AN ABSTRACT OF THE PROJECT OF

Victoria Bohlen for the degree of Master of Science in Marine Resource Management presented on August 27, 2019.

Title: Evaluation of a Habitat Suitability Model to predict the geospatial distribution of Olympia oyster presence in Yaquina Bay, Oregon.

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A massive reduction in historic populations of Olympia oysters (*Ostrea lurida*), the only native oyster found on the west coast of North America, has contributed to a loss of ecosystem and cultural services once provided by this species. Resource management agencies and environmental organizations are working to protect and enhance remaining populations, but in many locations, information to characterize the current geospatial distribution of Olympia oysters is lacking. Advances in mapping technology and increased availability of geospatial, ecological data allow for more effective tracking and monitoring of Olympia oysters, which can support protection efforts. However, resource management agencies often face financial and staffing constraints that limit their ability to inventory the species across its range. Habitat Suitability Modeling (HSM) provides a promising approach for making predictions about the geospatial distribution of wild Olympia oyster populations by understanding and analyzing the physical environmental variables that influence its specific habitat. This project evaluates the use of an HSM, developed using geospatial raster layers of salinity, substrate, and elevation, in Yaquina Bay, Oregon to predict locations of Olympia oyster presence. This study was unable to make a conclusive determination regarding the predictive capacity of the HSM due to a small number of field samples. Recommendations are provided for expanding the HSM and supporting several other management applications, including characterizing the abiotic and biotic attributes of the habitat occupied by Olympia oysters and identifying biological monitoring sites.

Evaluation of a Habitat Suitability Model to predict the geospatial distribution of Olympia oyster presence in Yaquina Bay, Oregon.

by
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1. Executive Summary

A massive reduction in historic populations of Olympia oysters (*Ostrea lurida*), the only native oyster found on the west coast of North America, has contributed to a loss of ecosystem and cultural services once provided by this species. Resource management agencies and environmental organizations are working to protect and enhance remaining populations, but in many locations, information to characterize the current geospatial distribution of Olympia oysters is lacking. Advances in mapping technology and increased availability of geospatial, ecological data allow for more effective tracking and monitoring of Olympia oysters, which can support protection efforts. However, resource management agencies often face financial and staffing constraints that limit their ability to inventory the species across its range. Habitat Suitability Modeling (HSM) provides a promising approach for making predictions about the geospatial distribution of wild Olympia oyster populations by understanding and analyzing the physical environmental variables that influence its specific habitat. This project evaluates the use of an HSM, developed using geospatial raster layers of salinity, substrate, and elevation, in Yaquina Bay, Oregon to predict locations of Olympia oyster presence. This study was unable to make a conclusive determination regarding the predictive capacity of the HSM due to a small number of field samples. Recommendations are provided for expanding the HSM and supporting several other management applications, including characterizing the abiotic and biotic attributes of the habitat occupied by Olympia oysters and identifying biological monitoring sites.

2. Introduction

Populations of native Olympia oysters (*Ostrea lurida*) were historically abundant along the Pacific coast of North America where they were once important components of estuarine ecosystems (Cook et al. 2000; Polson and Zacherl 2009; Pritchard et al. 2015). Healthy Olympia oyster populations furnished a suite of ecosystem services, including water filtration and creation of functional reef habitat that supported diverse communities of marine organisms (Wasson et al. 2014; White et al. 2009; zu Ermgassen et al. 2013), as well as provided an important food source for local indigenous people (Baker 1995; Couch and Hassler 1989; Dall 1897).

Extensive commercial harvesting, removal of oyster bed structure, and reduced water quality in the late 1800s contributed to a rapid decline in the populations of Olympia oysters in Oregon bays and estuaries (Couch and Hassler 1989; Groth and Rumrill 2009; McGraw 2009). Depletion of native oyster beds led to the deliberate introduction of the larger, faster-growing Pacific oyster (*Crassostrea gigas*) from Japan in the 1930s, which continued to feed consumer demand and ultimately discouraged commercial cultivation of Olympia oysters (Polson and Zacherl 2009).

2.1 Problem Statement

Due to unsustainable harvesting practices and low interest in restoration of degraded populations, it is estimated that 90-99% of the original Olympia oyster populations have been lost throughout the Pacific Northwest region (Beck et al. 2011). Without robust populations, the ecosystem and cultural services they once provided are lacking. Olympia oyster populations have struggled to recover on their own, but increased acknowledgement and understanding of their ecological role and importance as a historical food source have helped the species gain support from resource managers, tribes, oyster growers, and conservation organizations (Cook et al. 2000; McGraw 2009; zu Ermgassen 2013).

However, the scale of restoration activity to date is still relatively modest and many resource managers spearheading restoration efforts experience substantial limitations in personnel, time, and/or financial resources (B. Peabody pers. comm.; Lewis et al. 2019).

Additionally, there is a lack of detailed, scientific research available on the ecology of the Olympia oyster compared to the Pacific oyster (Gray and Langdon 2018; McGraw 2009; Pritchard et al. 2015), as well as detailed information about the current abundance and spatial distribution of the species throughout its biogeographic range (Norgard et al. 2010; Polson and Zacherl 2009). Consequently, many restoration and enhancement efforts are taking place without reliable, quantifiable data to characterize the status of current populations. Furthermore, resource managers are often required to make quick, possibly uncertain decisions for management of a species due to political pressures, stakeholder interests, or budgetary constraints (Rosenberg and Sandifer 2009). Resource managers are inherently working within a social-ecological system that requires consideration of both the human and ecological environment (Berkes 2011).

2.2 Rationale

Emerging recognition of the large-scale loss of Olympia oysters from their historic range has contributed to a renewed interest in conservation and protection of the remaining populations as well as enhancement of habitat to facilitate species recovery (Cook et al. 2000; Dinnel et al. 2009). Reestablishment of Olympia oysters has become a high priority in British Columbia, Washington, Oregon, and California in recent years (McGraw 2009; Wasson et al. 2014; White et al. 2009). Recovery of robust populations is expected to convey multiple benefits for stakeholders, including restoration of ecological habitats and ecosystem services (Brumbaugh and Coen 2009; Dinnel et al. 2009), diversification of the commercial shellfish mariculture industry (Polson and Zacherl 2009), and provision of opportunities for recreational harvests (S. Rumrill pers. comm.; White et al. 2009).

Updated baseline information about the geospatial distribution of current populations of Olympia oysters is needed to assess their current status and to support species recovery efforts (Dinnel et al. 2009). Baseline data can be used to advocate for legally recognized species protection. For example, in British Columbia, Olympia oysters have been designated a ‘Species of Special Concern’ (COSEWIC 2011; Norgard et al. 2010) and in Washington state, a ‘Candidate Species’ for state protection (Cook et al. 2000; Trimble et al. 2009). Conversely, in cases where

Olympia oysters are not currently legally protected, conveyance of special status has the potential to trigger mitigation and conservation measures that could impact land use planning decisions.

Additionally, understanding the current status of Olympia oysters can also contribute to the design of biological monitoring programs (DFO 2009) and help evaluate how those populations shift in space in response to changing environmental conditions (Noon et al. 2011). One approach used to develop biological monitoring programs for Olympia oysters is the identification and assessment of Index Sites. Index Sites are locations within a geographic area that are representative of the larger population (DFO 2009). These sites are determined following a comprehensive survey of the geographic area to determine the geospatial distribution of Olympia oysters, then used to collect Olympia oyster abundance data at regular time intervals (Norgard et al. 2010). Establishing Index Sites as the initial component of a biological monitoring program for Olympia oysters allows the species to be continue to be tracked into the future without repeated, expensive, and time-consuming field surveys (DFO 2009).

Advancements in mapping technology and increasing availability of geospatial data allow resource managers to visualize species' distributions across a landscape more effectively. The Coastal and Marine Ecological Classification Standard (CMECS) is a comprehensive, internationally recognized platform that provides an important framework for streamlining ecologically-based, geospatial data. CMECS aims to classify marine habitats using an approach that is universally acknowledged and can be easily communicated, so that data collected can be used to its fullest potential (CMECS 2012). CMECS is capable of characterizing the physical, biological, and chemical features of the marine environment as discrete units or in combination with species occurrence data as a 'biotope'. A biotope defines the abiotic and biotic habitat that a species occupies, and is one product of the CMECS framework that can culminate from integrating data across the species' geographic range (CMECS 2012). For Olympia oysters, connecting the habitat features from different wild populations can help form a more comprehensive picture of its geospatial distribution and support long-term protection.

Habitat Suitability Modeling (HSM) has recently emerged as another empirically-based method to evaluate a species' relationship to its environment by quantifying its ecological niche (Guisan et al. 2017). HSMs integrate multiple sources of habitat-specific geospatial information for a species and synthesize it to predict species occurrence and geographic distribution. HSMs are typically developed within a Geographic Information Systems (GIS) platform that incorporates a subset of field observations (Ottaviani et al. 2004). An HSM approach was recently used by Lewis et al. (2019) to assess suitable habitat for five species of bay clams in Yaquina Bay and Tillamook Bay, Oregon. Results from the bay clam study showed that the probability of species presence occurred within the classes of habitats deemed most suitable for four out of the five clam species, thus supporting the overall framework for the HSM approach.

Given the broad accessibility of geospatial data, the purpose of this project is to develop and apply a simple HSM to predict the distribution of Olympia oysters in Yaquina Bay, Oregon. Yaquina Bay is one of only three estuaries in Oregon with substantial evidence of Olympia oyster occurrence, in addition to Netarts Bay to the north and Coos Bay to the south (Groth and Rumrill 2009). Yet, contemporary baseline data to characterize the geospatial distribution of Olympia oysters has not been collected in Yaquina Bay. This project was completed in part to help collect baseline data in a location of interest for future habitat restoration and population enhancement, but also to explore the efficacy, accuracy, and practical application of the HSM approach.

2.3 Research Questions

The central research questions for this investigation are:

1) What is the predictive capacity of a Habitat Suitability Model (HSM) based on a review of natural history-based literature sources to determine the geospatial distribution of Olympia oysters in Yaquina Bay?
2) Are the environmental variables parameterized in the HSM appropriate for predicting Olympia oyster presence?

Recommendations from this project include exploring whether this data can support the development of an Olympia oyster biotope, how to modify the HSM for increased accuracy, and information to support a biological monitoring protocol based on Index Sites in Yaquina Bay.

2.4 Approach

This project addressed the central research questions with three integrated components. First, field data collection was used to record where Olympia oysters were present and absent in the intertidal and subtidal regions of Yaquina Bay. Second, a basic HSM was developed by reviewing natural history information from the available literature on Olympia oysters to select which environmental variables were appropriate for parameterizing the model. Specifically, seawater salinity, substrate, and elevation were selected as habitat parameter inputs and analyzed to quantify oyster sensitivities. These inputs were overlaid with spatial data layers sourced from state and federal natural resource agencies. The HSM was then used to classify the areas of habitat as most suitable, somewhat suitable, least suitable, or unsuitable. Field observations were then compared to the HSM and to each of the habitat parameters to better understand how these impacted the prediction of Olympia oyster presence. Study limitations are discussed, as well as recommendations for additional research and opportunities to incorporate this data into resource management applications.

2.5 Objectives

The specific objectives for the project are to:

1) Develop and evaluate the practical use of a simple Habitat Suitability Model to accurately predict the geospatial distribution of Olympia oysters;
2) Collect field observations of Olympia oysters *in situ* and develop an updated map of their geospatial distribution in Yaquina Bay;
3) Contribute to the future development of a biotope through the CMECS protocol by providing updated information on the environmental thresholds that Olympia oysters experience; and

4) Provide recommendations on the development of a long-term biological monitoring protocol for Olympia oysters in Oregon bays and estuaries.

3. Literature Review

Habitat Suitability Modeling (HSM) and the development of species-specific biotopes are both emerging areas of ecological research that can be used to predict the distribution of a species by evaluating its appropriate habitat conditions (Guisan et al. 2017; Shumchenia and King 2010). Evaluating the geospatial distribution of Olympia oysters in Yaquina Bay using a simple HSM has the potential to be a useful, easily applied approach, one that may be sufficiently robust for resource managers to make informed management decisions. This chapter provides background information on the target species, Olympia oysters, as well as the status of current management efforts across its range and the use of HSMs to predict species distribution.

3.1 Overview of Olympia oysters

The Olympia oyster (*Ostrea lurida*) is the only native oyster species found on the west coast of North America, historically ranging from Baja California up to southern Alaska (Pritchard et al. 2015). The following sections describe the species' role in the estuarine ecosystem, as well as the history of exploitation that led to the current status of the depleted populations.

3.1.1 Ecology and Habitat

Like most other bivalves, Olympia oysters are filter feeders with phytoplankton making up the majority of their diet (Archer 2008; Baker 1995). They are sessile as adults and relatively slow-growing; they may reach only 3 to 5-centimeter shell heights over a period of 3 years (Couch and Hassler 1989). Adults are hermaphroditic, alternating between male and female several times within their lifespan, and are capable of reproducing within a year (Trimble et al. 2009). Females brood fertilized eggs internally for a period of 10 to 12 days before young larvae are released into the surrounding water body. The planktonic veliger and pediveliger larvae inhabit the water column for 8 to 10 days before they attach to a suitable substrate on the bottom (Waldbusser et al. 2016).

Olympia oysters tolerate a range of salinity conditions, notably even full-strength seawater at 32 practical salinity units (psu) (Couch and Hassler 1989). However, exposure to very low salinities (<10 psu) and substantial freshwater pulses are lethal to larval oysters prior to settlement and can result in early mortality of adults (Fasten 1931; Gillespie 2009; Pritchard et al. 2015; Wasson et al. 2015). Olympia oysters most commonly occur in the polyhaline region of estuaries that experience a range of 15-25 psu (Pritchard et al. 2015). In Yaquina Bay however, productive commercial harvests of Olympia oysters have historically occurred in areas that experience a range of 5-30 psu (Groth and Rumrill 2009). While there is some evidence that the species is able to withstand full strength seawater (32 psu) (Couch and Hassler 1989), they are most commonly found in brackish conditions further upstream from the mouth of the estuary. Conversely, Olympia oysters do not tolerate prolonged freshwater exposure; reproductive failure (Pritchard et al. 2015) and evidence of feeding stress was observed at low salinity levels (Gray and Langdon 2018).

Estuaries generally provide suitable habitat for settlement of larval oysters because the tidal waters are retained for a sufficient time period to allow the free-swimming pediveligers to attach and complete metamorphosis without being washed out to sea on ebb tides. Attachment by Olympia oyster larvae to a hard substrate is required for metamorphosis, post-larval survival, and later development of the juvenile oysters into adulthood (Groth and Rumrill 2009; White et al. 2009). Preferred substrate for settlement is oyster shell, a characteristic which allows Olympia oysters to build expansive, multi-generational layered beds in large communities. Other hard substrata can be feasible in the absence of oyster shell, including rock, rip-rap, gravel, wood, and anthropogenic materials like pilings and derelict boating equipment (Baker 1995; Fasten 1931; Gillespie 2009; White et al. 2009). Much of the historic oyster shell and bed structure was removed from Oregon bays and estuaries through harvesting and dredging (Groth and Rumrill 2009). Instead, the planktonic larvae of Olympia oysters currently settle on whatever hard surface is available, including rocks, rip rap, pilings, and even improperly disposed anthropogenic items such as metal shopping carts, motorcycle frames, automobile engines, logging cables, and other abandoned hard substrata (Baker 1995; Couch and Hassler 1989; Fasten 1931; Gillespie 2009; S. Groth pers. comm.).

In the Pacific Northwest, Olympia oysters naturally occurred in patches, clusters, and beds in the intertidal and shallow subtidal zones of estuaries and protected bays (McGraw 2009; Groth and Rumrill 2009). Typically, larger communities were found in the subtidal zone, a distinction separating this species from introduced oyster species to the region (White et al. 2009), but they can also be found up to 2 meters above mean low water (Baker 1995). Other reports noted that Olympia oysters subsist at depths from 50 to 71 meters (Couch and Hassler 1989; Gillespie 2009; Pritchard et al. 2009). Figures 1 and 2 depict representative examples of adult Olympia oysters from Yaquina Bay, Oregon.

Figure 1. A representative adult Olympia oyster attached to a hard substrate in the intertidal zone in Yaquina Bay.

Figure 2. Several adults Olympia oysters attached to a hard substrate in the intertidal zone in Yaquina Bay. Shell shape can vary between individuals.

3.1.2 Ecosystem and Cultural Services

All oyster species, including the Olympia oyster, are considered important providers of ecosystem services in coastal and estuarine ecosystems (Gray et al. 2018; zu Ermgassen 2013). One of these beneficial services is the ability to create structural habitat for itself and other marine organisms. In persistent assemblages, larval Olympia oysters will settle on the existing shells of adults, and the successive generations subsequently build layered beds that provide shelter for several other marine organisms, including small fishes and other invertebrates (Groth and Rumrill 2009; Wasson et al. 2014). As a filter feeder, the Olympia oyster cleans up to 25 gallons of water each day (Wasson et al. 2014; White et al. 2009). To a lesser degree, Olympia oysters may be able to improve overall water quality by sequestering pollutants from the water column and aid in nutrient cycling (Pritchard et al. 2015). They also contribute to overall increased biotic diversity and provide expanded foraging areas for other invertebrates, fish, and shorebirds (Groth and Rumrill 2009).

For several thousand years, local indigenous people living in the Pacific Northwest relied on Olympia oysters as an important food source (Cook et al. 2000; Dinnel et al. 2009; White at al. 2009). The small oyster shells are sometimes a conspicuous component of shell middens along the shores of estuaries (Baker 1995; Dall 1897). Proximity of oyster beds may have been an important factor in the determination of locations where some tribal settlements were established (Couch and Hassler 1989).

3.1.3 Population Decline

Olympia oysters became the target for a lucrative commercial fishery from the 1860s to the late 1890s during the period of early occupation of the west coast by European settlers (Archer 2008; Dinnel et al. 2009; Polson and Zacherl 2009; Pritchard et al. 2015; White et al. 2009). Earnest Gold Rush settlers in California quickly discovered the oysters as a readily available food source, leading to mass extraction of oyster beds locally (Fasten 1931). Continued demand in San Francisco markets eventually led to unsustainable harvesting practices in Oregon and Washington, where oyster beds were excavated more quickly than they could be naturally replenished (White et al. 2009). Landings of Olympia oysters across the west coast states peaked at over 2 million pounds in 1895 before plummeting around 1915 (McGraw 2009).

Depletion of native oyster beds led to the introduction of the larger, faster-growing Pacific oyster (*Crassostrea gigas*) from Japan in the 1930s, which continued to feed consumer demand (Polson and Zacherl 2009). Interest in reviving the commercial Olympia oyster market quickly faded (zu Ermgassen et al. 2013). Preference for the Pacific oyster as a more marketable alternative has discouraged oyster growers from producing Olympia oysters for consumption, and today the Pacific oyster is the primary crop cultivated by the oyster industry on the west coast (Gillespie 2009; Gray et al. 2019; Zacherl et al. 2009). This shift has reduced potential habitat for Olympia oysters by devoting these areas to production of Pacific oysters almost exclusively. Additionally, a study in Willapa Bay, Washington, found that Olympia oyster growth and survival rates were significantly reduced with the presence of increasingly dense Pacific oyster assemblages (Buhle and Ruesink 2009).

3.2 Current Management Practices for Conservation and Recovery

Resource managers use two primary approaches to facilitate recovery of the Olympia oyster. The first is to conserve and protect remaining wild populations. Strategies for conservation include establishing a moratorium on recreational harvest, as in Oregon (ODFW 2018) and British Columbia (DFO 2009), as well as designating protected areas. The other approach is to actively pursue population enhancement through restoration and recovery. Typically, this means that environmental conservation organizations, tribal governments, and resource management agencies implement habitat restoration and enhancement projects by growing oysters specifically for restoration and seeding shell (cultch) for placement directly in the estuary (Wasson et al. 2015).

Though efforts to restore and enhance Olympia oyster populations have been modest to date, academic investigators, coastal tribes, resource management agencies, and non-governmental organizations are working to develop sustainable restoration practices that will rebuild oyster populations over the long-term. Ongoing oyster recovery work in Washington, Chesapeake Bay, and several Atlantic coast states demonstrates that population enhancement can be substantially bolstered by partnerships with the commercial mariculture industry (B. Peabody pers. comm.). If Olympia oysters are desirable as a niche seafood product, then increased commercial production of Olympia oysters could indirectly augment the wild stock population. Recent interest arising from oyster growers and retailer operators indicate that there may be an opportunity to produce Olympia oysters as a specialty food item (Polson and Zacherl 2009), which could serve to add value and enhance natural recruitment in estuaries. Additionally, increased consumer demand for local seafood (L. Anderson pers. comm., L. Gildersleeve pers. comm.) can support the development of a more robust shellfishery for Olympia oysters.

Regionally, a new West Coast-wide effort called the Olympia Oyster Network has identified recovery of Olympia oysters as a critical component of ecosystem recovery on a large biogeographic scale. Other environmental agencies and organizations, such as the state Shellfish Initiatives in Washington, Oregon, and California, also call for increased effort toward recovery of Olympia oysters as a component of coastal ecosystem recovery.

