

Opportunities for Freshwater Mussel Conservation in the Pacific Northwest and Intermountain West in a Changing Climate

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A floater mussel in rapidly drying habitat in the Pacific Northwest. Photo credit: Xerces Society/Laura McMullen

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EXECUTIVE SUMMARY

Freshwater mussels are one of the most endangered groups of species worldwide, with more than 10% of North America's mussels already extinct. With declines in mussel populations, freshwater ecosystems also lose the substantial contributions mussels provide to the ecological health of aquatic communities and habitats. Remaining mussel populations are at risk from multiple threats, including habitat destruction, poor water quality, and invasive species. Yet, climate change threatens freshwater mussels at an unprecedented scale. Because climate change impacts have the potential to simultaneously influence water quantity, water quality, host fish behavior and health, and mussel behavior and health, identifying and conserving climate refuges for freshwater mussels is becoming ever more important for mussel conservation efforts.

Recent advances in climate models for freshwater ecosystems in the western U.S. have provided a starting point for evaluating the potential for rivers and streams to serve as climate refugia for aquatic species. Using mussel distribution data for western North American mussel species (Xerces/CTUIR 2018), data developed for the Northwest Stream Temperature Database project (Chandler et al. 2016; Isaak et al. 2016, 2017), we ranked HUC8 watersheds in the Pacific Northwest and Intermountain West for their potential to serve as climate refugia. We also conducted a step-down analysis for the Willamette Basin in northwestern Oregon, a priority basin for mussel conservation in Oregon, by ranking HUC12 watersheds for their potential to serve as climate refugia. We supplemented our assessments of watersheds with datasets describing current aquatic resource management (e.g. known or potential barriers to fish passage, surface water points of diversion (PODs), and permitted discharge sites or other pollutant points of interest, such as superfund sites), and with locations of conservation and restoration priorities westwide and locally within the Willamette Basin in northwestern Oregon. These additional datasets place mussel conservation in the context of existing conditions, as well as priority geographies for conservation and restoration in the western U.S.

Our analysis identified 57 HUC8 watersheds with the highest potential to provide climate refugia for a priority species (the western ridged mussel) or a diverse assemblage of mussels (Figure A). These watersheds are distributed across states in the Pacific Northwest and Intermountain West, though basins with the greatest number of potential climate refugia include the Klamath and the Upper Columbia, followed by the Salmon and Middle Snake-Boise. An additional 14 watersheds were found to provide cooler future conditions; however, these watersheds did not contain any observations of freshwater mussels. These watersheds are recommended for additional surveys to determine whether mussels occur. Indeed, additional surveys for freshwater mussel populations can and should be used to further refine potential climate refugia, particularly where abundance estimates are also available.

It is worth noting, however, that several watersheds identified as potential climate refugia are also sites with reported mussel bed die-offs, which are instances where large numbers of mussels, possibly an entire mussel bed dies suddenly. Watersheds where die-offs have been reported include the Middle Fork John Day, Lower Crooked, Lower Chehalis, and the Lower Owyhee. Until these die-offs are further investigated and possible causes are identified, including the potential role of higher water temperatures, the potential for these watersheds to serve as climate refuges is questionable.

In our step-down analysis of the Willamette Basin in northwestern Oregon (Figure B), we identified 24 HUC12 watersheds with the highest potential to provide climate refugia for a priority species (the western ridged mussel) or a diverse assemblage of mussels. These watersheds are distributed across 10 HUC8 watersheds in the Willamette, though basins with the greatest number of potential climate refugia include the Middle Fork Willamette, Clackamas, McKenzie, and Upper Willamette. Many more watersheds ranked higher for future climate condition but had no mussel records. The potential for many of these watersheds to provide mussel habitat may be inherently low, particularly at the highest elevations of the western Cascades. However, recent surveys targeting the Willamette have increased the number of watersheds from which mussels are reported by 30%, indicating the basin has been under sampled or mussels have been underreported in the past. Therefore, we recommend additional surveys in the basin to further improve our understanding of mussel distribution.

This project provides an important snapshot of current conditions and understanding of mussel distribution, as well as predicted future conditions. Because we considered future climate in terms of fish-based temperature thresholds, this work is directly applicable to a wider range of aquatic species of conservation concern. As such, the priority areas identified in this analysis are intended to support collaboration between mussel conservation efforts and the restoration community in places providing the greatest benefit, not just for mussels, but also for multiple species and ecosystem. Although priority areas will continue to evolve as freshwater mussel research and conservation efforts advance, these priority areas can be used to guide next steps in western mussel conservation. In addition to identifying priority watersheds for freshwater mussels, this work also highlights:

- the need for additional research investigating western mussel species' responses increased water temperature, altered timing of temperatures and flows, and other conditions that will be experienced under climate change, as well as the role that aquatic resource management has on ecosystem services provided by mussels,
- the need for increased survey and reporting efforts for western freshwater mussels,
- the potential to identify areas within watersheds providing climate refuges where specific stressors, such as barriers to aquatic connectivity, or restoration activities could be targeted to the benefit of fish as well as mussels, and
- the need to conserve existing mussel populations to ensure resiliency of mussels and the aquatic species and habitats they support under a changing climate.

Additional information about freshwater mussel climate refugia, the Western Freshwater Mussel Database, and mussel-friendly restoration practices is available through the Xerces Society at www.xerces.org.

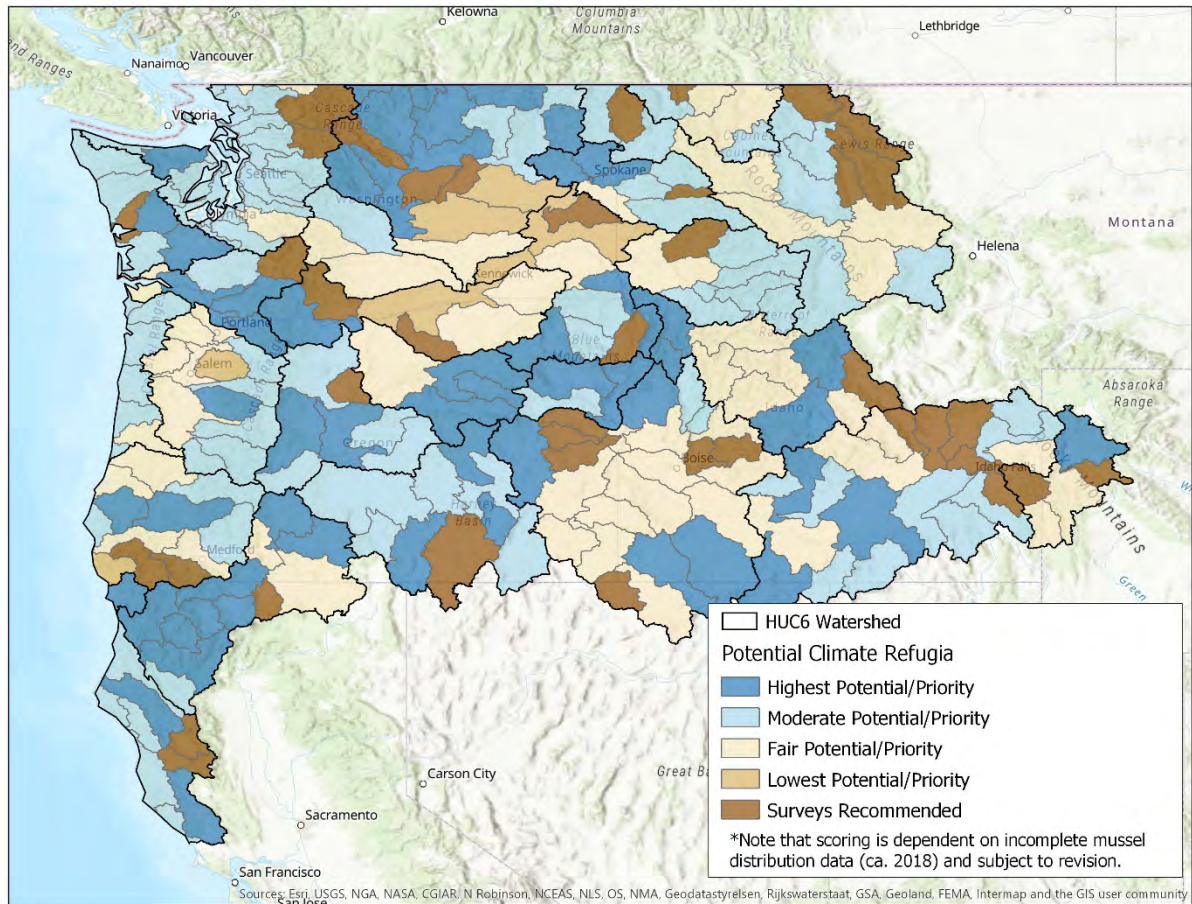


Figure A. Watersheds ranked for their potential to provide climate refugia for mussels, based on reported observations of mussel species (Xerces/CTUIR 2018) and predictions of August mean temperature in 2080 ($^{\circ}\text{C}$; Chandler et al. 2016/NorWeST) summarized to HUC8 watershed.

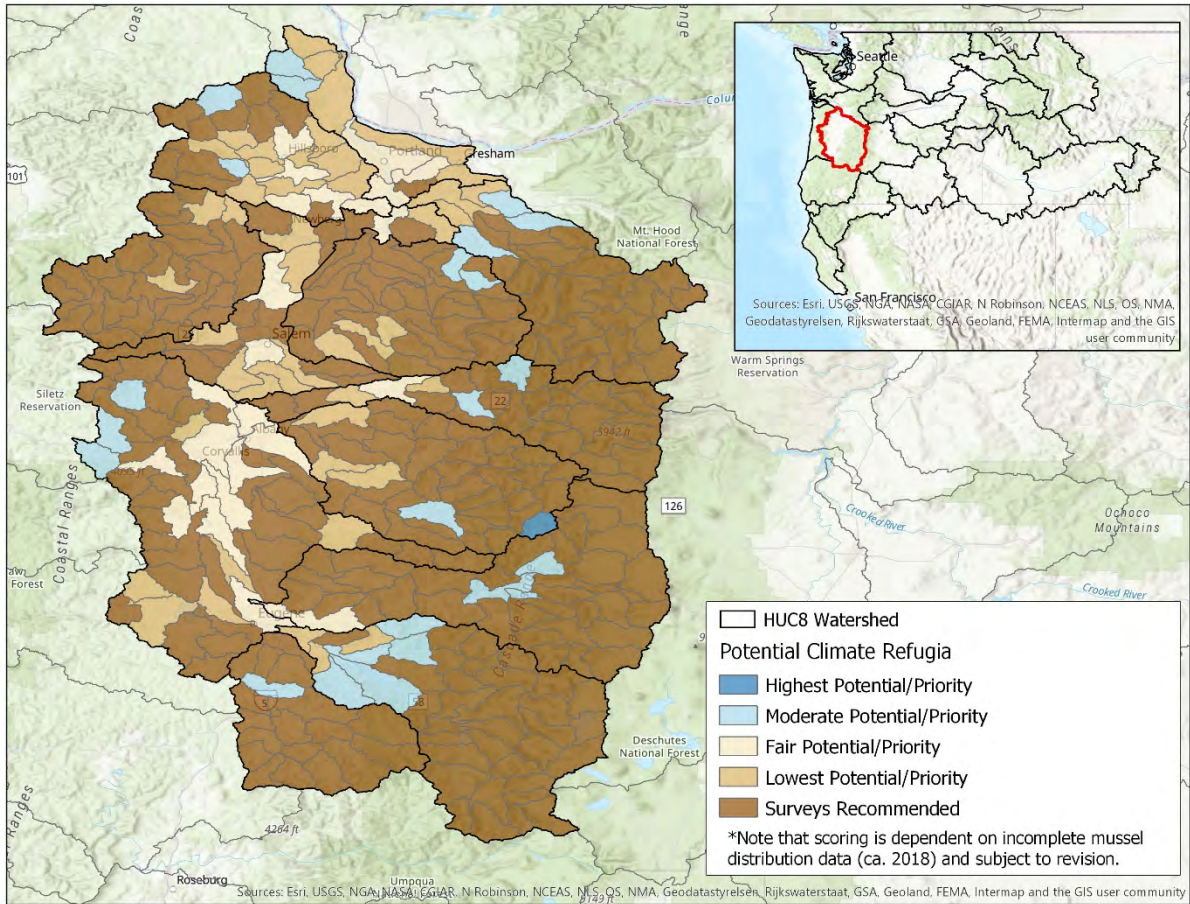


Figure B. Watersheds ranked for their potential to provide climate refugia for mussels, based on reported observations of mussel species (Xerces/CTUIR 2018) and predictions of August mean temperature in 2080 ($^{\circ}\text{C}$; Chandler et al. 2016/NorWeST) summarized to HUC12 watersheds in the Willamette Basin.

INTRODUCTION

Freshwater Mussels of the Western U.S.

Aquatic ecosystems in the western U.S. support a diverse array of native species, including many endemic and rare species and economically and culturally important fish stocks. These systems have also experienced significant human pressure. An estimated 49% of all western U.S. river miles have been modified, 21% of rivers are not considered not to be “free-flowing,” and 42% of rivers flow through altered floodplain landscapes. As a result of straightening and channelization of rivers, the average length of western U.S. rivers is estimated to have been reduced by 84% (Harrison-Atlas et al. 2017).

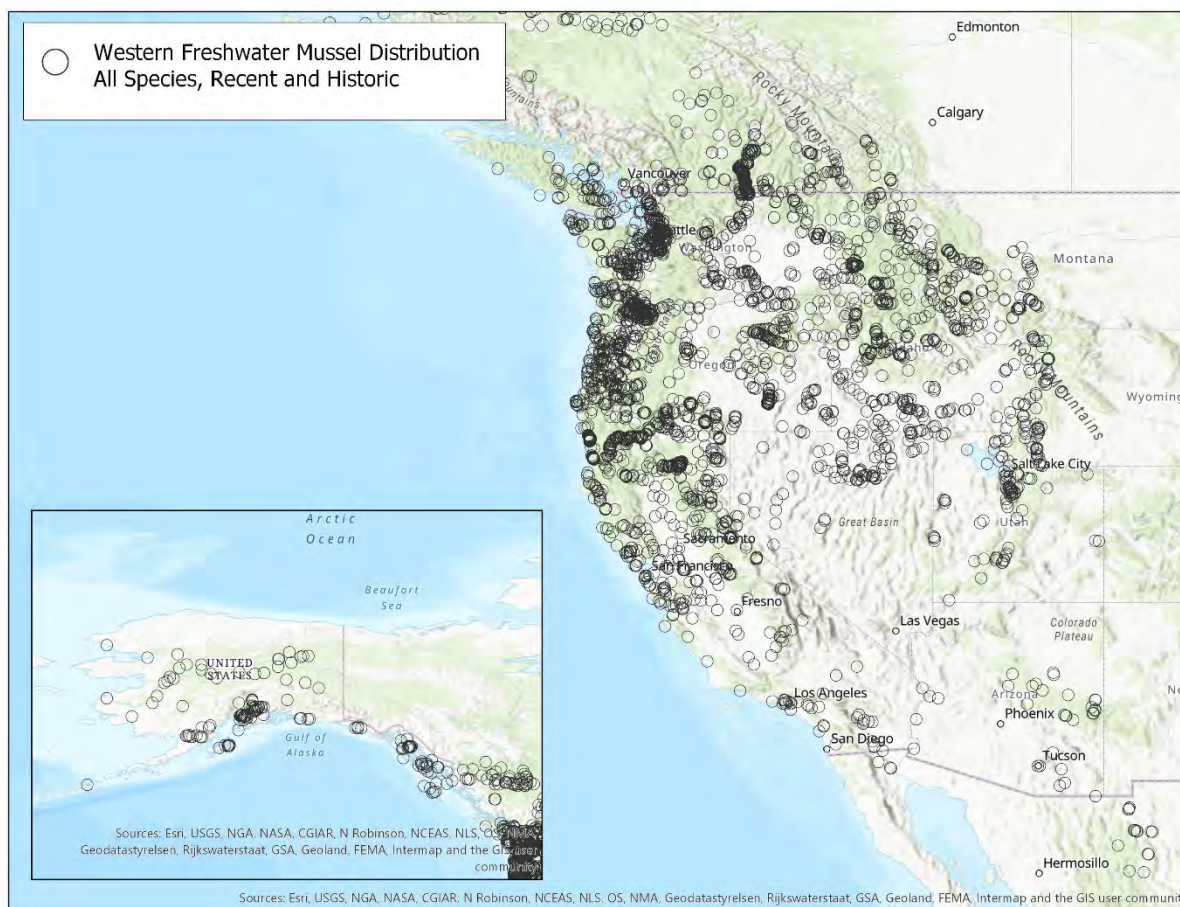


Figure 1. Occurrence of freshwater mussels in the western US. Data from the Western Freshwater Mussel Database (Xerces/CTUIR 2018).

Native species of freshwater mussels (*Bivalvia*: *Unionoida*) inhabit many of the fish-bearing aquatic ecosystems in the western U.S. (Figure 1). These benthic mollusks are characterized by their sedentary nature, comparatively long lifespans (10-100+ years), and requirement of a host fish for reproduction. Freshwater mussels are ecologically and culturally important, yet like many native aquatic species, they too have been impacted by the loss and degradation of aquatic ecosystems. Recent research by Blevins et al. (2017a) evaluated the extinction risk of four groups (species or clades) of western freshwater mussels using data from the Western Freshwater Mussel Database (Xerces/CTUIR) and methods developed by the International Union for Conservation of Nature (IUCN) Red List.

