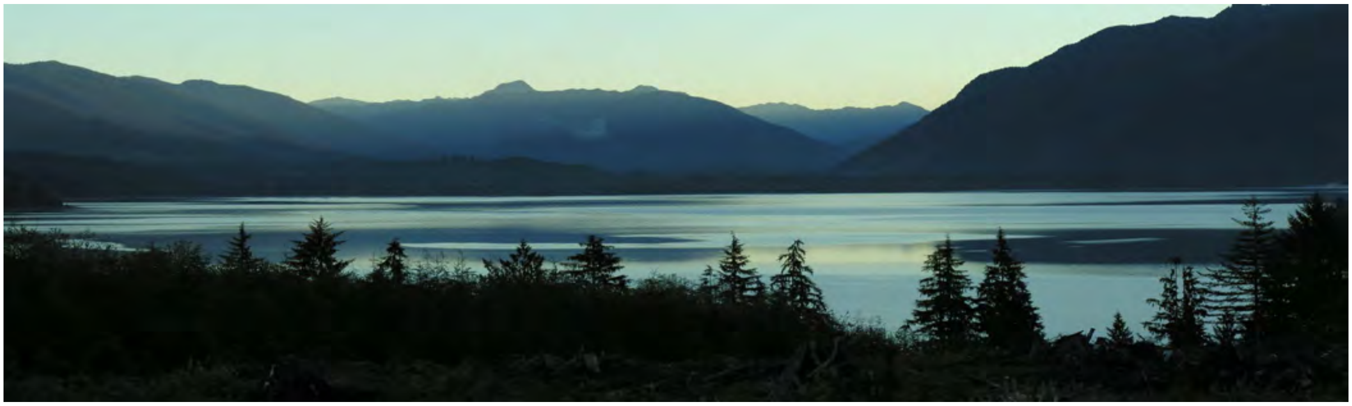

Climate Change Vulnerability Assessment for the Treaty of Olympia Tribes

A Report to the Quinault Indian Nation, Hoh Tribe, and Quileute Tribe
Prepared by The Oregon Climate Change Research Institute
February 2016


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Cover photo credits:
(top) Lake Quinault, Larry Workman
(left) First Beach, Quileute Reservation, Katie Krueger
(right) Western hemlock forest, Quinault Indian Reservation, Larry Workman

Executive Summary

Chapter 1: Introduction

Climate change stands to affect tribal quality of life through changes in the landscape and waters that influence changes in cultural practices and impact the economy of natural resource industries and the subsistence way of life. The Quinault Indian Nation in partnership with the Quileute and Hoh tribes contracted with Oregon State University to develop a climate change vulnerability assessment of culturally and economically important natural resources such as forests, streams, native plants and wildlife, coastal habitats, and ocean and fresh water fisheries. Because native culture is holistic, the vulnerability assessment integrates both Traditional Ecological Knowledge and Western science in order to achieve a fuller understanding of climate change vulnerability.

The assessment focuses on four areas of concern: the terrestrial environment encompassing forests, wetlands, and prairies (upland bogs) and the supported animal and plant species; the freshwater aquatic environment encompassing streams and riparian areas that host important salmonid species; coastal hazards encompassing shoreline erosion and inundation risk zones, and the marine environment encompassing important nearshore and open ocean natural resources. This vulnerability assessment will serve as a basis for building tribal climate change adaptation plans for the unique coastal ecosystems and communities on the Pacific Coast of Washington’s Olympic Peninsula.

Chapter 2: Regional Climate Change

The western Olympic Peninsula receives the most precipitation and hosts the only temperate rainforest in the continental U.S. Yearly precipitation totals range from 70 to 100 inches along the coastal plains to up to 150 inches in the Olympic Mountains. Home to several species found nowhere else and to Native peoples who rely on the natural resources, the unique environment of the western Olympic Peninsula is already experiencing changes in climate that are likely to continue in the future under growing global greenhouse gas emissions.

Over the past century, temperatures on the Olympic Peninsula, like for the Pacific Northwest average, have warmed and spring precipitation has increased. Spring snowpack has also declined over the past half a century coinciding with reductions in summer streamflows. Treaty of Olympia tribes have observed that September has been drier than normal and the usual return of fall rains has been later in recent years. In 2015, as a result of warmer temperatures, much of Washington, including the Olympic Mountains, had less than a quarter of the normal snowpack. The Queets River valley also had a wildfire burning in the summer of 2015, which is a rare occurrence for the Olympic Peninsula. In many ways, 2015 can be thought of as a preview of what normal conditions may look like around the middle of the century; however, climate variability will continue to modulate differences in weather conditions from year to year.

With continued increases in greenhouse gas emissions, the Earth will continue to warm throughout the 21st century and beyond causing far-reaching impacts to natural ecosystems and human populations. Assuming a high future emissions scenario in which greenhouse gas emissions continue to increase with little in global mitigation efforts, annual temperatures averaged over the Northwest are projected to increase by 5.8°F on average by mid-21st century with more warming projected for the summer (6.5°F) (Table ES.1). Future warming of the western Olympic Peninsula may be slightly smaller than the Pacific Northwest average due to the moderating effect of the Pacific Ocean. Annual precipitation is projected to increase slightly (3.2%) with increases during winter (7.2%) and spring (6.5%) and decreases during summer (-7.5%) by mid-21st century under the high emissions scenario (Table ES.1). For watersheds on the Olympic Peninsula, snowpack is projected to decline and streamflows are projected to shift toward higher winter flows and lower summer flows. The occurrence of large wildfires is also expected to increase in the future.

Table ES.1 *Multi-model mean projected changes in Northwest-averaged annual and seasonal mean temperature and precipitation for mid-century (2041-2070) compared with the baseline period (1950-1999) for a high emissions scenario. Projected temperature increases for coastal areas are generally likely to be smaller than the Pacific Northwest-average projections shown here due to the moderating effect of the Pacific Ocean. (Source: Mote et al., 2013)*

Mid-21st Century Projections (High emissions scenario)	**Temperature**	**Precipitation**
Annual	5.8°F	3.2%
Winter	5.8°F	7.2%
Spring	5.4°F	6.5%
Summer	6.5°F	-7.5%
Fall	5.6°F	1.5%

Chapter 3: Terrestrial Environment

The terrestrial environment, including forests, wetlands, and prairies (upland bogs) and the flora and fauna comprising these habitats, is vulnerable to transformation through direct climate sensitivity to temperature and precipitation changes, but also through indirect sensitivity to disturbances such as wildfire, insects and diseases, and invasive species. Forestry practices also substantially influence the landscape.

In response to warmer and drier summers projected for the future, fire activity in the Northwest is projected to increase potentially threatening timber resources and habitat for certain species. Warming temperatures may give pests, such as the spruce weevil (*Pissodes strobi*), and tree diseases, such as Swiss needle cast (*Phaeocryptopus gaeumannii*), more opportunity to establish. The role of climate change in the invasion of non-native species in particular areas is largely unknown, however, climate change may exacerbate some of the existing problems the Treaty of Olympia tribes are already experiencing with invasive species.

Vulnerability of wetlands on the Olympic Peninsula is high due to past degradation and susceptibility to invasive species such as knotweed (*Polygonum* spp.) and reed canarygrass (*Phalaris arundinaceae*). Generally, wetlands with sustained sources of water are less vulnerable to climate change. Bogs, fens, wet meadows, isolated ponds and wetlands near headwater streams and alpine ecosystems are more vulnerable to climate change. Prairies—openings of bogs, fens, and grasslands—provide foraging grounds for wildlife and host many traditionally gathered resources. Increased wildfire activity could benefit prairies, however, warming and changing hydrology could alter vegetation composition and increase pressure from invasive species.

When considering the impact climate change may have on plant and animal species, it is important to remember that a species' vulnerability is a function of its sensitivity, exposure (to a changing climate), and its adaptive capacity. Hence, a species may have high sensitivity but low vulnerability.

Trees

The Treaty of Olympia tribes identified twelve trees with economic (e.g., Western hemlock), cultural (e.g., Western red cedar), and ecological (e.g., red alder) importance. The Sitka spruce was relatively more sensitive to climate change than other tree species due to its restriction to coastal areas, physiological sensitivity to temperature and precipitation regime changes, poor dispersal ability, and high sensitivity to changes in disturbance regimes such as fire, wind, and disease. Tree species moderately sensitive to climate change, largely due to limited dispersal ability and sensitivity to disturbances, include: western white pine, western red cedar, Douglas-fir, Pacific yew, and Lodgepole pine. Pacific silver fir and Western hemlock have low to moderate climate change sensitivity due to limited dispersal ability and interaction with non-climatic existing stressors, such as invasive species and insects and diseases. Big leaf maple and red alder are least sensitive due to wide climatic ranges and good dispersal ability.

When considering the vulnerability of these trees to climate change, the conclusions are somewhat different than when just considering sensitivity (Table ES.2).

Understory Vegetation

Much less information is available on climate change vulnerability of understory vegetation, such as berries, compared with trees. Huckleberries, salal berries, salmonberries, native blackberries, strawberries, and cranberries are all traditionally gathered by the tribes. The die off of certain overstory tree species due to climate change could potentially benefit understory vegetation, but the effect on individual species and competition between native and non-native species is largely unknown. Salal, one of the most common forest understory shrubs in the Pacific Northwest, has low to moderate climate change sensitivity due to limited dispersal ability and low physiological sensitivity to temperature and precipitation changes. Beargrass, used in basketry, may benefit under climate change due to increasing fire frequency, which could reduce competition with trees and shrubs.

***Table ES.2** Climate change vulnerability ranking of all terrestrial species important to the Treaty of Olympia tribes. Ranking based on Devine et al. (2012) (Table 3.1, last column) and Range Projection[1] % net changes in suitable habitat over the Olympic Peninsula (Tables 3.2 and 3.3; % net change ≥ 0 = Low, % net change < 0 = Low-Moderate).*

Vulnerability	Species
High	Pacific silver fir, Yellow cedar
Low-Moderate	American beaver, Roosevelt elk, Cougar
Low	Sitka spruce, Western white pine, Western red cedar, Douglas-fir, Western hemlock, Black cottonwood, Big leaf maple, Red alder, Black bear, Black-tailed deer, River otter, Bald eagle, Common raven, Rufous hummingbird, American crow, Great blue heron
Little Information	Salal, Pacific Yew, Lodgepole pine, Huckleberries, Salmonberry, Native blackberry, Strawberry, Cranberry, Beargrass, Labrador tea, Skunk cabbage, Forbs, Devil's club, Nootka rose, Cascara, Mushrooms, Snowshoe hare, Gulls, Harlequin duck, Canada goose, Brown pelican

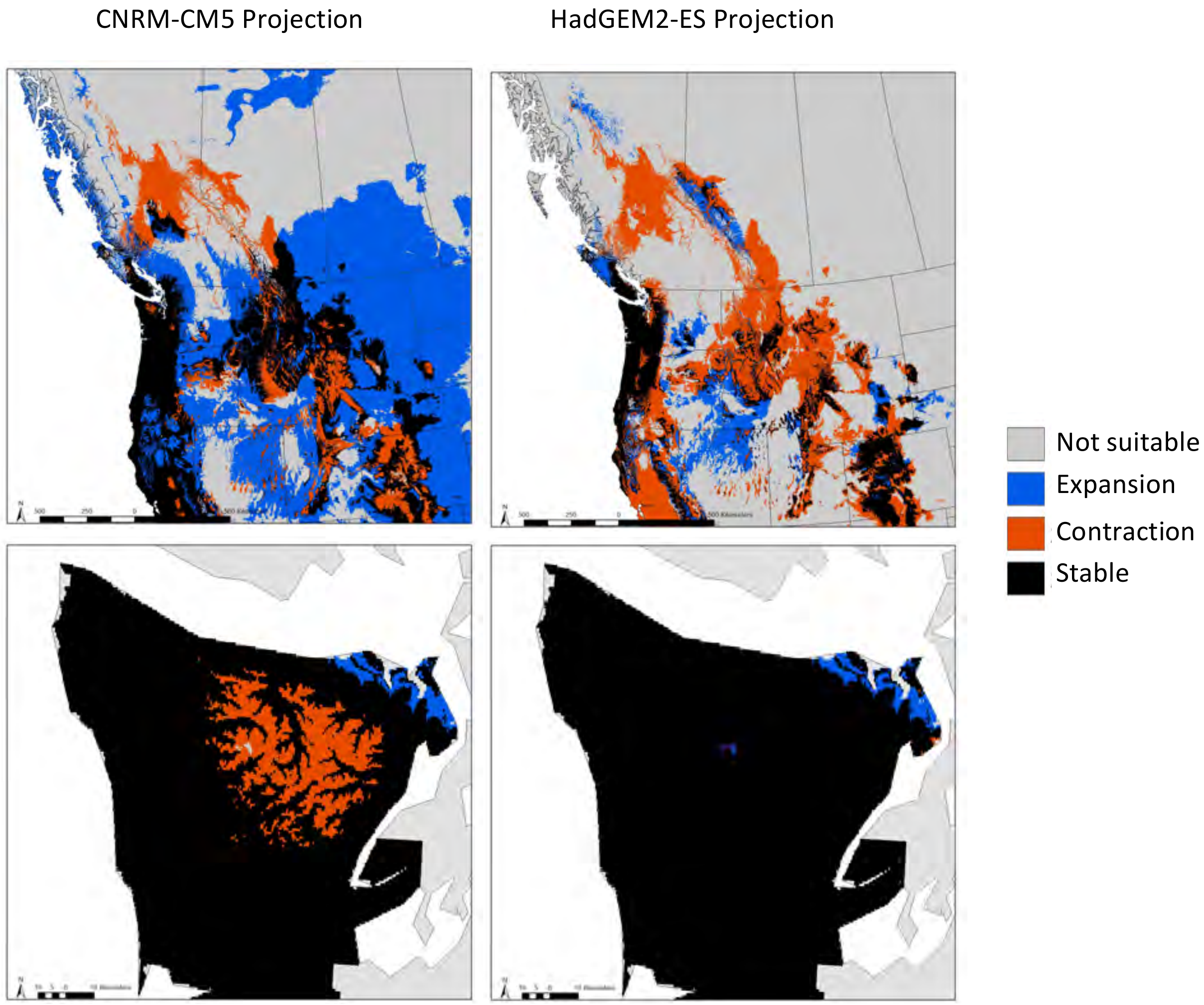
[1] climatevulnerability.org

Mammals

Both the beaver and elk have low to moderate vulnerability to climate change (Table ES.2). Beavers can disperse relatively long distances and are generally not sensitive to changes in disturbance regimes. However, they have a somewhat sensitive life history and are also sensitive to habitat loss or degradation and direct human conflict, such as harvesting. The beaver was projected to have a positive net change of current habitat implying they may be less vulnerable to future changes in climate and vegetation. Elk have a flexible diet, excellent movement capabilities (although those on the Olympic Peninsula tend not to disperse very far), and are not restricted to a narrow thermal niche. The Roosevelt elk are being challenged by a diminishing food supply due to forest practices and invasive weeds and declines in summer precipitation, longer dry seasons, and increased wildfire burn areas could further reduce food resources for elk.

Elk, black bear, and black-tailed deer had the largest projected declines in current habitat assessed over their entire range. Roosevelt elk found on the Olympic Peninsula may in fact be more vulnerable to climate change because they had the largest net change in suitable habitat assessed over the Olympic Peninsula (Figure ES.1). Black bear also had the largest decrease in overall net change between current and future habitats, implying that this species may be more vulnerable to future changes in climate change and climate-driven changes in vegetation. However, black bear suitable habitat is projected to increase at high elevations on the eastern side of the Olympic Mountains. Black-tailed deer is projected to retain its current suitable climate space throughout the Olympic Peninsula in the future.

Figure ES.1 *Suitable climate space projections for elk. The maps show where the current climate space is projected to potentially remain stable (black), contract (orange) and expand (blue) for two different global climate models (CNRM-CM5 and HadGEM2-ES) under the RCP 8.5 greenhouse gas emissions scenario. Olympic Peninsula projection maps were clipped by Clallam, Jefferson, Mason, and Grays Harbor counties.*

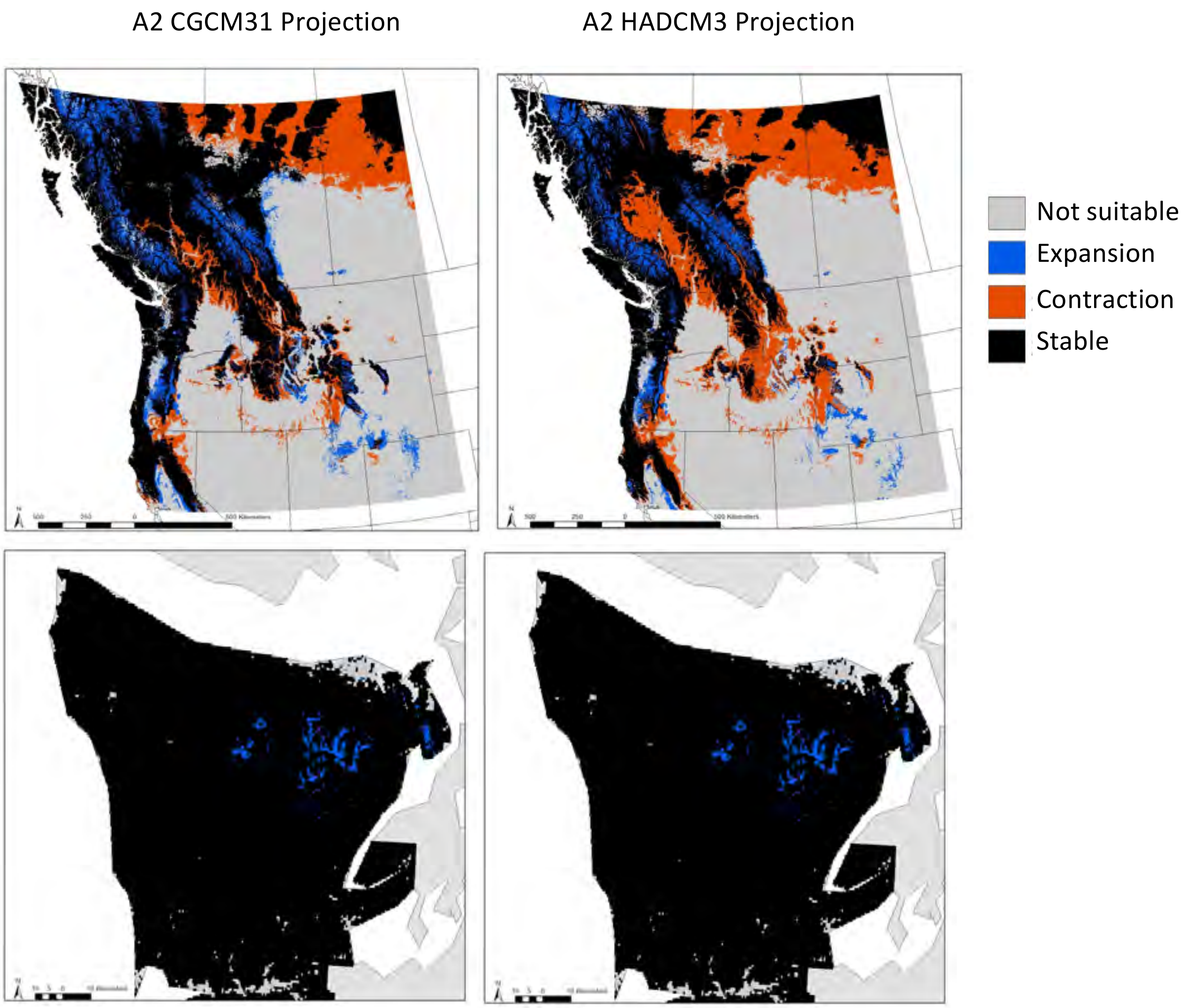


Birds

In general, the birds of greatest importance to the tribes (e.g., bald eagle, raven) were also considered least vulnerable to climate change (Table ES.2). The bald eagle, common raven, and the Rufous hummingbird had the largest projected declines in suitable habitat assessed across their entire range, however, changes were relatively minor on the Olympic Peninsula. Because these species have very large ranges, they may be more capable of adapting to future climatic changes than species that have small ranges. The bald eagle could potentially expand its habitat on the eastern Olympic Peninsula (Figure ES.2). The raven is projected to retain its current habitat on the Olympic Peninsula. The American crow and great blue heron are least vulnerable to future changes in climate and vegetation since suitable habitat across their entire range and on the Olympic Peninsula are projected to increase.

The migratory birds (brown pelican, harlequin duck, Canada goose) had moderate or high sensitivity to climate change. Brown pelicans are sensitive to the availability of small fish (the primary food resource), which in turn are highly sensitive to changing ocean conditions. The Canada goose has specific foraging and phenology dependencies and requires a somewhat specialized nesting habitat. The Harlequin duck has unique habitat dependencies, specific food requirements, and is physiologically sensitive to changes in temperature and precipitation.

Figure ES.2 *Habitat suitability range projections for the bald eagle. The maps show where the current range is projected to potentially remain stable (black), contract (orange) and expand (blue) for two different global climate models (CGCM31 and HADCM3) under the A2 greenhouse gas emissions scenario. Olympic Peninsula projection maps were clipped by Clallam, Jefferson, Mason, and Grays Harbor counties.*



Chapter 4: Freshwater Environment

Pacific salmon (*Oncorhynchus* spp.) are integral to tribal culture and identity and are vulnerable to climate changes throughout their life cycle via changes in the marine, estuarine, and freshwater environments. The major river basins in the Treaty of Olympia area are likely to experience warmer waters, lower summer flows, and higher winter flows in the future. These changes, combined with human alteration, will have unprecedented effects on the freshwater ecosystem. Warmer and more acidic marine waters will also challenge Pacific salmon.

Adults & Spawning. Adult salmon spend one or more years growing in the marine environment before returning to freshwater to spawn. More acidic marine waters will disrupt the calcifying organisms at the base of the marine food web that supports salmon in the ocean and warmer surface waters may reduce the preferred thermal habitat. This could result in fewer and smaller returning adults and affect reproductive success. Some spawning salmon (e.g., spring Chinook and summer steelhead) require pools of cool water for holding and migrating, which may become increasingly difficult to come by as stream temperatures increase. This may diminish reproductive potential and increase pre-spawning mortality. Fall Chinook may fair better under climate change by avoiding the warm, low-flow summer conditions. In addition, sea level rise could reduce spawning habitat for some species that spawn near tidewater (e.g., pinks, chums).

Eggs & Developing Embryos. Altered streamflow and increased incubation temperatures are the main climate change impacts affecting eggs and developing embryos. Higher winter flows would increase the risk of scouring, especially in small streams for fish spawning in the late fall and winter (e.g., summer steelhead). Warmer stream temperatures could result in accelerated development leading to earlier emergence, but smaller individuals. This is especially problematic for species adapted for cooler water temperatures during development (e.g., Coho).

Juveniles. Juveniles will be primarily affected by elevated stream temperatures and altered streamflows though the type and extent of flow impacts will vary depending on the time of emergence and geomorphic setting. Salmon fry in low gradient streams (e.g., Chinook, Coho, Pink, Chum) with intact floodplain vegetation and secondary channels are less vulnerable to displacement from higher winter flow conditions than fish that emerge in late fall and winter in steeper streams (e.g., summer steelhead). Warmer temperatures during the summer could reduce growth resulting in decreases in juvenile survival over winter; however, this could be offset by increased growth rates under warmer conditions during other seasons. Elevated water temperatures could enhance aquatic food availability, but competition by non-salmonids may increase. The susceptibility of juvenile salmonids to disease could increase at warmer temperatures as well as predation by non-native warm-water fish.

Smolt. Increasing water temperatures will affect the physiological aspects of smolting while changes in hydrology will affect downstream migration. Higher winter temperatures could result in earlier smolt migration, as has been observed in Chinook salmon; however, the effect is species-dependent. Summer low flows are projected to occur earlier affecting populations that tend to migrate later or are required to move long distances. Changes in timing and type of marine food availability as well as the nearshore predator community would threaten smolt upon ocean entry, especially those that enter the ocean earlier and are smaller.

Virtual watersheds of the Quinault, Queets, and Hoh Rivers, and the Quillayute River basin were created in NetMap. Climate change projections of summer stream temperatures and summer and winter average streamflows based on a medium emissions scenario by the 2040s were aggregated into the virtual watersheds. In addition, the habitat intrinsic potential (IP), which serves as an indicator of the potential of a given stream-reach to provide high-quality habitat for a particular species, for Coho, Chinook, and steelhead was developed for each watershed.

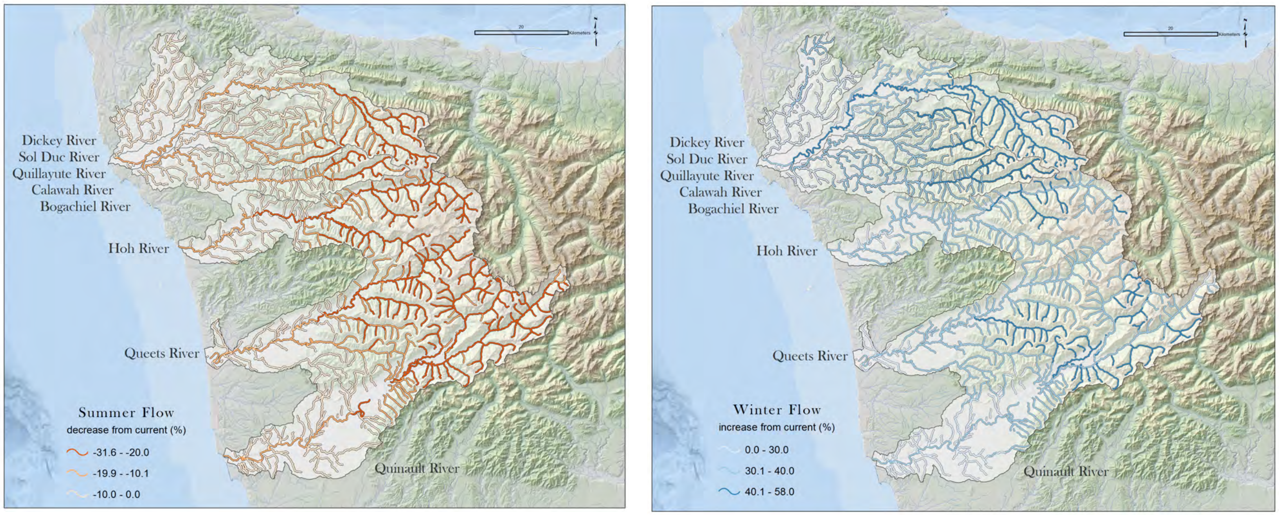
Streams in all four basins during summer are projected to warm. Summer water temperatures in the majority of habitat in the Hoh and Quinault Rivers will remain <15^{o}C while the Queets River and Quillayute River basin will see more stream areas with temperatures >15°C. Chinook salmon will be most affected by such stream temperature increases. Much of the area will remain within suitable thermal ranges for Pacific salmon; however, summer temperature increases could reduce growth and increase predation by and competition with warm-water fish. Providing a coordinated network of riparian restoration actions extending from headwaters to estuaries (and laterally onto floodplains) would help mitigate potential temperature increases.

Average summer flows (Figure ES.3) are projected to decline by up to 30% across large areas of streams in all basins. High IP areas, in the Hoh River especially, for Coho and Chinook salmon will be most affected by these summer flow reductions, as will high IP areas for Chinook in the Quillayute River basin. Reduced summer flows could disrupt migration of returning adults, such as delays until water cools, but the relatively short migration distances and diel variation in water temperatures could minimize such effects.

Average winter flows (Figure ES.3) are projected to increase by at least 30% over the majority of stream reaches. The greatest increases of more than 40% will be in the Quinalt River and Quillayute River basin. Increased winter flows could reduce survival of developing eggs, embryos, and juveniles due to scour, however, this is species- and stream-dependent. Restored floodplain connectivity provides seasonal protection for rearing salmonids by increasing access to slack-water areas during high flow.

Future conditions are very unlikely to resemble historic ones. The magnitude of climate-driven changes vary among the river basins within the Treaty of Olympia area, but overall changes in the freshwater ecosystems are relatively small by mid-century so ecological consequences are likely to be minimal. It is likely that a major challenge for Pacific salmon in the study area will result from changes in the marine environment. Salmonids exhibit large genetic and phenotypic diversity and can adapt to changing conditions rapidly, which will be a key to their future survival. However, it is unknown how quickly salmonids can adapt to current and future rates of climate change, effects of invasive species, and altered ecological processes. It will be imperative to develop local management strategies to minimize the effects of climate change, and to recover and maintain the productivity of Pacific salmon and other native fish and aquatic organisms.

Figure ES.3 *(left) Percent reduction in average summer flow and (right) percent increase in average winter flow from current to 2040 in study basins in the Treaty of Olympia area.*



Chapter 5: Coastal Hazards

Coastal ecosystems and communities along the outer coast of the western Olympic Peninsula (see Figure 5.1) are currently at risk of erosion and flooding hazards driven by extreme total water levels (TWLs)—mean sea level combined with storm surge, high tide, seasonal and interannual variability in sea level, and ocean wave characteristics. Understanding the magnitude and frequency of these extreme water level events will better prepare coastal communities for dealing with both present day and future coastal hazards which effect critical shoreline habitats and infrastructure. TWLs along the shoreline of the Treaty of Olympia area are modeled for both present day conditions and future conditions under rising sea levels and increasing wave heights.

Along the Pacific Northwest coast, sea level is projected to rise by 4-56” by 2100 considering uncertainties in regional effects. The central and southern Washington coast is uplifting at a slower rate than the northwest Olympic Peninsula, even subsiding in some areas, and thus is poised to experience the effects of sea level rise sooner than the northwest coast. In this analysis, sea level projections for 2050 range from -0.10 to 0.5 meters (-3.9” to 19.7”), corresponding with the projected range for 2100. The observed increasing wave height trend is allowed to continue to mid-century. Two types of high water events are analyzed: nuisance events (everyday hazards characterized by the average amount of days per year that the coastline experiences either overtopping or collision) and extreme events (such as the annual maximum event or the 100-year return level event).

The type of backshore[1] is important for characterizing TWLs and their impacts. By comparing elevations of TWLs to the elevation of the foremost backshore feature, we can estimate the risk of overtopping and inundating the backshore area and the risk of colliding with and eroding the backshore

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[1] The backshore is the region of the beach extending from the high water line to the landward extent of the beach. The most foremost backshore feature is therefore the first feature (dune, cliff, bluff, etc.) in which high water levels may impact.

feature be it a bluff, cliff, dune, or engineered structure. The Hoh, Quileute, and Quinault coastlines, and surrounding beaches, consist of highly variable morphology including both low-sloping and steep beaches comprised of either sand or gravel and are backed by dune, bluffs, or cliffs. In general, however, the most characteristic morphology includes steep cliffs and bluffs, occasionally fronted by ephemeral beach berms. The number of days per year that these smaller fronting features experience impact (erosion) and overtopping (flooding) varies along the coastline (Table ES.3), as do extreme TWL return level events. These ephemeral features most likely act as a buffer to backing cliff or bluff erosion and critical habitat.

The beach segments from south of Ozette Lake to Rialto Beach, along the Quileute reservation, and Ruby Beach to the Queets River experience impact (erosion) regime on the leading backshore feature for at least half the year largely due to steep beach slopes and low dune toes. Most other areas along the Treaty of Olympia coastline experience impact days about a third of the year. In general, overtopping occurs much less often than the collision regime, but is most common near Kalaloch and some parts of the Taholah area where it occurs about 100 days per year. Under all sea level rise scenarios water levels increase along the coast, driving increases in number of impact or overtopping days per year (Table ES.3). The largest increases in impact days per year occur along the beach segment from Ruby Beach to the Queets River (Figure ES.4) and areas within the Cape Alava to Rialto Beach segment. The overtopping regime remains infrequent, due to the large amount of cliffs and bluffs backing the majority of the coastlines, but increases by a few more weeks per year along the Cape Alava to Rialto Beach segment and the Hoh Reservation coastline.

The annual maximum TWL event increases under all SLR scenarios for the Hoh, Quileute, and Quinault coastlines, but the Hoh coastline may receive the largest changes (Figure ES.5) likely due to the overall steeper beaches. Likewise, the steeper beaches from Ozette South may result in larger increases in the annual maximum TWL event compared with First Beach (Table ES.3). The southern Quinault coast segment experiences the smallest increase in the annual maximum event. However, even slight increases in water levels may matter more in locations with critical habitat or infrastructure (e.g., the Taholah area) rather than locations where little infrastructure or high backing cliff morphology exists.

Figure ES.4 *Impact days per year (IDPY; middle) and overtopping days per year (ODPY; right) for Ruby Beach to the Queets River. Bolded black lines indicate the average (across 35 simulations) IDPY/ODPY computed using the present-day simulations while blue, green, and red lines indicate future simulations for low, medium, and high sea level rise, respectively.*

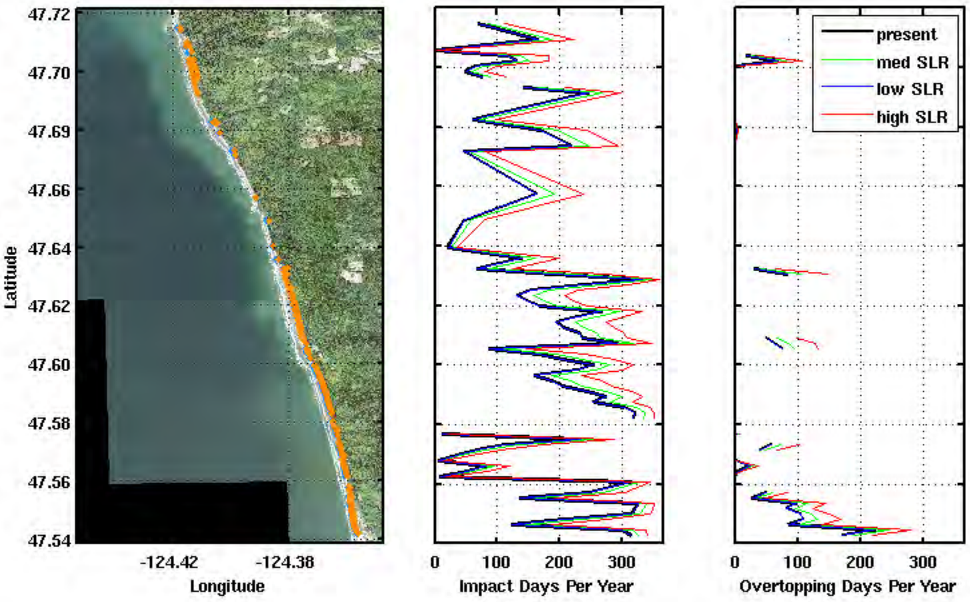
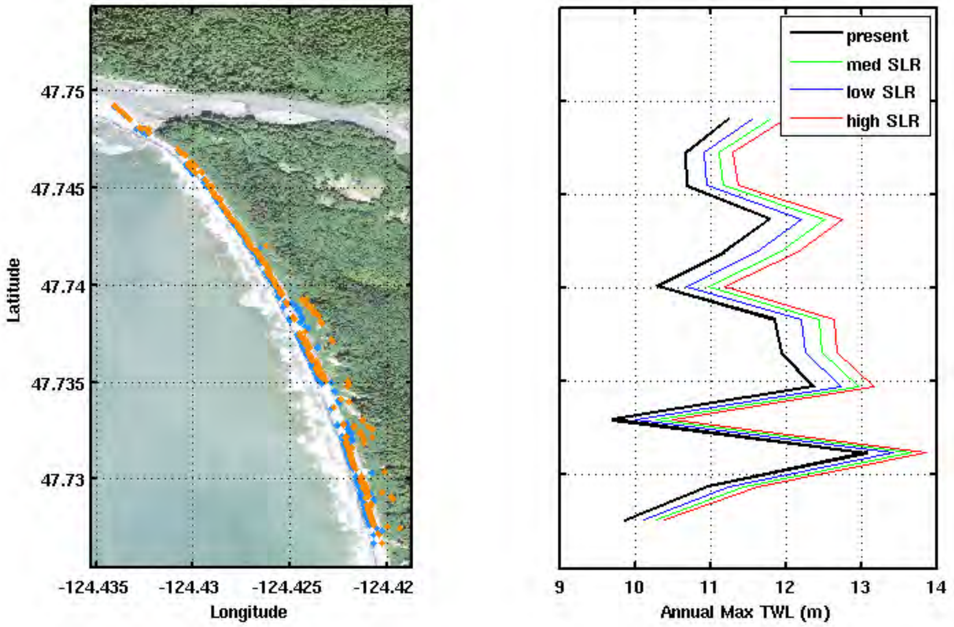


Figure ES.5 *The annual maximum TWL for the Hoh reservation. Bolded black lines indicate the average (across 35 simulations) annual maximum TWL computed using the present-day simulations while blue, green, and red lines indicate the average annual maxima of future simulations (12 each scenario) for low, medium, and high sea level rise, respectively.*



Certain species with economic and cultural significance to the Treaty of Olympia tribes (e.g., surf smelt, razor clams, shorebirds) may be impacted by the projected future changes in extreme total water levels.

While the projected changes in TWLs by 2050 are likely not severe enough to significantly threaten coastal habitat, some intertidal species may shift landward. For example, across all of the locations, the 3m contour is inundated every day of the year during the maximum daily TWL under a high SLR scenario. The largest amount of change, on average, is in the southern extent of the Quinault area. While intertidal species, like razor clams and surf smelt, may have the ability to move vertically up the beach, snowy plovers and other back-barrier nesting species may face habitat loss as sea levels continue to rise.

Table ES.3 *Percent change (and standard deviation) in impact (erosion) and overtopping (inundation) days per year for present conditions and mid-21st century high sea level rise projections and increase in the average annual maximum TWL event for segments of the Treaty of Olympia coastline. The coastline segment is ranked by the average amount of Impact Days Per Year (e.g., on average, Quileute presently experiences the most IDPY and Southern Quinault experiences the least IDPY). See chapter for projected values.*

Coastline Segment	**% Change in IDPY**	**% Change in ODPY**	**Average Increase in Annual Maximum TWL Event**
Quileute (Rialto Beach and First Beach)	+18% (±11%)	+35% (±31%)	+50 cm
Kalaloch (Ruby Beach to the Queets River)	+30% (±25%)	+55% (±34%)	+50 cm
Ozette (Cape Alava to Rialto Beach)	+25% (±36%)	+50% (±45%)	+60 cm
North Quinault (Northern Taholah to Queets River)	+18% (±15%)	+35% (±60%)	+50 cm
Middle Quinault (Point Grenville to Northern Taholah)	+17% (±40%)	+25% (±55%)	+50 cm
Second Beach	+54% (±10%)	+90%[1]	+43 cm
Hoh	+16% (±13%)	+27% (±12%)	+77 cm
Third Beach	+47% (±6%)	+43%[1]	+63 cm
Southern Quinault (Moclips to Point Grenville)	+65% (±33%)	+95% (±30%)	+30 cm

[1] Only one point was included in the analysis, so no standard deviation could be calculated.

Chapter 6: Marine Environment

The marine environment is culturally, economically, and ecologically important to the Treaty of Olympia tribes. The main climate change drivers affecting the marine environment include ocean acidification, increasing sea surface temperature, altered hydrology, altered frequency and severity of storms, sea level rise, altered patterns of coastal upwelling and hypoxia zones, and harmful algal blooms. Marine species (invertebrates, fish, mammals, algae) are likely to respond to changes in marine and coastal nearshore habitats by shifting ranges and distributions, altering phenology and development, shifting community composition, competition, and survival, and altering interaction with non-native and invasive species.

Sea Level Rise & Storminess. Global sea level is rising and is expected to continue, even on the west coast of the Olympic Peninsula under moderate to high sea level projections. Future sea level rise, combined with the expected continued trend in increasing ocean storm waves, will lead to greater risks of coastal erosion and flooding potentially resulting in habitat loss.

Ocean Acidification, Upwelling, Hypoxia. The absorption of atmospheric carbon dioxide by the world's oceans is increasing the acidity and reducing the saturation state of the seawater challenging calcifying organisms crucial to the marine food web, such as zooplankton and shellfish. The oceans are also warming with sea surface temperatures off Washington's Pacific coast projected to increase more than 2°F by mid-21st century. Coastal upwelling is expected to intensify, which could mediate the effects of coastal marine habitat warming, but also lead to more frequent hypoxic (oxygen deficiency in a biotic environment) events and even higher coastal seawater acidity. Combined, these changes could disrupt ocean nutrient cycling, productivity, and food web dynamics.

Harmful Algal Blooms. Warming seawater and higher nutrient levels from enhanced upwelling could also lead to more frequent harmful algal blooms in the future affecting marine life and the commercial and subsistence harvest of shellfish.

Estuaries. Estuaries are crucial habitats for many culturally and ecologically important species, including juvenile salmon, forage fish, and larvae of various shellfish species. The combination of ocean acidification, altered upwelling, sea level rise, and changes in freshwater runoff could substantially alter the quality of this critical habitat.

Marine Invertebrates. Survival and growth for most calcifying organisms will be negatively affected by ocean acidification. However, different species within a taxon may be more resilient than others depending on phenology and other factors. Calcifying mollusks (including clams, mussels, snails, limpets, and pteropods) and echinoderms (including sea stars and sea urchins) are vulnerable to reduced calcification and weakened calcified structures under ocean acidification, particularly during the larval and juvenile stages, but also potentially during adult stages. Crustaceans (including crabs, lobsters, crayfish, shrimp, krill, and barnacles) are generally considered tolerant to ocean acidification with little response or even increases in the calcification of the exoskeleton, but could still experience weakened calcified structures during the larval stage.

Marine Finned Fish. Marine fisheries such as blackcod (sablefish), lingcod, rockfish, halibut, sardines, salmon, and smelt, provide commercial and subsistence livelihood to the Treaty of Olympia tribes. Fisheries will exhibit varied responses to changing water conditions and the local species assemblages may shift. Future warming may increase abundance of species that thrive during warm periods of natural variability, such as sablefish, halibut, and sardines. Warm water species, such as mackerel or Bluefin tuna, may become more abundant. Changing ocean conditions could be particularly challenging for salmon through a reduction in pteropods (a significant food source for some species), degraded coastal rearing habitat, and warming seawater, which is correlated with decreases in salmon abundance south of Alaska.

Marine Mammals. Climate change is likely to impact marine mammals indirectly through alteration in food availability and prey communities. Seasonally migrant whales (humpback, gray) may range farther north and stay longer as Arctic waters warm and sea ice declines. Pinnipeds (seals, sea lions, and walruses) may experience loss of resting habitat from sea level rise and food sources may shift away from existing resting areas. However, most marine mammals may be able to adjust migration or feeding habits to adapt to changes. Marine mammals that eat shellfish, such as marine otters and sea lions, are susceptible to harmful algal blooms that may become more prevalent in their food supply.

Marine Algae. Fleshy macroalgae beds (often called kelp forests) form major habitat for marine fish harvested by the Treaty of Olympia tribes. Macroalgae in temperate regions have generally low vulnerability to temperature changes and may experience enhanced growth from the fertilization effect of ocean acidification. Microalgae (phytoplankton) are crucial to the marine food web and will have varied responses to climate change. The make up of local phytoplankton communities is projected to change substantially due to warming, with an average poleward shift in phytoplankton range, and differing responses to ocean acidification spurring competition among species. In general, ocean acidification will negatively affect calcifying phytoplankton (coccolithophores), positively affect cyanobacteria, and have largely no effect on diatoms and dinoflagellates. However, warming temperatures and increased nutrients could result in more frequent harmful algal blooms of the latter phytoplankton taxa.

Chapter 7: Conclusions

Through original analysis and literature review, we assessed the climate change vulnerability of the forests, streams, coastline, and ocean within the Treaty of Olympia area on the western Olympic Peninsula along with the associated plant and animal species most important to the Quinault Indian Nation and Hoh and Quileute tribes. Conducting a vulnerability assessment is often one of the first steps in the iterative and collaborative process of adapting to climate change. The research on localized climate change impacts and vulnerability of species and ecosystems is accelerating, but several knowledge and data gaps remain. Filling the gaps in understanding about how the species and ecosystems important to the culture and economy of the Treaty of Olympia tribes will respond will be important for building resiliency to climate change impacts. Next steps in climate change preparation include building capacity, engaging the community, monitoring key components of the ecosystem, incorporating climate change impacts into existing plans, increasing resilience, adapting governance, conserving, restoring and protecting natural resources. More fully integrating Traditional Ecological Knowledge and Western science will produce a more comprehensive understanding of the climate change vulnerability of the landscape, surrounding waters, and plant and animal species important for maintaining traditional culture and lifestyle.

Chapter 1: Introduction

Authors: Meghan Dalton, Samantha Chisholm Hatfield

1.1 Project Genesis

The Quinault Indian Nation (QIN) in partnership with the Quileute and Hoh tribes (collectively termed the Treaty of Olympia tribes) contracted with Oregon State University (OSU) to develop a vulnerability assessment to project climate change impacts on culturally and economically important natural resources such as forests, streams, native plants and wildlife, coastal habitats, and ocean and fresh water fisheries within the Treaty of Olympia area (Figure 1.1). Because native culture is holistic, the vulnerability assessment integrates both Traditional Ecological Knowledge (TEK) and Western science in order to achieve a fuller understanding of climate change vulnerability. This vulnerability assessment will serve as a basis for building tribal climate change adaptation plans for the unique coastal ecosystems and communities on the Pacific Coast of Washington's Olympic Peninsula.

1.2 Western Olympic Peninsula

The western Olympic Peninsula receives the most precipitation in the continental U.S. Yearly precipitation totals along the coastal plains ranges from 70 to 100 inches and on the western slopes of the Olympic Mountains annual precipitation can reach 150 inches or more (Western Regional Climate Center). This wet, rainy climate hosts the only temperate rainforest and one of the largest areas of old growth forests in the continental U.S. as well as many unique species found only on the Olympic Peninsula. Beginning at least 12,000 years ago, people have inhabited the primeval forests and coastal plains of the Olympic Peninsula as fishers, hunters, and gatherers deriving sustenance from the natural resources provided by the forest, rivers, lakes, coast, and ocean (Olympic National Park).

1.3 Treaty of Olympia

In the Treaty of Olympia of January 1856, the Quinault and Quileute Indians (Hoh was not yet separate from Quileute) ceded to the U.S. the western Olympic Peninsula while reserving "tracts of land sufficient for their wants" (Figure 1.1). The tribes reserved the right to access fish, game, and plants off the reservations. Fishing rights were limited to all usual and accustomed areas. Usual and accustomed fishing areas include both freshwater and ocean fisheries, in which tribes are co-managers with other tribes, federal agencies, and the State of Washington. Also reserved for all three tribes is the right to hunt and gather on all open and unclaimed lands in the entire ceded area. These reserved areas may exceed the treaty area as may be demonstrated by anthropological evidence in federal court.

***Figure 1.1** Ceded lands of the Treaty of Olympia, 1856 (Source: Quileute Tribe, http://www.quileutenation.org/the-treaty-of-olympia)*

1.4 Treaty of Olympia Tribes

All three Treaty of Olympia tribes depend greatly on freshwater and marine fisheries. In addition, traditional plants, forests, water, and wildlife are resources of economic and cultural importance. The principal ecosystems in the tribes' coastal area of interest that are vulnerable to climate change impacts are the ocean, shorelines and beaches, low-lying terrain, forests, rivers and lakes, and the economically and culturally important natural resources within those areas.

The economic, cultural, and subsistence importance of certain species or impacts may vary between the tribes. One major difference is the much greater size of the Quinault Reservation, consisting of over 200,000 acres, while Hoh and Quileute’s reservations consist of about two square miles each. The economy of the QIN is therefore the largest of the three tribes owing both to a large timber industry and to its owning and operating a casino and other enterprises. However, the Quileute own and operate a marina and a resort commercially, on the reservation. All three tribes’ members depend heavily on commercial and subsistence harvest of both freshwater and marine fish and shellfish, and on subsistence harvest of game and plants, a major reason for reserving treaty rights to access them within the usual and accustomed or ceded areas.

1.5 Tribal Culture & Climate Change

Tribal cultural identity and livelihood are tied to the landscape and surrounding waters. Climate change stands to affect tribal quality of life through changes that influence cultural practices, including traditional harvests, and impact the economy of natural resource industries (especially timber and the fisheries) and the subsistence way of life. Tribes have intrinsic values in caring for all the resources that sustain populations of fish, shellfish, plants, and animals critical to their livelihood. Tribal adaptation involves building resilience to climate change in order to sustain their traditional way of life. Cultural practices that involve natural resources, such as materials for basketry, or specific areas, or foods for ceremonial events stand to be impacted significantly as well. In addition to these intrinsic interests in sustainability, however, all three tribes co-manage the fisheries with the State of Washington (as held by numerous federal court decisions) and collaborate with the State and Olympic National Park on forestry management. Accordingly, the tribes have extensive collaborative management duties that are shared with agency personnel to determine the best actions to protect and preserve natural resources.

1.6 Vulnerability Assessment Approach

Climate change vulnerability is defined by the exposure of a given species, resource, area, or system to climate changes, the sensitivity or response to such climate changes, and the adaptive capacity or inherent safeguards or coping mechanisms (Glick et al., 2011). This vulnerability assessment focuses on four areas of concern to the Treaty of Olympia tribes: terrestrial environment, freshwater environment, coastal hazards, and the marine environment. We define the terrestrial environment to include forests, wetlands, and prairies (upland bogs) and the animal and plant species supported by these habitats. The freshwater environment includes streams and riparian areas and the supported salmonid and other fish species. The area of coastal hazards is defined to include erosion and inundation risk zones along the shoreline and beaches and the affected natural ecosystems. We define the marine environment to include both nearshore and open ocean natural resources important to the Treaty of Olympia tribes. The climate change impacts and sensitivity are assessed separately with different methodologies for each of these four components.

In this vulnerability assessment, we define Traditional Ecological Knowledge (TEK) as defined from the Dene Cultural Institute’s 1995 definition:

> *“TEK is a body of knowledge and beliefs transmitted through oral tradition and first-hand observation. It includes a system of classification, a set of empirical observations about the local environment and a system of self-management that governs resource use.*

> *Ecological aspects are closely tied to social and spiritual aspects of the knowledge system. The quantity and quality of TEK varies among community members, depending upon gender, age, social status, intellectual capability and profession (hunter, spiritual leader, healer, etc.). With its roots firmly in the past, TEK is both cumulative and dynamic, building upon the experience of earlier generations and adapting to the new technological and socioeconomic changes of the present" (Stevenson 1996, 281).*

The TEK of the tribal members of all three Treaty of Olympia tribes is expansive, and not fully documented. A full TEK study would be invaluable, however, this project did not undertake a full TEK study, but includes excerpts from limited interviews with tribal members and staff. It is important to note that while not all species have clear, concise TEK information associated with them, they are nevertheless considered an important and vital aspect of the local ecological environment. Indigenous culture is holistic in nature, and taxonomic compartmentalization is a western science application that TEK rarely relies on. All species are interdependent and each has a role within any given environmental system. This understanding of place and cohesive cooperation of species is vital to effectively managing, providing sustainability practices, and maintaining spiritual and physical relation in Indigenous practices.

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Chapter 2: Regional Climate Change

Authors: Meghan Dalton, Philip Mote, Samantha Chisholm Hatfield

2.1 Introduction

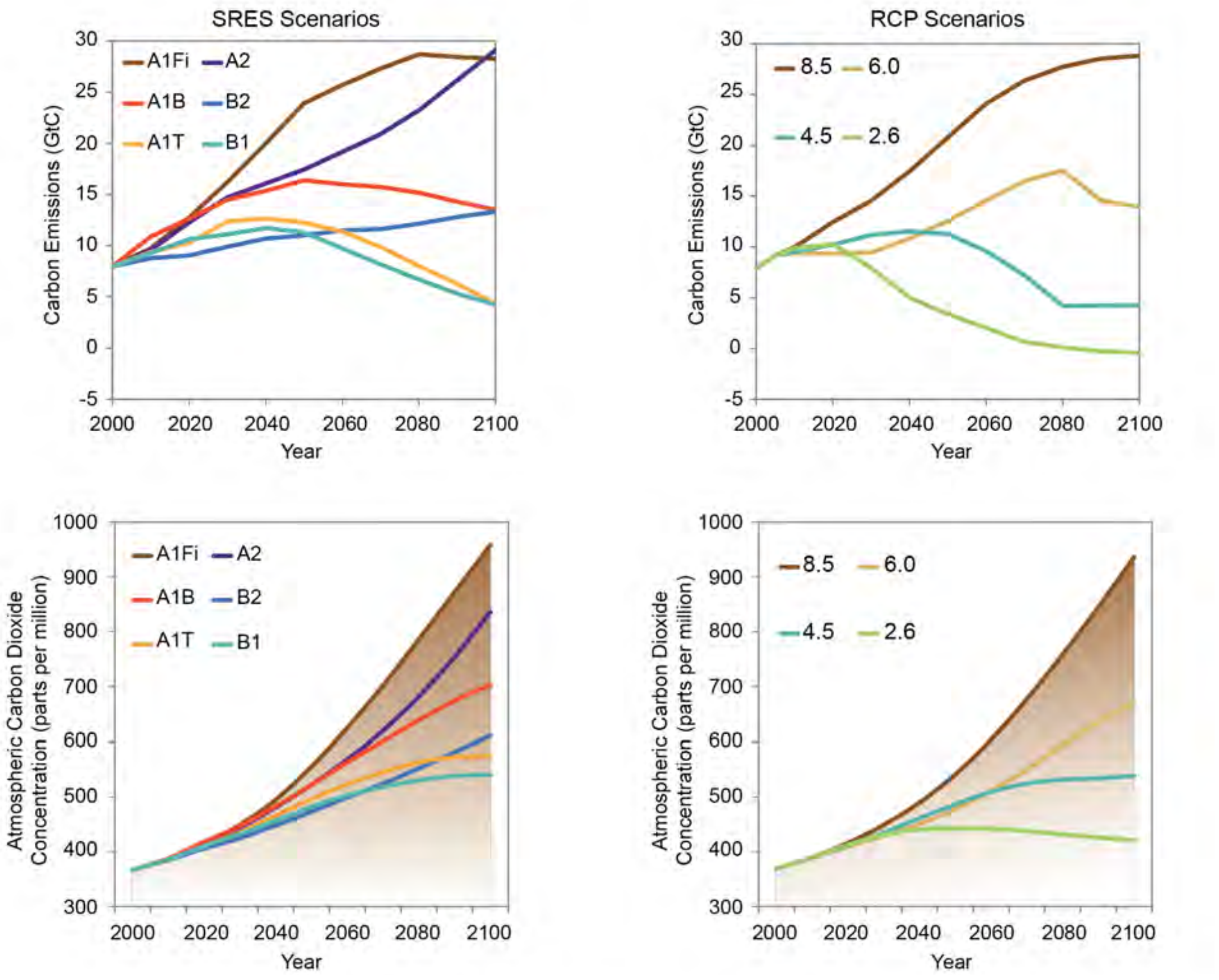
Since the beginning of the Industrial Revolution, humanity has been moving unprecedented amounts of carbon dioxide stored deep within the Earth into the atmosphere through burning of fossil fuels. The increasing level of carbon dioxide and other greenhouse gases in the atmosphere is causing the Earth to warm. With continued increases in greenhouse gas emissions, the Earth will continue to warm throughout the 21st century and beyond causing far-reaching impacts to natural ecosystems and human populations.

2.2 Emissions Scenarios

The projections of future temperature and precipitation used in this report are based on a set of emissions scenarios that describe future trajectories of greenhouse gas emissions based on assumptions about global population growth, economic development, and technological advancement throughout the 21st century. The latest set of emissions scenarios is called the Representative Concentration Pathways (RCPs) (van Vuuren et al., 2011). The RCP scenarios are bounded by RCP2.6 (achieving net negative carbon dioxide emissions before the end of century) and RCP8.5 ("business-as-usual" continuation of emissions). In this chapter, 21st-century climate projections are based on the latest generation of global climate models (CMIP5) forced by RCP8.5 and a second scenario that assumes moderate efforts to curb emissions (RCP4.5) (Figure 2.1). While no one scenario is considered more likely than another, our current trajectory of emissions places us nearest to RCP8.5.

Because the latest set of global climate models and emissions scenarios are still relatively new, subsequent impact analyses based on these latest projections are largely still under development. Thus, the species range projections in Chapter 3 and the stream channel projections in Chapter 4 are based on the previous set of global climate models (CMIP3), which were forced by the greenhouse gas emissions trajectories of the 2000 Special Report on Emissions Scenarios (SRES) (Nakićenović et al., 2000). The SRES scenarios are bounded by B1 (low emissions scenario representing a global economy becoming less resource intensive) and A1FI (high emissions scenario representing fossil intensive rapid global economic growth) (Figure 2.1). The species range projections rely on SRES A2 while the stream channel mapping relies on SRES A1B. Taken all together, the scenarios referenced in this report span a range of possible future emissions: high (RCP8.5), medium-high (SRES A2), medium (SRES A1B), low (RCP4.5).

Figure 2.1 *Carbon emissions and atmospheric carbon dioxide concentrations for SRES and RCP scenarios (Source: Walsh et al., 2014a)*



2.3 Temperature

Global mean temperatures warmed by about 1.5°F over the past century (IPCC 2013); averaged over the Northwest (defined as Oregon, Washington, and Idaho), temperatures rose by about 1.3°F (Mote et al., 2013). Warming is expected to continue throughout the 21st century (IPCC 2013) with Northwest-averaged temperatures projected to increase by about 3-8°F for a low emissions future (RCP4.5) and by about 7-14°F for a high emissions future (RCP8.5) by the end of the 21st century (Mote et al., 2013; Figure 2.2). This rate of warming is noteworthy as it is the same order of magnitude as the warming between glacial and interglacial periods. Mid-century temperature projections for the Northwest both annually and seasonally are listed in Table 2.1. Warming is projected year round with the largest temperature increases in the summer.

Figure 2.2 *Observed (black line) and simulated Northwest-average mean annual temperature for a lower emissions scenario (RCP4.5, blue) and a higher emissions scenario (RCP8.5, red). Thick lines indicate the multi-model mean and thin lines indicate individual models (Source: Mote et al., 2013)*

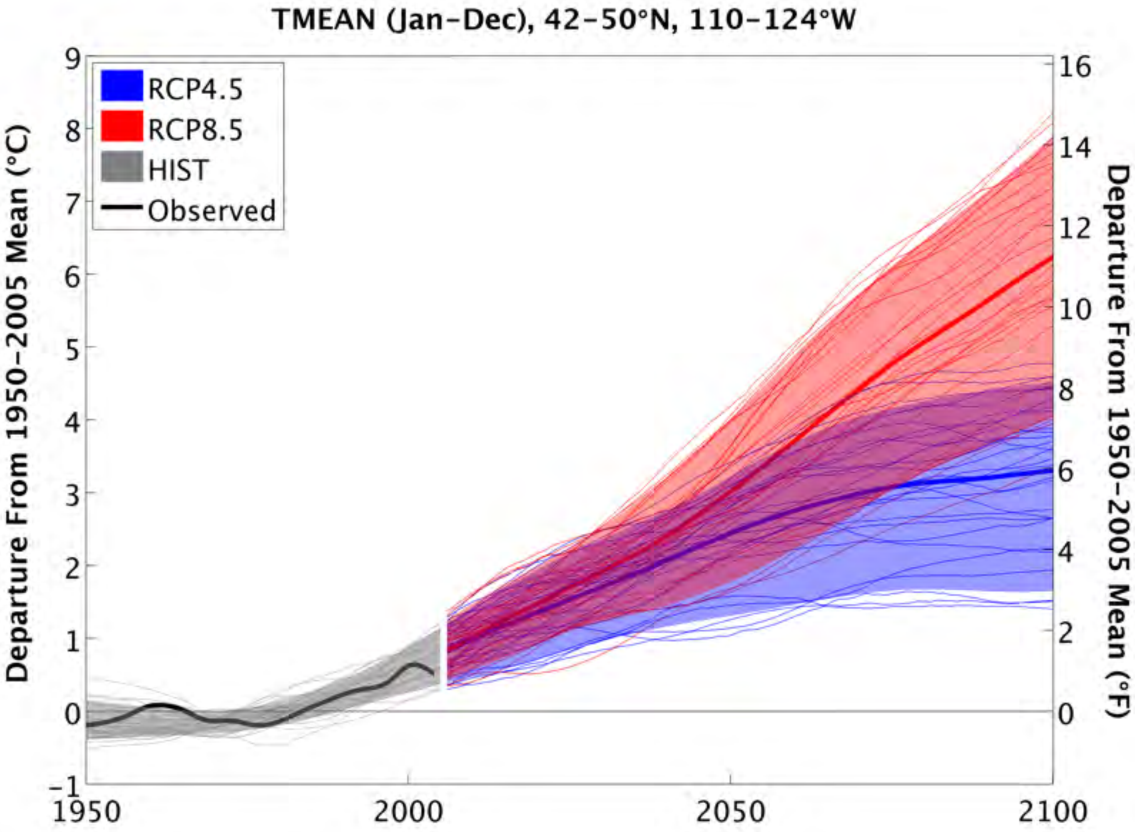


Table 2.1 *Projected changes in Northwest-averaged annual and seasonal mean temperature for mid-century (2041-2070) compared with the baseline (1950-1999) giving the multi-model mean (and range) for a low (RCP4.5) and high (RCP8.5) emissions scenario. (Source: Mote et al., 2013)*

Mid-21st Century Temperature Projections:	**RCP4.5**	**RCP8.5**
Annual	4.3°F (2.0, 6.7)	5.8°F (3.1, 8.5)
Winter (DJF)	4.5°F (1.6, 7.2)	5.8°F (2.3, 9.2)
Spring (MAM)	4.3°F (0.9, 7.4)	5.4°F (1.8, 8.3)
Summer (JJA)	4.7°F (2.3, 7.4)	6.5°F (3.4, 9.4)
Fall (SON)	4.0°F (1.4, 5.8)	5.6°F (2.9, 8.3)

The Olympic Peninsula, like the entire Northwest is expected to experience warming year-round with the largest temperature increases in summer (Halofsky et al., 2011). Because of its proximity to the

Pacific Ocean, the west Olympic Peninsula may experience temperature increases of a slightly smaller magnitude than the Northwest-average. Downscaled climate projections are available for the areas encompassing the Queets and Quinault watersheds (hereby referred to as the Queets-Quinault region) and the Hoh and Quillayute watersheds (hereby referred to as the Hoh-Quillayute region). Projected minimum and maximum temperatures for the Queets-Quinault region (USGS ID 17100102) and the Hoh-Quillayute region (USGS ID 17100101) are shown in Figures 2.3 and 2.4.

