaminants in the river, but also factors such as water temperature, dissolved oxygen, and pH. Larval lamprey mortality occurred at Willamette Falls in 2009 due to elevated temperatures during the month of August (Columbia River Inter-Tribal Fish Commission, 2011). Adult lamprey collected at Willamette Falls were found to contract a lethal fungus disease during months that had higher than average water temperatures; the Columbia River Inter-Tribal Fish Commission's member-tribes advocate for improved water quality monitoring stations at dams and throughout the Columbia River's mainstem, tributaries, and estuaries to track and predict contamination within the river (Columbia River Inter-Tribal Fish Commission, 2011). While contaminants are a cause for concern in the Columbia River Estuary, they are part of a larger issue surrounding water quality and its impact on larval Pacific lamprey.

Ongoing efforts to restore contaminated areas may provide ideal habitat conditions for larval Pacific lamprey. Blanchard et al. (2021) studied the occupancy of larval lamprey within five restoration sites at Portland Harbor to compensate for damages outlined in the Portland Harbor Natural Resource Damage Assessment. In 2000, the U.S. Environmental Protection Agency declared that part of the lower Willamette River between river kilometer 3.2 and river kilometer 18.9 was a Superfund Site (Blanchard et al., 2021). The Natural Resource Damage Assessment established several habitat restoration projects and assessments in the area, along with five restoration sites and seven reference sites (Blanchard et al., 2021). The authors sampled three of the five restoration sites and six of the seven reference sites in 2020 to detect lamprey presence (Blanchard et al., 2021). They found larval lamprey at one restoration site and four reference sites, which tended to be within the river's confluence or shoreline habitats (Blanchard et al., 2021).The authors noted that lamprey weren't detected within the newer restoration sites, and they were unsure if lamprey will use these newer sites (Blanchard et al., 2021). The Portland Harbor Natural Resource Damage Assessment is ongoing and could provide a model for lamprey conservation by setting aside habitat to compensate for environmental contamination. If they provide ideal habitat conditions for larval lamprey, restoration sites should provide ideal habitat conditions for larval Pacific lamprey to support their populations.

Limitations

There were several data-related limitations that affected the Habitat Suitability Analysis, its ability to model the region of interest for *primary* and *secondary* habitat, and its overall results. Some of these limitations include a lack of geospatial sediment data spanning the entire region of interest and a lack of species distribution data, which prevented the analysis from showing areas of the river that explicitly contain fine sediment or areas that larval lamprey tend to utilize. As a result, the Habitat Suitability Analysis was only able to use salinity, temperature, and geomorphology data to determine suitable habitat for larval Pacific lamprey. Future research that uses our Habitat Suitability Analysis should overcome these limitations to refine the suitable habitat within the region of interest.

There was a lack of geospatial sediment data for the region of interest within the Columbia River which affected the types of environmental parameters that appeared in the Habitat Suitability Analysis. Sediment is an important environmental factor for larval lamprey because they primarily burrow in fine sediment, which includes silt, sand, and detritus (Crandall & Wittenbach, 2015). If this type of habitat is unavailable, larvae have been known to utilize shifting coarse sand and small gravel, albeit to a lesser extent (Crandall & Wittenbach, 2015). The lack of geospatial information meant that sediment information could not be directly input into the Habitat Suitability Analysis. Instead, the analysis used geomorphological data from the Lower Columbia Estuary Partnership that consisted of landforms within the Columbia River's ecosystem complexes that were created during the past 2,000 years (Simenstad et al., 2011). The geomorphology data represented natural changes within the ecosystem and was used to describe habitat, but it did not indicate the distribution of fine sediment within the Columbia River. While geospatial sediment data may not increase the amount of suitable habitat, it would help refine the overall analysis. The types of sediment information that are currently available include reports from the Columbia River Estuary Data Development Program from the 1970s and 1980s, which only covers the lower 45 miles of the Columbia River Estuary (K. Marcoe, personal communication, October 14, 2021), and scientific literature that describes sedimentary environments (J. O'Connor, personal communication, October 19, 2021). It would be worthwhile to investigate this sediment information with our Habitat Suitability Analysis results, however, this was beyond the scope of this project. These reports and papers provide insight into the geomorphic makeup of the Columbia River and highlight the lack of existing geospatial data. Researchers should find ways to create geospatial sediment data that can identify potential habitat for larval Pacific lamprey and assist in ongoing conservation efforts.

The overall gaps in larval Pacific lamprey data are due to factors such as a lack of ongoing conservation projects, a lack of funding, and sampling challenges that are associated with habitat conditions within the river. There are few ongoing projects that focus on Pacific lamprey conservation and there is a lack of funding for lamprey research when compared to species such as salmon (Poirier, 2019; J. Skalicky, personal communication, November 16, 2021). This results in uncertainty about the types of landcover habitat that would support larval Pacific lamprey (J. Skalicky, personal communication, November 16, 2021). In addition, the Columbia River's habitat conditions can affect sampling rates and data collection. Researchers use electrofishing equipment in the river to acquire larval samples; however, electrofishing equipment won't work in areas where salinity levels exceed 1 part per thousand (J. Skalicky, personal communication, November 16, 2021). Deep water electrofishing devices can act as an alternative, though they have a varied success rate due to the large variation in salinity across the river (J. Skalicky, personal communication, November 16, 2021). The lack of larval Pacific lamprey catch, presence, and species distribution data meant that the Habitat Suitability Analysis could not pinpoint specific areas within the region of interest that may support larval lamprey. Due to this limitation, we used the Habitat Suitability Analysis to identify whether parts of the river met the *primary* and *secondary* suitable habitat criteria, where less than 1% of the region of interest ended up meeting either criteria.

There were uncertainties with some of the data that was used as inputs for the Habitat Suitability Analysis. The Center for Coastal Margin Observation & Prediction's Virtual Columbia River modeling system provided salinity and temperature models that were based on 20-year averages between 1999 and 2018. All the modeling system's databases began on January 1, 1999 (Center for Coastal Margin Observation & Prediction, 2022b). These datasets are unable to show any habitat conditions before the year 1999, and they cannot show long-term trends in the Columbia River's salinity and temperature levels. The Habitat Suitability Analysis model results can only show where *primary* and *secondary* habitat may appear within the region of interest using 20-year averages, and this results in uncertainty because the results cannot represent any recent changes to the Columbia River Estuary or current habitat conditions.

The Habitat Suitability Analysis ended up including habitat criteria for tributaries within the westernmost part of the Columbia River, even though tributaries were outside of its scope. For example, the analysis displayed habitat conditions for Youngs River and the Lewis and Clark River, two tributaries located to the south of Astoria, Oregon. It is possible that other tributaries may exist throughout the region of interest, however tributaries were outside the scope of this project. Joe Skalicky noted that larval lamprey that are unable to pass the Bonneville Dam could potentially spawn in tributaries of the Columbia River Estuary (J. Skalicky, personal communication, November 16, 2021). This results in uncertainty about the types of tributary conditions that would support larval Pacific lamprey, specific tributaries that lamprey may use, and how dams have affected lamprey spawning. Since less than 1% of the Columbia River Estuary met *primary* or *secondary* habitat conditions year-round, future research should evaluate habitat conditions within the river's tributaries. Any research, especially data analysis, should incorporate the non-environmental parameters that were described in this report, especially barriers. The Columbia River Inter-Tribal Fish Commission has found that screens, culverts, and dams can prevent adult lamprey from navigating through tributaries, which can result in lamprey mortality (Columbia River Inter-Tribal Fish Commission, 2011; A. Whiting, personal communication, January 7, 2022). Future studies of tributaries should consider installing lamprey passage structures or removing barriers to improve passage throughout tributaries. In addition, they should collaborate with organizations such as the Lower Columbia River Watershed Council, who are actively studying the impacts of barriers in the Columbia River Estuary and its tributaries on historical lamprey habitat.

CONCLUSIONS AND RECOMMENDATIONS

This report outlined a Habitat Suitability Analysis of potential larval Pacific lamprey habitat within the Columbia River Estuary and discussed how anthropogenic impacts can affect larval Pacific lamprey. The Habitat Suitability Analysis revealed that almost no *primary* and *secondary* suitable habitat can sustain larval lamprey for all 12 months of the year. The distribution of *primary* and *secondary* suitable habitat varies spatially and temporally, where spatial limitations reduce the amount of suitable habitat in the region and temporal variations limit suitable habitat to the spring and fall months. Due to these results, restoration efforts may need to assess how seasonality affects larval lamprey burrowing habits.

However, several data-related limitations resulted in uncertainty about Pacific lamprey distribution within the area of study. Geospatial sediment data and Pacific lamprey catch data would have helped refine the Habitat Suitability Analysis and further identify areas where larval lamprey would be likely to burrow. The limitations in this report demonstrate the existing knowledge gaps about Pacific lamprey and their life cycles. In turn, knowledge gaps limit the types of research on suitable lamprey habitat and hinder conservation efforts that could evaluate the impact of levees, dredging, and other anthropogenic impacts on larval Pacific lamprey.

Based on the results of our analysis, we provide three sets of recommendations to expand the Habitat Suitability Analysis and explore additional areas of research. These sets are General Recommendations, Habitat Suitability Recommendations, and Recommendations for Areas of Focus, for a total of 13 recommendations described below.

General Recommendations: We have three overarching recommendations that relate to the project objectives and address challenges related to larval and adult Pacific lamprey use of the Columbia River Estuary.

1. Knowledge gaps and areas for future studies:
    - Identify knowledge gaps and research projects that address larval and adult lamprey life stages.
    - Identify locations in the Columbia River Estuary where larval and adult lamprey currently reside to obtain data to support understanding of Pacific lamprey.
    - Study habitat parameters and anthropogenic factors that may impact lamprey in the Columbia River Estuary.
2. Use the Habitat Suitability Analysis results to identify locations that will best support larval and adult lamprey in terms of sediment, temperature, water

velocity levels, and connect these locations to seasons to account for changes in salinity and temperature. Organizations can utilize these locations for future studies and projects that focus on Pacific lamprey.

3. Propose research projects with the Pacific Lamprey Conservation Initiative that will evaluate how and where larval lamprey use the Columbia River Estuary. These projects should identify prime locations for conservation and restoration efforts, and factors that may prevent lamprey movement or may harm lamprey within the Columbia River Estuary (e.g., barriers, dredging, contamination sites).

Habitat Suitability Analysis Recommendations: Due to the data limitations that arose when completing our Habitat Suitability Analysis, we suggest that future iterations of the analysis should refine the model by updating and/or incorporating the following four inputs:

1. *Temperature*:
    - Update the model's *primary* and *secondary* temperature criteria to reflect the most up-to-date information about larval Pacific lamprey thermal tolerances in the Columbia River Estuary.
2. *Sediment*:
    - Generate geospatial data of the Columbia River Estuary's sediment distribution to identify each type of sediment (Types I, II, and III) outlined by Crandall and Wittenbach (2015).
    - Incorporate Columbia River Estuary geospatial sediment data to identify locations for future studies and projects concerning potential larval lamprey habitat.
3. *Water Flow*:
    - Define criteria for water flow velocity and incorporate geospatial water flow velocity data into the model to identify areas that contain safe velocity levels for larval lamprey.
4. *Climate Change:*
    - Update the model using data and estimated conditions for temperature, salinity, and sea level rise to make predictions of future climate change scenarios in the Columbia River Estuary. Forecast and assess how these scenarios and environmental changes may impact larval lamprey habitat.

Recommendations for Areas of Focus: The Columbia River Inter-Tribal Fish Commission is currently updating their Tribal Pacific Lamprey Restoration Plan for the Columbia River Basin. We suggest the incorporation of the following six overarching recommendations into their updated plan to address factors that may impact lamprey survivability and outreach about their conservation status:

1. *Dredge Sites (this may require collaboration with the Army Corps of Engineers and the Lamprey Technical Workgroup)*
    - Salvage larval lamprey before and during the dredging process to prevent larvae from being displaced or buried under sediment layers.
    - Define sites to relocate dredged sediment to areas of the Columbia River Estuary that have fast moving currents, which could separate larvae from dredged material.
    - Study the impacts of dredging on Pacific lamprey life stages and behavior.
2. *Restoration Projects*:
    - Determine regions of the Columbia River Estuary from the Habitat Suitability Analysis (containing fine sediments) that are within the *primary* and *secondary* suitable habitat temperature and salinity parameters.
    - Identify locations in the Columbia River Estuary to implement restoration projects (e.g., replanting native vegetation) for larval lamprey rearing habitat that will provide ecosystem benefits for additional species and ecosystems in the Estuary. Restoration sites should provide ideal habitat conditions for Pacific lamprey and connect suitable habitats on a seasonal basis.
    - Implement wooden structures using locations outlined in the Habitat Suitability Analysis that may support fine sediment habitat for larval lamprey and study the restoration results (as demonstrated by Gonzalez et al. 2017).
3. *Barriers (this may require collaboration with Allan Whiting of the Lower Columbia River Watershed Council)*:
    - Identify and assess potential barriers to lamprey within tributaries and determine passage solutions in high priority sites located within the Columbia River Estuary. This process will provide additional spawning and rearing grounds for lamprey and may require collaboration with organizations who maintain the estuarine and tributary barriers.
    - Study barriers, lamprey passage structures, and barrier removal strategies to improve passage and understanding of lamprey usage of tributaries of the Columbia River Estuary.
4. *Contamination Sites*:
    - Continue studies and implementing water quality monitoring stations at Bonneville Dam and throughout the Columbia River Estuary and Columbia River mainstem, to track and predict contamination sites.
5. *Tracking Lamprey (this may require collaboration with the Pacific Lamprey Conservation Initiative, U.S. Fish and Wildlife Service, the Lamprey Technical Workgroup, and community organizations)*:

    - Continue working towards the implementation of a lamprey tagging program to track their movements throughout tributaries, the Columbia River, and the Columbia River Estuary.
6. *Outreach*:
    - Develop public outreach and educational materials to communities along the Columbia River that explain Pacific lamprey's importance to the local aquatic ecosystem and tribal communities. These materials should describe anthropogenic impacts on lamprey populations and the need for community support to aid in restoration efforts.