Of the western species of mussels evaluated [the winged floater clade (*Anodonta nuttalliana* and *A. californiensis*), the Oregon floater clade (*A. oregonensis* and *A. kennerlyi*), the western ridged mussel (*Gonidea angulata*), and the western pearlshell (*Margaritifera falcata*)], two mussel groups were assigned an IUCN Red List status of “Vulnerable” (western ridged mussel and the winged floater clade), while one was assigned a status of “Near Threatened” (western pearlshell), and one “Least Concern” (Oregon floater clade). Impacts to mussel populations are also important to other native species and human communities, which benefit from the ecosystem services mussels provide, such as increasing the complexity of benthic stream habitat, serving as food for other wildlife, and filtering water (Vaughn et al. 2017).

Climate Change and Freshwater Mussels

Notably, western mussel populations are disappearing from areas that are becoming increasingly arid—including most of southern California, Arizona, Utah, and Nevada—where water temperatures have risen and water quantity has diminished in recent years. Multiple causes have been implicated in these declines including impacts from both a changing climate and water management activities. Less water is available, return flows (water used and then returned to the environment) and water from reservoirs flowing downstream can be warmer, fish barriers like dams reduce connectivity (and resiliency) of mussel populations, higher flows from increased storm events or changes in snowpack can alter habitat and affect food resources. Warmer waters also negatively affect the fish species on which mussels depend for reproduction and can lead to thermal stress in mussels.

Climate change will ultimately result in changing precipitation patterns, increased severity and variability of events such as floods or droughts, and increased air and water temperatures (Bates et al. 2008; Figure 2). In the Pacific Northwest, this will translate to altered flow regimes (Tohver et al. 2014; DeBano et al. 2016). Where climate change reduces snowpack, less precipitation will be stored and late season flows will diminish. Decreased precipitation during summer months and increased precipitation in other months will result in not only greater intensity of low flows but also increases in flood risk (Tohver et al. 2014). Additionally, impacts from warming temperatures and changing patterns of precipitation will be modified at the local level by management of aquatic ecosystems, water resources, and infrastructure, including both existing and future conditions. For example, dams can affect the storage and release of flows, barriers to fish passage can eliminate access of both host fish and mussels to upstream habitats that may provide cooler water temperatures, and water diversions can limit the quantity and flow rate of streams and river (including causing habitat to completely dry, which is lethal to freshwater mussels). Water quality can be further limited by temperature and concentration of pollutants.

Research also suggests that higher water temperatures and/or low flow can

- result in death of individual mussels or loss of populations (Haag and Warren 2008).
- impact the ability of mussels to burrow, a critical adaptation to avoid emersion (becoming exposed to the air when water is low), to escape predation, or avoid fast flows that can wash them into unsuitable habitat (Archambault et al. 2013).
- affect the critical interaction for mussel reproduction via host fish, especially among rare species or those with a limited distribution (Terui et al. 2014; Archambault et al. 2018).



Figure 2. Western freshwater mussel populations can be directly impacted by drying habitat and higher temperatures, both of which are expected to occur in western North America under a changing climate. At left, a lakebed with an abundant mussel population dried during the summer of 2015, resulting in a large mussel kill (image at right). Photo credit: Al Smith.

As a result, a changing climate is expected to exacerbate many of the challenges mussel populations already face, and in 2016, the Freshwater Mollusk Conservation Society published a national strategy, specifically recognizing the importance of working to “identify and conserve habitats that will be resilient to changing climates.” Unfortunately, it is challenging to anticipate the specific effects of future higher water temperatures for freshwater mussels of the western North America. Research on eastern North American species of freshwater mussels is also limited, and indeed the upper thermal limits for most species of freshwater mussels is unknown (Newton et al. 2013; Figure 3). Additionally, mussel species can differ in their ability to withstand different water temperatures (Spooner and Vaughn 2008), although research suggests that elsewhere in North America water temperatures may already be at or exceed the threshold of tolerance for at least some species of freshwater mussels (Pandolfo et al. 2010).

Research has also shown that freshwater mussels provide important ecosystem services, including nutrient cycling, fish habitat improvement, biofiltration, and food provisioning (Vaughn 2017). Yet the functional role that mussels play in aquatic ecosystems can be modified by increasing water temperatures, both as a result of impacts to mussel physiological condition and ultimately shifts in community composition (Spooner and Vaughn 2008). Local aquatic resource management can further modify the effects of a changing climate on mussel community composition, potentially reducing the extent to which mussels are able to provide ecosystem services (Galbraith et al. 2010). As a result, finding ways to conserve mussel species and diverse assemblages of mussels is also important for protection of the benefits mussels provide to aquatic ecosystems and ultimately the resiliency of aquatic communities and ecosystems in a changing climate.

Assessment of Impacts and Opportunities

Because western watersheds vary considerably in climatic conditions, especially the role of snowpack in water availability, as well as in the use and management of aquatic resources, it is likely that some watersheds and waterbodies will provide better or worse habitat under a changing climate. Research in this vein has already improved our understanding of key activities and areas to make PNW salmon stocks more resilient in the face of climate change. Freshwater mussels could also benefit from conservation and restoration efforts in these areas, but it is unclear how existing and planned activities will contribute to mussel conservation or resiliency, or whether these activities are occurring in locations also important to freshwater mussels. In addition, because mussels are often overlooked in water

bodies, actions taken to restore fish habitat can actually sacrifice mussel populations. Losses of mussel beds during restoration projects will likely continue unless mussels are specifically considered in restoration planning.

To better understand the most important areas for mussels in the future, we sought to evaluate the potential for watersheds to provide climate refugia for western freshwater mussels. An assessment of impacts and opportunities in a changing climate is particularly relevant to the Xerces Society's work on freshwater mussel conservation. The Society's mission is to protect the natural world by conserving invertebrates and their habitat. By recognizing that the need for invertebrate conservation action is great, but time and resources are limited, we work to achieve a conservation impact by applying a strategic approach, including development of priorities to ensure that we are targeting the most imperiled species in places where the potential benefit or impact of our work is highest. Central to this is working to make ecosystems more resilient under a changing climate.

Thus, we set out to provide a template for mussel conservation opportunities under future climate change scenarios. To do so, we conducted an assessment to compare existing populations of mussel species in watersheds found in the Pacific Northwest/Intermountain West with datasets describing predictions of future climate, existing conditions (i.e., datasets documenting potential or known barriers to aquatic connectivity, potential impacts to water quality through point source or wastewater outfalls, potential for impacts from water use through points of diversion), and locations of conservation and restoration priorities (opportunities). We compared this with information on past and present freshwater mussel distribution data to identify geographies where development of collaborative opportunities with the restoration and land and water management communities has the greatest potential to achieve goals for freshwater mussel conservation under a changing climate. Criteria that have also helped to form our geographic priorities include selecting waterbodies that are part of the current and historic distribution of western ridged mussel, the most imperiled species of western freshwater mussel (Blevins et al. 2017a), and specifically watersheds identified as climate refugia for the species. In addition, watersheds that could serve as climate refuges for multiple species of freshwater mussels simultaneously are also of high priority.

Importantly, working within key geographies can help ensure that restoration and conservation priorities in these areas will have a greater potential for achieving multi-species benefits that will extend to mussels. In particular, the data products from this work can be used to improve outreach and analysis to support freshwater mussel conservation. Similarly, this work has helped to identify steps that could be taken to improve the resiliency of western freshwater mussel populations and thus freshwater ecosystems under future climate conditions.



Figure 3. Research to evaluate the upper thermal limits of western freshwater mussels is lacking, despite the need to better understand climate impacts. Photo credit: Xerces Society/Emilie Blevins.

METHODS

Study Area

Our study area is focused on a subset of watersheds in the Pacific Northwest/Intermountain West states of Oregon, Washington, and Idaho, as well as portions of Wyoming, Montana, California, and Nevada. Several major drainage basins comprise this region, including the Columbia River (as well as the Snake River and its tributaries), the Klamath River, Puget Sound, coastal watersheds in Washington, Oregon, and northern California, and the Oregon Closed basins (Figure 4). This study area is of interest because species of western freshwater mussels (western pearlshell, western ridged mussel, and several species of floaters) have historically been found throughout the region. Additionally, work by Blevins et al. (2017a) indicates that these states are relatively important for future resiliency of populations as compared with other regions, which have already experienced rather dramatic declines in freshwater mussels. Additionally, aquatic research and conservation efforts are coordinated across state boundaries, with the region sharing multiple endangered or threatened fish fauna and management concerns, such as the potential for introduction of nonindigenous aquatic species (i.e., zebra and quagga mussels).

Within this region, we also summarized information for northwestern Oregon, specifically including the Willamette Basin. The Willamette Basin includes watersheds with some of the greatest genetic diversity in freshwater mussels in the western U.S. (Mock et al. 2013). Within Northwestern Oregon, and specifically the Willamette Basin, there has been a major investment of conservation dollars intended to protect and restore aquatic habitat for declining native fish, including initiatives such as the Oregon Watershed Enhancement Board's Focused Investment Partnership (OWEB FIP), Meyer Memorial Trust's Willamette River Initiative (WRI), the Portland General Electric Habitat Support Fund (administered by The Nature Conservancy of Oregon), and others.

We chose to assess climate impacts and opportunities at multiple hierarchical levels using the USGS watershed boundary dataset (USGS et al. 2015) because fisheries and aquatic resources are often managed at a basin or watershed level. Because of data limitations associated with historical freshwater mussel data (see next section), we summarized all project data to the HUC8 watershed level (depicted as blue outlines in Figure 4). For a higher-level regional snapshot, we also summarize information at the HUC6 watershed level. With our additional focus on northwestern Oregon, including the Willamette Basin, we included a separate analysis at the finer-scale HUC12 watershed level. We were not able to include portions of watersheds that span the U.S./Canada border in this analysis because the climate dataset was limited to within the U.S. boundary. We also excluded several watersheds that fall within the states of Oregon and Idaho where rivers drained to larger basins that fall outside of the two states.



Figure 4. Study area of this project, depicting the USGS National Hydrography Dataset's watershed boundary dataset (HUC8 and HUC6-level watersheds).

Data Summarization and Visualization

A full list of datasets described below can be found in the Appendix.

Freshwater Mussel Data

We queried the Western Freshwater Mussel Database (Xerces/CTUIR 2018) for occurrence records of western species of freshwater mussels within the study area. This database, a joint project between the

Xerces Society and the Confederated Tribes of the Umatilla Indian Reservation, is comprised of thousands of freshwater mussel collection or observation records resulting from information provided by numerous museums, researchers, citizen scientists, agencies, and published or gray literature (full list of contributors at: <https://xerces.org/western-freshwater-mussel-database-contributors/>). Records in the database vary greatly in time period (historic vs. recent), observation (live animal or shells), and location specificity (state, county, city, waterbody, TRS, GPS coordinates). Based on the analysis by Blevins et al. (2017a), we note that care should be taken with interpretation of current mussel population occurrence within watersheds. Instead, mussel data summarized to watersheds for the purpose of this study should be considered as having potential to support mussel populations based on historic or recent distribution. The HUC8 watershed level of summary was appropriate for many of the non-specific historic records (i.e., a record included only a stream name or general area). Records in the database that could not be attributed at least to the HUC8 level were excluded from this analysis. For the step-down Willamette Basin analysis, we summarized data at the HUC6, HUC8, and HUC12 levels as possible.

Climate Data

We conducted our analysis of climate impacts using the climate scenarios SRES A1B/RCP 6 for the 2040s and 2080s as developed by the Intergovernmental Panel on Climate Change (IPCC 2007) and used in spatial datasets developed for the western U.S., specifically the Northwest Stream Temperature Database (Isaak et al. 2016, 2017; see below). This model is considered a “medium” emission scenario, in which economic growth is rapid, global population peaks mid-century and then declines, and more efficient fossil and non-fossil energy sources are available (IPCC 2007).

The Northwest Stream Temperature Database (hereafter, NorWeST) is a dataset that covers the western U.S. and was developed from an extensive network of stream temperature monitoring projects. The metric used by this dataset to summarize stream temperature is mean August stream temperature, and temperature scenarios were developed at 1 km intervals. Detailed information describing the development and characteristics of this dataset is available in Isaak et al. (2017).

To assess differences in future water temperatures predicted in these climate change scenarios, we visualized and evaluated watersheds for the average August mean temperature (°C) for the historical time period (1993-2011) and three future scenarios [all corrected for differential sensitivity as described in Isaak et al. (2017)]: 2040, 2080, and a 3°C increase. For the 2080 scenario, we also considered the predicted rate of change to identify watersheds that are also predicted to warm at a faster rate relative to other watersheds. From these future scenarios, we selected a primary scenario to consider in greater detail.

Freshwater mussels occur in waterbodies across the region that vary considerably in hydrology, temperature, elevation, and habitat. To aid in interpretation and visualization of results of future scenarios, we visualized future temperatures in two ways. First, we mapped temperatures in one-degree Celsius increments to maximize the visualization of differences among watersheds. Second, we binned the average of August mean temperatures (°C) at the HUC8 watershed level into groups that characterize warming trends relative to fish-based temperature limit criteria (USEPA 2003). These bins were subsequently ranked (highest rank for <13°C; middle rank for 13°C to <18°C; and lowest rank for 18°C+). Values were binned using the Jenks natural breaks method, and ranks were used to inform ranking of potential climate refugia (described further below).

As described in the introduction, such temperature limits have not been developed for freshwater mussels. However, fish-based temperature limits could be considered reasonably protective and perhaps even conservative for some species of western freshwater mussels. Use of these limits also has the benefit of interpreting freshwater mussel conservation under future climate scenarios with respect to declining salmonids, which are the focal species of many restoration and conservation projects, ensuring that freshwater mussel conservation priorities are more closely aligned with species that are the typical focus of restoration projects and funding. As our understanding improves with regard to freshwater mussel thermal limits, this analysis could be adapted to provide a tighter focus on climate impacts specific to freshwater mussels.

Aquatic Resource Management Data

We also mapped “existing condition” data (as compared to future climate scenario data) using several publicly-available datasets that describe management of aquatic resources (shortened to “ARM”). These include geospatially-referenced datasets that include information for known or potential barriers to fish passage, surface water points of diversion (PODs), and permitted discharge sites or other pollutant points of interest, such as superfund sites. These datasets provide baseline information on the extent of human alteration to watersheds and are also relevant to mussels. For example, barriers to fish passage can reduce the amount of habitat available to species like the western pearlshell, which rely on salmonids for recruitment of young mussels. Reduced water quantity, as described by the number of PODs, can also reduce the availability and quality of habitat for mussels. Although the number of PODs does not correspond directly to the amount of water withdrawn, this information is useful for examining the potential for reduction in water quantity. Poor water quality is also a threat to mussels, which may be especially sensitive to particular contaminants, such as ammonia. Mussels can encounter contaminants in the water column, as well as in the sediment, and permitted discharge sites or areas such as superfund sites may reduce habitat quality or exclude mussels.

For each of these datasets, the number of points (count) was summarized within each watershed. We visualized this data using heatmaps to depict areas of greater number of ARM points. We also applied the Jenks natural breaks method to assign a ranking to each HUC8 watershed, corresponding to fewer, intermediate, or greater numbers of ARM points, based on the lowest ranking of any of the three datasets in combination.

Conservation or Restoration Priority Area Data

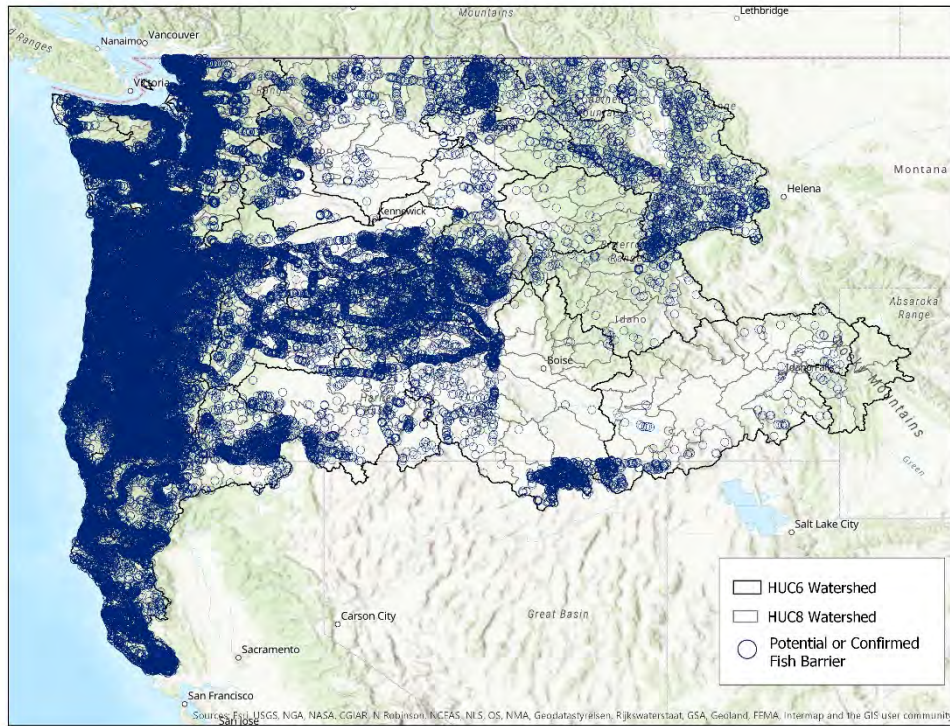
To visualize and interpret conservation and restoration priorities across the study area, we relied on the Crucial Habitat Assessment Tool (CHAT) dataset developed by states and the Western Association of Fish and Wildlife Agencies (WAFWA). This dataset was developed in order to identify areas of higher wildlife value for use in land planning. The dataset provides wall-to-wall designated priorities (“crucial habitats”) in the form of one- to three-square-mile hexagons (SWAWUS 2016). Inclusion of CHAT priority areas enabled us to review the number of areas where restoration or conservation efforts may be targeted in the future among watersheds, as well as areas of overlap with mussels. By identifying these areas of overlap, we intended to key in to geographies where additional outreach and partnerships could expand restoration and conservation efforts to benefit mussels. We summarized the number of CHAT hexagons of priority category 1 or 2 (out of 6 ranging from “most crucial” to “least crucial”) occurring within a watershed.