Figure 2.3 *Monthly averages of maximum (top) and minimum (bottom) temperature for four time periods for RCP4.5 (left) and RCP8.5 (right) for the Queets-Quinault region. The average of 30 CMIP5 models is indicated by the solid lines and their standard deviations are indicated by the respective shaded envelopes. (Source: USGS National Climate Change Viewer Summary of Queets-Quinault)*

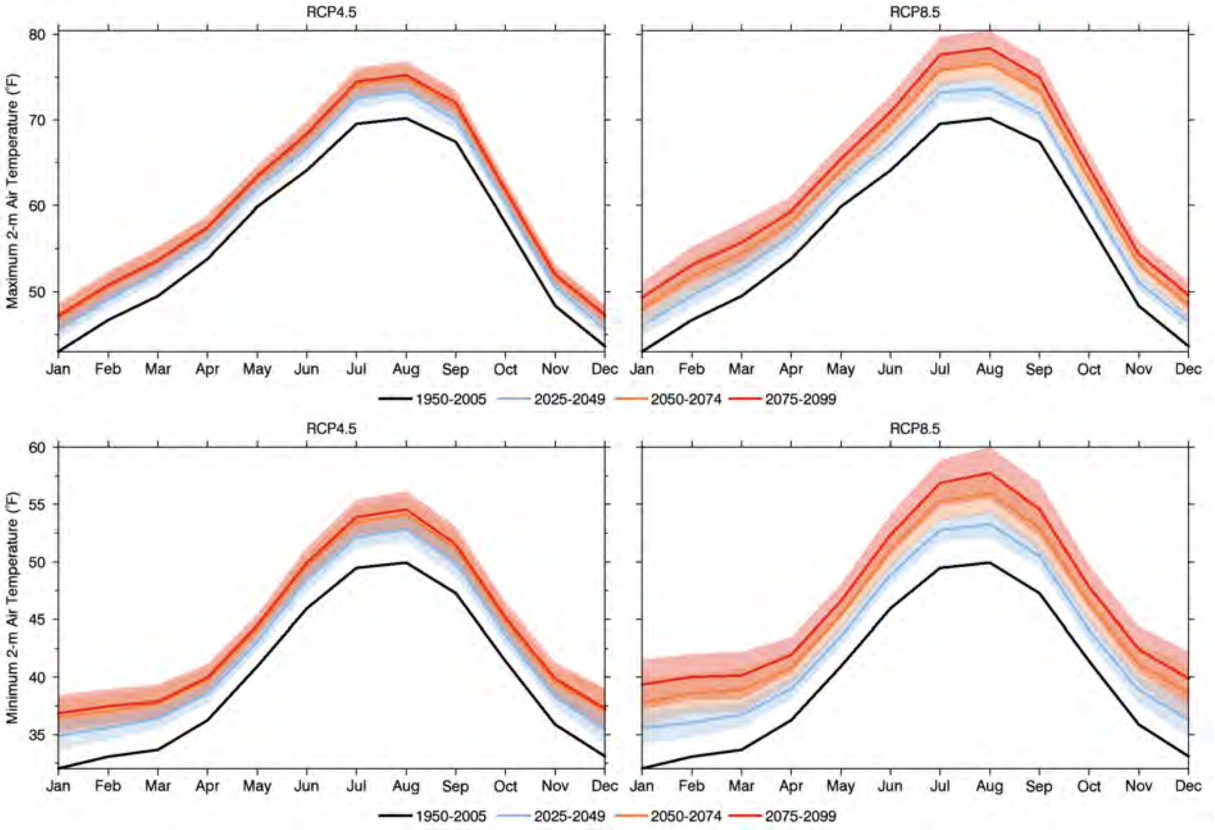
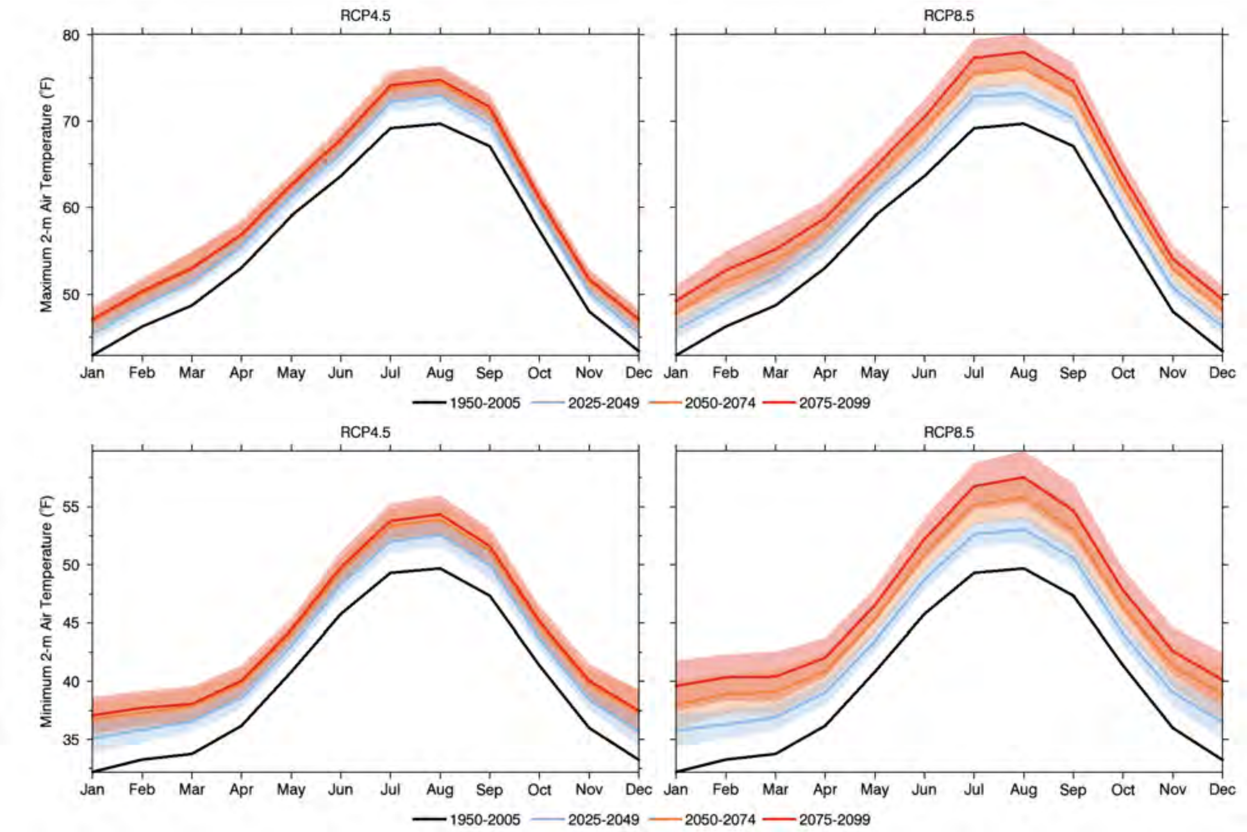


Figure 2.4 *Monthly averages of maximum (top) and minimum (bottom) temperature for four time periods for RCP4.5 (left) and RCP8.5 (right) for the Hoh-Quillayute region. The average of 30 CMIP5 models is indicated by the solid lines and their standard deviations are indicated by the respective shaded envelopes. (Source: USGS National Climate Change Viewer Summary of Hoh-Quillayute)*



2.4 Precipitation

Precipitation is quite variable and no significant trend in annual water year precipitation has been observed for the Northwest, but spring precipitation averaged over the Northwest (and at many sites including Forks, WA) has significantly increased by about 2%-5% per decade over the past century (Abatzoglou et al., 2014).

In the summer and fall of 2014, the western Olympic Peninsula experienced low rainfall and the rains that usually return in the fall were late. There was also a delay in fall freshets (high river flow from large rain events) that affected the timing and distribution of salmon runs. Typically, there are a few freshets in September accelerating into October, but tribal members have noted that this has been changing. In recent years, September has been drier with no freshets. The drought of 2015 started with low snowpack due to abnormally warm temperatures producing rainfall instead of snowfall. The season transitioned to a dry spring and a summer that was warmer and drier than normal (K. Dello, pers. comm.). Despite a couple of warm and dry recent years that are in line with future climate projections, year to year climate variability will likely continue to dominate the signal in the near term.

TEK information from tribal members is also apparent. Tribal member Norman Capoeman notes the change seems elevated:

> *“Before we have like a lot of rain and a lot of colder weather, where we're at on the coast, on the Northwest coast and like raise our rivers and wash it out and things like that, and our winters aren't as cold as they used to be, and we're right by the Olympics and the Olympic is what makes our Quinault River and without the colder weather we used to have, there's less snow up there and with less snow water in the river now, and I've noticed it in the creek water and wash water. Our river actually changed color, from I believe the climate change or whatever reason… Our rivers used to have a really pretty greenish blue crystal clear color to it, when I talk about the river, I'm talking like maybe the first ten miles of the mouth of the Quinault, up to the river because our river from the mouth to the full length of the river which goes to Lake Quinault is approximately thirty eight miles. I don't get way up river that much but when we fish, we fish the seven miles from the mouth up to the river and that's where we set our nets in and fish but the river now is more of a brownish looking color and like a grayish looking color - the brownish looking color is after the rains quits and everything stops because we have a lot of logging that pours into the river.”*

Future projections in annual precipitation indicate slightly wetter conditions annually for the multi-model mean, but climate models disagree on the sign of the future change (Table 2.2). However, most climate models project a slightly drier Northwest in the summer and slightly wetter Northwest during the other seasons (Mote et al., 2013). Some measures of extreme precipitation are projected to increase (Mote et al., 2013). This will affect the fishing and gathering that traditionally accompanies the seasonal flow and patterns of growth along these river systems.

Table 2.2 *Projected changes in Northwest-averaged annual and seasonal precipitation for mid-century (2041-2070) compared with the baseline (1950-1999) giving the multi-model mean (and range) for a low (RCP4.5) and high (RCP8.5) emissions scenario. (Source: Mote et al., 2013)*

Mid-21st Century Precipitation Projections:	**RCP4.5**	**RCP8.5**
Annual	2.8% (-4.3,10.1)	3.2% (-4.7,13.5)
Winter (DJF)	5.4% (-5.6,16.3)	7.2% (-10.6,19.8)
Spring (MAM)	4.3% (-6.8,18.8)	6.5% (-10.6,26.6)
Summer (JJA)	-5.6% (-33.6,18.0)	-7.5% (-27.8,12.4)
Fall (SON)	3.2% (-8.5,13.1)	1.5% (-11.0,12.3)

Projections for the western Olympic Peninsula follow suit; expected changes include increased winter precipitation, decreased summer precipitation, increased potential evapotranspiration, and increased precipitation intensity (Halofsky et al., 2011). Projected precipitation for the Queets-Quinault region (USGS ID 17100102) and the Hoh-Quillayute region (USGS ID 17100101) are shown in Figures 2.5 and 2.6.

Figure 2.5 *Monthly averages of precipitation for four time periods for RCP4.5 (left) and RCP8.5 (right) for the Queets-Quinault region. The average of 30 CMIP5 models is indicted by the solid lines and their standard deviations are indicated by the respective shaded envelopes. (Source: USGS National Climate Change Viewer Summary of Queets-Quinault)*

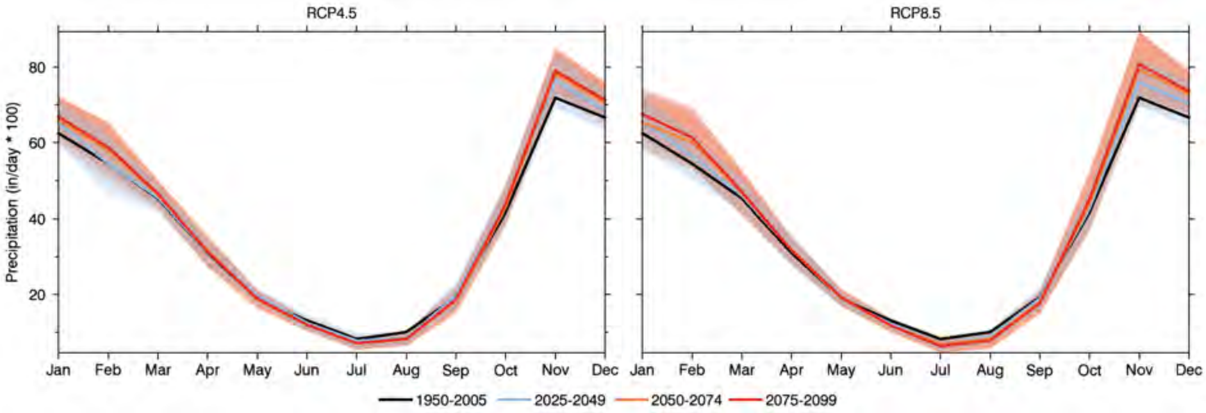
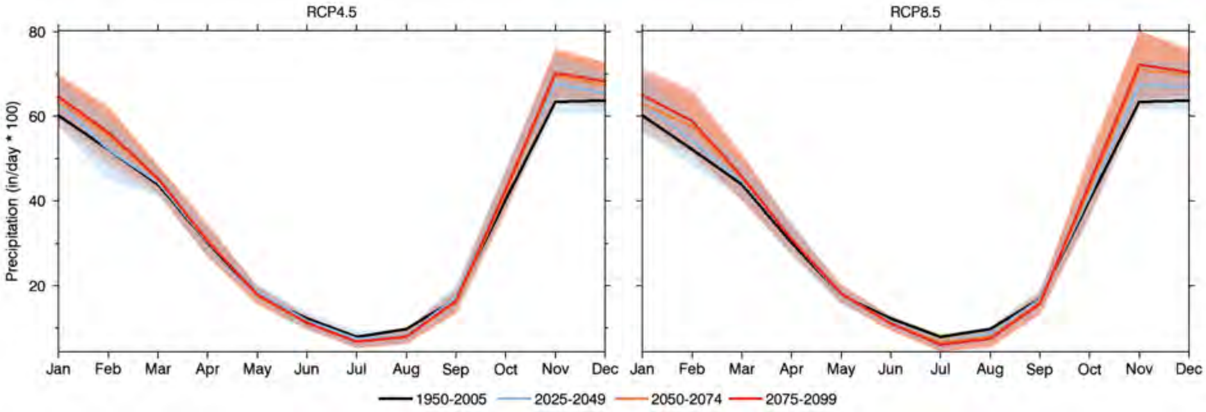


Figure 2.6 *Monthly averages of precipitation for four time periods for RCP4.5 (left) and RCP8.5 (right) for the Hoh-Quillayute region. The average of 30 CMIP5 models is indicted by the solid lines and their standard deviations are indicated by the respective shaded envelopes. (Source: USGS National Climate Change Viewer Summary of Hoh-Quillayute)*



2.5 Snowpack


Quinault Queets Divide. Photo courtesy Larry Workman, QIN

Warmer temperatures have led to a larger fraction of the winter precipitation falling as rain rather than snow, particularly at mid-elevation areas in which the average winter temperature is near freezing. This has resulted in wide spread declines in spring snowpack across the western U.S. (Mote et al., 2005), including in the Olympic Mountains over more than half a century (Figure 2.7). Tribal members have noted these changes and have been able to articulate the changes via TEK information. Mr. Capoeman relates:

> *"now with our snow melt going on warmer climate change we have I'm thinking it's not keeping the river's not as clean, as purified, for some reason, I'm not a biologist or a scientist of anything, but it seems like the snow water would keep our river clean because it was so cold, and it filtered out a lot, kill like algae and stuff like that, probably toxic algae and things like that."*

Much of Washington and Oregon had less than 25% of normal snowpack during the winter of 2015, largely due to warmer than normal temperatures (Figure 2.8). Some sites in the Olympic Mountains had only 3% of normal snowpack as of April 1, 2015 (NRCS 2015) owing to warm temperatures sustained by the abnormally warm ocean temperatures in the North Pacific.

Figure 2.7 *Trends in April snowpack in the western U.S. from 1955-2015 measured in terms of snow water equivalent. Blue circles represent increased snowpack; red circles represent a decrease. (Source: Mote and Sharp, 2015; www.epa.gov/climatechange/indicators)*

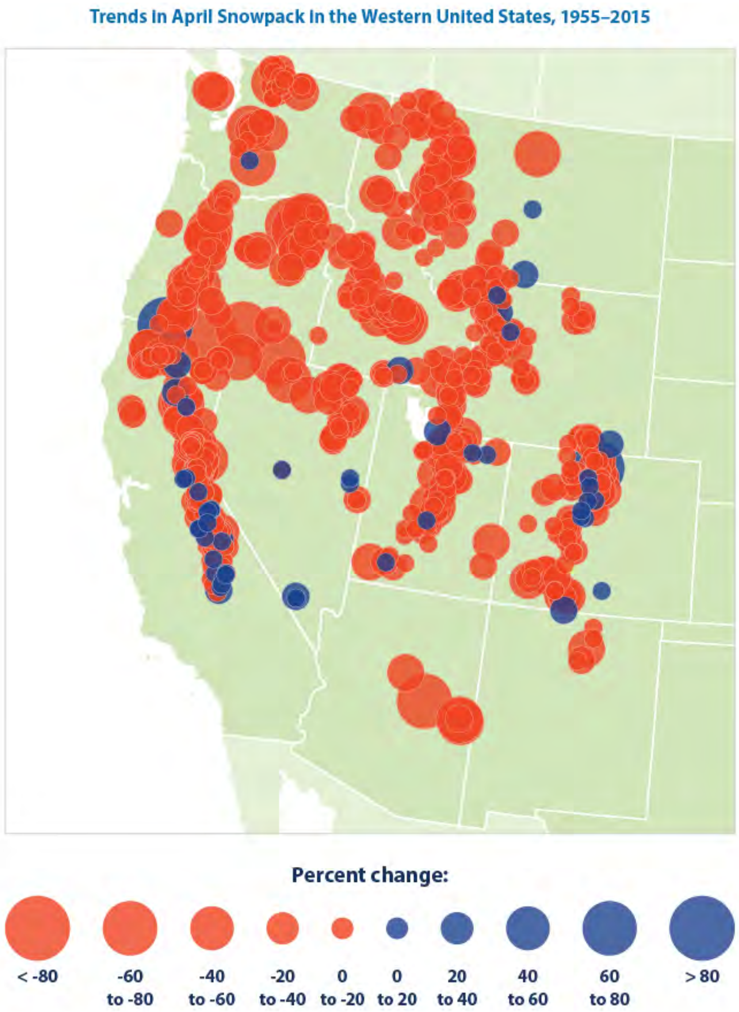
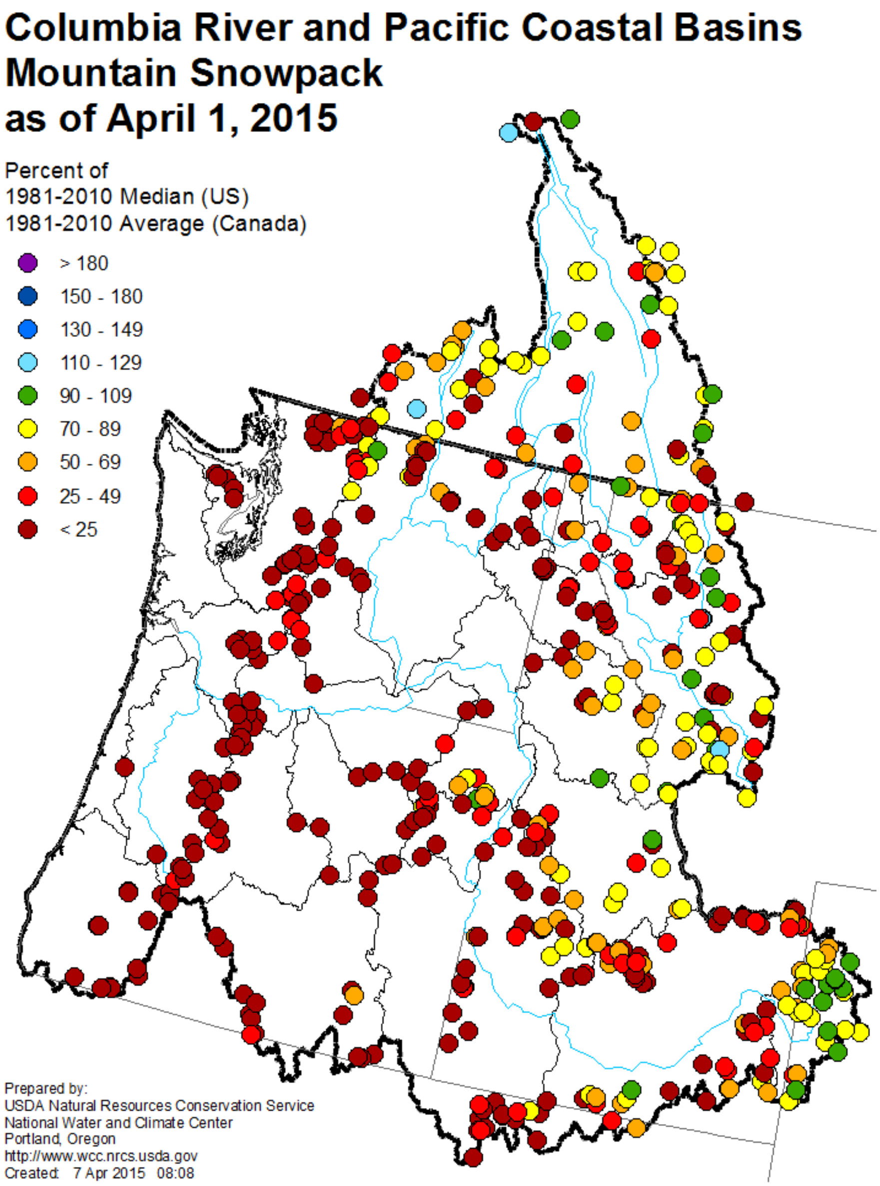


Figure 2.8 *Percent of normal mountain snowpack in the Columbia River and Pacific Coastal Basins as of April 1, 2015. (Source: Natural Resources Conservations Service, http://www.wcc.nrcs.usda.gov/cgibin/colusnow.pl?state=columbia_river)*

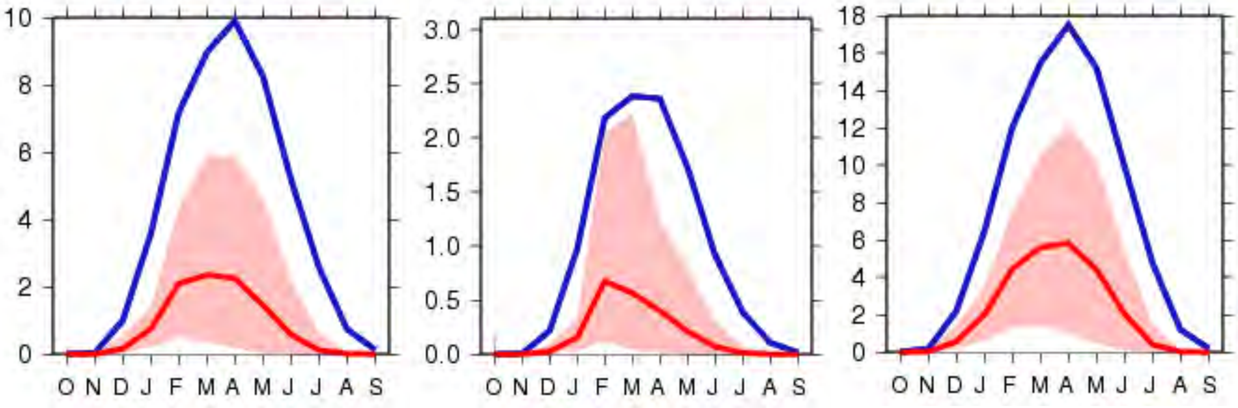


Averaged over Washington state, April 1st snowpack is projected to decline by up to 65% for a medium emissions scenario by the 2080s (Elsner et al., 2010; Table 2.3). Projected future snow water equivalent for the Hoh River, Queets River, and Quinault River basins are shown in Figure 2.9 based on the Columbia Basin Climate Change Scenarios Project (http://warm.atmos.washington.edu/2860/). The Quillayute River was not included in this database.

Table 2.3 *Projected changes in April 1 snow water equivalent in Washington state for the 2020s, 2040s, and 2080s and for a low (SRESB1) and medium (SRESA1B) emissions scenario. (Source: Elsner et al., 2010)*

April 1st Snowpack Projections:	**SRESB1 (Low)**	**SRESA1B (Medium)**
2020s (2010-2039)	-27%	-29%
2040s (2030-2059)	-37%	-44%
2080s (2070-2099)	-53%	-65%

Figure 2.9 *First day of month total snow water equivalent (quantifies natural storage as snowpack) averaged over the Hoh River (left), Queets River (center), and Quinault River (right) basins expressed as an average depth in inches. Blue line shows the simulated historical values, light red bands show the range of 10 global climate models for the 2080s and a medium (A1B) emissions scenario. Dark red lines show the ensemble average of the 10 GCMs. (Source: Columbia Basin Climate Change Scenarios Project, http://warm.atmos.washington.edu/2860/. These materials were produced by the Climate Impacts Group at the University of Washington in collaboration with the WA State Department of Ecology, Bonneville Power Administration, Northwest Power and Conservation Council, Oregon Water Resources Department, and the B.C. Ministry of the Environment.)*



2.6 Streamflow

In streams across the Northwest within snowmelt watersheds that rely on mountain snowpack to fill the riverbeds in the summer, the fraction of June streamflow to annual flow has decreased over the past 60 years, including some streams in the Olympic Peninsula (Mote et al., 2014). This is a result of reduced accumulation of snowpack as precipitation falls more as rain than snow causing high winter flows and earlier spring snowmelt. By the 2040s, total summer runoff and streamflow are projected to decrease across much of the Northwest, including the Olympic Peninsula (Figure 2.10) stressing freshwater fish species (See Chapter 4: Freshwater Aquatic Environment). In summary, the effects of warming are already apparent in many basins; that is, earlier snowmelt and lower summer flow. The largest future changes in summer flow will be in mild snowy basins. For the Olympic Peninsula, future changes are modest, but the driest scenarios would be problematic. In the case of the Quinault, they have also lost a glacier (Anderson) that fed the Quinault River. Projected future runoff for the Hoh River, Queets River, and Quinault River basins are shown in Figure 2.11 based on the Columbia Basin Climate Change Scenarios Project (http://warm.atmos.washington.edu/2860/). The Quillayute River was not included in this database, however, it is also likely to be affected by loss of snowpack because the headwaters are also high in the Olympic Mountains.

Figure 2.10 *Projected changes in local runoff (shading) and streamflow (colored circles) for the 2040s compared to the period 1915 to 2006 under a moderate warming scenario (Mote et al., 2014).*

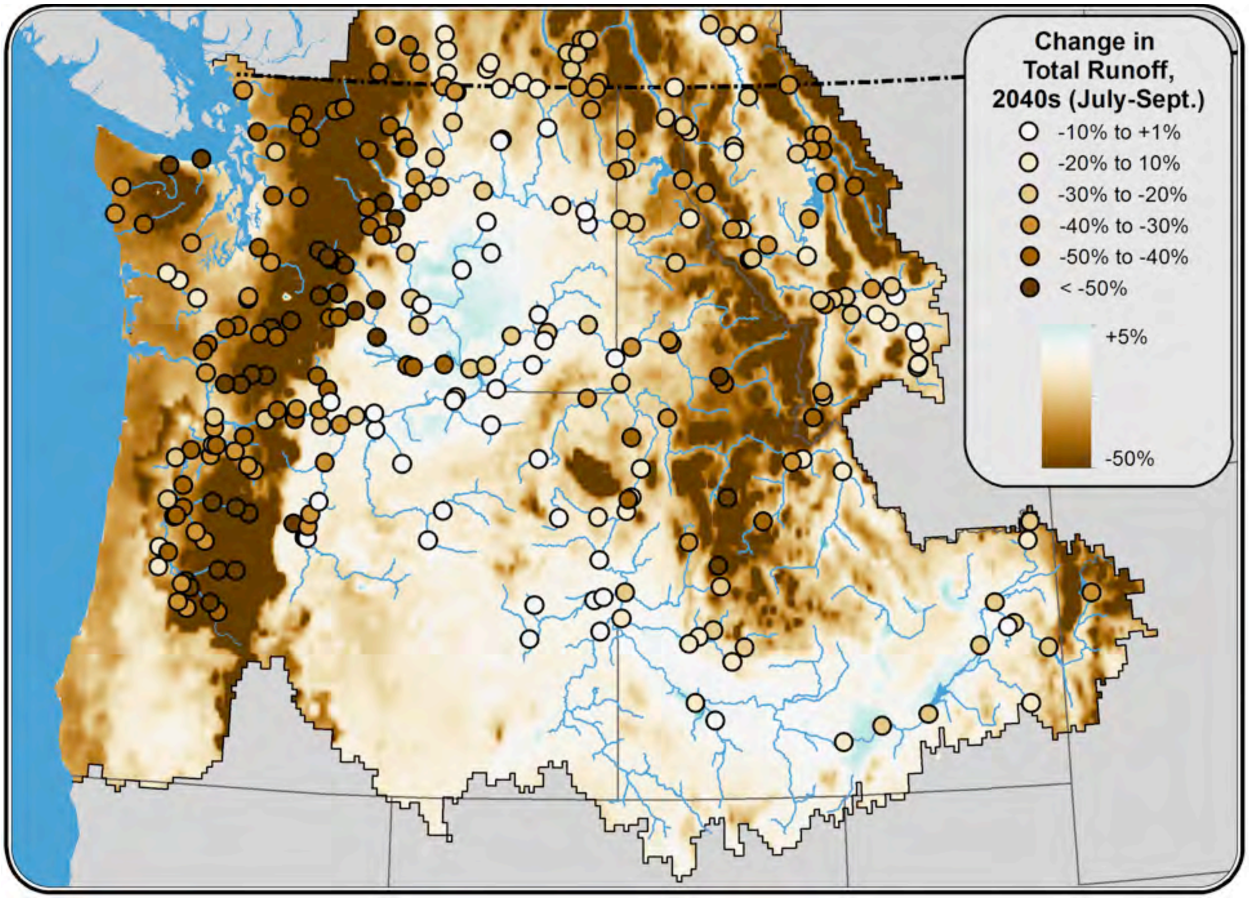
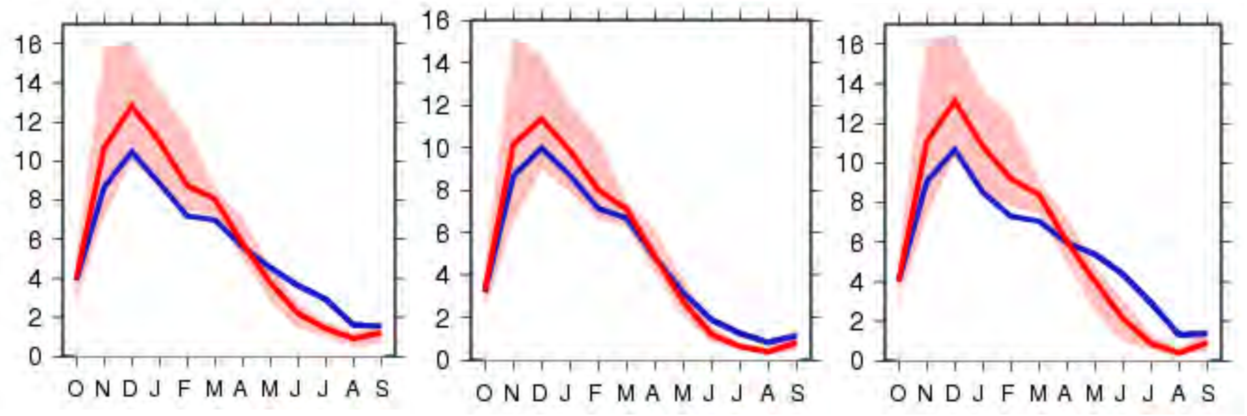


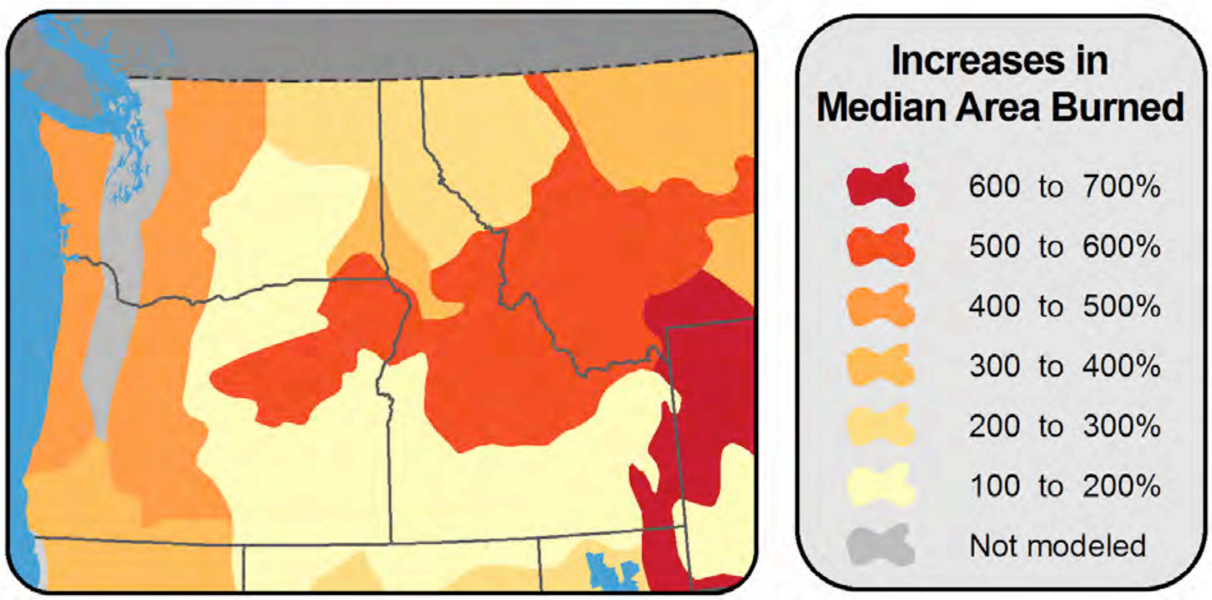
***Figure 2.11** Combined monthly average total runoff and baseflow over the Hoh River (left,* USGS ID 12041200*), Queets River (center,* USGS ID 12040500*), and Quinault River (right,* USGS ID 12039500*) basins expressed as an average depth in inches. This variable is a primary component of the simulated water balance, and is one of the primary determinants of streamflow. Blue line shows the simulated historical values, light red bands show the range of 10 global climate models for the 2080s and a medium (A1B) emissions scenario. Dark red lines show the ensemble average of the 10 GCMs. (Source: Columbia Basin Climate Change Scenarios Project, http://warm.atmos.washington.edu/2860/. These materials were produced by the Climate Impacts Group at the University of Washington in collaboration with the WA State Department of Ecology, Bonneville Power Administration, Northwest Power and Conservation Council, Oregon Water Resources Department, and the B.C. Ministry of the Environment.)*



2.7 Wildfires

The occurrence of large wildfires has increased across the west (Dennison et al., 2014; Littell et al., 2010). In recent years, large fires have occurred in the wet coastal mountain ranges including the Paradise Fire along the Queets River in the Olympic Mountains, which started in May and lasted throughout the summer of 2015. Across the western Olympic Peninsula, fires are estimated to have occurred about every 600 years or more (Agee 1993). Because of the low fire frequency on the Olympic Peninsula, it is different to draw statistical inferences about future fire on that small of a scale. Wildfires are expected to increase across the Northwest as the climate continues to warm (Littell et al., 2013). Under expected temperature increases of 2.2°F global warming and precipitation changes, the Pacific Northwest coastal strip that includes the Olympic Peninsula is projected to experience a 400-500% increase in median area burned (Figure 2.12). Typically, the sensitivity of area burned to climate warming is higher for those places not accustomed to frequent fires. Changes in climate and increases in wildfires along with changes in other forest disturbances can affect forest vegetation and wildlife species (See Chapter 3: Terrestrial Environment).

Figure 2.12 *Sensitivity of area burned to a 2.2°F global warming, including both the expected temperature and precipitation change (NRC 2011). The divisions are areas that share broad climatic and vegetation characteristics.*



2.8 Sea Level Rise

As the climate warms and melts glaciers and ice sheets and thermally expands seawater, sea level will continue to rise. Along the Pacific Northwest coast, sea level is projected to rise by 4-56" by 2100[2] considering uncertainties in global greenhouse gas emissions, thermal seawater expansion, melting land ice, and vertical land movements (Reeder et al., 2013; NRC 2012). Projections are similar for the Olympic Peninsula, although variations in vertical land movement and other local effects could alter this projected range by several inches (Reeder et al., 2013). Vertical land motion in Washington is dominated by regional tectonics associated with the Cascadia Subduction Zone. The average rate of uplift from both glacial isostatic adjustment and tectonics (an ongoing, not sporadic process) varies (see NRC 2012) but is on the order of a couple of mm/yr. The northwest Olympic Peninsula is uplifting at a rate similar to or greater than the rate of global sea level rise such that local sea levels may decrease under low emissions scenarios or increase at a slower rate under higher emissions scenarios (Mote et al., 2008; Miller et al., 2013). The central and southern Washington coast may experience the effects of sea level rise earlier than the northwest coast due to a lower rate of tectonic uplift and even subsidence in some areas (Miller et al., 2013). Mote et al. (2008) estimate sea level rise of 2-43" for the central and southern Washington coast. Along the Olympic Coast National Marine Sanctuary, Miller et al. (2013) suggest that a planning horizon of 1.0 meters (~39 inches) of sea level rise by 2100 is reasonable although lower and higher rates are justified. In the analysis in the Coastal Hazards chapter, sea level projections from NRC (2012) for 2050 are used, which range from -0.10 to 0.5 meters (-3.9" to 19.7") (NRC 2012). Sea level rise combined with storm surge, high tide, and wave heights pose a threat to

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[2] The large range is due to the uncertainty in regional effects (steric and ocean dynamics, cryosphere, fingerprinting effects, vertical land motion from tectonics, glacial isostatic adjustment, and subsidence) out to 2100. A sea level rise (SLR) scenario of 4" could be thought of as reflecting lower rates of SLR but also larger rates of uplift. NRC (2012) provides in depth analysis of these regional variations and uncertainties.

shoreline habitat, resources, and infrastructure (See Chapter 5: Coastal Hazards). While sea level rise is a gradual change, the tectonic setting of the Washington coast sets the stage for an inevitable major subduction earthquake that would almost instantly change the coastline as the land sinks.

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Chapter 3: Terrestrial Environment

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3.1 Introduction

The terrestrial environment assessed in this chapter includes forests, wetlands, and prairies (upland bogs) as well as the flora and fauna that comprise these habitat types. Streams, and salmonids in particular, are addressed in Chapter 4: Freshwater Environment. In this chapter, we discuss expected climate changes that terrestrial vegetation and wildlife may experience. Then, we discuss the climate change sensitivity and expected responses of individual vegetation and wildlife species of concern as identified by the Treaty of Olympia tribes (See Appendix A). Many Native tribes are place-based (Barnhardt 2005; Basso 1996) and their identities rely heavily upon the surrounding geographic landscape, with cultural identification and expression portrayed through species inhabiting nearby areas. While the Treaty of Olympia tribes are located along the coast, they are also heavily reliant on the natural resources abundant in the surrounding environments. Many tribes maintain an extensive database of Traditional Ecological Knowledge (TEK), which according to Huntington (2000) is the knowledge and insight acquired through extensive observation of a specific area or species, and can be one of the most comprehensive and long-term datasets available to climate change scientists. This knowledge can often surpass other types of documentation because of the depth, breadth, and duration of TEK observances.

3.2 Forests

Forest health and function is particularly important for elk and salmon, and other fish and wildlife too, such as black-tailed deer, black bear, and cougars. All of these animals are culturally important to the Treaty of Olympia tribes. Forests are directly sensitive to climate change through temperature increases and changes in moisture availability, which could considerably change the suitable climate for many Northwest tree species and vegetation by the end of the 21st century. Forest ecosystems are also indirectly sensitive to climate change through disturbances such as wildfire, insects and diseases, and invasive species (Littell et al., 2013). Forestry practices also influence the landscape. Potential impacts on forests due to these climate changes, combined with human alteration of the ecosystem, include shifting abundance and distribution of many fish and wildlife species through habitat changes, disturbances, and altered population dynamics (Littell et al., 2013), degradation of forest ecosystem goods and services such as species habitat, forest products, flood protection, and water purification (Littell et al., 2013), and changes in carbon storage capacity, though to what degree is largely unknown.

Campbell Tree Grove. Photo courtesy Larry Workman, QIN.

3.2.1 Wildfires

Climate influences both vegetation growth prior to the fire season and short-term vegetation moisture during the fire season, which influence fire-season activity. Historically, high fire activity in most Northwest forests is associated with high summer temperatures and low summer precipitation. In response to warmer and drier summers projected for the future, fire activity in the Northwest is projected to increase. Years with abnormally high area burned may become more frequent and increases in extreme events, particularly heat waves and droughts (such as the "snow drought" that brought more rain and less snow during the wet season prior to the 2015 fire season), will likely exacerbate fire activity (Littell et al., 2013).

Wildfires can be beneficial for the natural environment. However, increased fire activity may threaten timber resources or alter habitat for certain species. More frequent fires in old growth and mature forests may negatively affect species that thrive in such habitats such as marbled murrelets (*Brachyramphus marmoratus*) and northern spotted owls (*Strix occidentalis caurina*). However, species that thrive in post-fire conditions such as the northern flicker (*Colaptes auratus*) and the hairy woodpecker (*Picoides villosus*) may benefit under future climate change. Increases in wildfires could affect stream temperatures potentially reducing spawning habitat for some fish (Littell et al., 2013). Wildfires can also change soil properties accelerating runoff and sediment transport (Ice et al., 2004).

3.2.2 Insects & Diseases

Warming temperatures may give pests and tree diseases more opportunity to establish. Some examples that concern one or more of the Treaty of Olympia tribes include Swiss needle cast on Douglas fir, red band needle blight on lodgepole pine, Spruce tip weevil, and white pine blister rust.

The pathogen causing Swiss needle cast (*Phaeocryptopus gaeumannii*) is directly affected by climate. Warmer winter temperatures are associated with increased abundance of the pathogen and the severity of Swiss needle cast is expected to increase under future climate change (Stone et al., 2008). Swiss needle cast is a native pathogen affecting Douglas-fir. In mixed-species stands in western Oregon and Washington, Western hemlock can experience increased growth where Douglas-fir are severely affected by Swiss needle cast (Zhao et al., 2014).

The spruce weevil (*Pissodes strobi*) is an insect native across North America that typically attacks Sitka spruce trees hindering regeneration. The insect's brood overwinters and emerges when it becomes warm enough. As the climate warms, spruce weevil may proliferate (Woods et al., 2010).

White pine blister rust (*Cronartium ribicola*) affects the western white pine and whitebark pine and can infect up to 75% of a stand. The fungus appeared in western North America a century ago and there is no evidence that climate change will influence the occurrence of white pine blisters in the future. However, maintaining resiliency of forests to diseases is a key part in adapting to climate change (Devine et al., 2012).

3.2.3 Invasive Species

Changes in climate and other environmental factors can alter ecosystem composition and species interactions potentially leading to range expansion or contraction of certain species, native or non-native. The Treaty of Olympia tribes are concerned about invasive species outcompeting native species and disrupting ecosystems. Some invasive species currently causing problems include Scotch broom (*Cytisus scoparius*), Himalayan blackberry (*Rubus armeniacus*), ivy (*Hedera helix, Hedera hibernica*), Herb robert (*Geranium robertianum*), reed canarygrass (*Phalaris arundinaceae*), and knotweeds (*Polygonum* spp.). Some of these invasive species are sensitive to climate, however, large information gaps remain as to understanding the precise role climate change plays in invasion of particular non-native species in particular areas (Burgiel et al., 2014).

Scotch broom. Photo courtesy Katie Krueger, QIN.

Invasive weeds, such as Scotch broom and Himalayan blackberry, are establishing in cleared areas from timber harvest and displacing native forbs. This negatively impacts elk nutrition as the weeds are of lower nutritional value compared with native plants (Cook et al., 2013). Scotch broom is an exotic ornamental shrub native to Europe. In the western U.S., Scotch broom already occupies most of the climatically suitable habitat and future climate projections indicate a northward and upward shift in the suitable range (Potter et al., 2009).

Ivy most negatively affects forest understory and tree seedlings. *Hedera* species are native to parts of Europe and northern Africa and have been present in the Pacific Northwest since the turn of the 20th century and appeared on the Olympic Peninsula sometime between 1936 and 1979 (Jones et al., 2010). Herb robert is native to Europe and has been present in western Oregon and Washington since the beginning of the 20th century and was first recorded on the Olympic Peninsula in the 1970s (Jones et al., 2010). Herb robert inhibits riparian succession. Though not directly based on future climate scenarios, one study considers most of the western Peninsula and river valleys toward the center of the peninsula to be at moderate to high risk of long-term invasion of Herb robert and ivy (Jones et al., 2010). A higher presence of both Herb robert and ivy was associated with fewer frost days (Jones et al., 2010). Climate change is expected to decrease the occurrence of frost days as temperatures warm (Mote et al., 2013), thus potentially increasing the habitable areas of which Herb robert and ivy can grow.

Reed canarygrass and species of the knotweed family are aggressive non-native plants invading wetland areas and displacing riparian vegetation in western Washington forests (Aubry et al., 2011). Many invasive species are capable of rapid genetic change (i.e., high phenotype plasticity), including reed canarygrass, which may evolve more rapidly than expected in response to climate change, especially at the edge of its range (Clements and Ditommaso, 2011). When subjected to higher temperatures in a controlled experiment, reed canarygrass experienced enhanced photosynthesis and higher growth during early stages, but reduced photosynthesis and earlier leaf senescence at plant maturity (Ge et al., 2011). Thus, these species will continue to challenge restoration efforts under future climate change.

Japanese knotweed (*Polygonum cuspidatum*) "currently thrives in some watersheds on the peninsula" and "prevents establishment of conifers in riparian forests" negatively affecting stream habitat quality (Halofsky et al., 2011; Urgenson et al., 2012). Knotweed varieties were introduced to the U.S. in the 1870s as an ornamental plant and have since spread to inhabit most of its highly suitable range on a regional level, but is likely to continue expanding on a local scale (Barney et al., 2008). Knotweed prefers moist soils and its distribution is limited by frost (Barney et al., 2008). Climate change is expected to increase the frost-free season potentially enhancing the climatic suitability of knotweed on the Olympic Peninsula.

3.3 Wetlands

Wetlands typically exist where the land surface is flooded for extended periods of time or where groundwater is at or near the land surface resulting in repeated saturation of the soil surface (Lewis 1995). Lakes, ponds, and the fringed habitat along their borders are examples of wetlands. Wetlands are commonly classified based upon the Cowardin System (Cowardin et al., 1979) as marine, estuarine, riverine, lacustrine, or palustrine. Some wetlands have water year-round whereas others have water seasonally. Types of wetlands include bogs and fens (in which the only source of water is groundwater), swamps (forested wetlands), marshes (herbaceous vegetation, includes wet meadows), isolated ponds, high elevation wetlands, wetlands near bodies of water, coastal and estuarine wetlands (Aubry et al., 2011). "Warming temperatures and changes in hydrology with climate change could have significant impacts on moisture levels and species composition in wetlands on the peninsula, especially bogs and fens" (Halofsky et al., 2011). Vulnerability of wetlands on the Olympic Peninsula is high due to past degradation (e.g., logging, beaver trapping, motorized recreation) and susceptibility to invasive species such as knotweed and reed canarygrass (Aubry et al., 2011). The vulnerability of different types of wetlands depends on the water source, whether it is derived from rainfall precipitation, snowmelt, surface runoff, groundwater, or some combination of these sources (Aubry et al., 2011).

Generally, wetlands near more sustained reliable water sources are less vulnerable to climate change. Bogs, fens, wet meadows, isolated ponds and wetlands near headwater streams and alpine ecosystems are more vulnerable to climate change. Wetlands that rely on seasonal precipitation may experience even more pronounced seasonal extremes in water levels, such as more extreme drying during the summer months and larger inundation during winter months (Aubry et al., 2011).

Marshes and swamps are less vulnerable to climate change than bogs and fens because they "receive water from multiple sources" and "vegetation is adapted to wide range of seasonal water level fluctuation" (Aubry et al., 2011). However, marshes and swamps "are likely to experience greater seasonal extremes than they have historically, and may expand or contract in response, depending on their hydrologic setting" (Aubry et al., 2011). Wetlands near bodies of water are less vulnerable to climate change because they receive more sustained water input from both ground and surface water (Aubry et al., 2011). However, that presumption depends on continued water supply from consistent precipitation, which may not always prove to be the case.

High elevation wetlands that rely on snowpack and localized groundwater or surface water runoff are highly vulnerable to reduction in snowpack, earlier snowmelt, and changes in timing of runoff with warmer temperatures (Aubry et al., 2011). This would likely lead to drying of such alpine ponds and wetlands reducing the habitat quality for dependent species (Halofsky et al., 2011). Isolated wetlands (e.g., vernal ponds, wooded kettles, wet meadows) are also highly vulnerable to climate change because they depend on precipitation and runoff (Aubry et al., 2011). Bogs and fens are highly vulnerable to climate change because they require a stable water source to maintain organic soils, which may be challenging in altered hydrologic conditions (Aubry et al., 2011).

Coastal and estuarine wetlands are also highly vulnerable to climate change through rising sea levels. Additionally, if natural or man-made features impede inland migration, or if accretion rates are slower than sea level rise, coastal wetlands may decrease over time (Aubry et al., 2011). Water quality of coastal wetlands is also likely to decline with ocean acidification, warming temperatures, and brackish water inundation (Aubry et al., 2011).

Climate change impacts on wetlands can include changes in the plant community structure and composition and change in the ecological function resulting in either the loss or gain of a wetland (Aubry et al., 2011). “Wildlife species that depend on wetlands may be particularly sensitive to changing habitat conditions with climate change because there is little opportunity for migration to other suitable habitats” (Halofsky et al., 2011). Species associated with lakes, wetlands, and bogs likely to be influenced by climate-induced habitat changes include: Garter snake, Cascades frog, long-toed salamander, northwestern salamander, western toad, and the Makah copper butterfly (Halofsky et al., 2011).

3.4 Prairies

Amid the coniferous forests of the Olympic Peninsula there exist many prairies—openings of bogs, fens, and grassland. Prairies are biologically diverse areas containing grasses, ferns, sedges, rushes, and herbaceous perennials including many unique plant and animal species. The prairies provide foraging ground for wildlife, such as Roosevelt elk, and host many resources (e.g., salal, cranberries, camas, Labrador tea [a type of rhododendron], bear grass [used for weaving and increasingly harder to find], Nootka rose [used for medicinal purposes]) traditionally gathered and used by Native American tribes on the Olympic Peninsula. The Treaty of Olympia tribes are concerned with how climate change will affect the cultural importance of prairies.

Native Americans traditionally managed prairies through controlled burning in order to prevent encroachment of bordering trees, the presence of invasive species and to maintain the prairie species and resources utilized by their people (Wray and Anderson 2003). The prairies are no longer managed through traditional burning and the encroachment of trees and shrubs is reducing the area of prairies as well as their habitat quality. With increased natural fire activity projected under climate change, prairie area and habitat quality may actually increase (Halofsky et al., 2011). However, warming temperatures and changes in hydrology could alter the plant species composition, increase pressure from invasive species, such as Scotch broom, knotweed, and reed canarygrass, and reduce habitat quality for associated species, such as Roosevelt elk and Taylor’s checkerspot butterfly (Halofsky et al., 2011).

3.5 Vegetation & Wildlife Species

Vegetation and wildlife species of concern (Appendix A) were identified by representatives of the Treaty of Olympia tribes during the project kick-off workshop. Each identified species was rated as high, medium, or low importance in each of four categories: cultural, ecological function, economical, and subsistence. Cultural importance pertains to species that have been used traditionally in cultural practices. Ecological importance pertains to species that are critical to ecological function. Economical and subsistence importance pertains to harvesting natural resources for income or food. In general, the cultural and ecological importance is considered the same for all three tribes, but the economical and subsistence importance may be different for each tribe depending on circumstances. For example, the Quinault Indian Nation has a large timber industry so certain trees (e.g., Western hemlock) have a high economical importance for QIN, but a lower *direct* economical importance for the other tribes. (Because the other tribes depend on healthy forests for cervids and salmon, even if they do not own the forests, they value them and work with the landowners on management through regulatory permitting programs in which they participate as full partners; e.g. state Timber/Fish/Wildlife). Aggregating the rankings in these four categories, the vegetation and wildlife species that rose to the top of the list included Western red cedar, Western hemlock, and elk. The complete list of species and importance rankings are provided in Appendix A and further discussed in the remainder of this chapter.

To assess the potential impacts of climate change on these species, we examined two types of data sets; 1) the Climate Change Sensitivity Database[3] and 2) Species Range Projections[4]. Although both types of datasets are regional in extent, it is appropriate to apply them to smaller areas, such as the Olympic Peninsula.

The Climate Change Sensitivity Database is a publicly available, on-line database that summarizes information from peer-reviewed literature and expert knowledge. Information on species sensitivity was provided by species experts that participated in a series regional workshops and/or and independent work. The goal of these expert workshops was to identify the sensitivities of species to climate change by answering a series of questions related to each of the sensitivity factors described below. This process included approximately 300 experts with a diversity of backgrounds, expertise, and affiliations, and all held advanced graduate degrees in ecology, forestry, or biology. One such expert workshop included experts from both the Olympic National Forest and Olympic National Park. The workshop procedure was designed to calibrate experts' scoring systems to reduce some of the inherent biases of expert judgment assessments (see Case et al. 2015 for more information). All species and habitat profiles were completed between 2009 and 2012.

Before discussing the sensitivity and vulnerability of species to climate change, it is necessary to clearly understand the definition of (and difference between) those two terms, as well as the definition of two other related terms (Dawson et al., 2011).

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[3] climatechangesensitivity.org

[4] climatevulnerability.org

- **Vulnerability** "is the extent to which a species or population is threatened with decline, reduced fitness, genetic loss, or extinction owing to climate change".
- **Sensitivity "**is the degree to which the survival, persistence, fitness, performance, or regeneration of a species or population is dependent on the prevailing climate, particularly on climate variables that are likely to undergo change in the near future. More sensitive species are likely to show greater reductions in survival or fecundity with smaller changes to climate variables. Sensitivity depends on a variety of factors, including ecophysiology, life history, and microhabitat preferences. These can be assessed by empirical, observational, and modeling studies**".**
- **Exposure** "refers to the extent of climate change likely to be experienced by a species or locale. Exposure depends on the rate and magnitude of climate change (temperature, precipitation, sea level rise, flood frequency, and other hazards) in habitats and regions occupied by the species. Most assessments of future exposure to climate change are based on scenario projections from Global Climate Models often downscaled with regional models and applied in niche models".
- **Adaptive capacity** "refers to the capacity of a species or constituent populations to cope with climate change by persisting in situ, by shifting to more suitable local microhabitats, or by migrating to more suitable regions. Adaptive capacity depends on a variety of intrinsic factors, including phenotypic plasticity, genetic diversity, evolutionary rates, life history traits, and dispersal and colonization ability. Like sensitivity, these can be assessed by empirical, observational, and modeling studies".

In essence, vulnerability is a function of sensitivity, exposure, and adaptive capacity. Sensitivity has a positive relationship with vulnerability; in other words, a species with a higher sensitivity to climate change could *potentially* have a higher vulnerability. Exposure also has a positive relationship with vulnerability, meaning that a species that is exposed to a greater amount of climate change could *potentially* have a higher vulnerability. Adaptive capacity has a negative relationship, meaning that a species that is highly adaptable might have a *potentially* lower vulnerability. Mathematically:

$$\text{Vulnerability} = \text{Sensitivity} + \text{Exposure} - \text{Adaptive Capacity}$$

As can be seen from the equation above, a higher sensitivity does not necessarily lead directly to a higher vulnerability. The exposure and adaptive capacity of the organism must be factored in when calculating vulnerability. The contribution of exposure to climate change and the species' adaptive capacity explain how a species may have a high sensitivity, but a low vulnerability (or vice-versa). As such, since vulnerability is a more comprehensive metric than sensitivity, it can be more useful when assessing risk than just a species' inherent sensitivity score. However, given the compounding uncertainties when computing a species' vulnerability, documenting a species' sensitivity provides useful information for management decision making in light of climate change (Case et al., 2015).

3.5.1 Climate Change Sensitivity Factors

Individual species' sensitivities were assessed based on nine factors. These included: 1) whether the species is generalist or specialist, 2) aspects of physiology, 3) life-history characteristics, 4) whether the species depends on sensitive habitats, 5) dispersal distances and the presence of barriers, 6) dependence on disturbance regimes, 7) climate-dependent ecological relationships, 8) interacting non-climatic stressors, and 9) other aspects of sensitivity not previously captured. These factors were chosen because they were identified as important in defining the sensitivity of species to climate change either in the literature or in preliminary discussions with the experts.

Generalist/Specialist. Species that have unique dependencies or that have relationships that are dependent on a relatively small number of other species are more likely to be sensitive to climate change than species that do not have these dependencies (Gilman et al., 2010). Experts were asked to rank the degree to which a species is a generalist (low sensitivity) or a specialist (high sensitivity). They then identified which, if any, of the following factors make the species more of a specialist: predator-prey relationships, foraging dependencies, seed-dispersal dependencies, host plant dependencies, phenological dependencies, pollinator dependencies, or other dependencies.

Physiology. Climate change has the opportunity to affect the chemical and physical functioning of species with some being able to tolerate less change than others. Species were ranked as to how physiologically sensitive they are to climate, and climate-change related factors from low to high. Experts also identified which of the specific factors contribute to physiological sensitivity: temperature, precipitation, salinity, pH, carbon dioxide, and dissolved oxygen.

Life-History. The timing and magnitude of growth, reproduction, and mortality of a species influences its sensitivity to climate change. Species were ranked on a scale of being more r-selected—species with many offspring and a short generation time (low sensitivity)—to more k-selected—species with few offspring, high parental investment, and potentially longer generation time (high sensitivity).

Sensitive Habitats. Species that depend on specific habitats that are known to be sensitive to climate change are likely to be more sensitive than species that do not rely on these habitats (Dawson et al., 2011). Examples of sensitive habitats include: coastal lowlands, some marshes, estuaries, and beaches, seasonal streams, wetlands and vernal pools, seeps and springs, alpine and subalpine areas, grasslands and balds, rocky intertidal zones, ecotones, or other habitats not already listed. We recognize that some may interpret this factor as representing more than just sensitivity; nonetheless, this list was a product of expert input and was refined during the first three workshops. The scoring for sensitive habitats was either 7 (one or more sensitive habitats were identified) or 0 (no sensitive habitats were identified).

Dispersal Ability. The capability of a species to move across the landscape will likely affect its ability to respond to climate change and thus will contribute to its overall sensitivity. Maximum annual dispersal distance—the maximum distance it would be feasible for a species to move within one year to establish a new population in a more suitable habitat—was identified on a scale of over 100 km (low sensitivity, “1”) to less than 1 km (high sensitivity, “7”). Experts then identified and quantified the presence of dispersal barriers on a scale from low (1) to many (7). The scores for maximum annual dispersal distance and dispersal barriers were then averaged together for one overall dispersal ability score. Again, we recognize that this factor could also be used to assess adaptive capacity.

Disturbance Regimes. Changes in the intensity and frequency of disturbances will likely affect some species more than others. Species were ranked as to how sensitive they are to one or more disturbance regimes, from not sensitive to the nature of any disturbance regime ("1") to highly sensitive to the nature of one or more disturbance regimes ("7"). Experts then identified the following relevant disturbance regimes: fire, flooding, wind, disease, drought, pollution, urbanization, pathogens, pests, or other.

Ecological Relationships. Species that have ecological relationships that may be altered in the face of climate change will likely be more sensitive than those species that do not. If applicable, the following relationships were identified: forage, predator-prey, habitat, hydrological, competition, or "other". Then experts identified which types of the following climate and climate-driven changes in the environment affect these relationships: temperature, precipitation, salinity, pH, carbon dioxide, or other. Finally, the species' ecological relationships were ranked as to how sensitive they are to the effects of climate change.

Interacting Non-Climatic Stressors. The sensitivity of species can be greatly affected by the degree to which other non-climate-related threats, such as habitat loss, already affect the species. Species that are greatly affected by other stressors may be more sensitive to climate change. Therefore, non-climate-related threats were identified from the following: habitat loss or degradation, invasive species, other interspecific interactions, direct human conflict (including harvesting), pollution, and other. Experts then ranked the degree to which those threats make the species more sensitive to climate change.