3.3 Geospatial Tools for Monitoring and Assessment of Olympia Oyster Populations

For many species with a reduced range, like Olympia oysters, understanding the specific environmental conditions of their habitat may ultimately support improvement in management decisions (Rosenberg and Sandifer 2009). Habitat mapping is an important approach to generate species-specific distribution information that allows resource managers to make better informed decisions for the conservation of a species (Shumchenia and King 2010). Two different geospatial tools are described and considered in the current project: 1) Habitat Suitability Modeling, and 2) Biotopes.

3.3.1 Habitat Suitability Modeling

Habitat Suitability Models (HSM) are used to visualize and understand important geospatial relationships between a sensitive species and the physical, chemical, and biological characteristics that define its habitat (Guisan et al. 2017). HSMs, often referred to as Species Distribution Models, aim to predict the presence of a species within a desired geospatial range or ‘envelope’ based on the environmental variables that limit its distribution (Fournier et al. 2017; Guisan et al. 2017). Environmental variables that are specific to the species of interest should be selected to parameterize the HSM. These parameters can either directly or indirectly influence the species, and typically align with one of three types: 1) variables that limit the species survival or physiology (e.g. freezing temperatures); 2) disturbances that affect the species’ habitat (e.g. recurrent wildfires); or 3) resources specifically required by the species (e.g. food availability) (Thuiller and Munkemuller 2010). However, HSMs are not designed to estimate the distribution of a species under future environmental conditions; rather, the models are based on current observations and cannot be depended upon to make reliable predictions about future geospatial distribution (Thuiller and Munkemuller 2010).

The HSM approach recently published by Lewis et al. (2019) to assess suitable habitat for five species of bay clams is an important contemporary example of the successful application of an HSM in Oregon. The authors hypothesized that the development of an HSM utilizing a subset of species observational data and existing geospatial information for certain environmental variables could readily predict the presence of the clam species in Yaquina Bay and Tillamook Bay, Oregon without additional extensive field surveying. It was observed that the HSM accurately predicted the probability of presence within the area of highest habitat suitability for four out of five clam species. This study highlighted the challenges faced by resource management agencies and organizations that are unable to complete intensive species sampling and inventories on a regular basis due to time and financial constraints. In light of these challenges, this approach is described as having the potential to provide meaningful species information for agencies or organizations that lack the resources to conduct larger sampling efforts (Lewis et al. 2019; Thuiller and Munkemuller 2010).

3.3.2 Biotopes

Similar to the concept of an HSM, a biotope is a tool put forth by the Coastal and Marine Ecological Classification Standard (CMECS). A biotope describes the abiotic and biotic features that define the environmental thresholds limiting the geospatial distribution of a species, as well as describe the specific characteristics of its habitat (CMECS 2012). The CMECS protocol was developed from a need to communicate and share ecological information across a wide range of users in order to improve management of marine and coastal resources. CMECS uses standardized terminology and a hierarchical, organizational structure and strives to provide the best-available data on species interactions with their habitat. Ecological information includes physical properties of the water column, geomorphology, substrate type, and biological communities. It can be applied internationally and is flexible enough to be utilized by many different users, including resource managers, scientists, and planners. Publicly available data for Oregon's coastal areas was made accessible through an effort by the Oregon Coastal Management Program.

Biotopes begin to take form as assemblages of a particular species are identified and mapped throughout its geographic range. As certain, recurring physical features of the environments are increasingly associated with these biological communities, a biotope can be classified (CMECS 2012). This recognition of similar environmental conditions for a species of interest can permit more rapid identification of the species' habitat in the future. It can also support biological monitoring efforts, understanding potential impacts of land-use planning, and evaluating large-scale environmental changes, such as climate change (Shumchenia and King 2010). The development of biotopes as proposed through a combination of abiotic and biotic features through the CMECS platform is shown in Figure 3.

The application of a biotope for Olympia oysters can be significant in understanding the geographic extent of the species not just in one bay, but throughout its range. Because of its inherently patchiness and that wild populations have become disparate due to harvesting pressures, it can be difficult to survey the entire population along the west coast of North America. The biotope can help to resolve this issue; by evaluating several wild populations throughout the entire Olympia oyster geographic range and recording the habitat characteristics found at each of those locations, similarities between each habitat can be identified. Noting the specific characteristics of Olympia oyster habitat in multiple locations can be incorporated into a biotope to be made available for resource managers throughout its entire geographic range. The information provided in an updated biotope can support restoration of Olympia oysters in locations where they have been lost, but the habitat is may still be appropriate. Conversely, the habitat information in the biotope can be used to target locations where habitat is suitable, but oysters have not yet been surveyed.

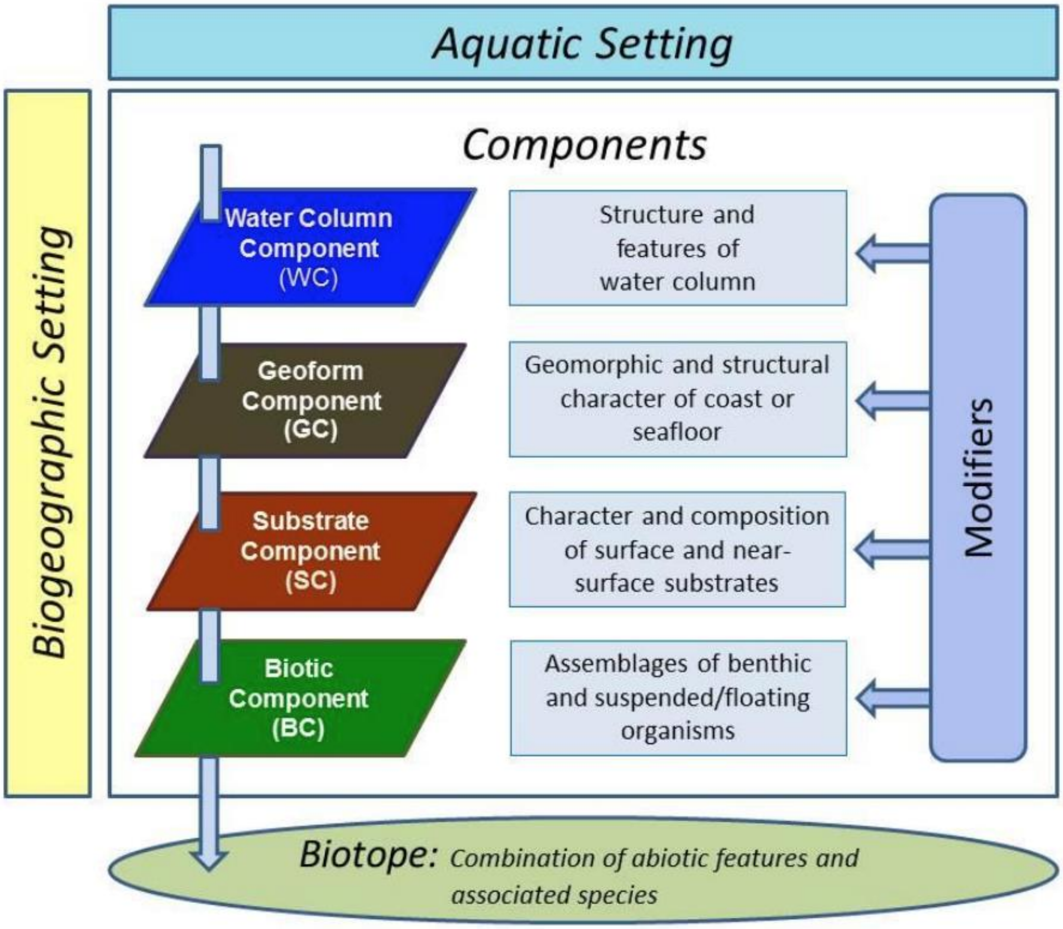

Figure 3. The components required to develop a biotope within the CMECS framework. Image sourced from CMECS 2012.

4. Methods

The technical approach followed by this study addressed the central research questions with three integrated components to characterize the spatial distribution of Olympia oysters in Yaquina Bay:

1) Development of a Habitat Suitability Model (HSM);
2) Collection of field observations of Olympia oysters *in situ*; and
3) Comparison of field observations to the areas of suitability predicted by the HSM.

4.1 Study Area

Yaquina Bay is located on the central coast of Oregon next to the city of Newport (44°37'12.0"N 124°01'12.0"W). It is a drowned river-mouth estuary supporting natural habitats for marine species, offering recreational opportunities, and serving as a harbor for commercial fishing and research vessels. It experiences a mixed semi-diurnal tidal regime typical of the northern Pacific coast. Yaquina Bay is one of only three Oregon estuaries known to historically support Olympia oysters and may be the only estuary to have maintained a continuous population since the arrival of European settlers to the west coast (Groth and Rumrill 2009).

4.2 Development of a Habitat Suitability Model for Olympia Oysters

A basic Habitat Suitability Model (HSM) was created to predict the geospatial distribution of Olympia oysters following the technical approach published recently by Lewis et al. (2019) to develop a “framework to identify suitable bivalve habitat in estuaries” for five clam species in Yaquina Bay and Tillamook Bay, Oregon. Researchers in this study analyzed available scientific literature to select four habitat parameters and established appropriate thresholds, or sensitivities, for each clam species within each of the environmental parameters. Using the geographic software program ArcGIS, habitat surfaces (in raster file format) were created based upon a ranking of the suitable areas for each species. The resulting model of suitable habitats was then statistically analyzed to assess the validity of the predictions. This project aligned with the intention of Lewis et al.’s work and was based upon modelling using a similar approach.

ArcGIS Pro (version 2.2.1) was used to format and analyze all geospatial data for this project. Raster layers, or collective compositions of pixels that form a surface, were used to represent habitat information. All geospatial data was projected in a common coordinate system specific to Oregon to minimize distortion (NAD 1983, UTM Zone 10N).

4.2.1 Selection of Habitat Parameters and Data Sourcing

To determine which habitat parameters would be most appropriate for an assessment of suitable habitat for Olympia oysters, a review of natural history literature was conducted and local shellfish experts were interviewed (Steve Rumrill and Scott Groth). Based upon the review, there are at least three important parameters that are critical for Olympia oyster settlement and survival: 1) salinity; 2) substrate; and 3) tidal elevation within the estuary. These parameters were also selected because they appear frequently in the literature and the availability of easily accessible geospatial data for each; data is available publicly for the substrate and salinity parameters. The following sections outline how spatial data was obtained for each habitat parameter.

4.2.1.1 Salinity

In Lewis et al. (2019), salinity was also used as a model parameter. Lead author Nate Lewis of the Environmental Protection Agency (EPA) provided instruction for creating a similar salinity raster for use in this project. Raw salinity data for Yaquina Bay was obtained from an existing, publicly available dataset offered through the Oregon Department of Environmental Quality's (DEQ) Ambient Water Quality Monitoring System (AWQMS 2019). This online water monitoring data portal identified the locations for multiple water quality monitoring stations and what data is collected at each (Figure 4). All salinity measurements dating back to 1960 were exported into an Excel spreadsheet and averaged over the wet-season in Yaquina Bay (November – April). An average value was used at each monitoring station as a proxy for the spatiotemporal variation in salinity that occurs due to Yaquina Bay's regular tidal cycle.

To create a raster layer of salinity, the coordinates from the water quality monitoring stations and their associated salinity were first imported into ArcGIS Pro as point data (Figure

5). Spatial autocorrelation, which is the degree to which objects or points near each other are similar to one another, was used to interpolate the point data into a raster layer. An interpolation technique called ‘Ordinary Kriging’ was used to take the known values of salinity from the water quality monitoring stations to make a prediction raster surface of estimated salinities across Yaquina Bay. Thresholds were established to represent the raster layer in four distinct bins; these bins guided the stratified random sampling approach used in the intertidal survey (Figure 6).

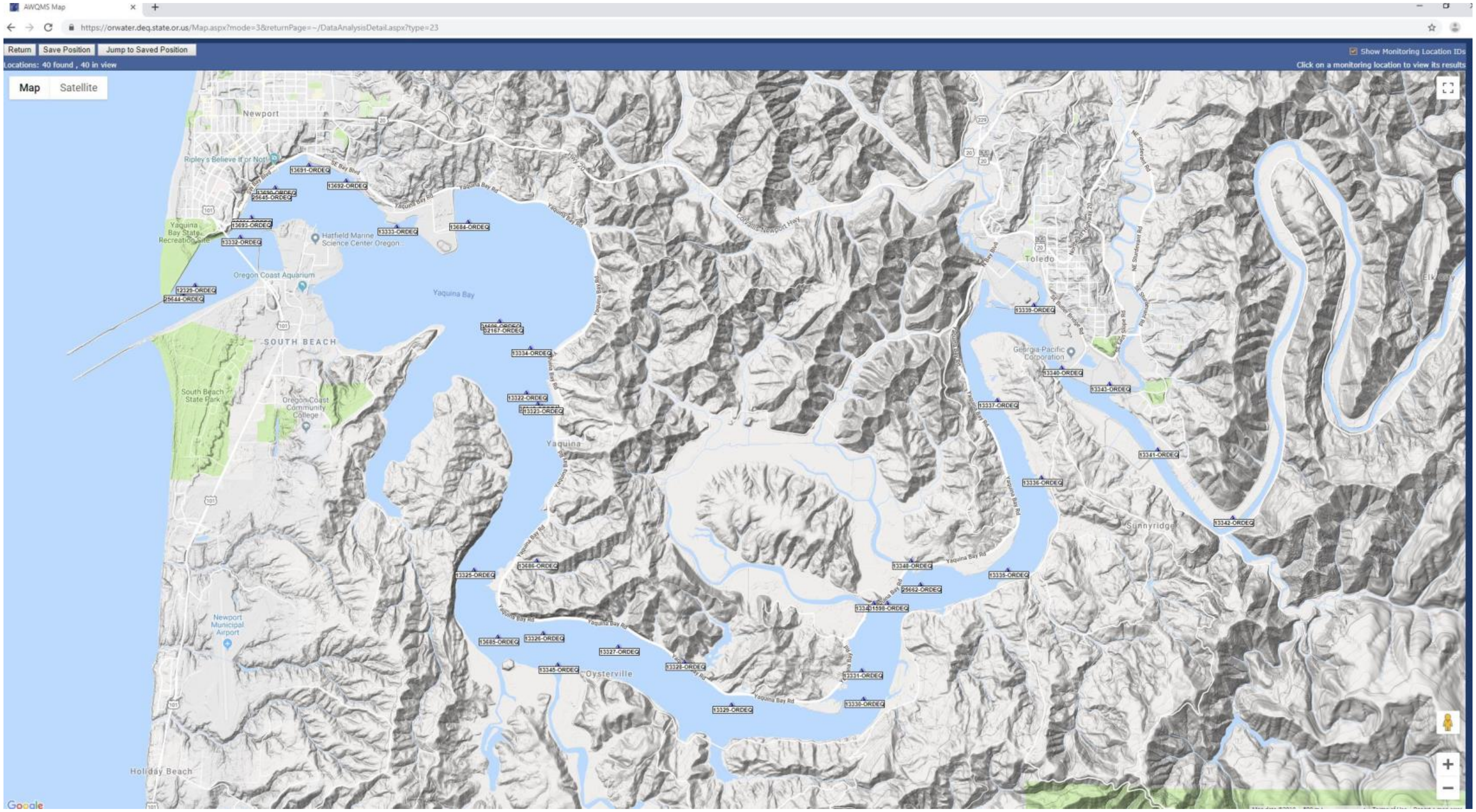

Figure 4. Screenshot from the Oregon Department of Environmental Quality's (DEQ) Ambient Water Quality Monitoring System (AWQMS) showing the monitoring stations (blue triangles with identifying station code) in Yaquina where salinity values were derived to create the raster layer of interpolated salinity for all of Yaquina Bay.

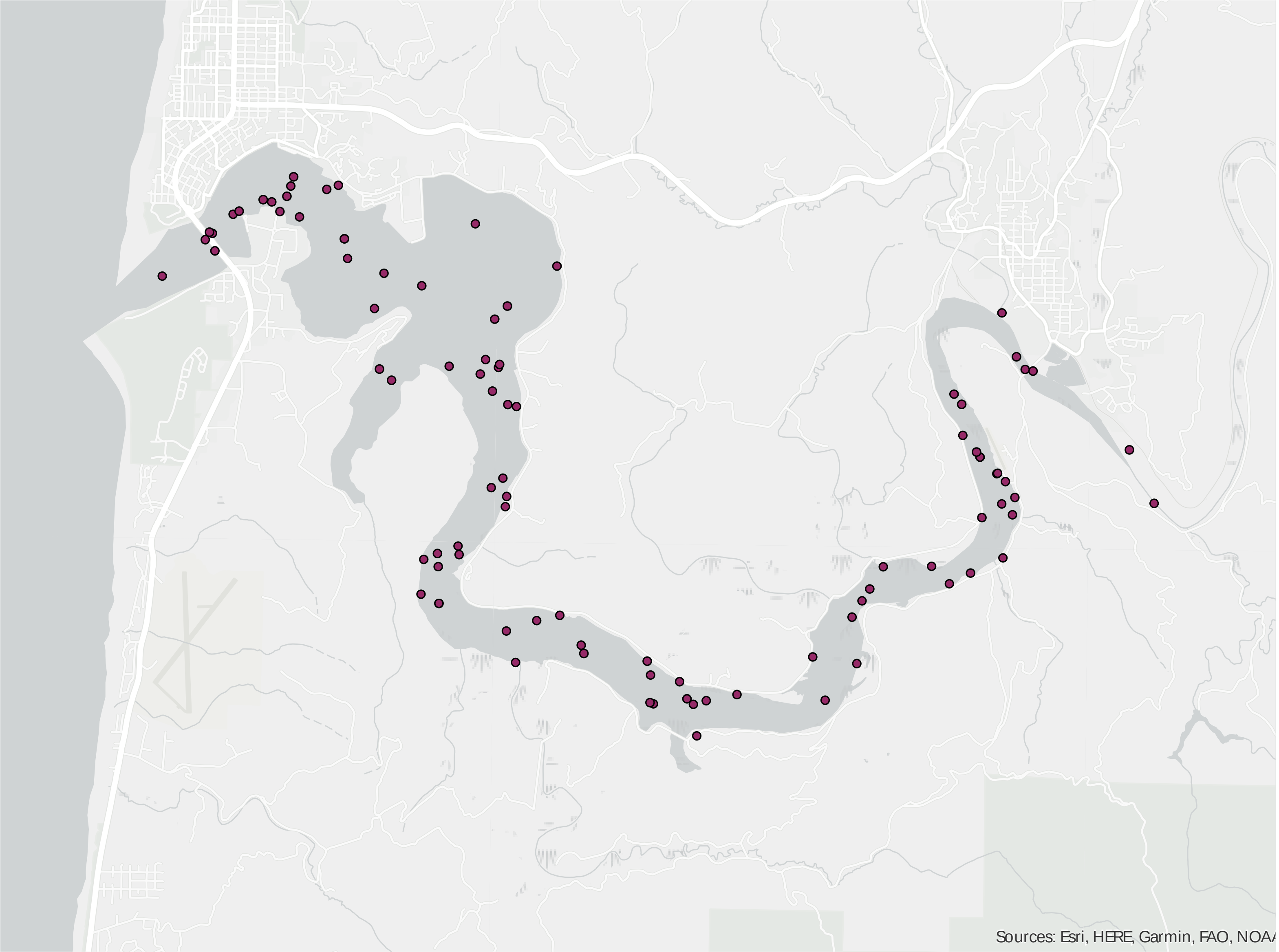

Figure 5. Point data representing water quality monitoring stations from the Oregon Department of Environmental Quality's (DEQ) Ambient Water Quality Monitoring System (AWQMS) with associated salinity data attributed to each in Yaquina Bay.