The project was able to use salinity, temperature, and geomorphology data to create maps that displayed if and where preferred habitat for larval Pacific lamprey exists in the Columbia River Estuary through the Habitat Suitability Analysis. It discussed knowledge gaps, larval and adult lamprey use of the Columbia River Estuary, and the need for additional information on their life cycles. The Habitat Suitability Analysis results can be used with the non-environmental parameters to locate areas in the Columbia River Estuary that may best support larval and adult Pacific lamprey. These areas may support lamprey on a seasonal basis and future projects may need to primarily focus on these areas to broaden the scientific community's understanding of Pacific lamprey. This report discussed areas of focus, both environmental and non-environmental factors, which may assist with conservation and restoration efforts, and support previous and current projects in the Columbia River Estuary. Factors such as sediment, dredging, barriers, contamination, and restoration strategies may play a role and impact the survivability of Pacific lamprey. Together, the Habitat Suitability Analysis and information on areas of focus may help identify and classify locations where studies and projects could be implemented to obtain additional information to address Pacific lamprey knowledge gaps. Between the results of our Habitat Suitability Analysis and the provided list of recommendations, our project will assist the Columbia River Inter-Tribal Fish Commission and other stakeholders in prioritizing areas for research and restoration of Pacific lamprey in the Columbia River Estuary.

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Appendix I: Data Obtained from the Columbia River Inter-Tribal Fish Commission

Data Name: Temperature
File Type: GeoTIFF (example: tembmxapr.tif)
Source: Columbia River Inter-Tribal Fish Commission
Website: http://www.stccmop.org/datamart/virtualcolumbiariver
Data Info:
The client generated temperature model outputs from the Oregon Health & Science University's Center for Coastal Margin Observation & Prediction model, which were used to analyze potential habitat for larval Pacific lamprey. Charles Seaton (the client's Coastal Margin Observation & Prediction Program Coordinator) used a 4D hindcast simulation modeling system, the Virtual Columbia River, and the system's most recent statistical hindcast simulation database (database 33) to create the outputs (Kärnä & Baptista, 2016).

The Virtual Columbia River provides model scenarios which include daily forecasts, decade-scale retrospective simulations, and a climatological atlas that provides several scales of data availability (Center for Coastal Margin Observation & Prediction, 2022c). Database 33 extracts time series information at 15-minute intervals and can convert time series data into a series of indicators that can be binned into days or processed to create daily maximum or minimum time series information (Center for Coastal Margin Observation & Prediction, 2022a). The database's summary statistics calculated temperature values from the Columbia River by day and they were later binned by month to produce temperature model outputs. Database 33 provides improved model results when compared with previous iterations of Columbia River hindcast simulation databases due to the database's higher mesh resolution, improved mesh quality, and increased temporal resolution (Kärnä & Baptista, 2016). This database contains more simulation triangles and nodes than its predecessors (Baptista et al., 2015).

The Center for Coastal Margin Observation & Prediction models cover the entire area of study (referred to in this report as the Region of Interest), which spans from the mouth of the Pacific Ocean (located at Columbia River Mile 0) up to Bonneville Dam (located at Columbia River Mile 145). Temperature model outputs were projections that were based on 20-year averages (between the years 1999 and 2018) and generated as GeoTIFF files. It should be noted that these model outputs were tested against a few point-scale measurements. These files consisted of 12 individual raster files for each month of temperature data from the bottom of the Columbia River. Each raster summarized temperature conditions for that month of the year (for example, the file tembmxapr.tif contained summary statistics for all Aprils between 1999 and 2018). The temperature data consisted of a monthly maximum value that was measured in degrees

Celsius. These raster files were used as an input for the Habitat Suitability Analysis to identify potential habitat for larval Pacific lamprey.

Data Name: Salinity
File Type: GeoTIFF (example: salbmxapr.tif)
Source: Columbia River Inter-Tribal Fish Commission
Website:
http://www.stccmop.org/datamart/virtualcolumbiariver/simulationdatabases/climatologicalatlas_db33
Data Info:
Similar to the temperature data, the client generated salinity model outputs using the Center for Coastal Margin Observation & Prediction's Virtual Columbia River modeling system and database 33. The salinity model outputs were projections that were based on 20-year averages (between the years 1999 and 2018) and resulted in daily summary statistics that were binned by month to produce GeoTIFF files for use in the Habitat Suitability Analysis. They consisted of 12 individual raster files for each month of salinity data from the bottom of the Columbia River (in Practical Salinity Units, which is roughly equivalent to Parts Per Thousand). Each raster summarized salinity conditions for that month of the year (like the example above for temperature data, the file salbmxapr.tif contained summary statistics for all Aprils between 1999 and 2018). Along with the temperature raster files, the salinity raster files were used as an input for the Habitat Suitability Analysis to identify potential habitat for larval Pacific lamprey.

Data Name: Hydrogeomorphic Reach
File Type: Geodatabase (example: Columbia_River_Estuary_Ecosystem_Classification.gdb)
Source: Lower Columbia Estuary Partnership
Website:
https://www.estuarypartnership.org/our-work/monitoring/habitat-mapping/columbia-river-estuary-ecosystem-classification
Metadata:
https://water.usgs.gov/GIS/metadata/usgswrd/XML/creec_hydrogeomorphic_reach.xml
Supplemental Report: https://pubs.usgs.gov/of/2011/1228/
Data Info:
Hydrogeomorphic reaches are one of several layers within the Lower Columbia Estuary Partnership's Columbia River Estuary Ecosystem Classification dataset (provided in a geodatabase file format). The Columbia River Estuary Ecosystem Classification is a series of ecosystem classifications that characterizes the Columbia River Estuary's biophysical characteristics using several hierarchical levels (which includes hydrogeomorphic reaches) (Simenstad et al., 2011). This dataset seeks to understand

physical factors that drive ecosystem development and list the contemporary landforms in the area (Lower Columbia Estuary Partnership, 2022a)The geodatabase file contains vector layers that display the Columbia River Estuary as eight separate regions spanning from the river's mouth to the Bonneville Dam (Simenstad et al., 2011). These parts were combined into one continuous layer for the Habitat Suitability Analysis and the continuous layer was used to map out the Region of Interest for the analysis (Simenstad et al., 2011). The hydrogeomorphic reaches incorporate ecosystem structure indicators and processes that include and incorporate tidal and freshwater controlling factors (Simenstad et al., 2011).

Data Name: Geomorphic Catena
File Type: Geodatabase (example: Columbia_River_Estuary_Ecosystem_Classification.gdb)
Source: Lower Columbia Estuary Partnership
Website: https://www.estuarypartnership.org/our-work/monitoring/habitat-mapping/columbia-river-estuary-ecosystem-classification
Metadata: https://water.usgs.gov/GIS/metadata/usgswrd/XML/creec_geomorphic_catena.xml
Supplemental Report: https://pubs.usgs.gov/of/2011/1228/
Data Info:
The geomorphic catena layer (referred to in subsequent sections as geomorphology) also appears in the Lower Columbia Estuary Partnership's Columbia River Estuary Ecosystem Classification dataset. This is a vector layer that contains individual landforms within the Columbia River's ecosystem complexes that were created during the past 2,000 years and represent natural changes in the ecosystem. Examples include natural levees, bedrock, and floodplains (Simenstad et al., 2011). This data was used to identify geomorphic regions where larval lamprey would likely be found based on their habitat requirements. This meant that aquatic catena that were likely to support habitat conditions for larval lamprey (such as deep channels) were incorporated into the Habitat Suitability Analysis, and terrestrial catena (such as bedrock and dune deposits) were excluded from the analysis.

Appendix II: Model GeoTIFF Documentation from the Columbia River Inter-Tribal Fish Commission

Charles Seaton, the client's Center for Coastal Margin & Observation Coordinator, provided the following information about the model GeoTIFFs for salinity and temperature that were used in the Habitat Suitability Analysis:

Model GeoTIFFs of Monthly Climatologies of Salinity and Temperature in the Columbia River

Owner: Columbia River Inter-Tribal Fish Commission

Contact: Charles Seaton

Contact Email: cseaton@critfc.org

GeoTIFF images were generated from the Columbia River Inter-Tribal Fish Commission-Center for Coastal Margin Observation & Prediction hindcast simulation database known as db33 (described in Kärnä et al., 2016 and Baptista et al., 2015).

The db33 simulation database covers 1999-2018. GeoTIFF images showing monthly climatology were generated by the calendar month (12 images for each variable), summarizing conditions over that month of each year (e.g., June images contain summary statistics compiled over all Junes from 1999-2018).

Raw db33 output has a 15-minute timestep, at 37 (terrain following) vertical levels within the area of interest for these images. Summary statistics were initially calculated on a daily basis for the surface and bottom vertical levels for temperature and salinity. Daily statistics were then binned by month to produce the monthly climatologies.

Salinity and temperature summary statistics are based on maximum values at the bottom of the river.

Results were initially produced in ArcGIS TIN format, before being converted into rasters in GeoTIFF format for convenience.

References:

Baptista, A. M., Seaton, C., Wilkin, M. P., Riseman, S. F., Needoba, J. A., Maier, D., Turner, P. J., Kärnä, T., Lopez, J. E., Herfort, L., Megler, V. M., McNeil, C., Crump, B. C., Peterson, T. D., Spitz, Y. H., & Simon, H. M. (2015). Infrastructure for collaborative science and societal applications in the Columbia River estuary. Frontiers of Earth Science, 9(4), 659–682. https://doi.org/10.1007/s11707-015-0540-5

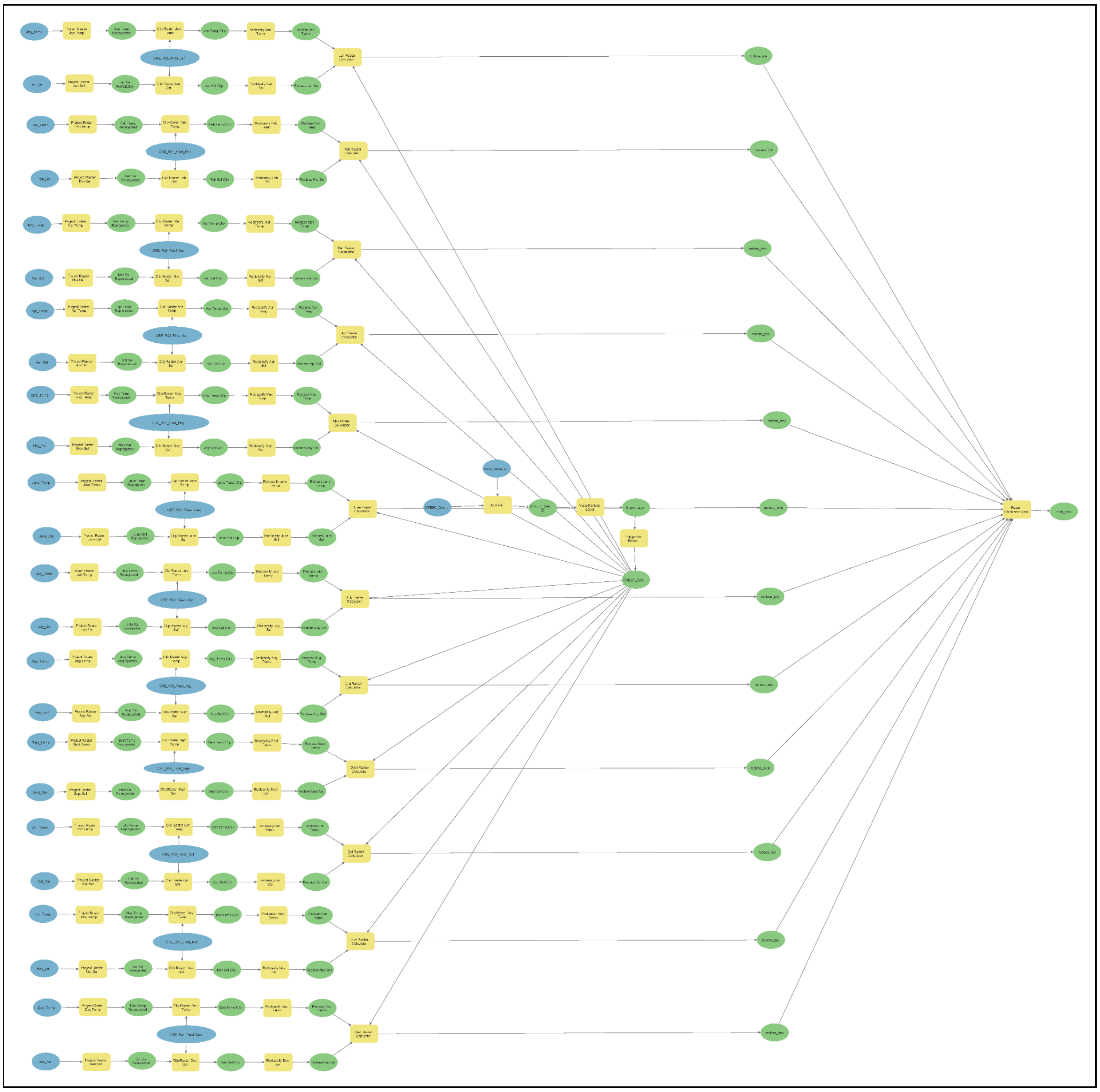
Kärnä, T., & Baptista, A. M. (2016). Evaluation of a long-term hindcast simulation for the Columbia River estuary. Ocean Modelling, 99, 1–14. https://doi.org/10.1016/j.ocemod.2015.12.007