Interpretation of Multiple Datasets

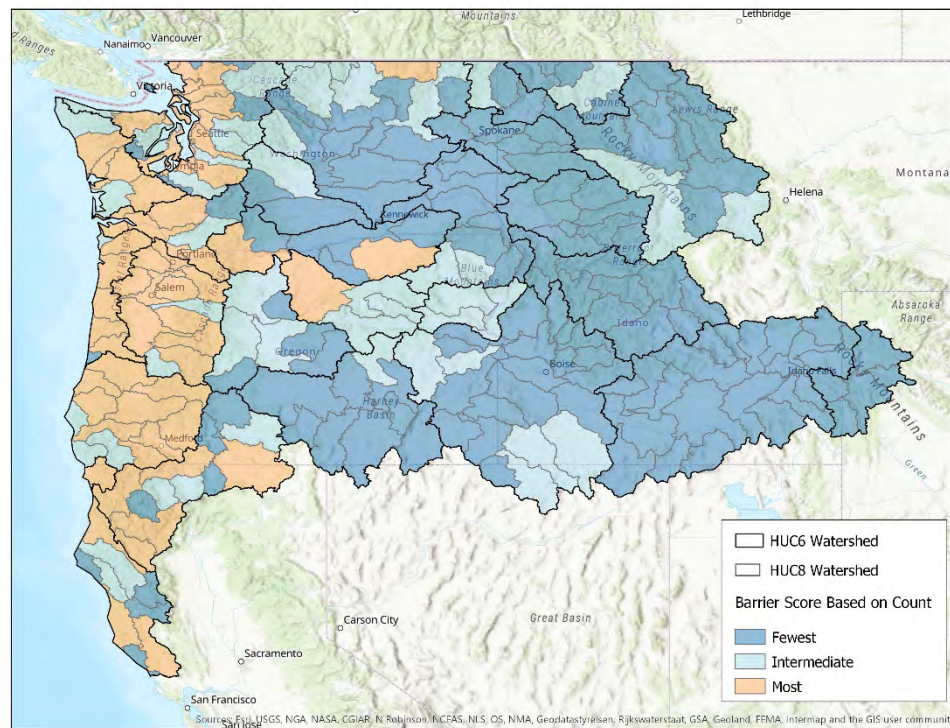
We conducted a preliminary review of various combinations of watershed rankings for each type of data. For example, we variously considered an average ranking of all metrics, weighting climate and mussel data more heavily than other metrics, or assigning the lowest rank across metrics (as with ARM data). However, this sensitivity analysis suggested that differences in dataset development methods or the comprehensiveness of datasets generally resulted in a biased final ranking of potential refugia. Figure 5 below provides an example of differences in data comprehensiveness affecting final ranks. Therefore, rather than determine a final rank describing all datasets in combination, we present each dataset individually and interpret results with these caveats in mind.

Northwestern Oregon/Willamette Basin Focal Area

For our analysis of the northwestern Oregon/Willamette Basin focal area, we followed similar methods, but also incorporated several datasets that identify conservation and restoration priorities specific to the focal area, including Willamette Anchor Habitats (priorities through OWEB, Bonneville Power Administration, and Meyer Memorial Trust's Willamette River Initiative), cold water refugia in the Willamette SLICES dataset (Hulse et al. 2002), and Willamette Synthesis Conservation Opportunity Areas (The Nature Conservancy). Other datasets, including the Bureau of Land Management's western Oregon Aquatic Restoration Strategy (2015) and the US Forest Service Watershed Condition Framework (2011), which were developed for a larger geographical area but encompassed the Willamette Basin, were also included. Together these datasets further describe areas that may provide additional opportunities to incorporate freshwater mussels into existing efforts.



5A.



5B.

Figure 5. A. When mapped, the geographic disparity in comprehensiveness of barrier data becomes apparent. B. The disparity in number of mapped points in Idaho and possibly eastern Washington compared to other regions could result in misleading rankings for watersheds. To reduce the impact of data gaps in the final ARM summary ranking, we excluded watersheds that registered 0 barriers from the Jenks natural breaks classification and then grouped those watersheds into the now more inclusive “fewest” category.

RESULTS AND DISCUSSION

Climate Refugia Study Area

A total of 24 HUC6 watersheds and 241 HUC8 watersheds were assessed within the study area. Of the HUC8 watersheds, 83% include a record for at least one species of western freshwater mussel (Figure 6). By mussel species/type, floater mussels have been reported from 53% of all watersheds, western pearlshell from 73%, and western ridged mussel from 32%.

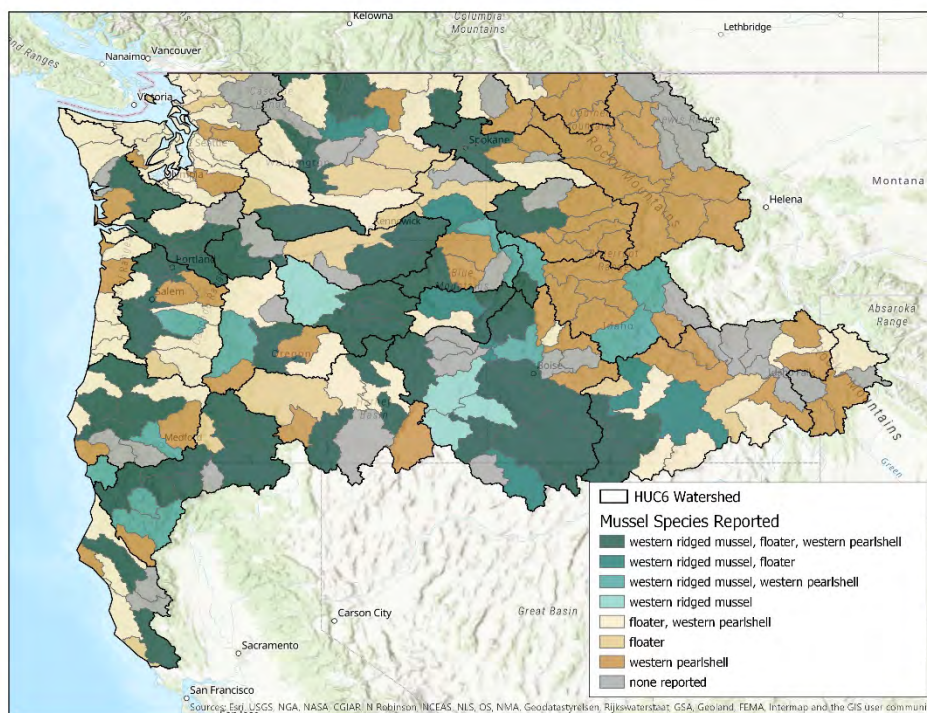


Figure 6. Freshwater mussel reported presence in HUC8 watersheds. Data from the Western Freshwater Mussel Database (Xerces/CTUIR 2018).

We also mapped historic climate from the NorWeST dataset (Figure 7), which is somewhat comparable to future climate predictions. Among the future climate scenarios assessed, we chose to use the 2080D predictions of future climate as our main climate metric. This scenario describes “future August mean stream temperature scenario based on global climate model ensemble average projected changes in August air temperature and stream discharge for the A1B warming trajectory in the 2080s (2070-2099). Future stream deltas within a NorWeST unit account for differential sensitivity among streams so that cold streams warm less than warm streams” (Isaak et al. 2017). We chose this scenario because freshwater mussels are relatively long-lived species, and conservation and restoration priorities should consider the long-term potential for suitable habitat. Comparison of the 2040 (Figure 8) and 2080 (Figure 9) scenarios indicated that a number of watersheds with potentially suitable or moderate conditions in 2040 could be under greater temperature stress by 2080.

We also selected the 2080 scenario over the three degrees’ Celsius increase (Figure 10), which describes comparatively greater warming trends across watersheds. Data describing the rate of change of 2080D August mean temperature (°C) is challenging to interpret (Figure 11). Therefore,

we relied on the single, more easily interpretable metric of 2080D August mean temperature (°C).

We also mapped ARM datasets for each watershed and found obvious spatial differences among metrics (Figure 5, 12—14). The final ARM rank (Figure 15) is intended to provide a general look at human use of aquatic resources, but the actual potential for these factors to reduce climate resiliency of watersheds for mussels is difficult to interpret.

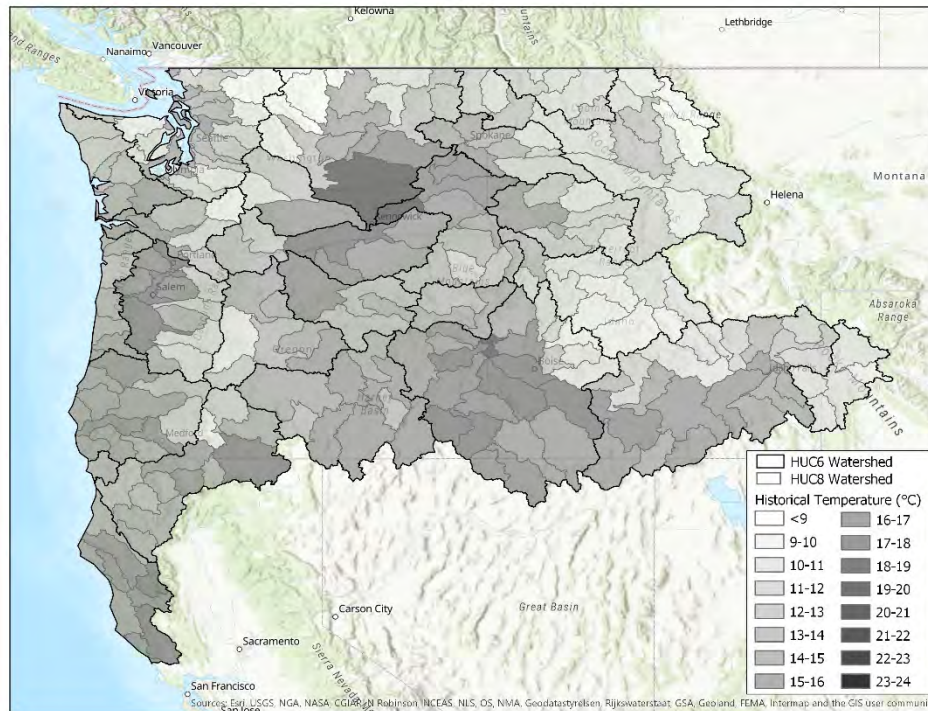


Figure 7. Historical mean August temperature (°C; 1993-2011) averaged to HUC8 watershed. Data source: Chandler et al. 2016/NorWeST.

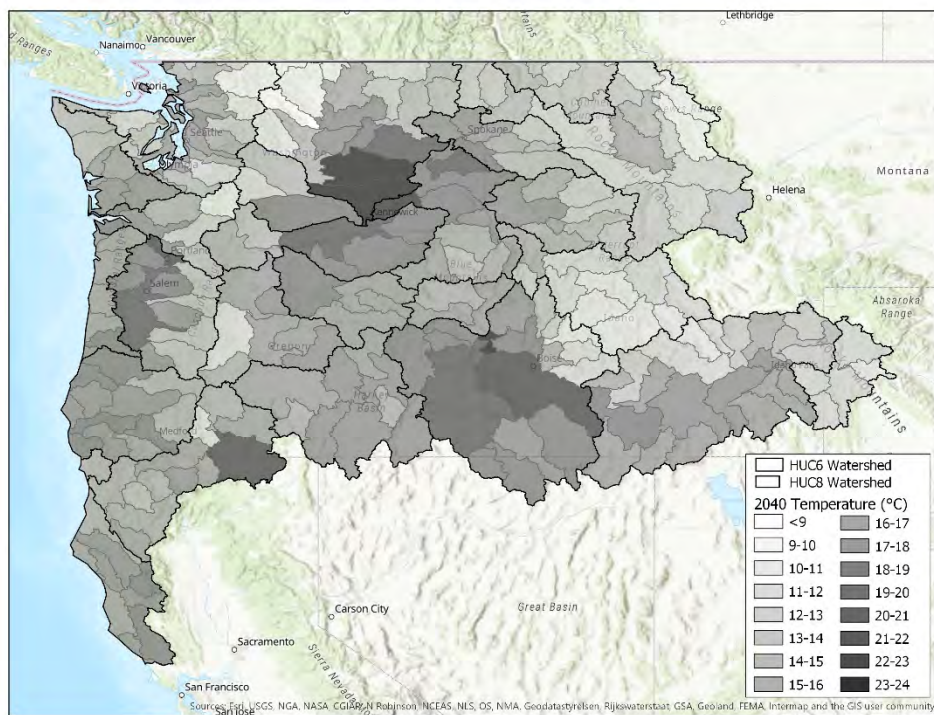


Figure 8. Mean August temperature (°C) averaged to HUC8 watershed as modeled for the 2040D climate scenario. Data source: Chandler et al. 2016/NorWest.

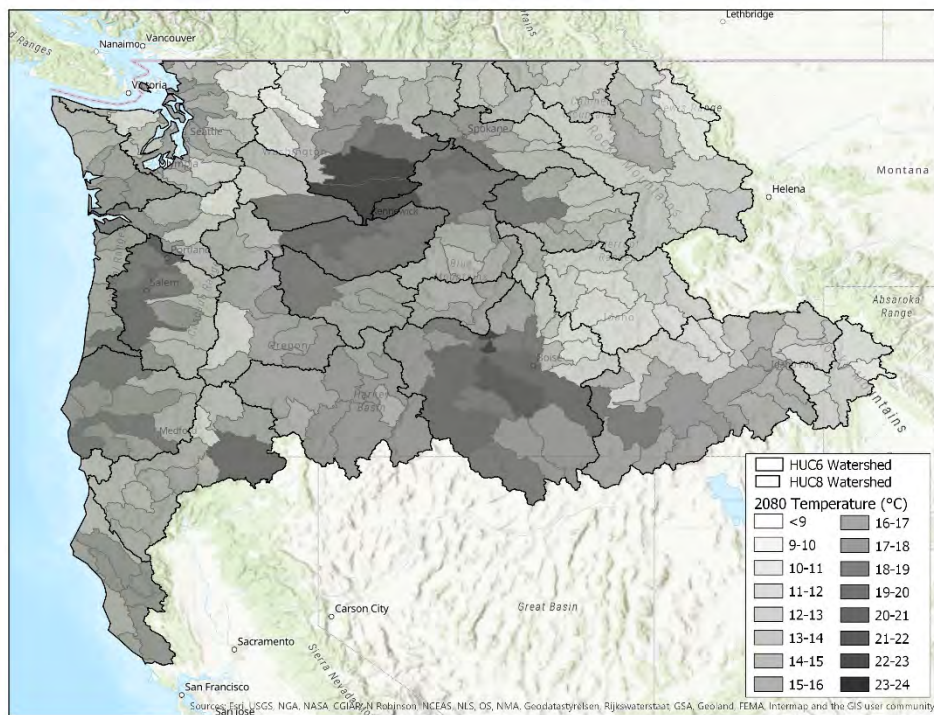


Figure 9. Mean August temperature (°C) averaged to HUC8 watershed as modeled for the 2080D climate scenario. Data source: Chandler et al. 2016/NorWest.

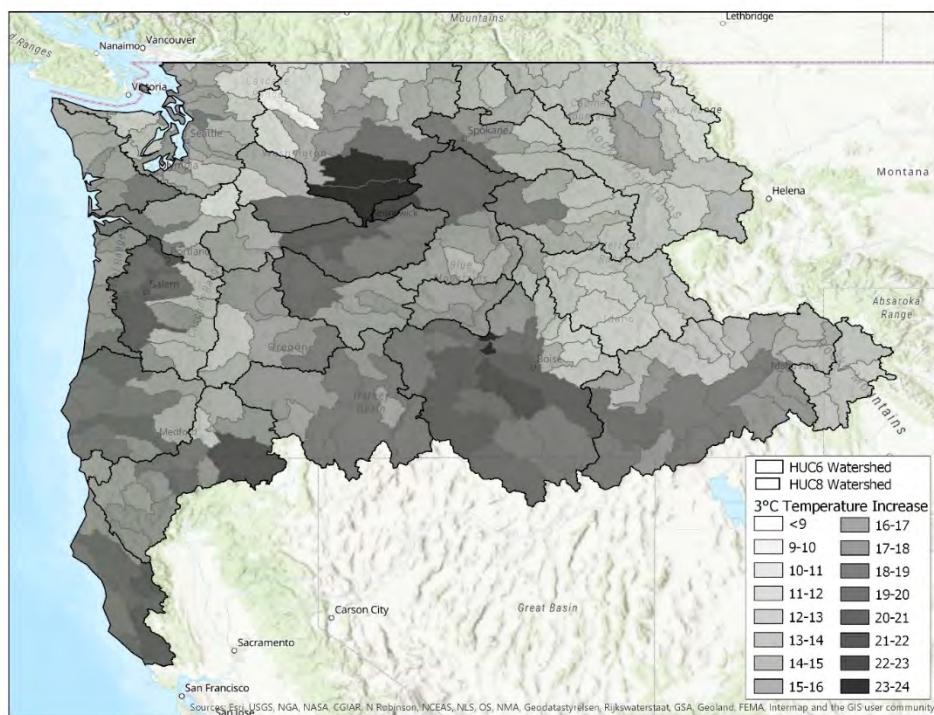


Figure 10. Mean August temperature (°C) averaged to HUC8 watershed as modeled for the 3°C climate scenario. Data source: Chandler et al. 2016/NorWeST.