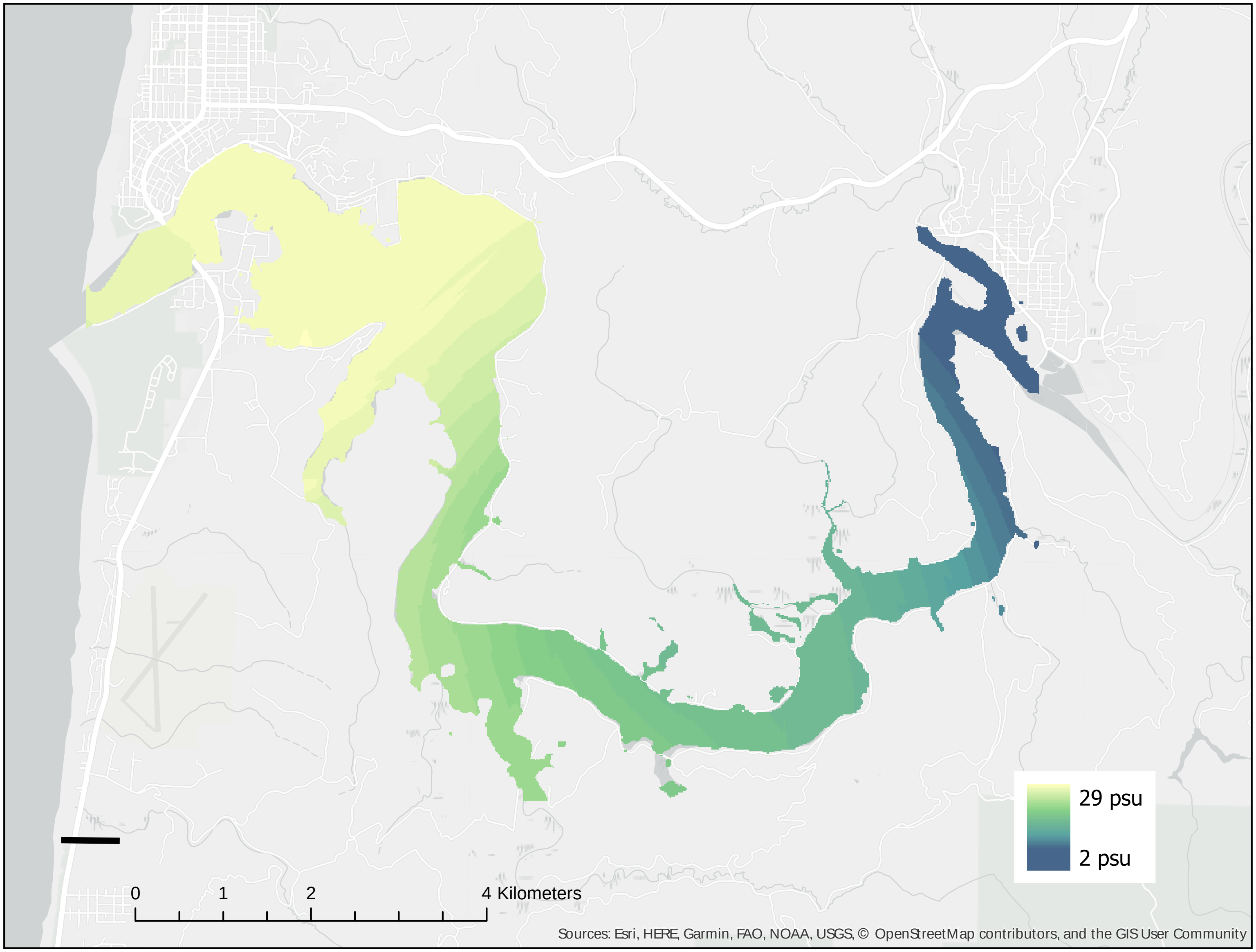

Figure 6. The interpolated raster surface of estimated salinity values (measured in psu) based on the point data shown in Figure 5.

4.2.1.2 Substrate

Substrate data was obtained from the Estuary Habitat Map of Oregon using the Coastal and Marine Ecological Classification Standard (CMECS 2012). The geospatial layer of interest for this analysis was the 'CMECS Estuarine Substrate Component', which is described as:

"…a polygon file containing CMECS Substrate Component classes for Oregon Estuaries. Substrate is defined in CMECS as 'the non-living materials that form an aquatic bottom or seafloor, or that provide a surface (e.g., floating objects, buoys) for growth of attached biota. Substrate may be composed of any substance, natural or manmade'."

The CMECS Estuarine Substrate Component layer was clipped to Yaquina Bay. Figure 7 shows the specific component classes and subclasses that were identified in the study site. Component classes and subclasses included and described in bold (CMECS 2012):

1.2 – Unconsolidated Mineral Substrate: "Geologic substrates with less than 50% cover of rock substrate. This class uses Folk (1954) terminology to describe any mix of loose mineral substrate that occurs at any range of sizes—from Boulders to Clay."

1.2.1.3.3 – Gravelly Mud: "Geologic Substrate is 5% to < 30% Gravel, and the remaining Sand-Mud mix is 50% or more Mud."

1.2.2.4 – Sandy Mud: "Geologic Substrate surface layer contains no trace of Gravel and is composed of 10% to < 50% Sand; the remainder is composed of Mud (particles less than 0.0625 millimeters in diameter)."

2 – Biogenic Substrate: "Substrates where percent cover of non-living biogenic substrate exceeds percent cover of both geologic substrate and anthropogenic substrates, when all are considered separately. Biogenic substrates are classified at the higher levels by taxonomy, and at the lower levels by median particle size."

3 – Anthropogenic Substrate: "Substrates where percent cover of anthropogenic substrate exceeds percent cover of both geologic substrate and biogenic substrates, considered separately. Anthropogenic Substrates are classified at the higher levels by composition, and at the lower levels by median particle size."

3.1 – Anthropogenic Rock: "Anthropogenic Substrate that is primarily composed of natural mineral materials that were purposefully or accidentally deposited by humans. This includes breakwaters made of natural stone, dredge material, artificial reefs made of natural stone, as well as beach nourishment and beach fill. Shape for this substrate class is covered in the GC (e.g., Groin, Breakwater, and Dredge Deposit). If the origin of a feature cannot be determined, it is assumed to be of natural origin and classified in the Geologic or Biogenic Substrate Origin."

3.1.2 – Anthropogenic Rock Rubble: “Substrate that is dominated by Anthropogenic Rock with a median particle size of 64 millimeters to < 4,096 millimeters (Cobbles and Boulders).”

3.1.3 – Anthropogenic Rock Hash: “Substrate that is dominated by Anthropogenic Rock with a median particle size of 2 millimeters to < 64 millimeters (Granules and Pebbles).”

9.9.9.9.9 – Unclassified: “Substrates that do not fit into other pre-defined classes.”

Unclassified areas are likely to result from one of several factors:

1) Low resolution of input data sources;
2) Inconclusive determination of class because one data component cannot reliably be associated with another; and
3) Limitations of mapping technology.

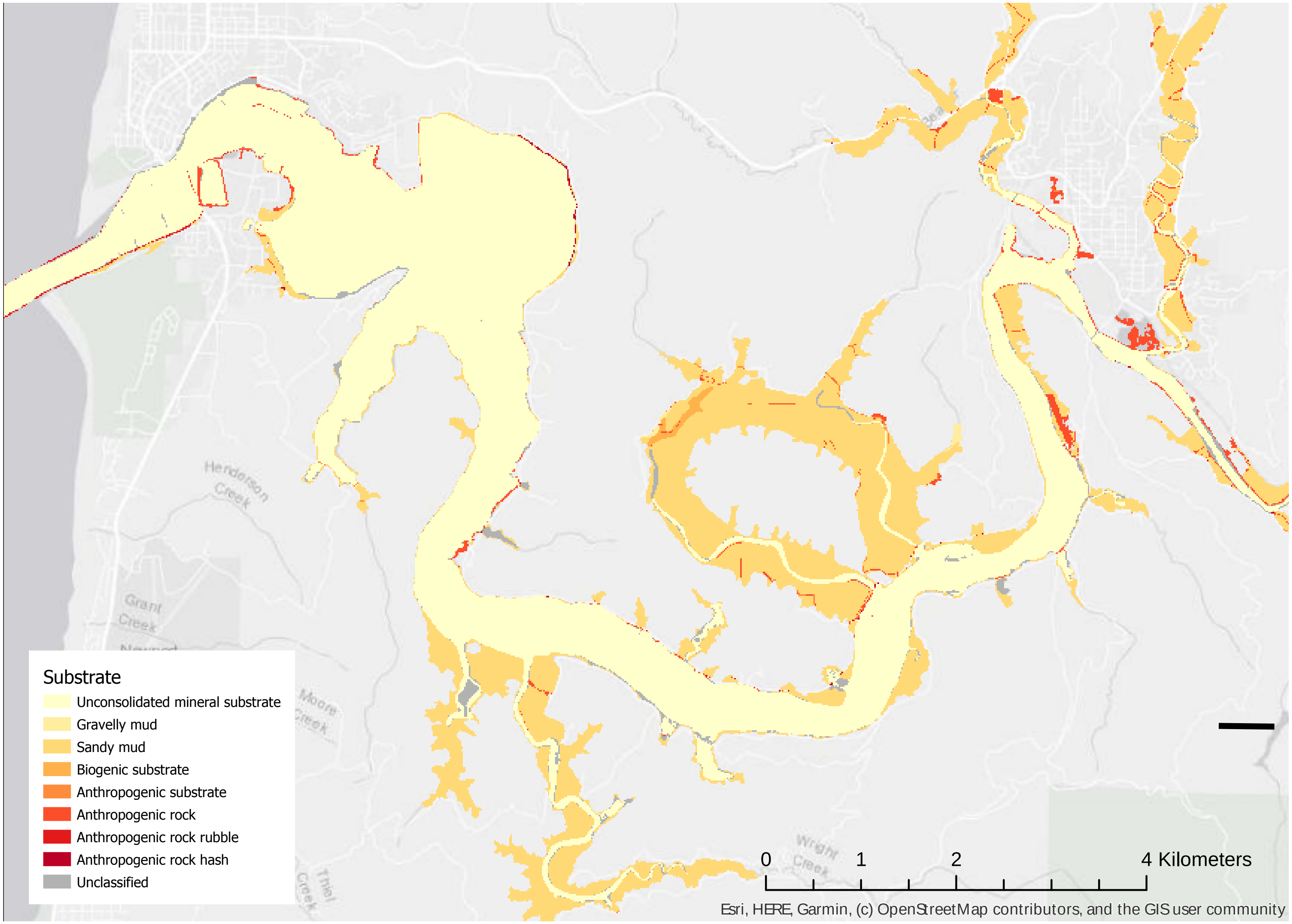

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Figure 7. Substrate component classes of Yaquina Bay based on data classifications from CMECS Estuarine Substrate Component layer.

4.2.1.3 Elevation

Elevation data to characterize the bathymetry of Yaquina Bay was sourced from the Newport, Oregon office of the Environmental Protection Agency (EPA) through contact with a staff geographer. The EPA provided a raster layer for use in this research, and the best available data is from 2003 (permission by EPA). The bathymetry of Yaquina Bay is shown in Figure 8.

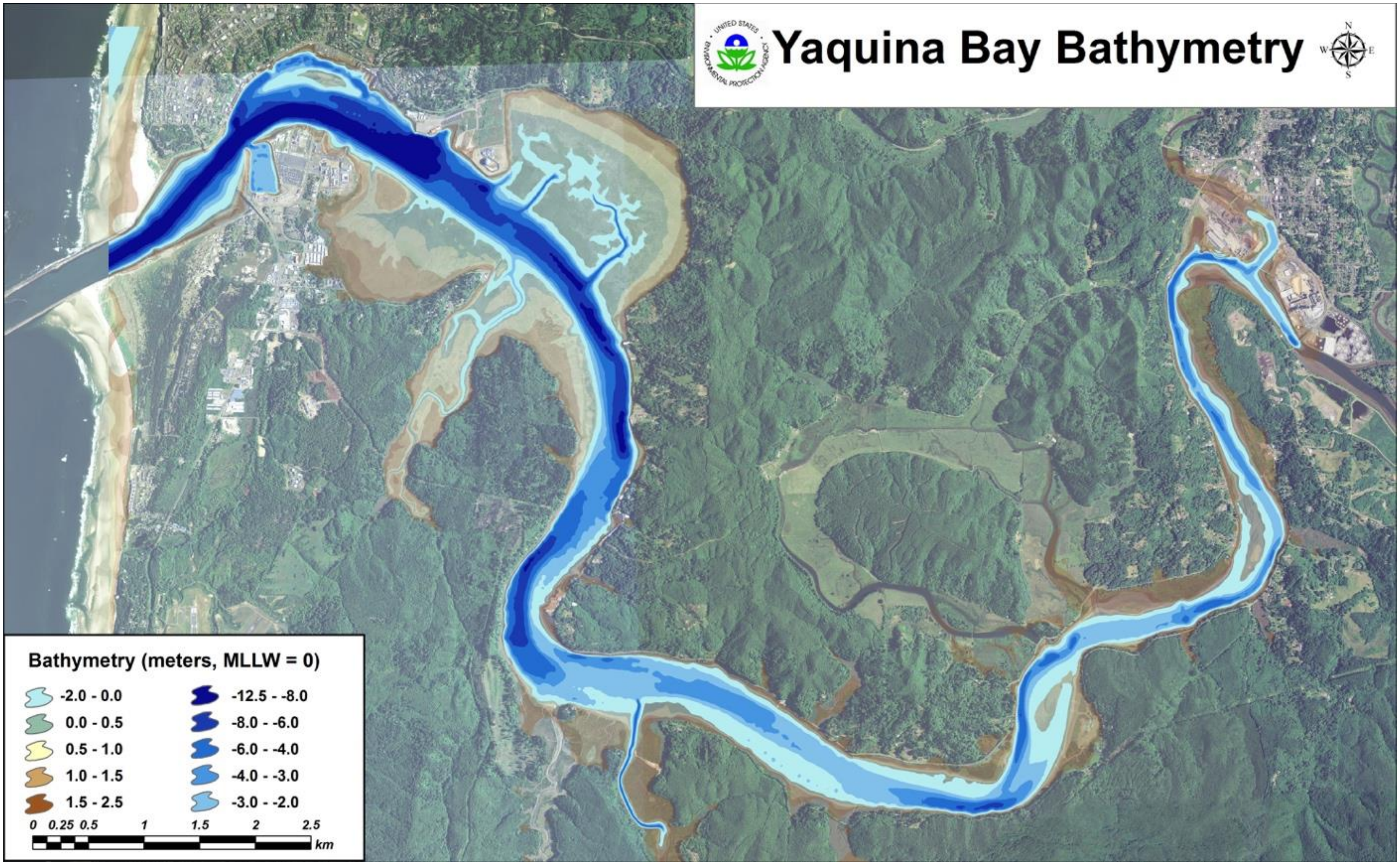

Figure 8. Yaquina Bay bathymetry derived from subtidal soundings in 1953, 1999, 1998, and 2000 by the U.S. Army Corps of Engineers.

4.2.2 Determination of Environmental Thresholds

A thorough literature review was completed to obtain information on the environmental thresholds that may limit the spatial distribution of Olympia oysters in Yaquina Bay. The results of the literature review appear in Section 5.2 – Development of Habitat Suitability Model. To establish the environmental thresholds for Olympia oysters, 6 to 7 peer-reviewed articles were selected for each of the habitat parameters (salinity, substrate, and elevation) that contained either quantifiable information or specific, qualitative descriptions of the species' relationship to that parameter. From this information, a table was created for each of the parameters. In the left-most column of each table, sources were listed with the corresponding lines of text that directly addressed the relationship between Olympia oysters and the habitat parameter. Classes within each of the parameters, as identified in the raster layers, were listed in the top row; for example, the substrate classes listed were "Unconsolidated mineral substrate," "Biogenic substrate," "Anthropogenic substrate," etc.

The environmental threshold information in the literature excerpts was then fitted as closely as possible to the classes within each of the parameters. An 'X' indicated whether Olympia oysters could tolerate the designated parameter class. Quantitative data were applied as numeric ranges across classes within the salinity and elevation parameters. Qualitative information was fitted based on the researcher's interpretation of the literature for the substrate parameter. Once the tables were completed, each class within each habitat parameter was assigned a ranking value: most suitable (rank 4), somewhat suitable (rank 3), least suitable (rank 2), or unsuitable (rank 1). The most suitable (rank 4) value was applied where the most literature sources agreed on the optimal threshold range for Olympia oysters.

Literature sources were also listed as either 'partial range' or 'full range.' Sources that cited the environmental conditions for Olympia oysters at a specific location, such as Yaquina Bay, were listed as 'partial range.' Sources that addressed the environmental conditions for Olympia oysters generally were listed as 'full range.' When applicable, Yaquina Bay-specific sources bore greater weight in determining ranking values.

To develop the representation of the HSM, the raster layers for each habitat parameter were opened in ArcGIS Pro and the Geoprocessing tool 'Weighted Overlay' was applied. Using

Weighted Overlay, the ranking values (1 – 4) were assigned to each of the classes within each habitat parameter raster. The classes within each habitat raster were assigned the same ranking value as designated in the Literature Review Tables. Additionally, each habitat parameter raster was weighted for relative importance to the overall HSM. For this project, the salinity, substrate, and elevation raster layers were given equal weights. The Weighted Overlay tool then used linear combinations to merge the three habitat parameter layers into a new raster which represents the areas of most suitable to unsuitable habitat. The resulting raster is the representation of the HSM based solely on the information provided in the Literature Review Tables.

4.3 Sampling and Methods of Field Data Collection

Field work was conducted on five dates in the Spring of 2019. All field data was collected by Steve Rumrill (Shellfish Program Leader for the Oregon Department of Fish and Wildlife - ODFW) and Tori Bohlen (Graduate Research Assistant at Oregon State University). The goal of collecting field observations was to obtain geospatial data on the distribution of Olympia oysters throughout Yaquina Bay. Data was collected separately in the intertidal and subtidal zones with the intertidal survey informing the design of the subtidal survey. Surveys in the intertidal zone were conducted to characterize the Olympia oyster population along the shoreline of Yaquina Bay as well as define the extreme upstream and downstream limits for the population. From these results, the subtidal survey was focused within the upper and lower limits of where oysters were observed in the tidal range.

4.3.1 Intertidal Survey

Data was gathered for the intertidal surveys on April 19, 20, and May 17, 2019. In order to access and survey the intertidal zone, intertidal surveys were conducted coincident with low-tide windows that occurred during daylight hours. The intertidal zone was divided into two broad search areas: the north and south shorelines. The north shoreline is mostly developed, much of it characterized by hardened features like riprap, and closely bordered by a moderately trafficked, paved roadway. The south shoreline is more natural with long stretches left undeveloped and no adjacent road.

A stratified random sampling design was used to select survey locations along each of the shoreline sections. This method partitions the sampling area into multiple, distinct sections and chooses random samples within each of the sections (Norgard et al. 2010). The north and south shorelines were stratified by average wet-season salinity regime which divided the estuary into four regions from downstream to upstream (Figure 9):

1) Greater than 27.1 psu;
2) Between 23.1 and 27 psu;
3) Between 16.1 and 23 psu; and
4) Less than 16 psu.

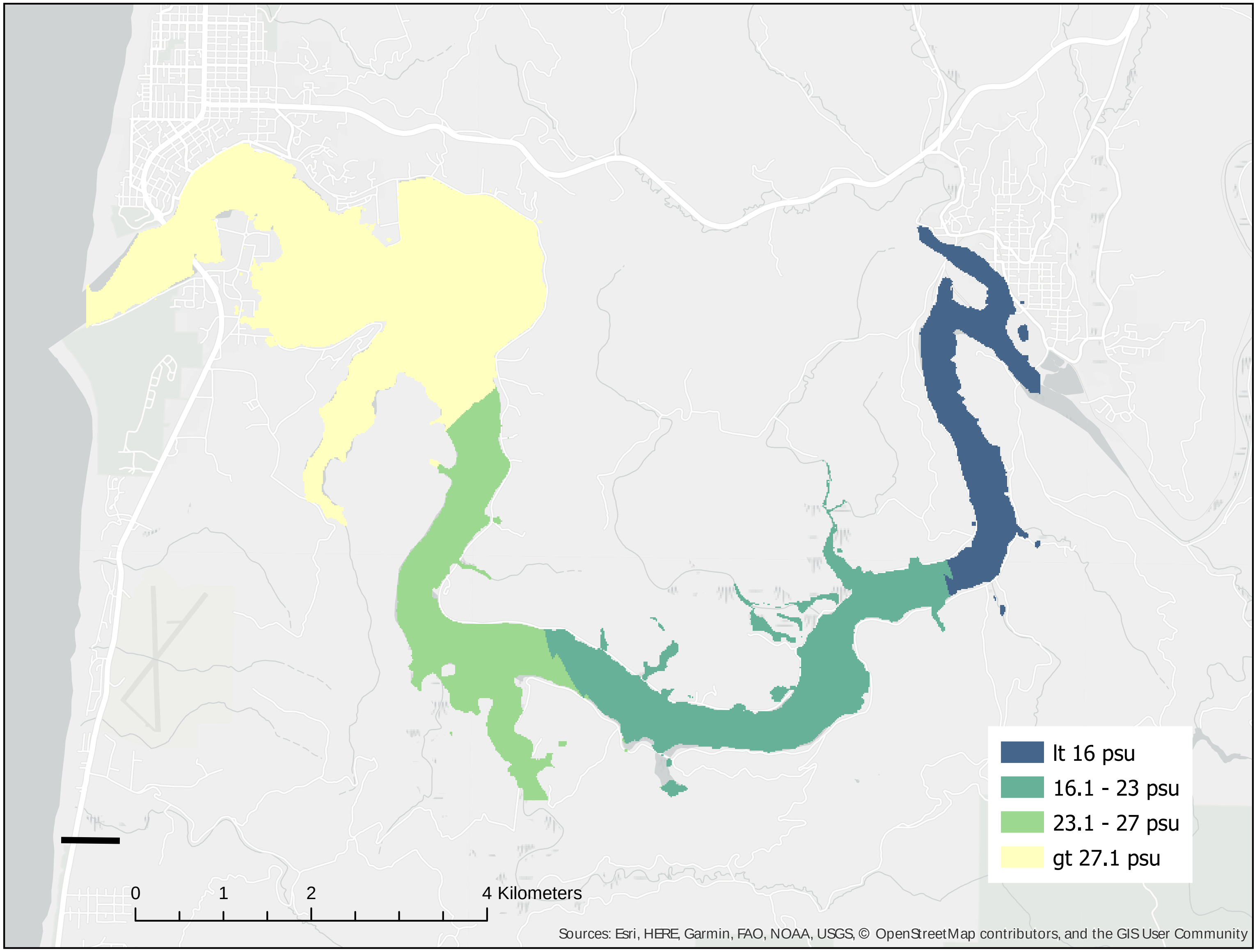

Figure 9. Wet-season salinity threshold bins used to stratify the random sampling approach in the intertidal survey of Olympia oysters in Yaquina Bay, Oregon.