Other Sensitivities. We found that experts were able to assess a species' sensitivity using the aforementioned factors the majority of the time. However, for species with unique natural histories, there were other aspects of sensitivity that could not be captured with the above set of criteria. These other factors have the potential to predispose species to be more sensitive to climate change. Therefore, experts had an opportunity to identify these factors, rank the degree of sensitivity to climate change and assign a relative weight of this factor ranging from 0.2 to 5. For example, a weight of 1.5 meant that the "other sensitivity" factor was 1.5 times the weight of any previous factor in influencing a species' sensitivity to climate change.

For each of the sensitivity factors, experts provided both a sensitivity score ranging from one (low sensitivity) to seven (high sensitivity) and a confidence score ranging from one (low confidence) to five (high confidence). Confidence scores represent how certain experts were about their sensitivity score. Individual scores were averaged when more than one expert assessed the sensitivity of a species or habitat. Experts also provided more detailed comments and citations when they were available (see climatechangesensitivity.org for more information).

3.5.2 Species Range Projections

For the Species Range Projections, we used two datasets. The first consists of suitable habitat models, which are correlative in nature, meaning their potential suitable habitat is modeled based on observed current distributions and how those distributions relate to current climatic conditions and basic biome distributions. These models were developed using a combination of bioclimatic variables and simple biome-level habitat associations (Langdon 2015). Future climatic conditions were simulated for the end of century (2070-2099) using two general circulation models (GCMs), the Hadley CM3 model (Gordon et al. 2000), and the Canadian Centre for Climate Modeling and Analysis CGCM3.1 model (Flato et al. 2000). The Hadley CM3 model simulates future climate conditions that are warmer and drier relative to CGCM 3.1 model projections. We used one greenhouse-gas emissions scenario—the A2 scenario, as described by the IPCC Special Report on Emissions Scenarios (Nakićenović et al. 2000). The A2 scenario represents a mid-high greenhouse gas emission scenario - a world with increasing population growth, regionally oriented economic development, slower development, and implementation of new technologies (Nakićenović and Swart 2000).

For each of the species of concern in the Species Range Projections database, we calculated the degree to which the area of suitable habitat was projected to increase (expansion), remain the same (stable), and decrease (contraction). For this dataset, suitable habitat is defined as an envelope of suitable climate that encompasses a species' range as well as relevant wildlife-habitat associations (see Langdon 2015). These wildlife-habitat associations also incorporate the influences of anthropogenic land use on species distributions. We then calculated the projected percent loss of the current habitat and percent net change in projected species habitats and averaged them across the two future GCM projections (e.g., Table 3.2).

Range projections from the "habitat suitability models" (Langdon 2015) were not available for two key culturally important species: Roosevelt elk (*Cervus canadensis*) and black-tailed deer (*Odocoileus hemionus*). These species are particularly important to the Treaty of Olympia tribes and therefore a second data set (S. Rinnan unpublished data) was included to provide range projections for elk and black-tailed deer.

Range projections for elk and black-tailed deer were modeled using bioclimatic variables downscaled to a 1-km^2 resolution, obtained from the WorldClim database (http://www.worldclim.org/). The historical dataset was based on averaged climate records from 1961 – 1990. Projections of future climatic conditions were derived from two different global climate models (CNRM-CM5 and HadGEM2-ES) run for the RCP 8.5 greenhouse-gas emissions scenario, and were based on averages from 2061 – 2080.

Occurrence data for these two species were obtained from the Global Biodiversity Information Facility database (www.gbif.org), comprising 3,275 observations for black-tailed deer and 25,876 observations for elk. We constructed a maximum entropy distribution model for each species using the MaxEnt software package. Spatial bias was removed from the models with a bias layer that represented the cumulative observations of mammals in the United States, based on observation records of 369 native mammalian species.

Elk. Photo courtesy Carolyn Kelly, QIN.

Not all species of concern were contained in the Climate Change Sensitivity Database and Species Range Projections data sets. Consequently, we provide results on sensitivities for some species and range projections for others. We were able to provide results from both key data sets for one species, the American beaver.

Some species of concern were not available in either database, such as berries. These species are addressed through literature review where information exists and noted below as an important knowledge gap where little information exists.

The remainder of this chapter addresses each of the important trees, sub-canopy vegetation, mammals, and birds in further detail in terms of their cultural, economic, and ecological importance to the tribes, TEK, their climate change sensitivity and expected response, and knowledge and information gaps.

3.5.3 Trees

Tree species on the western Olympic Peninsula are economically, culturally, and ecologically important to the Treaty of Olympia tribes. However, tribes have been seeing a loss of coastal trees, especially spruce and cedar trees that tribal members have traditionally used. No tribal members identified specific growth stands or ages of trees. Both yellow and red cedars are considered vital and heavily used for traditional cultural survival. Canoes, bows, masks, paddles, basketry, and regalia items are all primarily cedar based. (Long houses used to be constructed of them.) Tribal members have noted how stands are thinning, and yellow cedar is presently rare to obtain for use of cultural practices. Elder Richard Allen explains:

Harvesting cedar bark. Photo courtesy Katie Krueger, Quileute.

> *"The red cedar that's what they make the canoes out of, but the canoes are thick. And you can't make a paddle three inches thick, it'd be too much. Yellow cedar is tighter grained its real tight red cedar is still tight but still flexible. The yellow cedar is so tight it don't have no bend to it. Up in Canada where they have more of the yellow cedar they make the smaller canoes but like I said it's harder to get down here because it grows in certain areas here but it's scarce. And when you do find it, it costs you and arms and a leg. Five and a half foot board by two inches by six inches was ninety bucks."*

Cedar materials are culturally important, with regalia and traditional cultural items being made and woven from the cedar bark. These items are intricately connected with cultural practices, behaviors, and traditions that cannot be replicated with alternative resources. The cedar tree is a cornerstone for the identities of the tribal people, and remains a vital aspect of modern culture.

In addition to the climate change sensitivity information that was available for the important tree species (see Table 3.1), we also highlight the results of another study that examined the potential vulnerability of tree species (Devine et al. 2012). Devine et al., (2012) conducted an assessment of vulnerability of 57 individual forest tree species in the region. Applying the Forest Tree Genetic Risk Assessment System (GRAS) (Potter and Crane, 2010), Devine et al., (2012) ranked a series of variables in relation to climate change vulnerability for the following risk factors: distribution, reproductive capacity, habitat affinity, adaptive genetic variation, and major insect and disease threats. This assessment produced a ranking with high elevation species generally identified as being the most vulnerable to climate change. For example, Pacific silver fir (*Abies amabilis*) was identified as “high risk” in the Devine et al. (2012) study largely because it is a relatively high elevation species and can be susceptible to Armillaria and Heterobasidion root diseases. However, experts that assessed just the sensitivity of Pacific silver fir identified this species as having low to moderate sensitivity to climate change. As explained above, the sensitivity analysis does not contain information on potential exposure to future climate change, as does the Devine et al. (2012) study. Hence the difference between the sensitivity and vulnerability ratings for this species. Although the Devine et al. (2012) study provides insight as to why some species are more potentially vulnerable to climate change, it tends to under represent the exposure to climate change with a range of future climates. Furthermore, warming temperatures and more autumn and winter precipitation may in fact decrease the vulnerability of high elevation tree species, such as Pacific silver fir and lead to increased growth.

Table 3.1 *Tree species of concern and their climate change sensitivity ranking, confidence score, and domain over which the species was assessed (climatechangesensitivity.org). The climate change vulnerability was assessed in a separate effort by Devine et al. (2012). As explained above, vulnerability is a function of sensitivity, exposure, and adaptive capacity. Hence, a species' vulnerability score may be quite different than its sensitivity score, depending on its exposure and adaptive capacity.*

Common Name	Scientific Name	Sensitivity[1]	Confidence	Domain	Vulnerability[2]
Sitka spruce	*Picea sitchensis*	High (68/100)	Fair	PNW	Low risk (26/100)
Western white pine	*Pinus monticola*	Moderate (52/100)	Fair	Entire range	Low risk (38/100)
Western red cedar	*Thuja plicata*	Moderate (44/100)	Fair	Entire range	Low risk (26/100)
Douglas-fir	*Pseudotsuga menziesii*	Moderate (43/100)	High	PNW	Low risk (31/100)
Pacific Yew	*Taxus brevifola*	Moderate (52/100)	Fair	Entire range	--
Lodgepole pine	*Pinus contorta*	Moderate (49/100)	Fair	Entire range	--
Pacific silver fir	*Abies amabilis*	Low to Moderate (34/100)	Good	Entire range	High risk (81/100)
Western hemlock	*Tsuga heterophylla*	Low to Moderate (37/100)	Fair	PNW	Low risk (22/100)
Big leaf maple	*Acer macrophyllum*	Low (22/100)	Fair	PNW	Low risk (29/100)
Red alder	*Alus rubra*	Low (10/100)	Fair	PNW	Low risk (20/100)
Yellow cedar	*Supressus nootkatensis*	--	--	--	High risk (51/100)
Black Cottonwood	*Populus trichocarpa*	--	--	--	Low risk (28/100)

[1] climatechangesensitivity.org
[2] Devine et al. (2012)

Of the tree species assessed for sensitivity to climate change (Table 3.1), Sitka spruce was determined to be relatively more sensitive to climate change than the other tree species (more detail provided below). A number of tree species were determined to be moderately sensitive to climate change including: western white pine, western red cedar, Douglas-fir, Pacific yew, and lodgepole pine. The sensitivity factor that was most often identified for these species was dispersal ability and disturbance regimes. A number of tree species were determined to have relatively low sensitivity to climate change including: Pacific silver fir, western hemlock, big leaf maple, and red alder. In the following subsections, each of the tree species identified as important by the Treaty of Olympia tribes are covered in more detail.

Sitka Spruce

Sitka spruce (*Picea sitchensis*) is one of the world's largest species of spruce and is a dominant forest species along the northwest coast of North America. The range of Sitka spruce is limited along coastal areas with moist maritime air and relatively cool summers. It is generally not found very far from coastal areas.

Within the Treaty of Olympia area, Sitka spruce is an ecologically important lowland tree providing large woody debris for riverine-floodplain processes. They also provide roosting habitat for bald eagles. While not the most important tree economically for tribal timber industries, Sitka spruce is commercially harvested. Additionally, it is a resource used in cultural purposes. Spruce roots are common for weaving basketry or other woven cultural items, and the tree has been known to be used in the past for tools for carving such as adzes. It is a substituted or default wood for carving, but not a preferred wood.

Sitka spruce forest. Photo courtesy Larry Workman, QIN.

The climate change sensitivity ranking score for Sitka spruce is somewhat high (68 out of 100) with a fair (60 out of 100) confidence score. The relatively high sensitivity of Sitka spruce is a result of it being restricted to coastal areas and being physiologically sensitive to changes in temperature and precipitation regimes, its poor dispersal ability, and being highly sensitive to changes in disturbance regimes.

Although this species has a large range and is found from Alaska to northern California, it is limited to coastal areas that have a moist maritime climate with cool, foggy summers and relatively warm, moist winters. Annual precipitation varies within the range of Sitka spruce and is influenced greatly by local topography. For example, annual precipitation ranges from 5615 mm (221 in) at Little Port Walter, AK, to 635 mm (25 in) at Anacortes, WA. In the southern extent of its range fog (and moist maritime air) is important in maintaining moisture conditions needed for growth. A small amount of drying during the summer season could severely affect the species in some areas and allow other tree species to out-compete Sitka spruce on some sites. However, Sitka spruce may expand its range at its northern limits in Alaska and British Columbia. Furthermore, the synergist effects of drying and increased pests could affect reproductive success and survival in some areas.

Sitka spruce is also highly sensitive to changes in disturbance regimes, such as fire, wind, disease, drought, and flooding. Long-lived stands of Sitka spruce are dependent on there being a lack of disturbances; however, Sitka spruce regeneration can do well after a large disturbance, such as a blowdown. There are a number of pests, insects, diseases, and animals that also affect Sitka spruce. In general, problems tend to be more severe toward the southern portion of Sitka spruce's range.

Windstorms are also an important disturbance agent for Sitka spruce and therefore further research into areas that might experience changes in wind events are needed. Although not all that common along the coast, changes in fire intensity and area burned will also impact Sitka spruce regeneration in some areas. Although fire is not common in places like the Olympic Peninsula, particularly dry summers, such as the one we experienced in 2015, show that fires not only can occur in temperate rainforests, but that they can also burn until the autumn rains extinguish them.

Western White Pine

Western white pine (*Pinus monticola*) is an important commercial tree species in western forests and for all three Treaty of Olympia tribes. It grows in a range of climates from cool maritime areas along Vancouver Island, BC to dry, high elevation forests in the Sierra Nevada in California. On favorable sites, western white pine tends to grow fast and its lightweight, non-resinous, straight-grained wood exhibits dimensional stability that makes it particularly valuable for frames, doors, interior paneling, and building construction.

The climate change sensitivity ranking score for western white pine is relatively moderate (52 out of 100) with a fair (60 out of 100) confidence score. Western white pine is moderately sensitive to climate change due to its limited dispersal, sensitivity to changes in disturbance regimes, and its inherent ecology.

Western white pine seeds generally do not disperse more than 1 km and it requires open areas to regenerate. Although western white pine can be wind-dispersed, it is also dispersed by animals, including squirrels, mice, and birds. Dispersal by animals is usually within 120 m of the parent tree. There is also no natural reproduction via sprouting or layering with western white pine. Western white pine is also somewhat dependent on an ice/snow regime, with seeds requiring 30 to 120 days of cold, moist conditions before germination commences.

Western white pine requires stand-replacing disturbances, including harvest, fire, or wind, to regenerate. These disturbances reduce competing conifers and allow this early seral species to establish. However, western white pine is only intermediately fire-resistant – that is it has thin bark and has moderately flammable foliage.

Western white pine is sensitive to changes in precipitation regimes and hydrology. Large changes in precipitation and potential changes in hydrology could shift the competitive balance in which western white pine currently dominates. Excessive drying or an area becoming wetter could result in western white pine losing its competitive advantage on some sites. Western white pine is generally tolerant to frost but cold, drying winds can desiccate needles.

Western white pine is already impacted by white pine blister rust (*Cronartium ribicola*), but the effects of climate change on white pine blister rust are largely unknown and could substantially affect where western white pine survives. Warmer temperatures and wetter conditions could also increase the spread of needle cast fungi and pests, such as mountain pine beetle, and emarginated ips. Climate impacts on other pests, such as the mountain pine beetle, will also be major determinants in the future of western white pine.

Western Red Cedar

Western red cedar (*Thuja plicata*) is an economically and culturally important tree species that exists in mesic (wet) areas of the Pacific coast region and northern Rocky Mountains. It is one of the most important tree species for the Treaty of Olympia tribes due to its commercial timber value and high cultural value. Cedar wood does not readily decay and when thinned into manageable strips and kept damp, is highly malleable for crafts. The cedar trees are relied heavily upon and contain identity value in cultural practices. Weaving cedar regalia is currently a practice that is maintained and honored. In addition to the regalia items, canoes, basketry, paddles, rattles, vests, hats, drums, totem poles, and masks are made from cedar. Masks are valuable items because they can denote place and status. Some carved masks are hundreds of years old, remaining a centerpiece for cultural identity and connection. Richard Allen explains about mask importance:

> *"...it's for status who you are who the family is where you come from and that's kinda like the comparable to Governor, senator, stuff like that. But now it's getting to the point where it's being handed down, so it's being learned a little bit more because it used to be where it was only for certain people but now they're trying to lean it over the where other people can learn to carve their own if they're not given a mask, and how to learn to do it, and how to learn to do their dance and song to it, because there's different things for the different masks, there's face masks, there's heads masks, I was asked to make a two way wolf mask but I turned that down because that was a little too much of a job to do, and there's just different ways and family status it goes right on down the line."*

Cedar can also be used for ceremonial purposes, tea, medicine, as well as many spiritual components being tied with the tree and customary cultural practices. Harvest Moon explains:

> *"There's a cedar song when I'm harvesting cedar bark, you're always supposed to be in good health when you harvest. There were always songs the grandmas would sing, or the children would sing."*

The cedar species represents far more than just a collectable and useable natural resource. Its properties extend into the very identity and origin stories of the people, with songs and information being maintained and passed along. Harvest Moon shares some insight on the legends of the cedar, saying:

> *"ours was cedar and salmon, cedar, gave us canoes, houses, dresses, it was the food, and that's why the red button blankets and red represents cedar and salmon and the black represents the safest time in a person's soul which is at night time."*

The climate change sensitivity ranking score for western red cedar is relatively moderate (44 out of 100) with a fair (60 out 100) confidence score. Western red cedar is moderately sensitive to climate change mostly because of its somewhat limited dispersal ability and its moderate sensitivity to disturbances, such as fire.

The maximum annual dispersal distance of western red cedar seeds is estimated to be less than 1 km. Dispersal ability is limited by barriers, such as land-use change, clear cuts, rivers, and mountains.

Western red cedar is moderately sensitive to changes in disturbance regimes, such as fire, wind, and drought. The historical fire return interval – how often fires have occurred in the past – has been estimated to be about every 600 years or more across much of the western portion of the Olympic Peninsula (Agee 1993). However, as illustrated by the current Paradise Fire burning in the Olympic National Park, fires may become more frequent in the future and will reset forest succession. Western red cedar may not regenerate in some of these areas.

Although increases in carbon dioxide concentrations may stimulate growth and productivity of some tree species, it is not known how western red cedar will respond under warmer temperatures and changes in precipitation. Declines in summer precipitation, a longer dry season, and potential changes in hydrology could reduce growth, productivity, and regeneration of western red cedar in some areas.

Warming temperatures may also facilitate the spread of pests and diseases, some of which may be new to western red cedar. However, the susceptibility of western red cedar to invasive pests and diseases on the Olympic Peninsula is largely unknown.

Douglas-fir

Douglas-fir (*Pseudotsuga menziesii*) is one of the world’s most important and valuable timber species, including for the three Treaty of Olympia tribes. It is a major component in western forests. Douglas-fir can tolerate a range of climates from the wet, humid climate of the Pacific Coast region to the dry, interior of eastern Washington.

Douglas-fir forest. Photo courtesy Larry Workman, QIN.

The climate change sensitivity ranking score for Douglas-fir is moderate (43 out of 100) with a high (80 out of 100) confidence score as it has been researched much more than many other tree species. Douglas-fir is only moderately sensitive, in part, because of this wide tolerance of a range of temperatures and precipitation regimes. However, Douglas-fir is somewhat sensitive to poorly drained soils, it has irregular seed crops, it has limited dispersal abilities, and it is somewhat sensitive to changes in disturbances regimes.

Douglas-fir seed crops occur at irregular intervals- one heavy and one medium crop every seven years on average; however, even during heavy seed years, only about 25 percent of the trees produce an appreciable number of cones. Trees 200 to 300 years old produce the greatest number of cones. For example, a stand of old-growth Douglas-fir may produce 20 to 30 times the number of cones per hectare produced by a second-growth stand 50 to 100 years old. The majority of seedlings disperse 100 meters from the parent tree but distances of 1-2 km are possible. Dispersal ability is limited by development and land-use change.

Douglas-fir is moderately sensitive to disturbance regimes, such as fire, wind, drought, pathogens, and pests. Changes in fire intensity and area burned will impact regeneration. Summer precipitation declines and potential changes in pathogens, diseases, and pests could affect growth and productivity of Douglas-fir in the future. For example, some studies show how root rot occurrence may change in the future, which could affect Douglas-fir in some areas. Douglas-fir may also lose some of its competitive advantages on sites that are currently marginal.

Pacific Yew

Pacific yew (*Taxus brevifolia*) is a culturally and biologically important shade tolerant tree species that tends to grow in the understory of undisturbed stands. The bark of Pacific yew contains a drug, taxol, which is used in cancer research. The growth of Pacific yew is generally slow and if there are no disturbances, the trees can grow to be very old. The Pacific yew is a cultural species that is defaulted to when cedar is not available. It is utilized for the hard wood items such as paddles, spears, and bows but is not as heavily relied upon as cedar is. Its cultural importance is far diminished, but still respected as part of the ecosystem taxonomy.

The climate change sensitivity ranking score for Pacific yew is relatively moderate (52 out of 100) with a fair (60 out of 100) confidence score. The relatively moderate sensitivity of Pacific yew is a result of its high sensitivity to changes in disturbance regimes and its low sensitivity to non-climatic stressors.

Pacific yew is generally dispersed by animals – specifically, birds and small mammals. As a result of this dissemination, dispersal can be somewhat limited by the presence and location of seed burial. For example, the majority of animal dispersed seeds end up in the forest litter, which is a more challenging environment for seeds to germinate in, as compared to mineral soil.

Although changes in temperatures and precipitation regimes will not likely affect Pacific yew to a large extent, large-scale fire and wind disturbances could have substantial impacts. Pacific yew is highly sensitive to fire and canopy removal. Fire can easily kill this thinly barked tree and can sometimes create post-fire habitats that do not support its regeneration, growth, or survival. A shorter fire return interval could cause this species to be more vulnerable in the future. Also, Pacific yew is sensitive to large-scale disturbances (fire or wind), which could result in the loss of canopy trees that provide cover and retain soil moisture. Pacific yew is also sensitive to damage from the sun and strong wind.

Further research into potential changes of large-scale disturbances, such as fire and wind, could be examined in light of Pacific yew's sensitivity. Windstorms are an important disturbance agent throughout much of Pacific yew's range but are largely understudied. Also, not much is known about damaging agents, such as pests and diseases for Pacific yew. Much of the information that we have is based on other yew species.

Lodgepole Pine

Lodgepole pine (*Pinus contorta*) is a major component in western forests and can tolerate a range of climates from the wet and humid climate of the Pacific Coast region to the dry continental climate of the Rocky Mountains. However, it should be noted that lodgepole pine tends to have the best competitive advantage on drier sites. The Treaty of Olympia tribes commercially harvest lodgepole pine, but the species is sparse throughout the west Olympic Peninsula.

The climate change sensitivity ranking score for lodgepole pine is relatively moderate (49 out of 100) with a fair (60 out of 100) confidence score. Lodgepole pine is moderately sensitive because it has limited dispersal abilities and it is very sensitive to changes in disturbances regimes, namely fire.

Lodgepole pine seeds generally do not disperse more than 1 km from the parent tree. Additionally, dispersal ability is limited by barriers, such as development, land-use change, mountains, arid lands, and agriculture. Lodgepole pine is more of a specialist than some other tree species because in some areas it relies heavily on regeneration following fire. Although this characteristic is most common for the interior lodgepole pine sub-species, even coastal lodgepole pine requires some disturbance to expose mineral soil that is required for seed germination.

Lodgepole pine is highly sensitive to and will undoubtedly be impacted by changes in disturbance regimes, such as fire and pests. Although changes in temperatures and precipitation regimes will also affect lodgepole pine, changes in fire and pests will likely have much greater impacts. A longer and drier growing season could exacerbate some of these changes in some areas. Fires (or windstorms in some areas) help prepare sites for regeneration by exposing the mineral soil. The mountain pine beetle (*Dendroctonus ponderosae*) is a major pest and could drastically impact the survival of this species in some areas.

Compared to other species, such Douglas-fir, there is much less known about lodgepole pine's growth in light of climate change. Lodgepole competes with Douglas-fir and ponderosa pine in many places and changes in climate and disturbances could shift the dominance through changes in competitive interactions.

Pacific Silver Fir

Pacific silver fir (*Abies amabilis*) is an important component in montane forests. It is generally found on the western and upper eastern slopes of the Cascade Range and is found among Douglas-fir, western hemlock, and mountain hemlock. The climate within the range of Pacific silver fir is strongly maritime, with cool summers and relatively warm winters. Although summers are generally dry, Pacific silver fir is dependent on adequate soil moisture during the growing season. The Treaty of Olympia tribes commercially harvest Pacific silver fir.

The climate change sensitivity ranking score for Pacific silver fir is relatively low to moderate (34 out of 100) with a good (80 out of 100) confidence score. Pacific silver fir's limited dispersal and interacting non-climatic stressors makes this species moderately sensitive to climate change.

Pacific silver fir does not produce cones until it is 20 to 30 years old and good seed years usually only occur once every three years. Overall, Pacific silver fir is not considered a good seed producer. Additionally, once seeds are produced they usually only disperse 100 m from the parent trees. Because of this limited dispersal distance, there are obvious barriers to seed dispersal, such as mountains, arid lands, land-use change, and lowland forests where Pacific silver fir does not compete well with other tree species.

Pacific silver fir forest. Photo courtesy Larry Workman, QIN.

Pacific silver fir is very shade tolerant and is therefore sensitive to intensive forest management, such as clear cutting. Pacific silver fir is also very sensitive to fire because it has thin bark and is shallow rooted. Changes in fire intensity and area burned will also impact Pacific silver fir regeneration in some areas. A drier growing season, less soil moisture, and potential changes in pathogens, diseases, and pests could severely affect Pacific silver in the future. There are a number of damaging agents, such as western hemlock looper, budworms, cone maggots, silver fir beetles, fir root bark beetle, and the invasive balsam woolly adelgid. Climate change may contribute to the spread and severity of some invasive pests, such as the balsam woolly adelgid. In addition, Pacific silver fir may lose some of its competitive advantages on sites that are currently marginal and may disappear altogether on some sites.

Western Hemlock

Western hemlock (*Tsuga heterophylla*) is an important timber and habitat species of the Pacific Northwest. Western hemlock is abundant on the western Olympic Peninsula and is the most valuable timber species for the Quinault Indian Nation. It can serve as both a pioneer species in open canopies and as a mid-successional species in dense canopies. It thrives in humid areas across the Pacific coast region and northern Rocky Mountains.

The climate change sensitivity ranking score for western hemlock is relatively low to moderate (37 out of 100) with a fair (60 out of 100) confidence score. Western hemlock is moderately sensitive to climate change, mostly because of its somewhat limited dispersal ability and the role that interacting non-climatic stressors, such as exotic or invasive species have.

The maximum annual dispersal distance of western hemlock seeds is estimated to be between 1 and 2 km, with most seeds falling within 600 m of the parent tree. More seeds tend to fall from parent trees under a dense canopy as compared to the edge of an opening, such as a clear cut. Barriers such as agricultural land or development, can also limit seed dispersal.

Western hemlock is moderately sensitive to changes in disturbance regimes, such as fire, wind, drought, air pollution (i.e., acid rain), pathogens and pests. Western hemlock has thin bark and shallow roots making it more sensitive to fire than some tree species. In many areas that western hemlock thrives there has been a lack of disturbance agents, namely fire. Western hemlock can establish on recently disturbed sites but due to slow initial growth it can be out competed.

There are a number of damaging agents that can affect western hemlock, including root rots, dwarf mistletoe, bole pathogens, and foliage pests. The impact of climate change on pests and pathogens that affect western hemlock is unknown. Warming temperatures may also facilitate the spread of pests and diseases, some of which may be new to western hemlock. Changes in disturbance regimes will be major factors as to where western hemlock grows in the future.

Big Leaf Maple

Big leaf maple (*Acer macrophyllum*) is relatively long-lived and is tolerant of a wide range of climates - from the cool, moist, marine climate of coastal British Columbia to the warm, dry, growing seasons of southern California. Big leaf maple is one of the few commercial hardwood trees found in the Pacific Northwest. Big leaf maple is a valuable timber species for the Treaty of Olympia tribes. It is also used by all tribes as music wood, burls, and firewood, and traditionally, the leaves were sometimes used for cooking. Maple is used for carving and as a substitute wood for some cultural items when cedar or other woods are not available. Its status as a non-culturally vital resource is evident with the lack of cultural items being used from the species. Richard Allen explains that maple is sometimes used for mask carving:

Big leaf maple. Photo courtesy Larry Workman, QIN.

> *"I'll look on the beach to carve on, but you can make it out of spruce, maple the big maple trees, its harder a lot more time consuming, red cedar is pretty well common around here but other people will use the hard wood."*

The climate change sensitivity ranking score for big leaf maple is relatively low (22 out of 100) with a fair (60 out of 100) confidence score. Big leaf maple's wide climatic range and the fact that its dispersal ability has low sensitivity to climate change contribute to the overall low climate change sensitivity.

Big leaf maple grows on sites with a variety of climates, but its sensitivity to climate change is largely unknown. Increases in carbon dioxide, warming temperatures, and changes in precipitation may shift big leaf maple's competitive advantage on some sites. Some of these habitats may be sensitive to changes in temperature and precipitation. A longer summer drought could negatively affect establishment, growth, and productivity of big leaf maple in some areas, because they prefer to grow next to waterbodies. For example, on drier sites big leaf maple may experience a longer drought period during the already dry season and if these conditions persist for multiple years big leaf maple will likely not survive (or reproduce) on these drier sites.

Big leaf maple produces relatively light seeds that can travel long distances by wind. However, they are somewhat sensitive to soil conditions during establishment. Specifically, seedling establishment is best when soil substrates do not dry excessively during the growing season. Big leaf maple seedlings can establish and emerge under a full to partially open canopy under the right conditions, however, emergence in clear cut areas is poor. Therefore, fire and other large disturbances could affect the ability of this species to grow in some areas.

Warming temperatures may also facilitate the spread of pests and diseases, such as the Asian long–horned beetle (*Anoplophora glabripennis*) and the carpenter worm (*Prionoxystus robiniae*), which could significantly impact big leaf maple and thereby increase its sensitivity to climate change. Mammals that browse on young seedlings can also adversely affect growth and survival of big leaf maple. However, the adverse effect of pests and diseases is largely understudied for this species.

Red Alder

Red alder (*Alnus rubra*) is the most common hardwood in the Pacific Northwest. It is short-lived, has rapid juvenile growth, and establishes on recently disturbed sites. Red alder is ecologically important in riverine-floodplain processes. One of the first trees to return after a forest fire or land clearing, it fixes nitrogen in the soil and stabilizes stream banks. The Treaty of Olympia tribes commercially harvest red alder and also use it for cultural purposes such as smoking fish. It is also utilized as a main firewood for heating as Justine James explains:

> *"Seventy-five percent of the homes are heated by wood stoves, a majority of those people are low income, and they don't have any other means of heating their houses."*

The climate change sensitivity ranking score for red alder is relatively low (20 out of 100) with a fair (60 out of 100) confidence score. Red alder is a generalist species that is generally not physiologically sensitive to changes in temperature and precipitation regimes within its range and may actually become increasingly common on some sites.

Lone western hemlock in a red alder stand. Photo courtesy Larry Workman, QIN.

Red alder has a very prolific reproductive strategy with light seeds that are disseminated long distances by wind. The maximum annual dispersal distance of red alder seeds is estimated to be between 1 and 5 km.

Red alder was not identified as being particularly sensitive to changes in temperature and precipitation. The growth and distribution of red alder is limited by low winter temperatures and a lack of precipitation during the growing season. Summer precipitation declines, a longer dry season, and potential changes in hydrology could reduce establishment, growth, and productivity of red alder in some areas limiting its ability to adequately compete with other tree species on marginal sites. An increase in extreme weather events, such as winter or spring freeze events, could also affect red alder's ability to produce seed.

Red alder may in fact do better with an increase of fires because it can quickly establish and grow on recently burned sites. Given how quickly red alder can establish and grow on recently disturbed sites and the fact that it can fix nitrogen, this species may become increasingly common on some sites with climate change. Research into where suitable sites exist and how they could be managed in order to maximize productivity has not yet taken place. The competition of other pioneer species following disturbances, such as fire, is also unknown.

Warming temperatures may also facilitate the spread of pests and diseases, some of which may be new to red alder, which may negatively affect it. For instance, forest tent caterpillar (*Malacosoma disstria*) can have significant impacts during outbreaks and the potential effects of the gypsy moth (*Lymantria dispar*) are yet unknown.

Yellow Cedar

Yellow cedar (*Supressus nootkatensis*) is rare on the west Olympic Peninsula, but has high commercial value when harvested by Treaty of Olympia tribes. It is traditionally used to carve canoe paddles and masks. These are important cultural items that need to be made from a hard wood so they can be maintained and last for generations.

Yellow cedar was identified as an important tree species by the Treaty of Olympia tribes, but it is not included in the Climate Change Sensitivity database. However, Devine et al. (2012) assess the yellow cedar in the higher risk group of the 15 tree species assessed in western Washington. Of the risk factors assessed, the yellow cedar was among the group of highest-scoring trees for the reproductive capacity factor, largely due to regeneration and seed dispersal characteristics, and the adaptive genetic variation factor, due to its high elevation habitat and isolated populations. However, yellow cedar was among the lowest-scoring group in the insects and diseases risk factor (Devine et al., 2012).

Black Cottonwood

Black cottonwood (*Populus trichocarpa*) is a fast growing ecologically important tree species. It is important in riverine-floodplain processes and serves as large woody debris. It is also home to eagle nests.

Black cottonwood was identified as an important tree species by the Treaty of Olympia tribes, but it is not included in the Climate Change Sensitivity database. However, Devine et al. (2012) assess black cottonwood, like the other broadleaf tree species, in the lower-risk group of 15 tree species assessed in western Washington. The black cottonwood had one of the highest vulnerability scores for the distribution risk factor largely due to its small proportion of the canopy. Black cottonwood had low vulnerability for the reproductive capacity risk factor due a low minimum seeding bearing age and great dispersal distance. Vulnerability scores for the other risk factors were all low for black cottonwood (Devine et al., 2012).

3.5.4 Berries

Several understory shrub species were identified as important by the Treaty of Olympia tribes, especially subsistence gathering of various types of berries. Unfortunately, much less information exists on climate change vulnerability of such understory species compared with tree species. For example, the salal was the only shrub from the list of important species that was also included in the Climate Change Sensitivity database. Lack of information about the climate change vulnerability of berries constitutes a knowledge gap that merits future research. To the extent that literature exists, the climate change vulnerability of berry species identified by the Treaty of Olympia tribes is discussed below.

Salal

Salal (*Gaultheria shallon*) is one of the most common forest understory shrubs in the Pacific Northwest. It is found in both drier coniferous forests and wet coniferous forests. Salal can form thick, almost impenetrable thickets or it can exist as an individual plant among other species. Salal's berries have been used among many Northwest Coastal tribes and the plant is culturally important. Salal berries were traditionally consumed by the Treaty of Olympia tribes, but to a lesser extent today. They are also used decoratively. For the Hoh Tribe, salal has economic value.

The climate change sensitivity ranking score for salal is relatively low to moderate (31 out of 100) with a fair (60 out of 100) confidence score. Salal's relatively low to moderate sensitivity is a result of its limited dispersal ability and its relatively low physiological sensitivity.

Salal is generally dispersed by animals – specifically, birds and small mammals tend to eat the fleshy outside of the seed and either bury or deposit the remaining seeds. As a result of this dissemination, dispersal can be somewhat limited by the presence and location of seed burial and the likelihood of animal interaction. It has been found that the majority of animal-dispersed seeds end up in the forest litter as compared to mineral soil. Forest litter is a more challenging environment for seeds to germinate in.

Salal has been identified as not being physiologically sensitive to climate change, however, it is largely unknown and understudied how invasive or exotic pests and diseases may influence this species in the future. Changes in disturbance regimes, such as fire, could also greatly impact the survival and regeneration of the species in some areas. How changes in disturbances, such as fire and wind, could affect salal has largely not been examined. Salal has also been implicated in poor conifer regeneration and establishment in some areas and climate change could compound this effect.

Huckleberries

Huckleberries have traditionally been and still are gathered as an important subsistence food source. Blue huckleberry (*Vaccinium ovalifolium*) and red huckleberry (*Vaccinium parvifolium*) are gathered by all three Treaty of Olympia tribes as a subsistence food and the red huckleberry was also used as medicine.

The die-off of certain overstory tree species due to climate change has the potential to increase understory vegetation, but not necessarily the native species. The decline in yellow cedar (*Callitropsis nootkatensis*) over the past century has been associated with reduction of snow cover due to warming temperatures. Oakes et al. (2014) studied the decline in yellow cedar in southeast Alaska and corresponding changes in the forest and understory composition, including key forage species for the Sitka black-tailed deer (*Odocoileus hemionus sitkensis*). They found that forage production can actually increase over time in forests affected by declining yellow cedar. Blueberries (*Vaccinium ovalifolium/alaskaense*), along with the other key forage species for the Sitka black-tailed deer increased in average volume in forests affected by yellow cedar decline (Oakes et al., 2014). There is little information on climate change vulnerability of red huckleberry.

Salmonberry

Salmonberry (*Rubus spectabilis*) is gathered by all three Treaty of Olympia tribes as a subsistence food. Consistent with fewer hard frosts and a longer growing season, tribal members have observed flowers, shrubs, and berries blooming earlier. For example, salmonberry buds were seen in January 2015. Little information exists on the climate change vulnerability of salmonberry.

Native Blackberry

All three Treaty of Olympia tribes gather native blackberries (*Rubus ursinus*) for food. The Evergreen and Himalayan blackberries are both invasive species. There is little information about the climate change vulnerability of native blackberries.

Strawberry

Strawberries (*Frageria species*) are a traditionally gathered food for all three Treaty of Olympia tribes. There is little information on climate change vulnerability of wild strawberries.

Cranberry

Cranberries (*Vaccinium oxycoccus ovalifolium*) are a traditionally gathered food for all three Treaty of Olympia tribes. There is little information on climate change vulnerability of cranberries.

3.5.5 Other Understory Species

In addition to berries, the Treaty of Olympia tribes identified several other important understory species such as beargrass, Labrador tea, skunk cabbage, forbs, Devil's club, Nootka rose, cascara, and mushrooms. The cultural importance and climate change vulnerability are discussed for each where information exists.

Beargrass

Beargrass (*Xerophyllum tenax*) is rare, but has high commercial value for all three Treaty of Olympia tribes. Traditionally, the bulbs were used for food. Beargrass is also important culturally in basketry, as well as many regalia and traditionally worn items. Although usually found in the mountains, due to glacier movement beargrass can be found on the northern part of the Quinault Indian Reservation.

Much remains to be learned about the climate change vulnerability of beargrass including basic phenology, but changes in disturbance patterns within the range of beargrass by both natural factors (e.g., fire frequency) and human use factors (e.g., harvest, land use) have the potential to affect beargrass (Hummel et al., 2012).

Beargrass. Photo courtesy Larry Workman, QIN.

Wildfires are rare on the Olympic Peninsula with recurrence intervals of about 600 years (Agee 1993), but for many centuries Native Americans have managed the land through frequent, controlled burning. Beargrass is well-adapted to frequent burning and thrives after fire (Hummel et al., 2012). The decline in the practice of cultural burning has led to declines in beargrass. More frequent fires projected under climate change or through increased managed burning may benefit beargrass by reducing the competition with trees and shrubs (Hummel et al., 2012).

Changes in the pollinator community due to climate and non-climate factors have the potential to affect beargrass reproduction by having a larger proportion of reproduction through self-pollination, an inferior reproductive system for beargrass (Hummel et al., 2012). However, while insect pollination is critical, beargrass can be pollinated by multiple species, which may “ensure survival and reproduction in reduced pollinator environments” (Hummel et al., 2012).

Beargrass in coastal Douglas-fir forests in the Pacific Northwest may be affected by invasive species such as Scotch broom. Tree root diseases and resulting mortality may benefit beargrass by creating clearings in the forest canopy (Hummel et al., 2012).

Indian (Labrador) tea

Indian tea (*Rhododendron spp.*) has high cultural importance and has the potential to make revenue for tribal members. There is little information about the climate change vulnerability of Labrador tea.

Skunk Cabbage

Skunk cabbage (*Lisochitum americanum*) is a prevalent bog plant important in wetland ecosystems. It is a soil fixer and indicative of nitrogen-rich soils. Skunk cabbage is an early spring food source for black bear, elk, and deer. Traditionally, the leaves were used for wraps in cooking and to line baskets when gathering berries (Quileute Ethnobotany Appendix B-3). There is little information on climate change vulnerability of skunk cabbage.

Forbs (various species)

Many types of forbs and tree seedlings are primary sources of food for elk. Douglas-fir seedlings are highly palatable to elk and deer (Aubry et al., 2011). There is little information on climate change vulnerability of forbs, though a decline in forbs has been observed on the western Olympic Peninsula due to competition by invasive species. Continued pressure from invasive species and drought could decrease the native forbs that provide highly nutritious forage for elk.

Devil’s club

In the Quileute tribe, Devil’s club (*Oplopanax horridus*) is used “as an indicator of season (when it turns red, it is time to hunt elk because they will be fat).” It is also used medicinally for diabetes and spiritually for fishermen (Quileute Ethnobotany Appendix B-3). There is little information on climate change vulnerability of Devil’s club.

Nootka rose

Nootka rose (*Rosa nutkana*) was traditionally used as medicine, but its use is rarer today. There is little climate change vulnerability information for Nootka rose.

Cascara

Cascara (*Rhamnus purshiana*) can be used as a laxative and has potential economic value for all three Treaty of Olympia tribes as a start-up business for tribal members. There is little information on the climate change vulnerability of cascara.

Mushrooms

Mushrooms (various species) are gathered by all three Treaty of Olympia tribes as subsistence food and also for commercial value. Mushrooms are also used as medicine. During the summer and fall of 2014, the Olympic Peninsula experienced drought and the rains that usually return in the fall were late. Because of late fall rains, there were fewer fall mushrooms to pick.

In an analysis of various fungal species observations in a Switzerland nature preserve from 1975-2006, the amount of mushrooms increased and average fruiting time was delayed between periods before and after 1991. Improved growth conditions and longer growing seasons explained these changes. Higher precipitation totals led to higher mushroom yields while the fruiting time was associated with August (harvest) temperatures (Buntgen et al., 2012).

3.5.6 Mammals

Of the important mammals identified by the tribes, two were available in the Climate Change Sensitivity database (i.e., beaver, elk) and four were available in the Range Projections database (i.e., beaver, black bear, river otter, cougar). Range projections for elk and deer were included from a different data set. The snowshoe hare wasn't included in either data set (Table 3.2).

Both the beaver and elk were determined to have relatively low sensitivity to climate change. However, the climate change projections for both species considered their entire range, not just the Olympic Peninsula. Therefore, Roosevelt elk found on the Olympic Peninsula may in fact be more vulnerable to climate change. Of the six mammal species for which range projections were assessed, elk, black bear, and black-tailed deer had the largest projected declines in current habitat. Black bear also had the largest decrease in overall net change between current and future habitats, implying that this species may be more vulnerable to future changes in climate change and climate-driven changes in vegetation. The American beaver and river otter were projected to have a positive net change of their current habitat implying there may be more suitable habitat in the future and they may be less vulnerable to future changes in climate and vegetation. One future climate model projected substantial increase in suitable habitat for black-tailed deer as well, however, after considering the competitive interactions with other deer species in these regions (mostly northern Canada), this is a somewhat unlikely scenario.

Projected future changes in suitable habitat on the Olympic Peninsula were relatively minor compared to changes projected in other locations. A possible explanation for this trend is that the Olympic Peninsula is relatively far from the geographic range boundaries of the species reviewed here.

In the following subsections, each of the mammal species identified as important by the Treaty of Olympia tribes are covered in more detail. These species were identified in TEK information offered by tribal members and have a high role in cultural areas, identified in tangible or intangible ways, or both. Such sensitivities and shifts in ranges could affect how, and where cultural resource items are collected, as well as potentially how they are identified for traditional purposes.

Table 3.2 *Climate change sensitivity ranking and/or projected loss of current suitable habitat and net change for mammal species of concern over their entire range and for the Olympic Peninsula.*

Common Name	**Scientific Name**	**Sensitivity**[1]	**Entire Range**[2] **% Change in Current Habitat**	**% Net Change**	**Olympic Peninsula**[2] **% Change in Current Habitat**	**% Net Change**
American Beaver	*Castor canadensis*	Low to Moderate (36/100)	-2	16	-4	-2
Elk[3]	*Cervus canadensis*	Low (29/100)	-54	0	-5	-8
Black bear	*Ursus americanus*	--	-33	-47	0	0
Black-tailed deer[3]	*Odocoileus hemionus columbianus*	--	-31	196	0	0
River otter	*Lontra canadensis*	--	-8	4	2	0
Cougar	*Puma concolor*	--	-16	-21	-2	-2
Snowshoe hare	*Lepus americanus*	--	--	--	--	--

[1] climatechangesensitivity.org
[2] climatevulnerability.org
[3] Range projections for these species derived from alternative dataset retrieved from www.gbif.org

American Beaver

The American beaver (*Castor canadensis*) has a flexible diet and can use a variety of habitats. Although American beaver tend to prefer wide valleys with a low stream gradient, beavers will establish in higher gradient riparian areas with adequate dam building material. Sometimes beaver dams can disrupt watershed integrity. The beaver was traditionally and still is trapped by Treaty of Olympia tribes for pelts, which can be sold. Beaver is a culturally important animal both for pelts used in regalia and ceremonial use, but also as a status figure that is commonly found on totem poles as well as traditionally being used as family status. Richard Allen states:

> *"The different family status, the eagle the bear, the beaver, the frog all different symbols for the status of the people in the village and who you are and where you come from."*

Beaver has also been considered an indicator species for water quality and ecological patterns, utilizing TEK methodology of analyzing ecological information (Wright et al., 2002).

The climate change sensitivity ranking score for American beaver is relatively low (36 out of 100) with a poor (40 out of 100) confidence score. Beavers can disperse relatively long distances and are generally not that sensitive to changes in disturbance regimes. However, they have a somewhat sensitive life history and are also sensitive to habitat loss or degradation and direct human conflict, such as harvesting.

The reproductive strategy of American beaver is more “k-selected” than “r-selected”, meaning that they have fewer offspring and invest a high degree of parental energy in rearing their young. American beaver only reproduce once a year and typically give birth to two to four individuals.

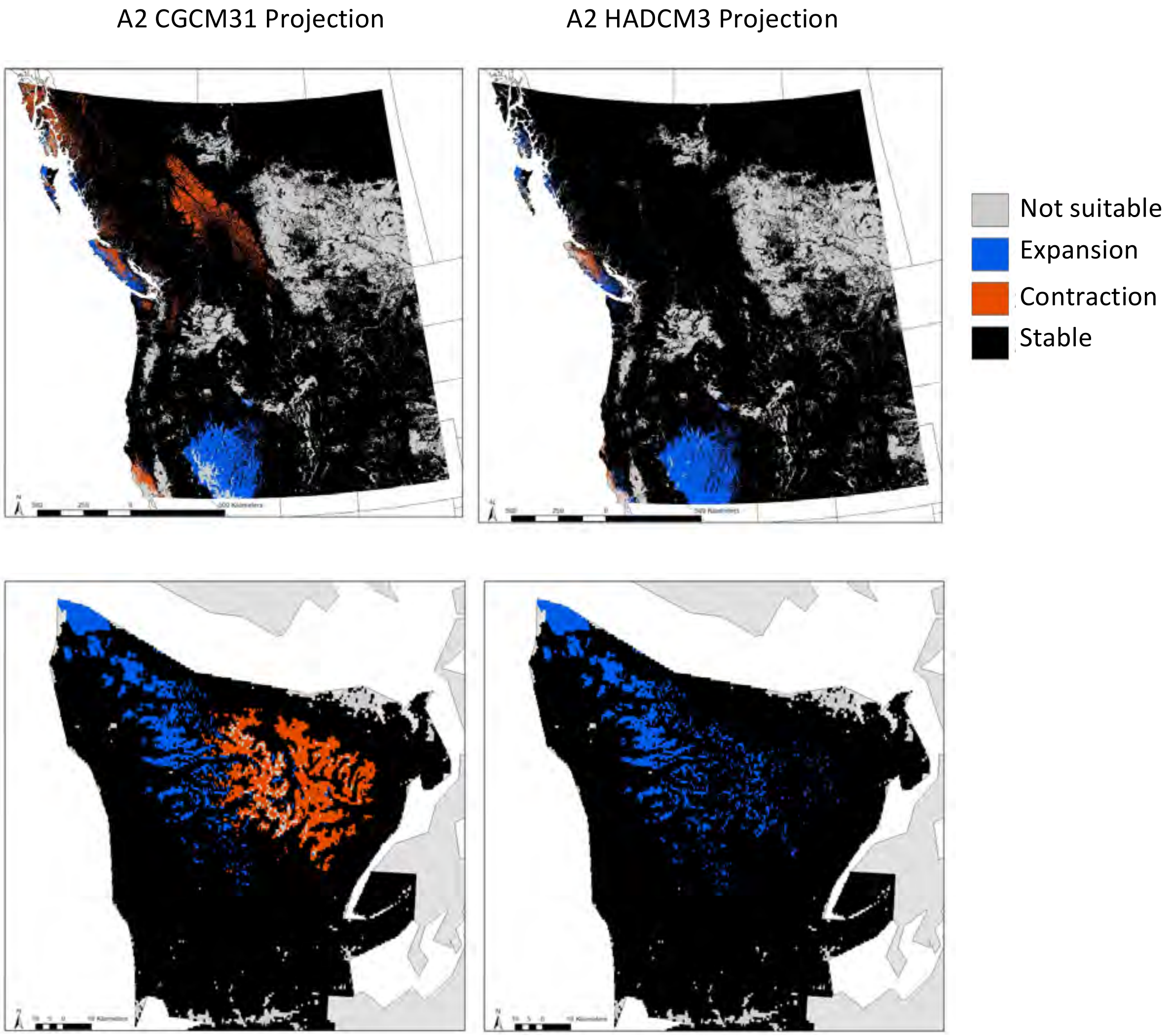
Habitat loss, degradation, pollution, and direct human conflict, such as harvesting, can greatly impact American beaver populations. This is demonstrated best by local extinctions from beaver trapping in the 1800s.

Although direct effects of climate change may not impact American beaver greatly, indirect effects on their habitat (streams) and food resources (aspen, willow, birch, maple, cottonwood, alder) could be affected by climate change. For instance, warming temperatures and changes in precipitation could affect American beaver food resources leading to population declines in some areas. An increase in the area burned may also affect foraging habitat.

An increase in the length of the freeze-free period (that is a decrease in the number of frost days) may facilitate the spread of diseases that were previously limited by cold temperatures. It is unknown if American beaver might be affected by diseases such as giardiasis or tularemia in an altered climate. Tularemia is a bacterial disease, which is fatal to animals and is transmitted by ticks, biting flies, and via contaminated water.

The suitable habitat range of American beaver is projected to increase overall, especially in the parts of Nevada, coastal British Columbia, including Vancouver Island, and portions of the Olympic Peninsula (see Figure 3.1).

Figure 3.1 *Habitat suitability range projections for the American beaver. The maps show where the current range is projected to potentially remain stable (black), contract (orange) and expand (blue) for two different global climate models (CGCM31 and HADCM3) under the A2 greenhouse gas emissions scenario. Olympic Peninsula projection maps were clipped by Clallam, Jefferson, Mason, and Grays Harbor counties.*



Roosevelt Elk[5]

The climate change sensitivity is assessed for elk (*Cervus canadensis*), which includes Roosevelt elk as a subspecies. The Roosevelt elk (*Cervus canadensis roosevelti*) is one of the most important subsistence foods for all three Treaty of Olympia tribes and also used for ceremonial purposes. As one of the cultural important species, these animals are used for hides, meat, ceremonial and regalia purposes, and are vital for the maintenance of cultural rituals. Items such as prayer fans and rattles are often used from Elk bones or horns, and carry high cultural value. There are also songs specifically regarding elk, solidifying their status in the culture.

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[5] Elk in North America have been previously referred to as *Cervus elaphus* and only recently after DNA analysis has the scientific name been changed to *Cervus canadensis*. Both scientific names are used in this study but refer to elk species that exist only in North America.

Roosevelt Elk. Photo courtesy Larry Workman, QIN.

The climate change sensitivity ranking score for elk (*Cervus canadensis*) is relatively low (29 out of 100) with a fair (60 out of 100) confidence score. Overall, elk have a flexible diet and excellent movement capabilities, which enable them to move to new locations as conditions change over time. However, it should be noted that Roosevelt Elk on the Olympic Peninsula do not tend to disperse very far. Nevertheless, elk are not restricted to a narrow thermal niche and could potentially tolerate increases in temperature better than a species that is confined to a narrow thermal niche or that has a more limited food requirement.

The life history sensitivity of elk to climate change was determined to be relatively high. Specifically, the reproductive strategy of elk is more “k-selected” than “r-selected”, meaning that they have fewer offspring and invest a high degree of parental energy. Elk also only reproduce once a year and typically only give birth to one calf. Although the maximum annual dispersal distance of elk is estimated to be between 25 and 50 km, on the Olympic Peninsula, elk movement can be limited by land-use and the presence of roads.

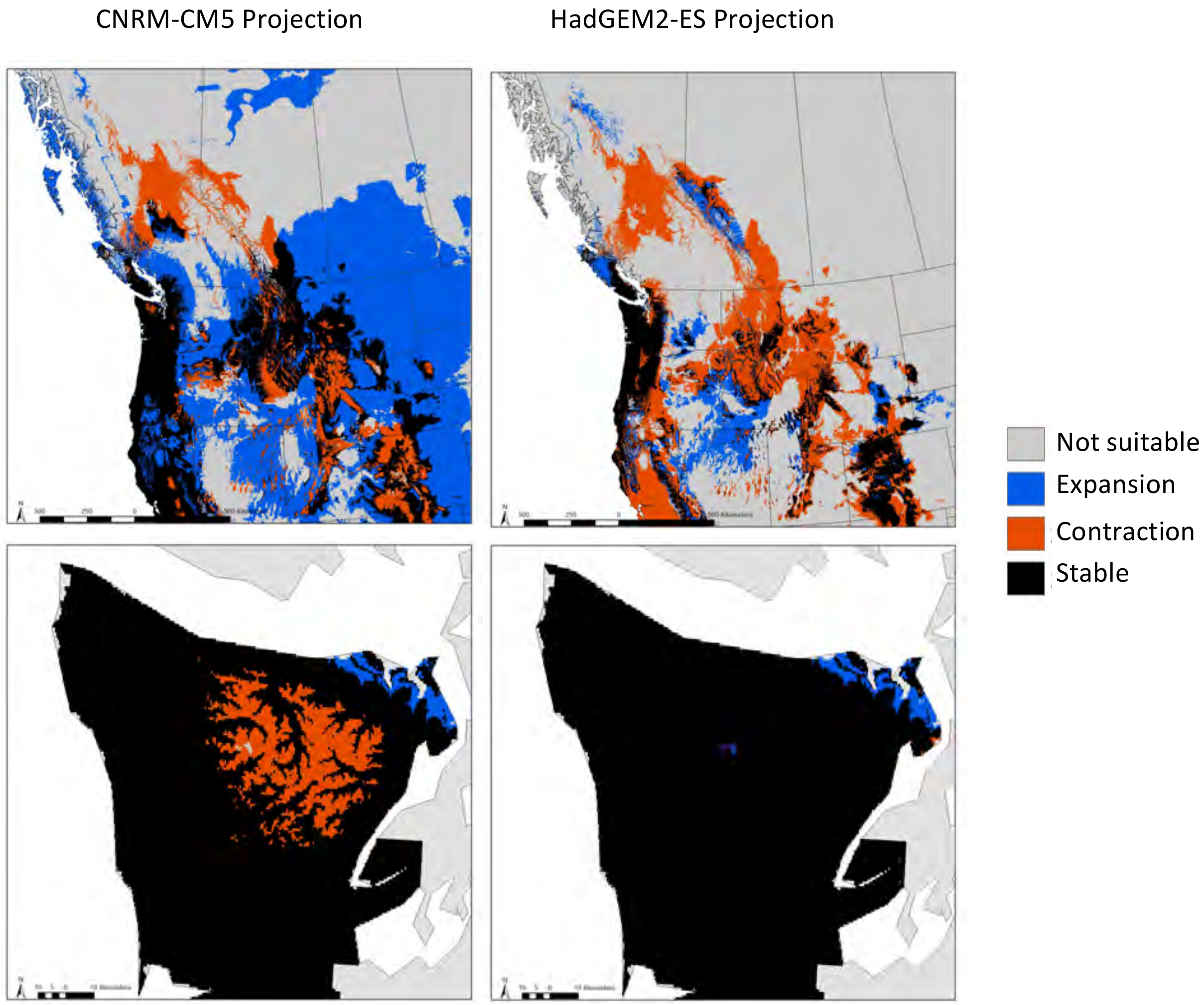
It is unknown if elk are exhibiting physiological responses to changing seasonal temperatures or precipitation patterns. Declines in summer precipitation and longer dry seasons could reduce food resources for elk and lead to population declines in some areas. Currently on the west Olympic Peninsula, the Roosevelt elk are being challenged by a diminishing food supply due to forest practices and invasive weeds out competing the more nutritious forbs that the elk eat. While elk have flexible diets, invasive plants have poor nutritional quality compared with native forbs. A decrease in the nutritional quality of forage could result in fewer and lower quality elk to harvest. Since elk is widely eaten by most members of all three tribes, this could increase the demand for elk and thereby contribute to food insecurity.

Elk are also somewhat sensitive to changes in disturbance regimes, such as fire and disease. Although fire is not all that frequent on the Olympic Peninsula, when it does occur it can be intense which could lead to high mortality and substantial habitat changes. An increase in the area burned may also affect foraging habitat.

An increase in the length of the freeze-free period (a decrease in the number of frost days) may facilitate the spread of diseases that were previously limited by cold temperatures. Bacterial hoof disease could also affect elk on the Olympic Peninsula. This disease, likely caused by bacteria similar to those found in livestock, is spreading across Washington State and affects the hooves of elk. It is believed that the bacteria are transmitted through the wet soil of lowland areas. However, it is unknown to what degree elk might be further affected by such diseases under a different climate.

The suitable climate space of elk was modeled using two different global climate models (CNRM-CM5 and HadGEM2-ES) under the RCP8.5 greenhouse gas emissions scenario (S. Rinnan, unpublished data – see section 3.2.2 for more information). The suitable climate space of elk is projected to remain stable when both models are averaged, but the CNRM-CM5 model shows large areas of potential expansion (map on the left), while the HadGEM2-ES model shows large areas of contraction (map on the right). The climate models also disagree for projections on the Olympic Peninsula, with the CNRM-CM5 model projecting large areas of contraction and the HadGEM2-ES model projecting large areas of stability (see Figure 3.2).

Figure 3.2 *Suitable climate space projections for elk. The maps show where the current climate space is projected to potentially remain stable (black), contract (orange) and expand (blue) for two different global climate models (CNRM-CM5 and HadGEM2-ES) under the RCP 8.5 greenhouse gas emissions scenario. Olympic Peninsula projection maps were clipped by Clallam, Jefferson, Mason, and Grays Harbor counties.*



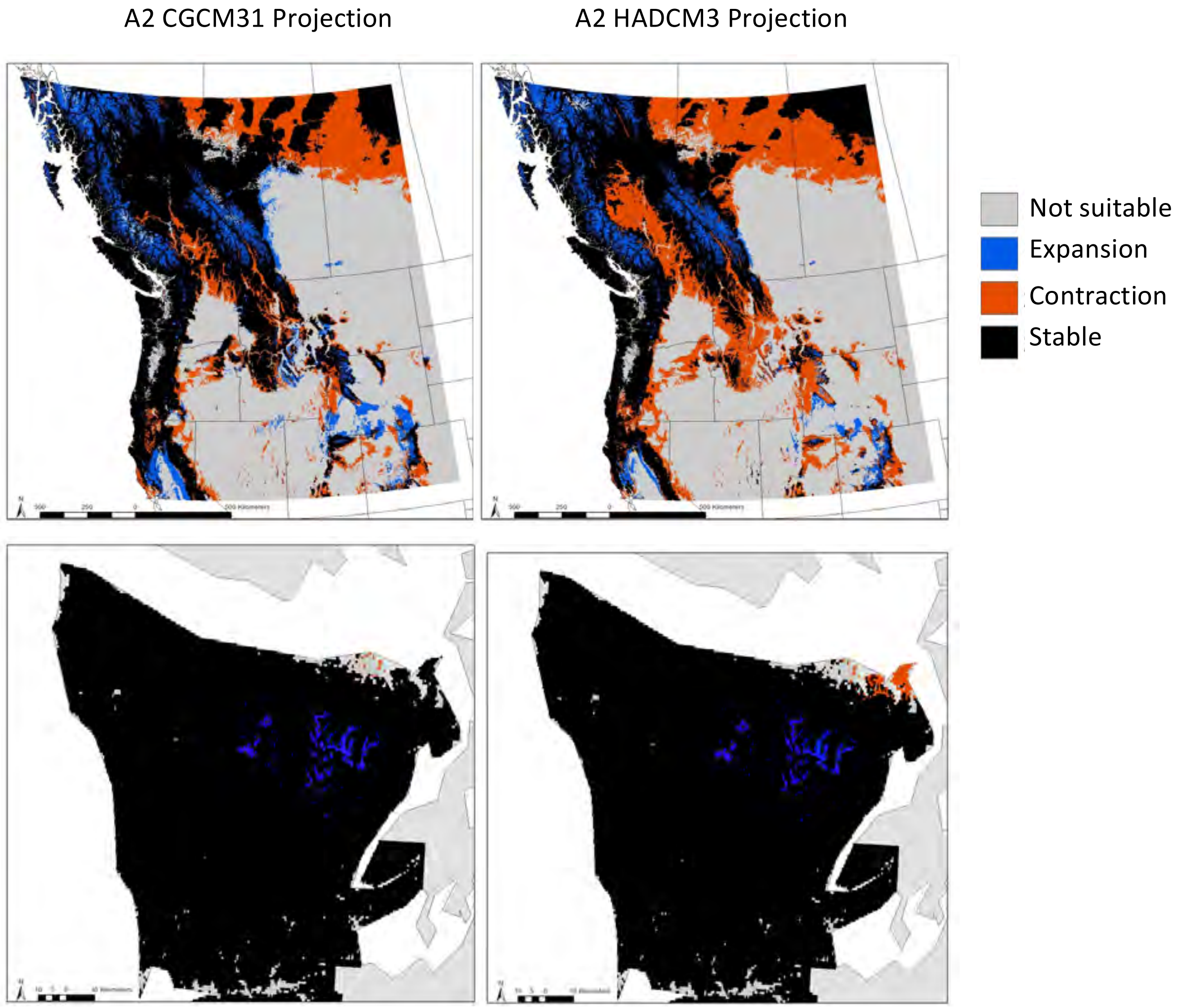
Black Bear

Black bear. Photo courtesy Larry Workman, QIN.