Appendix III: Data Obtained from the Lower Columbia Estuary Partnership

Data Name: Levee Features
File Type: Shapefile (ex: LCRE_Levees.shp)
Source: Lower Columbia Estuary Partnership
Website:
https://lcep.maps.arcgis.com/home/item.html?id=6b5bd7fce6244311a3c54f989219a60e&view=list&sortOrder=desc&sortField=defaultFSOrder#overview
Data Info:
The Levee Features shapefile contains information on the location of levees throughout the lower Columbia River and the Columbia River Estuary (Lower Columbia Estuary Partnership, 2022c). This shapefile includes the following levee classifications: man-made levees, breached levees, historical or removed levees, natural levees, and natural levees (Marcoe, 2022). An additional classification is the “sidecast of significance” which records the location of dredging waste products along the banks of the Columbia River (and could potentially affect fish habitat in low-lying lands) (Marcoe, 2022).

Data Name: Elevated Road and Rail Fill Features
File Type: Shapefile (LCRE_Levees_Other_Road_Rail.shp)
Source: Lower Columbia Estuary Partnership
Website:
https://lcep.maps.arcgis.com/home/item.html?id=6b5bd7fce6244311a3c54f989219a60e&view=list&sortOrder=desc&sortField=defaultFSOrder#overview
Data Info:
The Elevated Road and Rail Fill Features shapefile contains road and rail features along the Columbia River, which serve as a mapping product of the Columbia River Estuary Ecosystem Classification system (Marcoe, 2022).

Appendix IV: Schematic of Model Builder Workflow used in ArcGIS Pro to Identify Suitable Habitat



Appendix V: Table of Projects from the Pacific Lamprey Conservation Initiative- Lower Columbia/Willamette Regional Management Unit - Lower Columbia Sub-Unit

From the Pacific Lamprey Conservation Initiative, current Pacific Lamprey research has focused on gaining a better understanding of distribution and habitat use within the Columbia River mainstem and tributaries.

The following Pacific lamprey research and restoration actions were initiated or recently completed by Regional Management Units partners in the Lower Columbia River sub-unit from 2012-2020.

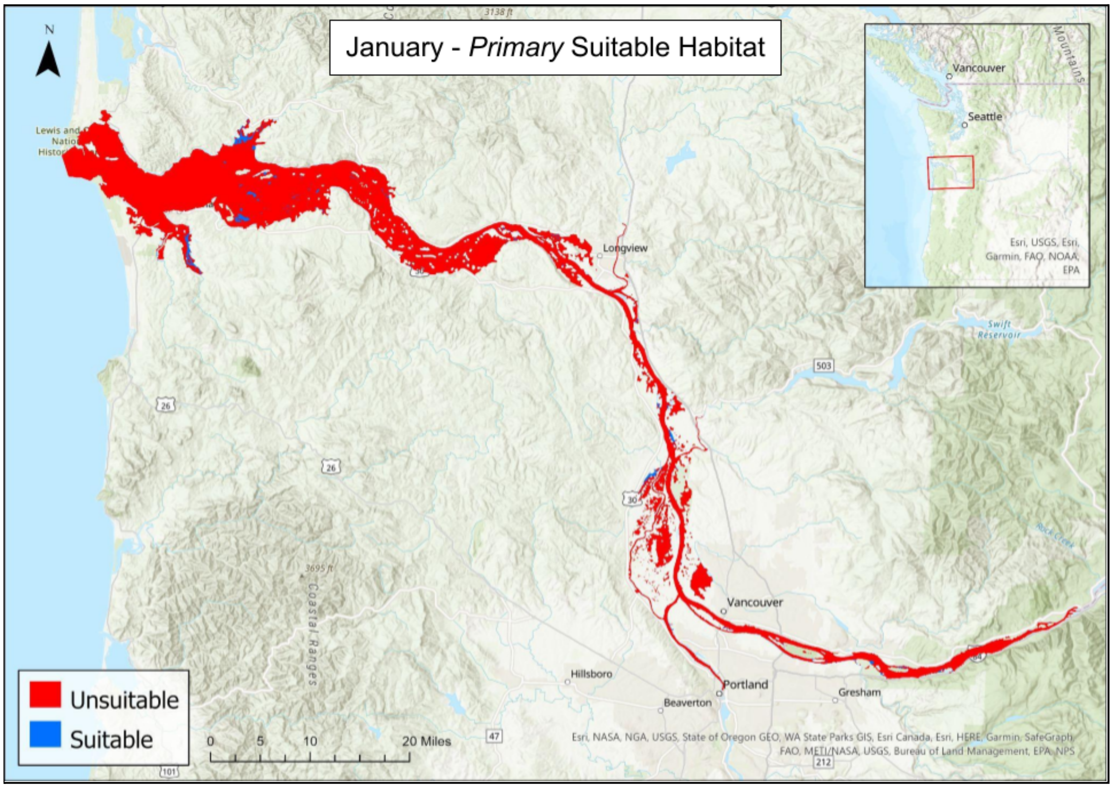
Hydrologic Unit Code (Areas in Regional Management Unit [RMU])	Focus Topic (Threat Categories)	Project Description	Type of Project	Status of Project
RMU	Population	Environmental DNA [eDNA], spawning ground surveys, smolt trapping and occupancy sampling to better understand lamprey distribution	Survey	Ongoing
RMU	Stream Degradation / Habitat Restoration	Implementation of instream and floodplain habitat restoration activities and culvert removal/replacement projects where lamprey salvage efforts occurred.	Instream	Ongoing
RMU	Passage	Evaluation of adult Pacific Lamprey passage efficacy at fishways and barrier dams associated with salmon hatcheries	Assessment	Beginning
RMU	Population	Distribution surveys in mainstem and principal tributaries	Survey	Ongoing
RMU	Population	Use of eDNA to monitor effectiveness of large wood placement projects and recolonization of larval lamprey following restoration	Assessment	Proposed/ Beginning
RMU	Lack of awareness	Consideration of lamprey when planning and implementing instream habitat restoration work (see LTW 2020b)- white paper made for projects	Coordination	Ongoing

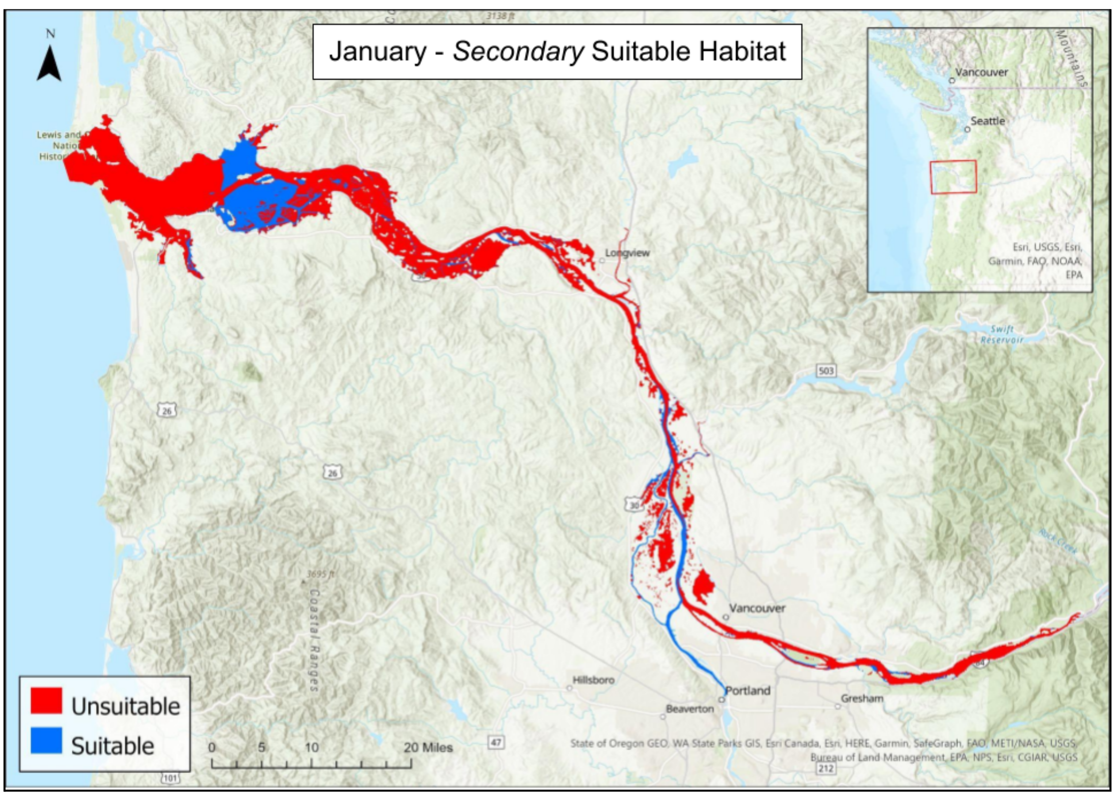
RMU	Lack of awareness	Compilation of lamprey data from SW Washington tributaries	Assessment	Complete
RMU	Passage	Map, assess and prioritize passage barriers in tributaries and evaluate available lamprey habitat upstream	Assessment	Proposed
RMU	Population	Adult/Juvenile Pacific Lamprey abundance data summary for Southwest Washington tributaries	Assessment	Beginning
RMU	Population	Oregon Department of Fish and Wildlife Conservation Plan for Lampreys in Oregon (Coastal, Columbia, and Snake Conservation Plan for Lamprey in Oregon)	Report	Complete
RMU	Population	Ongoing lamprey genetics work (Columbia River Inter-Tribal Fish Commission)	Assessment	Ongoing
Sandy	Stream Degradation	Sandy River floodplain reconnection, gravel augmentation in Bull Run River.	Instream	Complete
Sandy	Stream Degradation	Large wood augmentation, side channel reconnection in upper Sandy River.	Instream	Complete
Clatskanie	Population	Conduct adult spawning ground surveys to monitor Pacific Lamprey distribution, timing, and number of redds [spawning beds] to develop relative abundance indexes.	Survey	Ongoing
Clatskanie	Population	Deep water sampling to document distribution and habitat use of larval lamprey in the Columbia River mainstem.	Assessment	Complete
Clatskanie	Passage	Tide gate and culvert modification and removal projects to restore access to spawning and rearing habitat	Instream	Ongoing
Clatskanie	Stream Degradation / Habitat Restoration	Assessment of larval lamprey use in areas of salmonid restoration vs no restoration (Abernathy Creek).	Survey	Ongoing