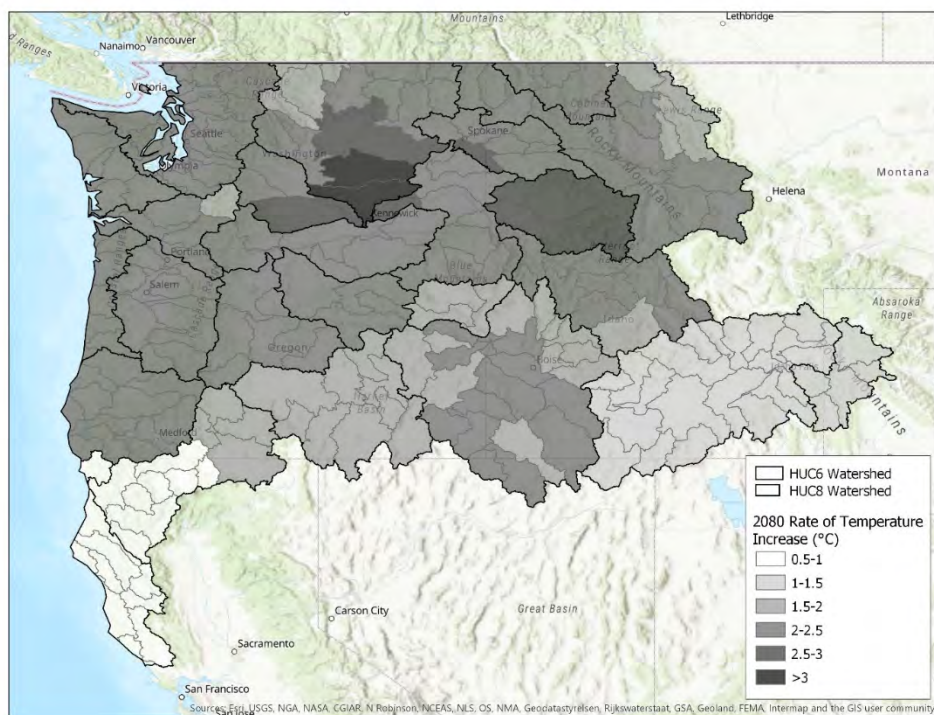


Figure 11. Mean August temperature (°C) rate of change averaged to HUC8 watershed as modeled for the 2080D climate scenario. Data source: Chandler et al. 2016/NorWeST.

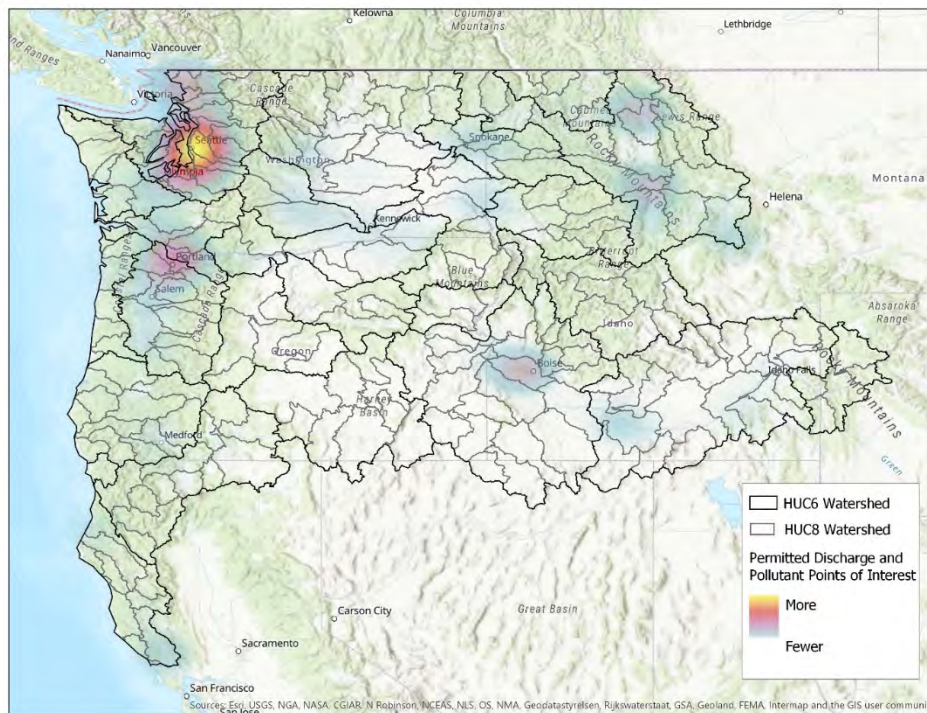


Figure 12. Heatmap of permitted discharge and pollutant points of interest.

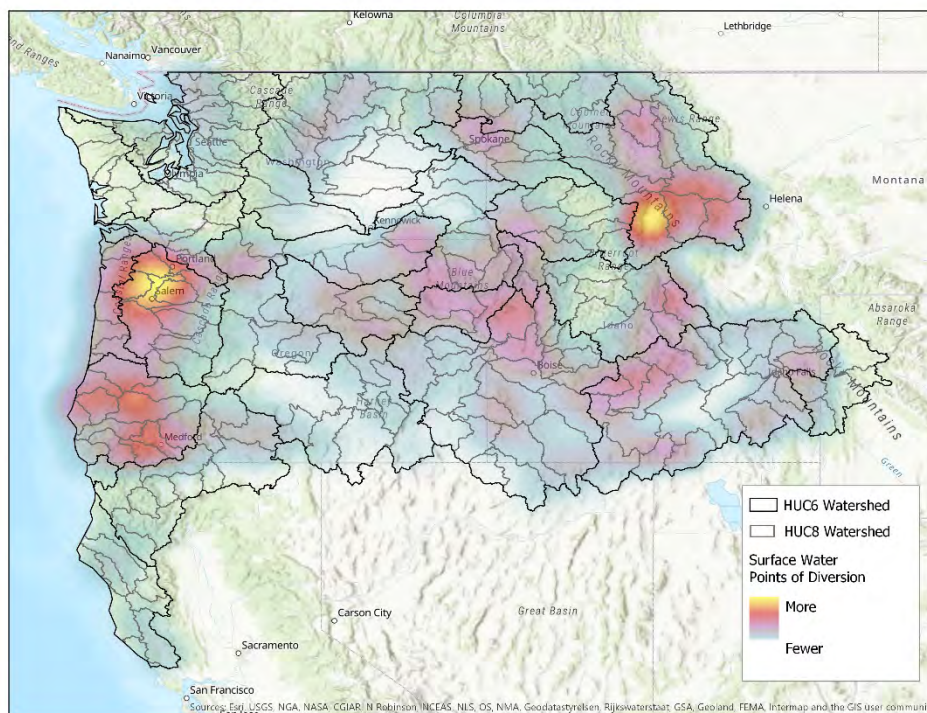


Figure 13. Heatmap of points of surface water diversion.

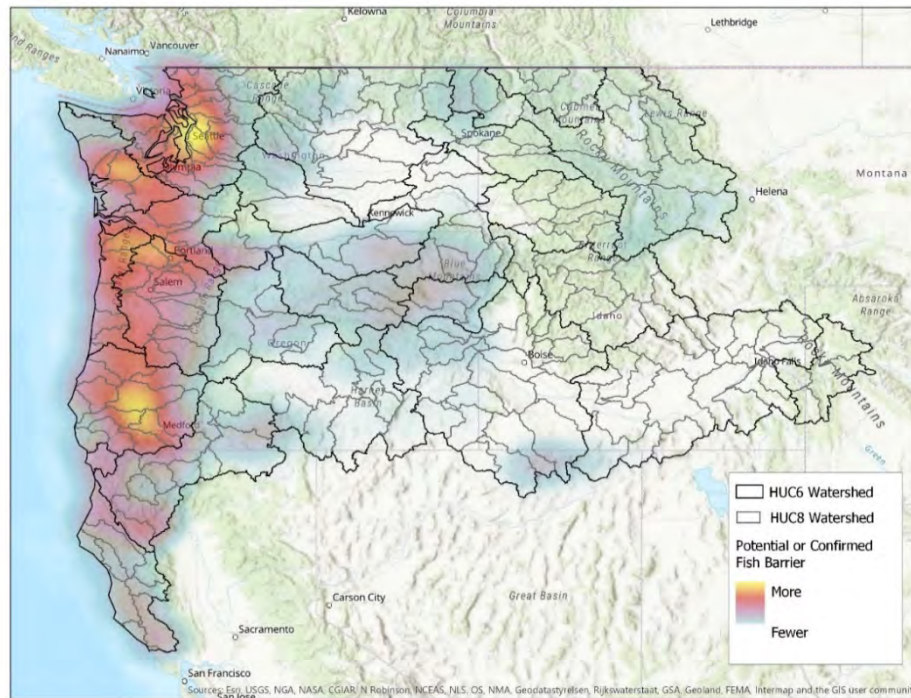


Figure 14. Heatmap of potential and confirmed barriers to fish.

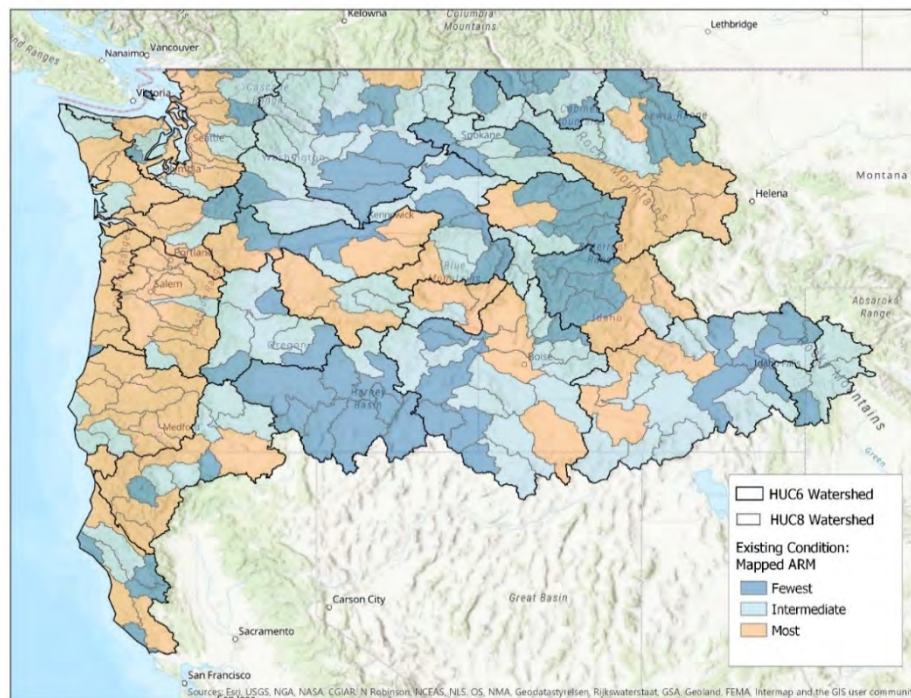


Figure 15. Watershed summary of combined aquatic resource management datasets (ARM; permitted discharge and pollutant points, points of surface water diversion, and potential and confirmed fish barriers). Watersheds in blue could have greater conservation potential under future climate because ARM datasets indicate they contain the fewest number of stressors.

As with other datasets, differences in CHAT data are also evident by state (Figures 16 and 17). States differed in the size of their hexagons, total number, and percent ranked as priority level 1 or 2. Therefore the CHAT ranking was not considered further in the analysis. Instead, the data was interpreted only where priority hexagons overlapped with freshwater mussel records (Figure 18). Of the watersheds in the study area, 79% had at least some overlap between mussels and CHAT priority level 1 or 2 hexagons. Of these, the greatest overlap was for western pearlshell (82%), then floater (13%), and western ridged mussel (5%). Additionally, most of those overlapping watersheds were ranked as either A or B for their potential to provide refugia, meaning that they also typically occur where predicted August mean temperatures (°C) are also lower (in addition to having records of freshwater mussel occurrence).

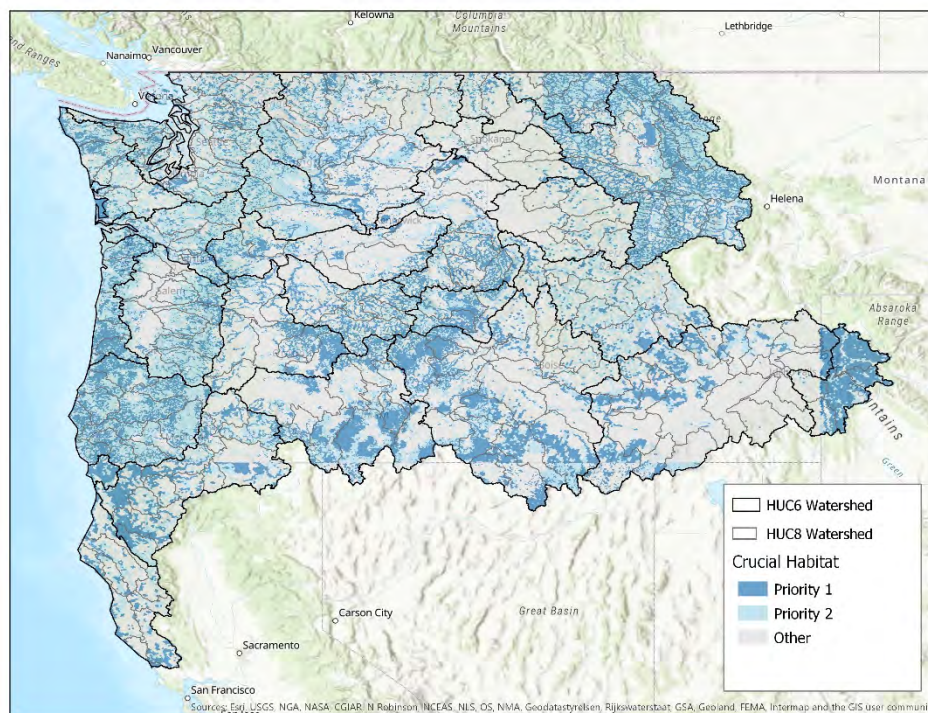


Figure 16. Crucial Habitat Assessment Tool (CHAT) hexagons mapped across the study area by ranking. CHAT priority areas 1 and 2 identify places of higher wildlife value for use in land planning (SWAWUS 2016).

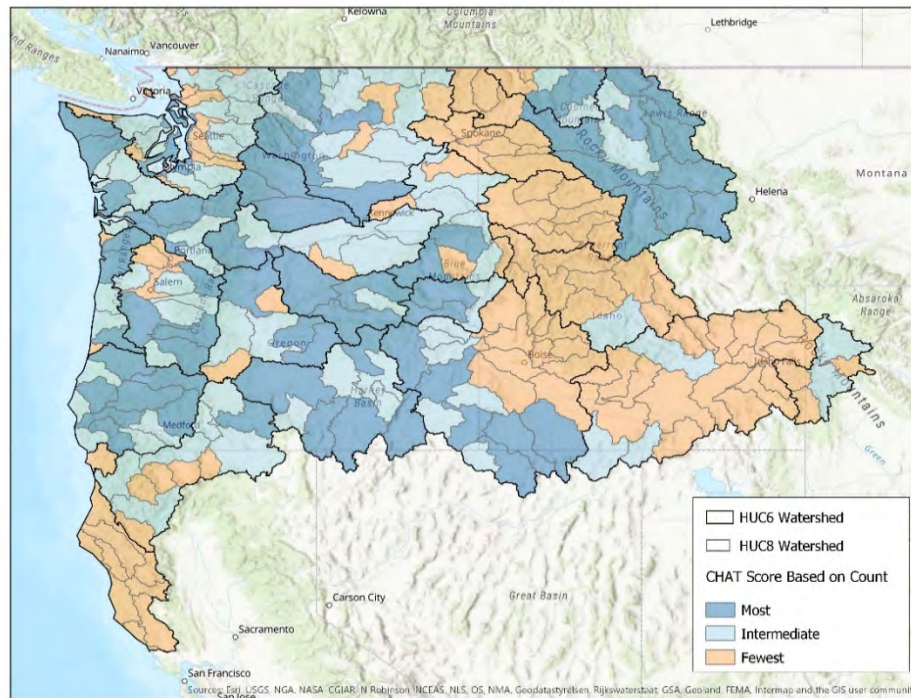


Figure 17. Watershed summary of number of CHAT hexagons ranked priority 1 or 2. CHAT priority areas 1 and 2 identify places of higher wildlife value for use in land planning (SWAWUS 2016).