American black bears (*Ursus americanus altifrontalis*) are a top predator species and are more prevalent near the Quinault Indian Nation, who leads commercial guided hunts. Black bears are a subsistence food for some people if one can be caught. Quileute and Hoh have hunting rights in the treaty area surrounding the Quinault reservation and actively hunt the bears. They are also culturally importantly for some clans. Bears can be a nuisance for forestry as they often girdle and damage trees. Black bear, or "Chitwin" in Quinault, holds high status amongst the Treaty of Olympia tribes. It is commonly seen on totem poles and has standing as a family status symbol as well. While families that recognize Bear as their clan animal do not hunt the animal, they will utilize it for medicinal properties in various ways.

The suitable habitat for black bears (*Ursus americanus*) is projected to decrease overall, especially in northeastern portions of the study area and in the Northern Rocky Mountains. However, black bear suitable habitat is projected to increase at high elevations on the eastern side of the Olympic Mountains (see Figure 3.3).

Figure 3.3 *Habitat suitability range projections for the American black bear. The maps show where the current range is projected to potentially remain stable (black), contract (orange) and expand (blue) for two different global climate models (CGCM31 and HADCM3) under the A2 greenhouse gas emissions scenario. Olympic Peninsula projection maps were clipped by Clallam, Jefferson, Mason, and Grays Harbor counties.*



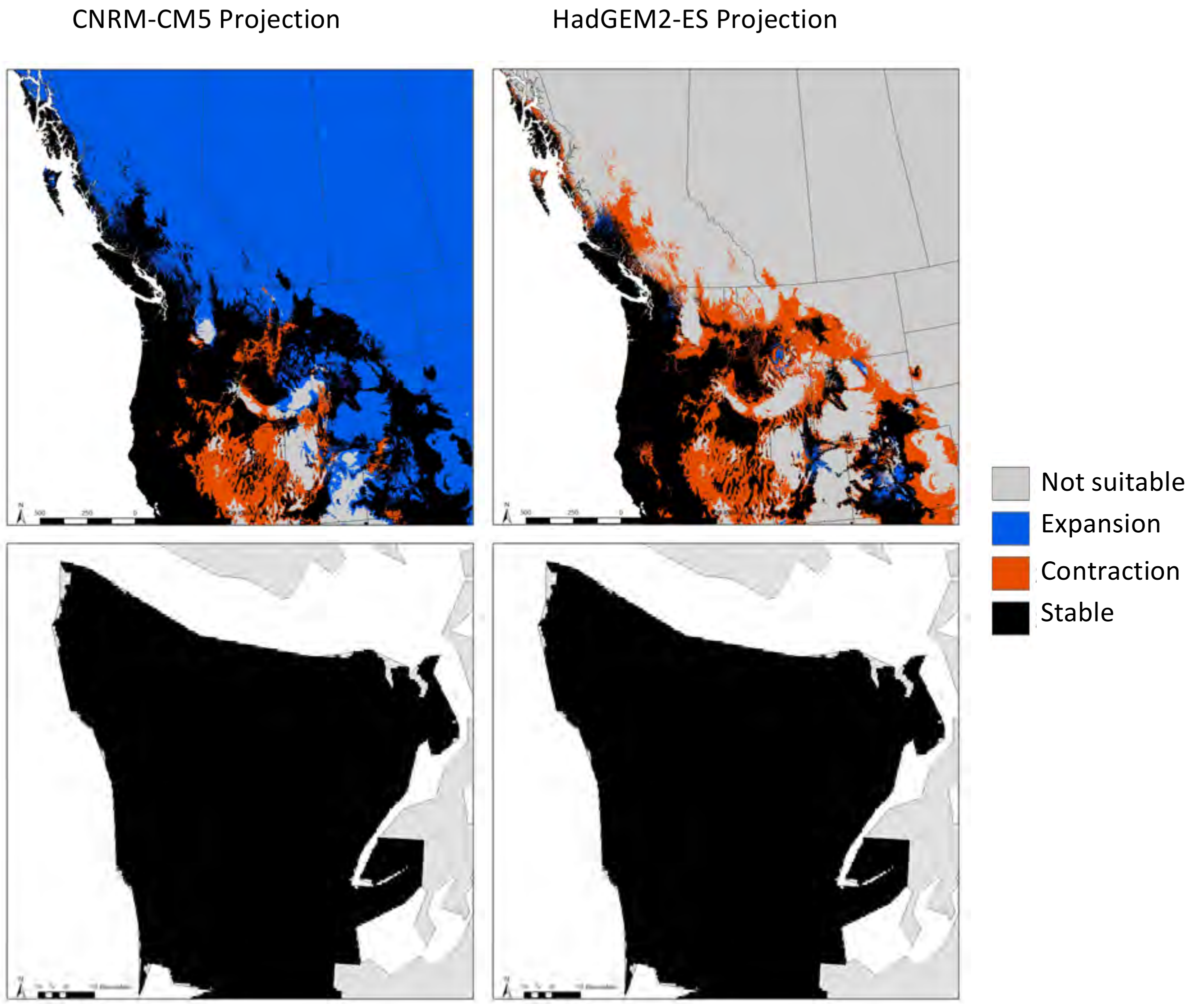
Black-tailed Deer

The black-tailed deer (*Odocoileus hemionus columbianus*) is important for all three tribes as a subsistence food and also for ceremonial purposes, though to a lesser degree than elk. Deer have been a longstanding cultural and ceremonial animal pre-dating elk's introduction, but are being carefully selected due to their progressive decline. Hide use, bones, antlers, and hooves are all frequently utilized for cultural purposes, as well as meat for consumption. The deer population is not robust as its population is currently diminishing due to Asian louse and increased predators (Mertins et al., 2011; Robison 2007). Asian louse causes severe mange, which has reduced the deer's ability to survive winter. The warmer winters projected under future climate change may actually aid survival. A decrease in the deer population could lead to changes in hunting practices and predation. Already among the tribes, there has been a voluntary cut back on hunting the deer.

Black-tailed deer. Photo courtesy Larry Workman, QIN.

While deer is important to the tribes, the species was not included in either the Climate Change Sensitivity database or in the original range projection database. An alternative database was found to have range projections for deer (S. Rinnan, unpublished data – see section 3.2.2 for more information). The suitable climate space of black-tailed deer is projected to increase overall, however, the CNRM-CM5 model is likely over projecting black-tailed deer suitable climate in the future. Both climate models agree that black-tailed deer will retain its current suitable climate space throughout the Olympic Peninsula in the future (see Figure 3.4).

Figure 3.4 *Suitable climate space projections for black-tailed deer. The maps show where the current climate space is projected to potentially remain stable (black), contract (orange) and expand (blue) for two different global climate models (CNRM-CM5 and HadGEM2-ES) under the RCP 8.5 greenhouse gas emissions scenario. Olympic Peninsula projection maps were clipped by Clallam, Jefferson, Mason, and Grays Harbor counties.*

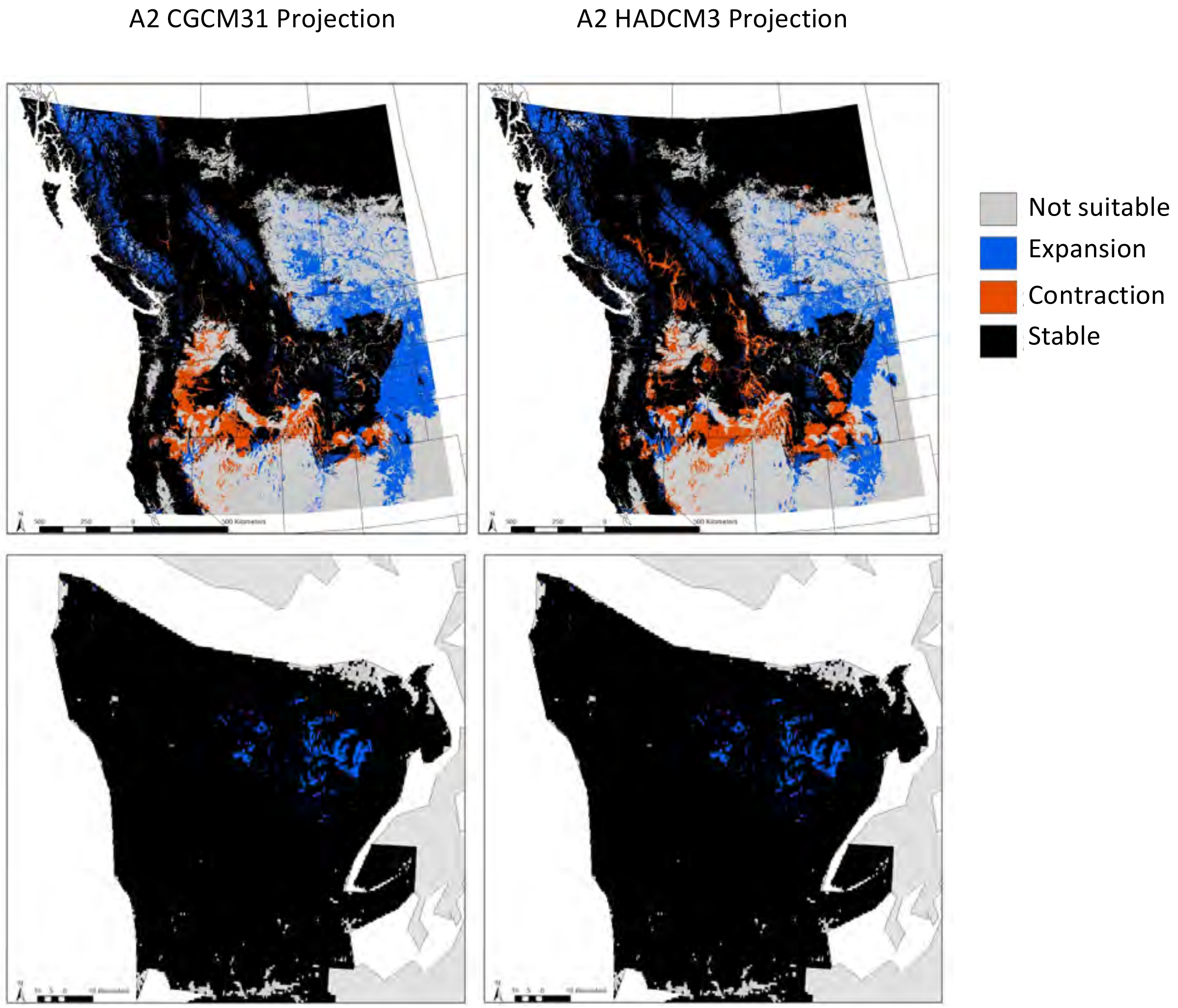


River Otter

The North American river otter (*Lutra candensis*) is trapped and pelts can be sold, though this is rarely done by the tribes currently. River otters eat salmon and so are in direct competition with human fishing. While river otters may be relatively robust to climate change based on increasing habitat suitability, the river otter may be indirectly affected through the fate of climate change impacts, including ocean acidification, on the fish they eat. Cultural aspects of otter are less significant than many of the other animal species, but do hold an important role (Butler 2004).

The suitable habitat for river otter is projected to increase mostly in the north and east of its current range. However it is also projected to lose some of its current range, mostly at the southern extent of its range. For the Olympic Peninsula, the river otter is projected to increase slightly (Figure 3.5).

Figure 3.5 *Habitat suitability range projections for the North American river otter. The maps show where the current range is projected to remain stable (black) or contract (orange) and expand (blue) for two different global climate models (CGCM31 and HADCM3) under the A2 greenhouse gas emissions scenario. Olympic Peninsula projection maps were clipped by Clallam, Jefferson, Mason, and Grays Harbor counties.*

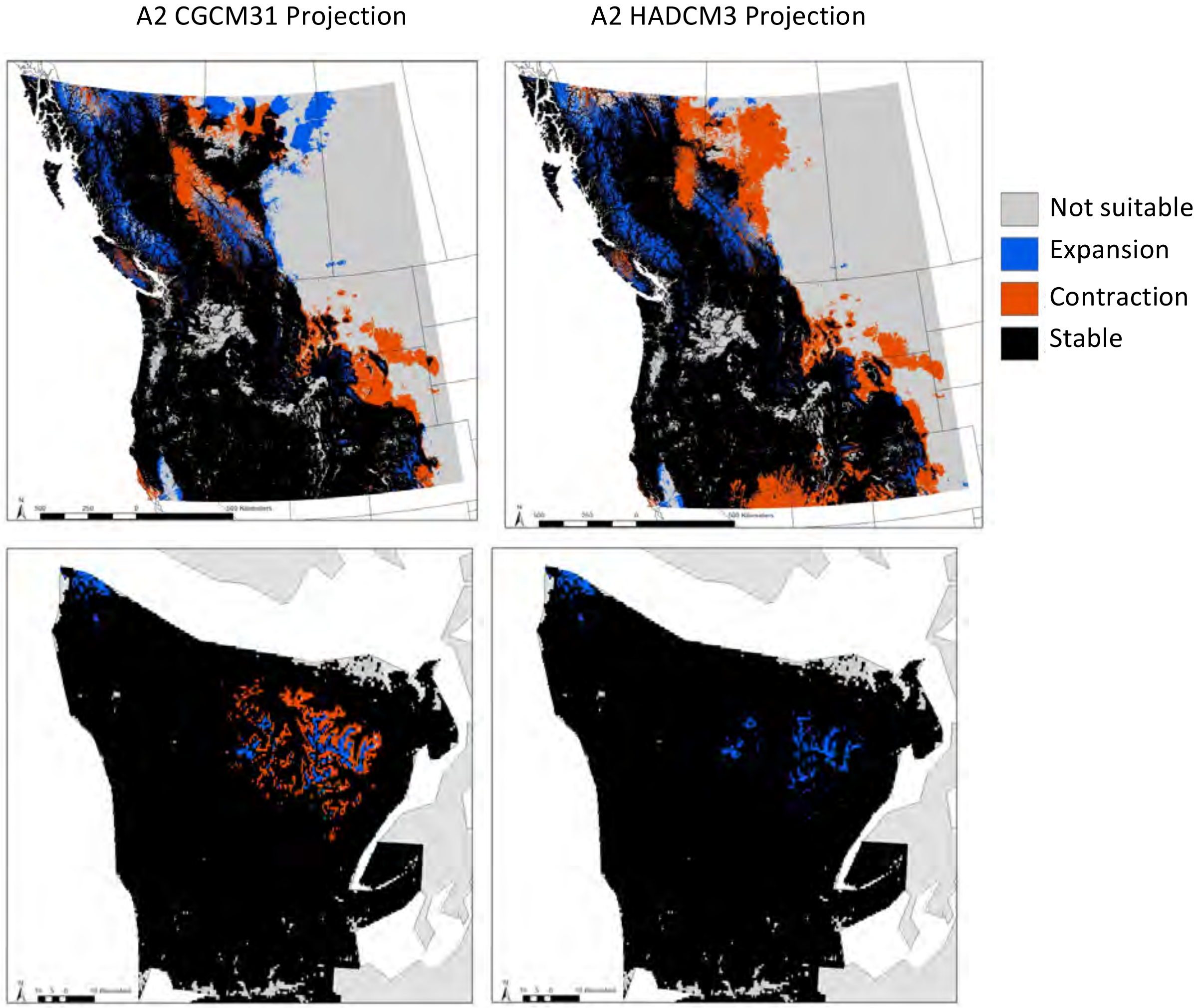


Cougar

The cougar (*Puma concolor*) is a top predator and is hunted as a food by the Quileute Tribe. The suitable habitat for the cougar is projected to shrink considerably for both climate models. Model projections show significant contraction in the east of its current range and in parts of Canada, with some expansion in the north. The CGCM31 climate model also projects some loss of suitable habitat on the Olympic Peninsula, but the HadCM3 model does not show the same contraction (Figure 3.6).

Cougar. Photo courtesy Carolyn Kelly, QIN

__Figure 3.6__ Habitat suitability range projections for the cougar. The maps show where the current range is projected to potentially remain stable (black), contract (orange) and expand (blue) for two different global climate models (CGCM31 and HADCM3) under the A2 greenhouse gas emissions scenario. Olympic Peninsula projection maps were clipped by Clallam, Jefferson, Mason, and Grays Harbor counties.



Snowshoe hare

The snowshoe hare (*Lepus americanus*) is hunted as a food and is also prey for other mammals and birds. This species is not available in the climate change sensitivity database or in the range projection database.

Snowshoe hare. Photo courtesy Larry Workman, QIN.

3.5.7 Birds

Of the important birds identified by the tribes, three were available in the Climate Change Sensitivity database (i.e., brown pelican, harlequin duck, Canada goose). Migratory ducks and geese in general were identified as important by the Treaty of Olympia tribes. The Harlequin duck, while not particularly important to the tribes, was the only duck in the Climate Change Sensitivity database and is presented below. Five important bird species were available in the Range Projections database (i.e., bald eagle, common raven, Rufous hummingbird, American crow, Great blue heron). Unfortunately, the seagull was not included in any data set (Table 3.3).

Of the three bird species contained in the Climate Change Sensitivity database, the Harlequin duck was determined to be relatively more sensitive to climate change than the others due to high physiological sensitivity to climate change. Brown pelican and Canada goose were determined to be moderately sensitive to climate change.

The bald eagle, common raven, and the Rufous hummingbird had the largest projected declines in current habitat and the largest decrease in overall net change between current and future habitats across their entire habitats. These results imply that although there are not large habitat changes projected for the Olympic Peninsula, these species may be more vulnerable to future changes in climate and climate-driven changes in vegetation across their entire range. However, it should be noted that these three species – bald eagle, common raven, and Rufous hummingbird all have very large ranges and therefore may be more capable of adapting to future climatic changes than species which have small ranges. Furthermore, Rufous hummingbirds are somewhat aggressive to other hummingbird species and breed farther north than any other hummingbird. Nevertheless, all bird species for which range projections are available were projected to lose some of their current habitat by the end of the century for their entire range; however, American crow and great blue heron were projected to have a positive net change. For these species, there may be more suitable habitat in the future and they may be less vulnerable to future changes in climate and vegetation.

Projected future changes in suitable habitat on the Olympic Peninsula were relatively minor compared to changes projected in other locations. A possible explanation for this trend is that the Olympic Peninsula is relatively far from the geographic range boundaries of the species reviewed here. Furthermore, projected climatic changes are generally smaller on the peninsula and the coast in general compared to more continental areas in the Pacific Northwest.

Table 3.3 *Climate change sensitivity ranking or projected loss of current suitable habitat and net change for bird species of concern over their entire range and the Olympic Peninsula.*

			Entire Range[2]		**Olympic Peninsula**[2]	
Common Name	**Scientific Name**	**Sensitivity**[1]	**% Change Current Habitat**	**% Net Change**	**% Change Current Habitat**	**% Net Change**
Bald eagle	*Haliaeetus leucocephalus*	--	-31	-38	0	1
Common raven	*Corvus corax*	--	-24	-43	0	0
Rufous hummingbird	*Selasphorus rufus*	--	-28	-45	0	0
American crow	*Corvus brachyrhynchos*	--	-11	1	0	25
Great blue heron	*Ardea herodias*	--	-15	13	-1	2
Brown pelican	*Pelecanus occidentalis*	Moderate	--	--	--	--
Harlequin duck	*Histrionicus histrionicus*	High	--	--	--	--
Canada goose	*Branta canadensis*	Moderate	--	--	--	--
Gulls		--	--	--	--	--

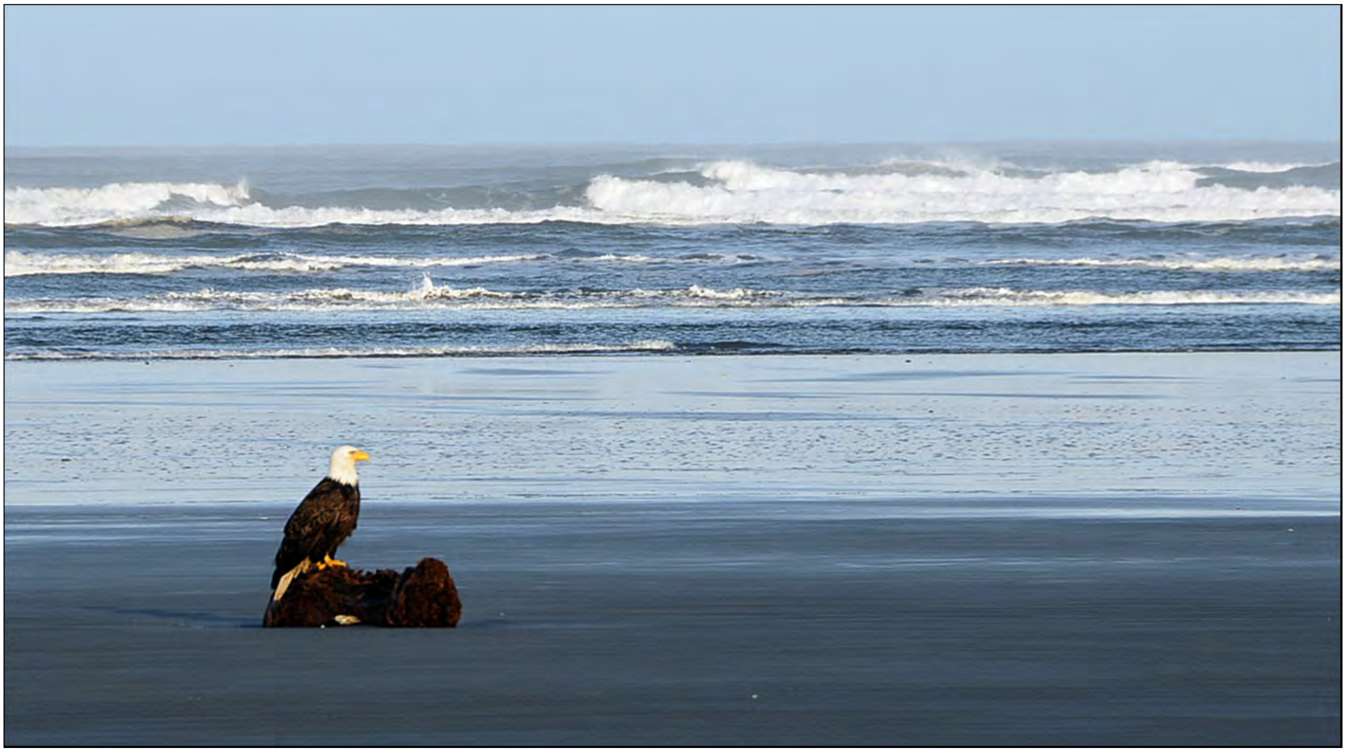
[1] climatechangesensitivity.org

[2] climatevulnerability.org

Bald eagle

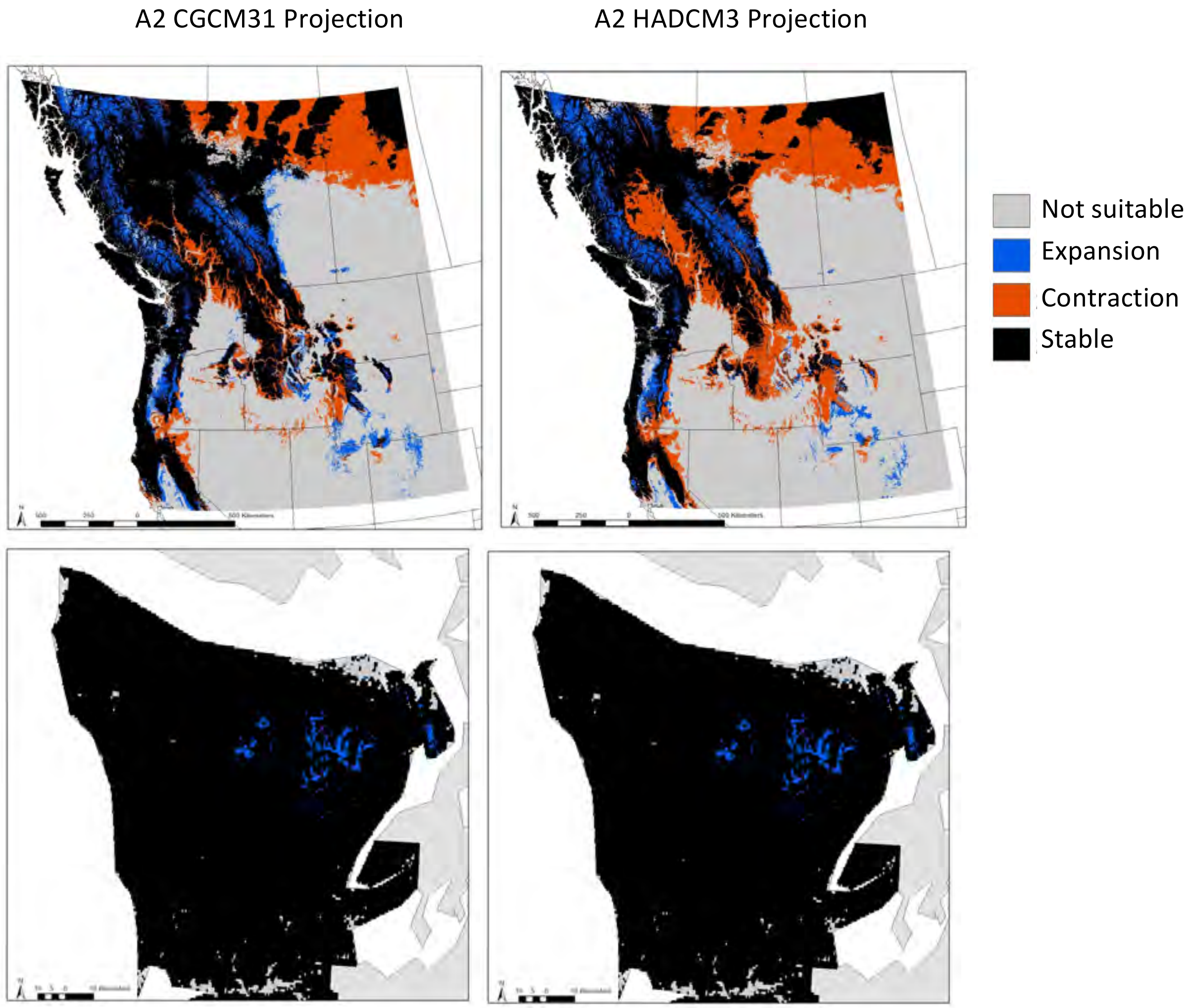
The bald eagle (*Haliaeetus leucocephalus*) is an ecological indicator. An “ecological indicator” species is one utilized for information on what is occurring within the environment (Bowerman et al., 2002; Landres et al., 1988). It is both a hunter and a scavenger and preys on fish and some smaller birds (e.g., seagulls and murres). The bald eagle has cultural importance: the Quinault Indian Nation and Quileute Tribe tribal members discussed using the feathers in ceremonial practices. Hoh tribal members available did not discuss. Eagle is a highly honored species in Native cultures, and this relates to the Treaty of Olympia tribes as well. The feathers are the most obvious utilized items, but other parts of the bird are used as well. This species is revered both physically and spiritually as a totem animal, a family clan crest, and also as a "guider" for ceremonial and spiritual practices (Tam et al., 2013).

The suitable habitat range of the bald eagle is projected to shrink considerably, especially in the Northern Rocky Mountains and portions of Canada (see Figure 3.7). However, both climate models agree that the bald eagle could expand its habitat on the Olympic Peninsula, depending on the continued availability of salmon, its main diet.



Bald eagle. Photo courtesy Larry Workman, QIN.

Figure 3.7 *Habitat suitability range projections for the bald eagle. The maps show where the current range is projected to potentially remain stable (black), contract (orange) and expand (blue) for two different global climate models (CGCM31 and HADCM3) under the A2 greenhouse gas emissions scenario. Olympic Peninsula projection maps were clipped by Clallam, Jefferson, Mason, and Grays Harbor counties.*

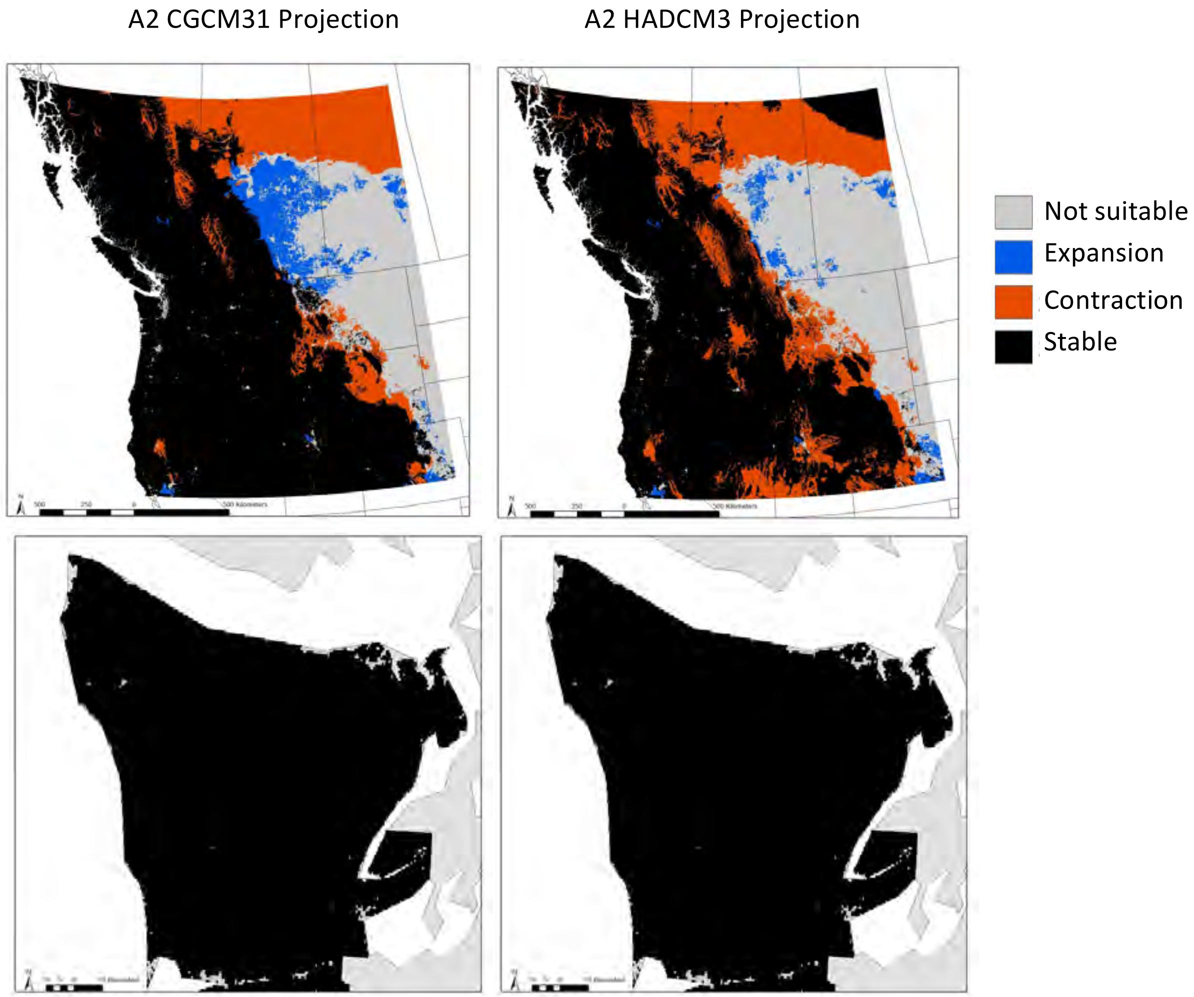


Raven

The common raven (*Corvus corax*) is a scavenger and predator and important in mythology of the Treaty of Olympia tribes. Culturally, Raven is noted for many of the important teachings, having stories that credited the species for relaying information about ecological phenomenon such as fire, the sun's behaviors, and issues that occur in forested areas. It is often seen on totem poles, is used in ceremonial and cultural activities, and is the head of a clan system. While its importance does not reflect that equivalent of an eagle or elk in the same category, it is equally important in relaying sacred and traditional information such as places, stories, songs, and change in various system regimes. Raven remains powerful in its importance as a teaching and physical metaphoric symbol of information and value systems (Alexander et. al, 2011; Watson, 2014).

The suitable habitat range of the common raven is projected to decrease substantially, especially on the eastern portion of its current range and in portions of Canada (see Figure 3.8). The raven's suitable habitat is not projected to change on the Olympic Peninsula. Although suitable habitat models project uniform suitability across the Olympic Peninsula (Figure 3.8), it should be noted that not all areas and elevations are equally suitable.

Figure 3.8 *Habitat suitability range projections for the common raven. The maps show where the current range is projected to potentially remain stable (black), contract (orange) and expand (blue) for two different global climate models (CGCM31 and HADCM3) under the A2 greenhouse gas emissions scenario. Olympic Peninsula projection maps were clipped by Clallam, Jefferson, Mason, and Grays Harbor counties.*

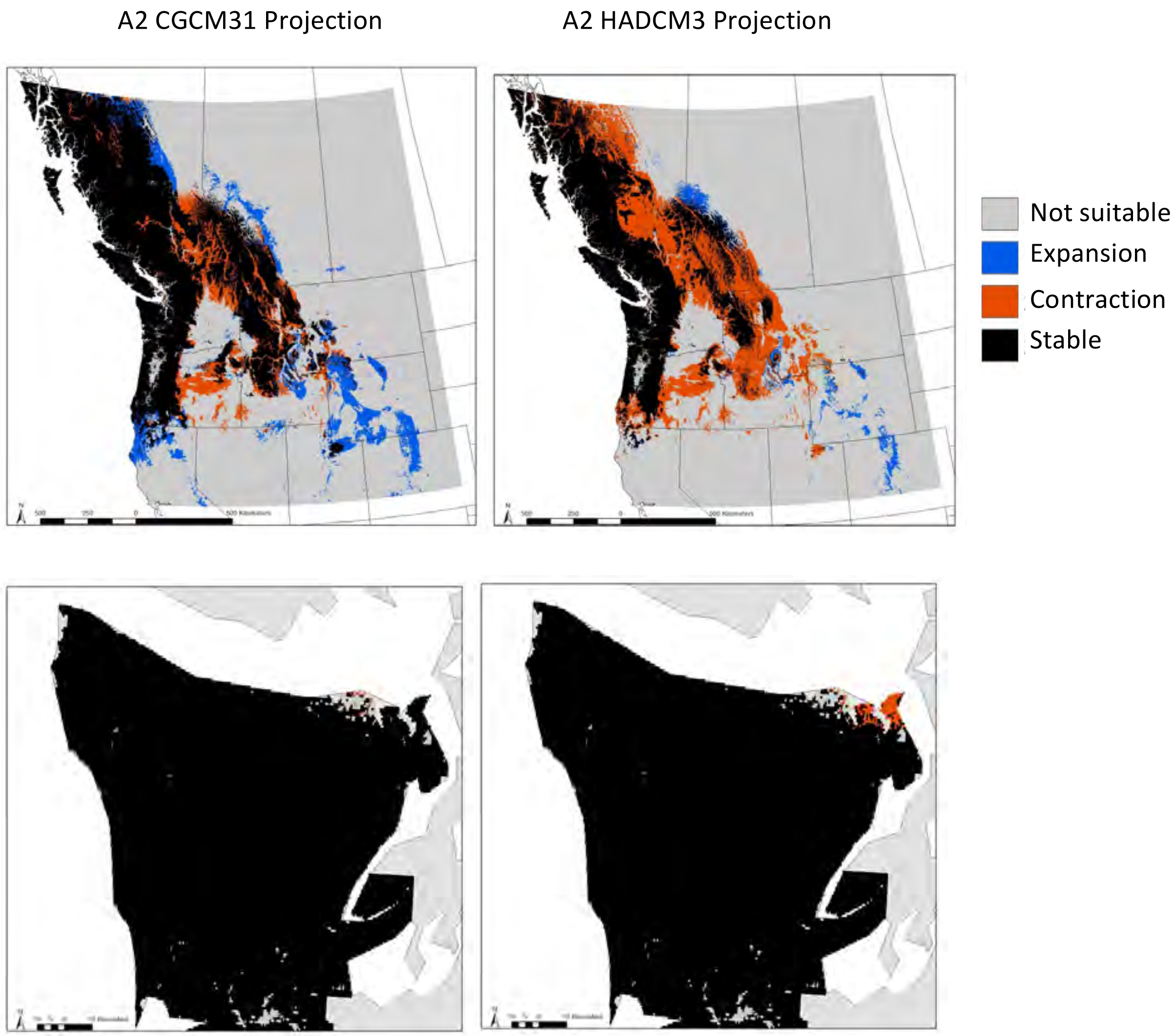


Pollinating Birds

Pollinating birds are important to the Treaty of Olympia tribes for their ecological function. Two species were identified: Anna’s hummingbird and Rufous hummingbird. Only the Rufous hummingbird (*Selasphorus rufus*) was available in the Range Projection database.

The suitable habitat range of Rufous hummingbird is projected to substantially decrease across its current range. Much of this decrease is projected to occur at the southern and eastern extents and in the Northern Rocky Mountains. However, the suitable habitat for Rufous hummingbird is projected to be relatively stable on the Olympic Peninsula (see Figure 3.9).

Figure 3.9 *Habitat suitability range projections for Rufous hummingbird. The maps show where the current range is projected to potentially remain stable (black), contract (orange) and expand (blue) for two different global climate models (CGCM31 and HADCM3) under the A2 greenhouse gas emissions scenario. Olympic Peninsula projection maps were clipped by Clallam, Jefferson, Mason, and Grays Harbor counties.*



Gulls

There are several coastal species of gulls, which as a group were identified as important by the Treaty of Olympia tribes. Gulls are scavengers and prey on fish. Gull eggs were traditionally gathered on islands as food, but now such gathering areas are protected areas by the U.S. Fish and Wildlife Service through a north-south string of National Wildlfe Refuges (see http://www.fws.gov/refuges/refugeLocatorMaps/washington.html). Unfortunately, gulls were not included in either database and little information on their climate change vulnerability is available.

Brown Pelicans

The brown pelican (*Pelicanus occidentalis*) was identified by the tribes as important due to the fact that each year they have been seeing more arriving in the summer and staying through the fall, though numbers vary annually. Typical breeding grounds are generally south of the Olympic Peninsula.

The climate change sensitivity ranking score for the brown pelican is relatively moderate (40 out of 100) with a fair (60 out of 100) confidence score. The brown pelican has a somewhat flexible diet and excellent dispersal capabilities, which enable them to move to new locations as conditions change. However, the brown pelican puts considerable energy into rearing its young and it is greatly affected by the availability of its primary food resource, small fish. Small fish can be highly impacted by warming ocean temperatures, changes in ocean currents, and extreme events, such as powerful El Niño Southern Oscillation (ENSO) events.

The reproductive strategy of brown pelicans is more “k-selected” than “r-selected”, meaning that they have fewer offspring and invest a high degree of parental energy. The brown pelican also only reproduce once a year.

Not much is known about the physiological sensitivity of brown pelicans to changing temperatures and precipitation regimes. However, brown pelicans are somewhat sensitive to changes in temperature. For instance, cold temperatures can cause mortality in brown pelicans through hypothermia, frostbite damage to foot webs and the gular pouch, and through starvation resulting from reduced availability of fishes in surface waters.

Brown pelicans are moderately sensitive to changes in ocean conditions, such as warming ocean temperatures, changes in ocean currents, and extreme events. Changes in ocean conditions can affect prey availability, which can be greatly reduced during severe ENSO events, resulting in mass starvation for brown pelicans. For example, during the 1982 - 1983 ENSO event large numbers of dead and dying brown pelicans were observed. Further research into how climate change and events such as ENSO impact food resources is understudied for this species. They are also sensitive to harmful algal blooms and may succumb to the toxins, when these accumulate in forage fish, especially anchovies.

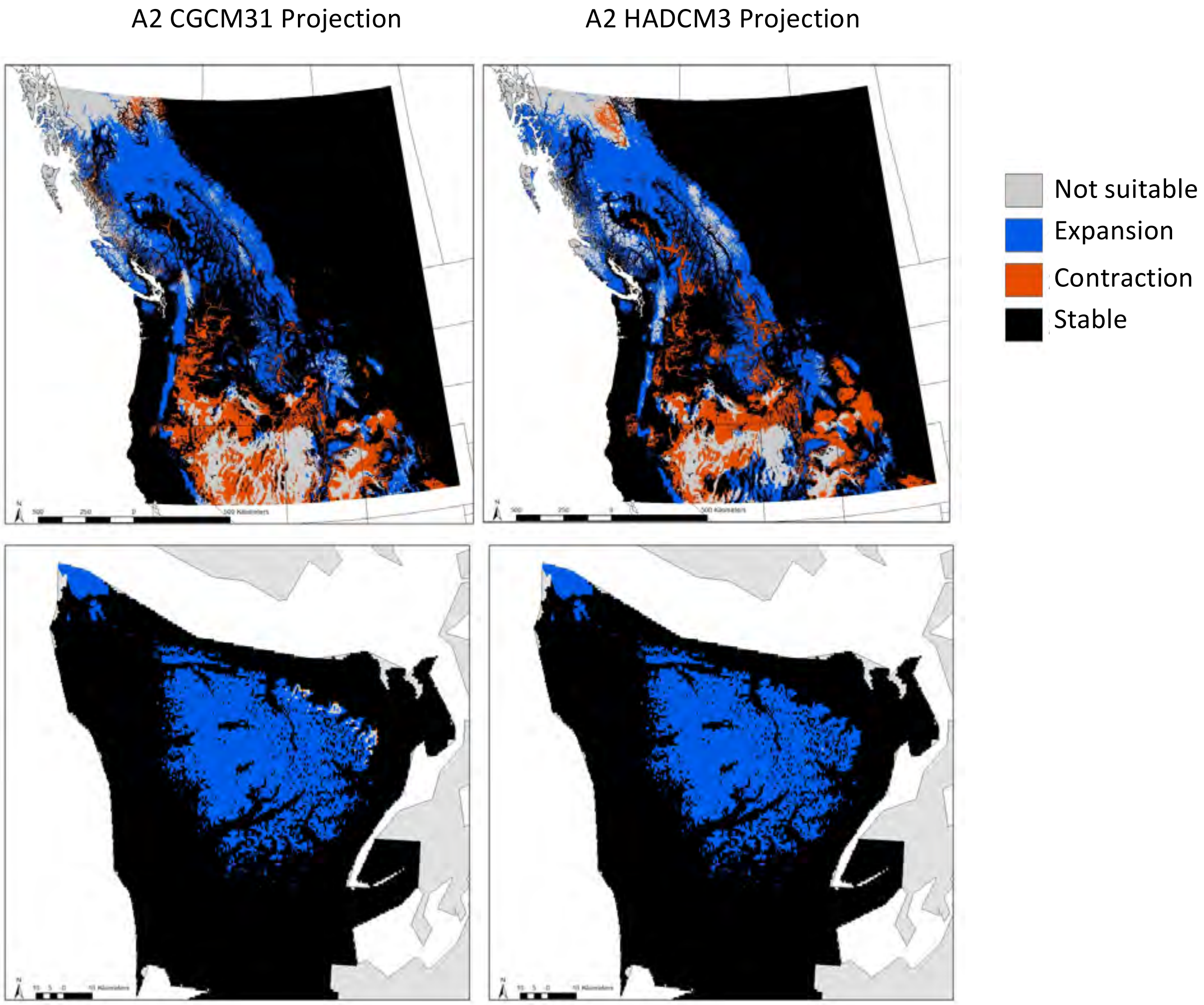
Climate change may affect diseases and pests of brown pelicans but to what extent is not known.

The brown pelican is also impacted by habitat quality and land-use change. For instance, pelicans are affected by the availability of preferred habitat in some areas, such as mangrove habitat in Caribbean, which has been reduced by fuel-wood cutting. Brown pelicans are also highly susceptible to pollution, such as oil spills and are very sensitive to organochlorine pesticides, particularly endrin and DDT.

Northwestern Crow

The Northwestern crow or American crow (*Corvus brachyrhynchos*) is a scavenger and predator and was identified as important by the tribes for its ecological function. Although the American crow is projected to lose some of its current suitable habitat over the next century, overall it is projected to slightly expand. Much of the potential contration is projected to occur in the Great Basin and Southern Rocky Mountains. The crow's suitable habitat is projected to increase across much of the Olympic Peninsula (see Figure 3.10).

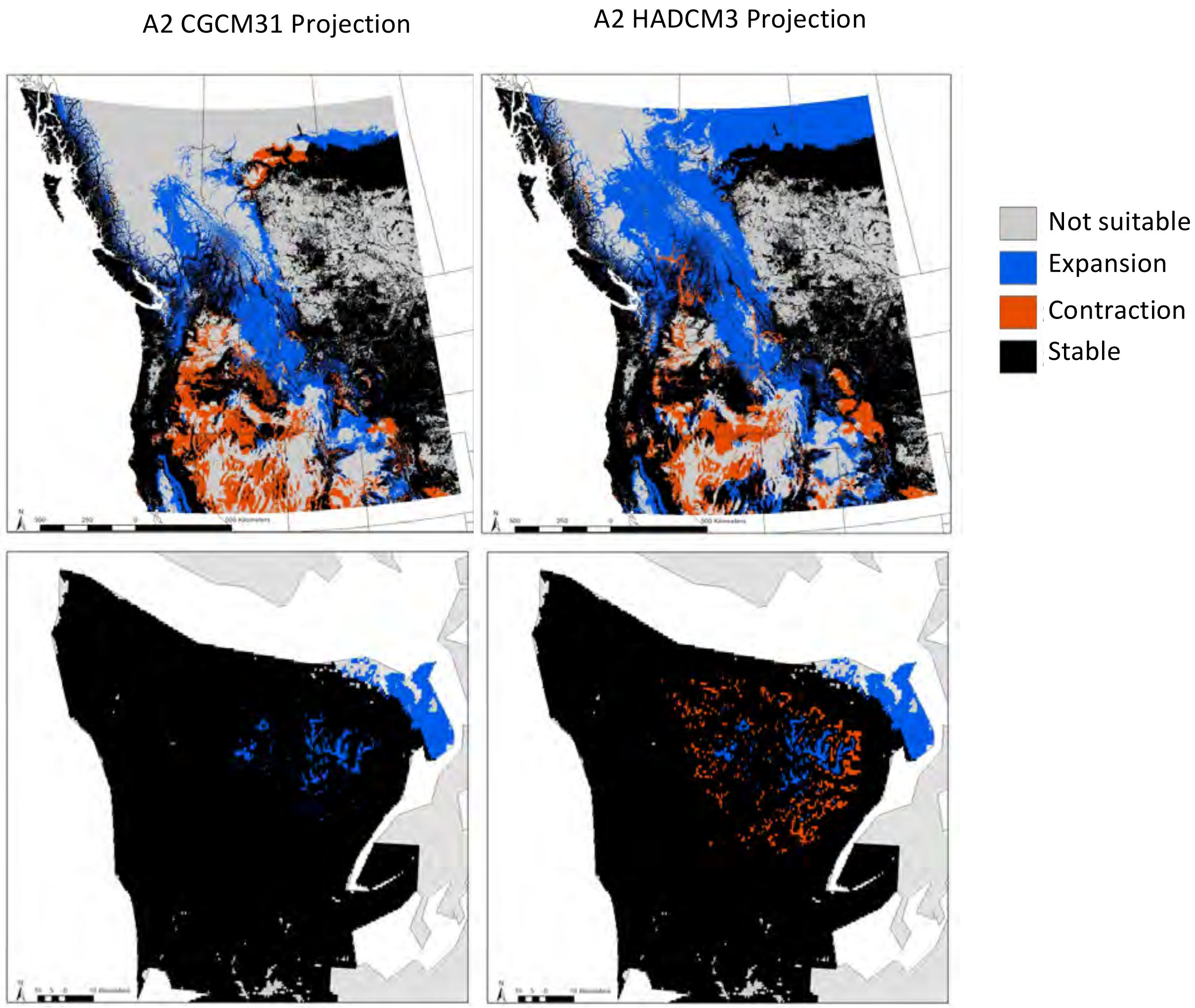
Figure 3.10 *Habitat suitability range projections for the American crow. The maps show where the current range is projected to potentially remain stable (black), contract (orange) and expand (blue) for two different global climate models (CGCM31 and HADCM3) under the A2 greenhouse gas emissions scenario. Olympic Peninsula projection maps were clipped by Clallam, Jefferson, Mason, and Grays Harbor counties.*



Great blue heron

The great blue heron (*Ardea Herodias*) preys on juvenile aquatic animals and was identified as important by the tribes for its ecological function. The suitable habitat range of the great blue heron is projected to increase overall, with significant areas of contraction in the southern portion of its range and significant areas of expansion in the north. Although the two climate models disagree somewhat, suitable habitat is projected to increase slightly on Olympic Peninsula (see Figure 3.11).

Figure 3.11 *Habitat suitability range projections for the great blue heron. The maps show where the current range is projected to potentially remain stable (black), contract (orange) and expand (blue) for two different global climate models (CGCM31 and HADCM3) under the A2 greenhouse gas emissions scenario. Olympic Peninsula projection maps were clipped by Clallam, Jefferson, Mason, and Grays Harbor counties.*



Migratory ducks and geese

Migratory ducks and geese as a group was identified as important by the Treaty of Olympia tribes due to their ecological function. Traditionally, ducks and geese were eaten as food, but that is now limited by the Migratory Bird Act. There are many different species that migrate through the west Olympic Peninsula, however, only the Canada goose (*Branta canadensis*) and Harlequin duck (*Histrionicus histrionicus*) were included in the Climate Change Sensitivity database and are presented in detail below even though they may not be among the most important migratory duck and geese species for the Treaty of Olympia tribes.

Harlequin ducks. Photo courtesy Larry Workman, QIN.

Climate change can affect migrating birds in a variety of ways. Changes in migration routes can occur in response to alteration of breeding grounds, stopover, or wintering sites due to changes in climate or land use. Changes in breeding activity and earlier spring arrival to breeding grounds has been observed in response to an earlier peak in food availability from warming spring temperatures. The distribution of many migratory birds has shifted poleward due to warming (Patterson and Guerin 2013). Climate change could also increase the spread of avian diseases among migrating populations, but there remain many knowledge gaps in this area of study (Fuller et al., 2012).

Canada goose

The climate change sensitivity ranking score for Canada goose is relatively moderate (42 out of 100) with a fair (60 out of 100) confidence score. Canada goose is moderately sensitive to climate change because of its foraging and phenology dependencies, its somewhat specialized nesting habitat requirement.

The Canada goose feeds primarily on grasses, sedges and other monocots and other plants (e.g., skunk cabbage leaves and eelgrass) during summer and spring. However, in fall and winter, their diet consists largely of grains, berries, fruits, and seeds. Many of these foods are higher in carbohydrates, which the birds need to make fat for the winter.

Canada geese have specific habitat requirements. During the breeding season they are generally found in treeless areas, high mountain meadows, prairies, arctic coastal plains, managed refuges, and other areas of human habitation. They also tend to nest individually or in small groups in areas permitting a clear view in all directions with permanent water nearby in the form of a lake, pond, large stream, or marsh. Canada goose nests may be on small islands, meadows, floating mats, or elevated platforms. They also breed successfully in agricultural and urban areas ranging from agricultural fields, parks and golf courses, to the tops of city buildings. Wintering habitat for Canada geese include mudflats, shallow tidal waters, and salt-water marshes. They can also nest near agricultural fields with grain or cover crops. Inland habitats include wet grasslands, marshes, lakes, reservoirs, and rivers within flying distance to agricultural fields. Female Canada geese are strongly philopatric and will return to the same area to breed. Individuals also exhibit strong philopatry to stop-over and wintering habitats.

Canada geese can disperse long distances but their dispersal varies from population to population. For instance, some may make more than 100 km migrations while others may remain resident in a particular area. Very generally, smaller bodied subspecies have the greatest migration, while large bodied subspecies remain resident or have short distance migration.

Canada geese are hunted but pollution, including pesticides, can have much more of a detrimental effect on reproduction. Lead poisoning is also a well-documented concern that affects them.

Not much is known about the physiological sensitivity of Canada goose to changing temperatures and precipitation. Climate change may also affect diseases and pests but to what extent is not known.

Harlequin Duck

The Harlequin Duck is a bird of fast-moving water, it breeds on fast-flowing streams, and winters along rocky marine coastlines in the crashing surf. This species feeds primarily on aquatic invertebrates and in northwest North America, it feeds on herring just before its spring migration. Because of these unique habitat dependencies, its somewhat specific food requirements, and being physiologically sensitive to changes in temperature and precipitation this species was deemed to be highly sensitive (63 out of 100) to climate change, but with a poor (40 out of 100) confidence score.

Harlequin ducks are physiologically sensitive to changes in climate both directly and indirectly. This species is restricted to relatively cold climates and warming temperatures will likely affect its ability to persist in some areas. Harlequin ducks are also indirectly physiologically sensitive because of the relationships that they have with prey species that are directly impacted by changes in climate. For example, macroinvertebrates and fishes are highly sensitive to changes in temperature, pH, and salinity and a change in prey abundance will impact harlequin ducks. Increased precipitation events (especially heavy rainfall events) that could alter river flow and cause siltation could also impact Harlequin ducks through a reduction in the aquatic invertebrate prey base.

Harlequin ducks breed among a variety of climatically sensitive habitats, such as fast-flowing streams in riparian and coastal habitats. In northwestern North America, breeding habitats tend to be along fast-flowing streams surrounded by undisturbed forests. Nest sites are variable including mid-stream islands, streamside under root balls or logs, tree cavities, and cliff ledges. Staging areas for Harlequin ducks that breed inland tend to be along river banks or gravel bars. Wintering and molting areas are in coastal areas along shorelines of intertidal and subtidal rocky benches, cobble beaches, and over shallow eelgrass and kelp bed - all areas that have been identified as being climatically sensitive.

Habitat degradation in breeding and wintering areas including changes in stream flow regimes by mining, roads, and timber harvest, impoundments and diversions on breeding streams and shoreline development will likely increase the sensitivity of Harlequin duck to climate change. Pesticides and oil spills could also affect some populations. Compared to many waterfowl, Harlequin ducks are understudied. Their specific habitat needs and food requirements are not entirely known and therefore they may be more or less sensitive to climate change than indicated here.

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Chapter 4: Freshwater Environment

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4.1 Introduction

Pacific salmon are vulnerable to a wide range of effects from climate change because of their reliance on marine, estuary, and freshwater environments to complete their life cycles. In freshwater, these changes will influence water supplies, water quality, and habitat conditions for fish and other aquatic organisms. The combined effect of climate change and human alteration is anticipated to have unprecedented effects on freshwater ecosystems and associated biota (Poff 2002; ISAB 2007). Similarly, marine environments are predicted to become less suitable for Pacific salmon because they will be warmer (Abdul-Aziz et al., 2011; Atcheson et al., 2012) and more acidic (Orr et al., 2005). Given these expectations, climate change impacts on salmon will likely be exacerbated wherever human alteration of the landscape is widespread.

The Treaty of Olympia tribes all rely on salmon both culturally and economically. Salmon are an important identity species for the tribes and are integrated into cultural practices and hold ceremonial value (Close et al., 2002; Lichatowich and Lichatowich, 2001). Harvest Moon explains one aspect of cultural importance that salmon hold through one traditional story summarized as follows:

> *“When bigfoot was standing in the water with dirty feet and the salmon won't come up the river, and teaches the people if you pollute the waters the salmon won't come up again."*

Vital information regarding the river and salmon patterns is relayed via Traditional Ecological Knowledge (TEK). In this way, established traditional practices have grown into economically viable options for the tribes. But as Norman Capoeman explains:

> *“Our tribal members aren't getting as much fish, which was one of our main foods that we ate, and salmon is one of the healthiest foods you can eat, but with our salmon declining and everything, we're eating less fish, and then also too it affects the economy because we commercially fish for a living and without you know as much fish as we used to have it can make it hard to make a living with less fish.”*

Norman Capoeman also relates his personal experience:

> *"I've fished probably twenty five years of my life and there's definitely a decline in our salmon runs they're not like they used to be."*

There is a wealth of work on the potential impacts of climate change on Pacific salmon (*Oncorhynchus* spp.). Among studies conducted in western Washington, the primary factors associated with climate change that will affect salmon and steelhead are water temperature and changes in streamflow (Mantua et al., 2010; Wade et al., 2013; Ward et al., 2015).

Because of the high degree of heterogeneity in habitat and life-history types, different species and even particular populations of the same species are known to respond differently to the same climate events (Crozier and Zabel, 2006; Schindler et al., 2010). Understanding the potential consequences of altered environmental conditions, particularly where the perceived impacts are not considered lethal, requires consideration of the impacts at each life-history stage (Fleming et al., 1997; ISAB 2007; Jonsson and Jonsson, 2009). Changes at one life stage can cascade throughout the remaining stages, significantly altering population response. Thus, while the extent to which a particular population will be affected by climate change depends to a large degree on changes that occur at the local level; these changes can be accumulated across multiple life-history stages in such a way that investigation of climate change impacts at a single life-history stage may well underestimate the overall impact at the population level.

Quinalt River. Photo courtesy Larry Workman, QIN.

In this report, we examine the potential impacts of climate change on Pacific salmon (*Oncorhynchus* spp.) in the Treaty of Olympia area by: (1) reviewing the literature to identify effects at each life-history stage and discuss how those impacts might be propagated through succeeding stages, starting with adults in the ocean, their migration to spawning grounds, and the subsequent incubation of eggs, emergence, growth of juveniles, smoltification, and finally the early ocean residency of juvenile salmon; and (2) determine the potential impacts of elevated water temperatures and winter flows on populations of selected Pacific salmon within the four main watersheds of the Treaty of Olympia area (Figure 4.1).

Figure 4.1 *Basins in the Treaty of Olympia area examined in this study.*

4.2 Potential Impacts of Climate Change by Life-History Stage

4.2.1 Adults

The marine environment is critical to the life history of Pacific salmon because it is where the majority of growth and the initiation of sexual maturity occur. Depending on the species, fish may spend from 1 to 5 or more years in the ocean before returning to freshwater, the exception being coastal cutthroat trout, which generally make short forays into nearshore areas (Trotter, 1989).

The primary impacts of climate change on the ocean that are potentially important to Pacific salmon are: (1) increased acidification (Orr et al., 2005); (2) increased near-surface ocean temperatures (IPCC, 2007); (3) changes in wind and current patterns (Rykaczewski and Dunne, 2010); and (4) sea-level rise (IPCC 2007). Absorption of anthropogenic CO_2 by the upper ocean decreases pH and carbonate ion concentrations (Orr et al., 2005), which reduces the ability of organisms with external skeletons to create biogenic calcium carbonate ($CaCO_3$), a key component of the exoskeleton. Many of these organisms form the base of the food chain that supports salmon in the ocean. Because the subarctic North Pacific Ocean naturally has higher carbon concentrations compared to most other ocean basins, the impacts of acidification are expected to occur sooner and be more pronounced there (Cooley et al., 2011).

Snowy Queets River. Photo courtesy Larry Workman, QIN.

Elevated surface temperatures may reduce the amount of preferred thermal habitat for salmon in the ocean and potentially limit their marine distribution (Welch et al., 1995; Abdul-Aziz et al., 2011; Atcheson et al., 2012). As the amount of area with suitable temperature decreases, salmon could become concentrated in smaller areas, resulting in increased competition for limited food resources (Welch et al., 1995; Grebmeier et al., 2006). Salmon may be able to at least partially compensate for these changes by using cooler subsurface waters; however, these environments may provide reduced food resources, increased competition, or greater risk of predation (Abdul-Aziz et al., 2011; Hinke et al., 2005).

Potential consequences resulting from decreasing pH and increasing temperature are that Pacific salmon will be smaller and younger upon return to freshwater, and marine survival rates are likely to decrease. The low fall Coho salmon returns in 2015, indicative of declining ocean health, prompted the Quinault Indian Nation to close their fisheries and declare an economic disaster (http://indiancountrytodaymedianetwork.com/2015/10/29/situation-dire-low-coho-salmon-returns-close-quinault-fisheries-162266). Overall, the size of returning adults of most Pacific salmon declined over the last three decades of the 20th century (Bigler et al., 1996), although there have been multi-year periods when both size and numbers of some species have increased (Helle et al., 2007). Some populations of Sockeye salmon in Bristol Bay, Alaska declined in the age of returning adults in the second half of the 20th century (Robards and Quinn, 2002; Hodgeson et al., 2006). There are many possible explanations for the observed declines. Several previously published examinations of adult salmon sizes, from either commercial fishing records (Helle et al., 2007) or Alaskan fishing derbies (Fagen 1988) attributed at least some of the decline in size to increased competition due to the large numbers of hatchery-produced fish (Bigler et al., 1996; Francis and Hare, 1997). However, such relationships are not simple. Helle et al. (2007) analyzed data for different species and stocks from northern Alaska to Oregon and showed that adult body size resulted from both density-dependent factors (competition) and density-independent factors (environmental conditions).

Returning salmon. Photo courtesy Larry Workman, QIN.