To select sample locations, each section of shoreline was measured using the Ruler tool in Google Earth Pro (version 7.3.2.5776). A random number generator (google.com) was used to produce 2 to 5 random numbers that fell between 1 and the maximum length of the shoreline section (in meters). The number of samples for each section was determined based on literature review of what salinity ranges Olympia oysters prefer and Steve Rumrill's personal observations. Maps of the survey points were created in ArcGIS Pro (version 2.2).

The first day of the intertidal survey occurred on April 19, 2019 along the north shoreline (low tide of -0.8 feet at 7:00 AM). A total of 13 sample locations was entered into Google Maps (maps.google.com). The survey team drove to each location and found nearby parking, then looked for an accessible route down to the shoreline. Of the 13 locations selected, 3 were inaccessible due to private property boundaries or unsafe conditions. Once at the sample locations, each member of the survey team conducted a time-constrained search for 5 minutes, starting from a central point within the sample location and each moving in opposite directions, assessing as much area as possible within the 5-minute period. These searches determined presence or absence of Olympia oysters. Oysters were characterized as 'present' if evidence of at least one oyster, alive or dead, was detected within the search area. A living oyster was considered as having two shells attached by a hinge, while a dead oyster was considered as one shell and no hinge. Both living and dead oysters needed to be attached to a substrate within the search area to qualify. No distinction was made between adult and young oysters in determining presence or absence. At the end of each 5-minute search, data was recorded in a field notebook, including sample location number, presence or absence of oysters, life stage of the oyster(s) present, substrate type, and other notes regarding details of the sample location and access. Photos of each sample location were taken using a waterproof camera. Latitude and longitude were noted using a hand-held Garmin GPSMAP 78sc receiver (for use in marine environments) and the coordinates were recorded by hand into the notebook. Coordinates represented the middle of the search area. An image of the conditions of a representative survey site is shown in Figure 10.

Figure 10. A representative intertidal survey site located along the north shoreline of Yaquina Bay.

The intertidal survey continued on April 20, 2019 along the north shoreline (low tide of -1.2 feet at 7:47 AM). An additional 12 sample locations were identified, but only 8 were surveyed due to access issues or redundancy with the previous day's survey. The same procedure for accessing the sample locations, conducting the 5-minute searches, and recording data was completed.

The south shoreline was surveyed on May 17, 2019 (low tide of -1.0 feet at 6:18 AM). A total of 11 sample locations was generated using the random stratified sampling approach, though only 9 of those were sufficiently accessible to be surveyed. Access by boat was required to complete this section of the survey. Coordinates for each random sample location were entered into the GPS receiver on a small ODFW boat and an ODFW staff member navigated the survey team to each location. Once there, each member of the survey team completed the 5-minute search and data was collected in the same manner as the north shoreline survey. Because the survey team could approach the shore from the water rather than from land, access was relatively unrestricted and substantially less time was spent traveling between each sample location. However, two of the randomly selected survey sites were inaccessible due to exposure of expansive mudflats located between the channel and the shore.

The relative speed and ease of boat travel allowed the survey team to also apply an ancillary, haphazard sampling approach along the south shoreline to add more sampling locations. Haphazard sampling is an opportunistic technique, and is considered a quick, low-cost way to gather more data, but it is not truly random or statistically rigorous (Norgard et al. 2010). A total of 10 additional intertidal sites along the south shoreline that offered appropriate substrate were sampled haphazardly using the 5-minute time-constrained search.

4.3.2 Subtidal Survey

The subtidal survey was conducted by small boat on June 26 and 27, 2019. The goal of the subtidal survey was to use an underwater camera to capture photos of the substrate and Olympia oysters present on the estuary floor. Random sites for surveying were selected within the subtidal zone delimited by the extent of Olympia oyster observations both upstream and downstream observed during the prior intertidal survey. A polygon of the subtidal zone was generated to define the broader survey area. Random sites within the subtidal polygon were selected using the free software product QGIS (version 3.6 formatted for MacBook Pro), an open-source mapping program similar to ArcGIS. QGIS was used as a substitute program because ArcGIS was unavailable at the time of selecting these survey sites. Using the 'Random Points in Layer Bounds' tool in QGIS, 25 survey points were generated. A separation of 0.001 degrees was established so that points were not overlapping.

The field portion of the subtidal survey to deploy the underwater camera was intentionally scheduled during a high tide within a neap tide cycle. Neap tide high and low water levels are less extreme and produce less water turbidity, which improved water clarity for taking underwater photos. Survey points were loaded into the GPS unit aboard an ODFW small boat, and the survey team navigated to the sites in numerical order. Sites numbered 1-12 were surveyed on June 26 and sites 13-25 were surveyed on June 27, 2019.

A waterproof camera frame (Benthic Lander) was constructed from aluminum in a manner that allowed for remote generation of plan-view underwater images of the bottom of the estuary (Figure 11). A waterproof GoPro Hero 3+ Black camera was attached to the top of the Benthic Lander frame, and illumination was provided by a BigBlue 1200 lumen LED dive light. The LED dive light was angled obliquely to provide extra light over the area of the bottom to be photographed. When the survey team arrived at a site, an anchor was dropped from the boat to provide stability against the wind and tidal current. The Benthic Lander was then lowered quickly into the water to maintain a vertical descent. The GoPro camera was set on a time-lapse interval of 30 seconds, and the Benthic Lander remained underwater for 5 minutes total at each site.

Figure 11. Benthic Lander set-up used to capture underwater photos in the subtidal survey. Aluminum frame provides a platform for a GoPro camera and for oblique illumination by a battery-operated, LED dive light. Surface area of the image frame is 0.5 m^2. A pair of plastic net floats provided buoyancy at the top of the lander and served to maintain the proper orientation during descent to the bottom.

4.4 Comparison of Field Data to Habitat Suitability Model

To address the central research questions, the data points generated from the intertidal and subtidal field surveys that indicated presence of Olympia oysters were analyzed against the HSM and the three habitat parameter raster files. Data was extracted from the raster of the HSM, as well as from each of the original raster layers for the three habitat parameters, at the location of the presence points using the ‘Extract Values to Points’ tool in ArcGIS Pro. With this tool, the value of a raster layer at a designated point is recorded. Presence points that overlapped with the raster layer of interest generated a set of numeric values. Presence points that did not overlap with the raster layer of interest produced a ‘NULL’ value and were ultimately excluded from analysis.

The immediate neighborhood surrounding each presence point was also assessed. To establish the neighborhood, the ‘Buffer’ tool in ArcGIS Pro generated a circular buffer with a 5-meter radius around each point. The buffer was used as a proxy for error due to: 1) possible inaccuracy associated with the Garmin GPSMAP 78sc unit used to collect the survey points; 2) possible inaccuracy associated with unequal search area coverage in the intertidal survey; and 3) possible inaccuracy associated with the physical movement of the boat due to wind and waves in the subtidal survey. As reported in the user manual for the Garmin GPSMAP 78sc hand-held device, less than 10-meter inaccuracy is associated with typical use (Garmin 2013). In the intertidal survey, the data point collected represented the middle of a timed search area, which was subject to researcher discretion and the area covered. In the subtidal survey, the boat used to navigate between survey sites was subject to more or less perturbation due to wind and waves at each site.

Once the buffers were created, the ‘Extract by Mask’ tool was used to extract values from the raster layer of interest within the area of the buffer. For the HSM, the suitability value found at each presence data point was recorded. For the salinity raster, the average value within the buffer was recorded. For substrate, the total percent coverage of the substrate classes within all the buffers was recorded. Finally, for elevation, the range of the values within each buffer was recorded representing the upper and lower limits of the buffer area.

5. Results

The three integrated components of this study were:

1) Development of a Habitat Suitability Model (HSM);
2) Collection of field observations of Olympia oysters *in situ*; and
3) Comparison of field observations to the areas of suitability predicted by the HSM.

In summary, 20 field sites of the total 60 field sites examined indicated presence of Olympia oysters in Yaquina Bay. Of those 20 sites, information from 11 sites was compared to the HSM, developed from a thorough review of scientific literature sources. Only 4 of the 11 points aligned with the predicted area of most suitable habitat. Salinity was identified as the most accurate parameter in predicting Olympia oyster presence.

5.1 Development of a Habitat Suitability Model for Olympia Oysters

A summary of findings from the literature review to determine environment thresholds and apply habitat suitability rankings is presented in Table 1. A Literature Review Table was created for each of the habitat parameters: salinity (Table 2); substrate (Table 3); and elevation (Table 4). The corresponding text excerpts for each literature source that guided the ranking value assignments are listed in Appendix A. All literature sources are referenced in the Bibliography. 'Most suitable' habitat classes are highlighted in green, 'Somewhat suitable' in yellow, 'Least suitable' in red, and 'Unsuitable' in gray. Unsuitable habitat classes were only found in the substrate parameter, according to the researcher's interpretation of the literature. For salinity and elevation, tolerance ranges were recorded. Unsuitable habitat (rank 1) was not assigned to any class within these parameters.

Raster layers were created in ArcGIS to spatially represent suitability for Olympia oysters within each of the habitat parameters based on the findings in the Literature Review Tables. Maps of suitability for each habitat parameter are displayed following the Literature Review Tables (Figures 12-14). These layers were then combined using the Weighted Overlay function in ArcGIS Pro to create the final representation of habitat suitability (Figure 15).

	Most suitable (rank 4)	**Somewhat suitable (rank 3)**	**Least suitable (rank 2)**	**Unsuitable (rank 1)**
Salinity classes	16.1 – 23 psu, 23.1 – 27 psu	27.1 – 32 psu	0 – 16 psu	
Substrate classes	Biogenic substrate (2)	Unconsolidated mineral substrate (1.2), Anthropogenic substrate (3), Anthropogenic rock (3.1)	Gravelly mud (1.2.1.3.3), Anthropogenic rock rubble (3.1.2)	Sandy mud (1.2.2.4), Anthropogenic rock hash (3.1.3)
Elevation classes	Deep and shallow subtidal (-12.5 – 0m)	Low intertidal (0 – 1m)	High intertidal (1 – 2.5m)	

Table 1. Summary of the results from the Literature Review Tables to assess habitat parameter thresholds for Olympia oysters as a component of the development of the Habitat Suitability Model (HSM).

5.1.1 Salinity

	Salinity -- average wet-season (psu or ppt)																																Range	
	Upper estuary																Upper mid estuary							Lower mid				Lower estuary					Full	Partial
Source:	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32		
Baker 1995																X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
Fasten 1931																	X	X	X	X	X	X	X	X	X	X	X	X						X
Gray et al. 2019							X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X				X
Groth and Rumrill 2009							X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X				X
Pritchard et al. 2015 ('Recent Advances')																X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
Pritchard et al. 2015 ('Larval Supply and Recruitment')																X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X

Color key:

most suitable (rank 4)
somewhat suitable (rank 3)
least suitable (rank 2)
unsuitable (rank 1)

Table 2. Literature Review Table for the salinity parameter. Salinity is measured in practical salinity units (psu) or parts per thousand (ppt); these units are considered equivalent for this project. The source column represents the scientific article referenced for this review. Text excerpts from each source are listed in Appendix B. An 'X' indicates that Olympia oysters *tolerate* this salinity value (psu or ppt) according to the literature. The *suitability* of each salinity value, indicated by the colors in the color key, was determined based on an interpretation of the literature by the researcher, unless otherwise explicitly stated. Sources that cited tolerable salinity values for Olympia oysters at a specific location, such as Yaquina Bay, were listed as 'partial range.' Sources that cited tolerable salinity values for Olympia oysters generally were listed as 'full range.'

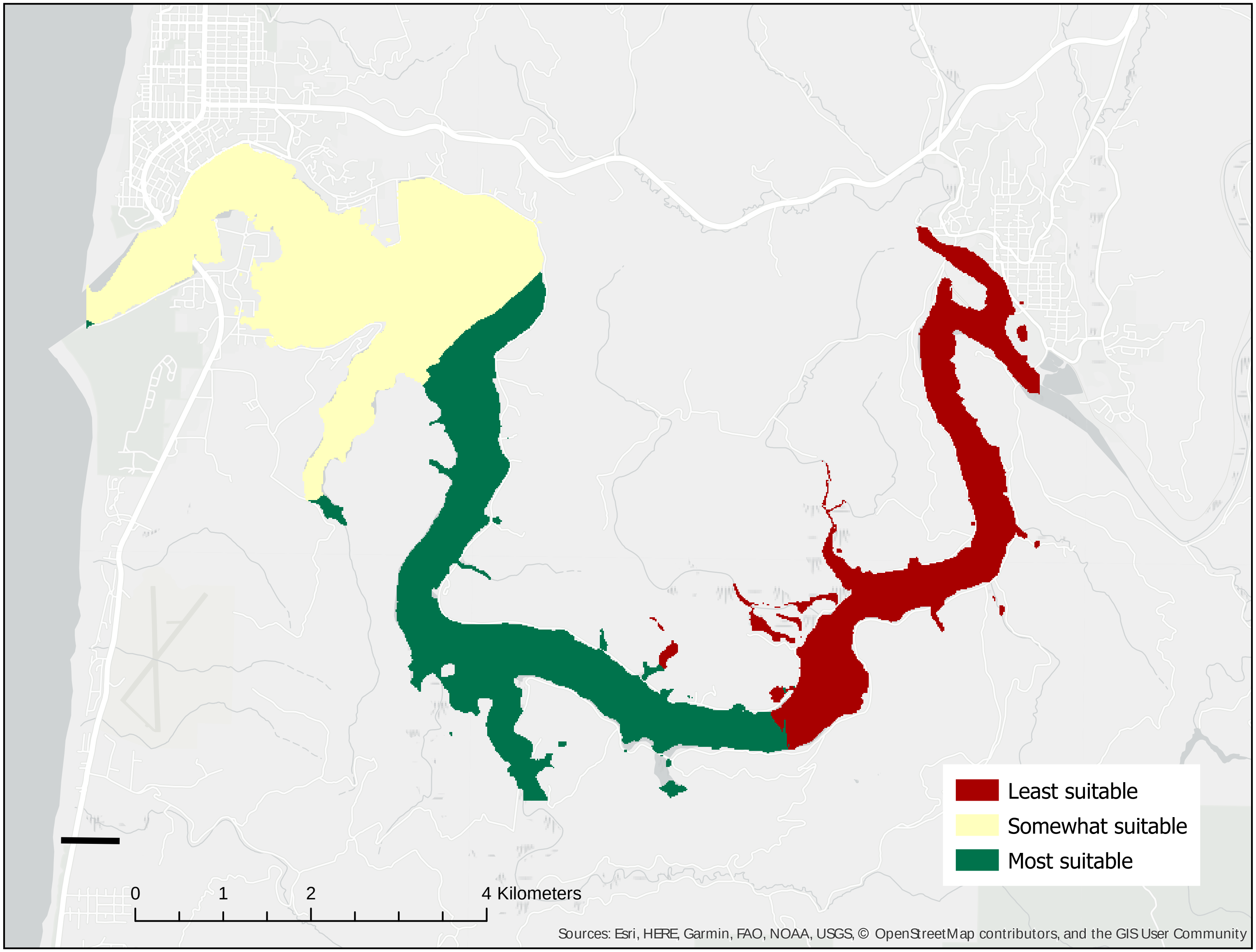

Figure 12. Map of habitat suitability for the salinity parameter based on application of suitability values from its corresponding Literature Review Table.

5.1.2 Substrate

	Substrate -- CMECS Estuarine Substrate Component classes									Range	
Source:	1.2 Unconsolidated mineral substrate	1.2.1.3.3 Gravelly mud	1.2.2.4 Sandy mud	2 Biogenic substrate	3 Anthropogenic substrate	3.1 Anthropogenic rock	3.1.2 Anthropogenic rock rubble	3.1.3 Anthropogenic rock hash	9.9.9.9.9 Unclassified	Full	Partial
Baker 1995	🟨 X	🟧 X	⬜	🟩 X	🟨 X	🟨 X	🟧 X	⬜	?	X	
Couch and Hassler 1989	🟨 X	🟧 X	⬜	🟩 X	🟨 X	🟨 X	🟧 X	⬜	?	X	
Fasten 1931	🟨 X	🟧 X	⬜	🟩 X	🟨 X	🟨 X	🟧 X	⬜	?		X
Gillespie 2009	🟨 X	🟧 X	⬜	🟩 X	🟨 X	🟨 X	🟧 X	⬜	?		X
Groth and Rumrill 2009	🟨 X	🟧 X	⬜	🟩 X	🟨 X	🟨 X	🟧 X	⬜	?		X
Wasson et al. 2014	🟨 X	🟧 X	⬜	🟩 X	🟨 X	🟨 X	🟧 X	⬜	?		X
White et al. 2009	🟨	🟧	⬜	🟩 X	🟨 X	🟨 X	🟧 X	⬜	?	X	

Color key:

- 🟩 most suitable (rank 4)
- 🟨 somewhat suitable (rank 3)
- 🟧 least suitable (rank 2)
- ⬜ unsuitable (rank 1)

Table 3. Literature Review Table for the substrate parameter. Substrate is divided into classes as identified by the Coastal and Marine Ecological Classification Standard (CMECS). The source column represents the scientific article referenced for this review. Text excerpts from each source are listed in Appendix B. An ‘X’ indicates that Olympia oysters *tolerate* this substrate class according to the literature. The *suitability* of each substrate class, indicated by the colors in the color key, was determined based on an interpretation of the literature by the researcher, unless otherwise explicitly stated. Sources that cited tolerable substrate classes for Olympia oysters at a specific location, such as Yaquina Bay, were listed as ‘partial range.’ Sources that cited tolerable substrate classes for Olympia oysters generally were listed as ‘full range.’

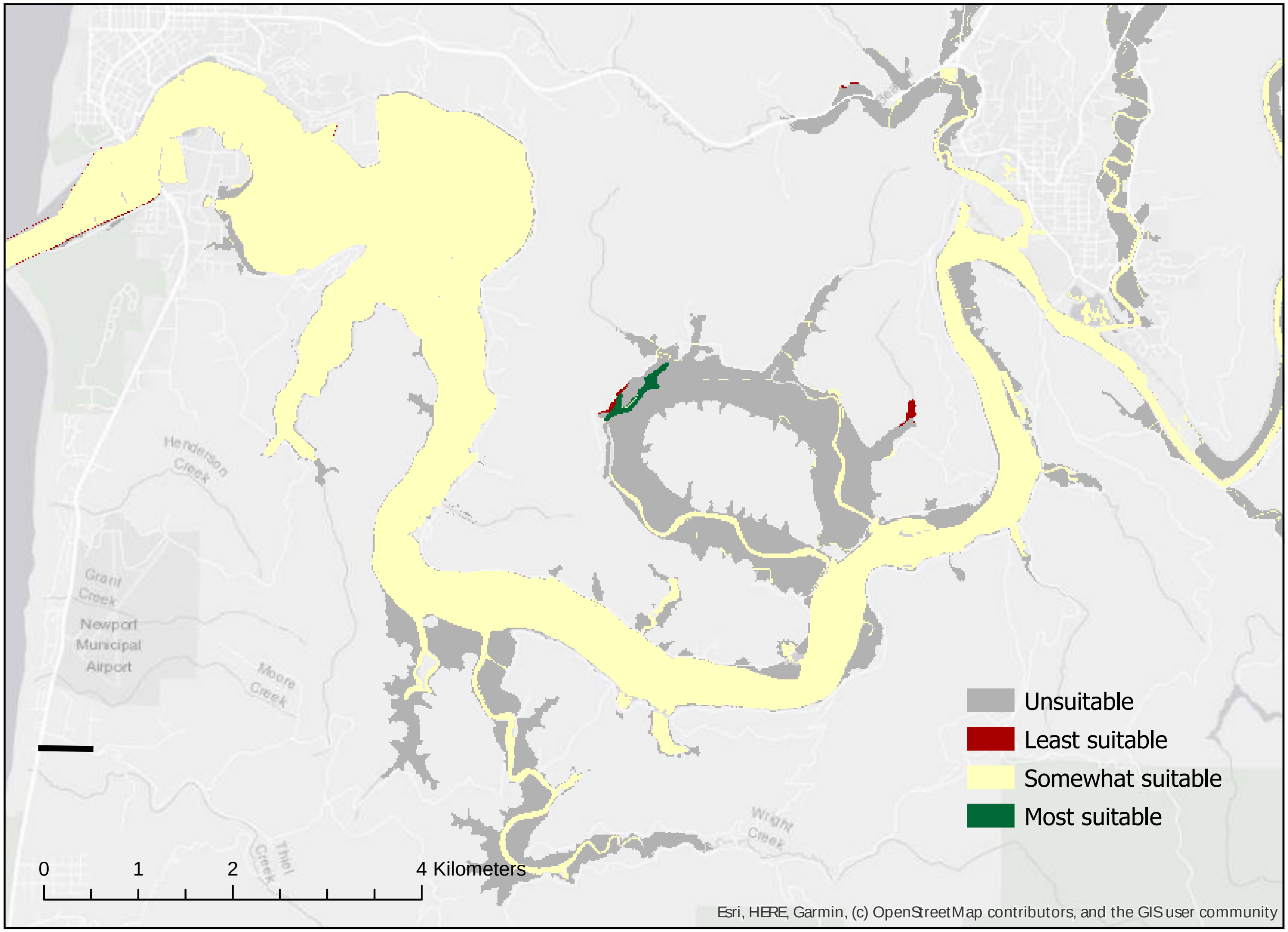

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Figure 13. Map of habitat suitability for the substrate parameter based on application of suitability values from its corresponding Literature Review Table.