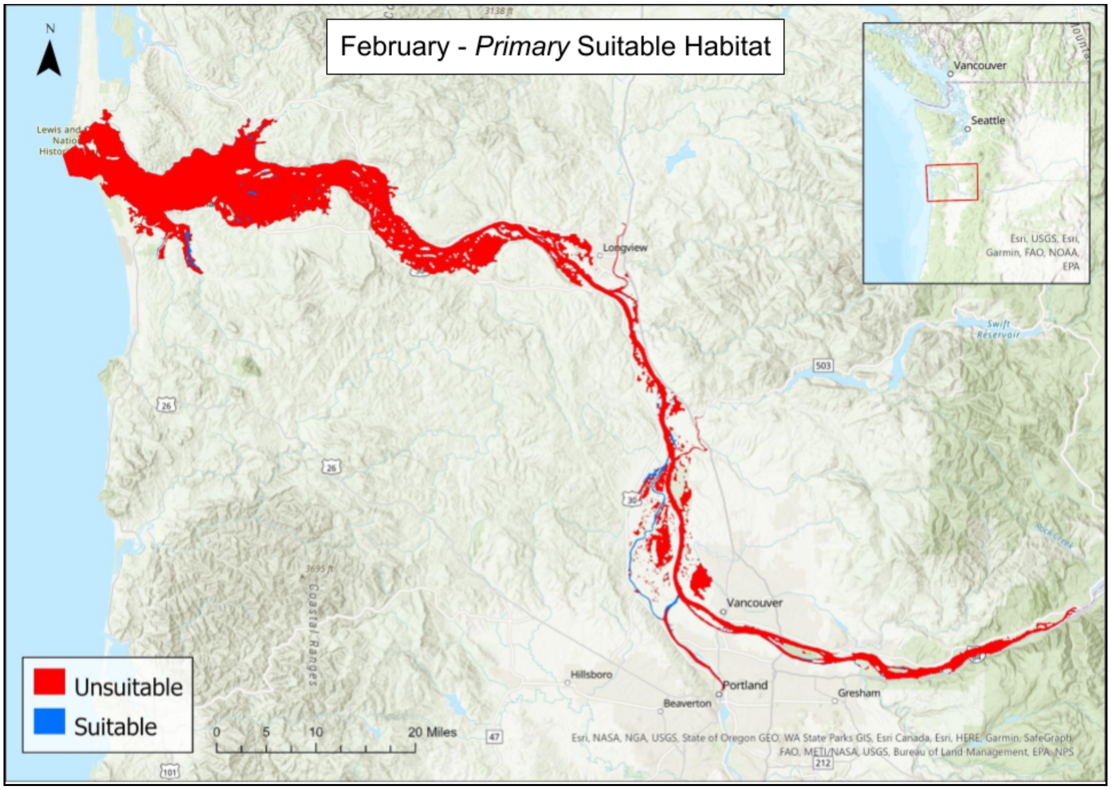
Lower Columbia	Stream Degradation	Floodplain reconnection on Lewis and Clark & junctions of Big and Little Creeks	Instream	Upcoming
Lower Columbia	Passage	Pilot test of acoustic telemetry array to monitor movement of juvenile lamprey	Instream	Upcoming
Lower Columbia	Passage	Lamprey friendly passage improvements at 3 dams at North Fork Klaskanine Hatchery	Instream	Beginning
Lower Columbia	Passage	Evaluation of passage constraints for lamprey at fish hatcheries in Washington State	Instream	Beginning
Lower Columbia	Population	Conduct adult spawning ground surveys to monitor Pacific Lamprey distribution, timing, and number of redds to develop relative abundance indexes.	Survey	Ongoing
Lower Columbia	Population	Pilot project to evaluate catchability of western river lamprey in coastal estuaries	Survey	Proposed
Lower Columbia	Passage (Restoration)	Tide gate and culvert modification and removal projects to restore access to spawning and rearing habitat.	Instream	Ongoing
Lower Columbia	Population	Investigation of salinity tolerance and larval lamprey occurrence in tidally influenced estuarine stream	Assessment	Complete
Lower Columbia	Passage	Formation of Oregon Tide Gate Partnership Group	Coordination	Ongoing
Lower Columbia	Passage	Tide gate inventory in lower Columbia River	Survey	Beginning
Lower Columbia	Passage	Restore Pacific Lamprey access to blocked high-quality habitats in the Lower Columbia region, inventory/assess potential barriers to lamprey, prioritize sites for providing passage, propose passage solutions for high priority sites	Assessment	Beginning/ Ongoing
Lower Columbia	Population/ Habitat Restoration	Install beaver dam structures, reintroduce beavers, assess lamprey presence and sample for Type I lamprey habitat pre- and post-project, gather important on-the-ground information to improve future efforts to restore	Instream, Assessment	Beginning/ Ongoing