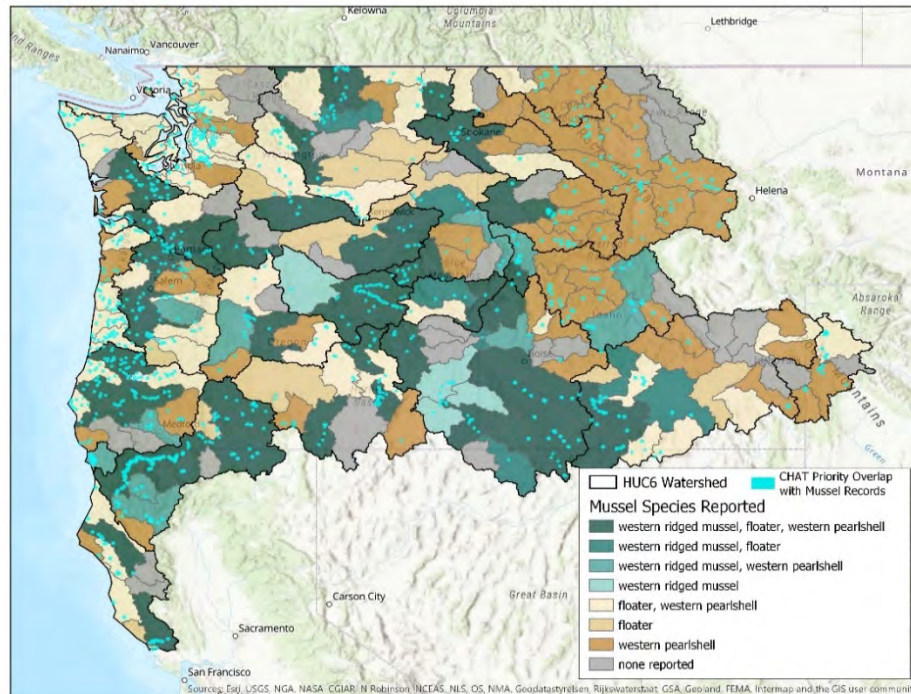


Figure 18. CHAT hexagons in aqua indicate overlap between mussels (Xerces/CTUIR 2018) and a hexagon. CHAT priority areas 1 and 2 identify places of higher wildlife value for use in land planning (SWAWUS 2016).

Because datasets for aquatic resource management differed in comprehensiveness, we elected to identify potential refugia primarily based on two factors: the 2080D climate scenario and the presence of target freshwater mussel species within a watershed.

The final ranking (Figure 19) summarizes the watershed ranking for each of these factors, where

- “Highest potential/priority” generally describes both the lowest future temperatures and the presence of our priority species (western ridged mussel) or greater mussel species diversity,
- “Moderate potential/priority” generally describes moderate future temperatures but with presence of priority species or greater diversity,
- “Fair potential/priority” generally describes lower or moderate future temperatures but lacking priorities with respect to mussel priorities,
- “Lowest potential/priority” generally describes higher future temperatures and no mussel records, and
- “Surveys recommended” generally describes lower future temperatures and no mussels present.

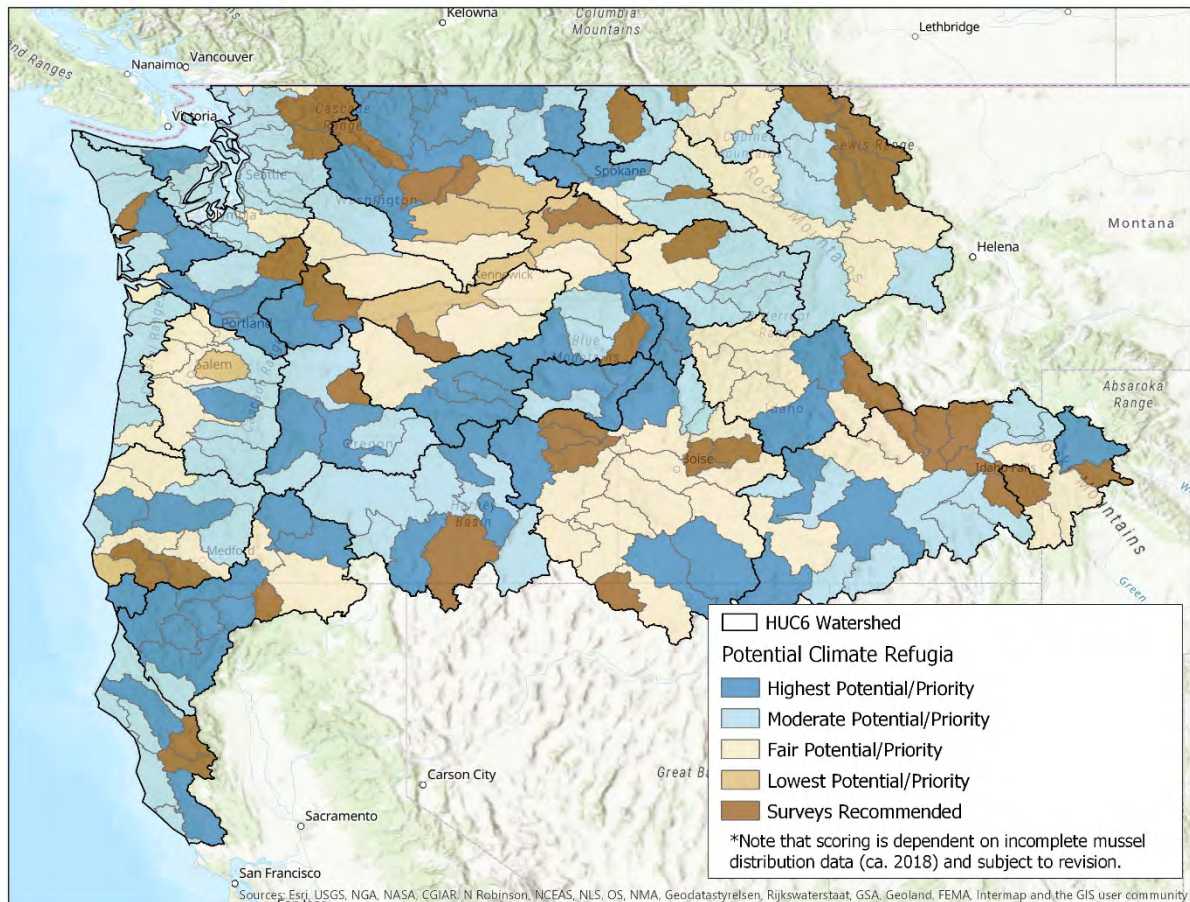


Figure 19. Watersheds ranked for their potential to provide climate refugia for mussels, based on reported observations of mussel species (Xerces/CTUIR 2018) and predictions of August mean temperature in 2080 (°C; Chandler et al. 2016/NorWeST) summarized to HUC8 watershed.

Of the 241 HUC8 watersheds, 57 are ranked with the highest potential, 84 with the second highest, with 53 and 47 considered to have the lowest potential. The highest ranking watersheds are distributed among HUC6 watersheds (Table 1), with the highest percentage occurring within the Klamath and the Upper Columbia, followed by the Salmon and Middle Snake-Boise (Figure 20). Other HUC6-level watersheds include multiple HUC8-level watersheds ranked as having the greatest number of potential refugia watersheds (Table 2). Of the highest ranked watersheds, many span state lines, though, Oregon has the greatest percentage (44%), with all other states having only a third or less. However, Oregon also shares borders with 4 of the other 6 states included in this analysis.

Of concern, however, is the fact that several of the watersheds are also sites with reported mussel bed die-offs, instances where large numbers of mussels, possibly an entire mussel bed dies suddenly, including the Middle Fork John Day, Lower Crooked, Lower Chehalis, and the Lower Owyhee. Until these die-offs are further investigated and possible causes are identified, the potential for these watersheds to serve as climate refuges is questionable. Indeed, additional surveys for freshwater mussel populations can and should be used to further refine potential climate refugia, particularly where abundance estimates are also available.

Interestingly, 14 watersheds were found to rank well under future climate, but there were no mussel records for these watersheds, resulting in a low final ranking (dark brown in Figure 19). Additional surveys for freshwater mussels in these watersheds could prove beneficial for identifying additional climate refugia.

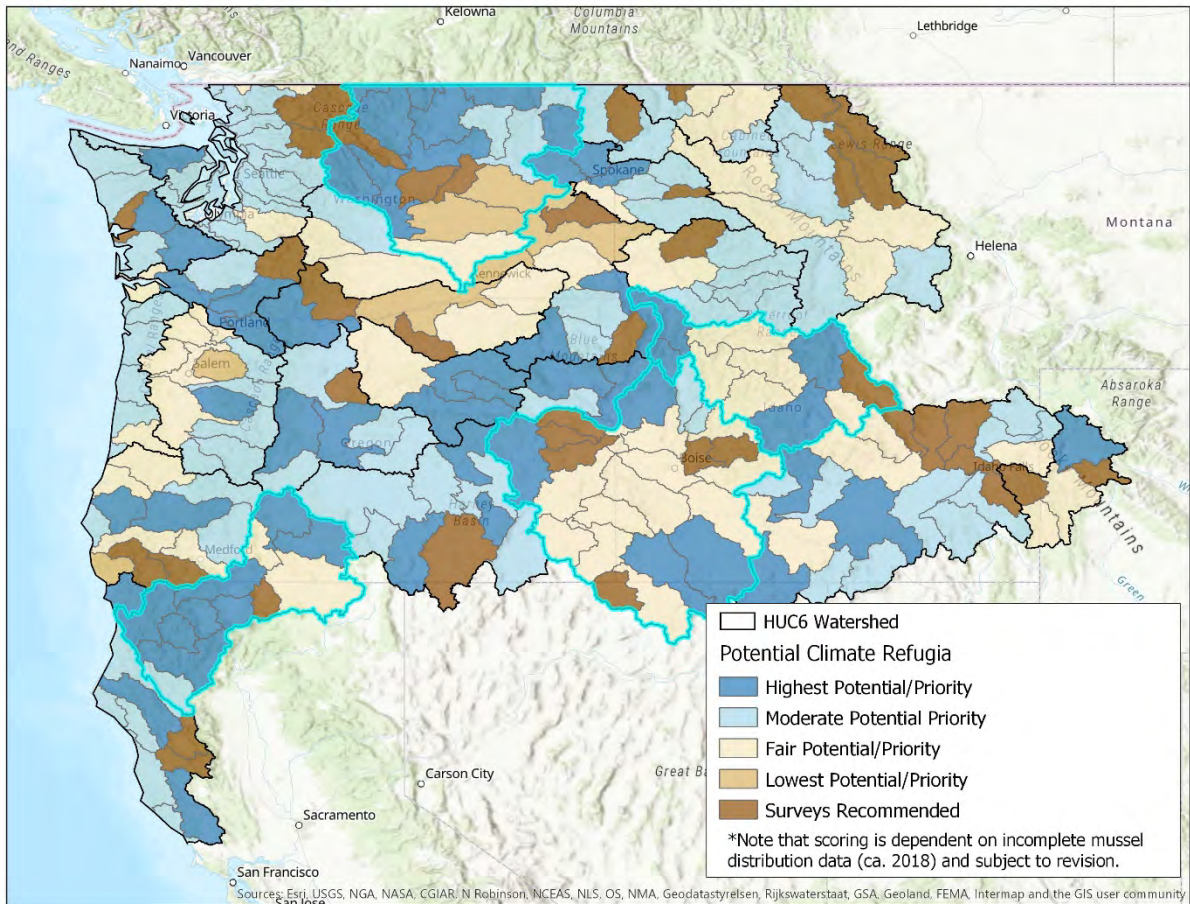


Figure 20. HUC6 watersheds with the most HUC8 watersheds identified as potential refugia (outlined in blue-green): Upper Columbia (top, middle), Klamath (bottom left), Middle Snake-Boise (bottom right), Salmon (bordering the Middle Snake-Boise).

Table 1. Refuge potential and associated metrics summarized by number of HUC8 watersheds for each HUC6 watershed in the study area.

HUC6 Watershed	Potential Refugia					2080D Climate			Species				Aquatic Resource Management			CHAT Overlap
	Highest Potential/ Priority	Moderate Potential Priority	Fair Potential/ Priority	Lowest Potential/ Priority	Surveys Recommended	Coolest	Warmer	Warmest	Highest Diversity or Priority Species Present	Moderate Species Diversity	Low Species Diversity	No Mussels Reported	Fewest Reported Points of Impact	Moderate Reported Points of Impact	Most Reported Points of Impact	Number of Priority 1 or 2 Hexagons Overlapping with Mussel Records
Clearwater		6	1		1		7	1	1		6	1	6	1	1	59
Deschutes	2	4			1	1	6		2	2	2	1	3	4		54
John Day	3		1				3	1	4					2	2	118
Klamath	8	1	2		1	1	10	1	9		2	1	2	5	5	568
Kootenai		2	2		1	2	3			1	3	1	4	1		49
Lower Columbia	3	1	1		1	1	4	1	3	2		1	1	1	4	106
Lower Snake	3	2	1	2	2		6	4	4		4	2	5	4	1	51
Middle Columbia	1		2	1	2		2	4	3		1	2	2	1	3	44
Middle Snake-Boise	4	2	12		6	3	8	13	14	1	3	6	8	12	4	110
Middle Snake-Powder	2	1					3		2	1				1	2	9
Northern California Coastal	3	5			2		10		3	3	2	2	4	2	4	239
Northern Oregon Coastal		6	1				6	1		5	2		1	1	5	113
Oregon Closed Basins	3	5			1		9		3	2	3	1	8	1		114
Pend Oreille		7	4		5	8	8			1	10	5	5	5	6	200
Puget Sound	1	16	2		2	5	16			12	7	2	4	7	10	368
Salmon	4		5		1	8	2		4		5	1	4	3	3	121
Snake Headwaters	1		2		2	5				1	2	2	1	4		50
Southern Oregon Coastal	2	3	4	1	2		7	5	5	3	2	2		3	9	227
Spokane	3	3	1		1		7	1	4	1	2	1	4	4		96
Upper Columbia	8	2	1	2	3	5	7	4	5	5	3	3	5	10	1	206
Upper Snake	3	9	4		5	5	15	1	4	5	7	5	6	12	3	78
Washington Coastal	2	3			1		6		2	2	1	1		2	4	108
Willamette	1	5	5	1			6	6	5	4	3			2	10	154
Yakima		1	2			1	1	1	1	1	1		1	2		27

Table 2. HUC8s with the highest potential to be mussel refugia, grouped by HUC6.

HUC6 Name	HUC8 Name	HUC6 Name	HUC8 Name
Deschutes	Lower Crooked	OR Closed Basins	Donner und Blitzen
	Upper Deschutes		Silvies
John Day	Middle Fork John Day		Warner Lakes
	North Fork John Day	Puget Sound	Dungeness-Elwha
	Upper John Day	Salmon	Little Salmon
Klamath	Lower Klamath		Lower Salmon
	Salmon		Middle Salmon-Panther
	Scott		Upper Salmon
	Shasta	Snake Headwaters	Snake Headwaters
	Sprague	Southern OR Coastal	Coquille
	Trinity		South Umpqua
	Upper Klamath	Spokane	Little Spokane
	Williamson		Lower Spokane
Lower Columbia	Lewis		Upper Spokane
	Lower Columbia-Clatskanie	Upper Columbia	Chief Joseph
	Lower Columbia-Sandy		Colville
Lower Snake	Hells Canyon		Kettle
	Lower Snake-Asotin		Methow
	Upper Grande Ronde		Okanogan
Middle Columbia	Middle Columbia-Hood		Similkameen
Middle Snake-Boise	Bruneau		Upper Columbia-Entiat
	Upper Malheur		Wenatchee
	Upper Owyhee	Upper Snake	Big Wood
	Weiser		Lake Walcott
Middle Snake-Powder	Brownlee Reservoir		Salmon Falls
	Powder	WA Coastal	Lower Chehalis
Northern CA Coastal	Lower Eel		Upper Chehalis
	Russian		
	Smith	Willamette	South Santiam

Willamette Basin, Northwestern Oregon Study Area

Within the Willamette Basin, we conducted a finer-scaled analysis at the HUC12 watershed level to both demonstrate how this project approach could be adapted regionally, as well as to identify watersheds within the Willamette Basin where freshwater mussel conservation efforts could have the greatest impact under a changing climate. This finer-scaled analysis is possible because the NorWeST dataset provides predicted August mean water temperature at 1km resolution.

A total of 382 HUC12 were assessed within the Willamette Basin. Of the HUC12 watersheds, only about 25% include a record for at least one species of freshwater mussel (Figure 21). By mussel species/type, western ridged mussels have been reported from 4%, floater mussels from 11%, and western pearlshell from 18% of all watersheds.