Decreases in adult body size resulting from changing environmental conditions in the ocean expected under climate change scenarios could likely propagate into the freshwater environment, leading to reduced reproductive success. In Pacific salmon, both fecundity (Healey and Heard, 1984; Hankin and McKelvey, 1985) and egg size (Quinn and Vϕllestad, 2003) are directly related to the size of adult females, so the reproductive potential of populations could be reduced if females have fewer eggs (McElhany et al., 2000). Egg size, primarily related to yolk reserve, is at least partially an adaptation to the environment in which eggs develop. Fish from warmer areas tend to have larger eggs compared to those from cooler areas, because of the reduced efficiency of yolk conversion to body tissue at higher temperatures (Fleming and Gross, 1990). The survival and body mass at hatching of smaller eggs could be reduced by elevated temperatures in the future. In the absence of rapid adaptive responses, these changes could be particularly pronounced in northern areas that currently have cold water temperatures during incubation.

Aquatic and riparian ecosystems use the influx of marine-derived nutrients from returning adults for food web productivity (Bilby et al., 1996; Schindler et al., 2003). Many streams and rivers within the distributional range of Pacific salmon are nutrient-limited and, thus, are influenced by the quantity of marine-derived nutrients from spawning salmon (Helfield and Naiman, 2001; Willson et al., 2004). A reduction in the size and number of returning adult salmon could compromise freshwater productivity. Juvenile and adult salmonids may also benefit from the consumption of eggs during the spawning period (Cederholm et al., 2001; Garner et al., 2009). The growth attained during the spawning season is important for overwinter survival of juveniles (Lang et al., 2006). Energy from egg consumption by adults also allows for longer migrations and extended spawning times (Copeland and Venditti, 2009).

Adult Coho salmon. Photo courtesy NMFS/Southwest Fisheries Science Center. https://www.flickr.com/photos/51647007@N08/11468631085/ by https://creativecommons.org/licenses/by/2.0/

According to climate change predictions, adult salmon will be returning to freshwater that will be warmer and have lower flows in late summer. Some species and life-history types, such as stream-type ("spring") Chinook salmon and summer steelhead, return to freshwater in spring or summer months and hold for up to several months before spawning. They require pools with cool water, and such habitat is currently least available in late summer and early fall. Such habitats are likely to become even less available as climate changes. This suggests that holding and migrating adults may become increasingly stressed, which will diminish their reproductive potential and increase pre-spawning mortality. Miller et al. (2011) presented evidence that elevated temperatures in British Columbia's Fraser River have likely contributed to the virulence of a virus that infects adult Sockeye salmon before entering the river, resulting in a high incidence of pre-spawning mortality. Beechie et al. (2006) believed that the loss of summer pre-spawn staging habitats in Puget Sound, Washington, could result in the replacement of stream-type Chinook salmon by ocean-type Chinook, whose fall run timing avoids exposure to warm, low-flow summer conditions. Some of these changes are already being noted in TEK by tribal members. Norman Capoeman notes:

> *"One of the biggest things I've noticed in the last four years was climate change ... before we have like a lot of rain and a lot of colder weather, where we're at on the coast, on the Northwest coast raises our rivers and wash it out and things like that, and our winters aren't as cold as they used to be."*

Sandbagging the Sol Duc. Photo courtesy Debbie Preston, Northwest Indian Fisheries Commission.

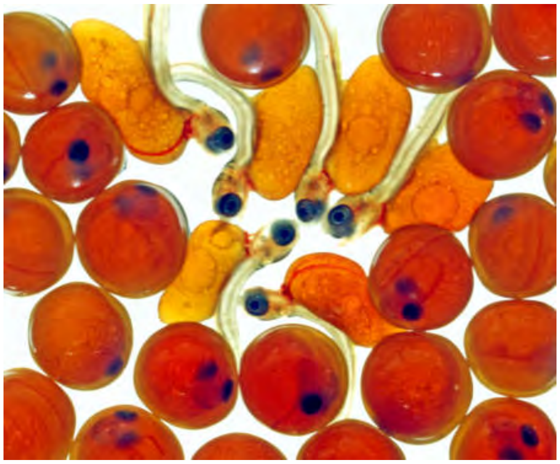
In August of 2015, both the state of Washington and the Quileute Tribe temporarily needed to close fishing (summer Chinook salmon) in parts of the Sol Duc River, because of low flows. They cooperated at sandbagging the Sol Duc near the hatchery to create a stream elevation sufficient to allow spawning fish to return to the hatchery.

The development and persistence of less favorable ocean conditions could potentially influence the degree of anadromy in populations of *O. mykiss*. The anadromous form, steelhead, persists at least in part because there is a fitness advantage associated with migrating to the ocean to feed and returning to freshwater to spawn (Quinn and Myers, 2004). If this advantage is reduced or lost, residency could increase in populations (see Sloat and Reeves, 2014), assuming that changes in the freshwater environment are suitable for the persistence of resident Rainbow Trout, the freshwater life-history variant.

Rises in sea level (IPCC 2007) may affect the reproductive success of species that spawn close to tidewater, e.g., some Pink and Chum salmon populations. For small populations that spawn in streams just above the high-tide level, elevated sea levels could reduce the available spawning habitat if suitable spawning sites upstream are inaccessible.

4.2.2 Eggs & Developing Embryos

Eggs and developing embryos will likely be affected by two different aspects of climate change: increased incubation temperatures and altered hydrographs. Most research on climate impacts on native fish has focused on the potential effects of elevated summer temperatures (e.g., Crozier and Zabel, 2006; Isaak et al., 2010). However, the impact of elevated winter temperatures may be as, and perhaps even more, pronounced and ecologically significant than increases in summer temperatures. Increased winter temperatures will result in more precipitation falling as rain rather than snow. In watersheds that historically develop a seasonal snowpack, this trend away from snowfall will result in a higher fraction of annual streamflow in winter and early spring, and a lower fraction in late-spring and early-summer snowfed streamflow (Hamlet et al., 2005; Hamlet and Lettenmaier, 2007; Tague and Grant, 2009). This effect is likely to relatively minor on the Olympic Peninsula because of the preponderance of watersheds dominated by rain (Mantua et al., 2010).



Salmon eggs and fry. Photo courtesy U.S. Fish and Wildlife Service, Public Domain. http://digitalmedia.fws.gov/cdm/singleitem/collection/natdiglib/id/3528/rec/7

Potential effects of the altered hydrograph are likely to vary among species and life- history forms. Changes in the hydrograph causing increased scour are likely to be more pronounced in small streams, particularly for fish that spawn in the late fall and winter when the most severe storms tend to occur along the northwestern Pacific coast. Summer steelhead spawn in small streams, and so may be especially vulnerable. Fish that spawn in large rivers, particularly low-gradient systems, or in the late winter or spring may be less affected (Sloat et al. in review). This would include some coho, ocean-type Chinook salmon and winter steelhead populations.

Consequences of changes in the hydrograph of many river systems in which Pacific salmon spawn could be exacerbated by the reduced size of returning adults. There is a direct relation between the depth of redds and the size of females (van den Berghe and Gross, 1989). Eggs in shallower redds will be more susceptible to being scoured than will those in deeper redds. Increased peak flows during the incubation period could result in decreased survival of eggs and embryos in populations exposed to altered hydrologic regimes. Cunjak et al. (1998) found that Atlantic salmon eggs and alevins had higher mortalities in warm years when flows increased compared to cold years when flows were low.

Rate of development of eggs and the size of fish at emergence is directly related to temperature. Egg development is dependent on the accumulation of degree days (Neuheimer and Taggart, 2007). Even slight increases in temperature can accelerate rates of development, and ultimately result in an earlier time of emergence from the gravel (McCullough 1999). Accelerated development also results in smaller individuals at emergence because of changes in the rate and efficiency of yolk use (Beacham and Murray, 1990; Elliott and Hurley, 1998). Smaller fish are more susceptible to displacement at higher flows. Some species may be more strongly influenced by thermal shifts during incubation than others. For example, Beacham and Murray (1990) suggested that coho salmon are adapted for low water temperatures during development and would be likely to suffer dramatic survival losses under warming climate scenarios.

4.2.3 Juveniles

Juvenile Pacific salmon (defined here to be recently emerged fry up to, but not including, smolts) face a number of challenges from the potential impacts of climate change. These challenges will be primarily in the form of elevated temperatures and altered streamflows, which can affect both physical and biological aspects of stream habitats. The type and extent of flow impacts will vary depending on the time of emergence. For example, fish emerging in the late winter and early spring may experience high flows caused by earlier snowmelt. The magnitude of the consequences of a changing hydrograph will depend to a large degree on the geomorphic setting in which spawning and emergence occurs. Fish in unconstrained channels (low gradient with wide valleys (Gregory et al., 1989) will potentially have more habitat available initially if floodplain vegetation is intact and secondary channel areas are available. Salmon fry generally found in such settings including Chinook, Coho, Pink, and Chum salmon. Low-gradient streams and rivers can be important areas for early growth (Moore and Gregory, 1988), and marginal areas with reduced water velocities provide refuge against downstream displacement. There may be the potential for fish to actually compensate for the smaller size at emergence, if water temperature is warmer and low-gradient habitats are available, by gaining an early start on the growing season (Holtby 1988). Fish that spawn and initially rear in steeper, more confined streams, such as summer steelhead, may be detrimentally affected by higher flows through displacement, particularly if fish are smaller at emergence.

Higher winter flows could potentially increase the amount of winter rearing habitat for older juveniles by flooding side channels and riverine ponds. Juvenile salmon (Peterson 1982; Solazzi et al., 2000; Ebersole et al., 2006) and pre-smolts (Everest 1975) may move into the lower reaches of the channel network or into off-channel habitats to overwinter. The most pronounced increases in available habitat could occur in areas where winter was formerly the period of low flow (i.e., areas where snow was the dominant precipitation). This was addressed through TEK as well, Norman Capoeman noticing:

> *"Without the colder weather we used to have, there's less snow up there and with less snow water in the river now, and I've noticed it in the creek water and wash water. Our river actually changed color, from I believe the climate change or whatever reason I*

> *don't know if it's because they're cutting too many trees down or if it's too many cars on the road or what, but Our rivers used to have a really pretty greenish blue crystal clear color to it, when I talk about the river, I'm talking like maybe the first ten miles of the mouth of the Quinault, up to the river because our river from the mouth to the full length of the river which goes to Lake Quinault is approximately thirty eight miles. I don't get way up river that much but when we fish, we fish the seven miles from the mouth up to the river and that's where we set our nets in and fish but the river now is more of a brownish looking color and like a grayish looking color- the brownish looking color is after the rains quits and everything stops because we have a lot of logging that pours into the river."*

It is likely that increases in winter flows could be accompanied by elevated turbidity levels but it is not possible to model such effects at this time. A review of studies in the scientific literature suggests that effects will not necessarily be negative. Results of field studies found that native salmonids can move to stream margins (Harvey et al., 1999), floodplains (Lang et al., 2006), seasonally flowing streams (Ebersole et al., 2006), or make extended movements downstream (Peterson 1982, Reeves et al. 2011) to minimize their exposure to elevated turbidity levels. Salmonids can also switch from preying on items drifting in the water column or surface to prey on the substrate during periods of high turbidity (Lang et al., 2006; White and Harvey, 2007). The effects on growth are mixed (positive Lang et al., 2006; neutral White and Harvey, 2007, negative Al Shaw and Richardson, 2001). Turbid conditions may reduce predation rates on juveniles salmonids (Gregory, 1993; Abrams and Kattenfeld, 1997; Gregory and Levins, 1998), which could increase survival and potentially offset, at least partially, the consequences of decreased growth during turbid conditions.

Under several climate scenarios, the onset of the low-flow period is expected to begin 4–6 weeks earlier in most areas as a result of warming (Hamlet et al., 2005; Hamlet and Lettenmaier, 2007; Tague and Grant, 2009). This extended period of baseflow recession over the dry season (Stewart et al., 2005) would be expected to decrease the amount of suitable habitat available to juvenile salmonids (May and Lee, 2004; Crozier et al., 2008), reduce growth and survival (Harvey et al., 2006; Ebersole et al., 2009), force shifts in the distribution of salmon populations within the stream network, and affect their ability to cope with natural disturbances, particularly drought, by reducing the extent of perennially flowing channels (Battin et al., 2007).

The consequences of climate-induced changes in flow to juvenile salmonids in larger channels are not as obvious, because the findings reported in the literature are variable. Larger channels would be used by Chinook salmon and steelhead juveniles for summer rearing. Hamlet et al. (2005) and Tague and Grant (2009) suggested that the low-flow levels should not be appreciably affected by climate change, the exception being that systems dominated by groundwater will see a 10–15% reduction in low summer flows (Tague and Grant, 2009). In contrast, Mantua et al. (2010) found widespread declines in the magnitude of summer low flows for many Washington streams under a climatic warming scenario. Such systems tend to have large amounts of water, so the suggested reductions may not be ecologically significant. In contrast, Luce and Holden (2009) examined hydrograph records from locations throughout the Pacific Northwest and found that summer flows in all types of systems are declining. If this is the case, juvenile salmonids could be restricted to increasingly smaller rearing areas as flows decline.

Juvenile steelhead. Photo courtesy NMFS/Southwest Fisheries Science Center; Salmon Ecology Team. [*www.flickr.com/photos/51647007@N08/11468667284/*](www.flickr.com/photos/51647007@N08/11468667284/) *by* [*https://creativecommons.org/licenses/by/2.0/*](https://creativecommons.org/licenses/by/2.0/) *Image cropped to fit available space.*

In addition to lower flows, elevated summer water temperatures will likely have strong ecological impacts on juvenile Pacific salmon, with the direction and magnitude of influence varying geographically, by species, and by life-history type. Water temperature influences the metabolism, food consumption, and growth of an individual (Coutant, 1999; McCullough et al., 2009). Age and size of an individual also influence thermal effects; younger and smaller fish are most susceptible to thermal extremes (Brett, 1952) and variation (Elliott, 1991). There is a temperature range in which an individual performs best given a certain level of food resources; beyond that range, metabolic costs increase and performance declines (Warren, 1971). Increased temperature could potentially affect juvenile salmonids in opposing ways (Li et al., 1994). Warmer water could enhance primary and secondary aquatic production, leading to greater food availability. However, if the increased metabolic demands of higher temperatures lower food conversion efficiency, or if the organisms benefiting from higher temperatures are not preferred food items, the net effect of warming could be reduced growth (Bisson and Davis, 1976). Growth rates of juveniles could increase if projected temperature changes stimulate aquatic productivity while remaining within the preferred physiological range for the species and populations.

If elevated temperatures resulting from climate change reduce summer growth (Scarnecchia and Bergersen, 1987; Royer and Minshall, 1997; Isaak et al., 2010), juveniles will be smaller entering the winter, and overwinter survival may decrease (Quinn and Petersen, 1996). However, thermal increases may be beneficial for growth during other seasons. Sogard et al. (2010) found that juvenile steelhead on the central coast of California attained the most growth in the spring and the fall. Similar patterns were observed for steelhead in the John Day River, Oregon (H. Li, Oregon State University, pers. comm.) and juvenile Coho salmon in coastal Oregon (Ebersole et al., 2006). The major growth season of age 1+ Coho salmon in Alaska was the fall, which coincided with the onset of increased flows and the spawning of adults (Lang et al., 2006). Juvenile Coho were able to forage in riparian areas on the floodplain during high flows and consumed drifting eggs during spawning. If such patterns are true in other areas, the impact of elevated summer temperatures and the ultimate effect on overwinter survival may not be as pronounced as expected. Elevated water temperatures could also exacerbate the effect of exposure to pesticides by increasing susceptibility to disease (Dietrich et al., 2014).

Interactions between salmonids and non-salmonids can be influenced by changing water temperatures. Rearing salmonids tend to out-compete non-salmonids for food resources and preferred feeding areas at cooler temperatures, while non-salmonids have the advantage at warmer temperatures (Reeves et al., 1987; Petersen and Kitchell, 2001). The susceptibility of juvenile salmonids to disease could also increase at warmer temperatures and could be compounded by the presence of competitors that are less susceptible to the pathogens infecting salmon and trout (Reeves et al., 1987). Additionally, warmer temperatures could lead to increased predation from non-native warm-water fish (Petersen and Kitchell, 2001). The aggregate results of these indirect effects are likely to be changes in the structure and composition of fish communities in the affected stream systems (ISAB, 2011), particularly in the southern and mid portions of the distributional range, where the potential for interaction with warm-water species is greatest due to both proximity of thermal ranges and widespread introduction of non-native warm-water fishes.


Sockeye salmon. Photo courtesy Ryan Hagerty, U.S. Fish and Wildlife Service, Public Domain. *digitalmedia.fws.gov/cdm/singleitem/collection/natdiglib/id/3528/rec/7*

Lakes, important rearing habitats for Sockeye salmon, will also be affected by climate change. The distribution and abundance of lakes has varied widely during previous periods of climate change because of changes in precipitation, evapotranspiration, glacial ice, and runoff. Potential effects will vary widely depending on the location and features of the lake, but a primary impact will be warming. In the continental U.S., lakes 4–13 m in depth may be most vulnerable (Stefan et al., 2001). Slight warming in deeper lakes could result in increased growth rates of fish if temperatures stimulate primary production without significantly affecting the availability of cooler water during periods when the epilimnion becomes too warm. However, this may be offset by a reduction in the delivery of inorganic nutrients and dissolved organic carbon (DOC) from terrestrial systems as a result of decreased streamflow. Lower levels of nutrients and DOC could result in diminished algal production, which would result in deeper light penetration and warming of the lake (Schindler et al., 1990).

The productivity of zooplankton, the principal food of juvenile Sockeye salmon in lakes, is likely to be affected by climate change. In Alaska, warming temperatures have resulted in earlier ice melt, greater density of zooplankton, and an increase in Sockeye growth rates (Schindler et al., 2005). In contrast, warmer springs in Lake Washington, near Seattle, have advanced lake stratification by 20 days in recent years, resulting in earlier blooms of diatoms and the decline of cladocerans (*Daphnia* spp.), which are important prey species (Winder and Schindler, 2004).

4.2.4 Smolts

Pacific salmon undergo smolting and move to the ocean predominantly in the spring, although smolts of various species may be moving throughout the year. Water temperature, day length, and changes in flow are the principal cues influencing the timing of parr-smolt transformations. Environmental factors that influence the smolting process can be divided into regulating and controlling (Byrne et al., 2004). Regulating factors act on juvenile salmon before the migration and influence the physiological aspects of smolting. Controlling factors operate during migration and control the speed of downstream movement.

Water temperature and day length are key regulating factors (Jonsson and Jonsson, 2009). Day length is not influenced by climate change, but increased temperature affects the development rate of individuals. Atlantic salmon smolts require a threshold accumulation of degree days for the smolting process to be initiated (Zydlewski et al., 2005). For Pacific salmon, elevated winter temperatures could result in earlier migration times of smolts. Chinook salmon have been observed to migrate earlier when water temperatures are higher compared to cooler years (Roper and Scarnecchia, 1999; Achord et al., 2007). Jonsson and Jonsson (2009) cite a suite of other studies on Atlantic salmon, brown trout, and steelhead where water temperatures did not affect the time of smolt migration. However, under certain conditions, elevated temperatures may inhibit parr-smolt transformation. Adams et al. (1973) found that smolting in steelhead held at 15^{o}C or higher led to reductions of ATPase activity needed to initiate the smolt transformation process. Thus, the effect of altered temperature on timing of smolt migration remains unpredictable and likely will vary widely across populations.

Streamflow determines, to a large extent, the rate at which smolts move downstream (Smith et al., 2002; Connor et al., 2003). Climate model projections of stream runoff (Hamlet and Lettenmaier, 2007; Tague and Grant, 2009) suggest that the onset of the summer low-flow period will occur 4–6 weeks earlier. The consequences of altered flows are likely to be population-specific, with the timing and smolt survival rates of those populations that tend to migrate later or are required to move long distances being the most affected.

Survival of smolts in the ocean depends on a number of factors (Pearcy, 1992). Larger smolts tend to have higher survival rates than do smaller fish (Slaney, 1988; Holtby and Scrivener, 1989; Quinn and Peterson, 1996). The size of an individual at smolting is influenced by its size at the beginning of the previous winter. As discussed above, the impact of climate change could be variable, depending on how the effects are expressed and the specific geomorphic features at the local level. Brown and Hartman (1988) found that stream and groundwater warming (caused by logging) in a coastal Vancouver Island watershed resulted in increased overwinter growth of pre-smolt Coho salmon, and Holtby and Scrivener (1989) suggested that this growth advantage led to higher smolt-to-adult return rates through improved ocean survival.

Conditions in marine nearshore areas at the time of ocean entry also influence ocean survival. In the area influenced by the California Current, potential changes in the timing and intensity of upwelling have important implications for smolts (Barth et al., 2007). Cold, nutrient-rich waters are pushed into nearshore areas by northerly winds in the late spring and early summer, producing favorable conditions for plankton production (Nickelson 1986; Scheurell and Williams, 2005). Under one climate change scenario, upwelling is projected to intensify but occur later in the summer (Snyder et al., 2003), which could affect the food availability to early-entry salmon smolts. However, Mote and Mantua (2002) found no evidence for changes in the timing and magnitude in coastal upwelling in the Pacific Northwest.

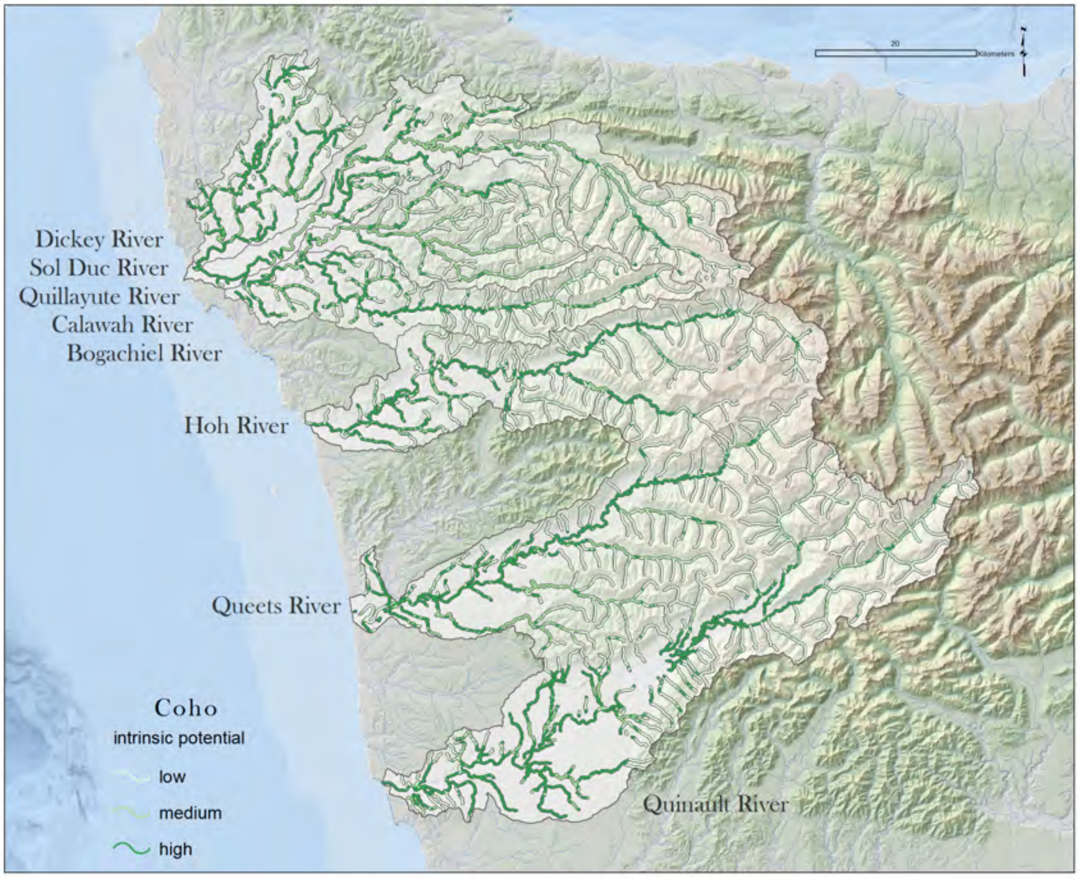
The presence of predators in nearshore areas can also influence marine survival (Pearcy, 1992). Coho salmon from Carnation Creek on the west coast of Vancouver Island, British Columbia, entered the ocean about two weeks earlier as a result of increased growth as juveniles (Holtby, 1988), and survival declined compared to the timing of pre-logging smolt migration. It was believed that predation by Pacific Chub Mackerel (*Scomber japonicus*) and Pacific Hake (*Merluccius productus*) contributed to the decline, as both species moved into Barkley Sound during periods of warm sea-surface temperatures. Elevated ocean temperatures could also result in the expansion of subtropical predators, such as the Humboldt Squid (*Dosidicus gigas*), into these waters, further increasing predation pressure on salmon smolts (ISAB, 2007).

4.3 NetMap Methodology & Products

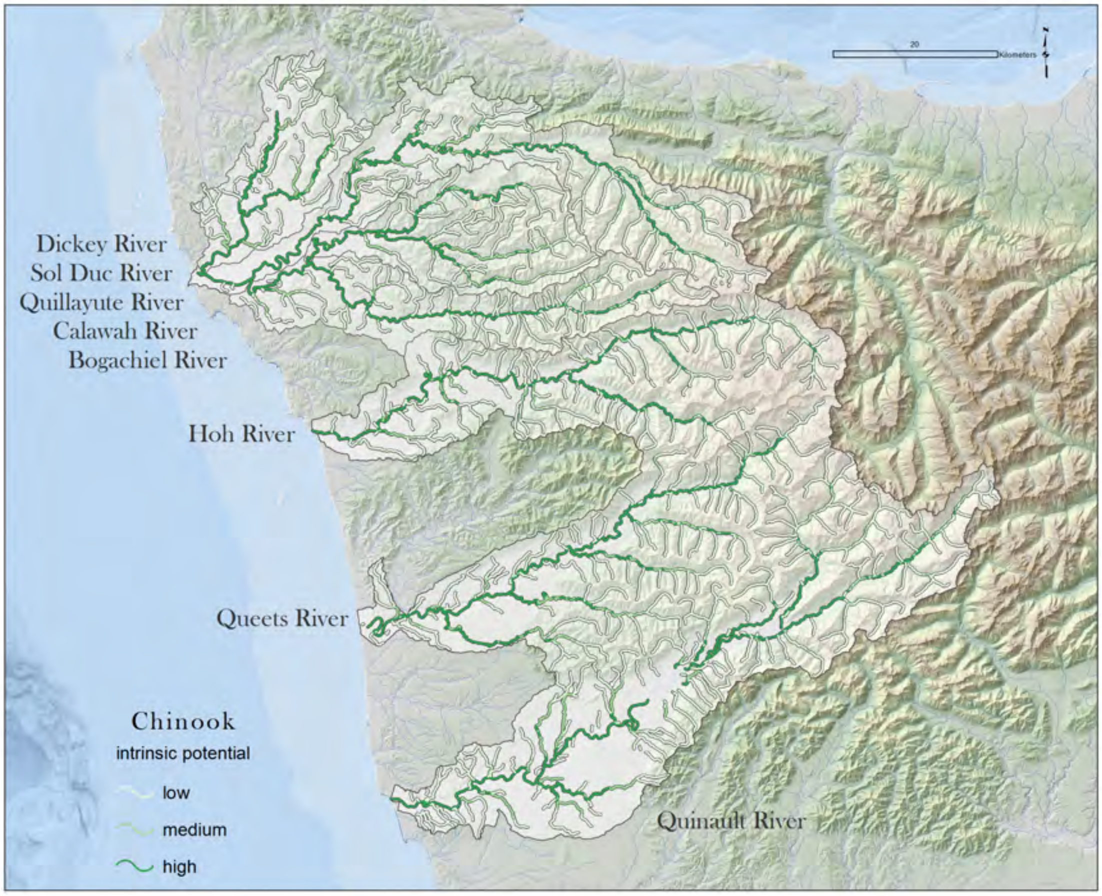
We built NetMap (Benda et al., 2007) virtual watersheds for the Quinault, Queets, Quillayute (inclusive of the Dickey, Sol Duc, Calawah, and Bogachiel Rivers), and Hoh River (Figure 4.1) basins using USGS National Elevation Dataset (NED) 10-m digital elevation models (DEM). This included developing a "synthetic stream network" (http://www.netmaptools.org/Pages/NetMapHelp/netmap_synthetic_stream_layer_derivation.htm) with channel segments approximately 100 m long. We employed the National Hydrography Dataset (NHD) to guide channel locations where channel gradients were less than 4%; the NHD was applied where flow accumulation and direction are insufficient to accurately delineate the low-relief portions of river networks using 10 m DEMs. All virtual watersheds contain the standard NetMap attributes, including habitat intrinsic potential (IP) for Coho and Chinook salmon and steelhead (e.g., Burnett et al., 2007) (Figure 4.2), which requires channel gradient, valley confinement (valley width divided by channel width) and mean annual flow. Intrinsic potential does not describe the current condition of that reach, but is an indicator of the potential of a given stream-reach to provide high-quality habitat for a particular species. It is useful in understanding the potential magnitude of an impact on a population or river system; effects on areas of high IP are likely to be more pronounced than those in lower IP reaches.

Figure 4.2 *The intrinsic potential of Coho (A) and Chinook (B) salmon and steelhead (C) in the study basins in the Treaty of Olympia area.*

(A)

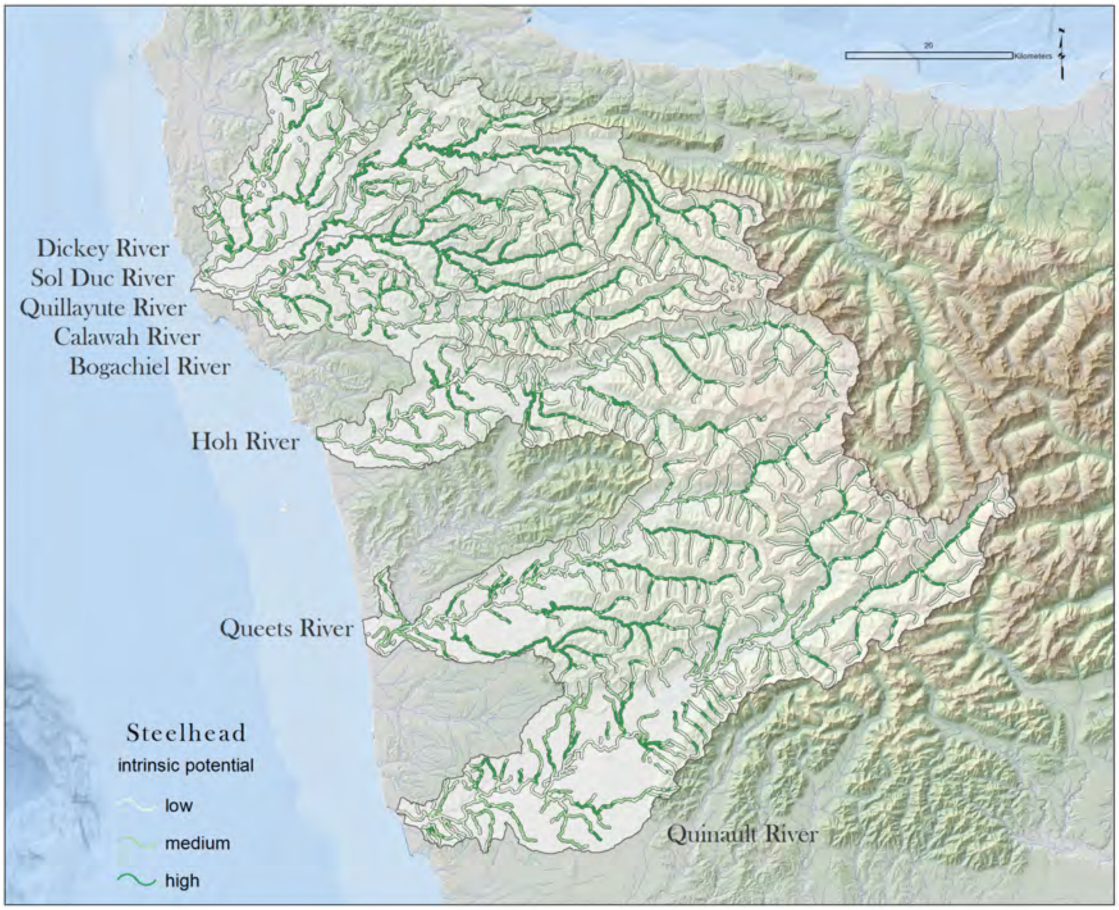


(B)



20
Kilometers
N
Dickey River
Sol Duc River
Quillayute River
Calawah River
Bogachiel River
Hoh River
Queets River
Quinault River
Chinook
intrinsic potential
low
medium
high

(C)



In the river network, we included climate change predictions for the three watersheds available from the Climate Impact Group (CIG, https://cig.uw.edu/) at the University of Washington. The approximate 7-km by 7-km gridded climate change data (rasters) includes air temperature, precipitation, snowmelt, snow-water equivalent, and average summer (June-August) and winter (January-April) runoff (streamflows). Climate change predictions were transferred to individual channel segments (entire network including headwaters) based on each individual channel's local contributing area on both sides of the stream (these local contributing areas are referred to as "drainage wings" in NetMap). Climate change forecasts are also aggregated downstream. For additional information on CIG climate change forecasts in NetMap see NetMap's online technical help for these attributes (http://www.netmaptools.org/Pages/NetMapHelp/7_2_climate_change_vulnerability.htm).

The scenarios used by CIG represent a composite average of ten global climate models (GCM) for the western U.S., using four bracketing scenarios based on four GCMs (ECHAM5, MIROC_3.2, HADGEM1, and PCM1). Predictions are for one greenhouse gas scenario (A1B, a middle-of-the-road scenario for future emissions). Predictions are reported in percent (%) change from historical (1916–2006) to forecasted values in 2040 (positive and negative values); however, the air temperature predictions are in absolute change in degrees C. For additional background information on how forecasts were made, see http://warm.atmos.washington.edu/2860/report/ and http://cses.washington.edu/db/pdf/littelletalregionalclimatic_reduced761.pdf. Forecasted summer and winter runoff were developed by CIG using the VIC (http://vic.readthedocs.org/en/master/) macroscale hydrological model.

In addition to incorporating CIG climate change forecasts, we also accessed stream temperature forecasts for the fish-bearing network of the three watersheds from the U.S. Forest Service NorWest (http://www.fs.fed.us/rm/boise/AWAE/projects/NorWeST.html) regional database on modeled stream temperatures. Forecasts included: (1) modeled stream temperature from 1993–2011 (Attribute: S1_93_11: Scenario 1); (2) modeled stream temperature from 2002–2011 (Attribute S2_02_11: Scenario 2); (3) future scenario based on global climate model ensemble averages that represent the A1B warming trajectory for the 2040s (2030–2059—future stream changes within a processing unit were similar and based on projected changes in August air temperature and stream discharge) (Attribute: S29_2040); and (4) future scenario based on global climate model ensemble averages that represent the A1B warming trajectory for the 2040s (2030–2059) (Attribute S30_2040D— future stream change within a processing unit were based on similar projected changes in August air temperature and stream discharge, but also accounted for differential warming of streams by using historical temperatures to scale temperature increases so that cold streams warm less than warm streams).

4.4 Results

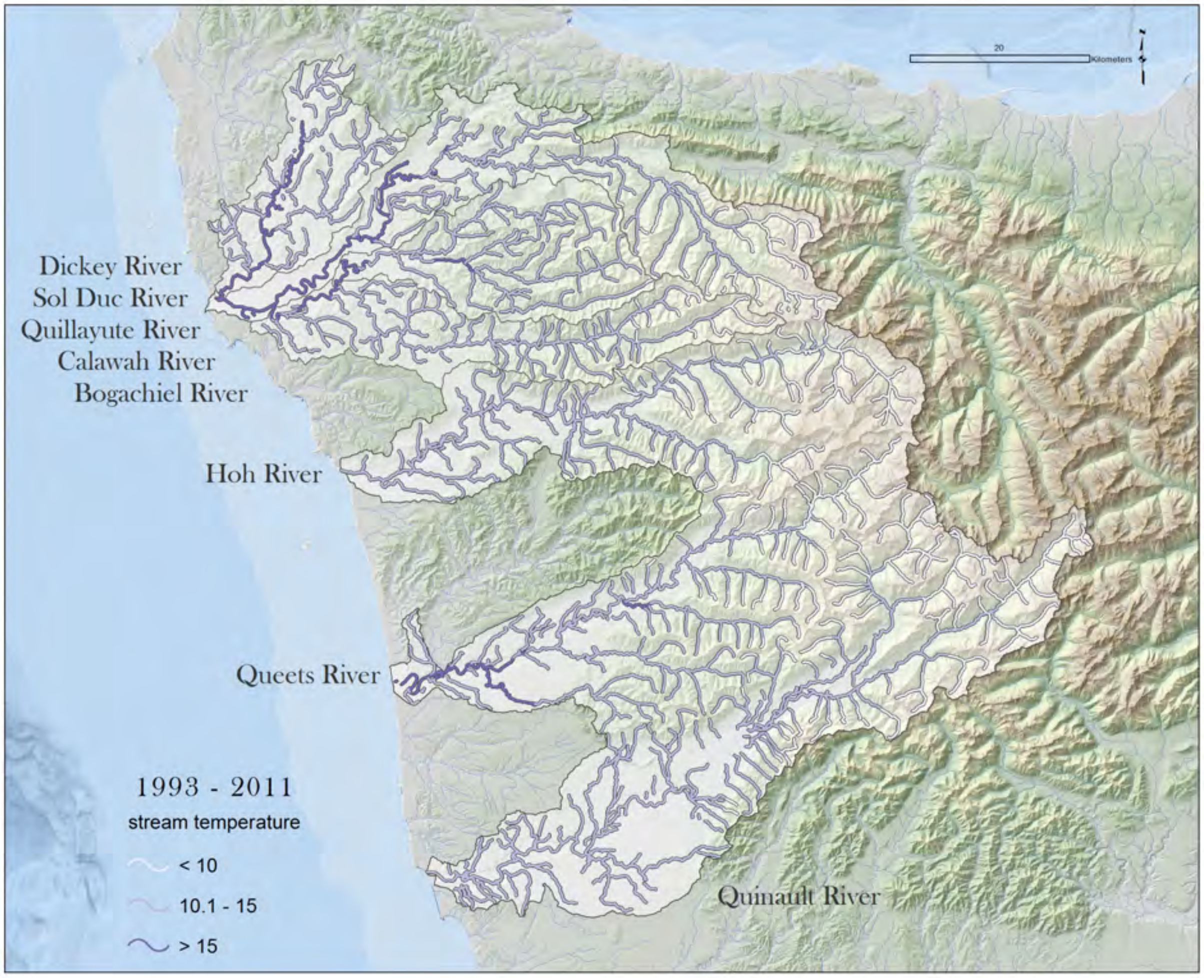
4.4.1 Summer Water Temperatures

Summer water temperatures are likely to increase in all basins (Figure 4.3); the greatest changes are a reduction in the length of stream that is <10^{o}C and an increase in the length of stream where temperatures exceed 10^{o}C, primarily in the lower portions of the watersheds (Fig. 4.3). The extent of these changes varies among watersheds. Water temperatures in the Hoh and Quinault Rivers (Figures 4.4C and 4.4A, respectively) will be <15^{o}C in the habitats of all the species considered across a vast majority of the basins. Both basins currently have small areas of streams where temperatures exceed 15^{o}C, and this will increase slightly in the future (Figures 4.4C and 4.4A).

In the Queets (Figure 4.4B) and Quillayute River basin (Figure 4.4D), the length of stream with summer water temperatures 15^{o}–19^{o}C will increase for all species, but the majority of the medium- to high-IP area for all species will be <15^{o} C in the future. Only <1 km of stream, in the Queets River, is projected to have summer water temperatures >18^{o}C. High-IP areas for Chinook salmon will have the greatest increases in the length of stream with temperatures 15^{o}–19^{o}C.; about 55% in the Queets and 65% in the Quillayute River basin will fall in this range in future. In the latter, habitat for Chinook and Coho salmon in the Clawah River will be most affected (Appendix 4.1).

Figure 4.3 *Current (A) and projected (2040) (B) summer water temperatures (°C) in the study basins in the Treaty of Olympia area.*

(A)



(B)

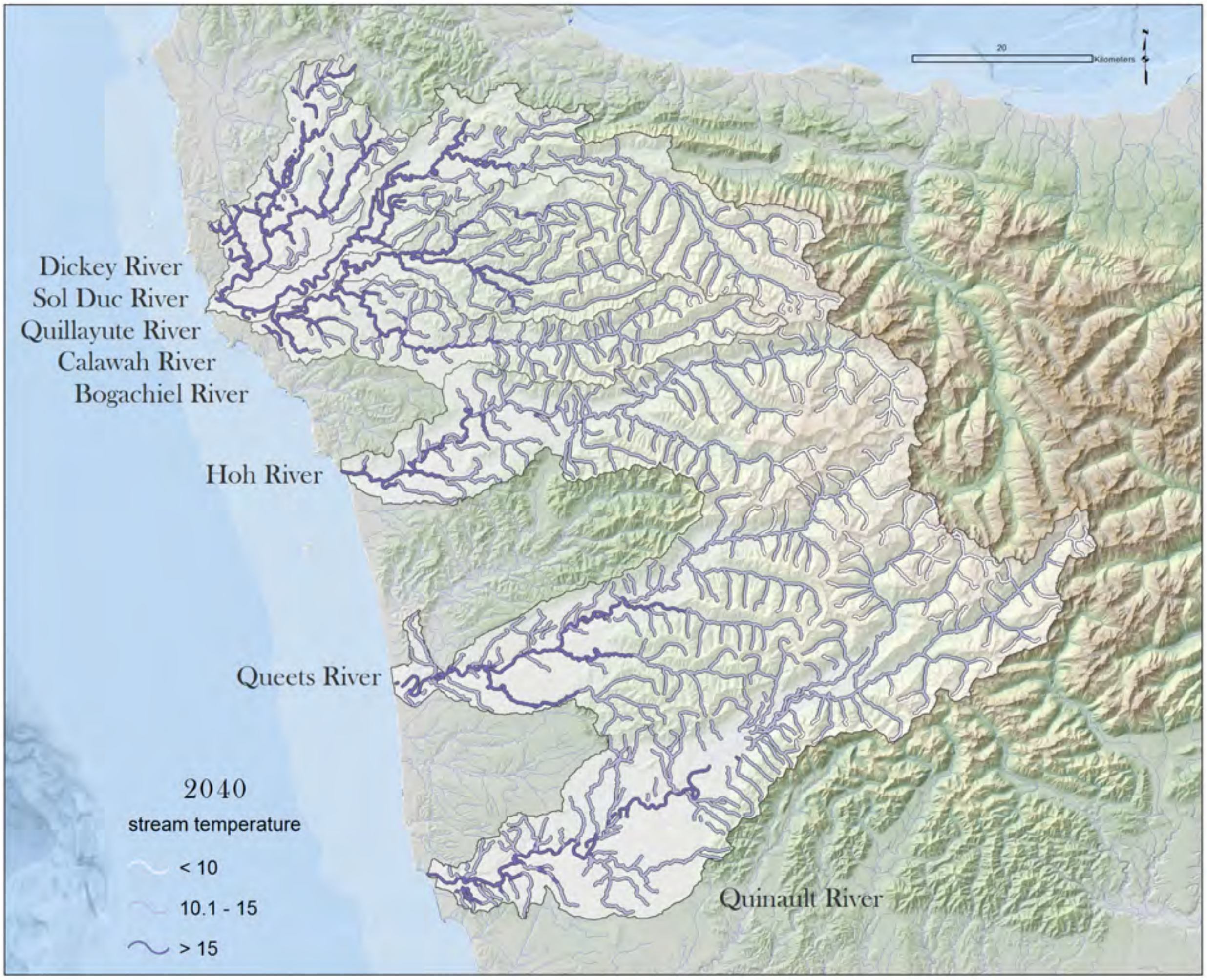
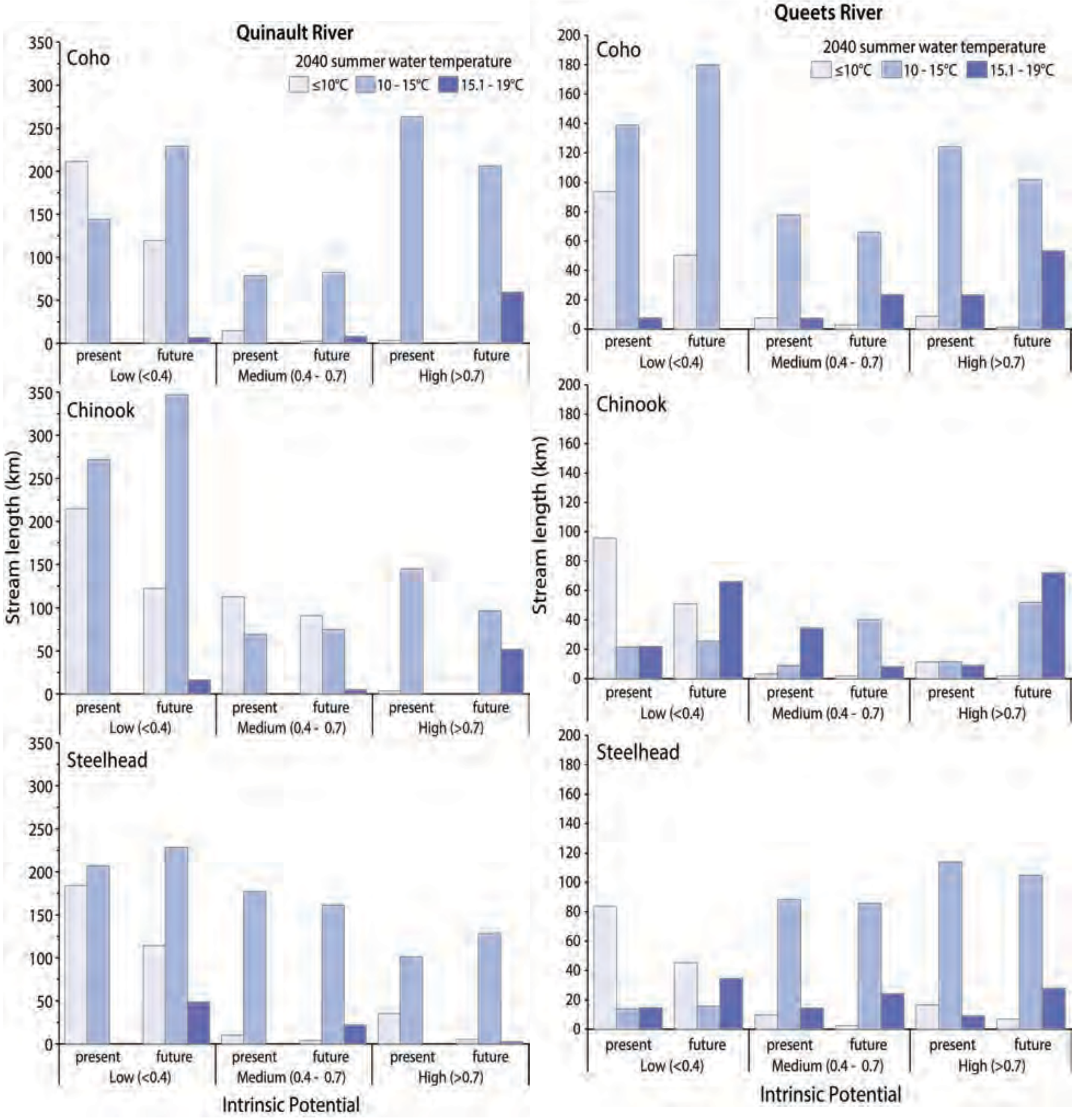

20
Kilometers
Dickey River
Sol Duc River
Quillayute River
Calawah River
Bogachiel River
Hoh River
Queets River
Quinault River
2040
stream temperature
< 10
10.1 - 15
> 15

Figure 4.4 *Length of stream of varying levels of intrinsic potential for different species with current and projected summer water temperatures (^{o}C) in the study basins in the Treaty of Olympia area.*

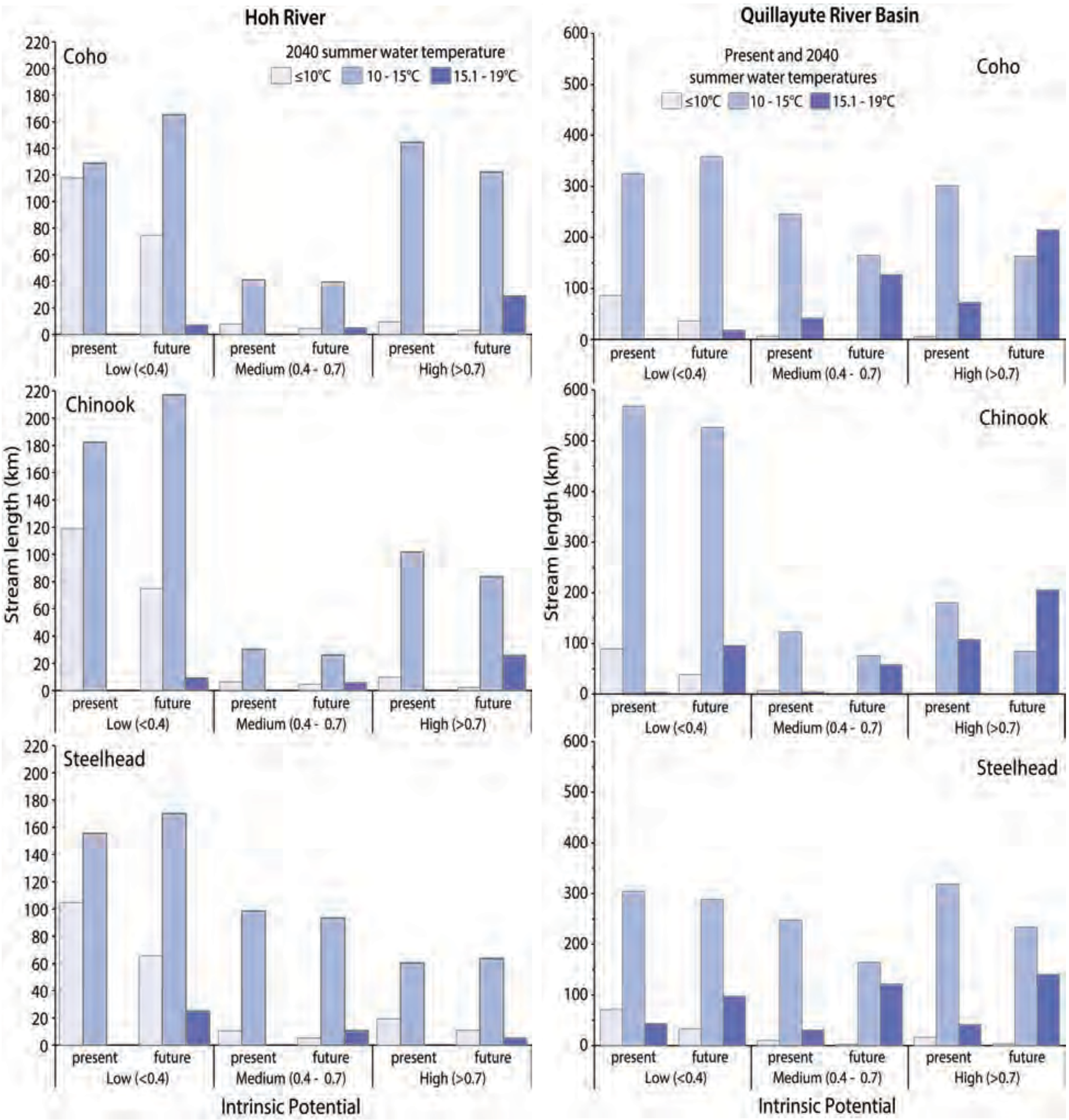


(A)

(B)

(C)

(D)



Hoh River
2040 summer water temperature
≤10°C
10 - 15°C
15.1 - 19°C
Coho
Chinook
Steelhead
Stream length (km)
0
20
40
60
80
100
120
140
160
180
200
220
present
future
Low (<0.4)
Medium (0.4 - 0.7)
High (>0.7)
Intrinsic Potential
Quillayute River Basin
Present and 2040
summer water temperatures
≤10°C
10 - 15°C
15.1 - 19°C
Coho
Chinook
Steelhead
Stream length (km)
0
100
200
300
400
500
600
present
future
Low (<0.4)
Medium (0.4 - 0.7)
High (>0.7)
Intrinsic Potential

4.4.2 Average Summer Flows

The tribes have already experienced low summer flows in recent years accompanied by altered timing of fall salmon runs. Average summer streamflows (June-August) are projected to decline by up to 30% across large areas of streams in all basins, primarily in the upper portions of the watersheds (Figure 4.5), with large changes in reaches of low IP (Figure 4.6). Reaches of medium to high IP could primarily experience reductions of <20%. The exception to this is the Hoh River (Figure 4.6B) and Quillayute (Figure 4.6D) River basin, where flows could be reduced 20–30% (or much more in the case of the Quillayute River basin) in large areas of high-IP areas for Coho and/or Chinook salmon. Changes in the Quillayute River basin will be most pronounced for Coho and Chinook salmon in the Sol Duc River (Appendix 4.2).

Figure 4.5 *Percent reduction in average summer flow levels from current to 2040 in study basins in the Treaty of Olympia area.*

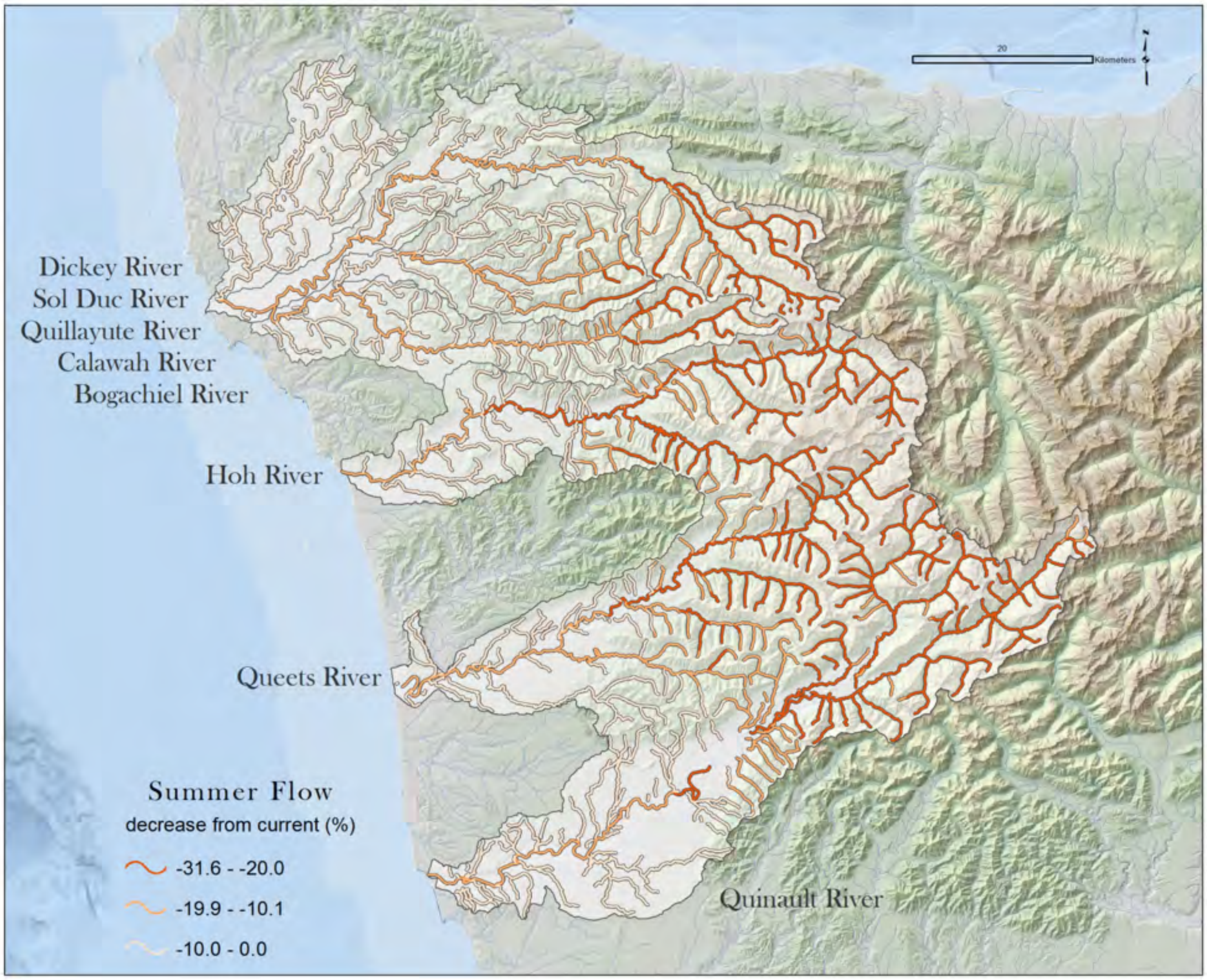
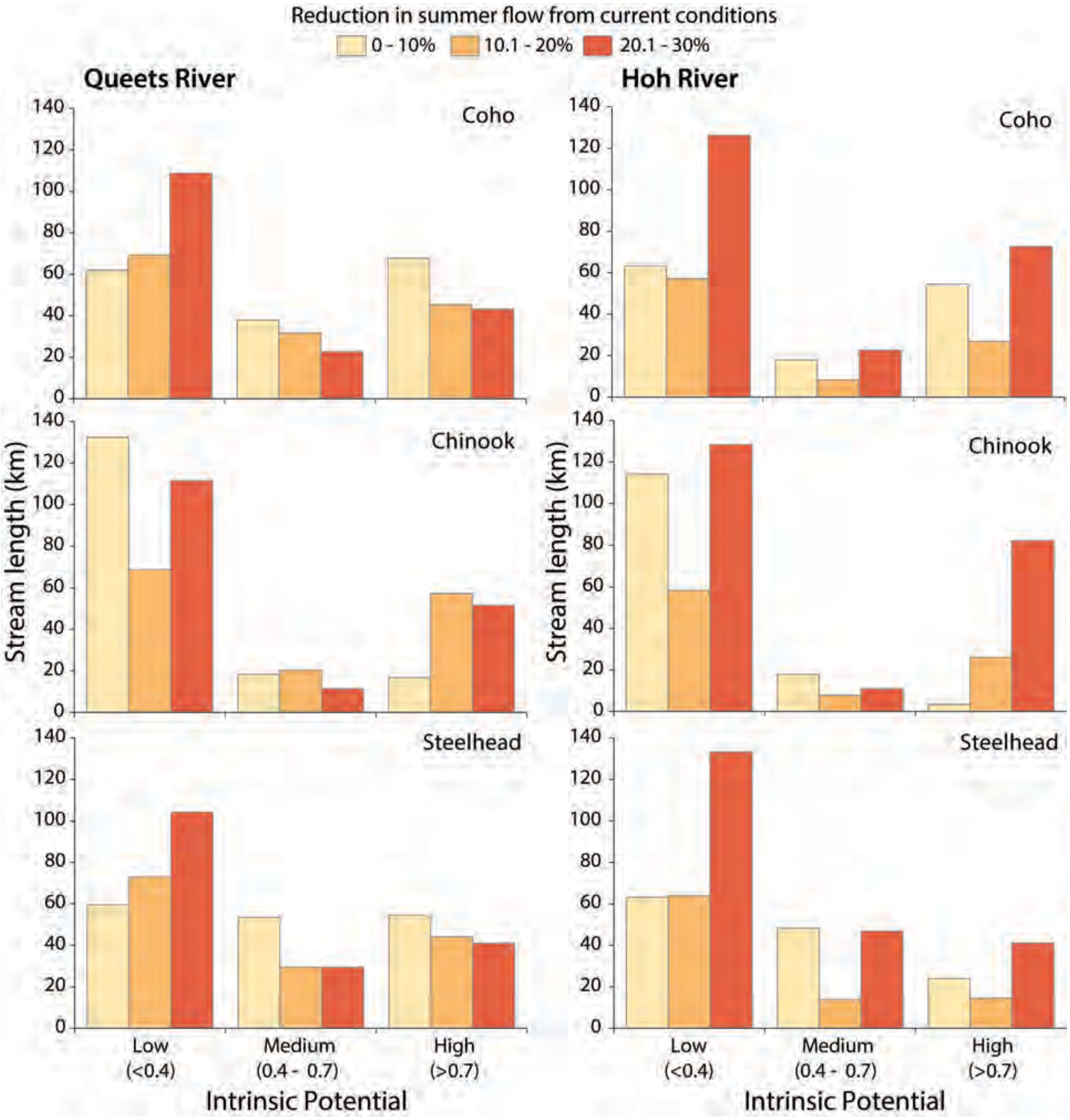
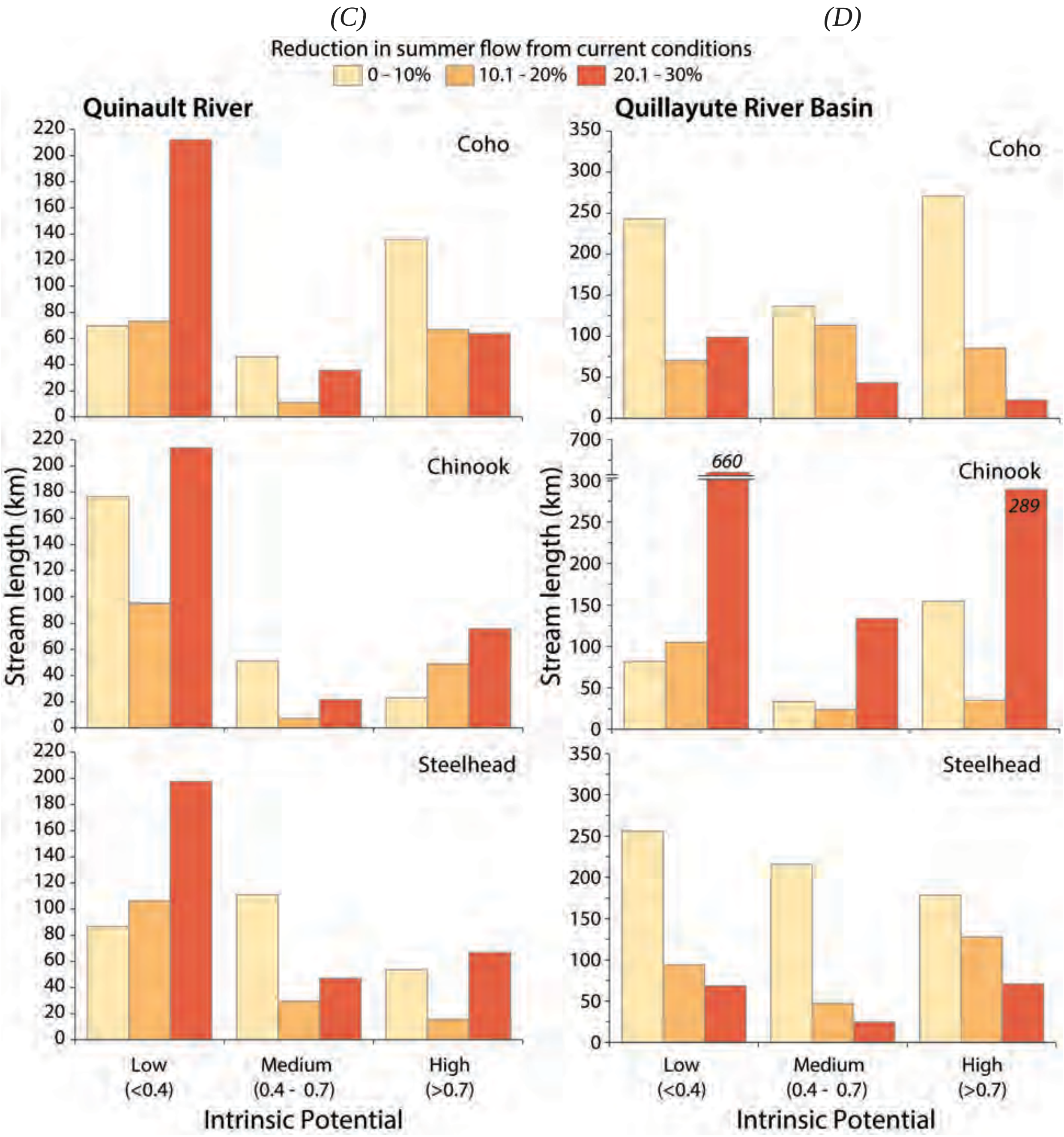


Figure 4.6 *Percent reduction in average summer flows from current to 2040 in segments of different intrinsic potential for Coho and Chinook salmon and steelhead in study basins in the Treaty of Olympia area.*

(A) *(B)*





(C)
(D)
Reduction in summer flow from current conditions
0 - 10%
10.1 - 20%
20.1 - 30%
Quinault River
Quillayute River Basin
Coho
Chinook
Steelhead
Stream length (km)
0
20
40
60
80
100
120
140
160
180
200
220
0
50
100
150
200
250
300
350
700
660
289
Low (<0.4)
Medium (0.4 - 0.7)
High (>0.7)
Intrinsic Potential

4.4.3 Average Winter Flows

Average winter flows (January–April) are expected to be at least 30% higher by 2040 than they are currently (Figure 4.7), in stream reaches in all basins considered, but the extent varies among the systems. Low-IP reaches for all species exhibit the largest increases in flows of >31% in all basins (Figure 4.8). The extent of change in areas of medium and high IP varies by basin. For all species, the increases will be primarily 31–40% in the Queets, Hoh, and Quinault Rivers (Figures 4.8A, B, and C, respectively). Flows in medium-IP reaches for Coho salmon and high-IP reaches for Chinook salmon on the The Sol Duc River in the Quillayute River basin will potentially experience the greatest changes (Appendix 4.3).