		and protect lamprey habitat in the region		

Appendix VI: Monthly Outputs of Habitat Suitability Analysis



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Vancouver
Portland
Hillsboro
Beaverton
Gresham
Coastal Ranges
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Seattle
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Unsuitable
Suitable
0 5 10 20 Miles
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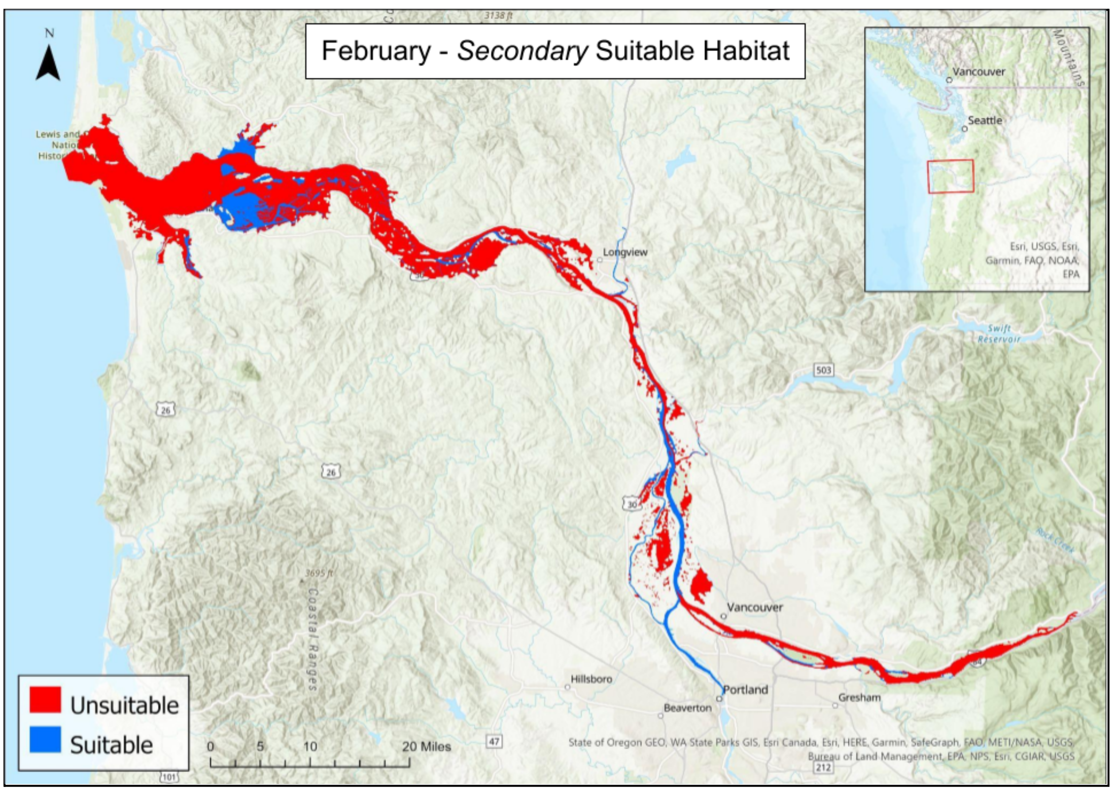
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Gresham
Coastal Ranges
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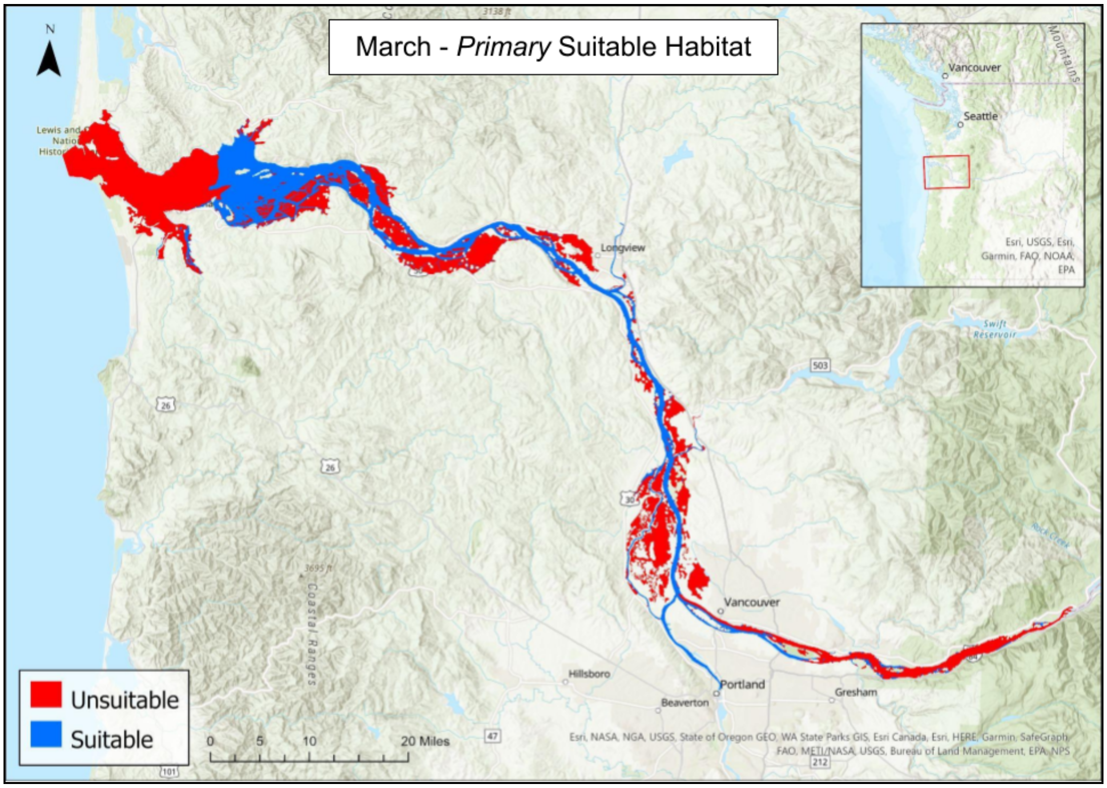