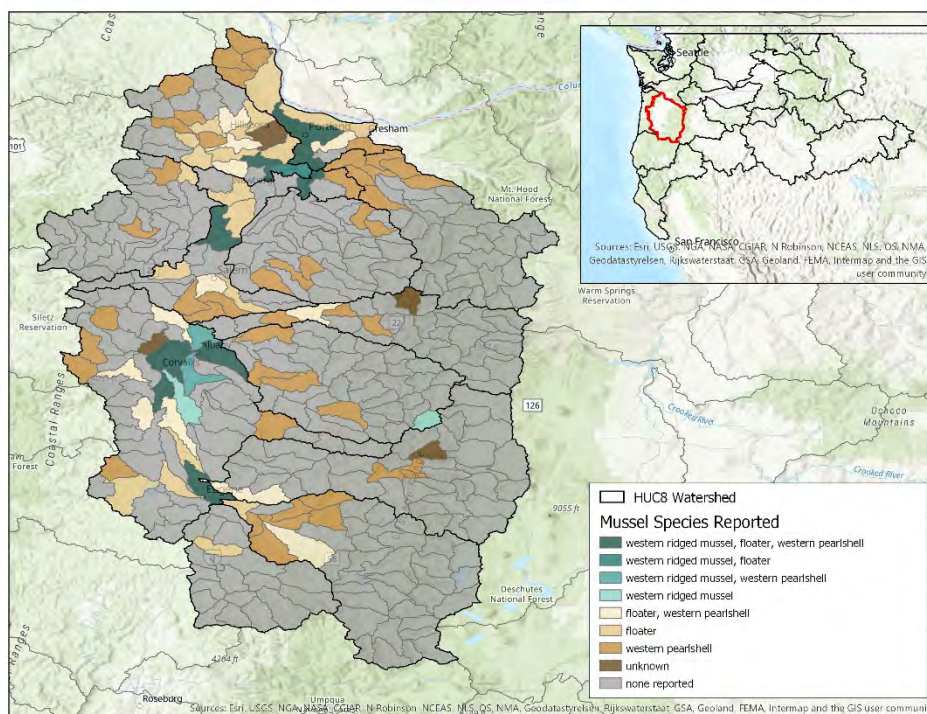
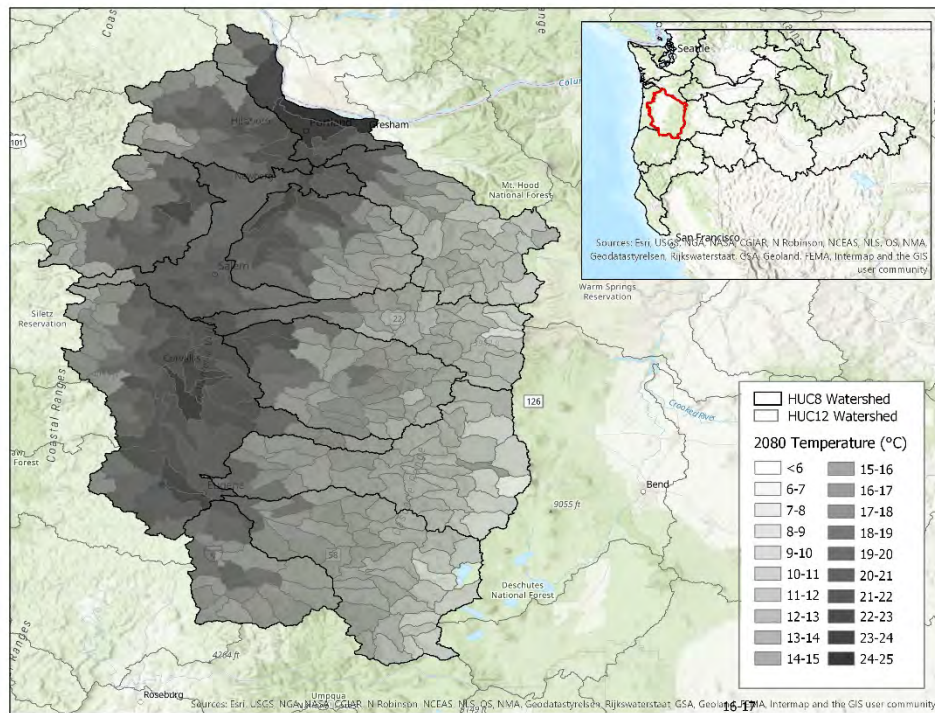
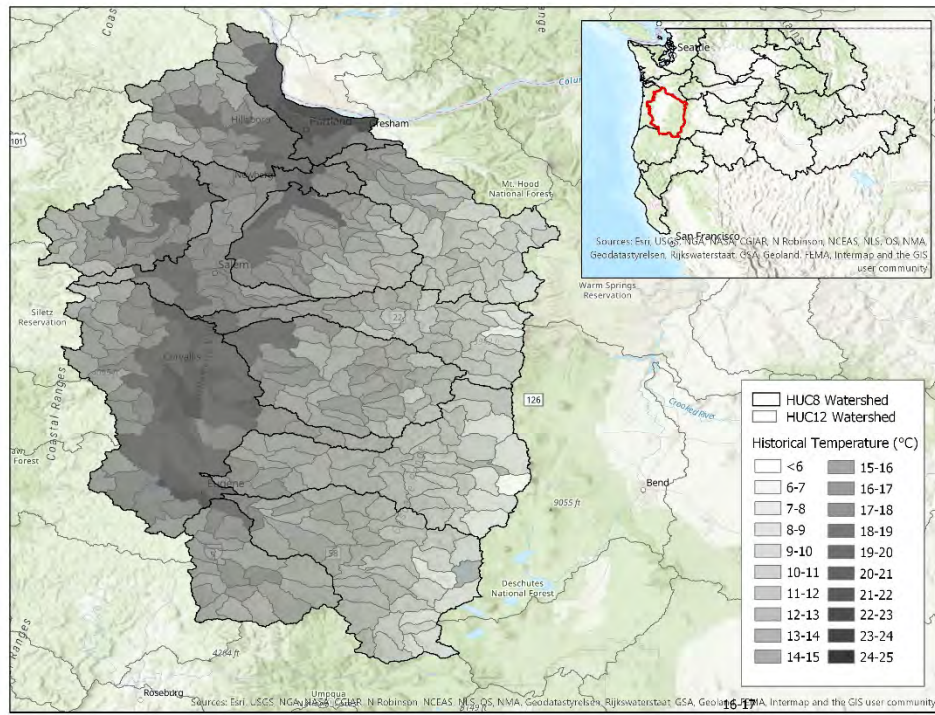


Figure 21. Freshwater mussel reported presence in HUC12 watersheds in the Willamette Basin. Data from the Western Freshwater Mussel Database (Xerces/CTUIR 2018).

We mapped historic August mean water temperature (Figure 22), and as with our broad-scale analysis, we used the 2080D predictions of future climate as our main climate metric (Figure 23). Unsurprisingly, when the two models are compared, differences are evident both at lower elevations, where watersheds are predicted to become increasingly warmer, as well as at higher elevations, where the number of cooler watersheds also shrinks.

Within the Willamette Basin, aquatic resource management metrics were also mapped (Figures 24—27). These metrics indicate that while some impacts are more distributed throughout the watershed, many are focused in watersheds incorporating the mainstem Willamette River and major population centers.



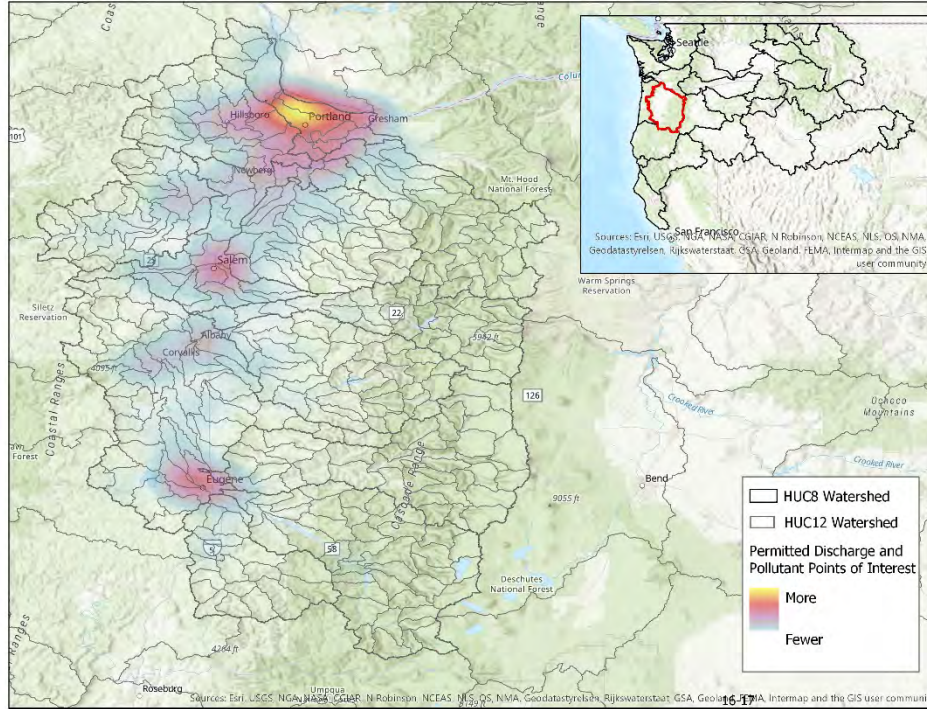


Figure 24. Heatmap of permitted discharge and pollutant points of interest.

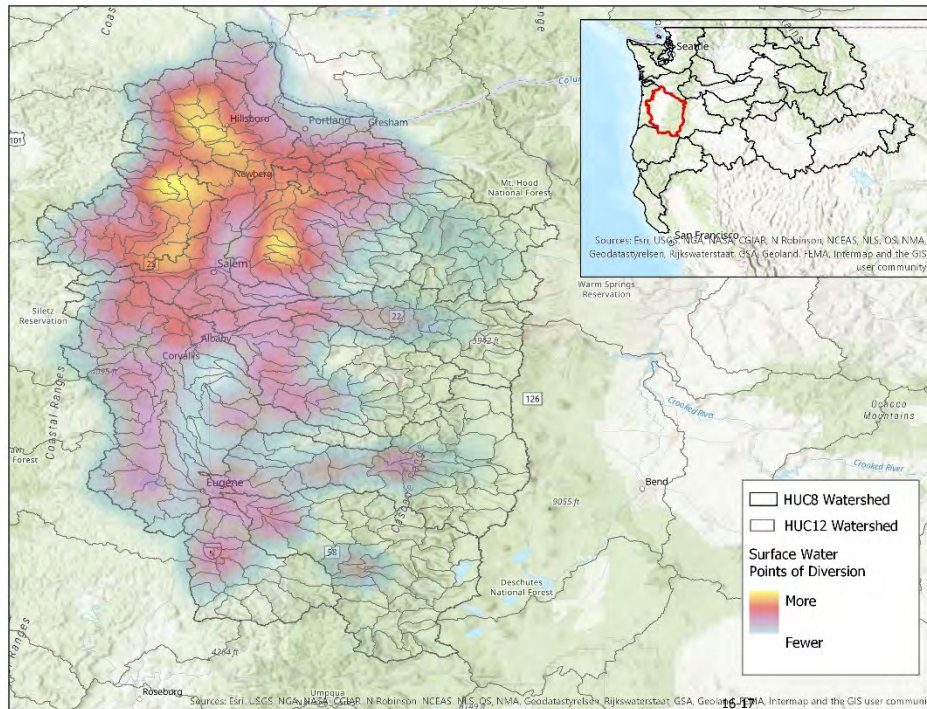


Figure 25. Heatmap of points of surface water diversion.

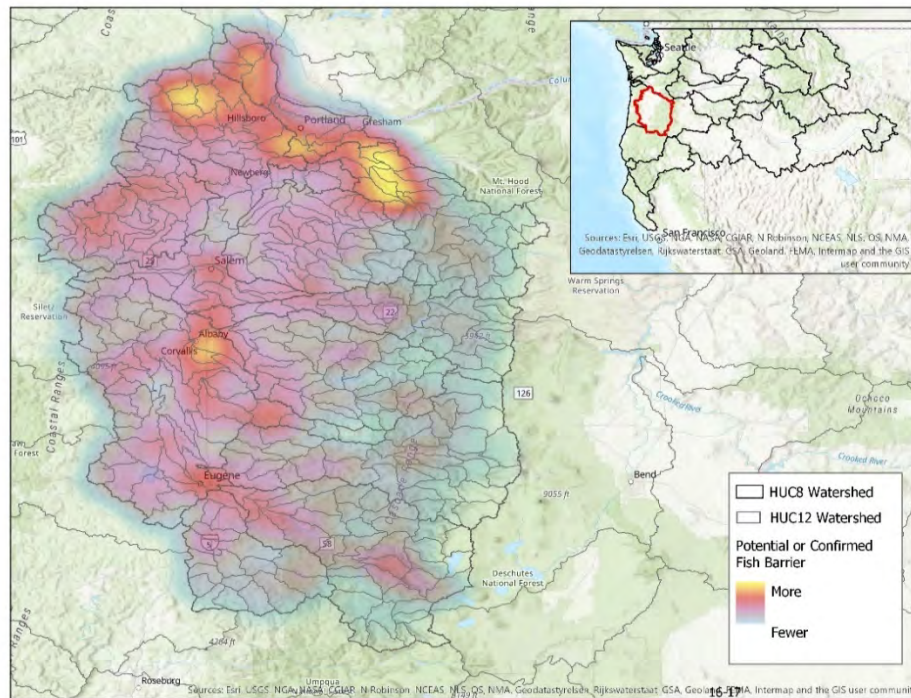


Figure 26. Heatmap of potential and confirmed barriers to fish.

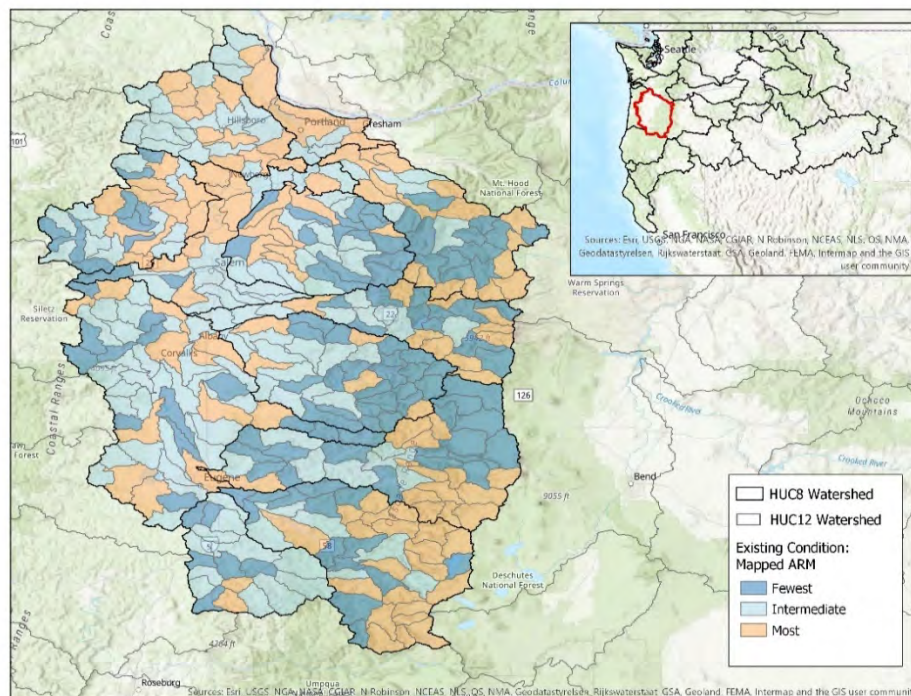


Figure 27. Watershed summary of combined aquatic resource management datasets (ARM; permitted discharge and pollutant points, points of surface water diversion, and potential and confirmed fish barriers). Watersheds in blue could have greater conservation potential under future climate because ARM datasets indicate they contain the fewest number of stressors.

We further visualized the overlap between Willamette Basin watersheds, freshwater mussels, and conservation and restoration priority areas (Figures 28 through 33). Of the more than 7,300 CHAT hexagons ranked 1 or 2 in the Willamette Basin, only a small percentage (~1%) were found to overlap with freshwater mussel records (Figure 30). In comparison, more than half of all anchor habitats (Figure 31) and more than one-quarter of all Synthesis COAs overlap with records for freshwater mussels (Figure 32). Only two cold water refuges mapped by SLICES data overlapped with records for freshwater mussels (Figure 33).

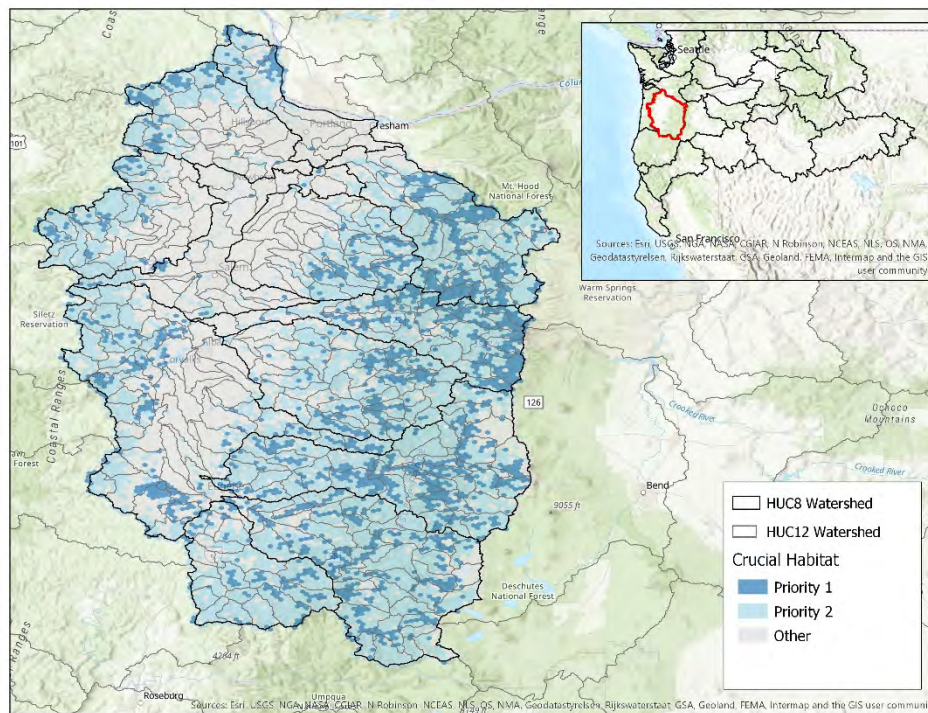


Figure 28. Crucial Habitat Assessment Tool (CHAT) hexagons mapped across the study area by ranking. CHAT priority areas 1 and 2 identify places of higher wildlife value for use in land planning (SWAWUS 2016).