5.1.3 Elevation

	Bathymetric depth -- compared to MLLW (m)											
	Deep subtidal			Shallow subtidal			Low intertidal		High intertidal		Full range	Partial range
Source:	**-12.5 - -8m**	**-8 - -6m**	**-6 - -4m**	**-4 - -3m**	**-3 - -2m**	**-2 - 0m**	**0 - 0.5m**	**0.5 - 1m**	**1 - 1.5m**	**1.5 - 2.5m**		
Baker 1995	X	X	X	X	X	X	X	X	X	X	X	X
Couch and Hassler 1989	X	X	X	X	X	X					X	
Gillespie 2009	X	X	X	X	X	X	X	X			X	
Groth and Rumrill 2009	X	X	X	X	X	X	X	X				X
Pritchard et al. 2015 ('Recent Advances')	X	X	X	X	X	X	X	X	X	X	X	
White et al. 2009	X	X	X	X	X	X					X	

Color key:

most suitable (rank 4)

somewhat suitable (rank 3)

least suitable (rank 2)

unsuitable (rank 1)

Table 4. Literature Review Table for the elevation parameter. Elevation is measured in meters compared to Mean Lower Low Water at 0 meter. The source column represents the scientific article referenced for this review. Text excerpts from each source are listed in Appendix B. An 'X' indicates that Olympia oysters *tolerate* this elevation range (m) according to the literature. The *suitability* of each elevation range, indicated by the colors in the color key, was determined based on an interpretation of the literature by the researcher, unless otherwise explicitly stated. Sources that cited tolerable elevation ranges for Olympia oysters at a specific location, such as Yaquina Bay, were listed as 'partial range.' Sources that cited tolerable elevation ranges for Olympia oysters generally were listed as 'full range.'

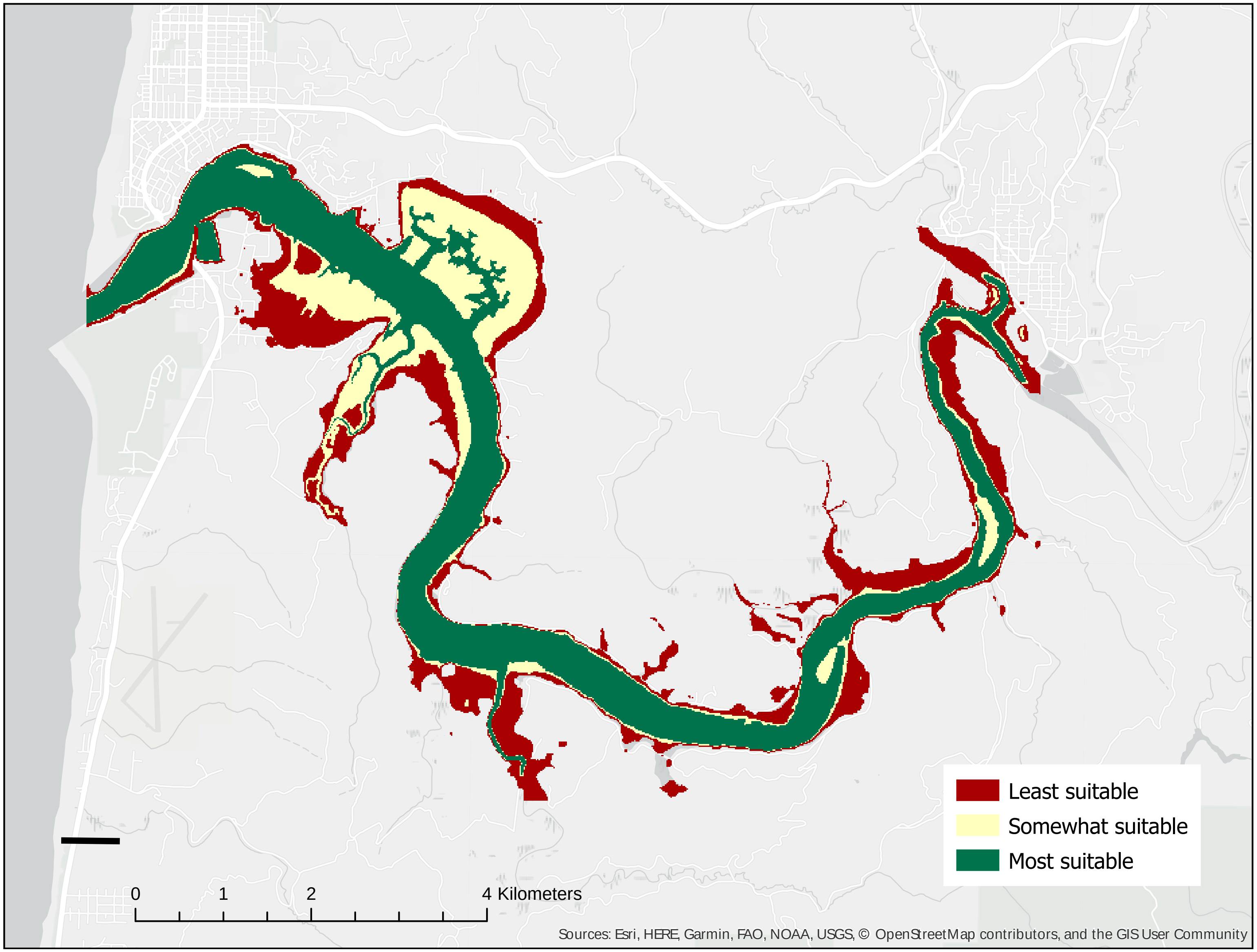

Figure 14. Map of habitat suitability for the elevation parameter based on application of suitability values from its corresponding Literature Review Table.

5.1.4 Final Habitat Suitability Model

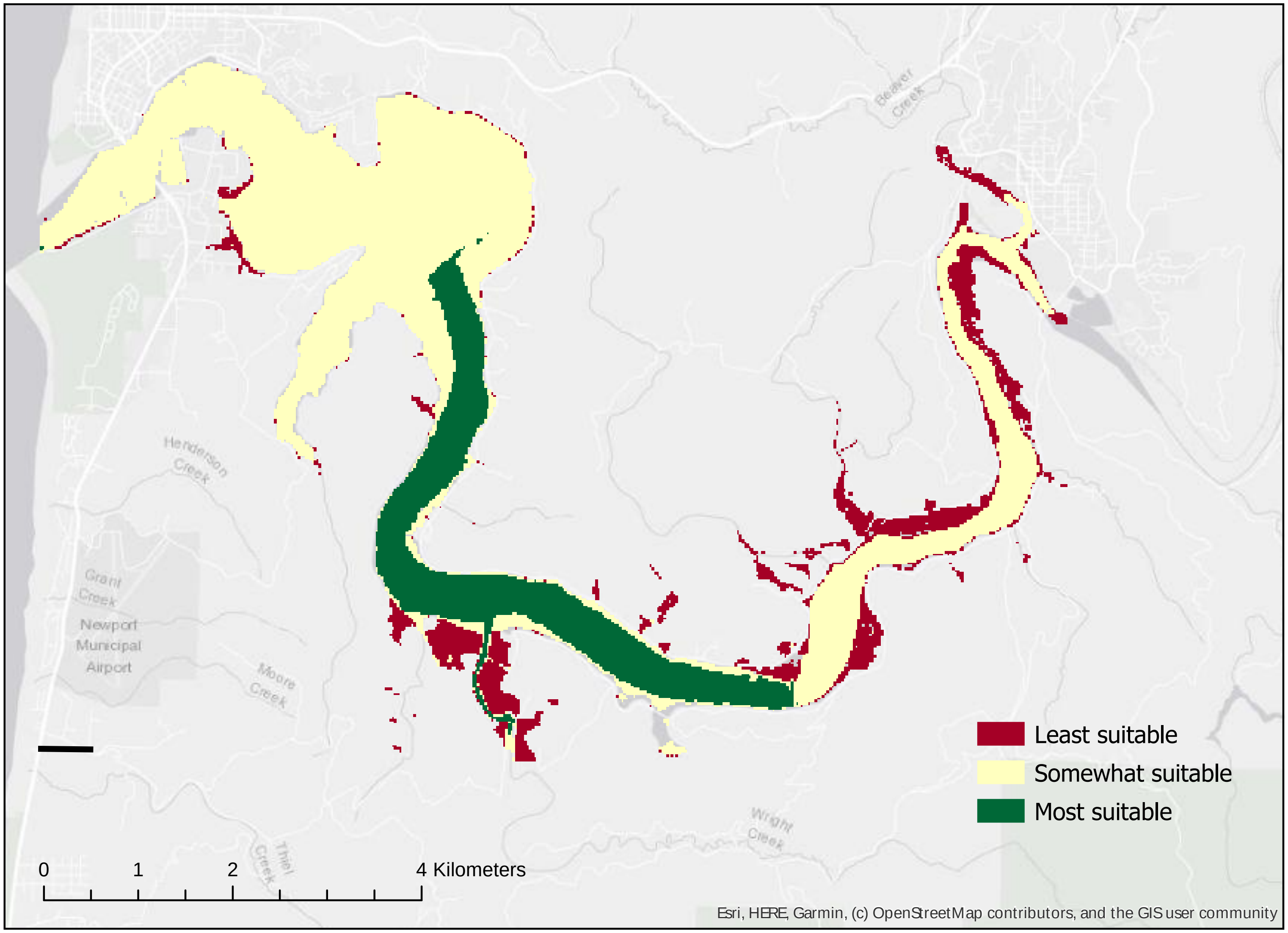

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Figure 15. Final representation of the integrated Habitat Suitability Model (HSM) for Olympia oysters in Yaquina Bay. The HSM combines the raster layers of suitability for salinity, substrate, and elevation.

5.2 Field Data Collection

A total of 60 data points was gathered over the course of the five field data collection dates in the Spring of 2019. These locations included 35 intertidal survey points and 25 subtidal survey points. Of those 60 field sites, 20 sites indicated presence of Olympia oysters (33.34%) and 40 sites indicated absence (66.67%). The intertidal survey captured 19 of the 20 presence data points; only one presence data point was identified in the subtidal survey.

A total of 37 sites were searched and evaluated for the intertidal survey. Of those 37 sites, 2 were eliminated due to redundancy for a total of 35 sites. Of the 35 sites, 19 indicated presence of oysters (54.29%) while 16 indicated absence (45.71%). Figure 16 represents a site in the intertidal zone where oysters were present. Underwater photos were taken at 25 sites in the subtidal zone; only one site revealed evidence of possible Olympia oyster settlement on the shells of Pacific oysters (Figure 17). Olympia oysters were absent from 96% (24 of 25 sites) of the field sites examined in the subtidal zone. The full results of the subtidal survey are listed in Appendix B. Figure 18 provides an overview of Yaquina Bay with all the Olympia oyster presence and absence data points collected from the intertidal and subtidal surveys. For further analysis, only the 20 presence data points were considered (Figure 19).

Figure 16. A representative intertidal survey site where adult Olympia oysters were identified as present.

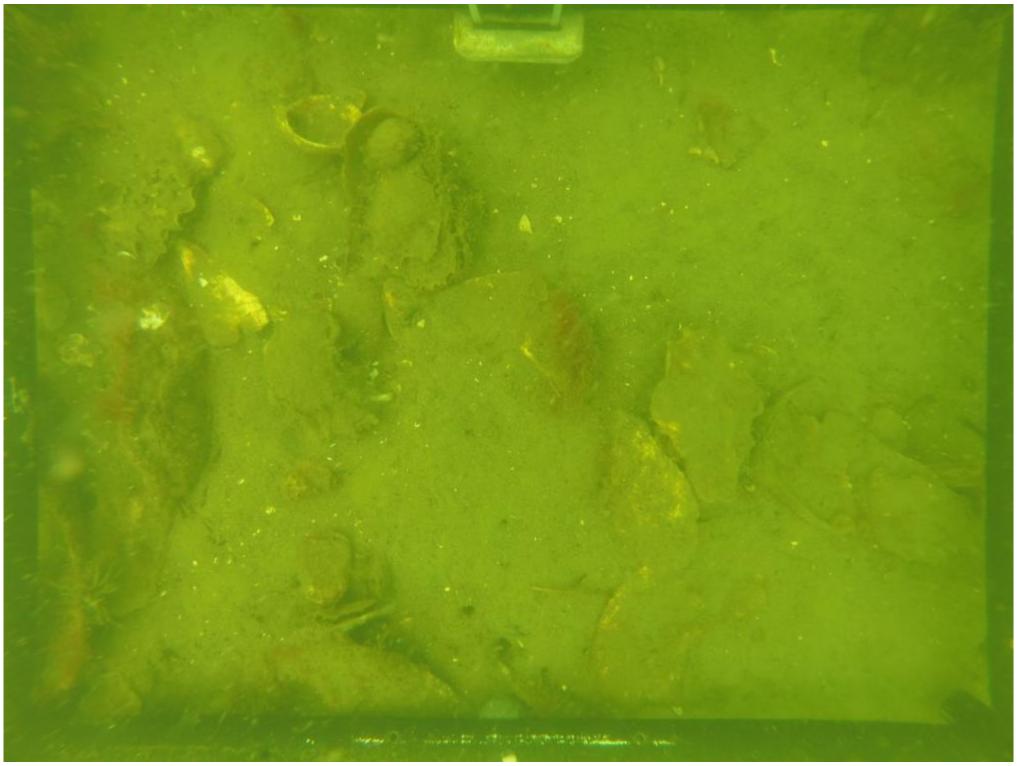


Figure 17. An underwater image taken at the only subtidal survey site where Olympia oysters were identified as present. Pacific oyster shells are also found in this image.

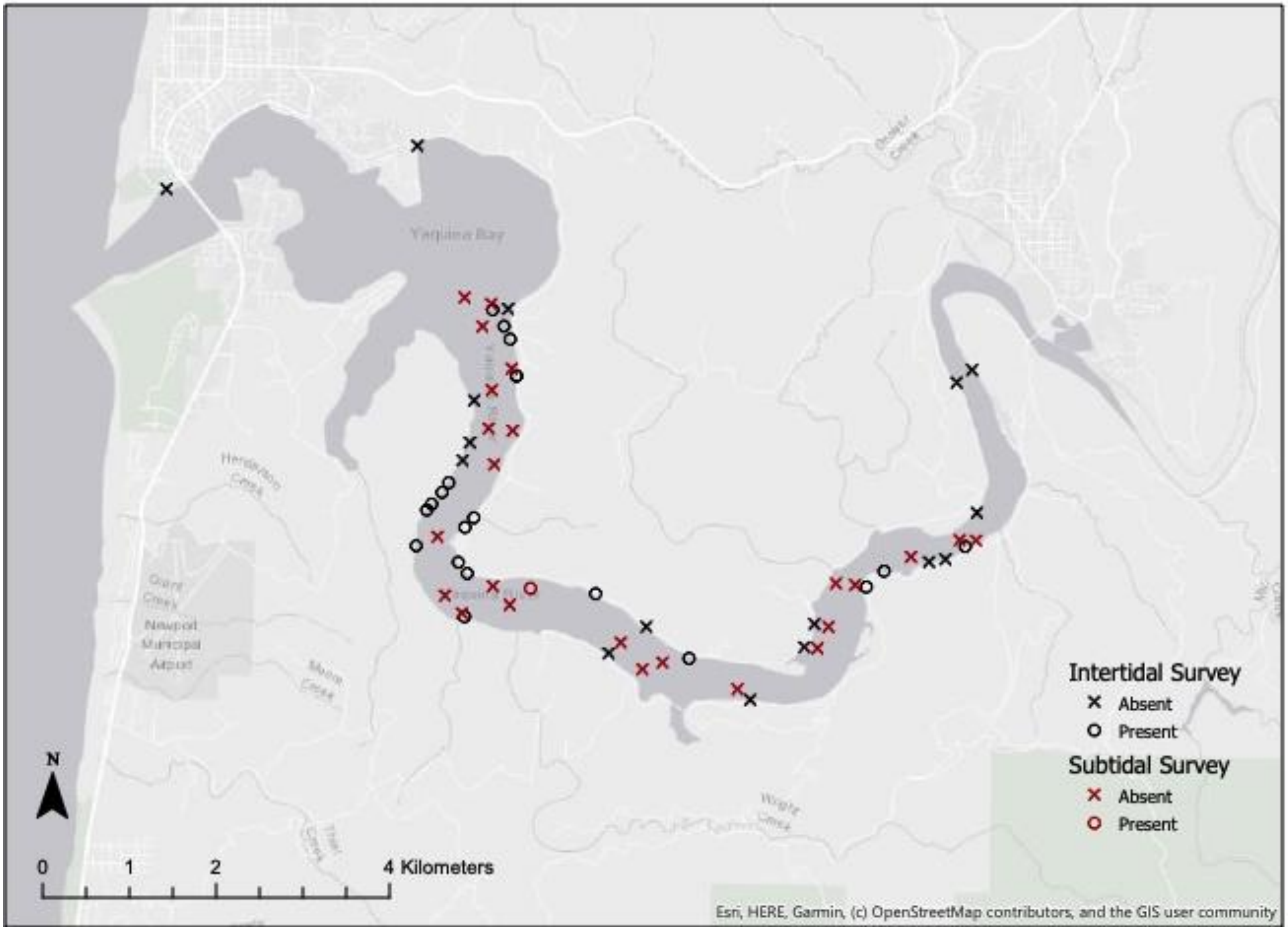


Figure 18. Olympia oyster presence and absence data points collected during two different field surveys (intertidal and subtidal) throughout Yaquina Bay, Spring 2019.

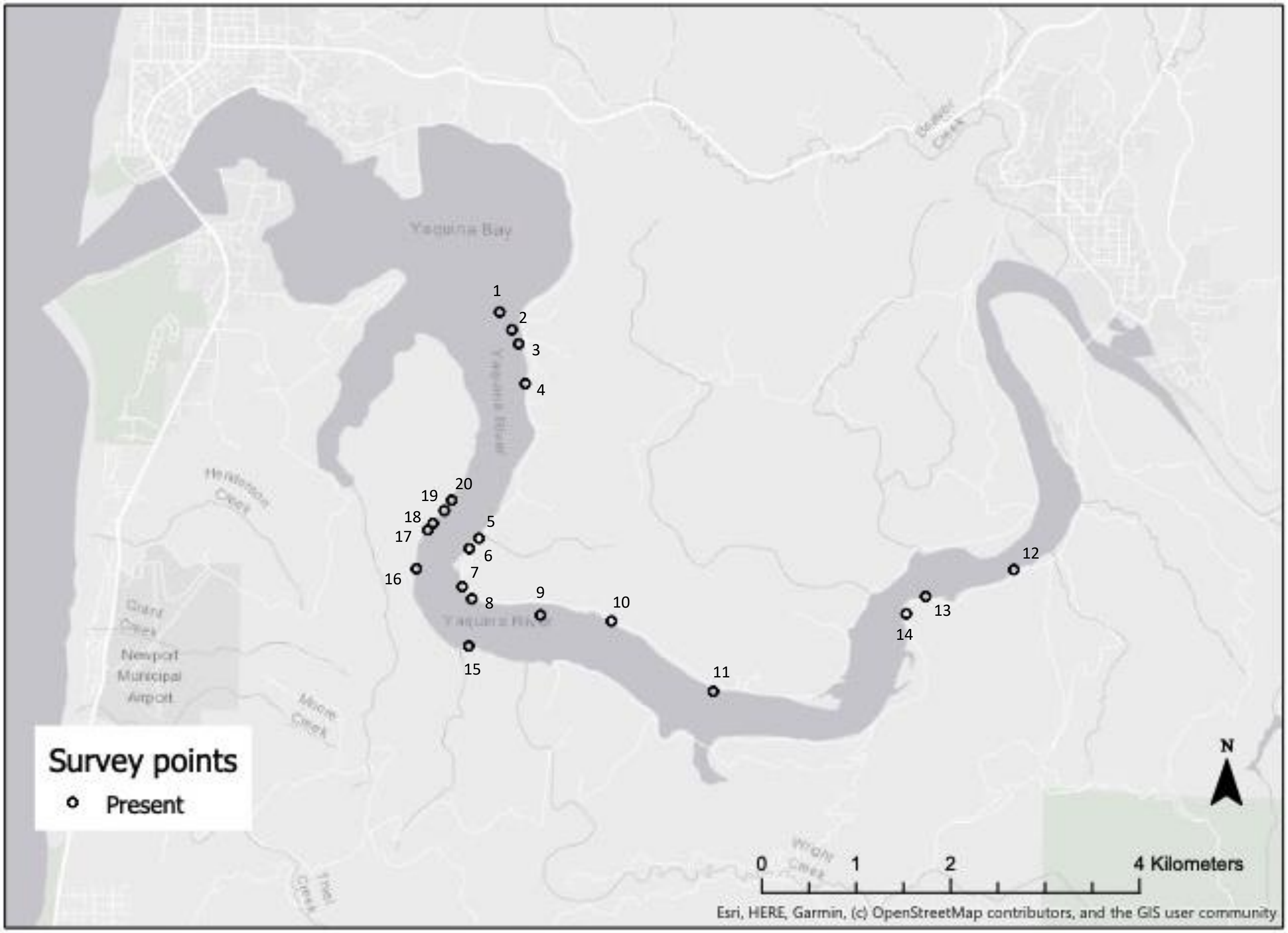


Figure 19. Olympia oyster presence-only data points collected during two different field surveys (intertidal and subtidal) in Yaquina Bay, Spring 2019. Numeric codes were assigned to indicate sequential location along the estuary shoreline.