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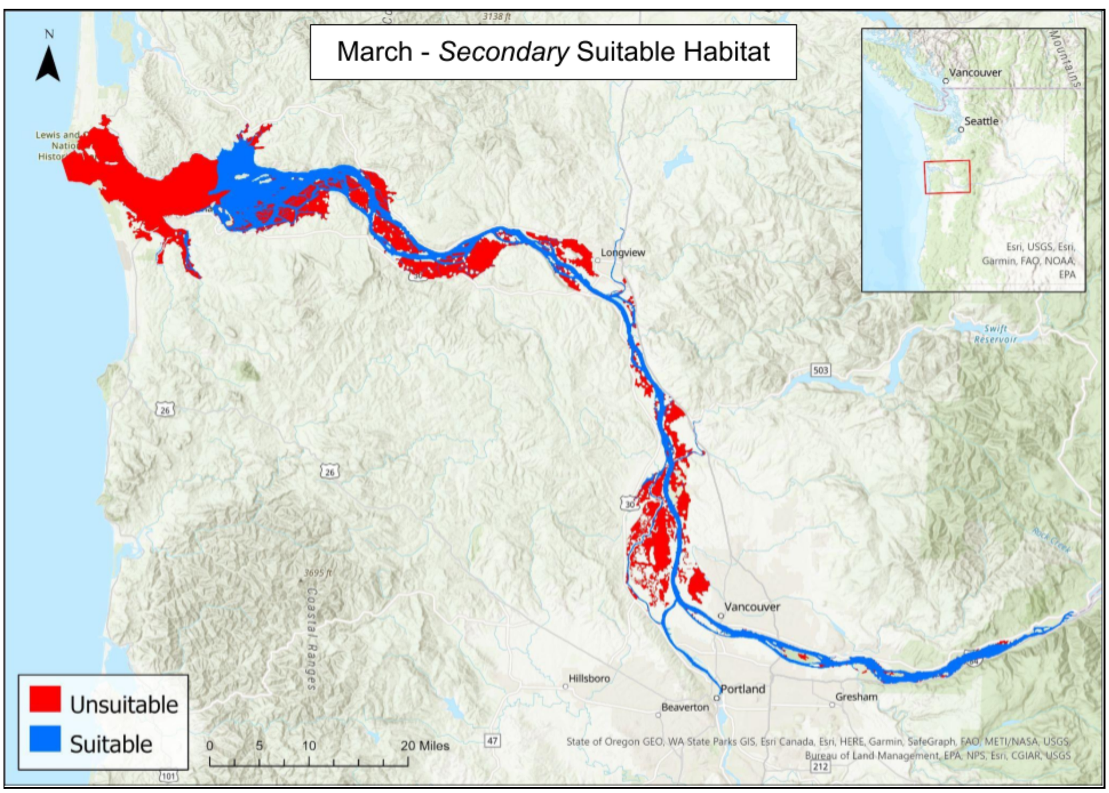
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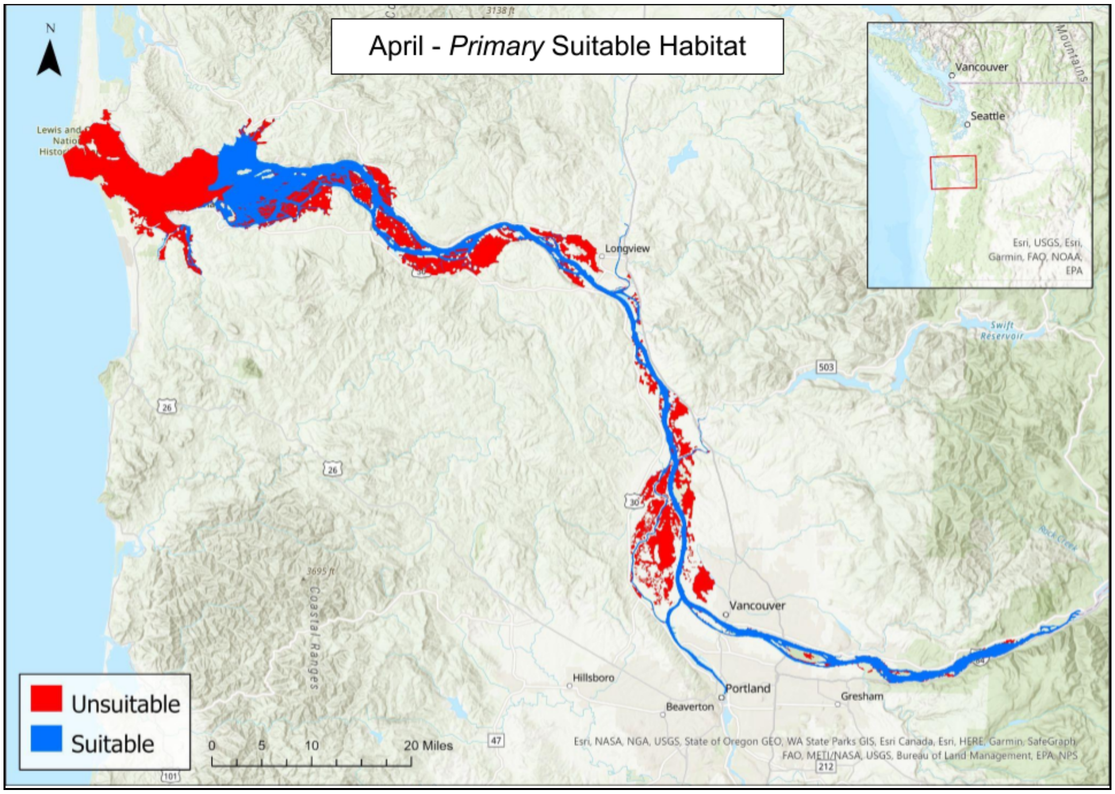
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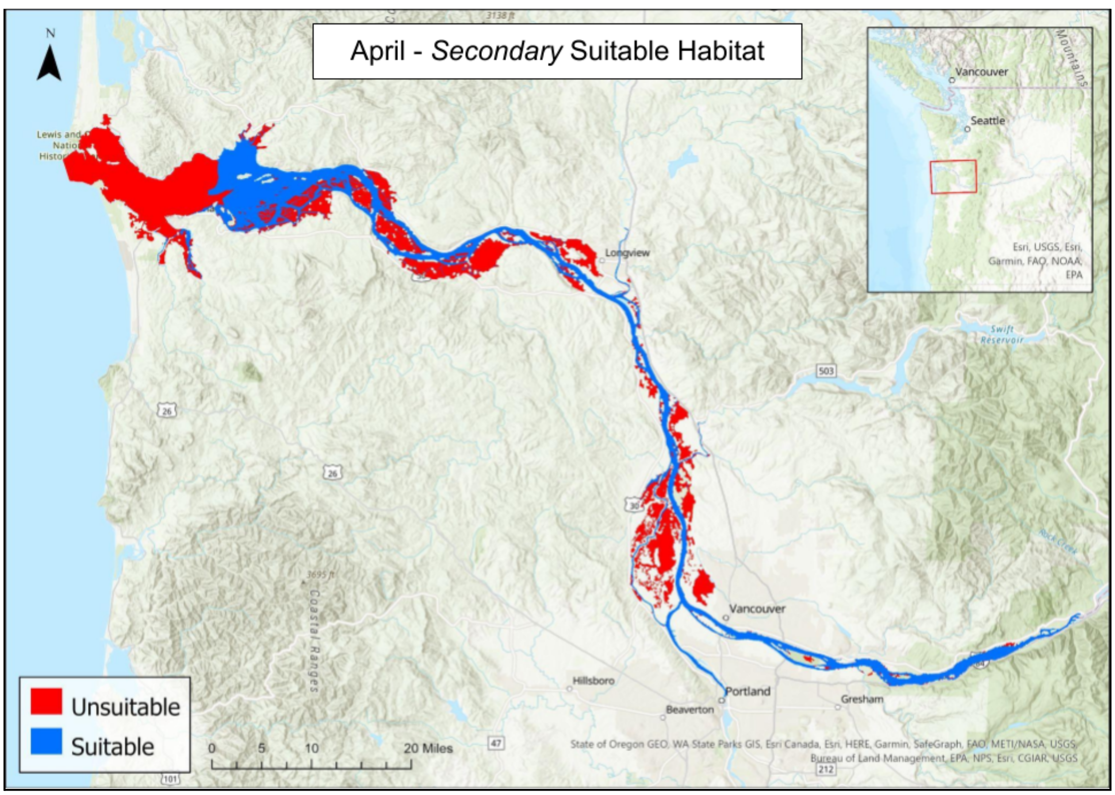
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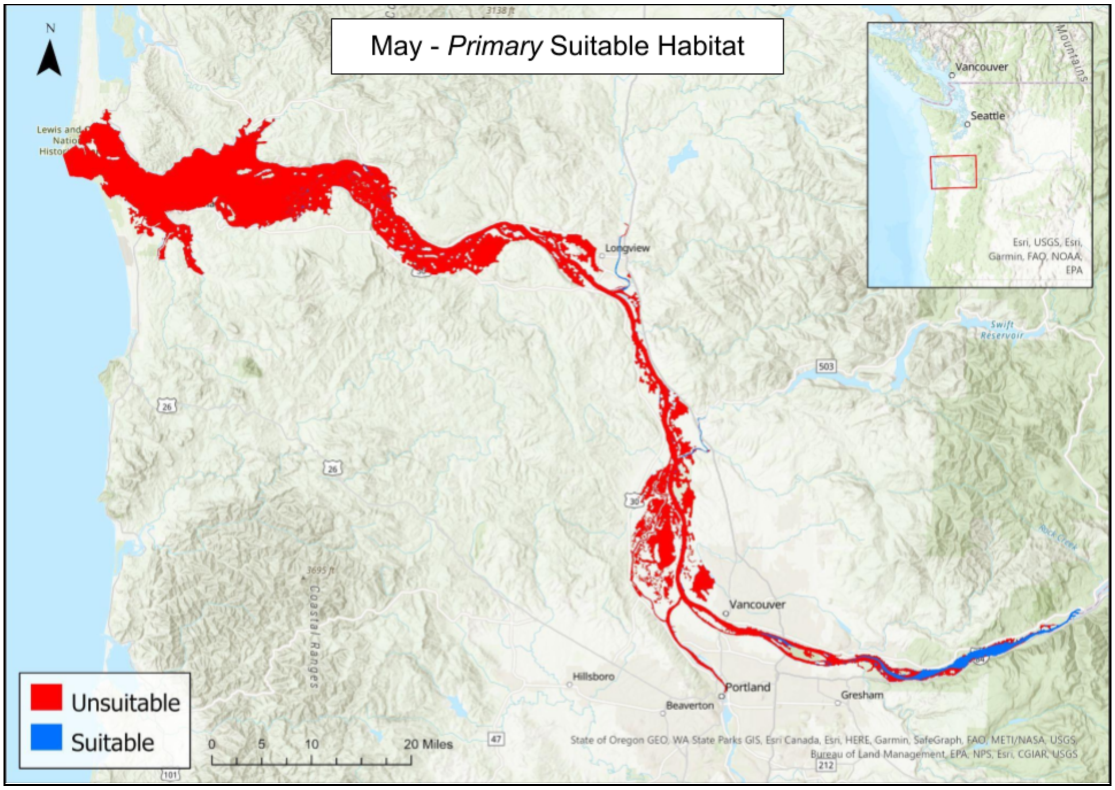
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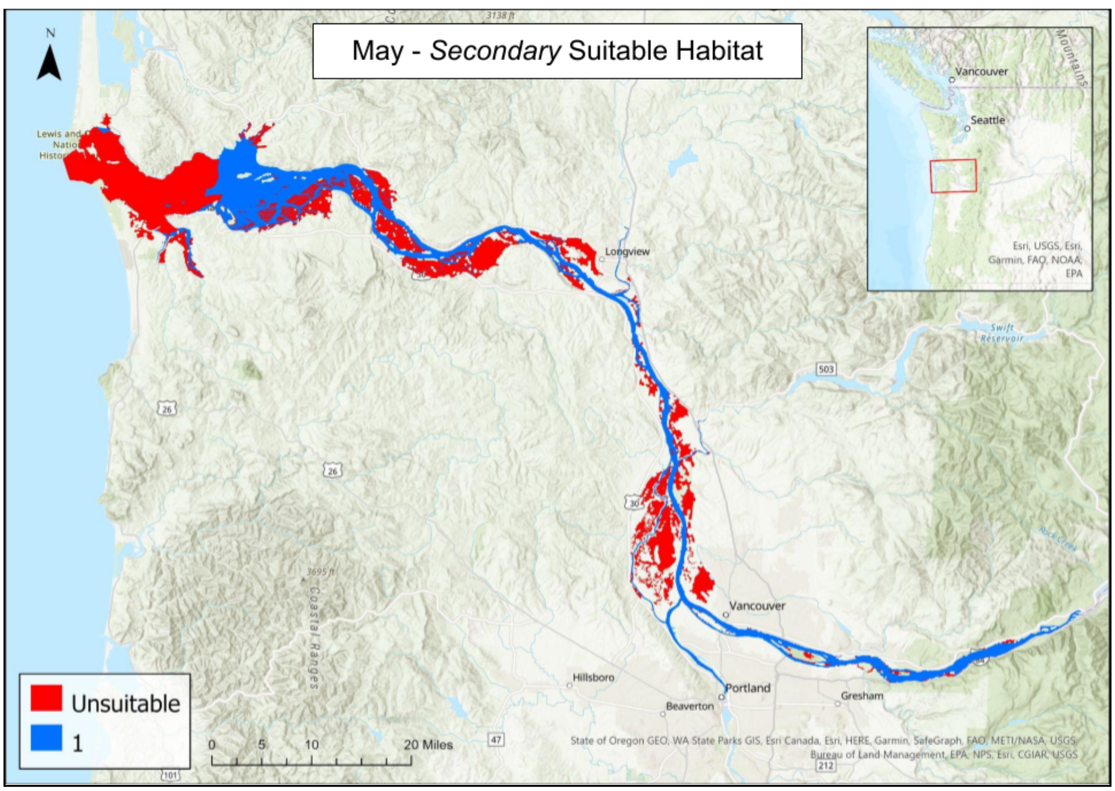
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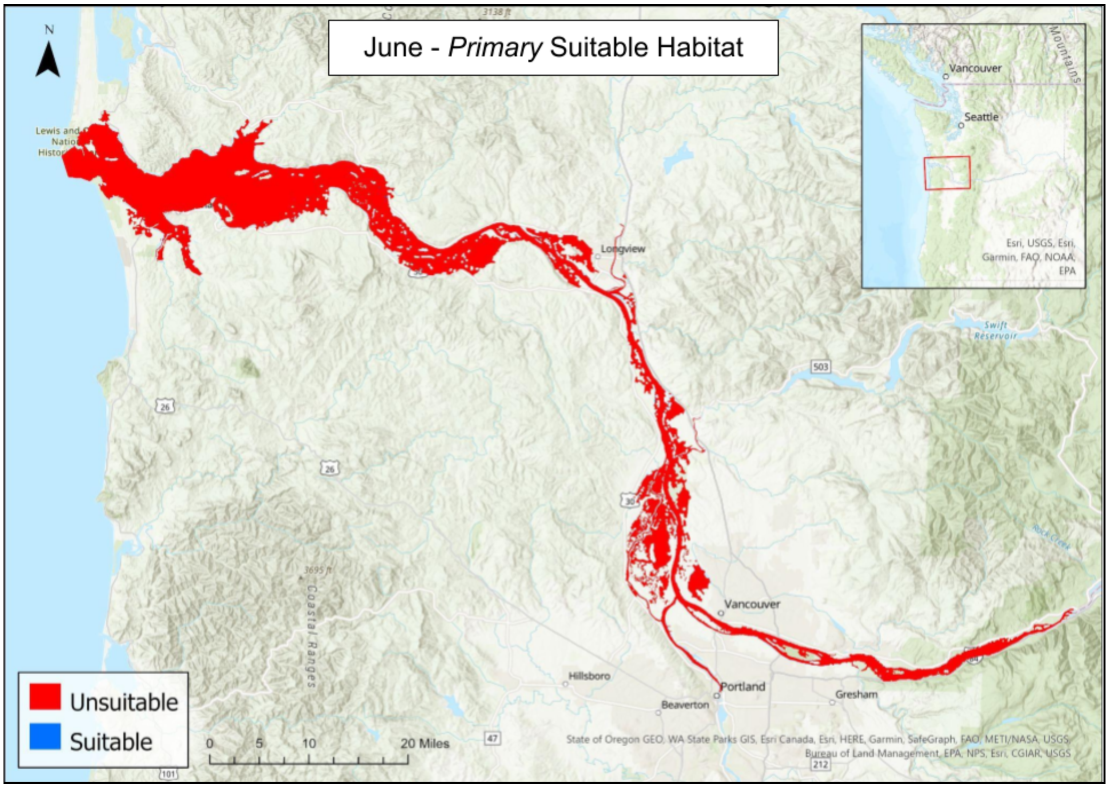