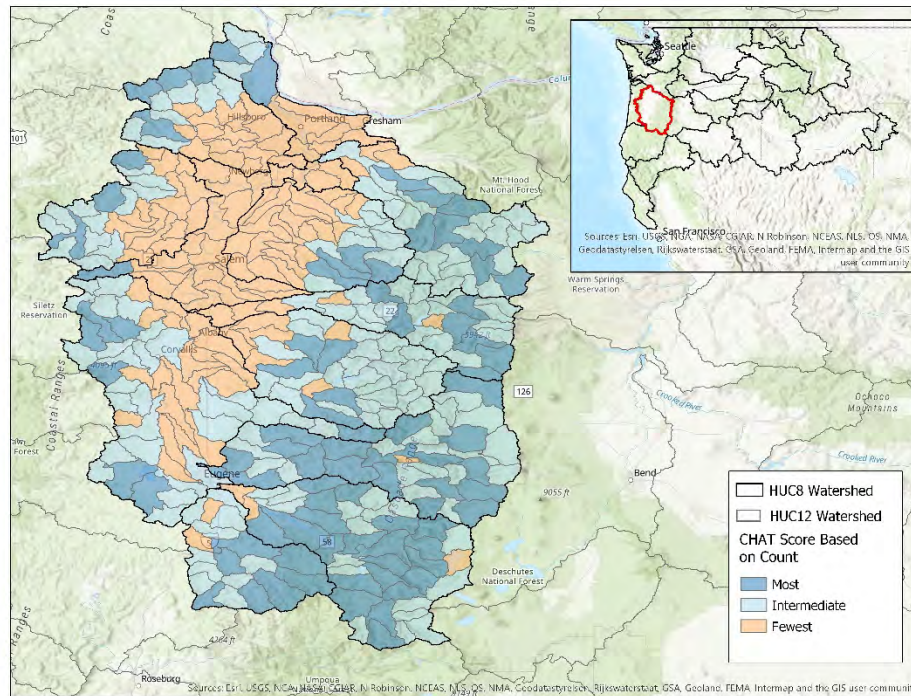


Figure 29. Watershed summary of number of CHAT hexagons ranked priority 1 or 2 per watershed. CHAT priority areas identify places of higher wildlife value for use in land planning (SWAWUS 2016).

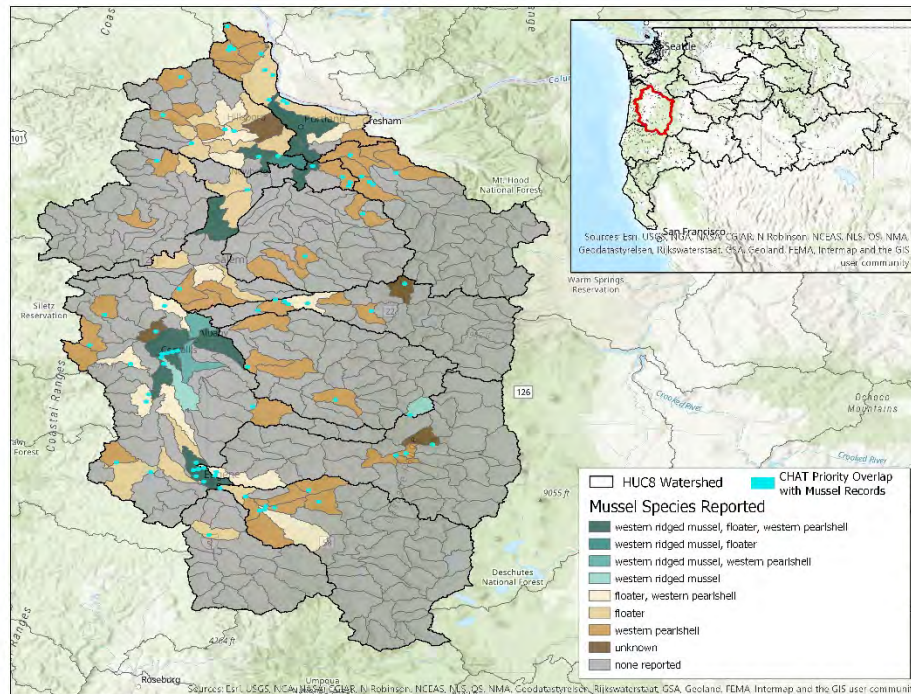


Figure 30. CHAT hexagons in aqua indicate overlap between mussels (Xerces/CTUIR 2018) and a hexagon. CHAT priority areas 1 and 2 identify places of higher wildlife value for use in land planning (SWAWUS 2016).

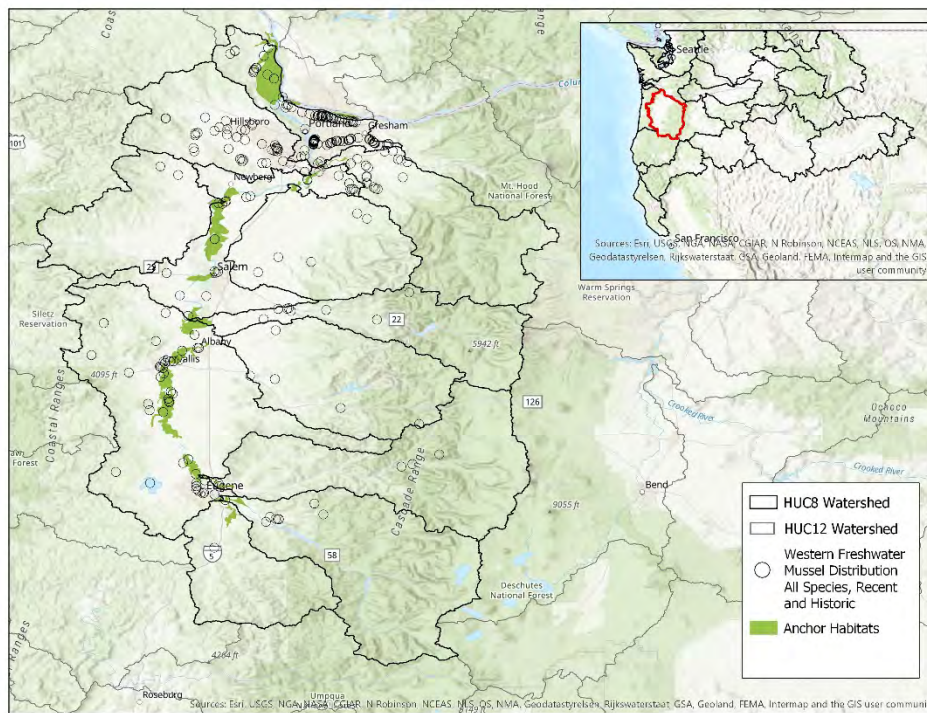


Figure 31. Overlap between anchor habitat (Willamette Mainstem Anchor Habitat Working Group) and freshwater mussels (Xerces/CTUIR 2018).

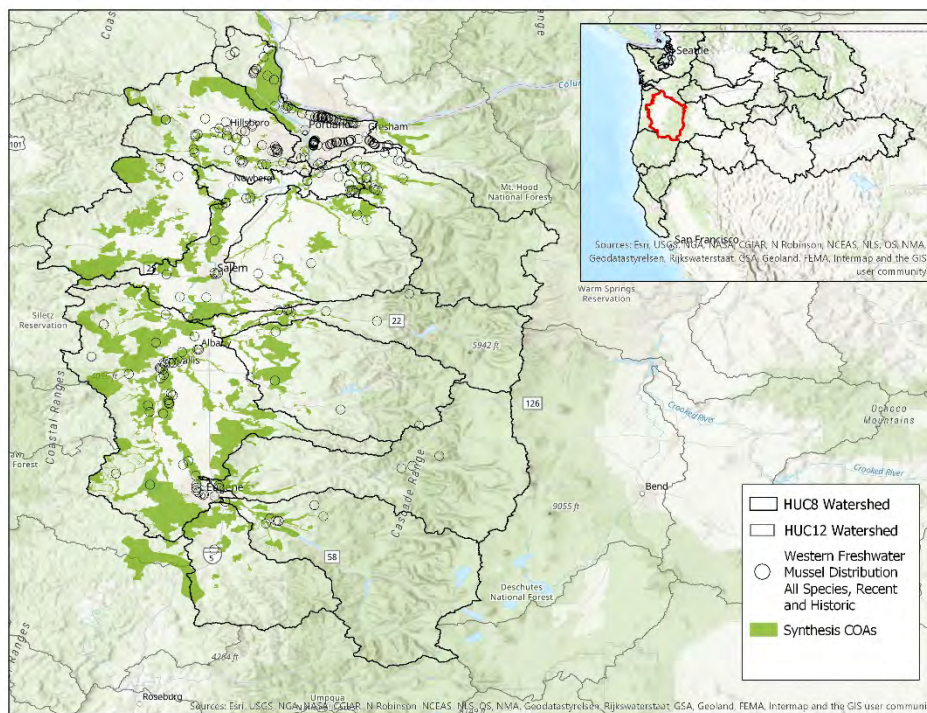


Figure 32. Overlap between Willamette Synthesis Conservation Opportunity Areas (COAs; The Nature Conservancy of Oregon) and freshwater mussels (Xerces/CTUIR 2018).

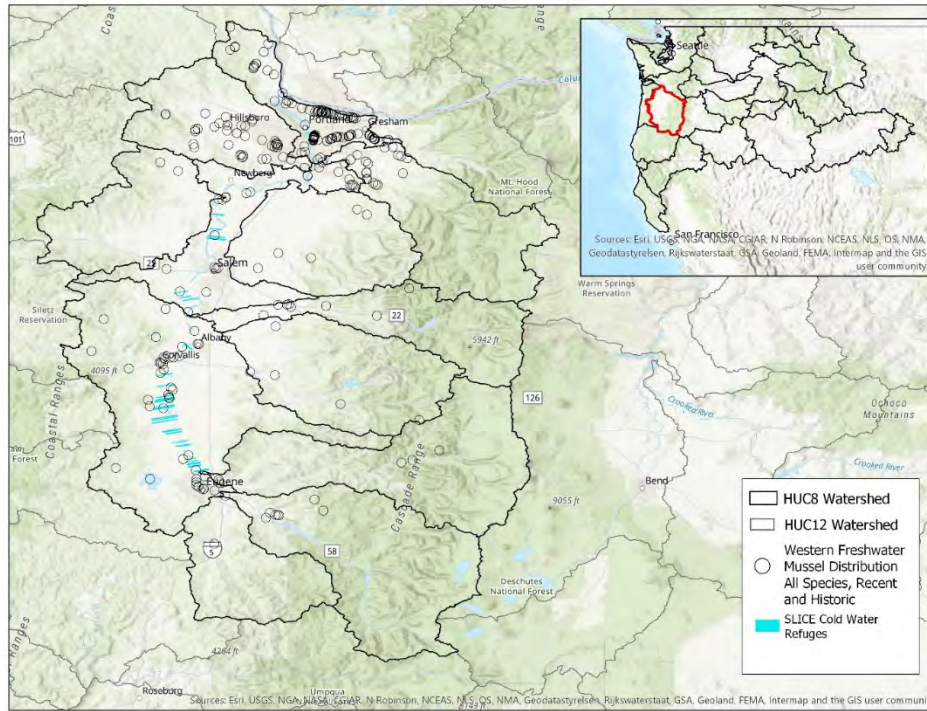


Figure 33. Overlap between mapped cold water refuge SLICES (ISE 2017) and freshwater mussels (Xerces/CTUIR 2018).

Among Willamette Basin WCF (USFS) watersheds, freshwater mussels are reported from 3 watersheds classified as “Functioning Properly,” 5 watersheds classified as “Functioning at Risk,” and 1 watershed classified as “Impaired Function” (Figure 34). Of these, most occurrence records are for western pearlshell, with 2 records not identified to species and 1 record dubiously identified to western ridged mussel. Among BLM aquatic priority watersheds, freshwater mussels are known to occur in 3 of the 6 (Figure 35), comprising a total of three occurrence records for western pearlshell.

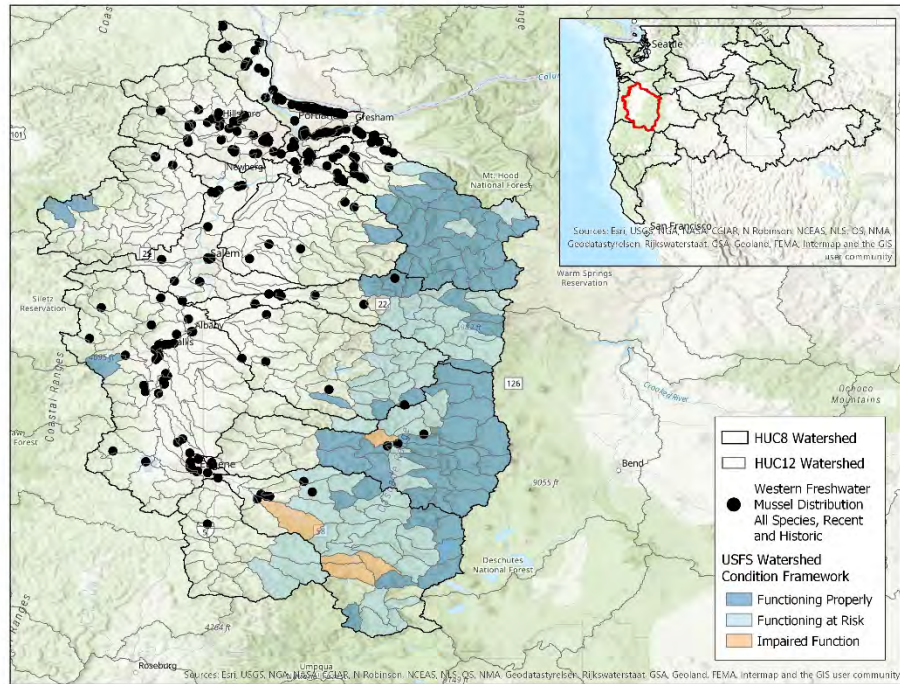


Figure 34. Overlap between watersheds ranked under the Watershed Condition Framework (USFS) for the Willamette Basin and freshwater mussels (Xerces/CTUIR 2018). Only watersheds crossing USFS land are included in the Watershed Condition Framework, thus some watersheds appear blank (lacking a rank).

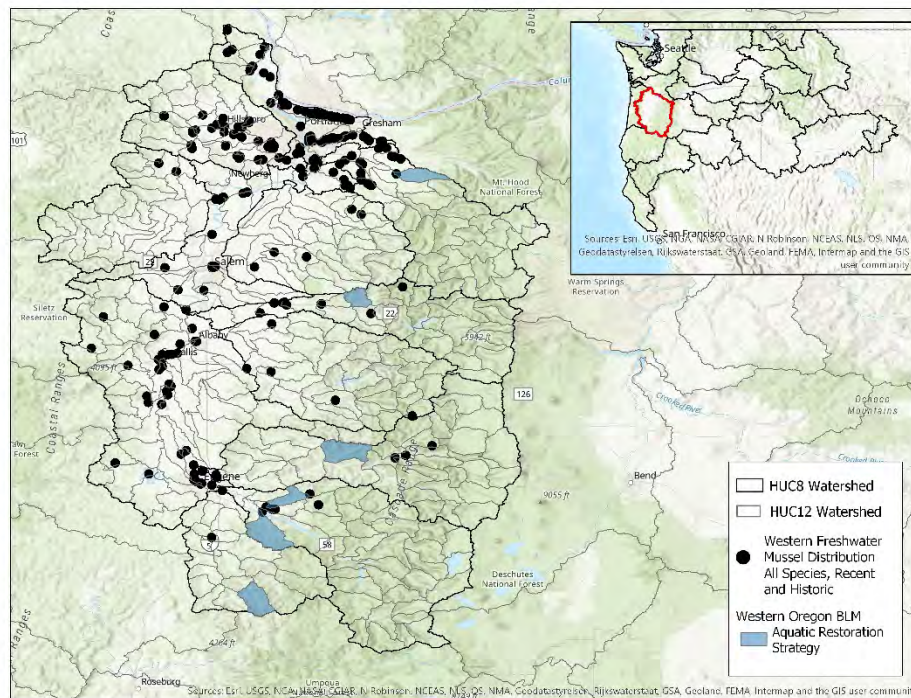


Figure 35. Overlap between Western Oregon Aquatic Restoration Strategy (BLM) priorities for Willamette Basin watersheds and freshwater mussels (Xerces/CTUIR 2018).