Figure 4.7 *Percent increase in average winter flow levels from current to 2040 in study basins in the Treaty of Olympia area.*

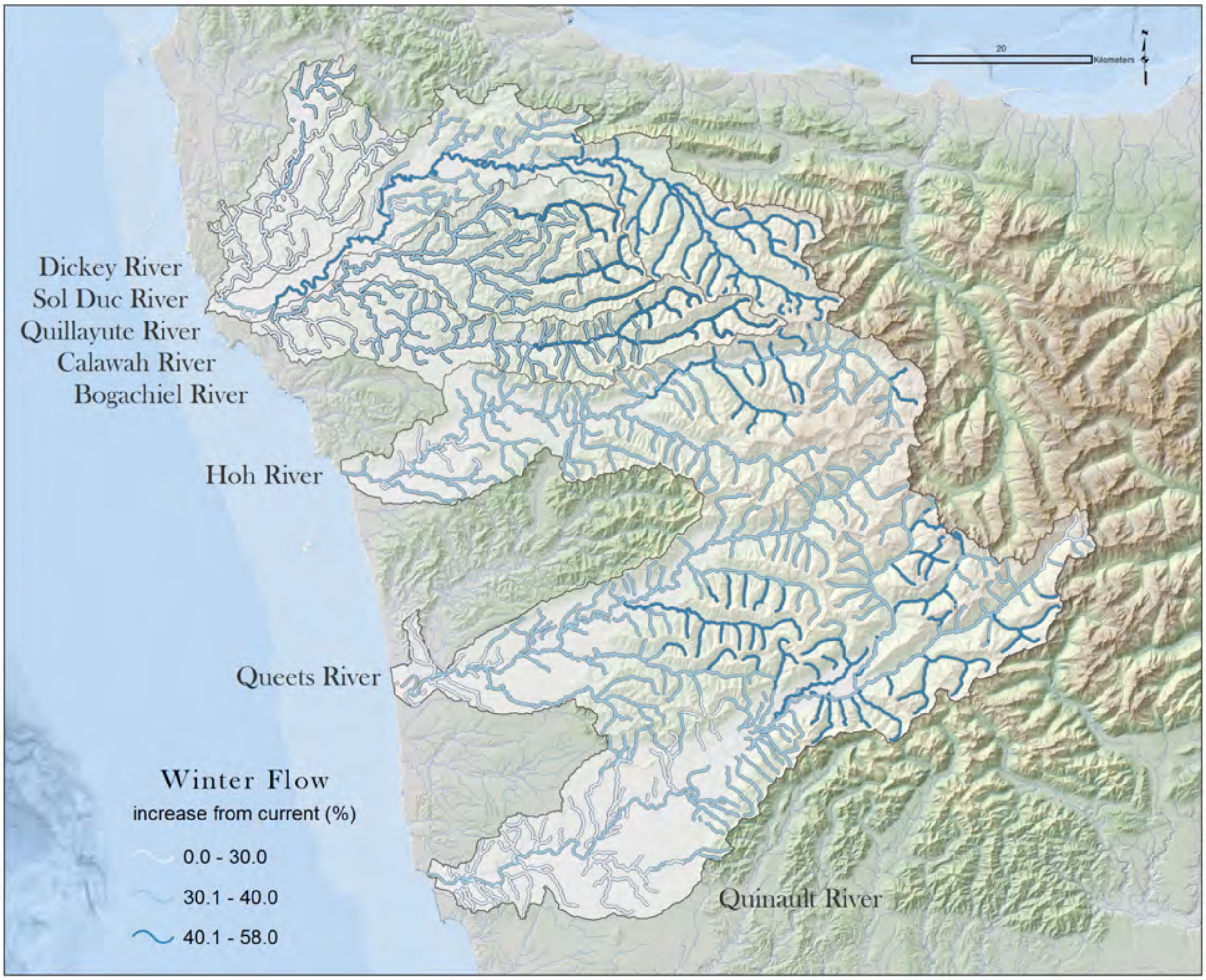
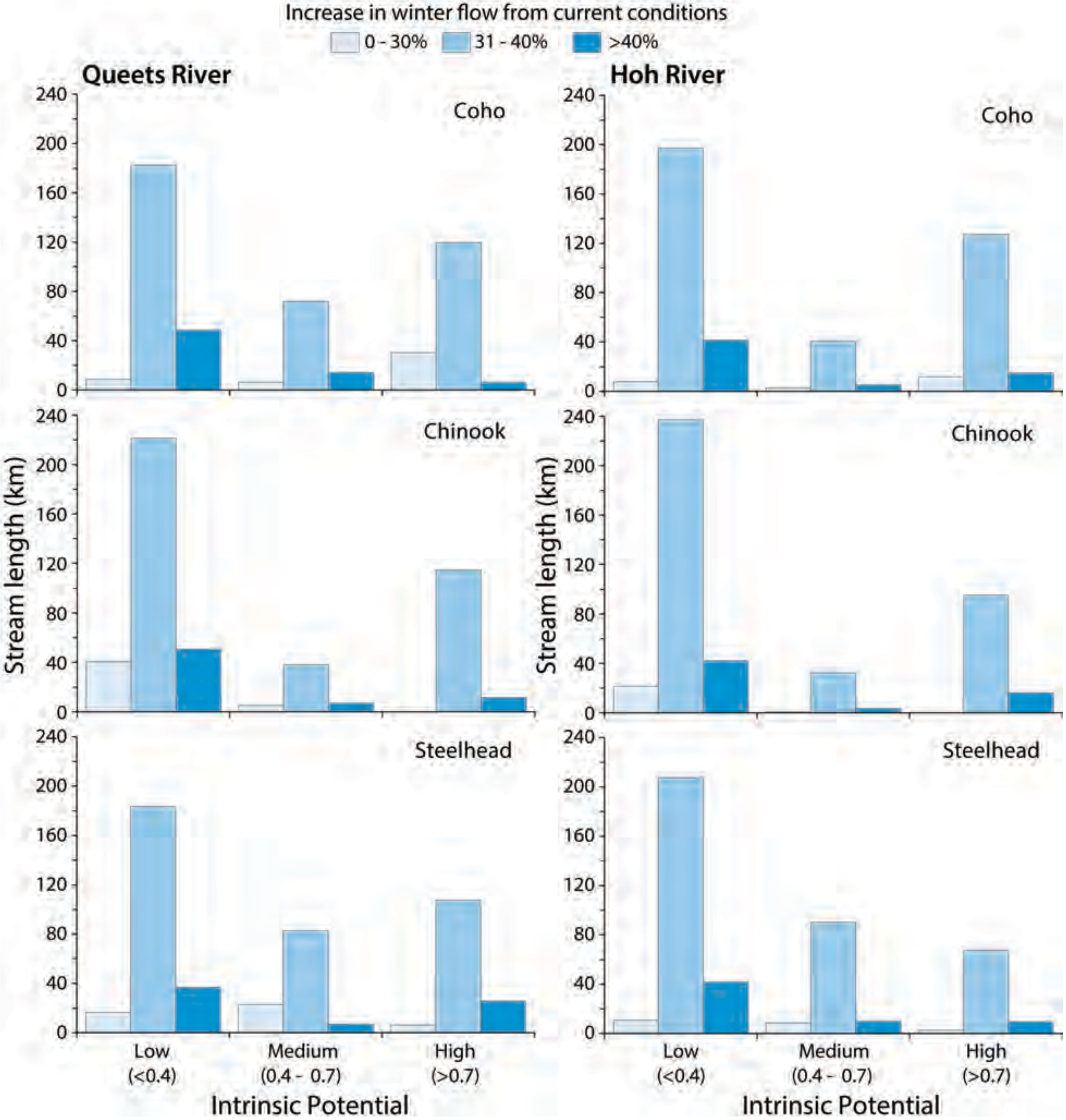
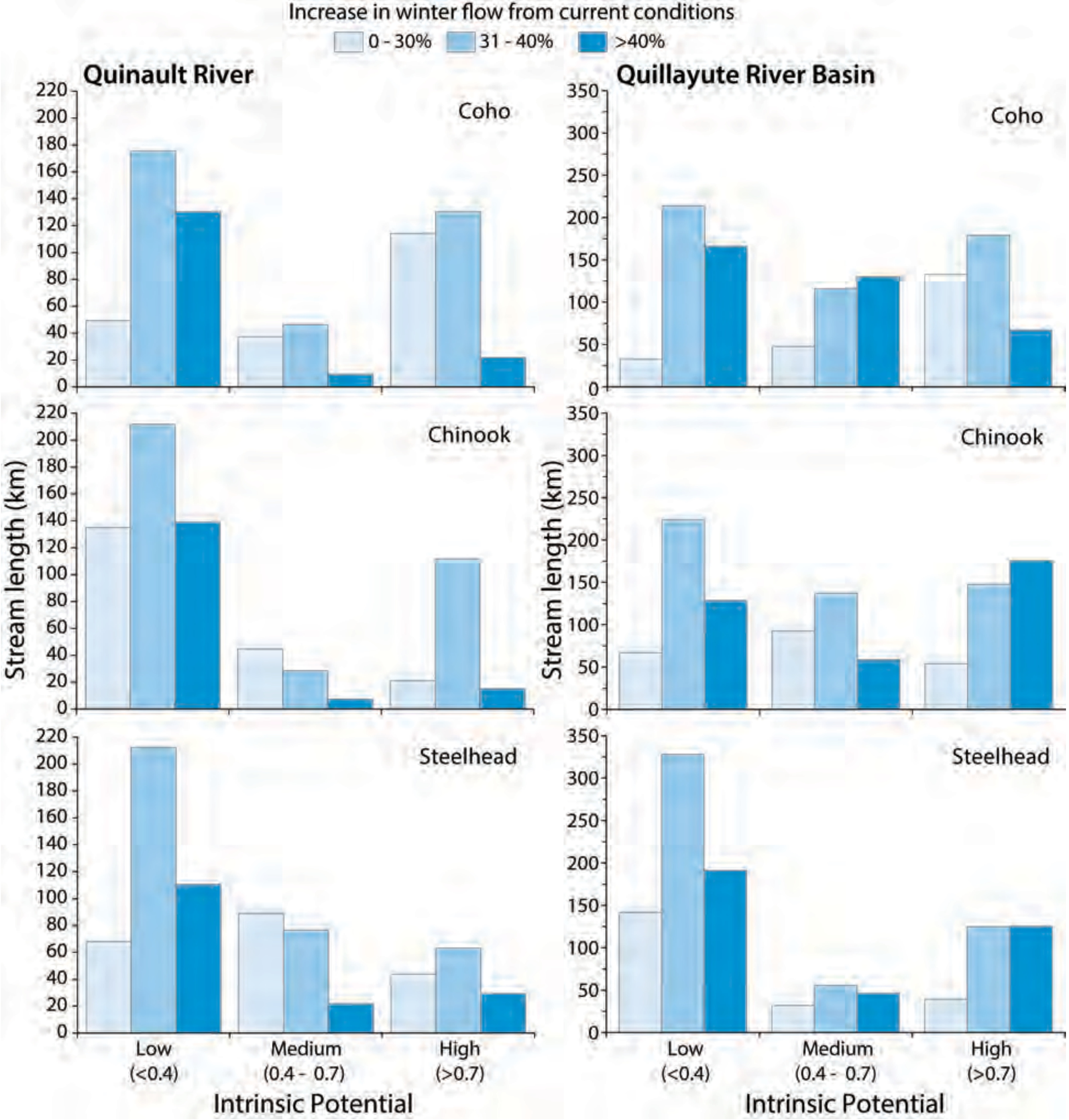


Figure 4.8 *Percent increase in average winter flows from current to 2040 in segments of different Intrinsic Potential for Coho and Chinook salmon and Steelhead in study basins in the Treaty of Olympia area.*

(A) *(B)*




Increase in winter flow from current conditions
0 - 30%
31 - 40%
>40%
Quinault River
Quillayute River Basin
Coho
Chinook
Steelhead
Stream length (km)
0
20
40
60
80
100
120
140
160
180
200
220
50
150
250
300
350
Low (<0.4)
Medium (0.4 - 0.7)
High (>0.7)
Intrinsic Potential

(C) *(D)*

4.5 Discussion & Conclusions

The major river basins in the Treaty of Olympia area considered in this analysis (Queets River, Hoh River, Quinault River, and Quillayute River) are likely to be affected by climate change; summer water temperatures and average winter flows will increase, and average summer flows decrease, which is consistent with the findings of Mantua et al. (2010). Summer water temperatures over much of the area in all systems will remain within a range suitable for Pacific salmon (<15°C) (McCullough 1999). The primary ecological concern of water temperatures of 15–18°C is not physiological stress but increased vulnerability to predation by and competition with warm-water fish, native and non-native (EPA 2007). Thus, the overall ecological impact of these changes is likely to be relatively small, particularly if the effects of current environmental challenges are reduced or eliminated.

Quillayute River fishery. Photo courtesy Katie Krueger, Quileute.

Providing a coordinated network of riparian restoration actions that extend from headwaters to estuaries (and laterally onto floodplains) would be particularly beneficial for mitigating potential temperature increases (Cristea and Burges, 2010). Any potential consequences of increased water temperatures, even in the lower portions of the river, could be mitigated by management of riparian areas with a priority in areas of mid-high intrinsic potential, or areas that influence these reaches. Re-establishing riparian vegetation in stream reaches where it has been lost (Lawrence et al., 2014) and improving existing stands (Cristea and Burges, 2010) should help maintain temperatures in favorable ranges and potentially minimize or retard potential future temperature increases from climate change. Priority could be given to doing this for areas used by Chinook salmon on the Queets River and Quillayute River basin.

Additionally, cooler temperatures in tributaries could create pockets of cool water in larger, mainstem portions of the network that could be utilized by adults and juveniles (Torgersen et al., 1999; Breau et al., 2007) to avoid less favorable conditions and reduce the potential for adverse consequences (Crozier et al., 2008). Protecting cool-water refugia such as springs and groundwater seeps from water appropriation or disconnection from the surface drainage network could also mitigate temperature increases during the summer. However, fish that congregate in such locations may be particularly vulnerable to harvest by anglers and other predators (Keefer et al., 2009), so minimizing mortality from these sources will be beneficial.

It will be critical to prevent the introduction or establishment of non-native fish in these basins and to control or eradicate existing populations. Maintaining water temperatures within ranges favorable to Pacific salmon and other native fishes can prevent the invasion or expansion of non-native fish, particularly warm-water fish. Laurence et al. (2014) showed that restoring riparian zones along the John Day River, OR, could reduce the impacts of climate change on water temperature and actually decrease the suitability of habitat for the introduced Smallmouth Bass (Micropterus dolomieu).

We were unable to examine the potential impacts of increasing water temperatures except in summer because projections are not available for other seasons at this time. However, it is safe to assume that temperatures at other times of the year will also rise. As discussed in the section that reviewed the potential effects of and responses to climate change on Pacific salmon, growth rates of salmonids could actually increase, assuming that the temperatures are within a favorable range and off-set potential declines in growth during the summer. This is likely to be the case in the streams examined here. Elevated winter water temperatures influence the development rate and time of and size at emergence, which could affect later life-stages (see Review section for more detail). Monitoring should provide better insights into these potential effects.

Our limited understanding of the relation between flow and growth and survival of salmonids (Bradford and Heinonen, 2008) and the magnitude of the changes in summer flows found make it challenging to fully understand the ecological consequences of reduced summer flows on streams and rivers in the Treaty of Olympia area. Reduced flows can have significant impacts on salmonids (see earlier summary). However, the changes in summer flows that affect growth and survival of juveniles reported in the scientific literature, generally >70% (e.g., Harvey et al., 2006; Grantham et al., 2012), are much higher than those projected for the streams and rivers in the Treaty of Olympia area. And results of such changes are mixed. For example, Harvey et al. (2006) found reduced growth rates of Rainbow Trout in a stream in northern California where flows were reduced 75–80%, but survival was not affected. Ebersole et al. (2009) found that the abundance and growth of juvenile Coho salmon in different segments (headwaters and middle portions) of a coastal Oregon river system were not statistically different when flows varied by 23%. If survival of juvenile salmonids in the study area is density-dependent, compensatory increases in survival at later life-stages could off-set a reduction in summer survival.

The effect of reduced summer flows could be exacerbated by accompanying increases in water temperatures. Water temperatures in the upper and middle portions of the network in the river systems considered here are projected to increase. However, they will remain within a favorable range for salmonids, and thus are not likely to magnify the potential consequences of reduced flows.

Upper Queets River. Photo courtesy Larry Workman, QIN.

Potential consequences of reduced summer flows on returning adults are similarly difficult to assess. Wade et al. (2013) predicted that lower summer flows would have significant impacts on steelhead on the Olympic Peninsula. It is not possible at this time to directly compare our predictions for flow reductions to the magnitude of changes predicted by Wade et al. (2013), but we would guess that theirs is higher. Ours appear closer to those predicted by Mantua et al. (2010), who showed that conditions on the Olympic Peninsula should remain in a range favorable to Pacific salmon. There could be some disruption of the migration of returning adults, such as delays until water cools, but the relatively short migration distances and the diel variation in water temperatures could minimize such effects.

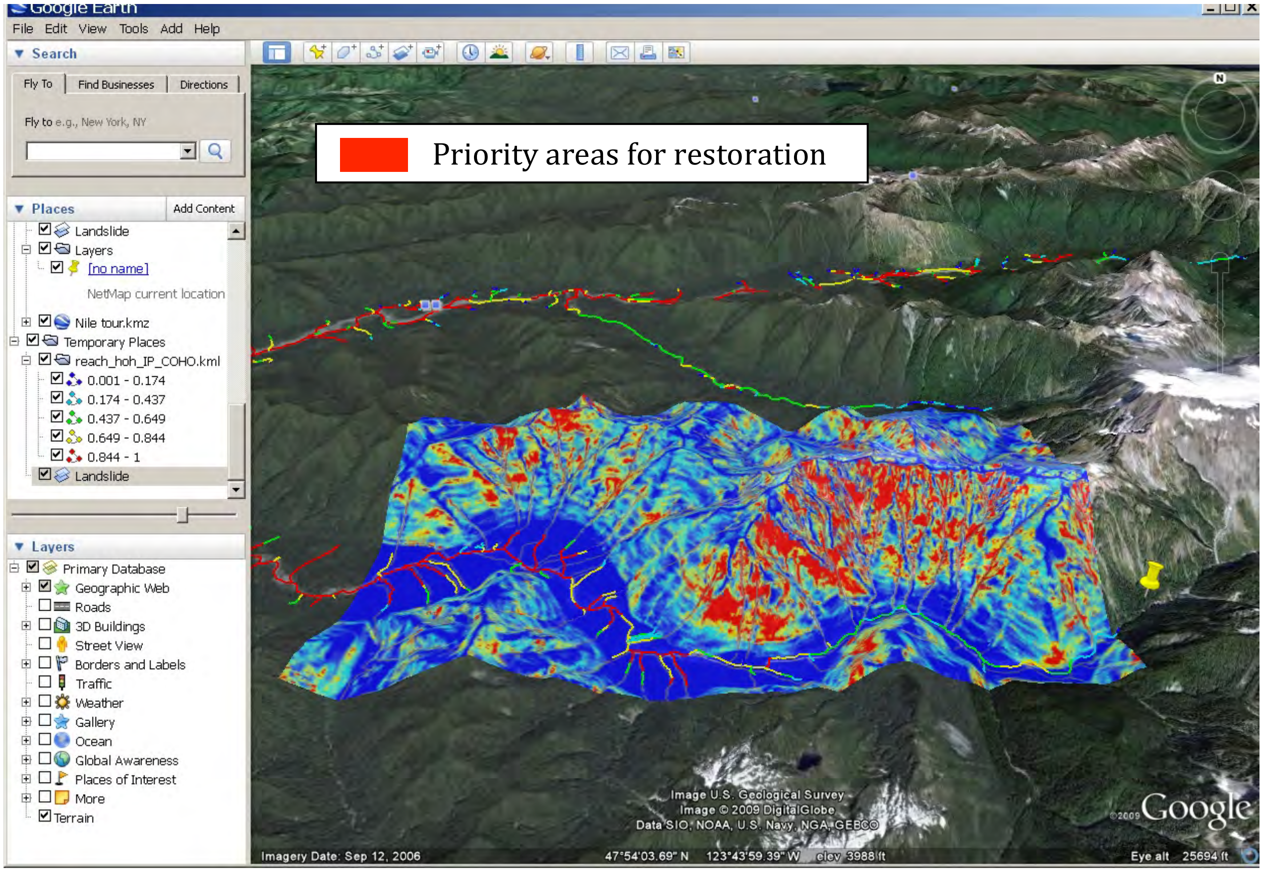
Previous studies of the impact of climate change assumed (Mantua et al., 2010) or concluded that increased winter flows reduced the survival of developing eggs and embryos (Battin et al., 2007; Leppi et al., 2014). These results were based on the assumption that higher flows increased streambed scour. The effect of increased flows on streambed scour is not uniform across the stream network, however, and is a function of the magnitude of the flow (Torizzo and Pitlick, 2004; Mueller et al., 2005), sediment input (Neupane and Yager, 2013), and geomorphic features of the channel (McKean and Tonina, 2013; Goode et al., 2013). Additionally, basin geology and the structure of the stream network all influence the response (Tague et al., 2008; Tague and Grant, 2009). Many species of Pacific salmon have adapted to high flows by selecting spawning sites in coarser substrates (the size depending on the species), in areas away from the middle of the channel (May et al., 2009), and in low-gradient reaches, where flows can move onto low-level floodplains, dissipating energy and reducing scour potential (McKean and Tonina, 2013). Given these adaptations and the relatively small change in winter flows in the basins in the Treaty of Olympia area, winter flows are not likely to have significant impacts on salmon and steelhead. However, this statement should be taken with caution. Ward et al. (2015) attributed the decline in populations of Chinook salmon in Puget Sound, WA, to increased variability in winter flows. During low-flow years, fish presumably spawn closer to the thalweg, where scour is greatest (May et al., 2009) and egg and embryo survival would be reduced. Future analysis of basins in the Treaty of Olympia area could consider this variability if data are available.

The effect of future increases in the size and frequency of winter flows could be exacerbated by the reduced potential of the stream to dissipate energy laterally onto the floodplain. Roads and other structures that constrict the channel will increase the potential for scour. Maintaining floodplain connections or reconnecting the channel with its floodplain helps mitigate flood damage to humans and their property, increases natural water storage, and reduces peak discharges (Poff 2002; Palmer et al., 2008; Opperman et al., 2010). Restored floodplain connectivity also provides seasonal protection for rearing salmonids by increasing access to slack-water areas during high flow (Henning et al. 2008) and to cool-water springs and seeps when water temperatures are high. Thus, removal or modification of artificial channel constrictions will reduce the potential impacts of high flow related to climate change with regard to the survival of eggs and embryos, and increase the available winter habitat of juveniles, increasing their survival.

Conservation is most successful when proactive actions are directed at protecting populations before they decline, and maintaining natural processes before they are impaired (McGurrin and Forsgren, 1997). In many cases, it is much more difficult to conserve or restore a population in decline than to maintain a robust and resilient population (Cabeza 2003). Thus, protecting areas of productive and ecologically intact habitat is imperative.

Unfortunately, many aquatic ecosystems, or at least parts of them, have been extensively altered by past and recent human activities. Funds and time are inadequate to deal with all areas, thus initial restoration activities should be focused on the portion of the landscape where they will be most effective. An example of priority restoration areas is shown in Figure 4.9. Increasing precipitation in the winter is likely to increase the risk of landslides and debris flows, shown in red (see legend). These areas are important sources of wood (Reeves et al., 2003; Bigelow et al., 2007), and sediment, the key building blocks of complex habitat for Pacific salmon. The presence of large wood in the channel could lessen effects of more frequent, intense storms caused by climate change by reducing substrate scour in spawning areas, which could improve survival of developing eggs and embryos (Shellberg et al., 2010). Also, the presence of whole trees in debris flows can actually change the properties of the debris flow and reduce detrimental effects (Lancaster et al., 2003). Such landslide-prone areas should be a priority for restoring riparian areas. Additionally, they are critical areas for road removal and decommissioning, and culvert replacement and removal.

Figure 4.9 *Example of landslide prone areas that should be a priority for restoration to mitigate the potential impacts of climate change.*



It is likely that a major challenge for Pacific salmon in the Treaty of Olympia area will be the marine environment. The predicted effects, acidification and increased temperatures, and ecological potential consequences, reduced survival and size adults, were described earlier. Pacific salmon have survived climate shifts in the past (Miller and Brannon, 1982; Waples et al., 2009) and likely have the ability to persist in many areas of their current range even in climate scenarios more pessimistic than projected in this analysis. Salmonid populations exhibit large genetic and phenotypic diversity relative to many other bony fishes (Waples 1991; Crozier et al., 2008; Schindler et al., 2010) and can adapt to changing conditions rapidly (Healey and Prince, 1995; Quinn et al., 2001). This genetic and phenotypic diversity allowed for persistence in highly dynamic and ecologically diverse environments in the past (Waples et al., 2009; Greene et al., 2009; Moore et al., 2014) and will be a key to their future survival (Mangel 1994). (However, we note that Gienapp et al. (2008) cautioned that our knowledge about the role of genetic variation and the ability of natural populations to respond adaptively to current and future environmental change is limited, and that assuming adaptation will or can happen is risky because of the uncertain rate and extent of climate change, effects of invasive species, and altered ecological processes.) The challenge to managers will be to conserve natural environmental complexity in space and time so it can provide the physical templates for maintaining genotypic and phenotypic diversity in populations that are currently strong, or to restore environmental complexity where it is currently compromised.

Monitoring will be essential to detecting the effects of climate change on physical and ecological factors that will affect Pacific salmon. This will require expanding existing monitoring programs and, just as importantly, examining data in different ways. Water temperatures should be monitored over the entire year to detect all seasonal changes. Accumulations of degree days may reveal threshold conditions that will have important life-history implications (e.g., time to hatching or onset of smolting) (Neuheimer and Taggart, 2007). As discussed previously, slight changes in temperature can have significant life-history implications that could be missed by examining summer maximum temperatures relative to putative hazard thresholds. Habitat types may respond differently to climate impacts; for example, monitoring temperature in a location where thermal conditions are already warm may give an exaggerated signal of change, while monitoring in locations that are groundwater-dominated may miss important changes.

It is also important to monitor genotypic and phenotypic trends in juveniles and adults, as well as the phenology of various life-history stages. The influence of climate change begins at the earliest life-history stage and extends throughout the life cycle, and interpreting climate impacts will be easily confounded by other environmental changes. Climate-related metrics can be added to existing programs that monitor fish movements. There is much diversity in the life-history of the freshwater phases of many species of Pacific salmon (Riemers, 1973; Bennett et al., 2014). Thus, monitoring of smolt production should be extended beyond the typical spring–early summer focus to better understand the potential for and mechanisms by which Pacific salmon may adapt to climate change. Otoliths from returning adults can be used to infer successful life-history strategies for different members of a given population, and changes in the frequency of life-history types (time in freshwater, estuary, and ocean) could be an indicator of the response to climate change. Analyses of stable isotopes from muscle tissues of different life stages can help determine food web relationships, which are also sensitive to climate shifts (Johnson and Schindler, 2008). Changes in the size of returning adults will also provide insights into the potential impacts of changing ocean conditions and the response of local populations to them. In summary, monitoring programs that cover the entire life cycle of Pacific salmon will be most effective at detecting and understanding the effects of climate change.

The potential response of some species to climate change may not be as expected or desired. Steelhead may be the most uncertain in how they could respond to climate change. Recent studies have predicted significant declines in or extirpation of steelhead populations in Washington and elsewhere (Wade et al., 2013; Katz et al., 2013), primarily as water temperatures increase with climate change. Steelhead are the migratory form of *Oncorhynchus mykiss*; Rainbow Trout are the resident form. These forms are not genetically distinct, and one life-history can produce offspring that exhibit another strategy (Christie et al., 2011; Sloat and Reeves, 2014). Recent work of Sloat and Reeves (2014) found that offspring of steelhead that had high rates of standard metabolism became steelhead, and those with lower rates were Rainbow Trout. Metabolic costs for fish are directly related to water temperatures (Beauchamp 2009). Benjamin et al. (2013), using models, found that at small temperature increases (0.6^{o}C from a baseline of 12.7^{o}C) resulted in an increase in smolt numbers. An increase of 2.7^{o}C, however, increased the number of resident fish. Changes in favorability of the marine environment, not considered by Benjamin et al. (2013), will also likely favor the expression of the resident Rainbow Trout life-history.

Assessments of the potential impacts of climate change on steelhead thus should consider the capacity of *O. mykiss* to express different life-history forms.

The role of hatcheries in helping to meet the challenges of climate change is unclear at present. There is much debate about the impacts of hatchery fish and practices on wild populations and how hatcheries could be used in the recovery of depressed stocks (Williams 2006). As a result, evidence for the potential contribution of hatchery fish to helping naturally spawning populations respond to climate change is mixed. Hatchery fish currently compete for food resources with wild salmon in the ocean (Ruggerone et al., 2003), and undoubtedly this competition will only increase if the amount of suitable ocean habitat or food-web productivity decreases in the future, as suggested by open-ocean habitat assessments under future warming scenarios (Welch et al., 1995; Abdul-Aziz et al., 2011; Atcheson et al., 2012). The fitness of hatchery fish declines within a few generations (Lieder et al., 1986; Araki et al., 2007), which may constrain their ability to respond to climate change and thus contribute to the long-term persistence of wild populations. Hatchery fish spawning with wild fish can lead to mismatches between development rates and environmental conditions (Fraser et al., 2010), which could reduce the potential of wild populations to adapt to climate change. However, it is very likely that hatchery fish will be needed to aid populations that are currently low in number. Improved strategies (e.g., Brockmark and Johnsson, 2010; Thériault et al., 2010) are needed to prevent or substantially minimize the potential negative impacts of hatchery fish on wild populations.

While all species of Pacific salmon in the study area will be affected by climate change, we could not assess the impacts on all of them at this time. The following is a brief description of the potential impacts on the species not considered.

Changes in stream flows will most likely have the greatest impact on Coastal Cutthroat trout. Juveniles rear in small streams, so lower flows will reduce the amount and quality of available habitat, most likely to a greater degree than for other species, because of the disproportionate reduction in habitat in smaller streams compared to larger ones. Also, Cutthroat Trout spawn in small streams, generally with moderate gradients, in the fall. And, because of their small size, eggs are buried very shallowly in the substrate. The combination of these factors makes these fish particularly vulnerable to increased winter flows resulting from climate change, similar to other cutthroat subspecies (Wenger et al., 2011).

The impacts of climate change on Sockeye salmon were reviewed earlier in this report. There is no projection of the potential impacts of climate change on the lakes in the study area at this time. However, if the lakes are affected to the same degree as surrounding streams and rivers, impacts on the freshwater life-history phase may be minimal. Larger and more pronounced affects may occur in the ocean (Abdul-Aziz et al., 2011; Atcheson et al., 2012) and could manifest themselves as smaller returning adults or declines in numbers.

Pink and Chum salmon use freshwater for spawning by adults and limited rearing by juveniles. Bryant (2009) believed the primary impact of climate change on Sockeye in freshwater was elevated summer water temperature during reduced flows, which would increase mortality of returning fish. This could occur in the Treaty of Olympia area but it is likely to be rare, given the current projections for flow and summer temperature. The largest impacts are likely to result from changes in the marine environment. Rising sea levels could inundate streams in low-lying areas near the coast and reduce spawning suitability. Also, similar to other species, the size and number of returning adults could decline.

While future environmental conditions are likely to depart, in some cases significantly, from historic patterns (Keane et al., 2002), the impacts of climate change may vary depending on the specific characteristics when considered at the local scale. Future climate scenarios have been applied to hydrologic models across wide areas in the Pacific Northwest (e.g., Hamlet and Lettenmaier, 2007; Elsner et al., 2010; Mantua et al., 2010). However, recent models being applied at smaller spatial scales suggest that the effects may vary significantly from consequences projected at larger scales. For example, Daley et al. (2007) suggest that ambient air temperatures were unlikely to change in deep valleys of the H.J. Andrews Experimental Forest in the western Oregon Cascade Range because of cold air drainage. Also, high-elevation portions of the H.J. Andrews Experimental Forest lie within the permanent winter snow zone, and streams draining higher-elevation watersheds above the projected snow-to-rain transition zone are less likely to be affected by warming winter temperatures than are those at lower elevations (Luce and Tarboton, 2004). Closer examination of the potential impacts on the watersheds in the Treaty of Olympia area is warranted to better understand the potential impacts of and develop a program to respond to climate change.

We can be assured that future conditions are very unlikely to resemble historic ones (Keane et al., 2002; Harris et al., 2006). New assemblages of native and non-native species will interact in novel ways (Poff et al., 2001; Montoya and Raffaelli, 2010), and make it difficult to predict the effects of climate change on Pacific salmon and other aquatic organisms. Although magnitude of climate-driven change is likely to vary among the river basins within the Treaty of Olympia area, it is likely to be relatively small, so the ecological consequences to salmon and steelhead of impacts on freshwater ecosystems are likely to be minimal. The largest impacts are likely to result from changes in the marine environment. It will be imperative to develop management strategies tailored to local conditions so as not to exacerbate the effects climate change, and to recover and maintain the productivity of Pacific salmon and other native fish and aquatic organisms.

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Appendix 4.1. Present and future (2040) summer water temperatures by IP class for three species of salmonids on four rivers in the Quillayute River basin.

		Stream Length (km)					
	Summer water temperature	Low IP (<0.4)		Medium IP (0.4 < IP < 0.7)		High IP (>0.7)	
River	(°C)	current	future	current	future	current	future
Coho salmon							
Sol Duc	<10°C	61.8	29.6	5.7	1.6	4.4	1.3
	10–15°C	77.0	106.1	92.5	77.1	74.5	56.3
	>15°C	0.8	3.9	22.0	41.5	31.3	52.6
Calawah	<10°C	1.8	0.0	0.0	0.0	0.0	0.0
	10–15°C	105.8	106.7	79.4	45.1	30.0	18.5
	>15°C	0.2	1.0	9.8	44.0	4.8	16.3
Bogachiel	<10°C	22.4	6.5	0.7	0.1	0.7	0.1
	10–15°C	108.0	119.9	39.7	31.8	92.5	48.5
	>15°C	0.0	3.9	3.2	11.6	7.2	51.8
Dickey	<10°C	0.0	0.0	0.0	0.0	0.0	0.0
	10–15°C	33.7	25.2	33.9	11.0	103.9	39.6
	>15°C	0.6	9.1	6.8	29.7	36.9	93.8
Chinook salmon							
Sol Duc	<10°C	64.3	32.0	6.3	0.5	1.3	0.0
	10–15°C	145.5	161.3	38.3	33.8	60.3	44.3
	>15°C	2.5	19.0	4.1	14.3	47.4	64.7
Calawah	<10°C	1.8	0.0	0.0	0.0	0.0	0.0
	10–15°C	132.1	132.8	36.5	24.5	46.6	13.0
	>15°C	0.0	1.0	0.3	12.3	14.4	48.0
Bogachiel	<10°C	22.9	6.7	0.6	0.0	0.2	0.0
	10–15°C	163.9	160.3	20.0	13.5	56.2	50.7
	>15°C	0.0	19.9	0.0	7.2	10.4	40.2
Dickey	<10°C	0.0	0.0	0.0	0.0	0.0	0.0
	10–15°C	12.7	72.1	27.8	3.7	17.1	0.0
	>15°C	0.1	55.8	35.6	24.2	36.9	52.7

Steelhead							
Sol Duc	<10°C	48.9	26.4	8.0	2.6	15.0	3.6
	10–15°C	64.8	81.2	65.9	55.0	113.3	103.4
	>15°C	20.5	26.8	12.7	29.0	20.8	42.2
Calawah	<10°C	1.8	0.0	0.0	0.0	0.0	0.0
	10–15°C	75.8	76.9	28.4	22.5	11.0	70.9
	>15°C	1.1	1.8	2.9	8.8	10.7	50.8
Bogachiel	<10°C	20.1	6.6	2.0	0.0	1.6	0.0
	10–15°C	105.9	95.1	76.1	54.4	58.2	50.7
	>15°C	5.6	30.0	3.2	26.8	1.5	10.5
Dickey	<10°C	0.0	0.0	0.0	0.0	0.0	0.0
	10–15°C	58.0	35.2	77.5	32.3	36.0	8.3
	>15°C	16.3	39.1	11.5	56.6	9.1	36.9

Appendix 4.2. Changes in summer streamflows by IP for three species of salmonids on four rivers in the Quillayute River basin.

River	Change in summer streamflow (% decrease)	Stream Length (km) Low IP (<0.4)	Medium IP (0.4 < IP < 0.7)	High IP (>0.7)
Coho salmon				
Sol Duc	<10%	65.6	43.4	28.5
	10–20%	31.0	42.0	5.6
	>20%	11.2	3.7	0.6
Calawah	<10%	65.6	43.4	28.5
	10–20%	31.0	42.0	5.6
	>20%	11.2	3.7	0.6
Bogachiel	<10%	84.9	24.6	44.9
	10–20%	17.4	9.5	48.2
	>20%	28.1	9.4	7.3
Dickey	<10%	34.3	40.7	133.4
	10–20%	0.0	0.0	0.0
	>20%	0.0	0.0	0.0
Chinook salmon				
Sol Duc	<10%	119.5	23.7	6.9
	10–20%	29.4	10.2	115.8
	>20%	63.4	14.7	104.1
Calawah	<10%	86.3	13.0	38.2
	10–20%	34.1	21.7	22.8
	>20%	13.4	2.1	0.0
Bogachiel	<10%	139.8	12.1	2.6
	10–20%	18.6	1.3	55.1
	>20%	28.4	7.2	9.2
Dickey	<10%	127.8	27.9	52.7
	10–20%	0.0	0.0	0.0
	>20%	0.0	0.0	0.0

Steelhead				
Sol Duc	<10%	59.1	54.8	?
	10–20%	31.9	16.5	?
	>20%	43.3	15.4	?
Calawah	<10%	49.8	24.7	63.0
	10–20%	21.9	5.6	51.2
	>20%	7.0	1.0	7.5
Bogachiel	<10%	72.8	47.4	34.2
	10–20%	40.4	25.5	9.1
	>20%	18.5	8.4	44.8
Dickey	<10%	72.8	47.4	34.2
	10–20%	40.4	25.5	9.1
	>20%	18.5	8.4	17.9

Appendix 4.3 Changes in winter streamflows by IP for three species of salmonids on four rivers in the Quillayute River basin.

River	Change in winter streamflow (% increase)	Stream Length (km)		
		Low IP (<0.4)	Medium IP (0.4 < IP < 0.7)	High IP (>0.7)
Coho salmon				
Sol Duc	0–30%	3.4	2.1	10.9
	30–40%	32.1	20.2	57.0
	<40%	104.0	97.9	42.3
Calawah	0–30%	0.0	0.0	0.0
	30–40%	80.0	71.6	24.8
	<40%	27.8	17.6	10.0
Bogachiel	0–30%	8.5	10.0	17.5
	30–40%	87.6	19.0	68.2
	<40%	34.2	14.5	14.6
Dickey	0–30%	20.5	36.7	10.5
	30–40%	13.8	5.0	29.0
	<40%	0.0	0.0	0.0
Chinook salmon				
Sol Duc	0–30%	16.1	22.5	13.5
	30–40%	73.4	26.2	95.2
	<40%	122.8	48.6	109.0
Calawah	0–30%	0.0	0.0	0.0
	30–40%	100.5	24.8	51.0
	<40%	33.3	12.0	10.0
Bogachiel	0–30%	28.1	7.0	1.0
	30–40%	123.9	5.3	45.7
	<40%	35.0	8.3	20.1
Dickey	0–30%	97.6	25.0	38.0
	30–40%	30.3	2.8	14.7
	<40%	0.0	0.0	0.0

Steelhead				
Sol Duc	0–30%	7.9	7.4	1.1
	30–40%	41.2	42.9	25.3
	<40%	85.1	36.3	122.8
Calawah	0–30%	0.0	0.0	0.0
	30–40%	59.8	23.9	92.7
	<40%	18.9	7.4	29.1
Bogachiel	0–30%	12.3	12.3	11.5
	30–40%	95.0	54.2	25.6
	<40%	24.3	14.9	24.2
Dickey	0–30%	46.7	72.7	41.2
	30–40%	27.7	16.2	3.9
	<40%	0.0	0.0	0.0

Chapter 5: Coastal Hazards

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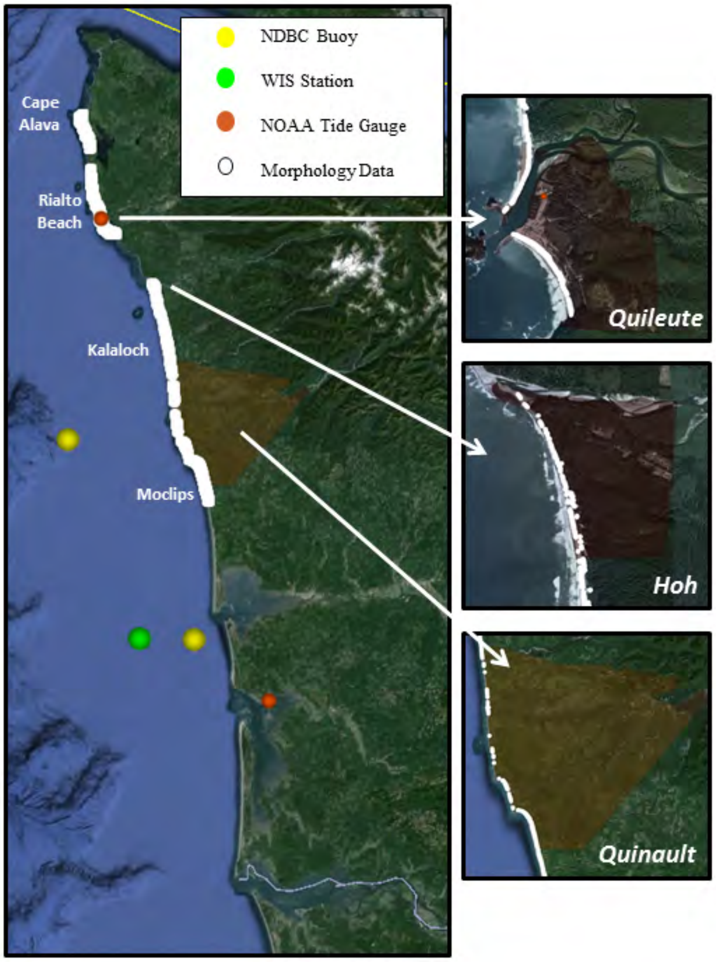
5.1 Introduction

Coastal ecosystems and communities along the outer coast of the western Olympic Peninsula are currently at risk of erosion and flooding hazards driven by extreme total water levels (TWLs). It is important to understand the magnitude and frequency of these extremes to better prepare coastal communities for dealing with both present day and future coastal hazards which effect critical habitats and infrastructure. The goal of this assessment is to quantify and map the relative exposure of the Treaty of Olympia area to extreme TWLs under present day conditions and a range of potential future climate change scenarios. Our work focuses on beaches on and adjacent to the reservations of the Hoh and Quileute tribes and the Quinault Indian Nation (Figure 5.1).

Figure 5.1 *Map of the Washington Pacific coast (left) with closer views of the reservation areas (right). Also plotted are the locations of the measurements used in this study.*



Quinalt Formation. Photo courtesy Larry Workman, QIN.

TWLs are computed by combining water level elevations extracted from tide gauges with estimates of wave-induced water levels. For the most part, our approach to quantifying and mapping extreme TWLs follows the methodologies developed in FEMA flood risk assessments along the Oregon coast (e.g., Allan, et al., 2012). In addition, we apply a full simulation model (Serafin and Ruggiero, 2014) to produce multiple, synthetic time series of TWLs, accounting for seasonality, interannual variability, and trends in wave heights and sea level. Synthetic time series are generated based on (1) present day TWLs and (2) projections of future TWLs using three sea level rise scenarios derived from the National Research Council report on west coast sea level rise (NRC, 2012). The impact of changes in SLR on TWLs is compared to present day TWLs to estimate the possible range of future flooding and erosion events. Understanding the variability and trends in extreme TWL events may aid in coastal planning, hazard preparedness efforts, and assessment of impacts to key species in these locations.

5.2 Total Water Levels

Extreme coastal total water levels (Figure 5.2) are the result of interactions between multiple oceanographic, hydrological, geological and meteorological forcings that act over a wide range of scales (e.g., astronomical tide, wave setup, large-scale storm surge, monthly mean sea level, vertical land motions (VLM), etc.). At any given time, the elevation of the TWL, relative to a fixed datum, is comprised of two components such that

$$TWL = SWL + R \qquad \textit{Eq. 1}$$

where the SWL is the still water level, or the measured water level from tide gauges, and R is a wave induced component, termed the wave runup. The wave runup calculation is often dependent on the wave height, wave length, and the local beach morphology (e.g., Holman and Sallenger, 1986; Ruggiero et al., 2001, Stockdon et al., 2006), making it a highly site-specific computation. Because we are interested here primarily in extreme events, R is parameterized using R2%, a standard statistic corresponding to the 2% exceedance percentile of runup maxima.

The SWL can further be broken down into

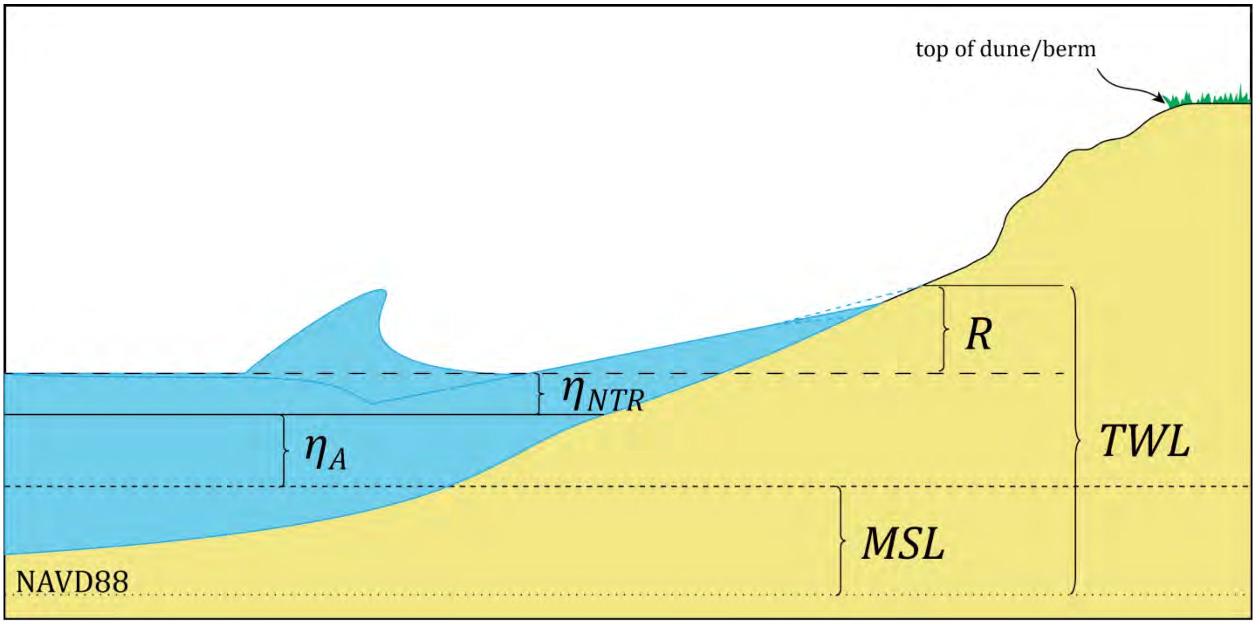
$$SWL = \mathrm{MSL} + \eta_{\mathrm{A}} + \eta_{NTR} \qquad \textit{Eq. 2}$$

where MSL is the mean sea level, η_A is the deterministic astronomical tide, and η_{NTR} is the non-tidal residual, or any elevation change to the water level not due to the tide. The elevation of the η_{NTR} is often driven by changes in the seasons, storm surges produced by discrete storm events, and interannual variability due to the El Niño Southern Oscillation (ENSO), a periodic change in the large-scale climate caused by variations in sea surface temperatures over the tropical eastern Pacific Ocean. The warming phase is termed El Niño, while the cooling phase is known as La Niña. During El Niño years, the PNW coastline experiences increased water levels for months at a time, along with changes in the frequency and intensity of storm systems (Komar 1986; Allan and Komar, 2002). In more sheltered environments, precipitation and river discharge also contribute significantly to η_{NTR} (e.g., Wahl et al., 2015), however, these processes will not be considered in this report which focuses on open ocean coast processes. From Equations 1 and 2, TWL time series can be constructed based on observational records of waves and water levels (e.g., Ruggiero et al., 2001).

5.2.1 Data Extraction

In order to develop a long, continuous TWL time series relevant to the northern/central Washington Pacific coastline, wave and water level time series must be extracted from buoys and tide gauges, respectively. TWLs can then be compared to backshore morphology to estimate the percentage of time certain contours are inundated as well as the risk of coastal flooding and erosion. Below we describe the approaches used to extract the relevant data sets (waves, water levels, topographic parameters).

Figure 5.2 *Definition sketch of total water levels (TWL). Dune/bluff erosion or infrastructure damage occurs when the TWL, relative to a datum such as the land based NAVD88 datum, exceeds the elevation of the dune/structure toe, and overtopping/flooding occurs when the TWL exceeds the elevation of the dune or structure crest (figure from Serafin and Ruggiero, 2014).*



5.2.1.1 Water Levels

Water level data was downloaded from various tide gauges along the study area (Figure 5.3). The National Oceanic and Atmospheric Administration (NOAA) La Push tide gauge (Station #9442396) is located within the study area; however, measurements at this station only began in 2002. Therefore, in order to analyze longer water level variations we combine this record with tide gauge station #9440910 (Toke Point, approximately 135 km south of La Push), which began measuring water levels in 1979. In order to combine water levels from different tide gauges, we first estimate any temporal offsets in the arrival of the daily tides due to the distance between the two stations. Once corrected for, η_{NTR} is split into seasonal, storm surge and monthly average sea level anomaly components, driven by changes in the seasons, discrete storm events, and interannual variability, respectively. Each of these components is examined for temporal and/or spatial offsets between the two stations. Because the seasonal signal, split into an annual and semiannual component, was slightly different between the two tide gauges, the seasonal signal from La Push was used for the combined time series. Estimates of the arrival times and amplitude of storm surge and monthly sea level anomalies show consistency between the La Push and Toke Point tide gauges and therefore did not require further corrections. Once the timing offset of the tides and seasonality were corrected for, the Toke Point tide gauge was combined with the La Push tide gauge, generating an hourly water level record from August 1979 through March 2015 which is approximately 98% complete (Figure 5.4).

Figure 5.3 *Map showing the locations of buoy measurements and WIS stations considered for this analysis.*

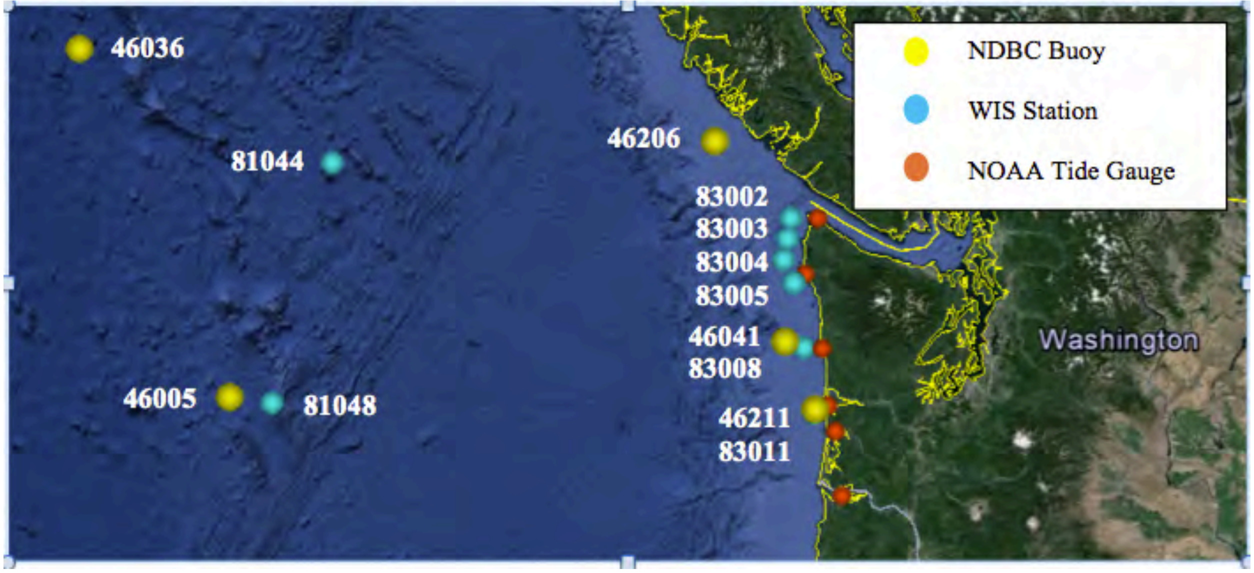
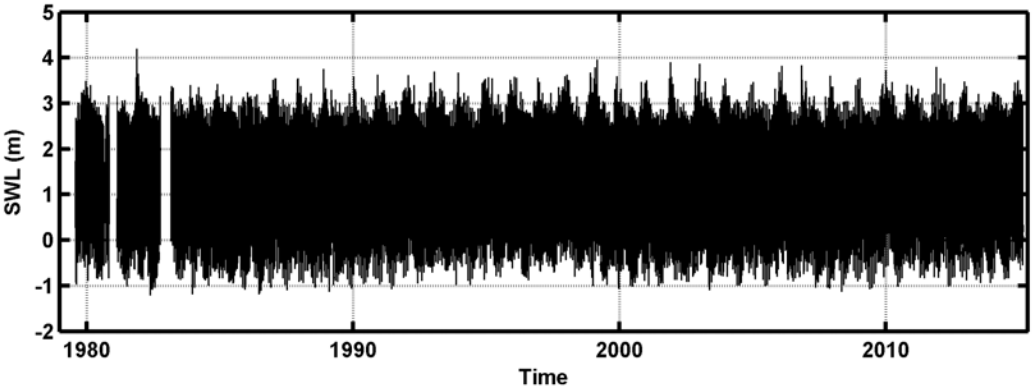


Figure 5.4 *Water Level measurements (datum MLLW) extracted from a combination of the La Push (Station #9442396) and Toke Point (Station #9440910) tide gauges.*



5.2.1.2 Wave Climate

For wave data we use a combination of existing measured and hindcast[6] wave time series to generate as long a time series of the deep-water wave climate as possible for the northern/central Washington Pacific coastline. For this study, we downloaded all available National Data Buoy Center (NDBC) and Coastal Data Information Program (CDIP) hourly buoy data in the region (Table 5.1, Figure 5.3). In addition to the measured wave data, we also obtained wave hindcast information for the region determined through the Wave Information Studies (WIS) (Hanson et al., 2009). Figure 5.3 displays the location of the various buoys and hindcast stations considered here to derive a combined northern/central Washington Pacific coast wave climate dataset. Because of the variation in location and water depth of the buoys, the wave climates (e.g., significant wave height, peak wave period, mean wave

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[6] Wave hindcasts are the prediction of waves on the water surface for past events. This allows complete, long records where measured data does not exist.

direction) observed at stations 46005 and 46036 have significant differences compared to the climates observed at 46041 and other buoys and hindcast stations closer to shore (NDBC 46211/CDIP 0036, 83003, 83004, etc.). These nearshore buoys provide long enough time series for the purposes of our analyses, so the buoys further from shore (46005 and 46036) were therefore not considered in the final analysis.

NDBC 46041, located in an intermediate water depth of 115m, is the closest buoy to the shelf edge in this region, and therefore was selected as the priority buoy for developing a combined time series. It was reverse shoaled[7] to deep water using linear wave theory to account for wave height and direction changes in shallower depths. Buoy NDBC 46211/CDIP 0036 was also included in this analysis, and also was reverse shoaled to deep water. For the purposes of this study, we used wave hindcast data for WIS station 83008, which is located 17 km east of NDBC 46041, to fill in any missing directional data.

Table 5.1 *Selected wave station measurements for the northern/central Washington Pacific coast.*

Station Name	Number	Latitude	Longitude	Period of Coverage	Depth (m)	Notes
Cape Elizabeth	NDBC 46041	47.353 N	124.731 W	1987-present	114.3	
Grays Harbor	NDBC 46211/ CDIP 0036	46.858 N	124.244 W	1981-present	38.5	
WIS Hindcast Station 83008	WIS 83008	47.330 N	124.500 W	1981 - 2011	47	17 km inland of NDBC 46041

We examined the empirical probability density functions (PDF) of the selected buoys' raw time series (using only the years where overlap between the buoys being compared occurred) and determined that the PDF's were similar enough to forgo any bias corrections between stations – in other words we could simply combine them. Gaps in the time series of Cape Elizabeth 46041 were filled in with the Grays Harbor buoy (NDBC 46211/CDIP 0036). Where gaps still remained, we filled in the time series with the WIS hindcast data. Because wave transformations across the continental shelf (particularly refraction) are dependent on wave direction, when this information was missing in the buoy records it was replaced with WIS data for the same date in the time series.