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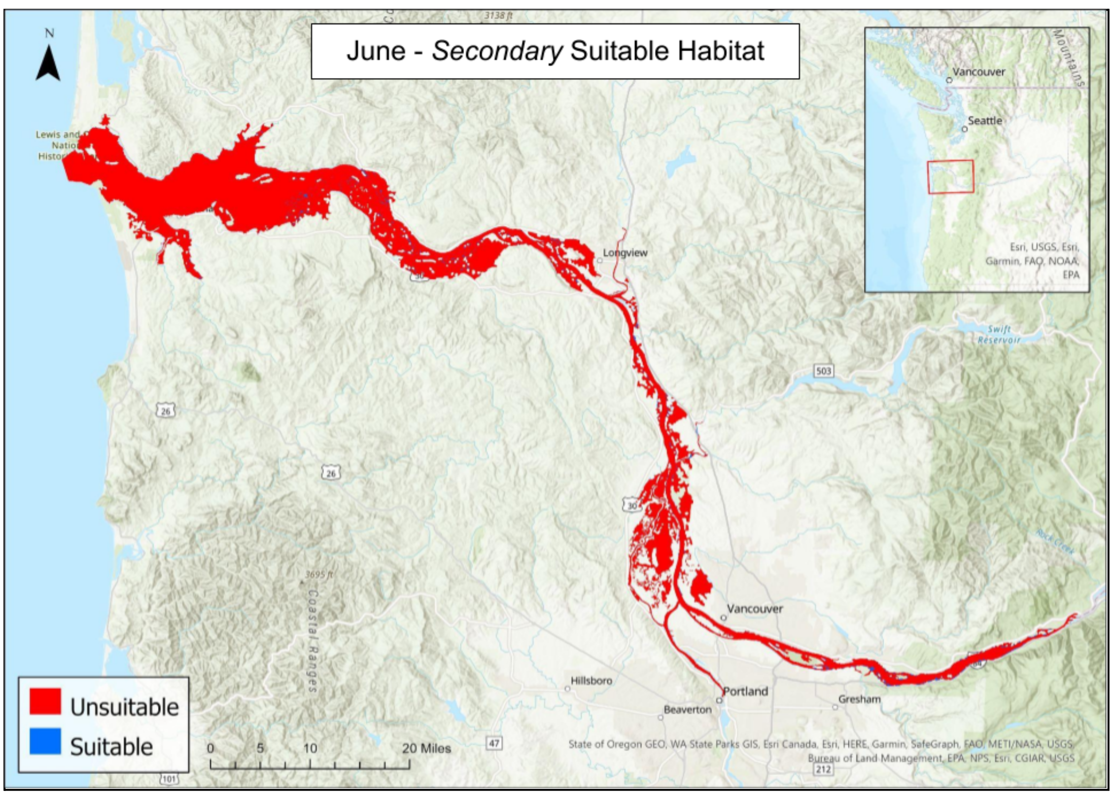
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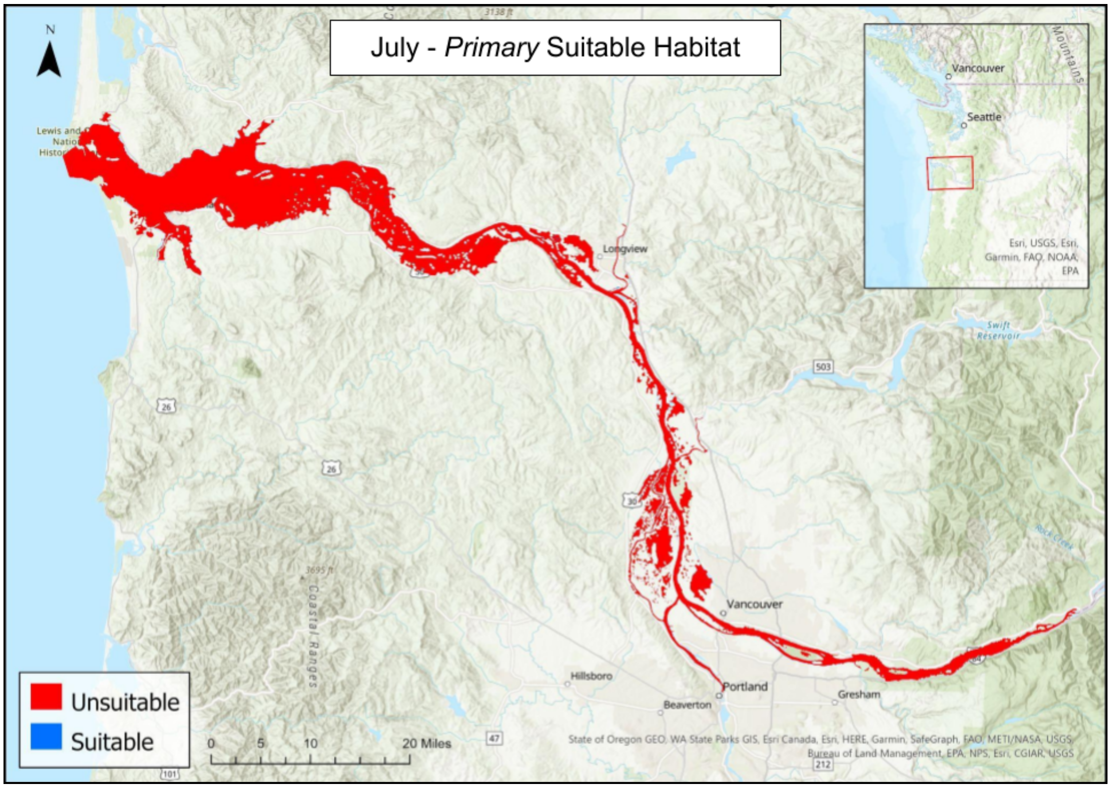
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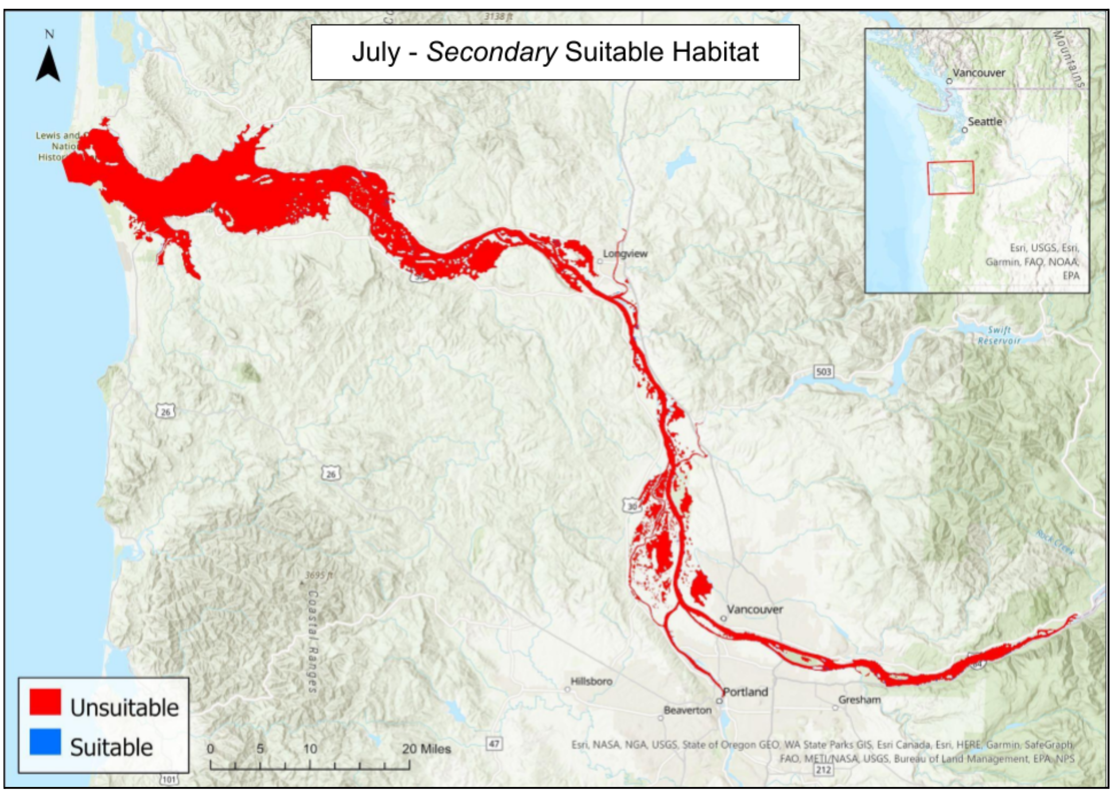
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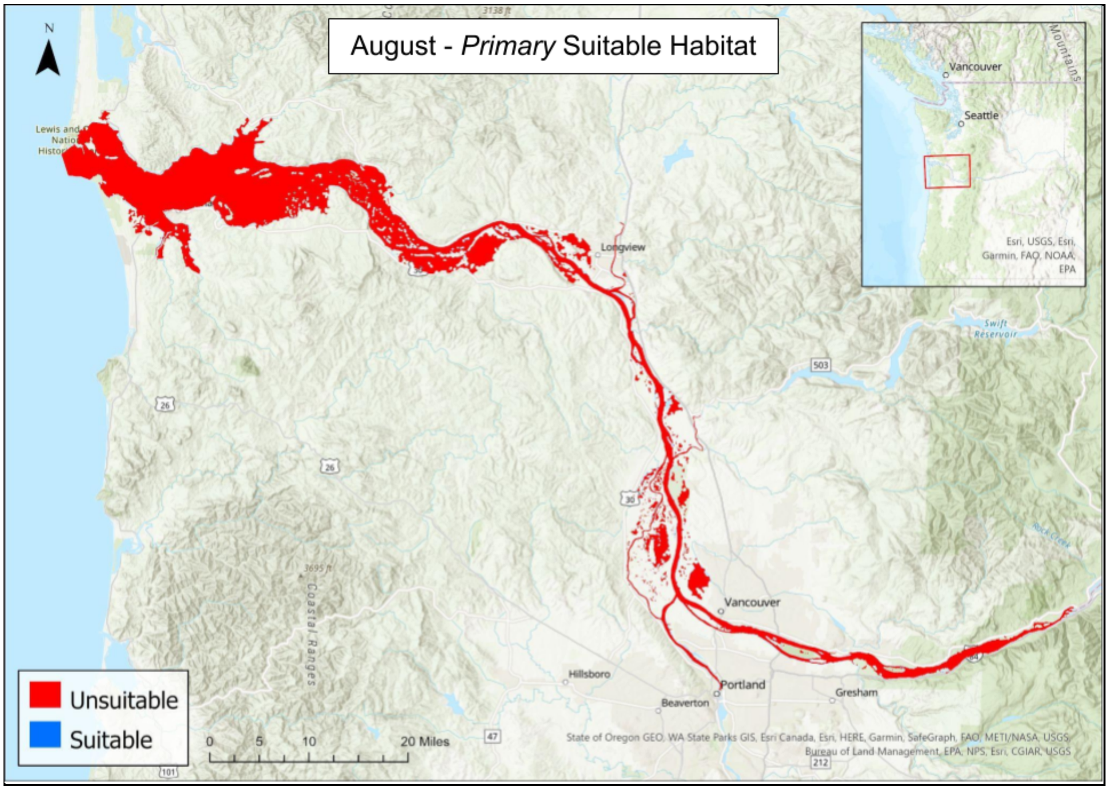
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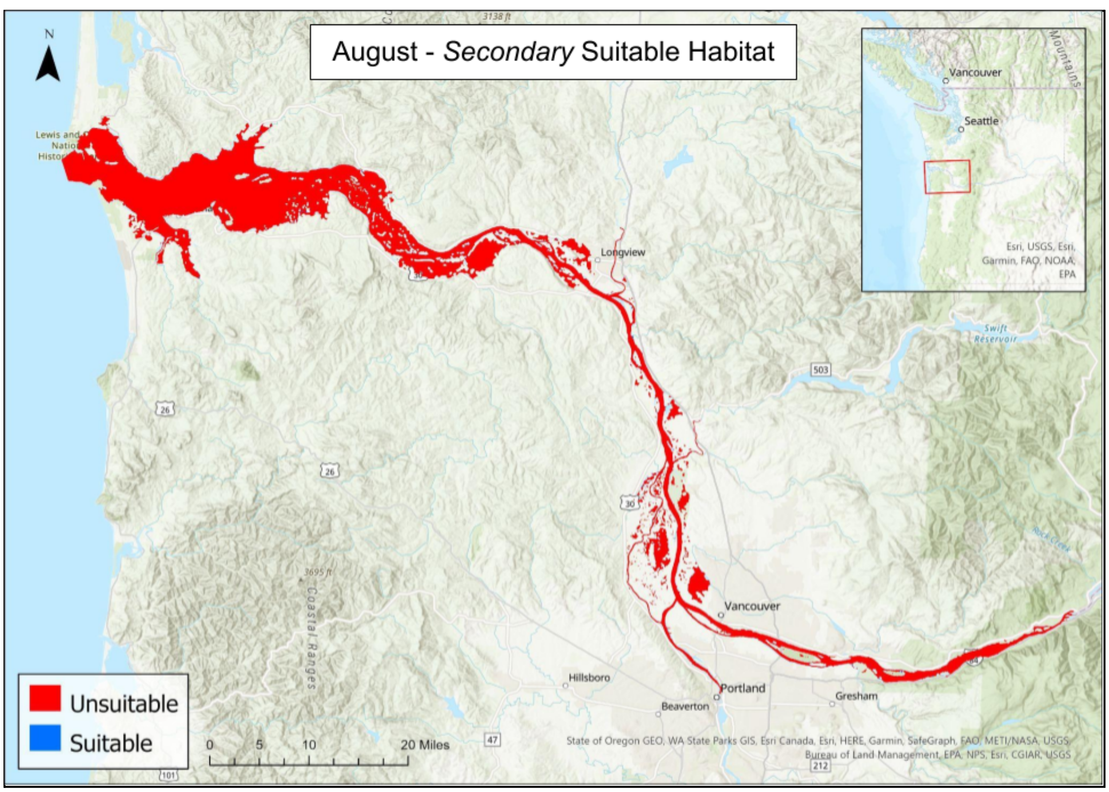
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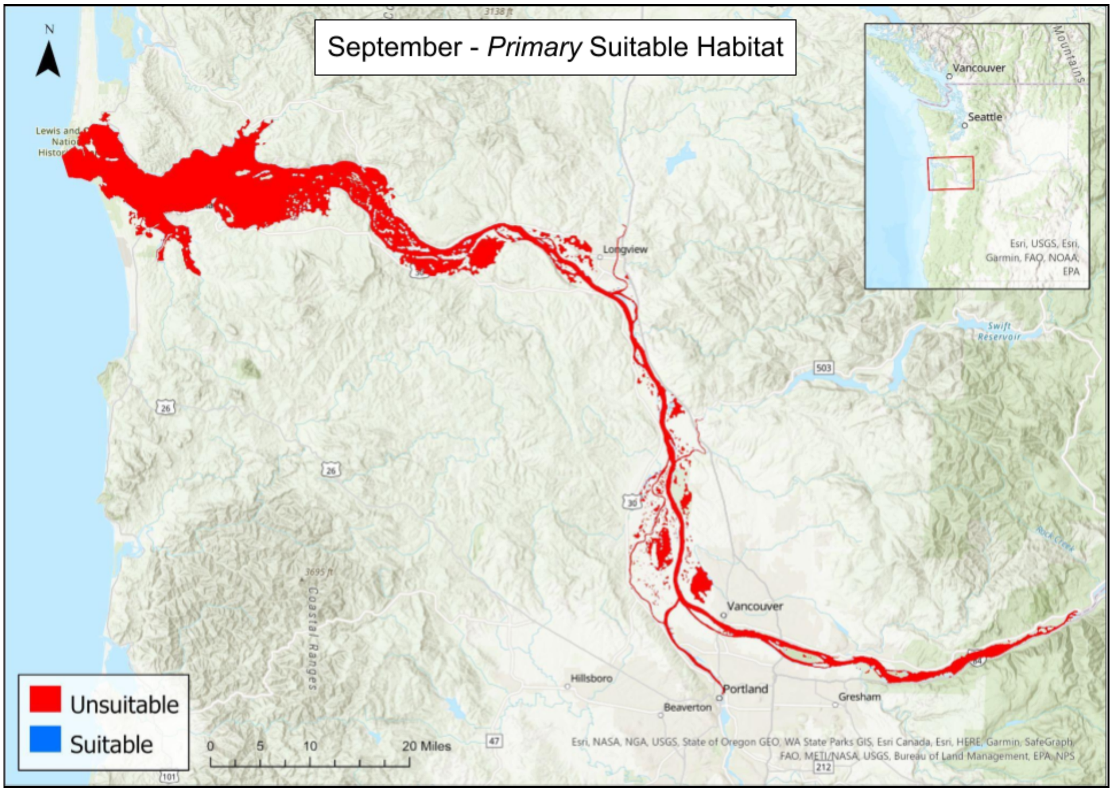
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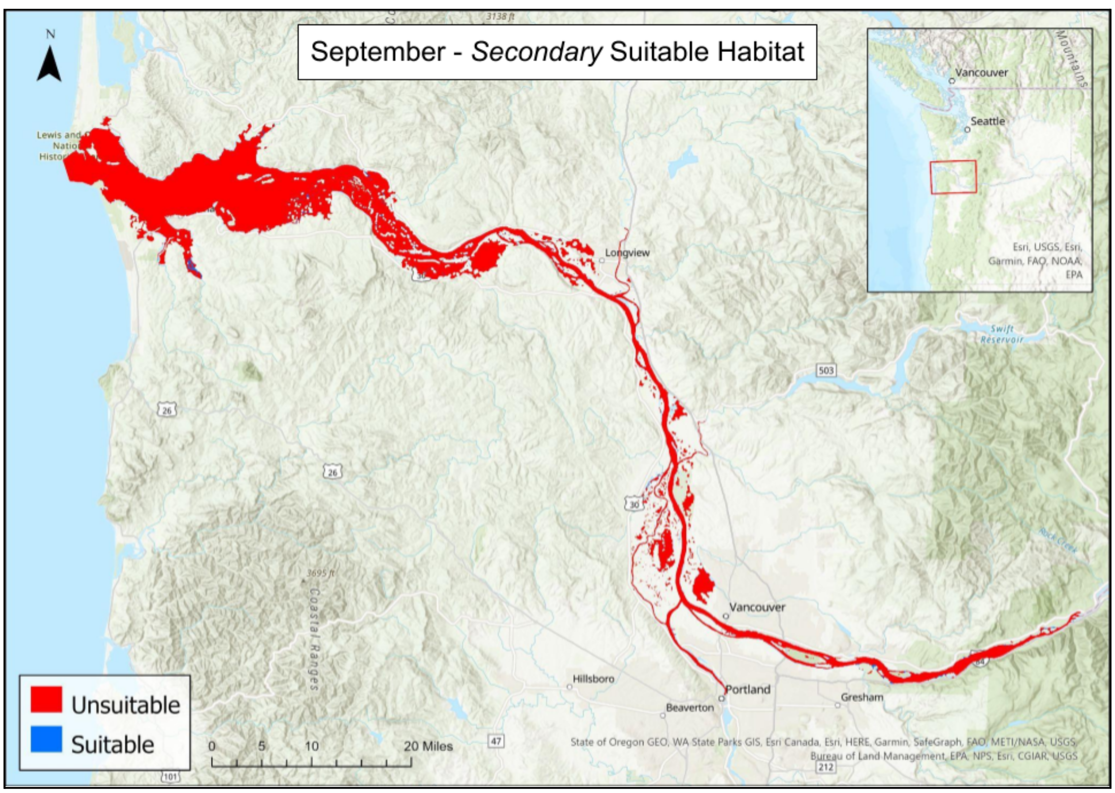