5.3 Comparison of Field Data to the Habitat Suitability Model

Data values were extracted from each of the original habitat parameter raster layers and the final HSM at the 20 Olympia oyster presence points. Data values were also extracted from the 5-meter buffer representing the neighborhood around each point. Presence points and/or buffers that did not directly overlap with the raster layer were excluded from analysis. The following sections describe how the presence points aligned with the predicted suitability ranks within each habitat parameter and ultimately the HSM.

5.3.1 Salinity

Of the 20 Olympia oyster presence data points, 11 directly overlapped with the original interpolated salinity raster layer (Figure 6 in Section 4.2.1.1). Figure 20 shows the salinity values identified at each of the survey points. The colors indicate the salinity values that aligned with each predicted habitat suitability ranking according to the Literature Review Table (Section 5.1.1). Nine presence data points aligned with the predicted most suitable salinity range; two data points were found in the predicted least suitable salinity range. The lowest salinity value observed where Olympia oysters were present was 10.8 psu; the highest salinity value observed was 26.3 psu.

Buffers were applied in ArcGIS Pro as a measurement of error due to inaccuracy of the GPS receiver and possible inaccuracies with field data collection methods. After applying 5-meter buffers around each of the 20 presence data points, 3 additional points that fell just beyond the geospatial extent of the salinity raster were included (Figure 21). All 3 of these points aligned with the predicted most suitable salinity range.

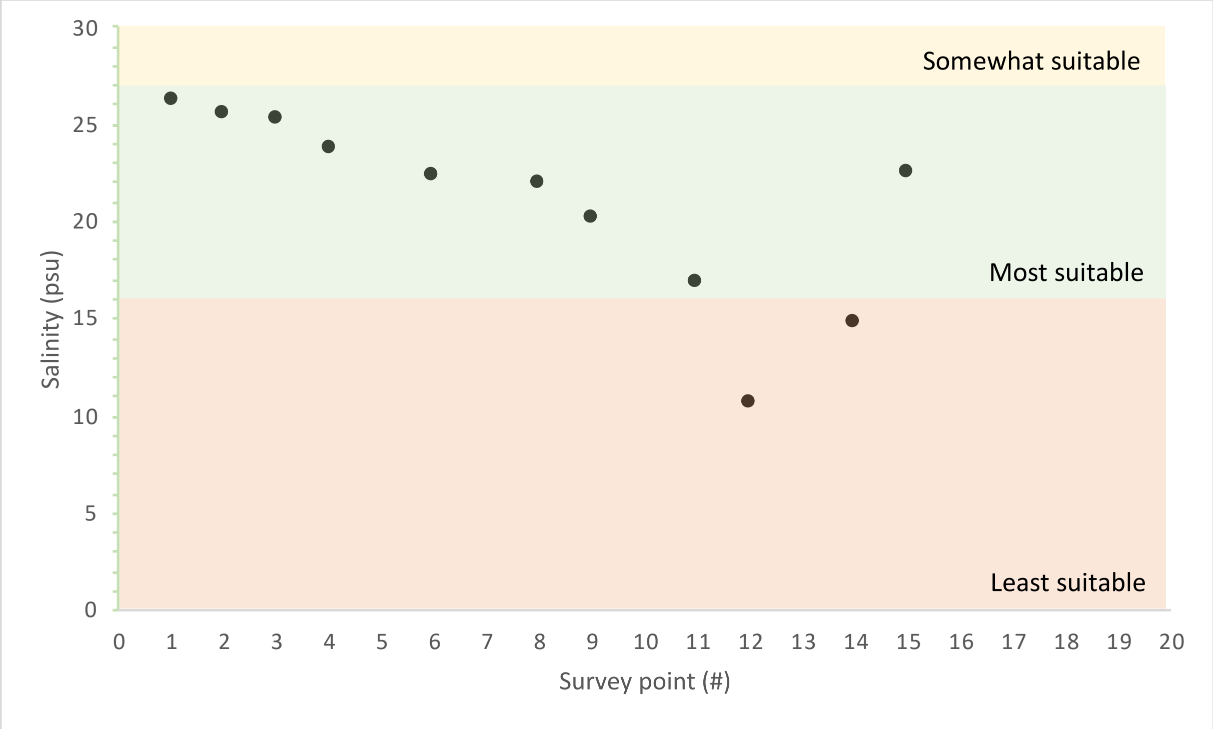


Figure 20. The measurements of salinity (psu) identified at each of the presence data points that overlapped with the original salinity raster layer. The ranges of predicted suitability are overlaid.

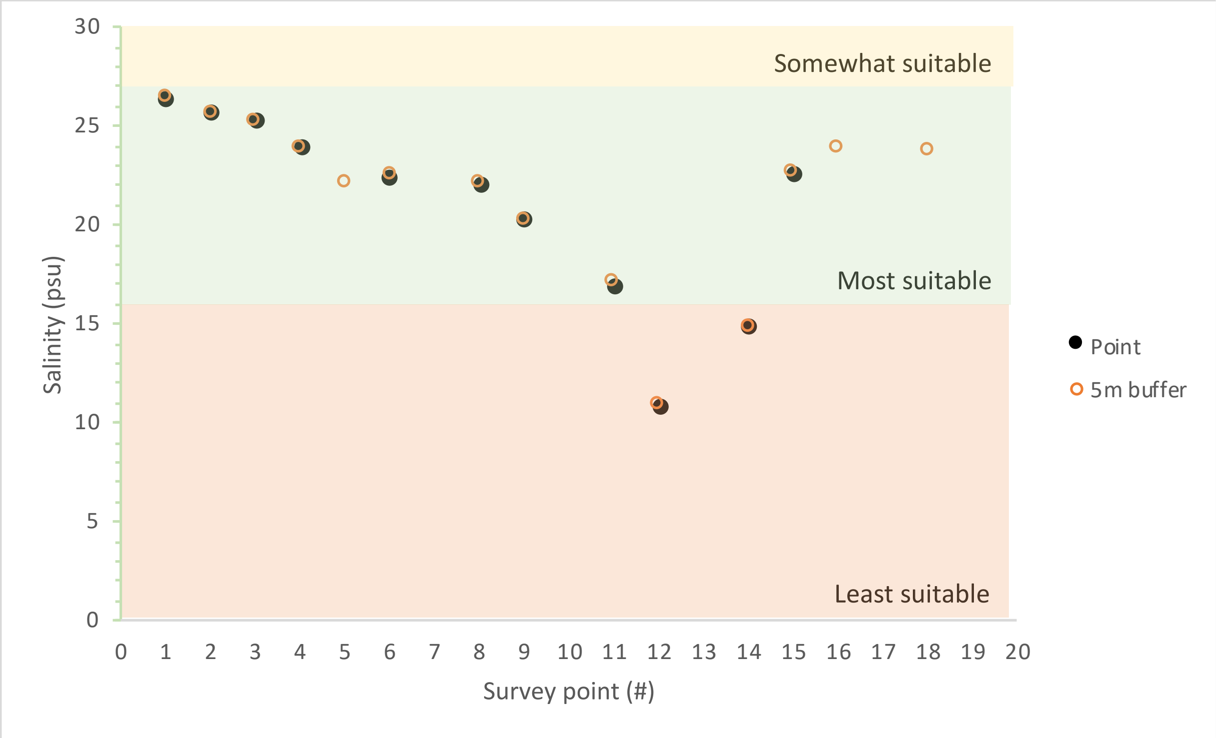


Figure 21. The measurements of salinity (psu) identified at each of the presence data points and in the 5-meter buffers that overlapped with the original salinity raster layer. The ranges of predicted suitability are overlaid.

5.3.2 Substrate

For the substrate parameter, 18 presence data points directly overlapped with the original substrate raster layer (Figure 7 in Section 4.2.1.2). Figure 22 shows the substrate class identified at each of the presence points. The colors indicate predicted suitability of the substrate classes according to the Literature Review Table in Section 5.1.2. Thirteen presence data points (72%) aligned with one of the somewhat suitable substrate classes (1.2 Unconsolidated mineral substrate). Four presence points (22%) were found in a substrate class that was predicted to be unsuitable (1.2.2.4 Sandy mud). One point was identified within the Unclassified substrate class. No additional presence points were included after applying the 5-meter buffers and no change was made to the assignment of substrate class.

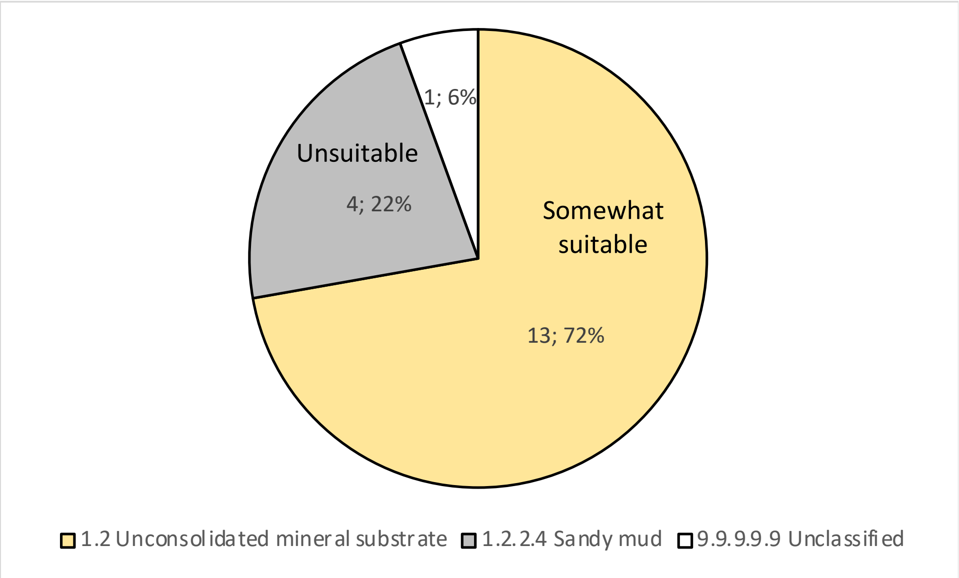


Figure 22. Substrate class detected at the presence data points and within the 5-meter buffer. Predicted suitability of the corresponding substrate class is included.

5.3.3 Elevation

For the elevation parameter, 11 presence points directly overlapped with the original raster layer of elevation (Figure 8 in Section 4.2.1.3). Figure 23 shows the elevation values identified at each of the overlapping presence points. The colors indicate the ranges of elevation that aligned with each predicted habitat suitability ranking according to the Literature Review Table in Section 5.1.3. Only 3 presence data points aligned with the predicted most suitable elevation (shallow subtidal, -4 – 0m). Two presence points landed in the somewhat suitable range (low intertidal, 0 – 1m), and 6 data points were found in the predicted least suitable elevation range (high intertidal, 1 – 2.5m). The lower limit of elevation where Olympia oysters were observed was -3 meters and the upper limit was 2.25 meters.

After applying 5-meter buffers around each of the 20 presence data points, 3 more points that fell just beyond the geospatial extent of the elevation raster were included. The upper and lower limits of each buffer was plotted alongside the elevation values at each of the points in Figure 24. All 3 additional presence points and their corresponding buffers aligned with the predicted least suitable elevation range.

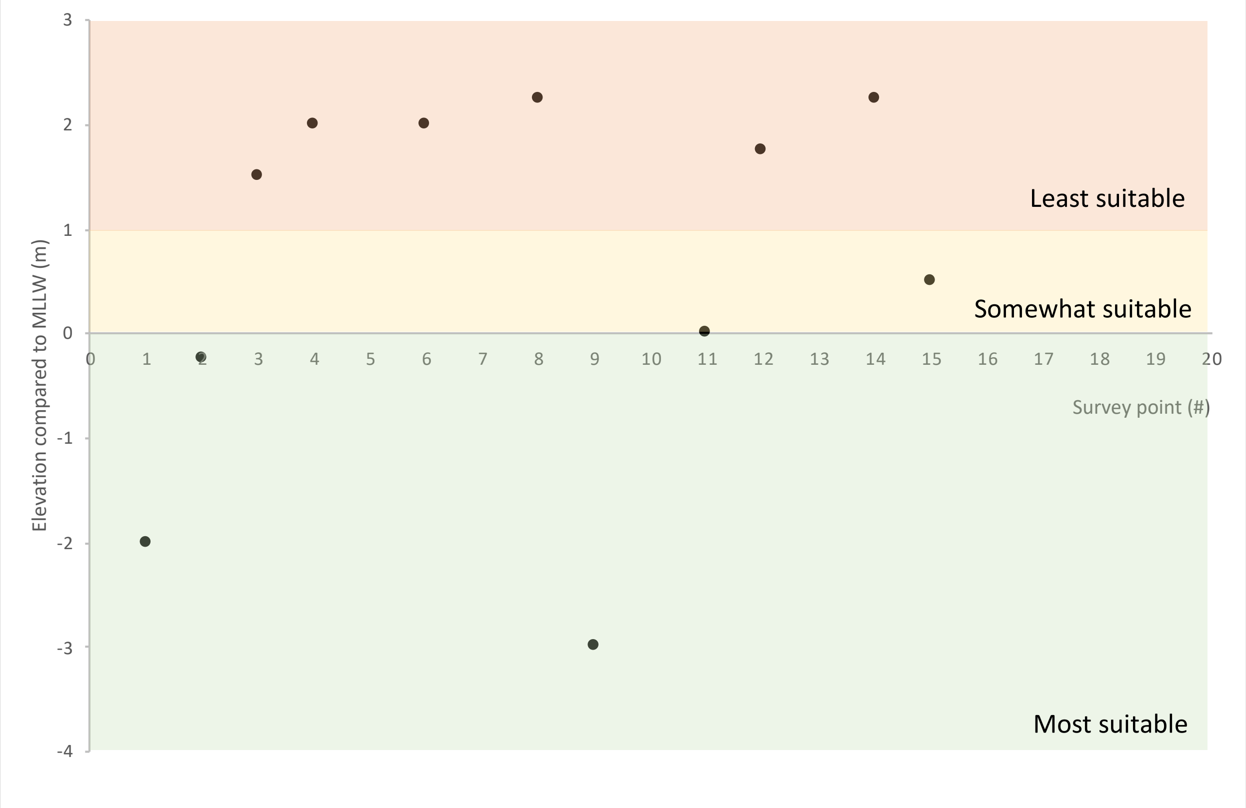


Figure 23. The measurements of elevation (m) identified at each of the presence data points that overlapped with the original elevation raster layer. The ranges of predicted suitability are overlaid.

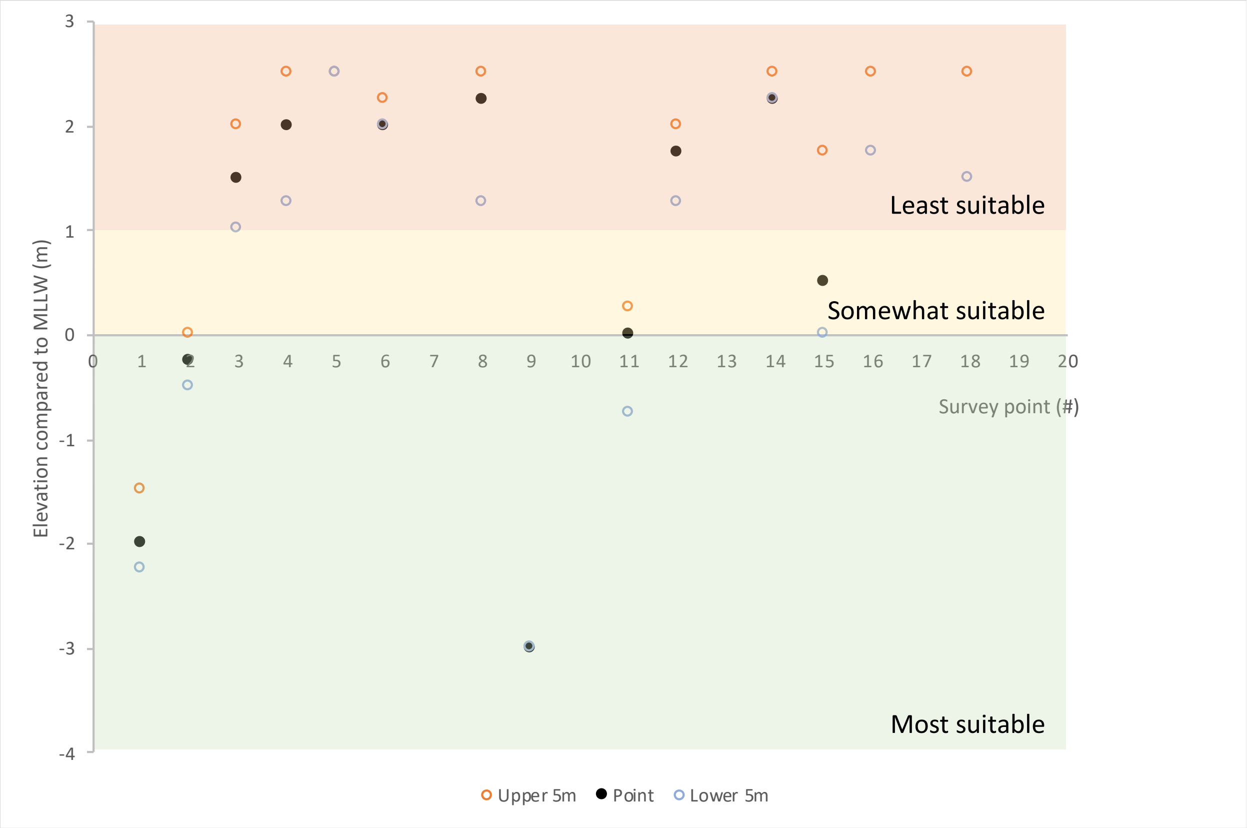
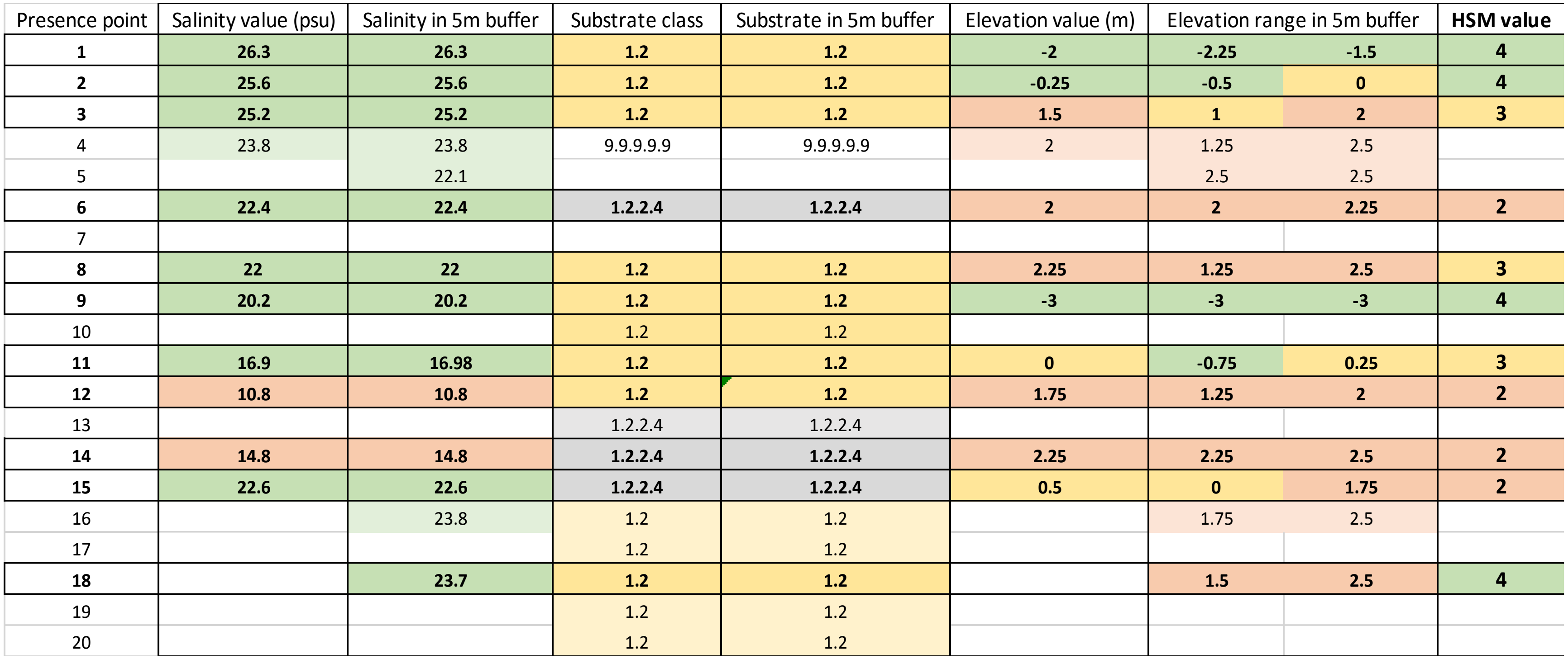


Figure 24. The measurements of elevation (m) identified at each of the presence data points and in the 5-meter buffers that overlapped with the original elevation raster layer. The 5-meter buffer is represented as the upper extent of the buffer ("Upper 5m") and the lower extent of the buffer ("Lower 5m"). The ranges of predicted suitability are overlaid.