Finally, we evaluated the watershed ranking based on species of freshwater mussels present and future climate (Figure 36). Of the 382 watersheds, just one is ranked with the highest potential. However, this watershed contains a record for a mussel observation dubiously identified as western ridged mussel, which elevated the ranking since western ridged mussel is of greater conservation concern than other species of western freshwater mussel. Assuming that this record is in error, the highest ranking watersheds total 24 and are distributed among HUC8 watersheds (Tables 3—5), especially the Middle Fork Willamette (home to western pearlshell and floater mussels), the McKenzie (also home to western pearlshell and floater mussels), and the Clackamas (home to western pearlshell mussels). One target species, the western ridged mussel, was found to generally overlap with watersheds with relatively higher future water temperatures (ranked “fair” in all but the dubious record). Yet these watersheds remain important to future freshwater mussel conservation efforts because of the level of imperilment of this species (Blevins et al. 2017a). In the Willamette Basin, this species is reported only from the Willamette River, Tualatin River, Calapooia River, Lake Oswego, and a tributary to Latiwi Creek (the dubious record). Of these, it is only recently (post-2000) known from the Willamette River, where typically only shells or a single live animal has been reported.

One of the most obvious influences of data comprehensiveness on the prioritization of potential refugia is the paucity of data on freshwater mussel distribution within the Willamette Basin. Although some watersheds may have inherently low potential to support mussel populations due to limited availability of mussel habitat, the number and distribution of mussel records more likely represents inadequate sampling or reporting of freshwater mussel populations across the basin as a whole. For example, since 2015, the Western Freshwater Mussel Database now contains mussel records for 345 new waterbodies occurring or spanning 180 HUC8 watersheds in western North America where mussels had not previously been reported—a 30% increase. In the Willamette Basin alone, this translates to an additional 38 new waterbodies where mussels have been identified.

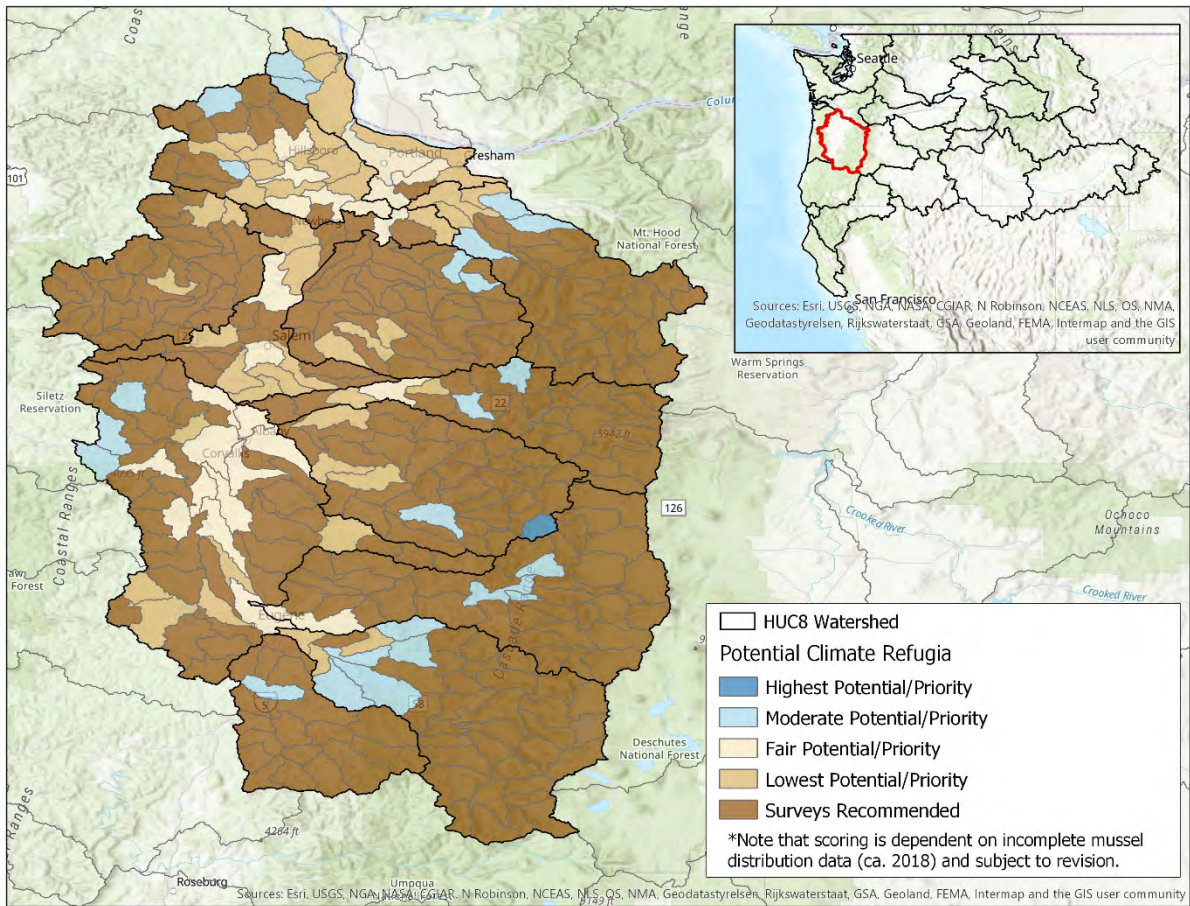


Figure 36. Watersheds ranked for their potential to provide climate refugia for mussels, based on reported observations of mussel species (Xerces/CTUIR 2018) and predictions of August mean temperature in 2080 ($^{\circ}\text{C}$; Chandler et al. 2016/NorWeST) summarized to HUC12 watersheds in the Willamette Basin.

Table 3. Refuge potential and associated metrics summarized by number of HUC12 watersheds for each HUC8 watershed in the Willamette Basin.

HUC8 Name	Potential Refugia					2080D Climate			Species				Aquatic Resource Management		
	Highest Potential/ Priority	Moderate Potential Priority	Fair Potential/ Priority	Lowest Potential/ Priority	Surveys Recommended	Coolest	Warmer	Warmest	Highest Diversity or Priority Species Present	Moderate Species Diversity	Low Species Diversity	No Mussels Reported	Fewest Reported Points of Impact	Moderate Reported Points of Impact	Most Reported Points of Impact
Clackamas		3		3	28	13	17	4			6	28	12	5	17
Coast Fork Willamette		1			18		11	8			1	18	6	11	2
Lower Willamette		2	3	5	1		2	9	2	1	7	1		6	5
McKenzie		3	1		34	14	22	2		1	3	34	17	7	14
Middle Fork Willamette		5		3	33	13	25	3		1	7	33	14	6	21
Middle Willamette			3	8	12		1	22	2	1	8	12	2	13	8
Molalla-Pudding		2		3	30		15	20			5	30	15	12	8
North Santiam		2	1	2	25	10	15	5		1	4	25	11	9	10
South Santiam	1	1		3	33	1	28	9	1		4	33	22	11	5
Tualatin		2	5	10	10		8	19	2	3	12	10		16	11
Upper Willamette		3	11	6	35		12	43	7	4	9	35	14	29	12
Yamhill				3	28		11	20			3	28	9	12	10

Table 4. Number of features overlapping with mussel records summarized by HUC8.

HUC8 Name	CHAT Priority 1 or 2	Anchor Habitat	Synthesis	Cold Water SLICES	WCF Functioning Properly/At Risk	Western Oregon BLM Aquatic Restoration Strategy
Clackamas	6	1	7		1	1
Coast Fork Willamette	2	1	2			
Lower Willamette	6	2	6			
McKenzie	6	2	2		2	
Middle Fork Willamette	9	1	4		2	2
Middle Willamette	6	5	11			
Molalla-Pudding	2		3			
North Santiam	6	1	4		1	
South Santiam	3		3		1	
Tualatin	11	1	4			
Upper Willamette	19	7	16	2	1	
Yamhill	2	1	3			

Table 5. HUC12s with the highest potential to be mussel refugia, grouped by HUC8.

HUC8 Name	HUC12 Name
Clackamas	Middle Clear Creek
	North Fork Eagle Creek
	Tickle Creek-Deep Creek
Coast Fork Willamette	Hill Creek-Coast Fork Willamette River
Lower Willamette	North Scappoose Creek
	South Scappoose Creek
McKenzie	Cougar Creek-South Fork McKenzie River
	Elk Creek-McKenzie River
	Lookout Creek
Middle Fork Willamette	Andy Creek-Fall Creek
	Dexter Reservoir-Middle Fork Willamette River
	Fall Creek Lake-Fall Creek
	Lost Creek
	Upper Little Fall Creek
Molalla-Pudding	Canyon Creek
	Upper Milk Creek
North Santiam	Headwaters Little North Santiam River
	Mad Creek-North Santiam River
South Santiam	Sevenmile Creek-South Santiam River

HUC8 Name	HUC12 Name
	Shot Pouch Creek-South Santiam River
Tualatin	Carpenter Creek-Tualatin River
	Upper West Fork Dairy Creek
Upper Willamette	Headwaters Marys River
	Pedee Creek-Luckiamute River
	Tumtum River

Challenges and Strategies to Advance Mussel Conservation in Light of Climate Change

Recent development of datasets and tools has greatly increased our ability to analyze the overlap between biodiversity, management of aquatic resources, and the response of watersheds to a changing climate. However, these efforts are still hampered by our limited understanding of how aquatic species, and indeed communities, will adapt to a changing climate. Although research has provided some general criteria for assessment of how water temperatures may influence native fish physiologically, it is unknown how additional factors, such as changing hydrology, water management, human infrastructure, and other factors will affect habitat suitability and freshwater mussel populations. Based on this project, we have identified the following challenges and recommendations for advancing freshwater mussel conservation in light of climate change:

- Because so little research has been conducted on western freshwater mussels, including thermal temperature limits, it is challenging to understand how resilient individual species or populations will be under changing climatic conditions. Thus, an important strategy to advance mussel conservation in a changing climate is to increase research into species' responses to conditions that will be experienced in the future, such as increased water temperature, altered timing of temperatures and flows, etc.
- Complicating any geospatial analysis of freshwater mussels is the fact that mussel distribution information remains incomplete (see discussion above). However, as awareness of freshwater mussels increases, the addition of new observations to the Western Freshwater Mussel Database has the potential to identify new areas of priority under a changing climate. Because the true utility of this analysis is the development of a process and use of an easily-updated and adapted database, as new observations are reported, prioritization and conservation actions can be quickly re-assessed. However, as a first step, targeting mussel surveys in watersheds with lower future temperatures could refocus survey priorities and then refine conservation priorities.
- One of the main challenges to this project has been how to best interpret the role of different metrics in their potential to influence the suitability of watersheds as freshwater mussel climate refugia. For example, the number of permitted nonpoint source pollutant discharge sites would be expected to influence overall water quality within watersheds. Yet, the type, volume, and concentration of pollutants permitted varies by watershed, but also by state-level water quality criteria. As such, the true value of this project likely lies in answering questions within individual waterbodies, where more detailed information can be used to assess impacts to populations. Such a step-down of the project is compatible with how data is mapped, if not summarized, and

can be queried to improve prioritization of waterbodies or watersheds for freshwater mussel conservation efforts.

This additional step-down approach is recommended in future work with restoration and conservation partners to help tailor recommendations to on-the-ground and local conditions, both current and future. Such an analysis is best conducted in partnership with organizations working within a specific watershed, where finer-scaled priority waterbodies, river reaches, or properties can be assessed. The Northwestern Oregon/Willamette Basin focal area provides a good template for this process. Xerces has already begun to reach out to partners in the Willamette Basin to gather additional mussel data, educate restoration practitioners about freshwater mussel best management practices, and develop plans to coordinate mussel conservation with existing efforts. The potential for this area of work to expand, both within the basin and throughout the study area is enormous and could have a large impact on freshwater mussel resiliency under a changing climate.

- Restoration of aquatic habitat (i.e., dam and barrier removals, restoration of instream flows, and enhancement of stream and riverine habitat) has the potential to decrease stress to aquatic ecosystems, and perhaps buffer some habitats against the effects of changing climate. For this reason, it is critical that freshwater mussels be incorporated into current and future restoration efforts. One strategy to address this issue has been to develop a set of best management practices that provide tools for conserving and protecting freshwater mussels (Blevins et al. 2017b). To follow up this work, continuing outreach, testing, and development of BMPs is critical to ensure BMPs are used, effective, and continue to be refined.
- An additional challenge to implementing mussel conservation efforts under a changing climate is the fact that a rare and imperiled species like the western ridged mussel appear to most commonly occur in watersheds expected to experience warmer water temperatures under future climate than many of the potential climate refuges identified in this project. Conservation efforts for this species, however, remain critical to retaining a diversity of mussel species in the western U.S. Additionally, many of these watersheds, which include large, lowland rivers, are important to human communities. Therefore, identifying a balance between targeted efforts in climate refugia and in places where rare species occur remains important.
- With so many uncertainties, a key point in western freshwater mussel conservation is the protection of existing habitat and populations. This and other points have been outlined in the Freshwater Mollusk Conservation Society's national strategy, updated in 2016.

The conservation of western freshwater mussels in a changing climate, as with other species, will require a dedicated and mindful effort. However, the benefits from this work have the potential to improve the resiliency of aquatic ecosystems as a whole because of the important services that freshwater mussels provide. Continued development of tools and strategies to reduce climate impacts, and coordination among groups to implement actions is critical. Next steps will be to apply lessons learned and the tools developed through the analysis and project to focus freshwater mussel conservation efforts in priority watersheds of the Pacific Northwest/Intermountain West.

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APPENDIX

Datasets used in the project

Category	Dataset	Source	Publication Year	Geography	Access
Barrier	Passage Assessment Database	CDFW	2018	CA	https://nrm.dfg.ca.gov/PAD/
Barrier	Streamnet Barriers	Streamnet	2013	ID, MT	https://www.streamnet.org/data/interactive-maps-and-gis-data/
Barrier	Passage Assessment Database	USFWS	2018	NV	https://mojavedata.gov/nvfish/
Barrier	Oregon Fish Passage Barriers	ODFW	2017	OR	https://nrimp.dfw.state.or.us/nrimp/default.aspx?pn=fishbarrierdata
Barrier	Fish Passage Barrier Inventory	WDFW	2017	WA	http://wdfw.wa.gov/conservation/habitat/fish_passage/data_maps.html
Barrier	Not Available	N/A	N/A	WY	N/A
Climate	NorWeST	USFS	2016	OR, WA, ID, MT, CA, NV, WY	https://www.fs.fed.us/rm/boise/AWAE/projects/NorWeST.html
Climate	NorWeST	USFS	2016	Willamette	https://www.fs.fed.us/rm/boise/AWAE/projects/NorWeST.html
Conservation	Crucial Habitat Assessment Tool	WAFWA	2015	OR, WA, ID, MT, CA, NV, WY	http://www.wafwachat.org/
Conservation	Watershed Condition Framework	USFS	2011	Willamette	https://www.fs.fed.us/biology/watershed/condition_framework.html
Conservation	BLM Western Oregon Aquatic Restoration Strategy	BLM	2015	Willamette	https://www.biodiversitylibrary.org/bibliography/121616#/summary
Conservation	Willamette Mainstem Anchor Habitat	Willamette Mainstem Anchor Habitat Working Group	2018	Willamette	Upon request.

Category	Dataset	Source	Publication Year	Geography	Access
Conservation	SLICES	Institute for a Sustainable Environment Lab, University of Oregon	2017	Willamette	http://ise.uoregon.edu/slices/Main.html
Conservation	Willamette Basin Synthesis COAs	The Nature Conservancy of Oregon	2014	Willamette	Upon request.
Diversion	eWRIMS	CA SWRCB	2018	CA	http://ciwqs.waterboards.ca.gov/ciwqs/ewrims/EWMMenuPublic.jsp
Diversion	WaterRightPointOfDiversion	IDWR	2017	ID	https://research.idwr.idaho.gov/index.html#GIS-Data
Diversion	MT Water Rights	MTDNRC	2017	MT	http://ftp.geoinfo.msl.mt.gov/Data/Spatial/NonMSDI/DNRC_WR/
Diversion	Hydrographic Abstract	NDWR	2018	NV	http://water.nv.gov/hydrographicabstract.aspx
Diversion	State Water Rights	OWRD	2017	OR	http://www.oregon.gov/owrd/pages/maps/index.aspx#Water_Right_Data_GIS_Themes
Diversion	Water Diversions NHD	WECY	2016	WA	https://ecology.wa.gov/Regulations-Permits/Guidance-technical-assistance/Water-Resources-Explorer
Diversion	Points of Diversion	WWDO	2007	WY	http://waterplan.state.wy.us/plan/statewide/2007/gis/POD.html
Mussel Occurrence	Western Freshwater Mussel Database	Xerces Society	2018	OR, WA, ID, MT, CA, NV, WY	https://xerces.org/western-freshwater-mussels/
Permitted Discharge	State Combined FRS Facilities	EPA	2017	OR, WA, ID, MT, CA, NV, WY	https://www.epa.gov/enviro/epa-state-combined-csv-download-files
Watershed Boundary	Watershed Boundary Dataset	USGS	2015	OR, WA, ID, MT, CA, NV, WY	ftp://rockyftp.cr.usgs.gov/vdelivery/Datasets/Staged/Hydrography/WBD/National/GDB/WBD_National_GDB.zip