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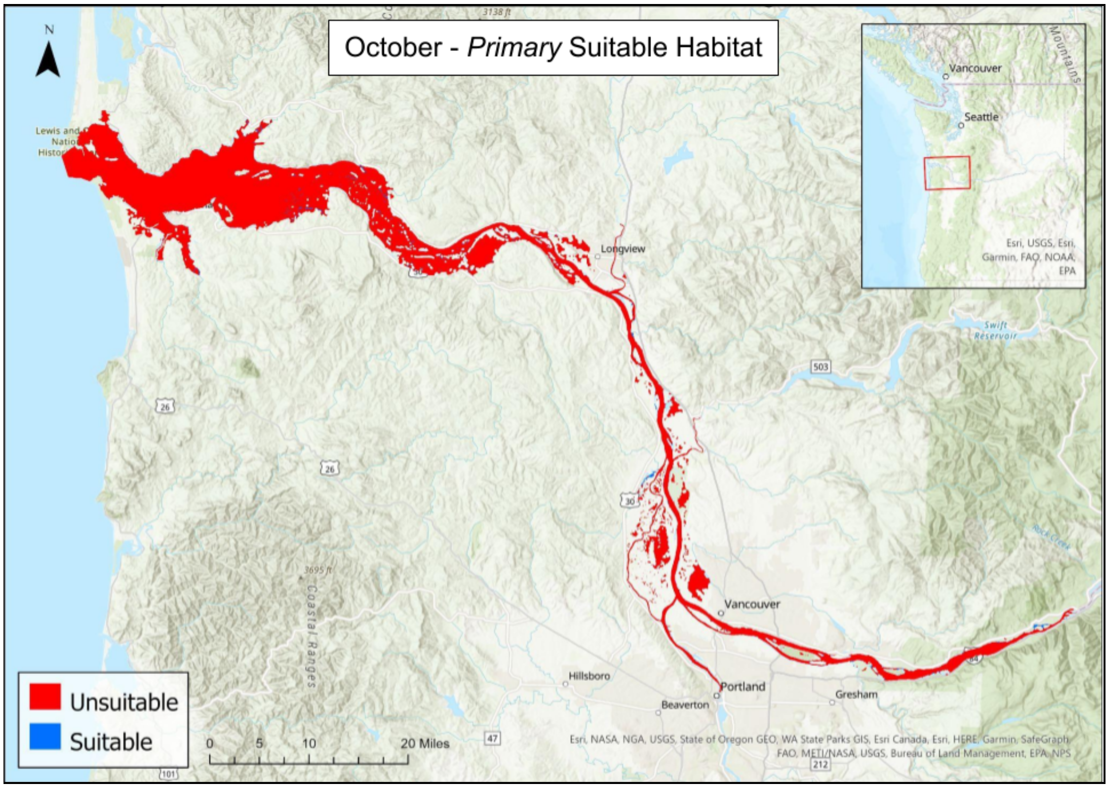
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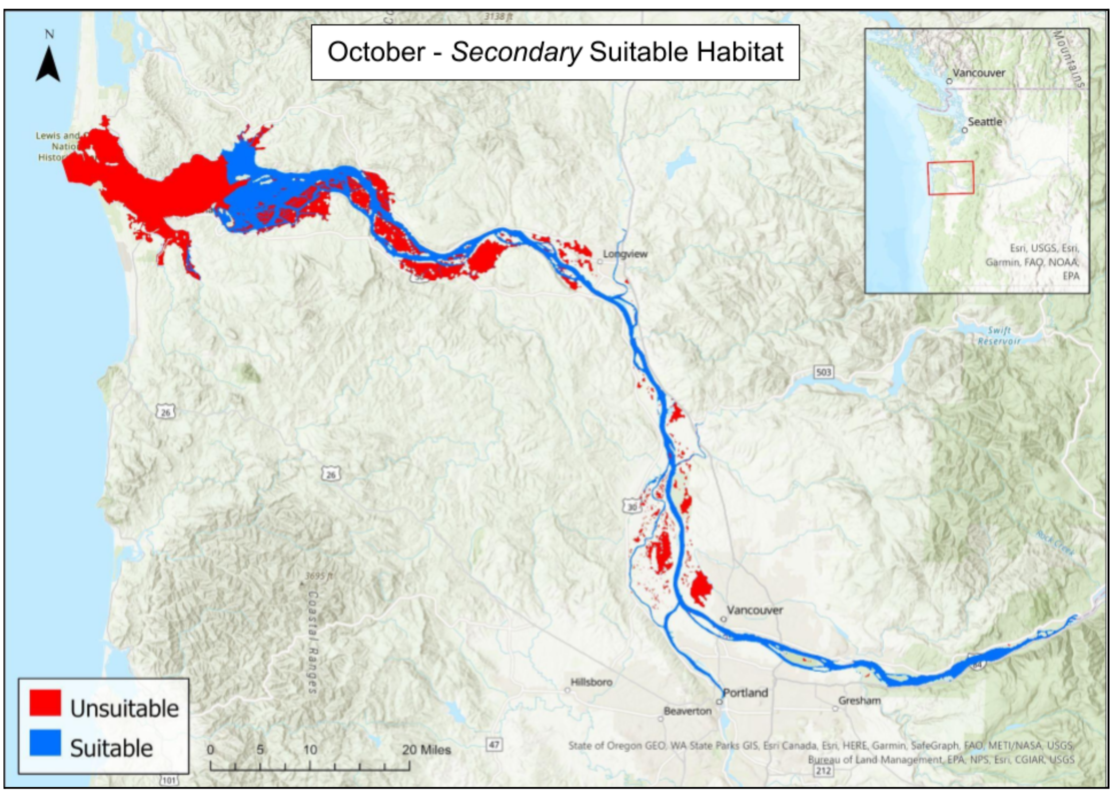
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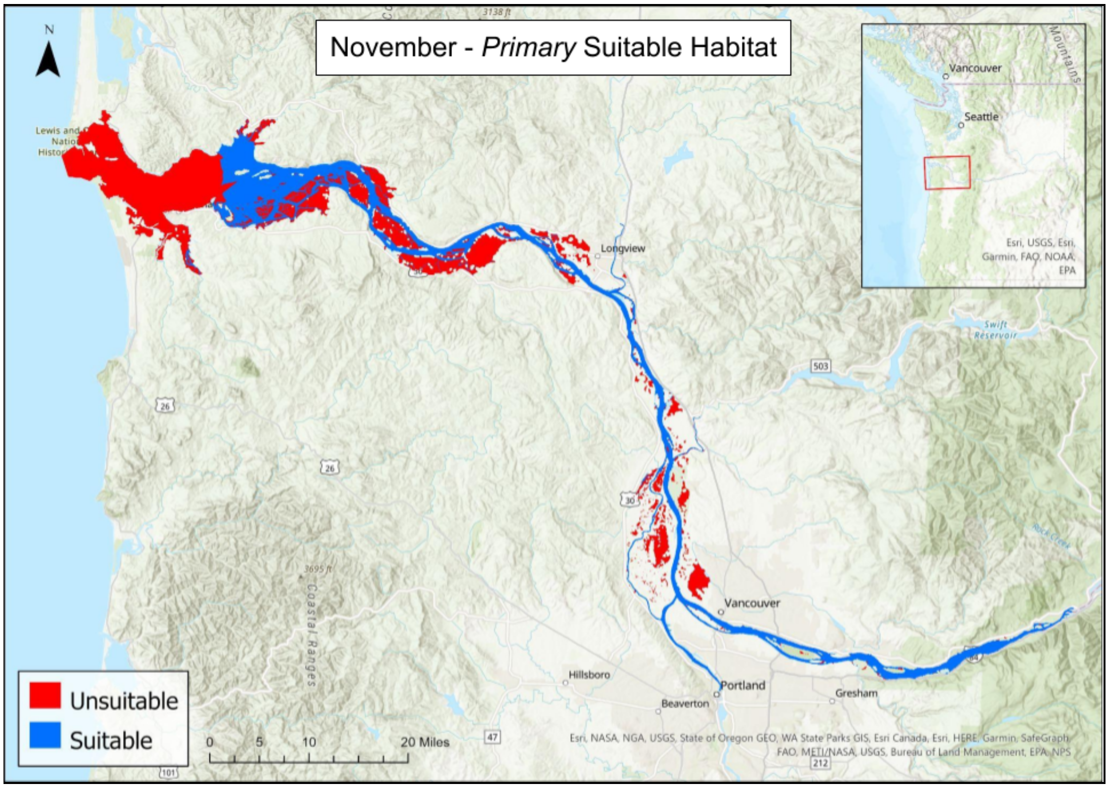
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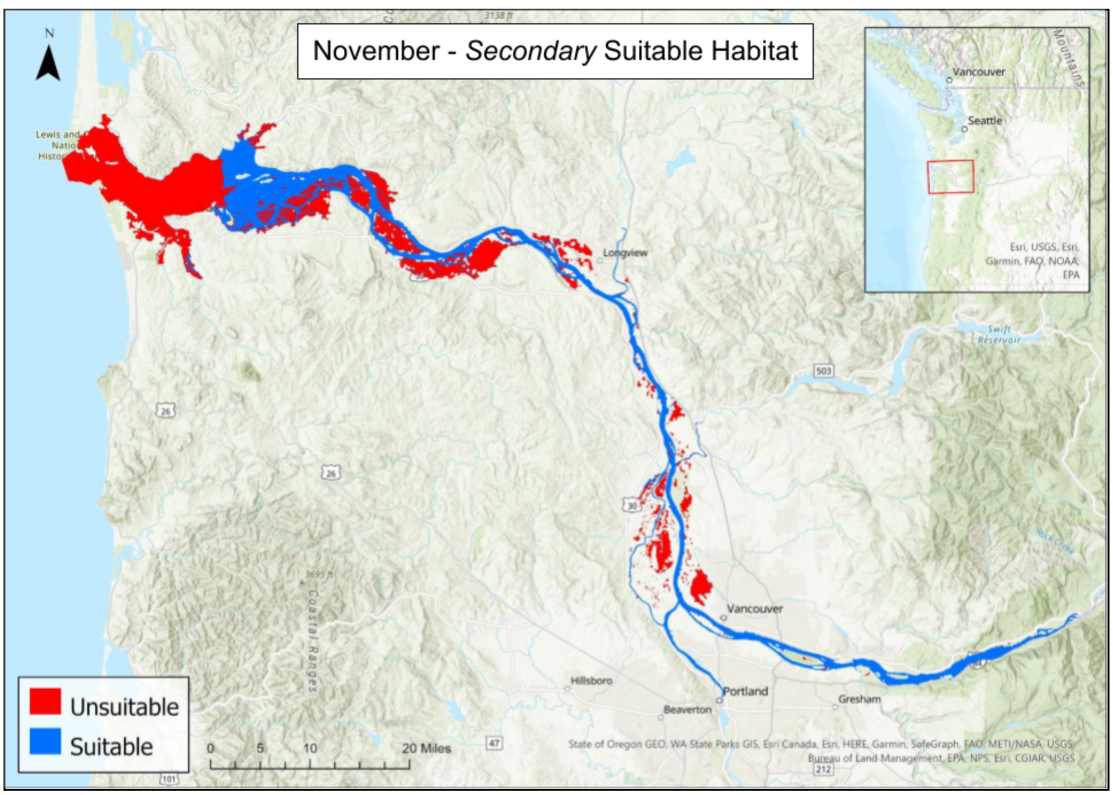
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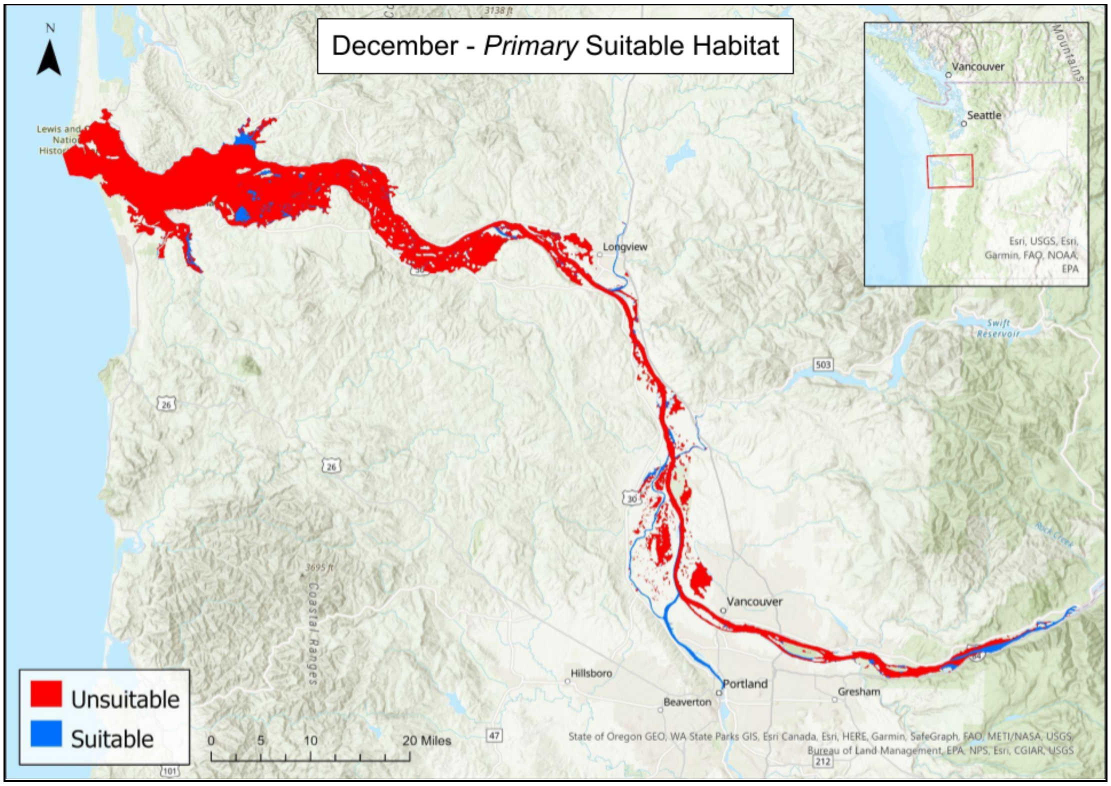
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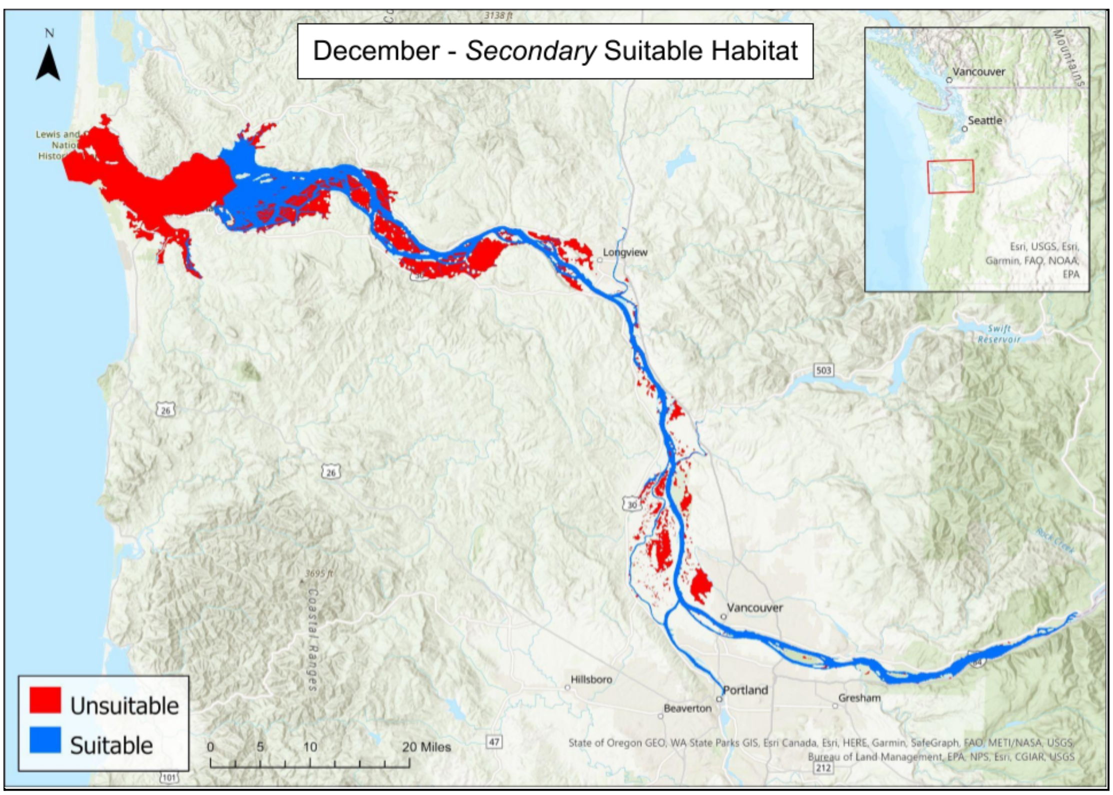
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