5.3.4 Final Habitat Suitability Model

Only 11 of the 20 presence points directly overlapped with the geospatial extent of the HSM for Olympia oysters in Yaquina Bay. Four presence points aligned with the predicted most suitable habitat, while 3 points were found to be somewhat suitable and another 4 points fell into the least suitable habitat. Table 5 displays the point and buffer values found at each Olympia oyster presence point within each of the habitat raster layers. Figure 25 shows a map of the presence points and the habitat suitability associated with them. It was not possible to apply buffers due to the large pixel size associated with the HSM.



Presence point	Salinity value (psu)	Salinity in 5m buffer	Substrate class	Substrate in 5m buffer	Elevation value (m)	Elevation range in 5m buffer		**HSM value**
1	**26.3**	**26.3**	**1.2**	**1.2**	**-2**	**-2.25**	**-1.5**	**4**
2	**25.6**	**25.6**	**1.2**	**1.2**	**-0.25**	**-0.5**	**0**	**4**
3	**25.2**	**25.2**	**1.2**	**1.2**	**1.5**	**1**	**2**	**3**
4	23.8	23.8	9.9.9.9.9	9.9.9.9.9	2	1.25	2.5	
5		22.1				2.5	2.5	
6	**22.4**	**22.4**	**1.2.2.4**	**1.2.2.4**	**2**	**2**	**2.25**	**2**
7								
8	**22**	**22**	**1.2**	**1.2**	**2.25**	**1.25**	**2.5**	**3**
9	**20.2**	**20.2**	**1.2**	**1.2**	**-3**	**-3**	**-3**	**4**
10			1.2	1.2				
11	**16.9**	**16.98**	**1.2**	**1.2**	**0**	**-0.75**	**0.25**	**3**
12	**10.8**	**10.8**	**1.2**	**1.2**	**1.75**	**1.25**	**2**	**2**
13			1.2.2.4	1.2.2.4				
14	**14.8**	**14.8**	**1.2.2.4**	**1.2.2.4**	**2.25**	**2.25**	**2.5**	**2**
15	**22.6**	**22.6**	**1.2.2.4**	**1.2.2.4**	**0.5**	**0**	**1.75**	**2**
16		23.8	1.2	1.2		1.75	2.5	
17			1.2	1.2				
18		**23.7**	**1.2**	**1.2**		**1.5**	**2.5**	**4**
19			1.2	1.2				
20			1.2	1.2				

Color key:

🟩 most suitable (rank 4)

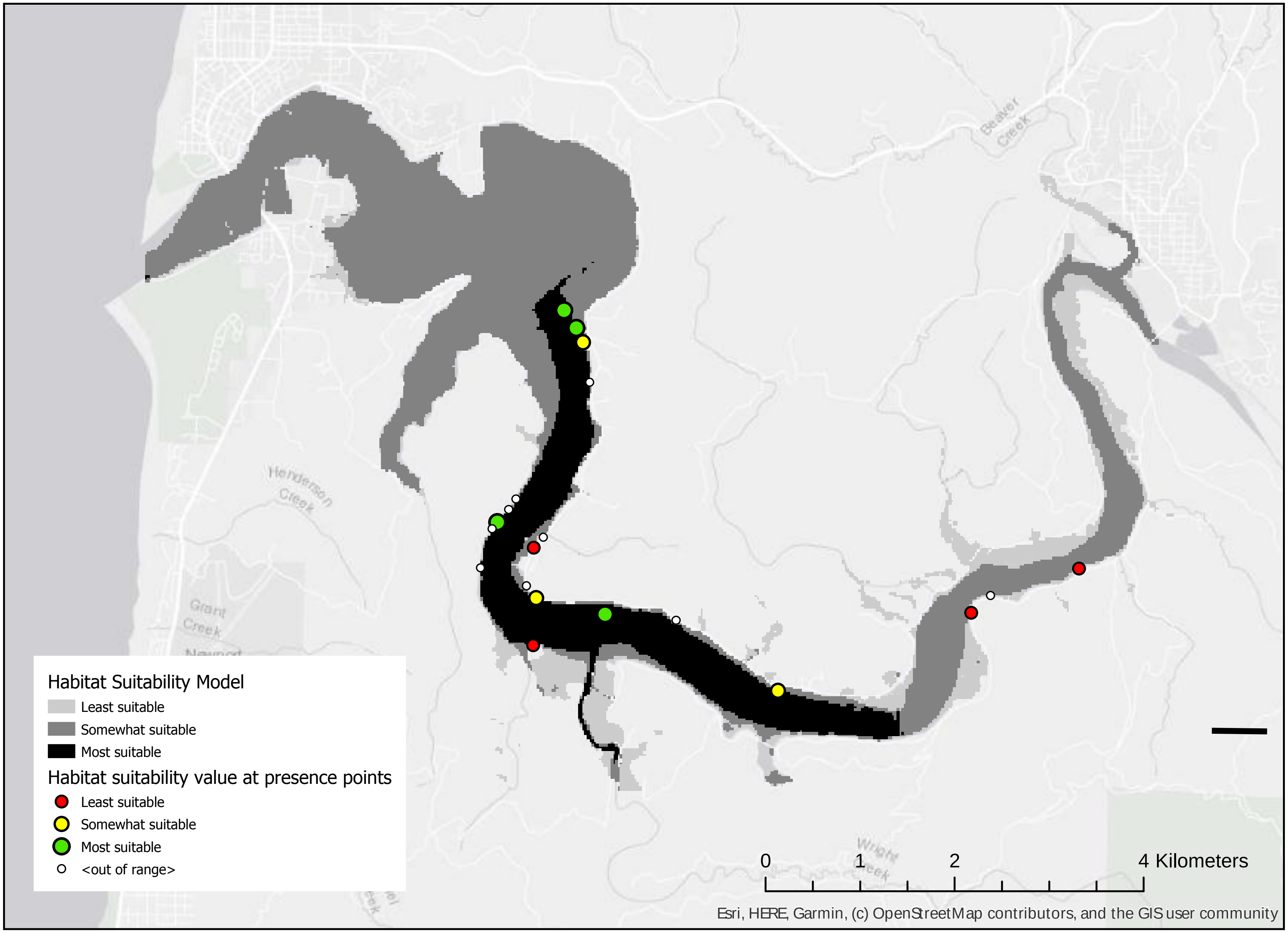
🟨 somewhat suitable (rank 3)

🟧 least suitable (rank 2)

⬜ unsuitable (rank 1)

*9.9.9.9.9 - Unclassified

Table 5. An overview of the habitat raster values detected at each of the presence points and within the 5-meter buffers. Values were gathered from each original parameter layer as well as the HSM. Colors indicate the suitability ranking applied in the literature review. Bolded values are those that ultimately contributed to the assignment of an HSM rank for that presence point.



Esri, HERE, Garmin, (c) OpenStreetMap contributors, and the GIS user community

Figure 25. Map of Olympia oyster presence points overlaid on the Habitat Suitability Model and their corresponding suitability values.

6. Discussion

This section will review the study limitations of each component of the field surveys and development of the HSM, followed by a discussion of the implications of the analysis. The research questions presented in the Introduction will also be addressed.

6.1 Study Limitations

6.1.1 Habitat Suitability Model

There are many considerations worth noting for the development of the HSM to be able to understand the results produced. One issue in creating the HSM was the resolution of the geospatial raster layers. Because the habitat raster layers were combined to create the HSM, the lowest resolution layer defines the resolution of the HSM. Some nuance and detail is lost in this process. Additionally, the level of classification within each habitat raster layer ultimately impacts the ranking of suitable habitat. For instance, the original substrate raster layer does not specifically identify small patches of hard substrate in the subtidal region of Yaquina Bay, and therefore may not truly reflect the available habitat. However, this level of detail in substrate would be very difficult to obtain. A majority of the photos (21 of 25, 84%) from the subtidal survey revealed substrate that was composed of entirely of soft mud, which does generally conform with the classification of the subtidal region in the CMECS Estuarine Substrate Component layer: 1.2 Unconsolidated mineral substrate. This highlights an important discrepancy in any sort of habitat mapping effort: What level of detail or resolution is required? For a framework like CMECS that covers a large geographic area, some generalization in identifying substrate classes, for instance, is needed to be broadly applicable and ensure consistency. However, this creates inherent uncertainties when attempting to predict suitable habitat for a rare or patchy species like the Olympia oyster.

Development of the HSM required an application of personal interpretation of the literature in the Literature Review Table. Another researcher might assign suitability ranking values differently according to his/her/their interpretation. Additionally, determining exactly how the text excerpts applied to the habitat parameter classes defined within each base raster layer was not always a natural fit. Qualitative descriptors, such as "oysters may do well at salinities above 25, can tolerate brief exposure to lower salinities…”, were difficult to readily assign into a specific class.

General cautions to bear in mind when creating HSMs include the use of too many parameters and the degree of dependence of the parameters on one another. Too many variables can result in creating a model that fits the initial set of field observations too closely and may not accommodate additional data points well. Conversely, oversimplification can lead to a less sophisticated model that has little predictive value. For this HSM, there may have been too few parameters and the addition of one more may help guide the assignment of suitable habitat. No additional complicating factors were considered, such as interactions of Olympia oysters with other species (namely Pacific oysters), temperature, or pH, but these may be choices to incorporate into a revised HSM.

A major limitation for this HSM and others like it is that population dynamics are often not considered (Thuiller and Munkemuller 2010). This includes the life stage of the species, the number of individuals found within a survey site, and the population structure. These types of models project what may be suitable habitat for a species in the short-term, but cannot be used to accurately assess changes in population or its geospatial distribution over time. Researchers or resource managers developing an HSM must be very clear on the overall goal for creating the model.

6.1.2 Field Data Collection

The major limitation of the field data collection portion of this project is the relatively small sampling size of sites located in both the intertidal and subtidal zones. A more robust collection of data would likely improve the ability of the researcher to assess trends in Olympia oyster distribution. Ideally, a more thorough survey of the entire shoreline would provide greater resolution of oyster presence and might manifest greater nuance in their preferences for settlement. However, ODFW Shellfish Biologists have reported that the nature of Olympia oyster distribution is inherently patchy, which could contribute to the difficulty of distinguishing trends in where oysters prefer to settle. Olympia oysters tend to be “opportunistic” in finding suitable substrate (S. Groth pers. comm.). For example, a small boulder or discarded metal shopping cart in the middle of a mud flat may be completely covered with Olympia oysters, but nowhere else. Consequently, these micro-habitats are less likely to be detected in a random sampling survey approach.

Another important point to address in both the intertidal and subtidal surveys is that no distinction was made between adult or juvenile oyster, living or dead, for determining presence/absence. Notes were recorded in the field data notebook regarding life stage of the oysters observed. Separating out this information might be interesting in determining where Olympia oysters are more likely to survive long-term. For example, it has been noted that young oysters may find an appropriate substrate to settle on in the summer season when salinity is generally stable, but may not be able to survive an influx of freshwater the following winter (S. Rumrill pers. comm.). The presence of only juveniles in some sections of the shoreline could indicate that freshwater pulses during the rainy season are driving the salinity of the estuary down too low for survival into adulthood.

Timing of the field surveys is also a crucial factor to consider when reviewing the results of this survey work. Presence and absence data points were collected over one spring season when spawning typically occurs (Fasten 1931). Since life stage was not a differentiating characteristic for determining presence/absence, a possible greater abundance of juvenile oysters in the spring could skew the results of the surveys. Regardless, sampling over one season of the year provides only a snapshot of Olympia oyster dynamics in Yaquina Bay.

Finally, the designation of 'absence' at a survey point is not entirely conclusive. There are several reasons that Olympia oysters may not have been detected:

1) The habitat is truly unsuitable;
2) The habitat is potentially suitable, but oysters have not settled there due to other factors, such as limited dispersal or a recent die-off due to freshwater influx or freezing temperatures; and/or
3) Oysters were present, but not detected by the survey team.

6.1.2.1 Intertidal Survey

The north and south sides of the Yaquina Bay shoreline are distinctive in a few ways that could have impacted the results of the survey. The north shoreline is closely bordered by

Yaquina Bay Road, a moderately trafficked, paved roadway stabilized by rocky rip-rap. Because of this, the profile of the shoreline from the water up to the road is relatively steep. This quick gain in elevation likely eliminated possible intertidal habitat for Olympia oysters along the north side of the shore. Additionally, much of the adjacent land is private property, which made access to sampling sites more difficult and occasionally impossible. In contrast, the south shoreline is less developed and maintains a more natural façade of shallowly sloping, rocky beaches, mud flats, and salt marshes. Fewer homes and businesses line the south shore. Access was gained by boat, rather than by car, which allowed for greater mobility between sites.

For the timed search component of the surveys (5-minute search at a randomly selected starting point), the area covered at each sampling site was not equal. The terrain inherently varied at each sampling site which impacted the rate at which the survey could be conducted. For example, extremely muddy locations or locations with a lot of large boulders made traversing through the sampling site more challenging and slowed the survey team down. Furthermore, more ground could be covered if little substrate was available for examination.

The methods of sampling and mode of travel varied between the north and south shoreline, resulting in more sampling sites along the south shoreline because the ease of boat travel allowed the survey team to add in 10 haphazard sampling sites. This resulted in more robust data along the south shoreline and greater exploration of available habitat for Olympia oysters in the intertidal zone.

Possible errors arising from the use of the hand-held Garmin GPSMAP 78sc receiver include the inherent inaccuracy associated with using a GPS receiver as well as user error. The Garmin model used for this study is reportedly accurate to 10 meters 95% of the time under “typical use”, but the accuracy can diminish up to 100 meters according to the user manual (Garmin 2013). This is significant when considering that Olympia oysters may be found in small, isolated patches. User error or bias may have arisen in selecting the specific location for recording GPS coordinates within a sampling site. An attempt was made to record the center of the sampling site, but because the size of the sampling area covered differed between sites, the center was difficult to discern. Additionally, latitude and longitude coordinates were recorded at each sample site by hand in a field notebook, using the GPS unit as a reference. It is possible that coordinates were recorded inaccurately.

Oyster populations in the intertidal zone may also be uniquely suited to those conditions due to the regular tidal inundation that occurs. Oysters in this zone close their shells when the tide is out and they are exposed to air. Because of these tidal fluctuations, the oysters here may be more prone to desiccation and survival of young oysters here is less likely.

6.1.2.2 Subtidal Survey

The subtidal survey was conducted by boat with the use of a Benthic Lander and GoPro camera to collect photos of the bottom of the estuary. Information on the presence or absence of oysters was determined by examining digital, underwater photos. Initially, error could arise from inability to identify Olympia oysters in the photos, especially if the photo was obscured by turbid water or some other physical obstruction like dense vegetation. Every attempt was made to lower the Benthic Lander directly downward off the side of the boat, but currents often caused it to drift.

Because of the nature of how the subtidal survey was conducted, the data points collected and displayed on the map only represent a very small spatial area at each location, approximately 0.5 meters squared. In contrast, the intertidal survey was able to assess a much larger area at each survey site and allowed for identification of appropriate habitat within the site. Consequently, the use of point data as a representation of presence and absence for both the intertidal and subtidal surveys could be misleading. One resolution for this issue is to conduct the subtidal survey using a dive team, but the expense, labor, and time commitment for such an approach is typically not realistic for a resource management agency. Commercial science divers can cost approximately \$5,000 - \$6,000 each day in Oregon (S. Rumrill pers. comm.).

It is important to note that the subtidal survey did reveal that little suitable substrate was available for Olympia oyster settlement. Much of the estuary bottom was identified as soft mud, which does not usually support Olympia oysters unless a hard substrate is present.

6.2 Analysis

The central research questions for this investigation are:

1) What is the predictive capacity of a Habitat Suitability Model (HSM) based on a review of natural history-based literature sources to determine the geospatial distribution of Olympia oysters in Yaquina Bay?
2) Are the environmental variables parameterized in the HSM appropriate for predicting Olympia oyster presence?

The results of the comparison between the field observations of Olympia oyster presence and the final HSM will be discussed to address these two questions in the following sections.

6.2.1 Predictive Capacity of the Habitat Suitability Model

The small number of presence data points (n = 20) was reduced to fewer points that overlapped with the final HSM (n = 11). In comparison to the Lewis et al. study (2019) which used 780 samples of bay-clams in Yaquina Bay, it was more difficult to assess the true predictive capacity of this HSM with few data points. Based on the 11 presence points available for analysis, the same number of presence points was found in the most suitable habitat compared to the least suitable habitat (n = 4). This could mean that the HSM should be modified or that the predictive capacity cannot be evaluated based on the small sample size. Suggestions for improvement and guidance for creating the next iteration of the HSM are outlined in Chapter 7 – Recommendations.

6.2.2 Habitat Parameters

The small number of presence data points available for analysis provided an important insight into how the habitat parameters performed in the HSM. Based on the results in Table 5, the presence point values and the 5-meter buffers aligned with the predicted most suitable habitat most frequently in the salinity parameter. This indicates that salinity may be a stronger predictor of Olympia oyster presence than substrate or elevation, and that polyhaline waters (> 18-30 ppt) may be most appropriate.

Outside of the scope of this project, experimental placement of adult and juvenile Olympia oysters in full-strength seawater (> 32 ppt) in aquaria tanks at the Hatfield Marine Science Center (located near the mouth of Yaquina Bay) has shown that the oysters are capable of survival and growth under this salinity regime (S. Rumrill pers. comm.). Despite this evidence that Olympia oysters are able to survive in full-strength seawater, their geospatial distribution was observed in Yaquina Bay to be restricted to salinity values less than 26 ppt. This discrepancy between the salinity range conducive to Olympia oyster survival observed *in situ* versus a controlled aquarium environment suggests that another phenomenon may be influencing their geospatial distribution. One hypothesis is that the short-term, planktonic veliger larvae of Olympia oysters that drift near the mouth of the estuary may be swept out into the coastal ocean on ebbing tidal currents. Planktonic larvae that are retained in the polyhaline regions of the mid-estuary are more likely to safely find suitable substrate for attachment before being pulled out to the sea by tides. Therefore, the retention time of estuarine waters within the tidal basin could be an important factor in determining the probability that larvae remain within the estuary or are swept out to sea. Salinity, which is closely associated with estuarine retention time, may serve as a proxy for the more complicated ecological process that ultimately established the spatial pattern of Olympia oysters in Yaquina Bay.

The substrate parameter provided little variation in suitability types based on the values found at the presence points and in the 5-meter buffers. What was surprising, however, was that 4 of the 18 presence points able to be evaluated against this parameter were identified in a substrate class deemed unsuitable (1.2.2.4 Sandy mud). This may signify that Olympia oysters are able to settle on hard substrates smaller than considered feasible in the assignment of suitability ranks, but also could support the tendency of the oysters to settle opportunistically; there may be a boulder or piece of wood in the middle of the sandy mud where an oyster settled. Overall, this could mean that the substrate class suitability ranks should be reevaluated, but also that the resolution of the substrate layer may not be appropriate for discerning Olympia oyster habitat.

For the elevation parameter, predicted ranges of suitability were nearly opposite the findings in the field surveys. Of the 11 presence points able to be analyzed, 6 were found in the least suitable habitat (high intertidal). This could indicate that the suitability ranks should be reassigned to consider the high intertidal as more suitable. Another consideration is that much of the literature describing the preference of Olympia oysters to settle in the subtidal region of Yaquina Bay is based on historic populations. Historic exploitation of the species as well as development in and around the estuary has altered the habitat drastically. Periodic maintenance dredging of parts of Yaquina Bay may remove substrate available for Olympia oyster settlement. Influxes of silt into the estuary during heavy rains could potentially smother juvenile oysters in the subtidal. Finally, the fact that 19 of the 20 presence points identified were found in the intertidal survey naturally skews the average elevation identified toward the intertidal zone.

7. Recommendations

Despite the small scale of this research, there are a couple Olympia oyster management implications for which this project can provide valuable preliminary data. First, by identifying important habitat parameters and refining environmental thresholds that impact Olympia oysters, the data from this project can serve as the first iteration for a more robust HSM. Second, this information can lead toward the drafting of a biotope under the CMECS protocol. Finally, updating the geospatial location data for Olympia oysters in Yaquina Bay can provide guidance for a biological monitoring protocol by identifying appropriate Index Sites. These management implications are discussed in the following sections.