The final combined wave time series developed for the northern/central Washington Pacific coast consists of approximately 35 years of data, extending from 1 January 1980 to 31 December 2014, and is approximately 99.9% complete (measurements including at least wave height and periods; Figure 5.5). As can be seen from Figure 5.5, the wave climate offshore from the northern/central Washington Pacific coast is episodically characterized by large wave events (> 10 m (33 ft)), with some storms having generated extreme waves on the order of 12.9 m (42 ft). The average wave height offshore from

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[7] As waves propagate into shallow water from deep water they slow down and steepen. Buoy measurements at shallow depths therefore may be taller than measurements offshore. Reverse shoaling reverses this steepening process thereby providing a more accurate representation of a "deep water" wave height for onshore buoys.

northern/central Washington is 2.3 m (7.5 ft; Figure 5.6), while the average peak spectral wave period is 11.1 seconds, although wave periods of 20-25 seconds are not uncommon. The wave climate is characterized by a distinct seasonal cycle that can be seen in Figure 5.6 by the variability in the wave heights between summer and winter. Monthly mean significant wave heights are typically highest in December and January, although large wave events have occurred in all of the winter months except January and March. The highest significant wave height observed in the wave climate record is 12.9 m (42 ft). In general, the smallest waves occur during late spring and in the summer, with wave heights typically averaging ~1.4 m during the peak of the summer (July/August). These findings are consistent with other studies that have examined the wave climate in the US Pacific Northwest (e.g., Allan and Komar, 2006, Ruggiero et al., 2010). About 50% of the time waves are less than 2.0 m (6.5 ft), and they are less than 4.1 m (13.5 ft) 90% of the time. Wave heights exceed 6.3 m (20.6 ft) only 1% of the time. However, it is these rare but extreme events that typically produce the most significant erosion and flooding events along coastlines.

Standing waves. Photo courtesy Larry Workman, QIN.

Figure 5.5 *Synthesized wave climate developed for the northern/central Washington Pacific coast.*

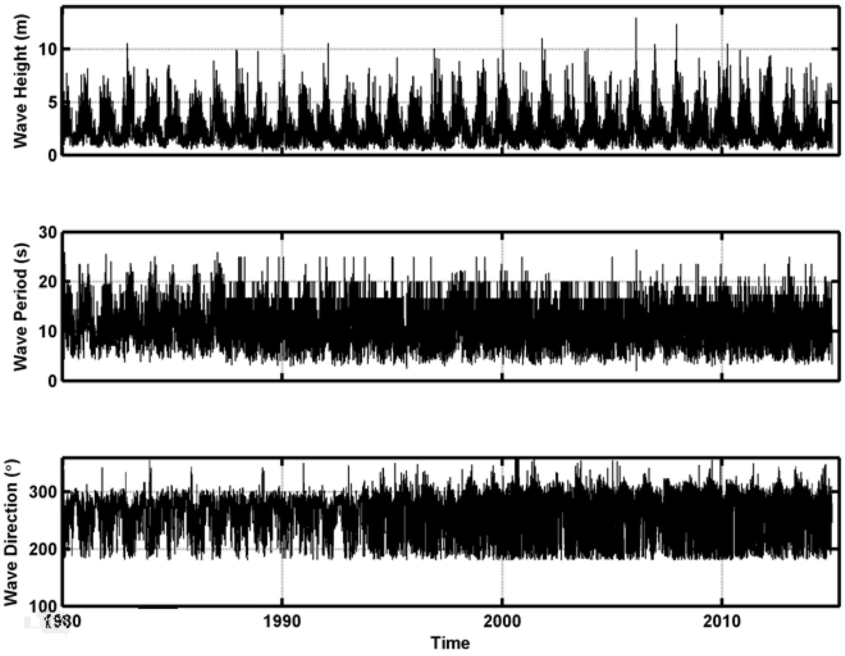


Figure 5.6 *Seasonal variability in the deep-water wave climate offshore from the northern/central Washington Pacific coast. (Top) The monthly average wave height (blue line) and standard deviation (dashed line); (Bottom) The maximum monthly significant wave height.*

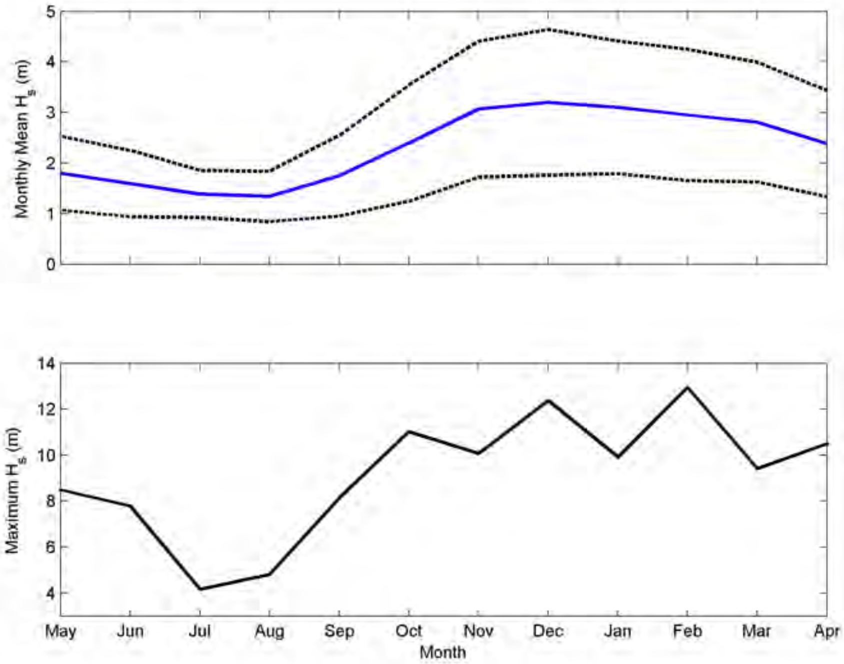
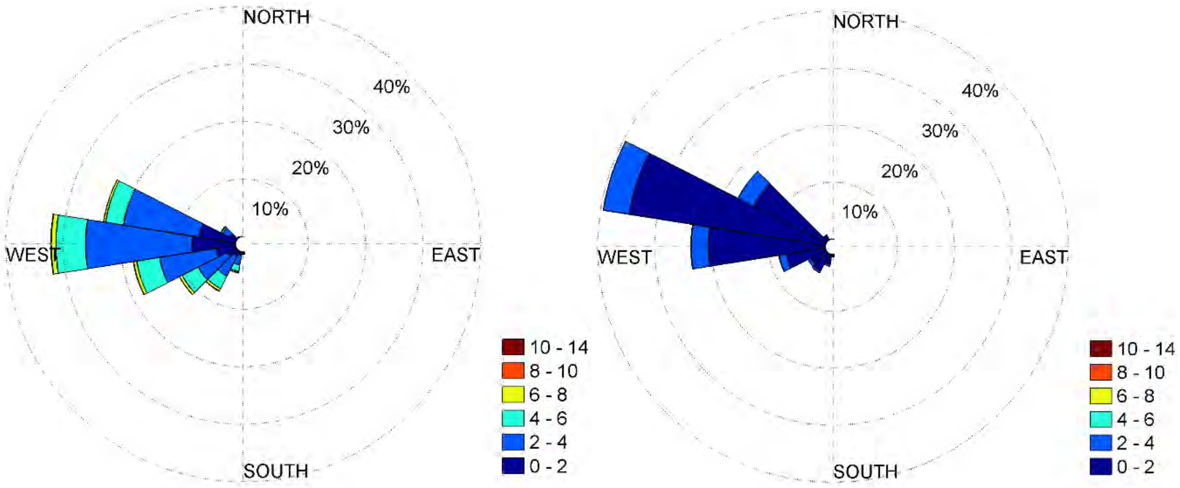


Figure 5.7 provides another way in which to characterize the Treaty of Olympia region's wave climate; a wave rose of the significant wave height versus direction. In general, the summer is characterized by

waves arriving from the northwest, while winter waves typically arrive from the west or southwest (Komar, 1997). This pattern is based on separate analyses of the summer and winter directional data developed from the combined time series. As can be seen in Figure 5.7, summer months are characterized by waves arriving from mainly the west-northwest to northwesterly quadrant (>50%) with few waves out of the southwest. The bulk of these reflect waves with amplitudes that are predominantly less than 3 m (9.8 ft). In contrast, the winter months are dominated by much larger wave heights out of the west (>30%), and to a lesser extent the northwest (~25%), while waves from the southwest account for ~25% of the waves.

Figure 5.7 *Predominant wave directions for the (left) winter months (Dec-Feb) and (right) summer months (Jun-Aug). Colored scale indicates the significant wave height in meters.*



In order to account for the alongshore variability of wave transformations from deep to shallow water, a numerical wave model (SWAN, Booij et al., 1999) is used. A nested grid approach was used with a coarse offshore grid (1 km x 1km) to propagate waves from the deep ocean to the shelf and a finer grid (200 m x 200 m) was used to resolve wave transformation over the shelf and into the nearshore. Using this approach, and again following methods developed for FEMA flood analyses (e.g., Allan et al., 2012), the alongshore variations in waves due to the bathymetry is adequately resolved for subsequently computing TWLs. Modeled wave information is extracted from the 30 m contour along the coastline of the study site to compute the wave-driven component of TWLs.

5.2.1.3 Wave Induced Water Levels

The Northwest Washington Pacific coastline has a variety of different backshore types (sandy beaches, mixed or cobble beaches, dunes, bluffs, cliffs, engineered, etc.) that are necessary for characterizing the appropriate runup (R) formulations for computing TWLs. For example, runup on a gravel beach or vertical bluff is often higher than on a shallower sloping sandy beach backed by a dune. If a model originally developed for a sandy beach is used on a cobble beach or vertical bluff, TWLs may be overpredicted. Therefore, for this analysis, we use two different approaches for calculating wave runup. For relatively shallow sloping beaches (slopes <=0.12 (1V:12H), assumed here to be sandy beaches), we use the Stockdon empirical runup parameterization (Stockdon et al., 2006). For TWLs on beaches with slopes >0.12, we use the approach developed by Allan et al. (2012) for flood studies along the Oregon coast. This approach provides a mechanism for calculating runup on steeper slopes, adjusting for various reduction factors (van der Meer 2002). Beaches with slopes >0.2 were not included in our analysis, as beaches this steep are beyond the limits of the two runup approaches we have chosen to implement. Since a site visit was beyond the scope of the present study, we have not been able to verify our interpretations of beach/backshore type.

Dunes. Photo courtesy Larry Workman, QIN.

5.2.2 Storm Impact Modeling

Estimates of extreme TWLs can be used to drive storm impact models, such as the Storm Impact Scaling Model of Sallenger (2000). The Storm Impact Scaling Model compares the elevation of the TWL to the elevation of the backshore beach for assessments of erosion and flooding hazards. Backshore features such as crests, (z_c), and toes, (z_t), of berms, dunes, or engineered structures and beach slopes (β), can be extracted from airborne Lidar[8] topographic surveys or land-based topographic surveys, allowing for estimates of wave runup and the corresponding storm-response regimes.

5.2.2.1 Geomorphology

Back beach morphometrics were extracted approximately every 5 m along the shore from a summer 2010-2011 U.S. Army Corps of Engineers (USACE) Joint Airborne Lidar Bathymetry Technical Center of Expertise (JALBTCX) lidar survey of the Washington coastline (NOAA, 2010) using methodologies described in Mull and Ruggiero (2014; Figure 5.8). Locations that lacked lidar coverage were filled in using topographic profile data from the Washington State Department of Ecology's Coastal Monitoring and Analysis Program (CMAP) collected in 2012-2013. While this dataset is more recent, it is relatively sparse compared to lidar data (profile spacing ranging from 200 m – 1 km, as opposed to every 5 m), and lacks quantitative information on bluffs or cliffs. Comparisons between the two data sets indicate that consistent morphological features can be extracted from both (not shown). While most coastal areas

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[8] Acronym for "LIght Detection And Ranging." Lidar is a remote sensing technology that measures distance by using a pulsed laser that sends light to the ground. The light signal reflects off the ground and then is analyzed to measure elevation.

in the Treaty of Olympia are sandy or gravel beaches backed by high bluffs and cliffs, we selected the crests of the most seaward morphological features with at least a 0.5 m drop between crest and heel (Figure 5.9). This objective criterion was chosen for automatically delineating the seaward most morphology, which would be impacted during a high water level event. These features may be embryonic foredunes or beach berms (gravel or sand), however, it is difficult to know for certain how permanent these features are without more ground surveys. If extreme water levels exceed the elevations of these features, the backing bluff/cliff may be impacted and subject to erosion. Therefore, while in some cases our estimates of feature overtopping, described below, may not indicate inland flooding, they do represent proxies for the potential of backshore erosion. Most of the coastal bluffs along this stretch of coastline are covered by conifer forests. As bluffs erode, the conifer trees are destabilized and the trunks may fall to the base of the cliff. These trunks provide a type of coastal stabilization and buffer to erosional events not found in locations that lack forested bluffs. While an important part of the ecosystem and coastal morphology, we lacked the ability to quantify and model these features along the coastlines.

Although lidar derived morphology measurements are available every 5 m in the alongshore, for computational efficiency we binned the beach morphometrics spatially every 200m in the Treaty of Olympia coastline. Estimates of the average z_c, z_t, and β (along with maximum, minimum and standard deviation statistics) were derived from each bin, in order to determine a representative morphological variability for each bin along the coast.

Figure 5.8 *An example schematic of a lidar-derived cross-shore profile and the beach and geomorphic parameters extracted from the profile. The back beach crest (z_c) elevation indicates the backshore morphology crest and is the most shoreward crest. The dune heel (dheel) is the lowest swale between z_c and a subsequent backing crest. The back beach toe (z_t) is picked at the slope change from z_c to shoreface. The shoreline is represented by the mean high water (MHW) line, generally 2.1m. Backshore slopes (β) for runup analysis are computed as the slope between the MHW and z_t (modified from Mull and Ruggiero, 2014).*

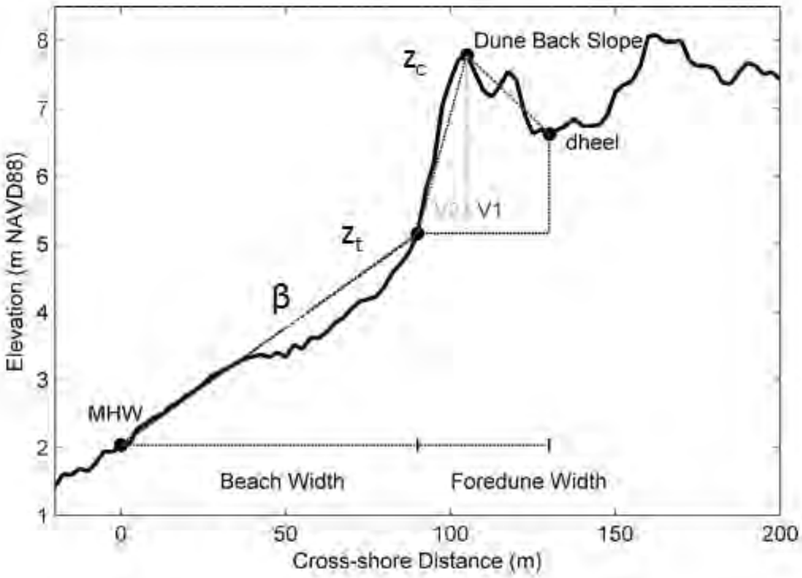
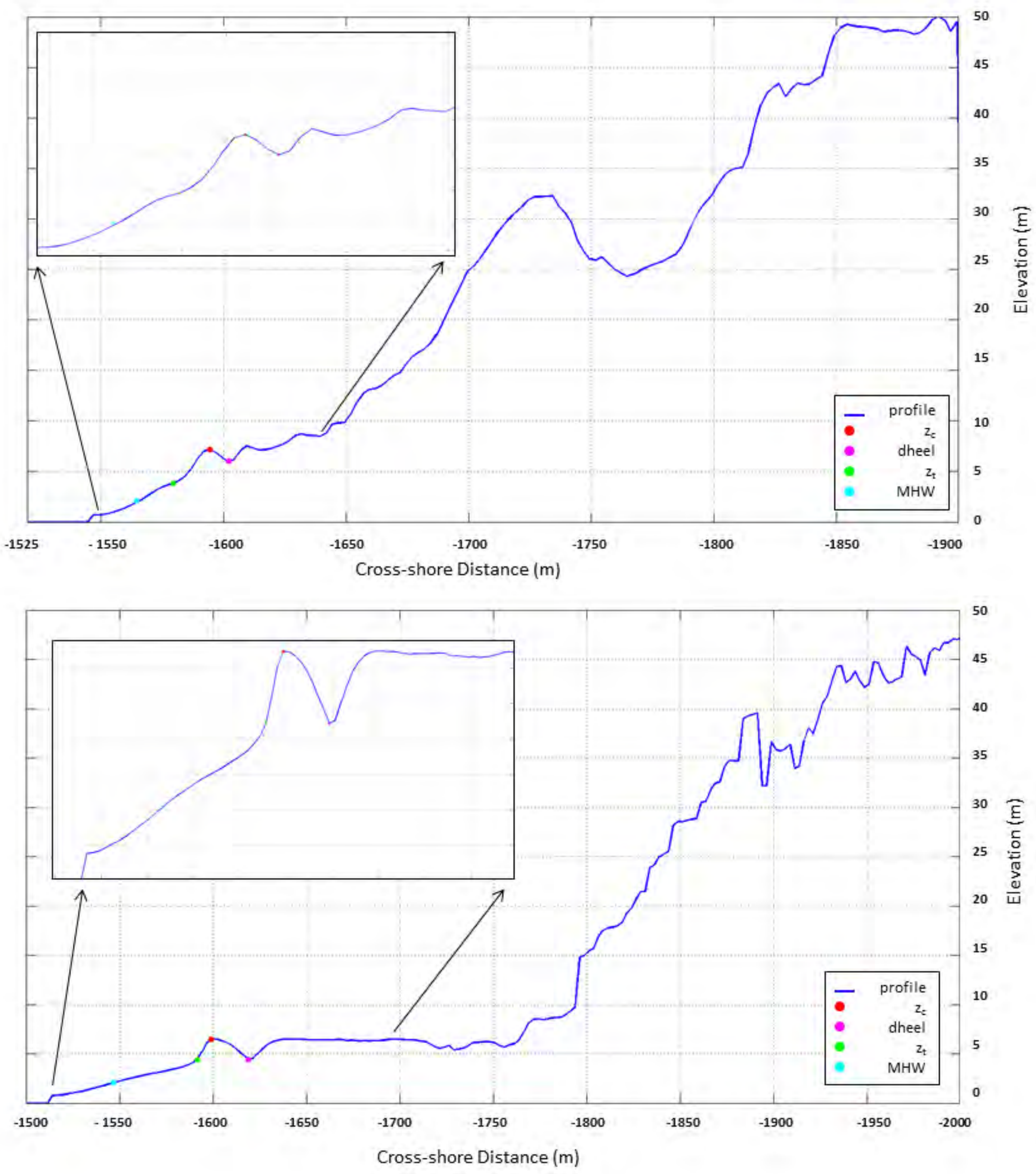


Figure 5.9 *Example profiles from the Hoh (top) and the Quileute (bottom) Reservations. While most locations have low elevation fronting toes and crests, these features are often backed by extensive bluffs.*



The Ozette area (Cape Alava to Rialto Beach) is largely characterized by tall, forested bluffs (>25 m) backing steep (on average, $0.1<\beta<0.2$), gravel beaches. Other systems have lower slopes (<0.1) and are mixed gravel and sand (Figure 5.10). Locations dominated by exposed, bedrock, wave-cut platforms were not analyzed. The Quileute reservation coastline is fronted by morphological features evident in the lidar data (possibly beach berms, Figure 5.9 bottom panel) approximately 6 m high (relative to NAVD88 – which is 6.25 m relative to MLLW) and z_t between 3 and 5 m (Figure 5.11). This morphology is at times backed by relatively high bluffs and cliffs. Beach slopes are relatively steeper on the coarse grained Rialto Beach (~0.1) than on First Beach (between 0.04 and 0.06; Figure 5.11). Second Beach and Third Beach, not on the reservation but immediately adjacent to it, are mixed gravel and sand beaches that have similar beach slopes (<0.1) to First Beach, but lack any morphological features fronting the high cliffs and bluffs (Figure 5.12). The Hoh reservation coastline, which has similar morphology to the Quileute, is largely characterized by gravel beaches with steep beach slopes, averaging ~0.15. High bluffs and cliffs in excess of 20 m (64 ft) elevation back these beaches. However, the crests of and toe elevations range between 4 and 5m (Figure 5.13). The Kalaloch to Ruby Beach area is comprised of both mixed sand and gravel beaches as well as coarse-grained gravel beaches. It is characterized by flat to steep beach slopes (between 0.05 and 0.2), tall cliffs and bluffs (>20 m), and a z_t between 5-7 m (Figure 5.14).

Outgoing storm tide. Photo courtesy Larry Workman, QIN.

Due to the size of the Quinault Indian Reservation, we have split the coast into three analysis regions; north (everything North of Taholah to the Queets River), middle (centered around Taholah), and south (Moclips to Point Grenville). North of Taholah, beach slopes range from <0.2 to 0.1. Z_c coverage is sparse in this region, due to limitations in the lidar data extraction process on steep morphology coasts, but the average z_t is around 5 m (Figure 5.15). The middle section of the Quinault reservation increases in beach steepness, and the Taholah area has beach slopes around 0.1. Backing morphology ranges from cliffs/bluffs to lower features in Taholah (Figure 5.16). The southern analysis region is relatively flat and sandy, with beach slopes <0.05. In this location, z_c and z_t are rarely over 8 m (Figure 5.17), although the northern and southern sections of the southern Quinault reservation are comprised of higher z_c, in excess of 10 m.

***Figure 5.10** Morphology estimates derived from lidar data for Cape Alava to Rialto Beach. The panels below display: the location of the extracted toes (blue) and crests (orange; left), the raw (grey circles) and average beach slope (red; middle), and the raw (grey circles) and average toe and crest (blue and orange, respectively; right).*

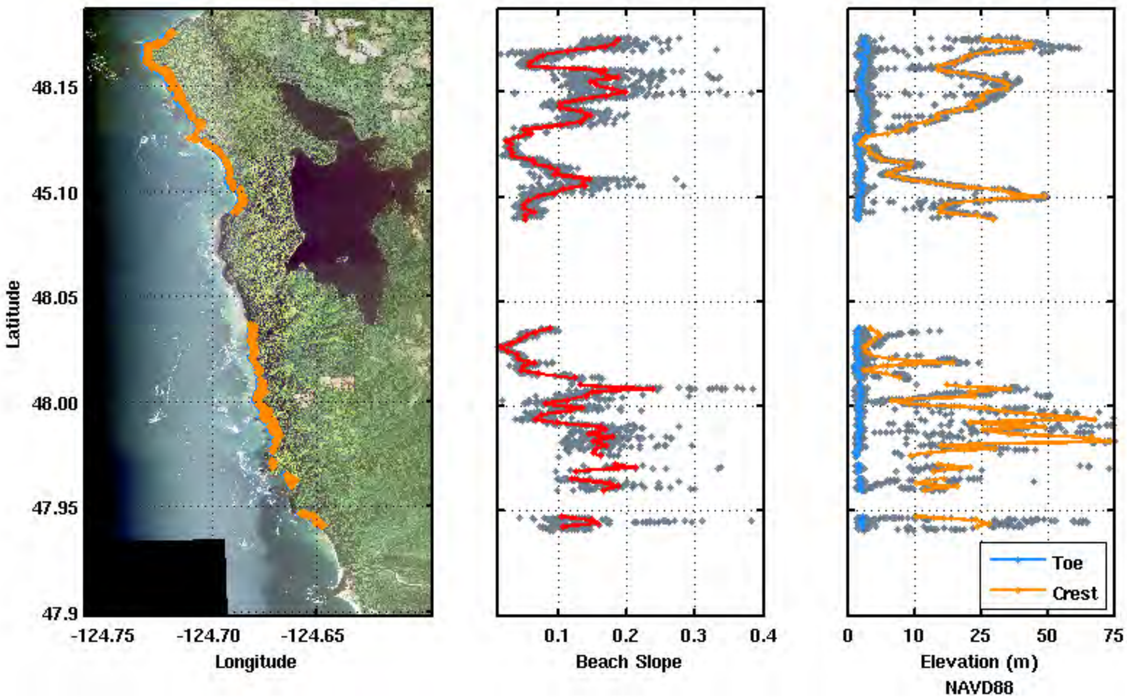


Figure 5.11 *Morphology estimates derived from lidar data for the Quileute Reservation. The panels below display: the location of the extracted toes (blue) and crests (orange; left), the raw (grey circles) and average beach slope (red; middle), and the raw (grey circles) and average toe and crest (blue and orange, respectively; right).*

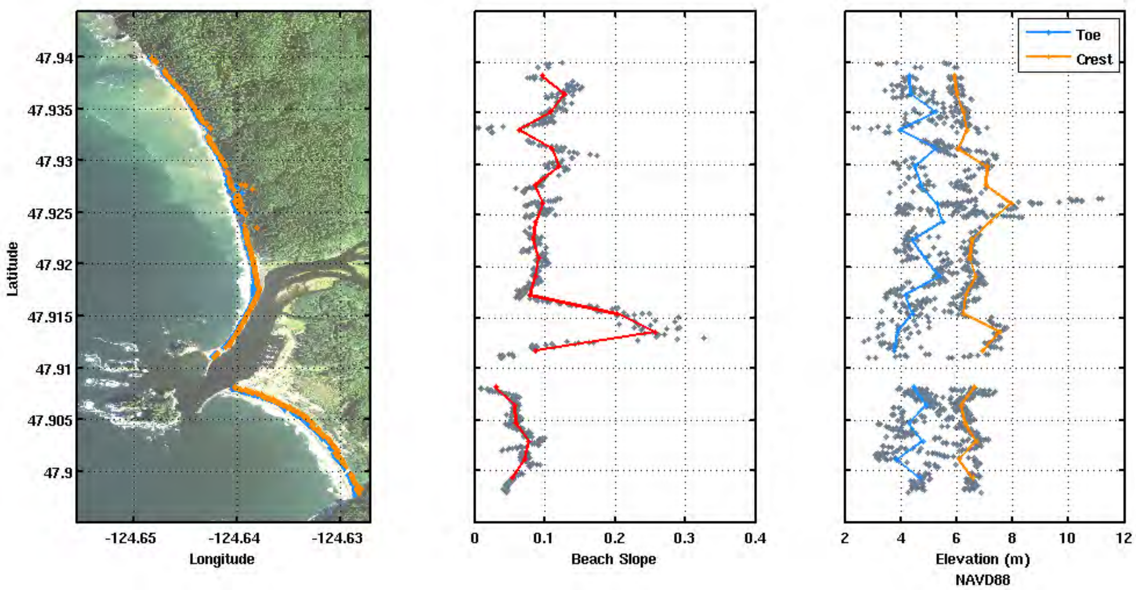


Figure 5.12 *Morphology estimates derived from lidar data for Second and Third Beach. The panels below display: the location of the extracted toes (blue) and crests (orange; left), the raw (grey circles) and average beach slope (red; middle), and the raw (grey circles) and average toe and crest (blue and orange, respectively; right).*

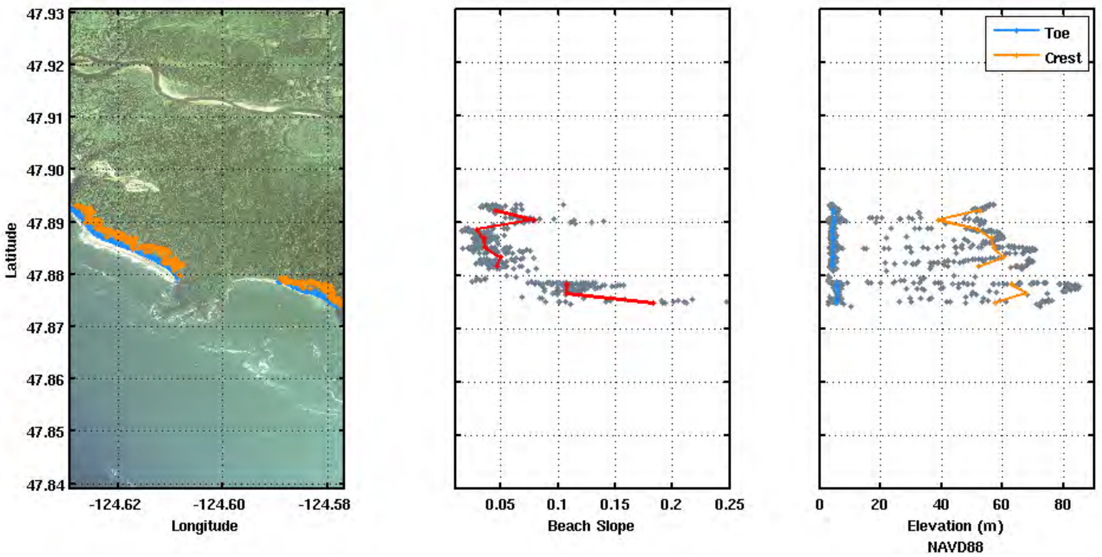


Figure 5.13 *Morphology estimates derived from lidar data for the Hoh Reservation. The panels below display: the location of the extracted toes (blue) and crests (orange; left), the raw (grey circles) and average beach slope (red; middle), and the raw (grey circles) and average toe and crest (blue and orange, respectively; right).*

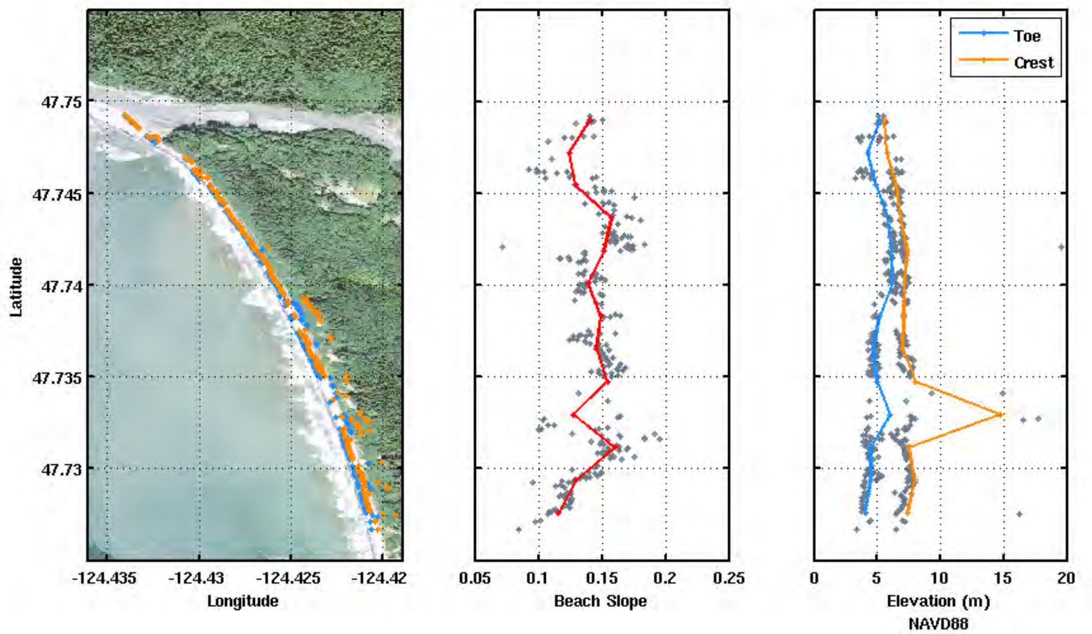


Figure 5.14 *Morphology estimates derived from lidar and topographic data for Ruby Beach to the Queets River. The panels below display: the location of the extracted toes (blue) and crests (orange; left), the raw (grey circles) and average beach slope (red; middle), and the raw (grey circles) and average toe and crest (blue and orange, respectively; right).*

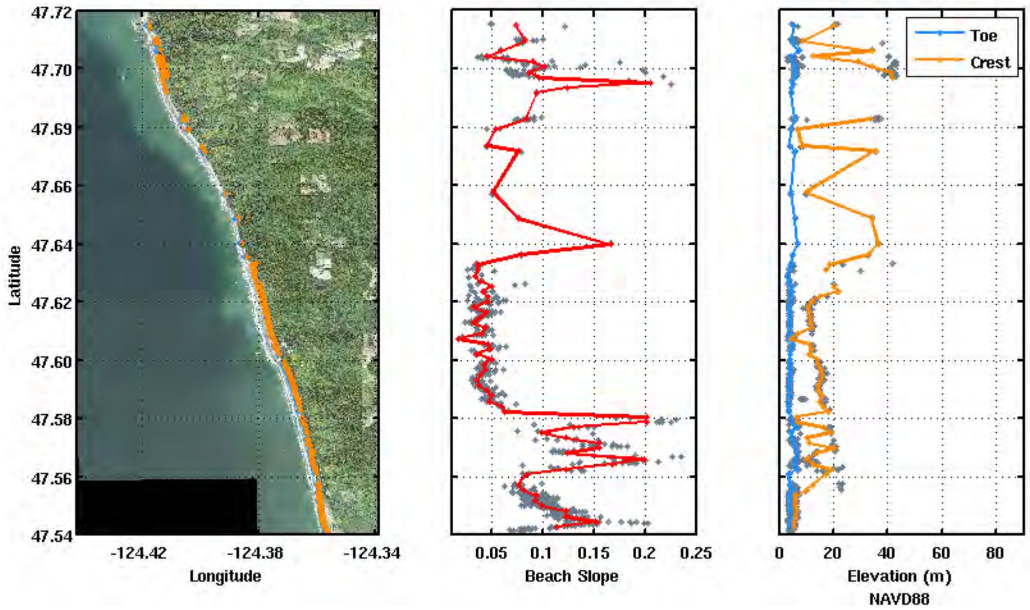


Figure 5.15 *Morphology estimates derived from lidar and topographic data for northern (Taholah to Queets River) section of the Quinault Indian Reservation. The panels below display: the location of the extracted toes (blue) and crests (orange; left), the raw (grey circles) and average beach slope (red; middle), and the raw (grey circles) and average toe and crest (blue and orange, respectively; right).*

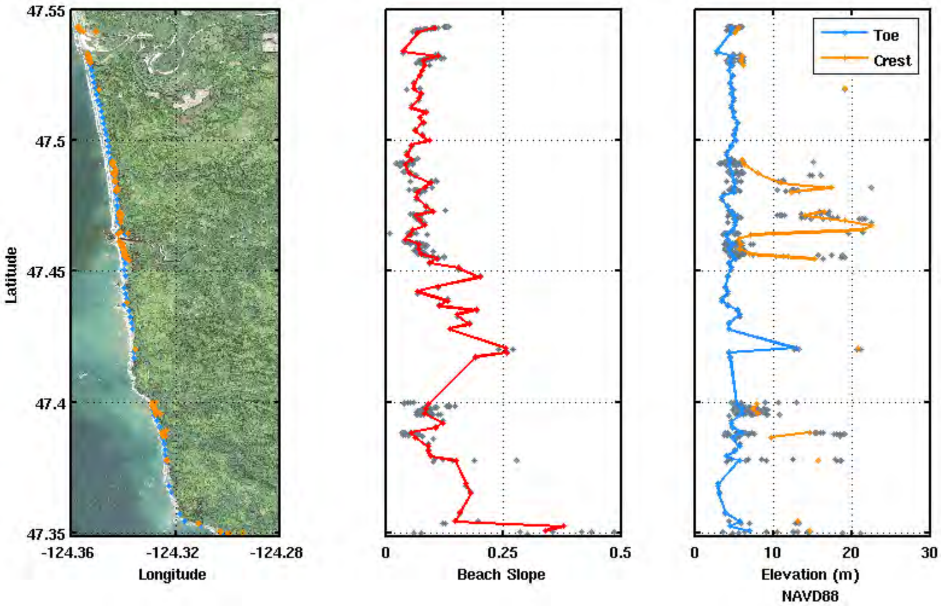


Figure 5.16 *Morphology estimates derived from lidar and topographic data for the middle (Point Grenville to Taholah) section of the Quinault Indian Reservation. The panels below display: the location of the extracted toes (blue) and crests (orange; left), the raw (grey circles) and average beach slope (red; middle), and the raw (grey circles) and average toe and crest (blue and orange, respectively; right).*

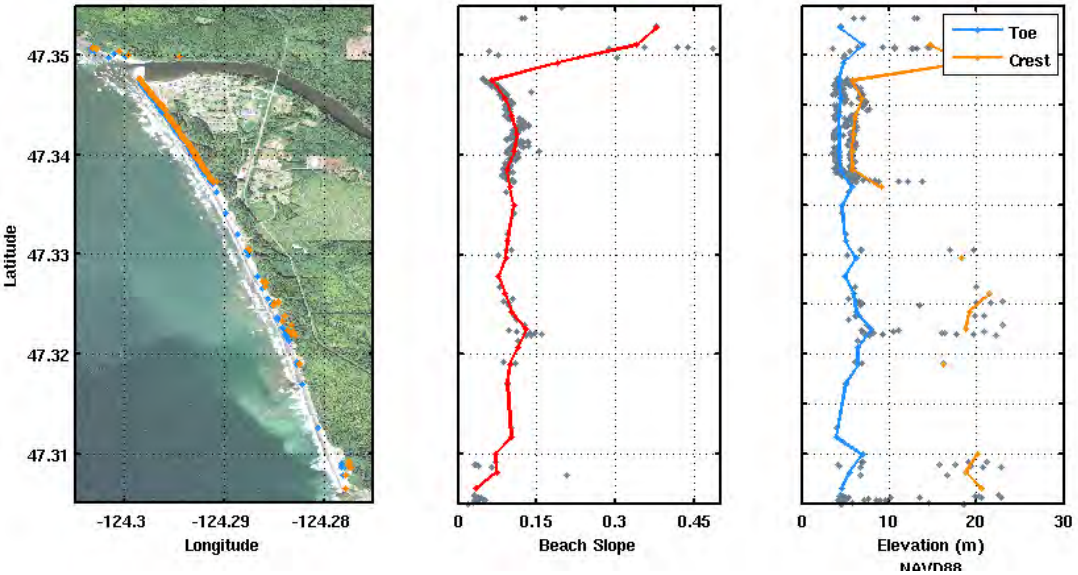
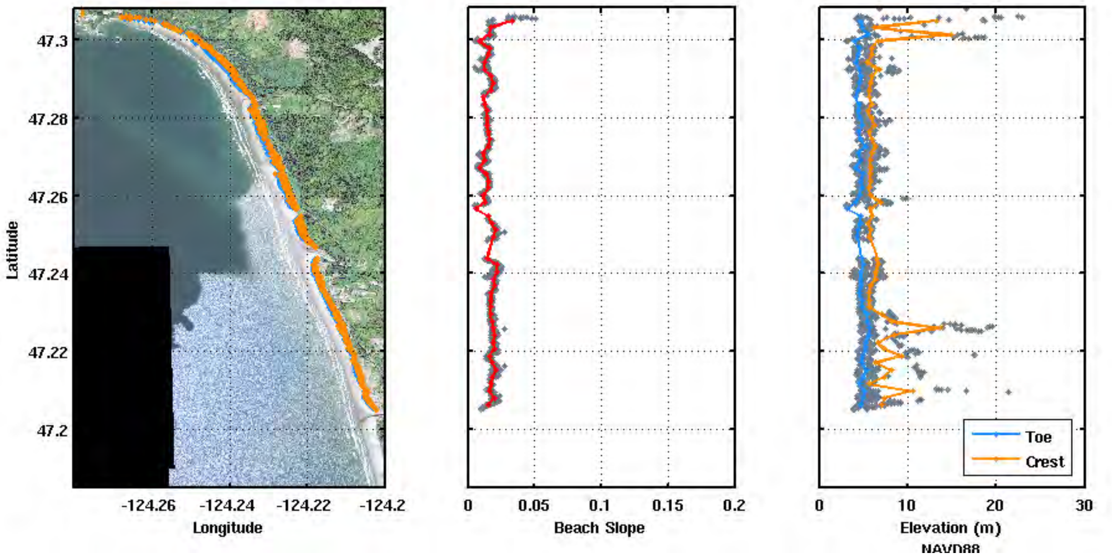


Figure 5.17 Morphology estimates derived from lidar and topographic data for the southern (Moclips to Point Grenville) section of the Quinault Indian Reservation. The panels below display: the location of the extracted toes (blue) and crests (orange; left), the raw (grey circles) and average beach slope (red; middle), and the raw (grey circles) and average toe and crest (blue and orange, respectively; right).



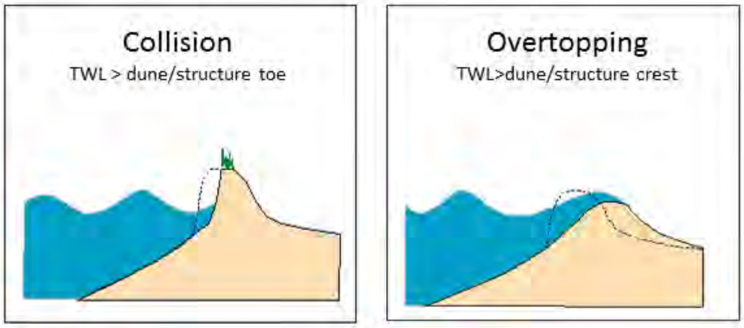
5.2.2.2 Storm Impact Scale

By comparing the elevations achieved by TWLs to the extracted coastal morphology metrics (Figures 5.10-5.17), we can effectively determine the risk to overtopping and erosion for a section of coastline (Sallenger, 2000; Ruggiero et al., 2001; Stockdon et al., 2007, Ruggiero, 2013). In the Storm Impact Scaling model, four storm-impact regimes, or thresholds for coastal change, are defined to provide a framework for examining the relative magnitudes of coastal change likely to occur (Sallenger, 2000). Here we only apply two of the regimes, collision ($z_t \leq$ TWL $< z_c$) and overtopping (TWL $\geq z_c$; Figure 5.18). Each of these regimes has implications for varying levels of morphologic change. In the collision regime, the water level is impacting the backshore feature, resulting in its erosion or possible damage to engineered structures. In the overtopping regime, the water level is over the z_c and the possibility exists for inundation of the backshore (Sallenger, 2000; Figure 5.18).

In this application, the Storm Impact Scale is used to estimate how exposed a coastline is to nuisance hazards, and collision and overtopping "days per year" are calculated (IDPY; ODPY). This provides an average amount of time the coastline experiences one of the two regimes (during the highest water level of the day), thus an estimate of a particular stretch of coastline's exposure to everyday hazards. Extreme events, such as the annual maximum event or the 100-year return level (i.e., a 1% chance of occurrence annually) can also be compared to the extracted morphology to assess the exposure of a particular study area to a specified extreme event scenario.

Here we compute TWLs every 200 m alongshore using the average beach slope for the wave induced water levels. We also compute TWLs using the average beach slope +/- one standard deviation of the bin average to represent the morphological variability present every 200 m. To identify areas impacted by water levels, we compare the TWL to the average z_t each 200 m. To conservatively identify areas that are overtopped, we compare the TWL to the minimum z_c in each bin.

Figure 5.18 *Schematics representing the two Storm Impact regimes of interest in this study (modified from Sallenger 2000), collision or overtopping. Collision is when the TWL > z_t and overtopping occurs when the TWL > z_c.*



5.3 TWL Full Simulation Model

Total Water Levels (TWL) can be determined using a structural function approach, where time series of TWLs are constructed based on observational records of waves and water levels (e.g., Ruggiero et al., 2001). Extreme TWL return levels can then be determined by extrapolation from a best fit extreme value distribution, dependent on record length. However, since the TWL is a combination of several individual physical processes that have happened to occur together in our measured records, how do we know our biggest wave heights have co-occurred with our largest storm surges during our highest tides? This simple approach of adding together wave and water level records may therefore under predict the most extreme TWL events that are physically capable of occurring.

To avoid this problem, full simulation models (e.g., Serafin and Ruggiero, 2014) can be applied to produce multiple, synthetic time series of TWLs, where each individual component (waves, non-tidal residuals, and tides) of the TWLs is statistically simulated while appropriately taking into account any dependencies that exist between the components (e.g., storm surge and large significant wave heights are often driven by the same storm event). This modeling technique is able to include non-stationary processes influencing extreme and non-extreme events, such as seasonality, climate variability (e.g., ENSO), and trends in wave heights and water levels (e.g., sea level rise). The resulting synthetic TWL records allow for the direct extraction of extreme return level events, rather than an extrapolation to a best-fit model. This methodology therefore provides a number of synthetic TWL records at different length scales (i.e., 500 years of simulation representing todays wave and water level climate instead of only 35) that produce alternate (but physically plausible) combinations of runup and water levels along the coast.

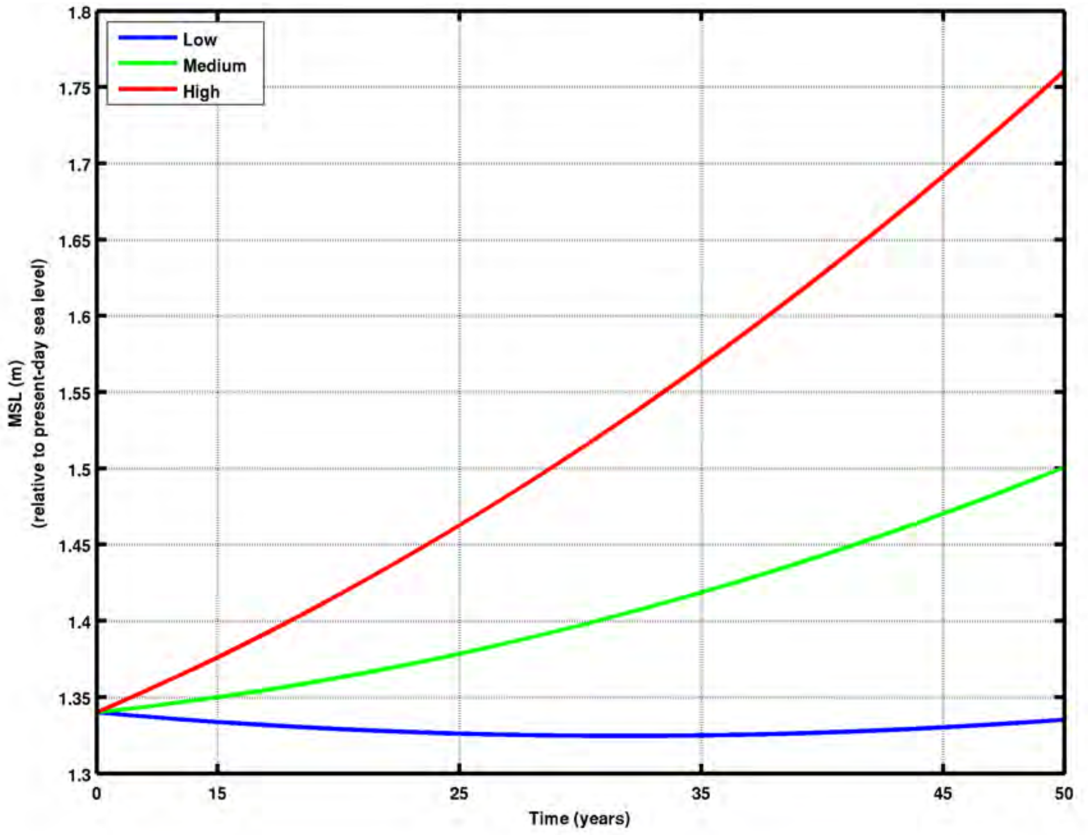
5.3.1 Future Scenarios

Here we model TWLs, and associated coastal hazards, out to the mid-century (~2050). In our initial assessments, we allow sea level to rise but assume that the frequency of major El Niño events stay similar to present day. We keep the frequency of major El Niño events constant because our ongoing work has demonstrated that SLR provides the largest relative changes to future water levels (e.g., Baron et al. 2015). The historical extreme wave climate has a linear trend of increasing wave heights (e.g., Ruggiero et al., 2010). This trend is included in the simulation model, and therefore our future scenarios include allowing this trend to continue from the present to 2050.

In this analysis we do not attempt to make specific estimates of local relative sea level rise rates in the study area, since a range of complexities involved in estimating local vertical land motions (tectonics, glacial isotactic adjustment, and subsidence) make this beyond the scope of this project. Our sea level rise projections are instead derived from the National Research Council's (2012) 'Sea-Level Rise for the Coasts of California, Oregon and Washington'. These projections take into account regional factors affecting sea level through a combination of steric and ocean dynamics, cryosphere and fingerprinting effects, and very general estimates of vertical land motion. Projections range from -0.10 to 0.5 m (-0.32 – 1.6 ft) by 2050 (Figure 5.19). In this projection, the low SLR projection dips below present-day mean sea level due to vertical land motions.

Quinalt Formation capped by outwash gravels. Photo courtesy Larry Workman, QIN.

Figure 5.19 *Sea level rise estimates for the Washington/Oregon coastlines derived from NRC, 2012.*

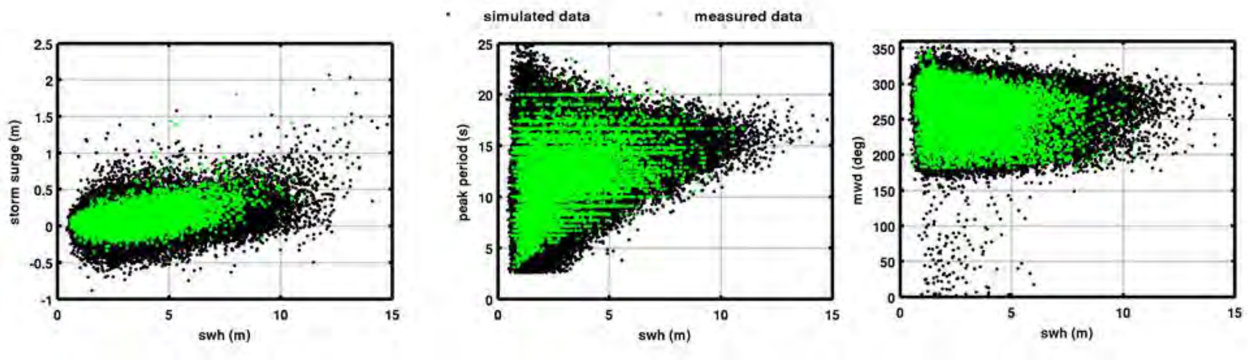


5.3.2 TWL Simulation Results

Using Serafin and Ruggiero's (2014) full simulation model, we simulate 35, 500-year time series as representations of present-day wave climate and water levels. Multiple time series are simulated in order to allow for enough variability in order to represent all possible wave and water level joint occurrences. Every parameter (wave height, period, direction; tide, storm surge, etc.) in each simulated time series is then analyzed to confirm it represents present-day distributions. The joint probabilities of all parameters are also analyzed to establish that the simulations represent all parameter dependencies adequately (e.g., strong storms drive both increased wave heights and storm surge; Figure 5.20).

We also simulate 36, 500-year time series representing the mid-century (~2050) future climate. The future climate time series are then split up into groups of 12 relating to the three different sea level rise scenarios (low, medium, and high, Figure 5.19). Combined, our simulations represent both present-day and future TWLs from which to investigate the relative impact they have on the coast. For all coastal vulnerability products below, average values across these simulations (i.e., the average of the 35 simulations for present day and the average of the 12 SLR simulations for each future climate change scenario) of parameters of interest are displayed.

Figure 5.20 *Joint probabilities of one example simulation (black) compared to the measured data (green).*



5.4 Coastal Vulnerability Products

This section describes a variety of products that assess the relative exposure of the Hoh, Quileute and Quinault reservation coastlines, as well as coastlines adjacent to the reservations, to present day and future coastal hazards. These products help illustrate both the current and future risk to coastal erosion and flooding each area faces using estimates of impact and overtopping days per year and estimates of extreme events like the annual maximum event and the 10, 25, 50, and 100 year return level events for each stretch of the coast.

5.4.1 Present Day Conditions

5.4.1.1 Nuisance Events

Near Cape Alava, beaches are impacted by water levels 1/3 of the year (approx. 117 days), while south of Ozette Lake to Rialto Beach, the combination of steep beaches and low z_t causes the z_t to be impacted on average 60% of the year (approx. 226 days; Figure 5.21). Beaches in or adjacent to the Quileute reservation are impacted, on average, 50% of the year (approx. 185 days; Figure 5.21). Because Rialto Beach is slightly steeper than First Beach, it receives, slightly more impact days per year than First Beach (Figure 5.22). Second Beach, which has lower dune toes (on average, 4 m) than Third Beach, receives 136 days (approx. 36% of the year) of impact per year. Although Third Beach has overall steeper beach slopes the z_t are at a higher elevation and it receives only 85 days per year of impact (approx. 20% of the year; Figure 5.23).

The extracted backshore morphological features in the Hoh reservation are at a low enough elevation that they are impacted by TWLs for 1/3 of the year (approx. 125 days; Figure 5.24). The stretch of coastline between Ruby Beach and Kalaloch on average is impacted approximately 50% of the year (Figure 5.25). The Quinault region as a whole is in the collision regime for approximately 40% of the year (Figures 5.26-5.28). The northern and middle sections receive a larger amount of impact days per year (140 and 165 IDPY, respectively; Figures 5.26 and 5.27), while the southern section of the Quinault reservation is impacted by water levels the least (115 IDPY; Figure 5.26). Areas impacted less frequently (e.g., less than 20 IDPY) are oftentimes locations where no morphology fronting the bluffs and cliffs exist, although impact to these areas could lead to bluff erosion.

Overtopping of the backshore morphology occurs on average, very infrequently (if at all) from Cape Alava to Rialto Beach due to the presence of large bluffs and cliffs backing the coarse-grained beaches. The areas that do overtop more frequently (16% of the year; 60 ODPY) are around inlets or on sandy pocket beaches (Figure 5.21). Along the Quileute coastline, overtopping occurs more frequently on Rialto Beach than on First Beach, due to higher water levels and steeper beach slopes (Figure 5.22), but on average the whole cell receives approximately 60 days a year (15%) of overtopping. Second and Third Beach overtop in only 2 of the 200 m spaced bins due to the lack of morphology fronting steep cliffs (Figure 5.23). The average overtopping along the Hoh reservation is similar to that of the Quileute reservation, approximately 15% of the year (Figure 5.24).

Due to low dune crests (<5 m) from the Queets River to Kalaloch, overtopping occurs approximately 1/3 of the year (106 ODPY; Figure 5.25). Overtopping can only be calculated in some locations along the Quinault coastline, due to a lack of an extracted z_c from the lidar data (high bluffs). However, the southern section of the Quinault coastline experiences overtopping infrequently (approx. 9 days a year; Figure 5.28), while the Taholah area may experience overtopping 50 – 100 days a year (Figure 5.27). Over the majority of these coastlines, overtopping occurs much less often than collision. While the morphology fronting any bluff/cliffs likely receives the majority of the impact from storm events, cliffs and bluffs could receive more energy during larger events during the few times the fronting morphology is overtopped.