7.1 Improvements to the Habitat Suitability Model

The most important improvement needed to properly evaluate the HSM created in this project is to gather additional data points. Resource managers must consider the time and cost-effectiveness of gathering field data in light of competing management priorities; however, improvements made to the model may mean that the model can be applied to other estuaries and bays in Oregon, limiting the need for extensive field surveying in those locations. Ideally, field sampling would occur in other seasons to capture a more comprehensive picture of the population.

Based on the findings of this project, the salinity parameter seems to be the most valuable and reliable input for the HSM. The classes within the elevation and substrate parameters should be reevaluated for their suitability. Another approach is to consider weighting the parameters differently based on their relative importance in determining Olympia oyster presence. In this project, all 3 parameters were considered of equal importance and therefore weighted equally. The next iteration of the HSM could give salinity a greater weight compared to elevation and substrate. Weights could also be applied based on the resolution of the raster layer inputs; higher resolution data could be considered of greater influence in determining presence than more generalized, lower resolution data.

The preliminary data from this project could also be fitted to the “framework to identify suitable bivalve habitat in estuaries” developed by Lewis et al. (2019). After discussion with authors of that study, there is interest in applying their model to Olympia oysters. Additional field observations are needed.

Shellfish biologists in Coos Bay have collected baseline data on Olympia oysters in the intertidal zone (S. Groth, S. Rumrill, pers. comm.). Surveys of the species take place on a decadal cycle; the most recent survey took place in 2018. With this current presence data and a more robust set of samples in Yaquina Bay, the HSM could be applied and compared between these estuaries. This could increase the robustness of the HSM and allow resource managers to properly evaluate whether the HSM can be applied to other estuaries in Oregon.

7.2 Draft Biotope

Biotopes are drafted using the descriptive language and classifications assigned in the CMECS framework. Each component of the abiotic and biotic environment is addressed as outlined in CMECS, providing greater detail to narrow in on the specific habitat envelope that describes the species of interest. From this project, some of the information required for the description of a biotope can be included in order to contribute to the improved characterization of Olympia oysters across their geographic range. This information supporting a draft biotope was guided by descriptions available in the Appendices of the CMECS protocol document (2012) and uses the standardized terminology coined in the framework. It aims to characterize the Olympia oyster population observed in the intertidal survey.

Biotope: Olympia oysters (*Ostrea lurida*) in Intertidal Zone (Tidal Riverine Coastal)
Biogeographic Component:
Realm: Temperate Northern Pacific
Province: Cold Temperate Northeast Pacific
Ecoregion: Oregon, Washington, Vancouver Coast and Shelf

Aquatic Setting:
System: Estuarine
Subsystem: Tidal Riverine Coastal
Zone: Intertidal, Subtidal

Water Column Component:
Water Column Layer: Estuarine Tidal Riverine Coastal Surface Layer and Upper Water Column
Salinity Regime: Mesohaline Water, Lower Polyhaline Water

Geoform Component:
Tectonic Setting: Convergent Active Continental Margin
Physiographic Setting: Riverine Estuary

Substrate Component:
Substrate Origin: Geologic Substrate
Substrate Class: Unconsolidated Mineral Substrate

7.3 Identification of Index Sites for Biological Monitoring

In addition to the evaluation of an HSM for Olympia oysters, this project also generated geospatial information to develop an updated baseline of the distribution of the population in Yaquina Bay. The last survey conducted of the entire bay was completed in 1941 (Dimick et al., Figure 26). In the time since, there has not been an official inventory of the geographic distribution of Olympia oysters in Yaquina Bay. Oregon Department of Fish and Wildlife recognized the need to fill this important data gap in order to improve management and recovery efforts for Olympia oysters, as well as serve as the first step in the development of a biological monitoring protocol.

Two of the objectives of the project focused on creating an updated map of the geographic extent of Olympia oysters in Yaquina Bay and providing recommendations for implementing a long-term biological monitoring program. Many resource management agencies acknowledge the importance of biological monitoring, especially for species like Olympia oysters with reduced wild populations, because understanding their condition can improve decision-making regarding their use (Karr and Chu 1997). Building a comprehensive picture of their geospatial distribution can help predict impacts to the population based on land-use changes and estimate population enhancement potential.

The establishment of the contemporary, geographic distribution of Olympia oysters in this project is the first, critical, data-gathering step in developing Index Sites. The use of Index Sites is one monitoring technique employed by shellfish biologists in which locations that are identified as representative of the larger population are assessed to determine relative abundance of Olympia oysters (DFO 2009). These sites are selected following a comprehensive survey of the geographic area, then used to collect Olympia oyster abundance data at regular time intervals (Norgard et al. 2010). Index sites are often selected using a set of pre-determined criteria, which ideally are easy to measure and interpret (Karr and Chu 1997). This approach allows Olympia oysters to be tracked into the future without repeated, extensive, and time-consuming field surveys (DFO 2009). A monitoring protocol using Index Sites to determine relative abundance of Olympia oysters has been established in the Coos Bay estuary by ODFW staff; this approach can be assessed for its applicability to Yaquina Bay. Since population abundance was not assessed in this project, selection of appropriate Index Sites provides the guidance for gathering abundance information in the future.

Index Sites are most appropriate for the intertidal zone due to easier access in this area. Several locations were identified through this project during the intertidal field survey that could be possible candidates for Index Sites. These locations are shown in Figure 27. These locations were selected based on the relative homogeneity of oyster abundance and the ability to access the location repeatedly in the future.

In the Coos Bay estuary, ODFW staff members monitor the Olympia oyster population on 10-year time intervals. Based on conversation with ODFW Shellfish Biologist Scott Groth, this monitoring interval is too infrequent to evaluate the health of the population; however, the Olympia oyster is not a state-listed Threatened or Endangered species in Oregon, nor is it allowed to be recreationally harvested (ODFW 2018), so it becomes a lower priority for monitoring. In British Columbia, shellfish biologists have used 5-year time intervals for assessing changes in Olympia oysters relative population abundances (DFO 2009). Based on the results of this project, a 5-year monitoring interval is recommended for Yaquina Bay.

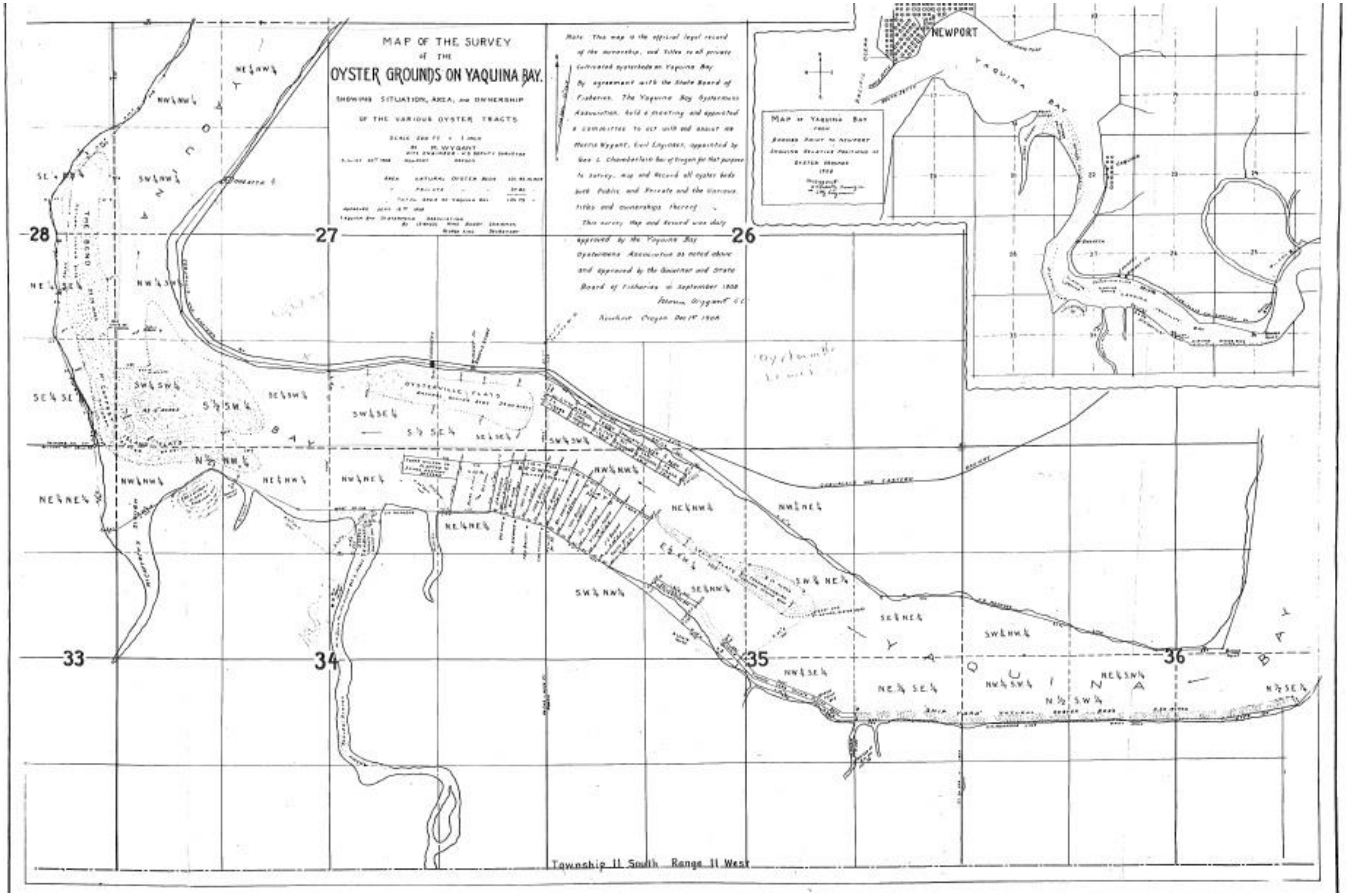


Figure 26. Survey of Olympia oysters in Yaquina Bay, 1941 (Dimick et al.).

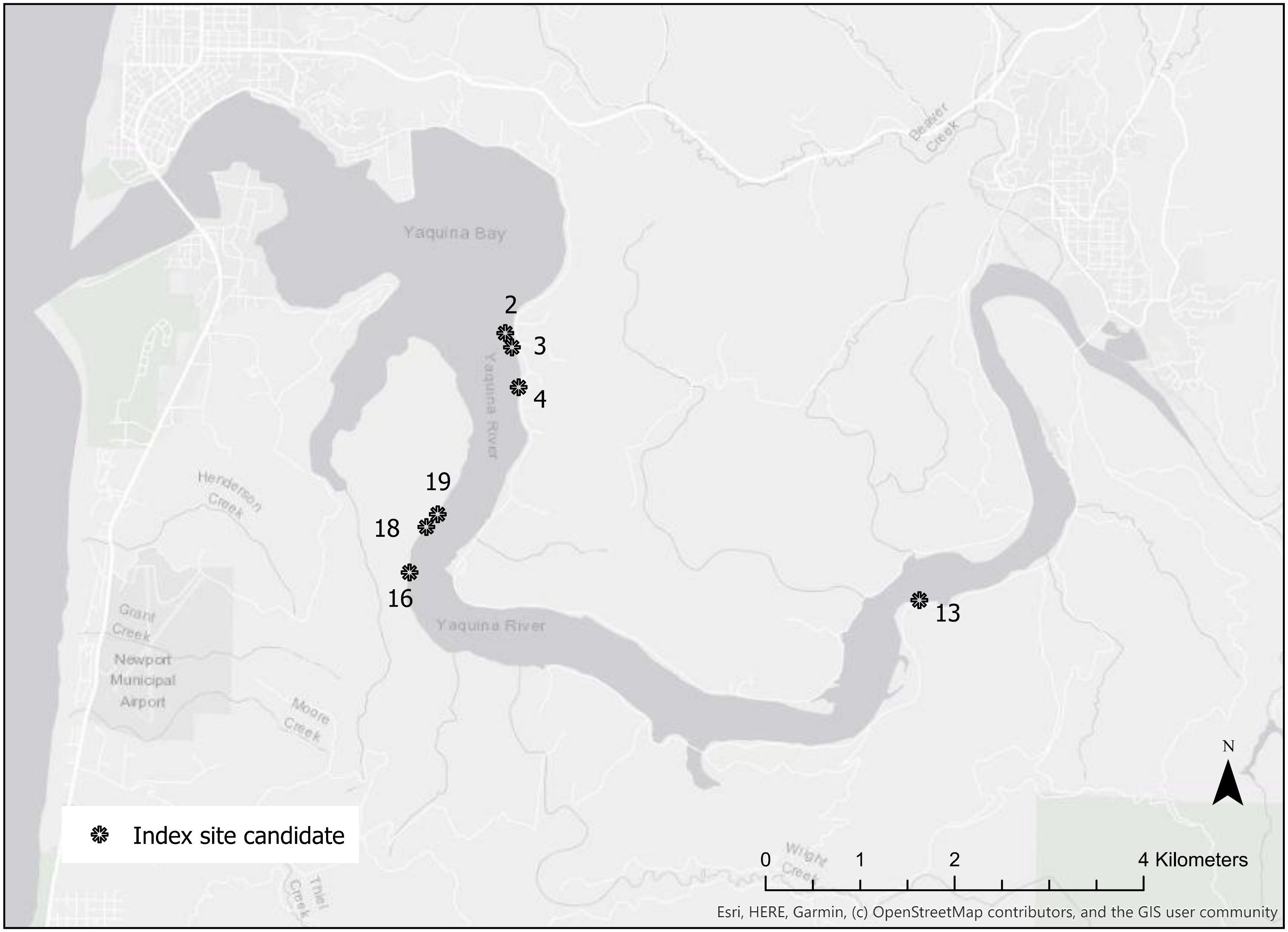


Figure 27. Presence points located in 2019 survey that were identified as candidates for Index Site monitoring.

8. Conclusion

The prospect of applying basic environmental variable thresholds to predict the geospatial distribution of a species without expending significant time and expense to thoroughly inventory the species throughout its range, has led many resource managers to consider the use of HSMs, biotopes, and other geospatially-based tools. These tools provide valuable information about the relationship of a species to its environment, but need careful attention and testing to be able to accurately make predictions about the suitability of habitat. This study provided a first iteration of an HSM for Olympia oysters in Yaquina Bay. More data points, refinement of the environmental thresholds, and consideration of additional habitat parameters are all lessons learned that can readily be applied to the next iteration of this model.

Despite the inconclusive results of the predictive capacity of the HSM, an updated baseline of Olympia oyster locations in Yaquina Bay was a priority resource needed for the ODFW Shellfish Program and this study was able to contribute current distribution data. This geospatial information can be readily utilized by Oregon Department of Fish and Wildlife to begin monitoring this species in Yaquina Bay. This data also supports the development of draft biotope when jointly evaluated with other research focused on the ecological niche that Olympia oysters occupy in Oregon. Future research potential lies in applying the HSM approach used by Lewis et al. to create a more robust and statistically valid habitat suitability map.

Appendix A. Text Excerpts from the Literature Review Tables for Salinity, Substrate, and Elevation

Salinity Literature Review Table

SOURCE	TEXT EXCERPT
Baker 1995	"although *O. lurida* is capable of living in full seawater, its distribution throughout the majority of its range is restricted to isolated bays and estuaries" "moderately euryhaline, 80% survival at 15 ppt for 49 days"
Fasten 1931	[referring to Yaquina Bay] "the best regions have been found to be located between the ranges of 1.012 and 1.020 [specific gravity]" about 15.9ppt - 26.5 ppt (conversion to ppt using Salinity Conversion Calculator at https://www.hamzasreef.com/Contents/Calculators/SalinityConversion.php)
Gray et al. 2019	[referring to Yaquina Bay] "the historic range of Olympia oyster beds and current location of Pacific oyster aquaculture in the estuary have primarily been constrained between polyhaline (salinity >18-30 ppt) and mesohaline (salinity >5-18 ppt) zones"
Groth and Rumrill 2009	[referring to Yaquina Bay] "most productive commercial harvests of native oysters were limited to a three-mile stretch of polyhaline (salinity >18-30) and mesohaline (salinity >5-18) waters"
Pritchard et al. 2015 ('Recent Advances')	"euryhaline" "does not appear to do well at extremely low salinities. Oysters may do well at salinities above 25, can tolerate brief exposure to lower salinities… at a salinity of 15 for 5 weeks experiences 83% survival, oysters survived salinities of 5 or lower for 2-3 weeks before suffering 100% mortality" "appears to be more tolerant of full-strength seawater than of freshwater"
Pritchard et al. 2015 ('Larval Supply and Recruitment')	"low salinity decreases settlement and recruitment success" "spatial distribution of adults is generally limited to areas where salinities are above 20 in Coos Bay" "up to 100% of adults died after 49 days of exposure to salinities <10, 17% of adults died after 49 days at a salinity of 15"

Substrate Literature Review Table

SOURCE	**TEXT EXCERPT**
Baker 1995	"apparently requires hard substrate to settle on, but readily settles on very small pieces of hard substrate. This allows species to form loose reefs in soft mud areas” “fairly large populations can also occur on rocky reefs, individuals or clusters are common on rocks” [referring to San Francisco Bay] “a common fouling organism on pilings and floating piers."
Couch and Hassler 1989	"the preferred substrate is old oyster shells, but rocks, wood, metal, or any other hard material may be used as a setting surface" "may attach to the underside of rocks higher in the intertidal zone where the bottom is gravel or rock"
Fasten 1931	"the objects to which they attach themselves are known as 'cultch', this may consist of stone, old shells, bits of wood, bark -- in fact, any object which affords a solid surface for attachment"
Gillespie 2009	[referring to British Columbia] "found on mud-gravel tidal flats, in splash pools, near freshwater seepage, in tidal channels, bays, and sounds or attached to pilings or the underside of floats" "Once the larvae have grown and are sufficiently developed, they settle and attach themselves to a hard substrate"
Groth and Rumrill 2009	[referring to Coos Bay] "hard surfaces (shell rubble, gravel, rip-rap, and rock) that are the preferred substratum for settlement of *O. lurida*" "our field observations indicate that the availability of suitable substratum is likely a limiting factor that hinders recovery in Coos Bay"
Wasson et al. 2014	[referring to California] "availability of hard substrate in the low intertidal and shallow subtidal zone is a requirement for Olympia oysters, and in areas with deep mud, oysters only survive if large hard substrates are available"
White et al. 2009	"completion of the life cycle requires clean shell in suitable habitats for larval attachment" "oysters also settle on other hard substrates such as glass plates, rock, and concrete, but these are not typically available in soft sediment environments"

Elevation Literature Review Table

SOURCE	**TEXT EXCERPT**
Baker 1995	"it is present in the main shipping channel, at a mean depth of over 10m, in Isthmus Slough of Coos Bay, OR and the main beds in Yaquina Bay, OR were also in the main shipping channel" "this species prefers shallow subtidal areas or large tide pools, but individuals can be found at least 2m above mean low water in the intertidal as well"
Couch and Hassler 1989	"found at depths 0m to 71m" "reefs are formed in the subtidal zone"
Gillespie 2009	"primarily found in the lower intertidal and subtidal zones of estuaries and saltwater lagoons" "they have been reported as common from the intertidal zone to 10-m depths, and occasionally to 50m"
Groth and Rumrill 2009	"living beds of oysters occurred with the lower intertidal and subtidal regions of the estuaries"
Pritchard et al. 2015 ('Recent Advances')	"found both intertidally and in shallow, subtidal, euryhaline waters" "reported as deep as 71m"
White et al. 2009	"the species is relatively sensitive to… desiccation stress and was naturally found primarily in accumulations of shell below mean lower low water" "four characteristics distinguish the species from most other commercial oysters: subtidal habitat…"

Appendix B. Results of the Subtidal Survey

Site #	Oysters?	Substrate	Photo #s	Notes
1	No	Mud	20760-20765	Small fish (sculpin)
2	No	Mud/vegetation	40770-40776	Eelgrass
3	No	Mud	50778-50784	
4	No	Mud	60787-60794	Crabs
5	No	Mud	70796-70803	Some crab carapace and shell debris (not oyster)
6	No	Mud	80806-80813	
7	No	Mud	90815-90820	Sculpin
8	No	Mud	100823-100831	Very little shell debris
9	No	Mud	110834-110840	One photo of bottom, then camera housing flipped on its side
10	No	Mud	120843-120852	
11	No	Unsure	130854-130860	Algae, string-like small piles of mud
12	No	Mud	140862-140868	Some clam shell pieces
13	No	Mud	190942-190947	
14	Yes	Mud/oyster shells	200950-200955	Mostly Pacific oyster shells, but at least one young Oly, maybe more
15	No	Mud	220969-220976	
16	No	Mud	230979-230983	
17	No	Mud	240986-240992	
18	No	Mud	250994-250999	One small piece of Pacific oyster shell or small rock, lots of small strings of mud like in site #11
19	No	Mud	261002-261009	Small holes in mud
20	No	Mud	271011-271018	Small holes in mud
21	No	Mud	281020-281028	One mussel or clam shell
22	No	Mud	291030-291037	One half clam shell, small holes in mud
23	No	Mud	301039-301044	
24	No	Mud	311047-311054	Some wood debris, small crab
25	No	Rocky cobble	321056-321062	

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