Figure 5.21 *Impact days per year (IDPY; middle) and overtopping days per year (ODPY; right) for Cape Alava to Rialto Beach. Bolded lines indicate the average (across 35 simulations) IDPY/ODPY computed using the average beach slope in each bin, and the dashed lines are +/- 1 standard deviation of the beach slope. Gaps in this figure are due to a lack of data (inlet mouth; wave-cut bedrock platform) or a beach slope >0.2.*

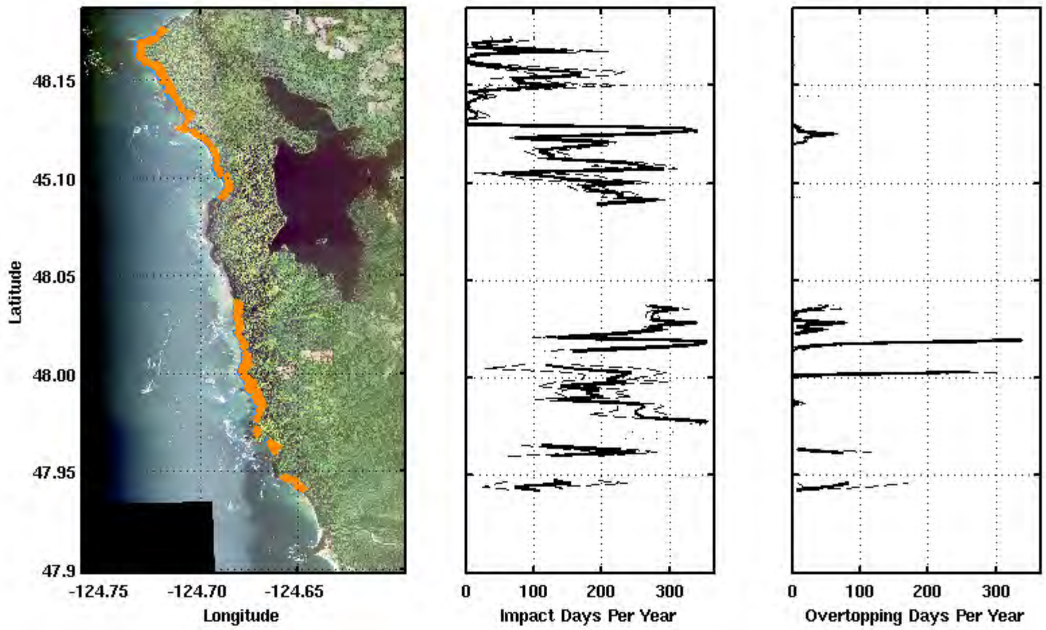


Figure 5.22 *Impact days per year (IDPY; middle) and overtopping days per year (ODPY; right) for Quileute Reservation. Bolded lines indicate the average (across 35 simulations) IDPY/ODPY computed using the average beach slope in each bin, and the dashed lines are +/- 1 standard deviation of the beach slope. Gaps in this figure are due to a lack of data (inlet mouth; wave-cut bedrock platform) or a beach slope >0.2.*

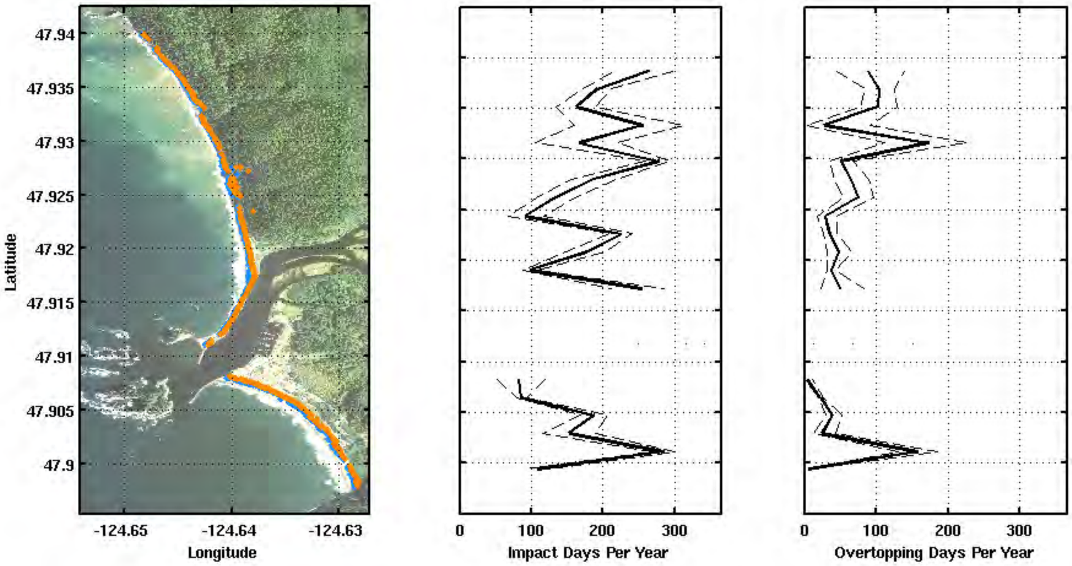


Figure 5.23 *Impact days per year (IDPY; middle) and overtopping days per year (ODPY; right) for Second Beach and Third Beach. Bolded lines indicate the average (across 35 simulations) IDPY/ODPY computed using the average beach slope in each bin, and the dashed lines are +/- 1 standard deviation of the beach slope. Gaps in this figure are due to a lack of data (inlet mouth; wave-cut bedrock platform) or a beach slope >0.2.*

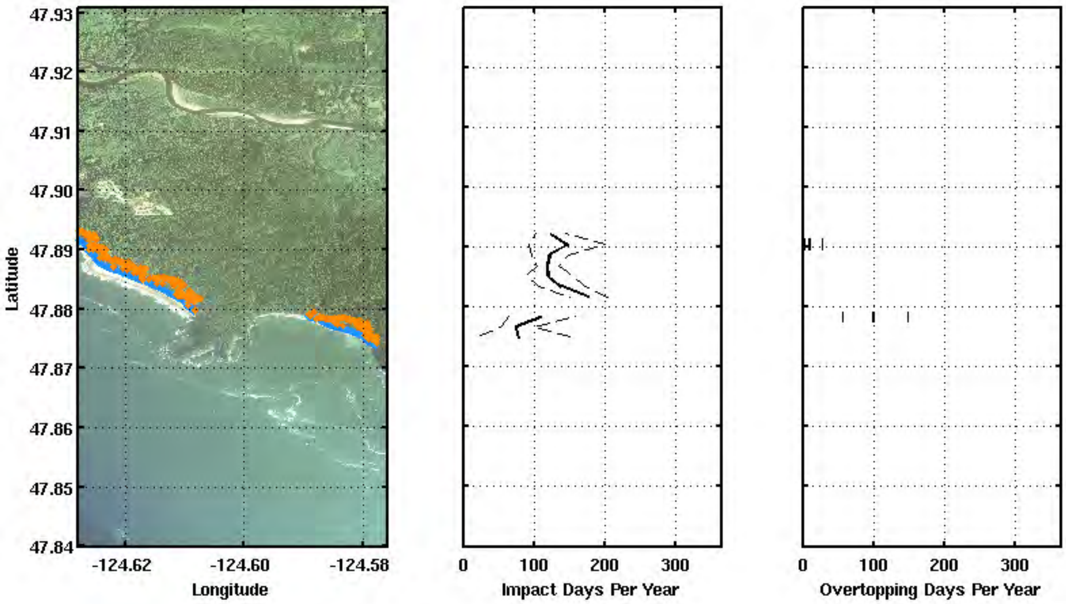


Figure 5.24 *Impact days per year (IDPY; middle) and overtopping days per year (ODPY; right) for Hoh reservation. Bolded lines indicate the average (across 35 simulations) IDPY/ODPY computed using the average beach slope in each bin, and the dashed lines are +/- 1 standard deviation of the beach slope. Gaps in this figure are due to a lack of data (inlet mouth; wave-cut bedrock platform) or a beach slope >0.2.*

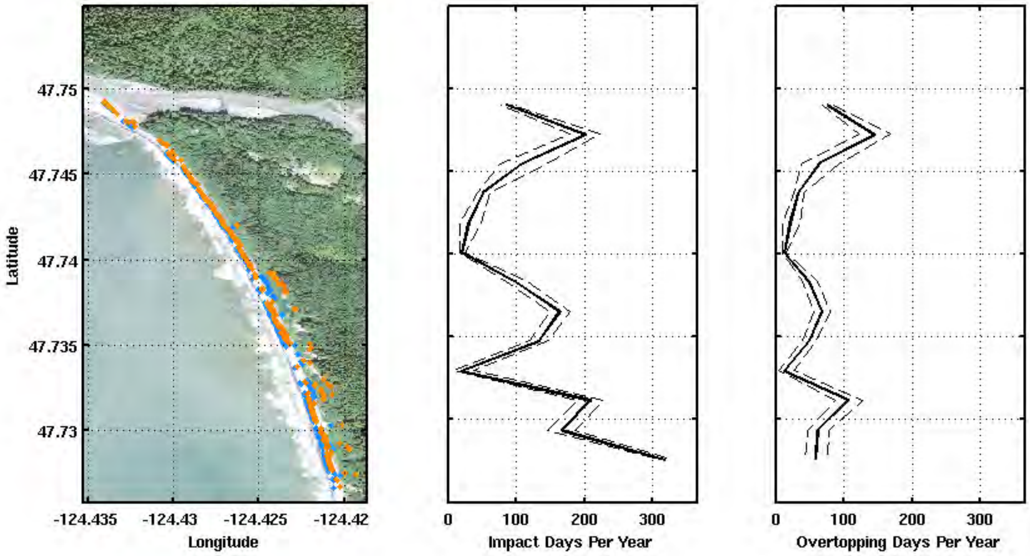


Figure 5.25 *Impact days per year (IDPY; middle) and overtopping days per year (ODPY; right) for Ruby Beach to the Queets River. Bolded lines indicate the average (across 35 simulations) IDPY/ODPY computed using the average beach slope in each bin, and the dashed lines are +/- 1 standard deviation of the beach slope. Gaps in this figure are due to a lack of data (inlet mouth; wave-cut bedrock platform) or a beach slope >0.2.*

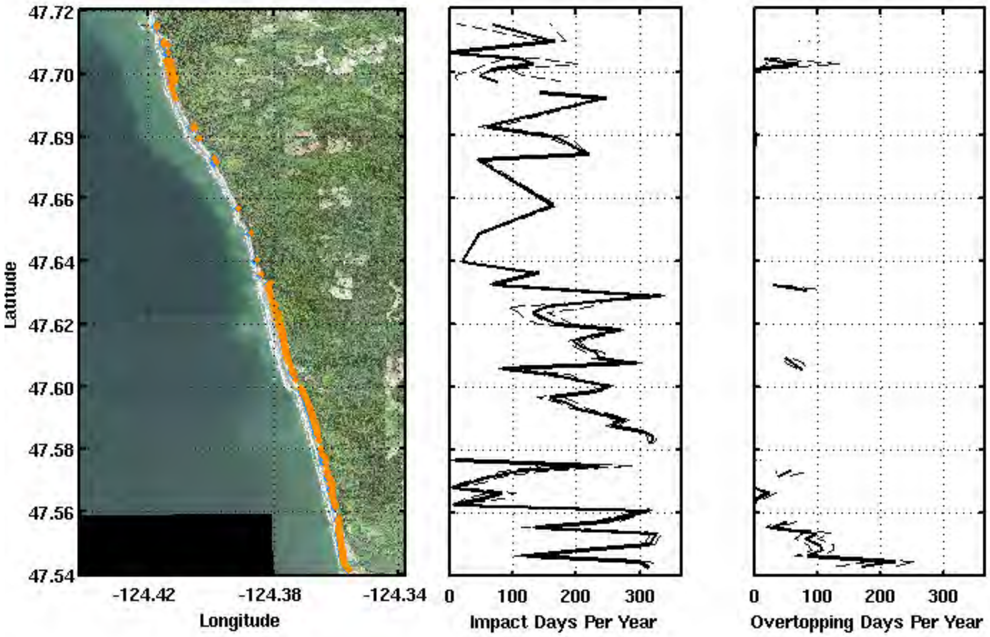


Figure 5.26 *Impact days per year (IDPY; middle) and overtopping days per year (ODPY; right) for the northern section of the Quinault reservation. Bolded lines indicate the average (across 35 simulations) IDPY/ODPY computed using the average beach slope in each bin, and the dashed lines are +/- 1 standard deviation of the beach slope. Gaps in this figure are due to a lack of data (inlet mouth; wave-cut bedrock platform) or a beach slope >0.2.*

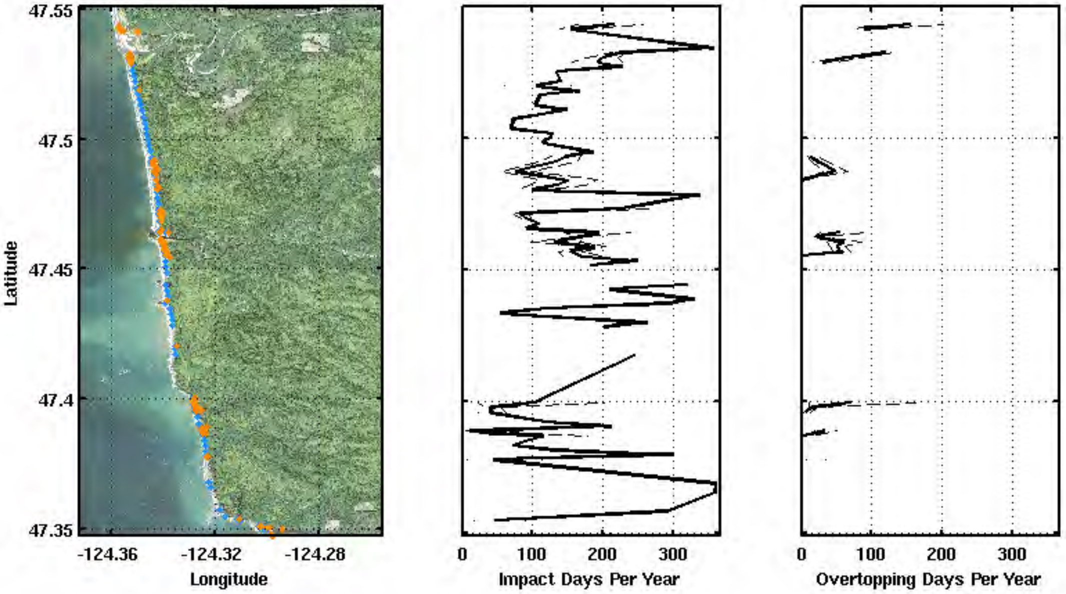


Figure 5.27 *Impact days per year (IDPY; middle) and overtopping days per year (ODPY; right) for the middle section of the Quinault Reservation. Bolded lines indicate the average (across 35 simulations) IDPY/ODPY computed using the average beach slope in each bin, and the dashed lines are +/- 1 standard deviation of the beach slope. Gaps in this figure are due to a lack of data (inlet mouth; wave-cut bedrock platform) or a beach slope >0.2.*

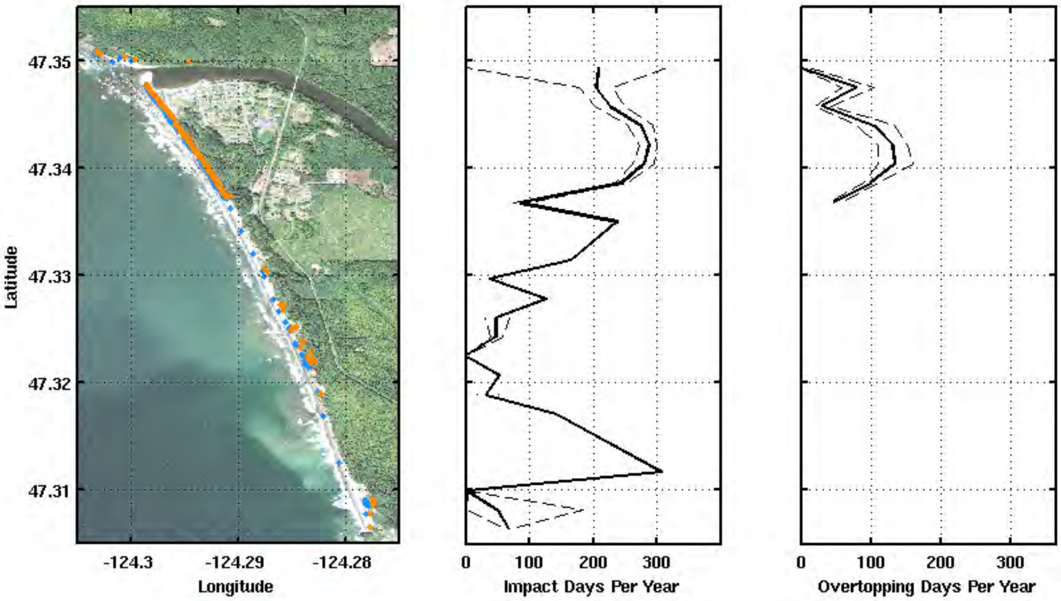
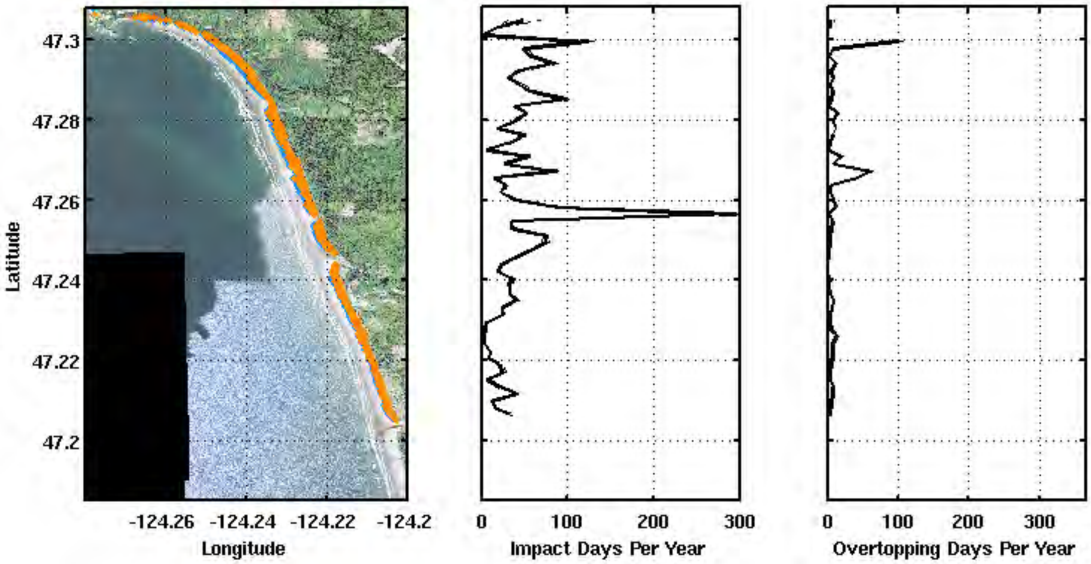


Figure 5.28 *Impact days per year (IDPY; middle) and overtopping days per year (ODPY; right) for southern section of the Quinault reservation. Bolded lines indicate the average (across 35 simulations) IDPY/ODPY computed using the average beach slope in each bin, and the dashed lines are +/- 1 standard deviation of the beach slope. Gaps in this figure are due to a lack of data (inlet mouth; wave-cut bedrock platform) or a beach slope >0.2.*



5.4.1.2 Extreme Events

Figures 5.29-5.32 display the alongshore variability, due to both wave and geomorphic variability, of the 10, 25, 50, and 100 year TWL return level events (events that have a 10%, 4%, 2%, and 1% chance, respectively, of occurring during each year). The average 10-year return level event is greater than 4 m (and in most places, > 6 m) along the entire Cape Alava to Rialto Beach coastline (Figure 5.29). In this region, the average z_t is approximately 5 m, indicating large expanses of this coastline would experience the impact regime for the prescribed extreme TWL return level events. The Quileute reservation coastline, on the other hand, experiences slightly lower return levels between 6-10 m (Figure 5.30, left). First Beach has much lower extreme TWLs than Rialto Beach, primarily due to differences in local beach morphology (Figure 5.30, left). On First Beach, the elevation is similar for the 10-100 yr event (6-8 m). TWL return level events along Rialto Beach increase by >1 m with increasing return levels. Second Beach is similar to First Beach, and extreme return levels are generally less than 6 m and increase as the return level increases (Figure 5.30, right). On the other hand, Third Beach's return level events stay consistent across all scenarios, between 8 – 12 m (Figure 5.30, right).

The Hoh reservation coastline has some of the highest water levels in the region, due to its steep beach slopes, with extreme TWL events ranging from 6-12 m in elevation (Figure 5.31, left). The stretch of coastline from the Queets River to Ruby Beach experiences similar extreme TWLs, except for Kalaloch, which experiences lower return levels (<8 m) due to this beach's shallow slope (Figure 5.31, right). Extreme return levels along the Quinault coastline are highly variable, however, the highest water levels are found along the southern edge of the northern extent (Figure 5.32, left). The lowest water levels are found in the southern extent of Quinault, where all return levels for this stretch of coast are between 4-6 m (Figure 5.32, right). Overall, some locations have lower TWLs than others, but the likelihood of risk depends on the elevation of the backing morphology (e.g. a 6 m TWL will overtop a 5 m dune, while a 10 m TWL will not overtop an 11 m dune).

Mouth of Queets River. Photo courtesy Larry Workman, QIN.

Figure 5.29 *The average 10, 25, 50, and 100-year TWL return level events for the coastline from Cape Alava to Rialto Beach. Gaps in this figure are due to a lack of data (inlet mouth) or a beach slope >0.2.*

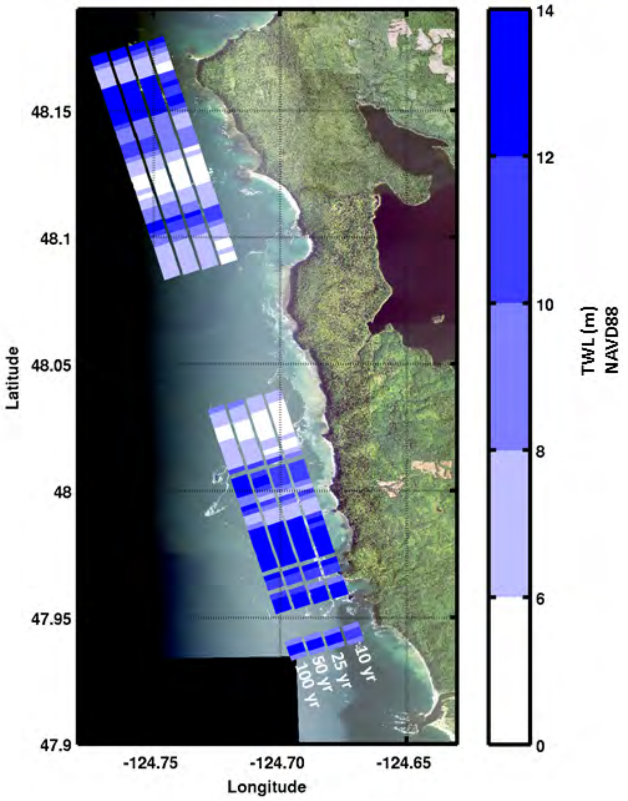


Figure 5.30 *The average 10, 25, 50, and 100-year TWL return level events for the (left) Quileute reservation coastline and (right) Second and Third Beach. Gaps in this figure are due to a lack of data (inlet mouth) or a beach slope >0.2.*

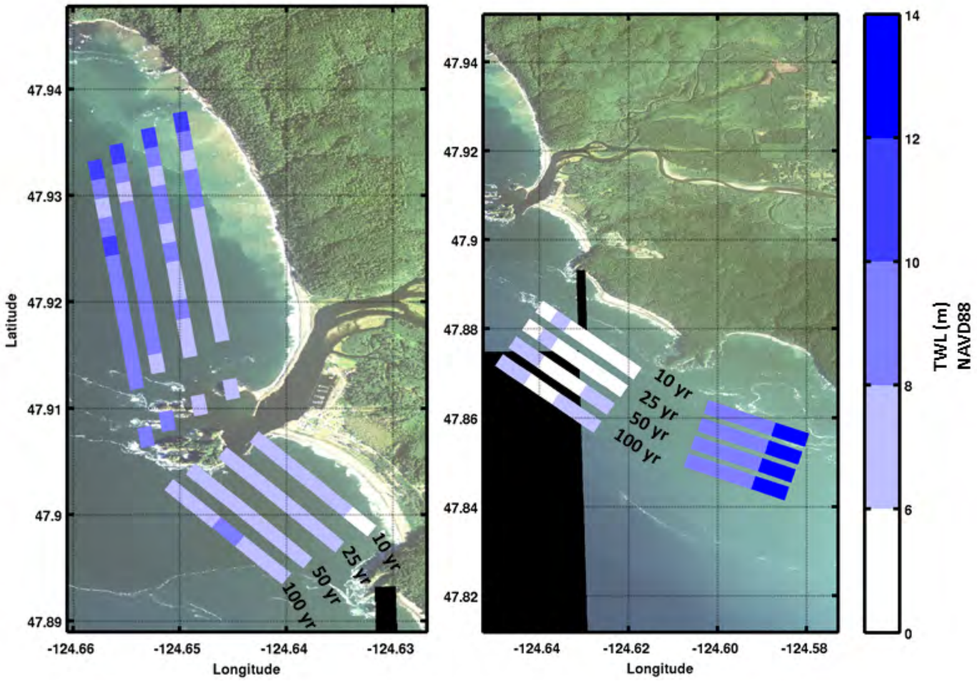


Figure 5.31 *The average 10, 25, 50, and 100-year TWL return level events for the (left) Hoh reservation coastline and (right) Ruby Beach to the Queets River. Gaps in this figure are due to a lack of data or a beach slope >0.2.*

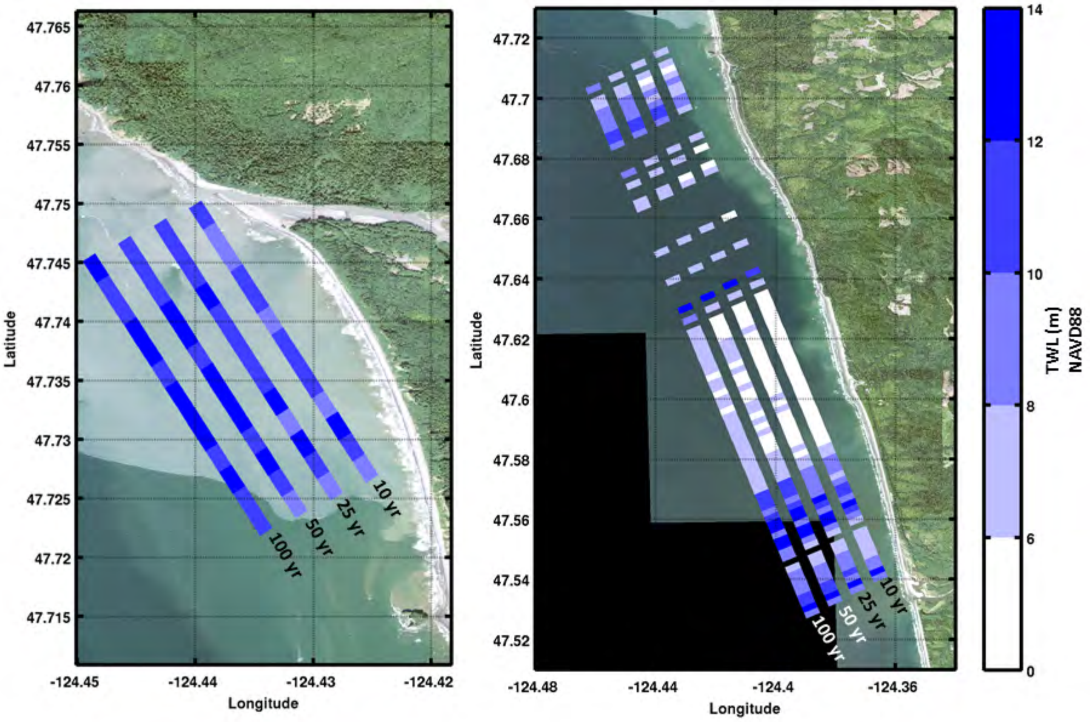
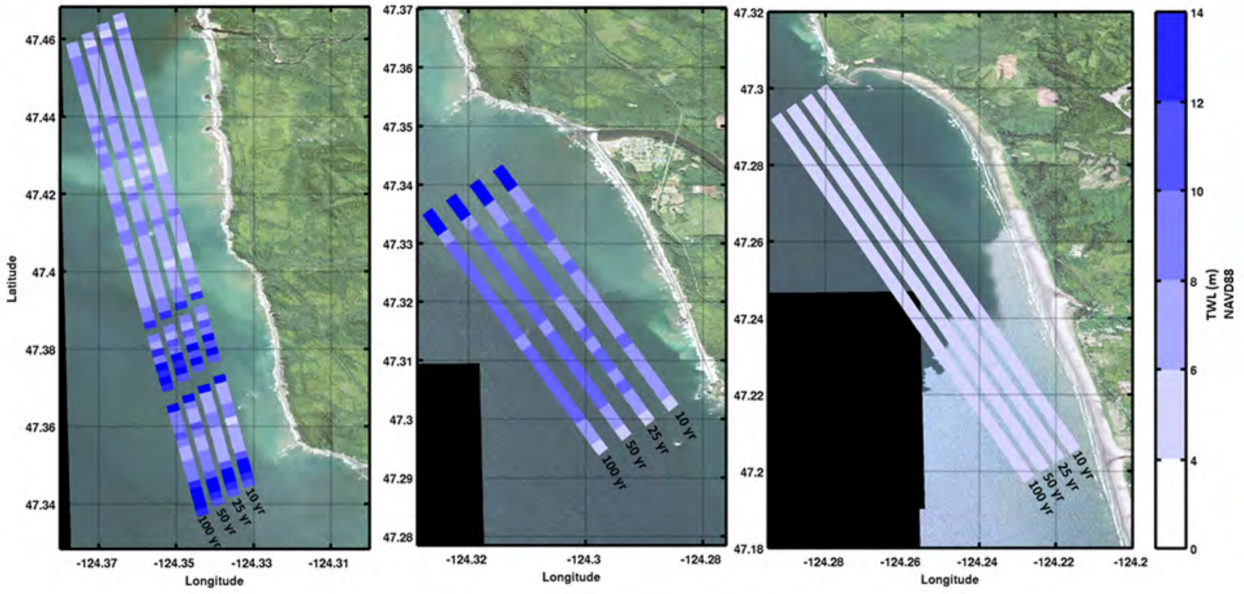


Figure 5.32 *The average 10, 25, 50, and 100-year TWL return level events for the (left) northern extent, (center) middle extent, and (right) southern section of the Quinault reservation coastline. Gaps in this figure are due to a lack of data or a beach slope >0.2.*



In Figures 5.29-5.32 we have not explicitly compared extreme TWLs to backshore morphology for two reasons, both related to the difficulty in interpreting beach morphology from lidar data. First, it is not always clear whether the local beach is composed of sand, cobble, or both, and therefore which runup formulation is most relevant. Second, for extreme events the backshore morphological feature explored in our nuisance impact analysis may not be the most relevant for the communities. Site visits, with detailed verification of the lidar data interpretation, will be necessary for a refinement of this analysis.

5.4.2 Future Conditions (~2050)

In this section, we compare simulations for 2050 under a high, medium, and low climate scenario to the present-day simulations.

5.4.2.1 Nuisance Events

On average, impact days per year (IDPY) and overtopping days per year (ODPY) are increased as sea level rise increases (Figures 5.33-5.40). Because the low SLR scenario is similar to that of present day mean sea level in 2050, IDPY and ODPY for the low SLR scenario can be slightly lower than or around the same as present day. Cape Alava to Rialto Beach experiences, on average, a 25% increase of IDPY under a high SLR scenario (Figure 5.33). This can range from as low as a 3% change to a 100% change. Under a high SLR scenario, ODPY increases from, on average, 30 DPY to 45 DPY (approx. 50%). The Quileute coastline experiences 18% increase in IDPY under a high SLR scenario. However, this increases collision to 60% of the coastline, on average (Figure 5.34). Second Beach experiences an increase in the collision regime from 36% of the year to 50% of the year under a high SLR scenario (Figure 5.35). IDPY on Third Beach increases by 47% during a high SLR scenario (approx. 87 IDPY to 128 IDPY; Figure 5.35). This translates to 1/3 of the year being impacted by water levels, as opposed to <1/4.

The Hoh coastline experiences similar trends to that of the Quileute and, on average, receives a 15-30% (15-20 DPY) increase in IDPY and ODPY between the present day and high SLR scenario (Figure 5.36). Under a medium SLR scenario, Ruby Beach to the Queets River increases from 173 to 193 IDPY (an approx. 11% increase). Under a high SLR scenario, this increases to 226 IDPY, with on average, 60% of the coast being impacted by water levels (Figure 5.37). Along the Quinault coastline, on average, the percentage of coastline in the collision regime increases by 33% under a high SLR scenario (Figures 5.38-5.40). While ODPY, or days in the overtopping regime, increase along the entire Quinault coastline, they still only affect approximately 14%, 25%, and 1%, of the northern, middle, and southern Quinault coastline by 2050.

***Figure* 5.33** *Impact days per year (IDPY; middle) and overtopping days per year (ODPY; right) for the Cape Alava to Rialto Beach. Bolded black lines indicate the average (across 35 simulations) IDPY/ODPY computed using the present-day simulations while blue, green, and red lines indicate future simulations for low, medium, and high sea level rise, respectively.*

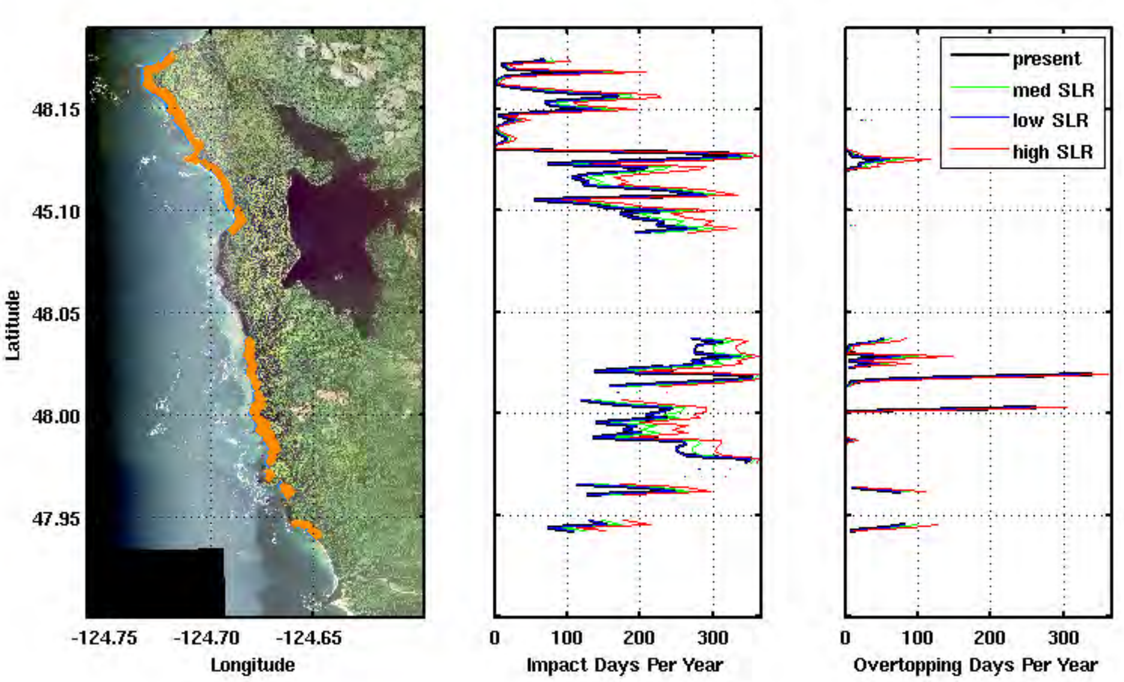


***Figure* 5.34** *Impact days per year (IDPY; middle) and overtopping days per year (ODPY; right) for the Quileute reservation. Bolded black lines indicate the average (across 35 simulations) IDPY/ODPY computed using the present-day simulations while blue, green, and red lines indicate future simulations for low, medium, and high sea level rise, respectively.*

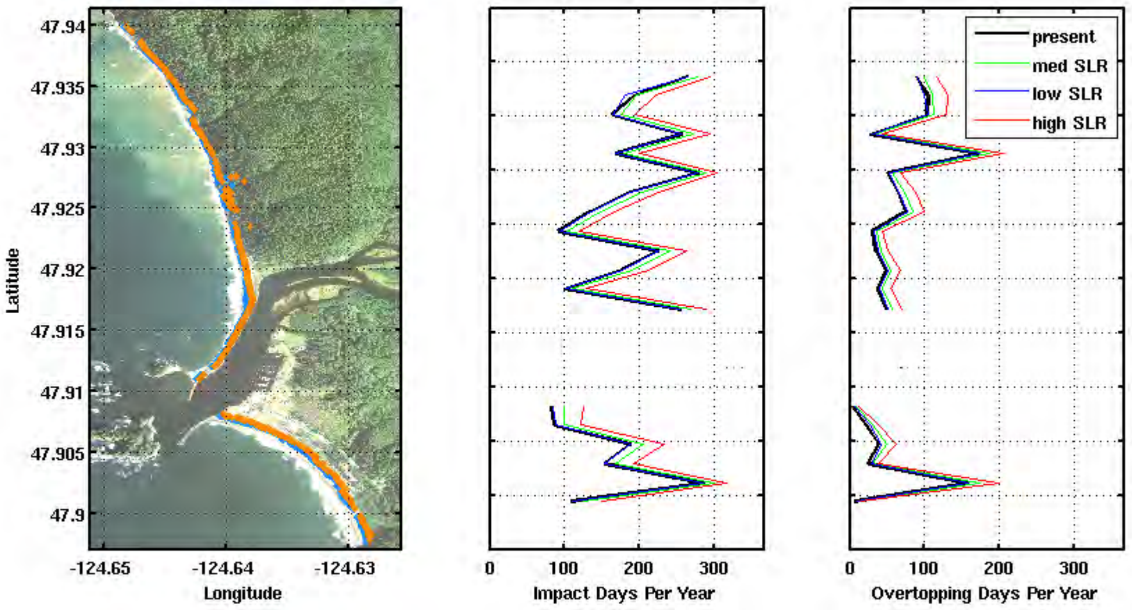


Figure 5.35 *Impact days per year (IDPY; middle) and overtopping days per year (ODPY; right) for Second Beach and Third Beach. Bolded black lines indicate the average (across 35 simulations) IDPY/ODPY computed using the present-day simulations while blue, green, and red lines indicate future simulations for low, medium, and high sea level rise, respectively.*

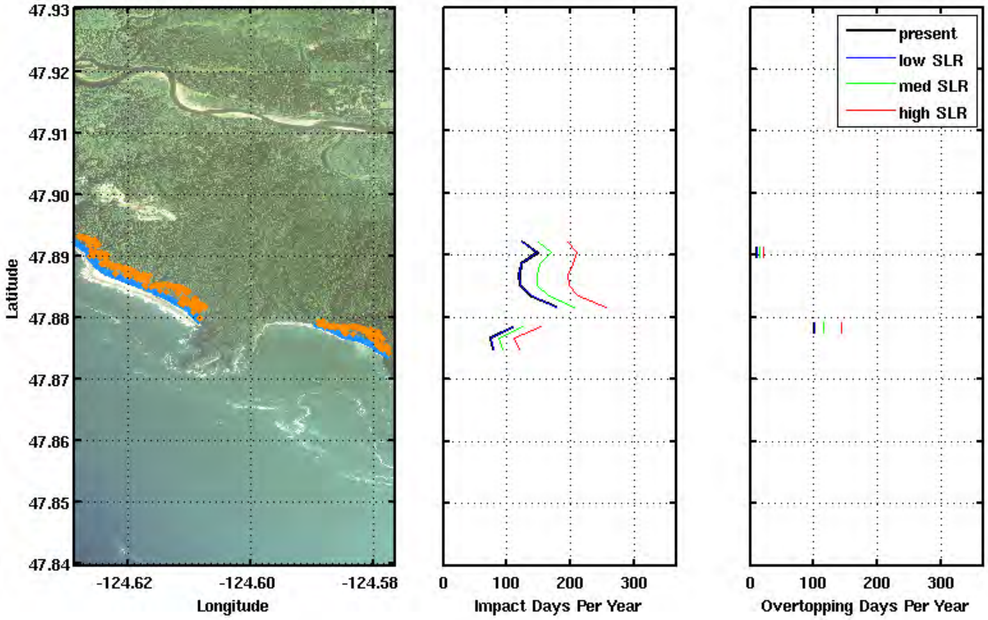


Figure 5.36 *Impact days per year (IDPY; middle) and overtopping days per year (ODPY; right) for the Hoh reservation. Bolded black lines indicate the average (across 35 simulations) IDPY/ODPY computed using the present-day simulations while blue, green, and red lines indicate future simulations for low, medium, and high sea level rise, respectively.*

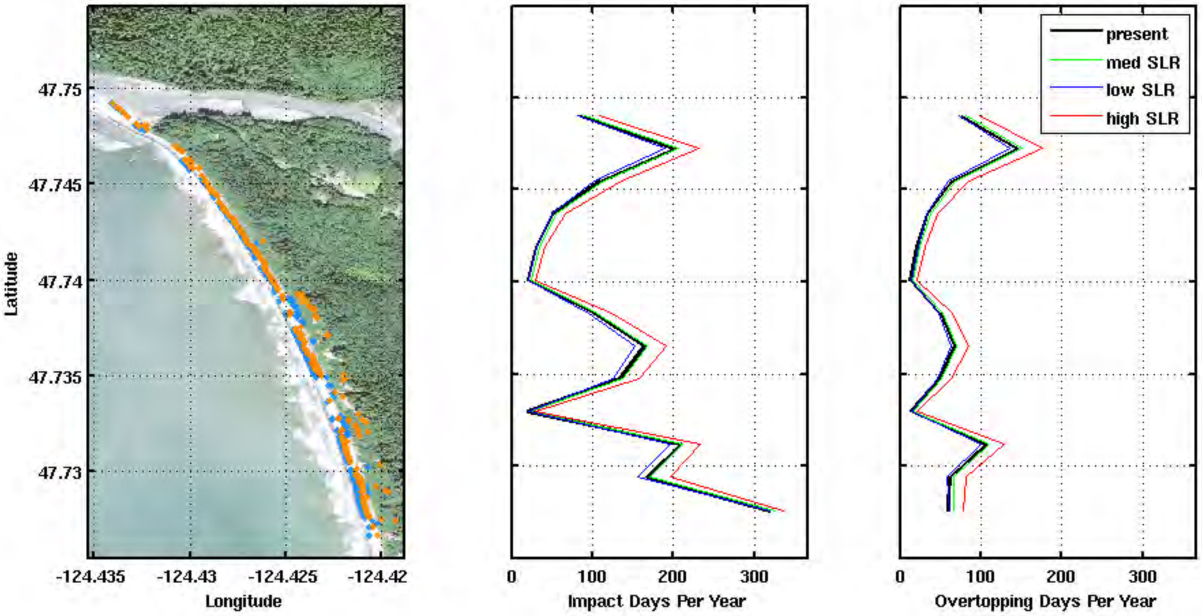


Figure 5.37 *Impact days per year (IDPY; middle) and overtopping days per year (ODPY; right) for Ruby Beach to the Queets River. Bolded black lines indicate the average (across 35 simulations) IDPY/ODPY computed using the present-day simulations while blue, green, and red lines indicate future simulations for low, medium, and high sea level rise, respectively.*

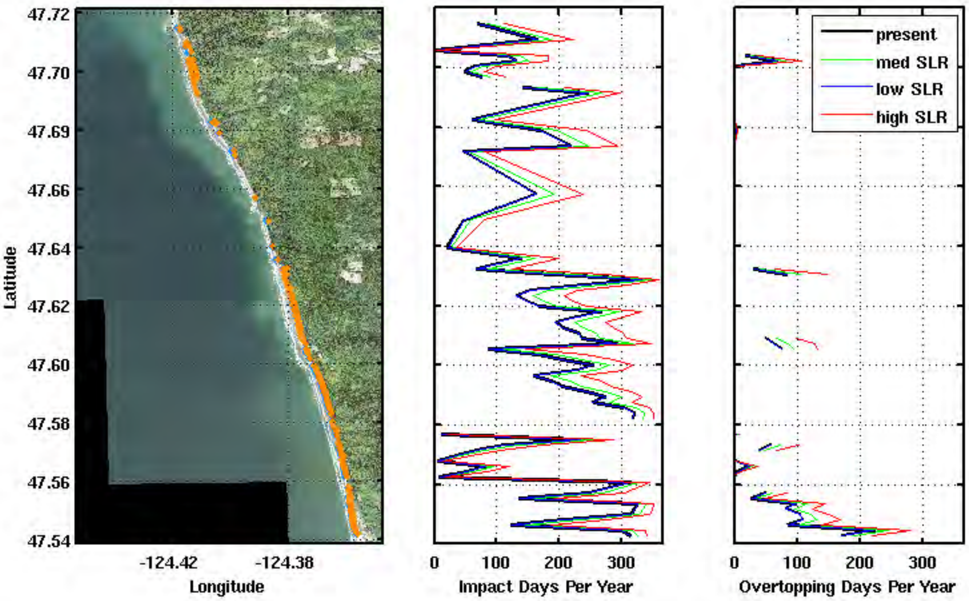


Figure 5.38 *Impact days per year (IDPY; middle) and overtopping days per year (ODPY; right) for the northern extent of the Quinault reservation. Bolded black lines indicate the average (across 35 simulations) IDPY/ODPY computed using the present-day simulations while blue, green, and red lines indicate future simulations for low, medium, and high sea level rise, respectively.*

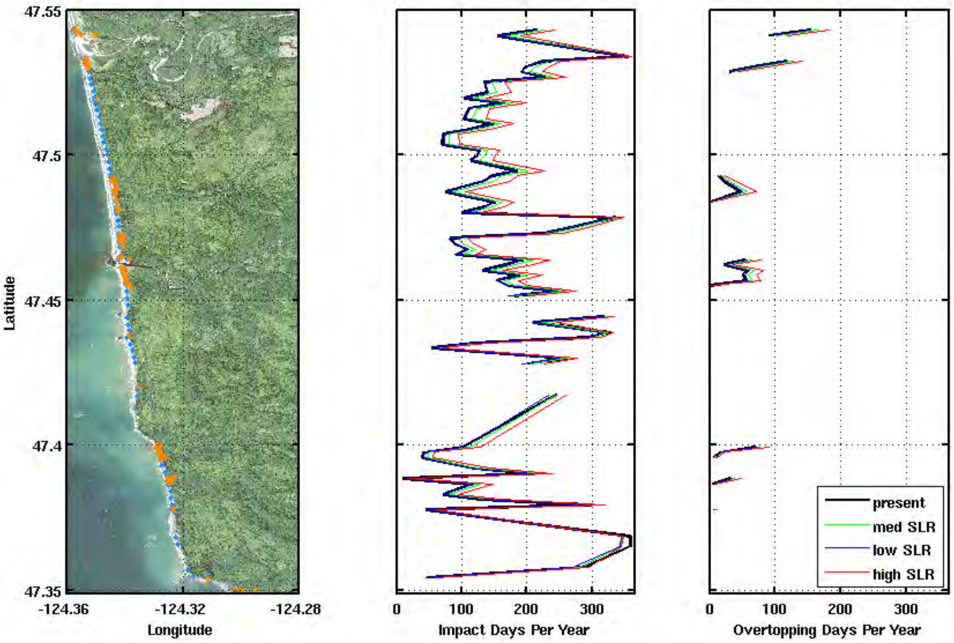


Figure 5.39 *Impact days per year (IDPY; middle) and overtopping days per year (ODPY; right) for the middle extent of the Quinault reservation. Bolded black lines indicate the average (across 35 simulations) IDPY/ODPY computed using the present-day simulations while blue, green, and red lines indicate future simulations for low, medium, and high sea level rise, respectively.*

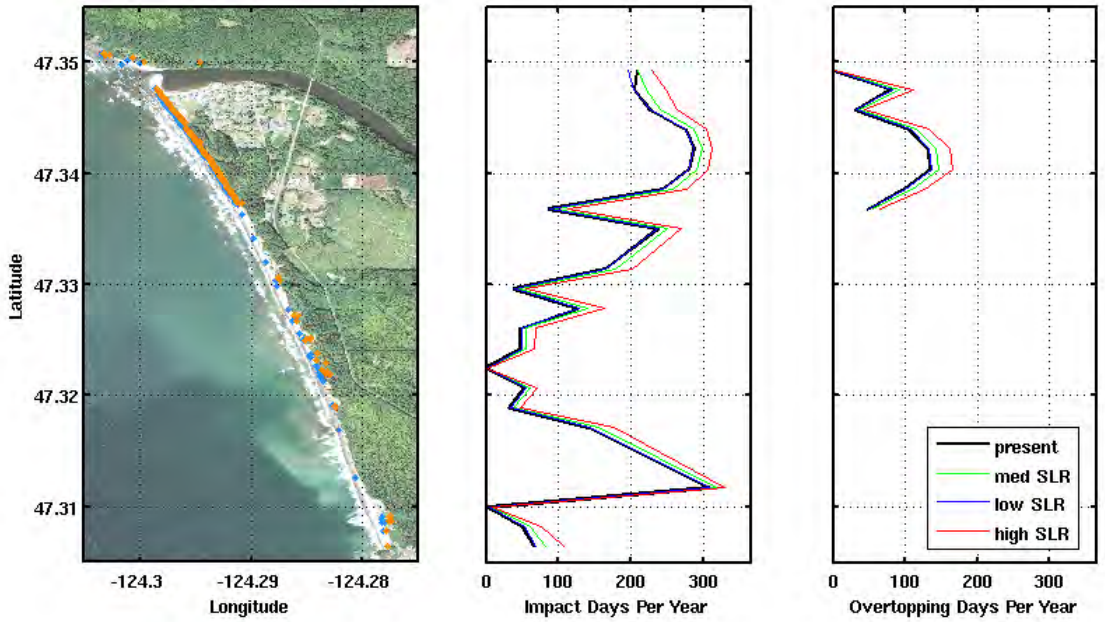
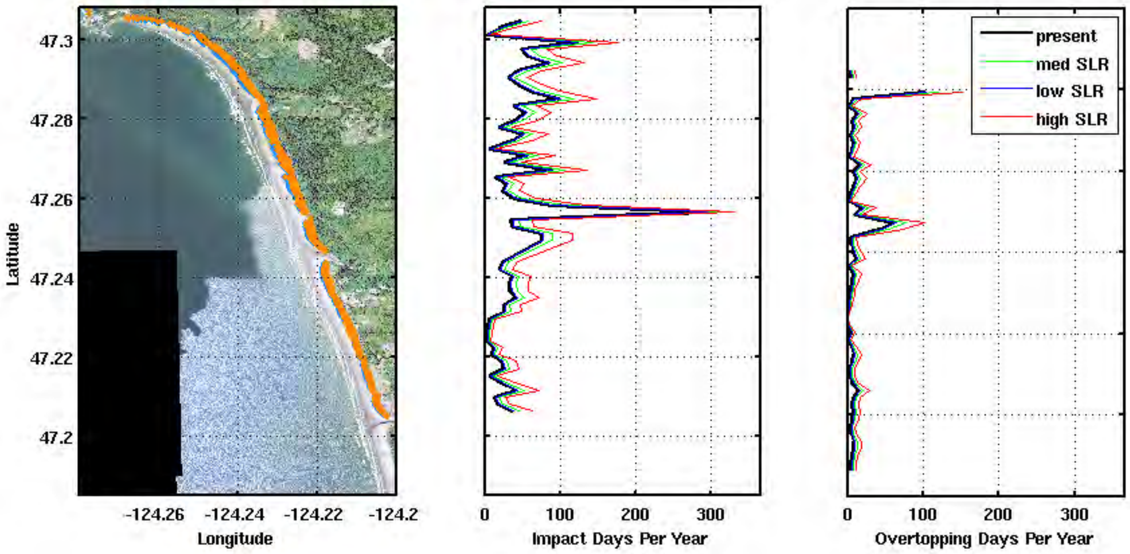


Figure 5.40 *Impact days per year (IDPY; middle) and overtopping days per year (ODPY; right) for the southern extent of the Quinault reservation. Bolded black lines indicate the average (across 35 simulations) IDPY/ODPY computed using the present-day simulations while blue, green, and red lines indicate future simulations for low, medium, and high sea level rise, respectively.*



5.4.2.2 Extreme Events

The annual maximum TWL event increases under all SLR scenarios for the Hoh, Quileute, and Quinault coastlines (Figures 5.41-5.48). Average increases are similar for Cape Alava to Rialto Beach (10, 25, 60 cm; Figure 5.41), the Quileute coastline (20, 35, and 50cm; Figure 5.42), Second and Third Beach (15, 35, and 47 cm; Figure 5.43), and Ruby Beach to the Queets River (18, 36, 50 cm; Figure 5.45) for the low, medium, and high SLR scenarios. The Hoh coastline experiences increases in water levels slightly higher than that of the Quileute, where on average, low, medium, and high SLR scenarios increase the annual maximum event by 30, 58, and 77cm by mid-century (Figure 5.44). The northern and middle sections of the Quinault coastline averages annual maximum event increases of 20, 40, and 50 cm for the low, medium, and high SLR scenarios, respectively (Figures 5.46-5.47). However, the high SLR scenario can be as much as 1 m bigger than the present day scenario, and as little as 30 cm larger. Water levels are lowest along the southern extent of the Quinault coastline, and water levels increase, but only slightly with an increase in each SLR scenario (e.g., the high SLR scenario only increases this event by 30 cm; Figure 5.48). The variability in the elevation of the annual maximum TWL across all scenarios is due to both the hydrodynamic and geomorphic variability of the respective coastlines.

Figure 5.41 *The annual maximum TWL for Cape Alava to Rialto Beach. Bolded black lines indicate the average (across 35 simulations) annual maximum TWL computed using the present-day simulations while blue, green, and red lines indicate the average annual maxima of future simulations (12 each scenario) for low, medium, and high sea level rise, respectively.*

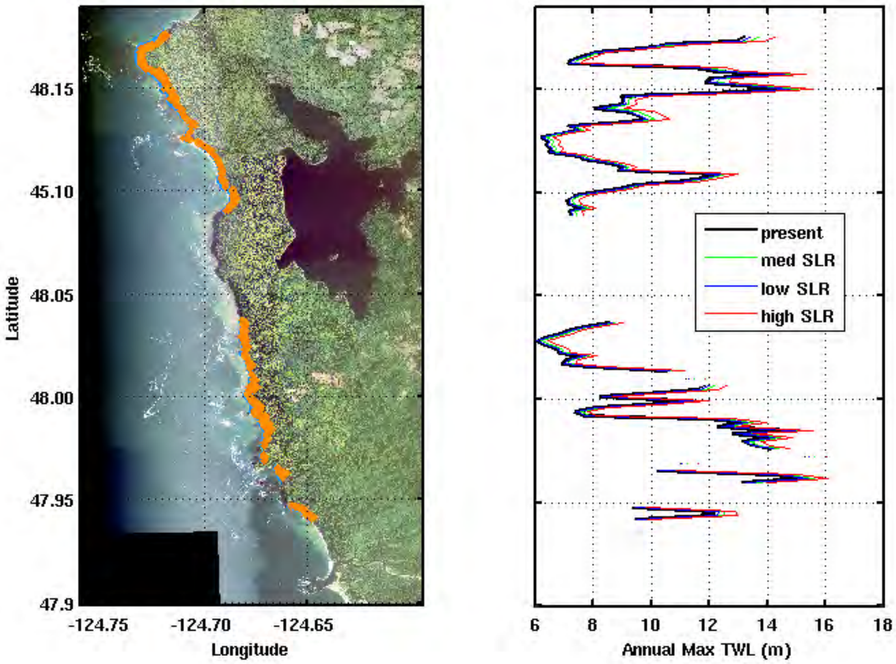


Figure 5.42 *The annual maximum TWL for the Quileute reservation. Bolded black lines indicate the average (across 35 simulations) annual maximum TWL computed using the present-day simulations while blue, green, and red lines indicate the average annual maxima of future simulations (12 each scenario) for low, medium, and high sea level rise, respectively.*

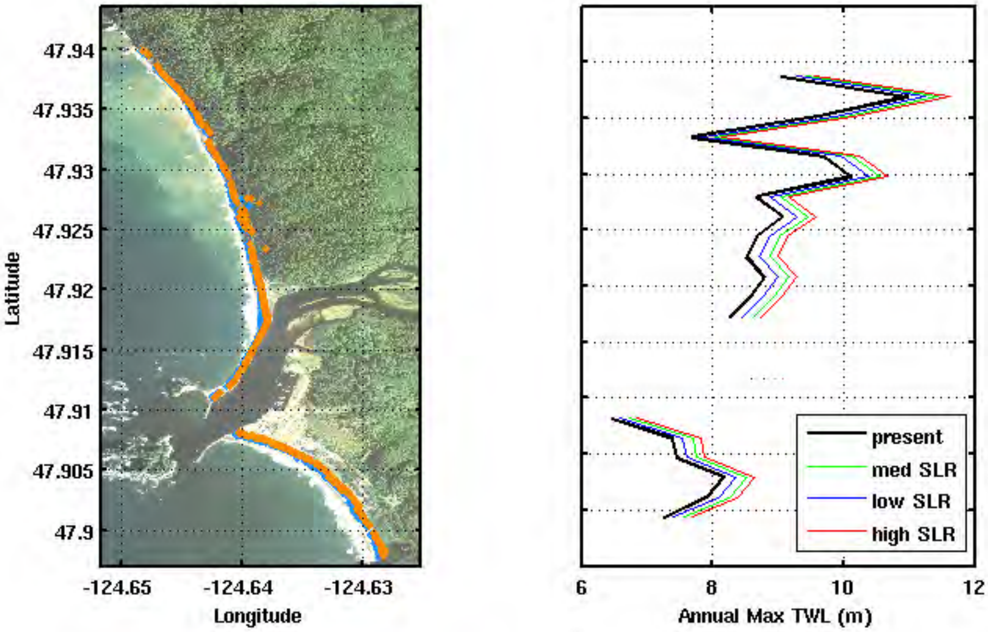


Figure 5.43 *The annual maximum TWL for Second Beach and Third Beach. Bolded black lines indicate the average (across 35 simulations) annual maximum TWL computed using the present-day simulations while blue, green, and red lines indicate the average annual maxima of future simulations (12 each scenario) for low, medium, and high sea level rise, respectively.*

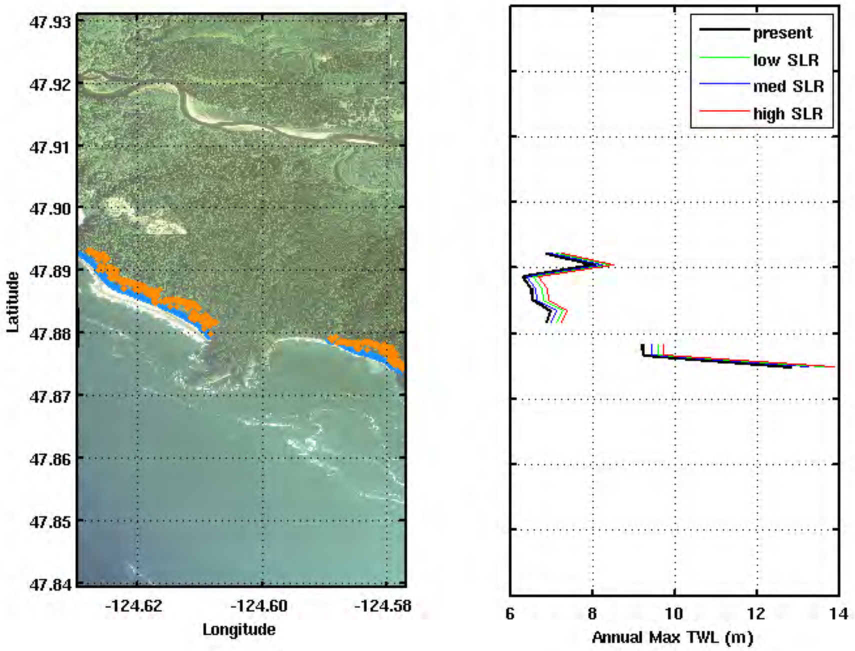


Figure 5.44 *The annual maximum TWL for the Hoh reservation. Bolded black lines indicate the average (across 35 simulations) annual maximum TWL computed using the present-day simulations while blue, green, and red lines indicate the average annual maxima of future simulations (12 each scenario) for low, medium, and high sea level rise, respectively.*

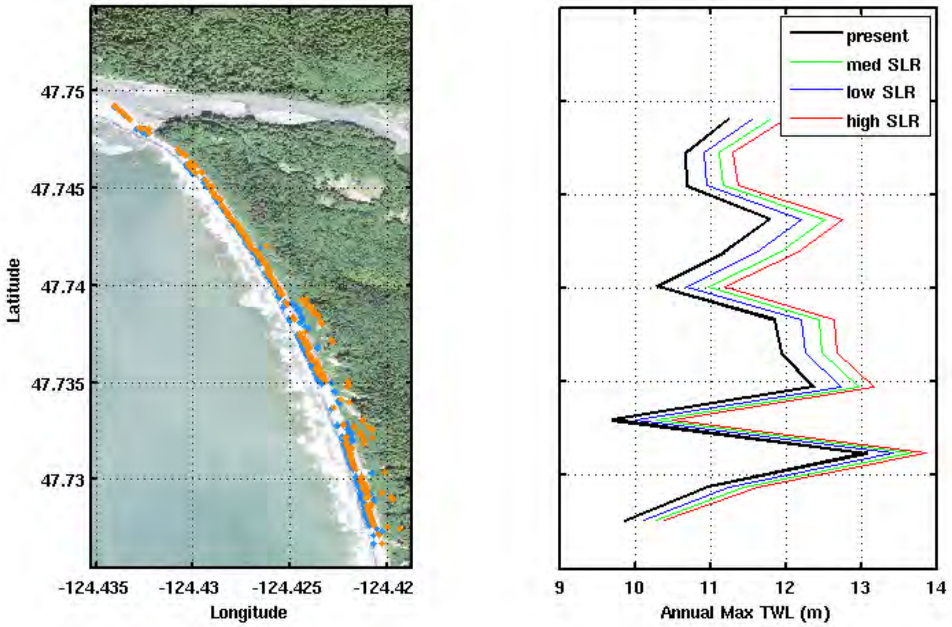


Figure 5.45 *The annual maximum TWL Ruby Beach to the Queets River. Bolded black lines indicate the average (across 35 simulations) annual maximum TWL computed using the present-day simulations while blue, green, and red lines indicate the average annual maxima of future simulations (12 each scenario) for low, medium, and high sea level rise, respectively.*

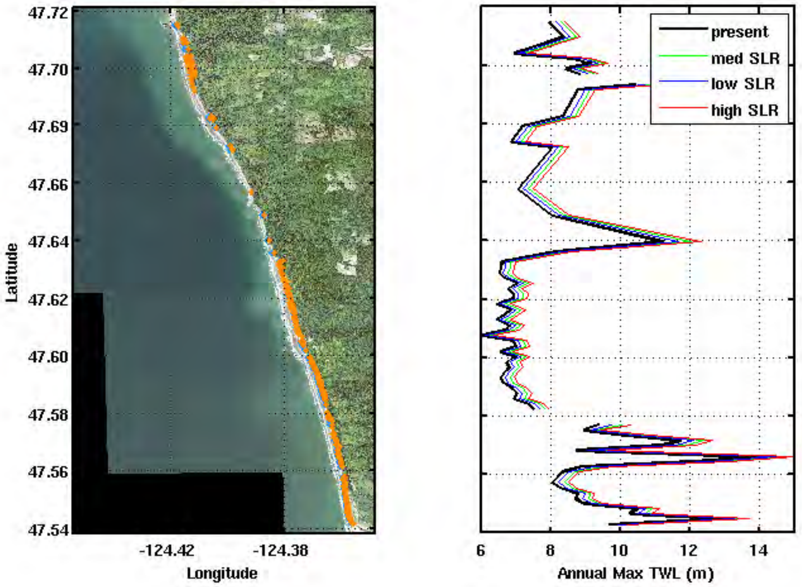


Figure 5.46 *The annual maximum TWL for the northern extent of the Quinault reservation. Bolded black lines indicate the average (across 35 simulations) annual maximum TWL computed using the present-day simulations while blue, green, and red lines indicate the average annual maxima of future simulations (12 each scenario) for low, medium, and high sea level rise, respectively.*

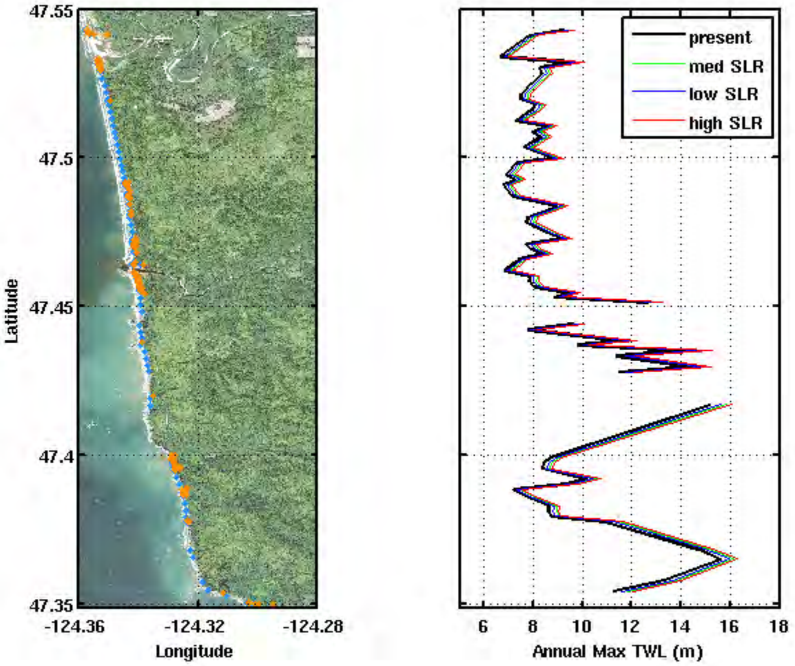


Figure 5.47 *The annual maximum TWL for the middle section of the Quinault reservation. Bolded black lines indicate the average (across 35 simulations) annual maximum TWL computed using the present-day simulations while blue, green, and red lines indicate the average annual maxima of future simulations (12 each scenario) for low, medium, and high sea level rise, respectively.*

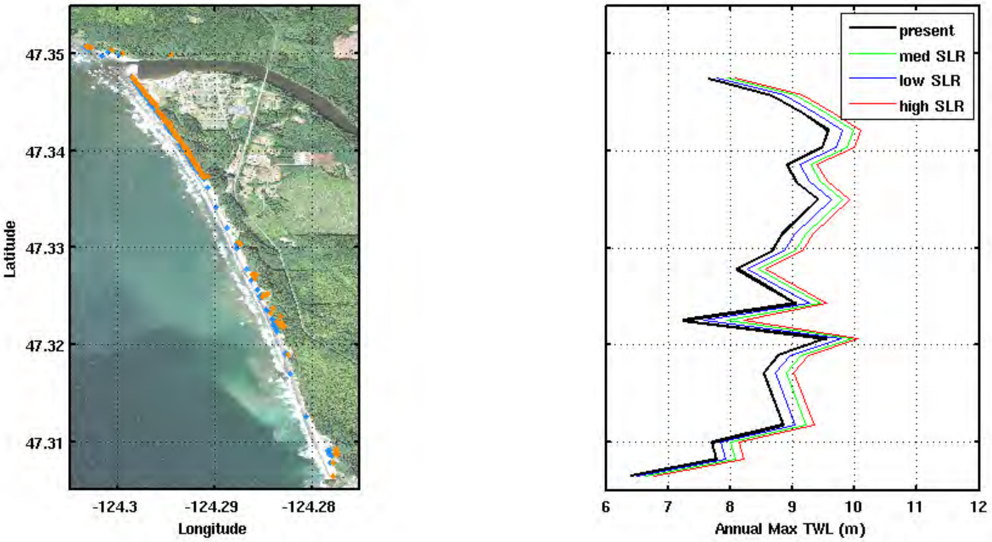
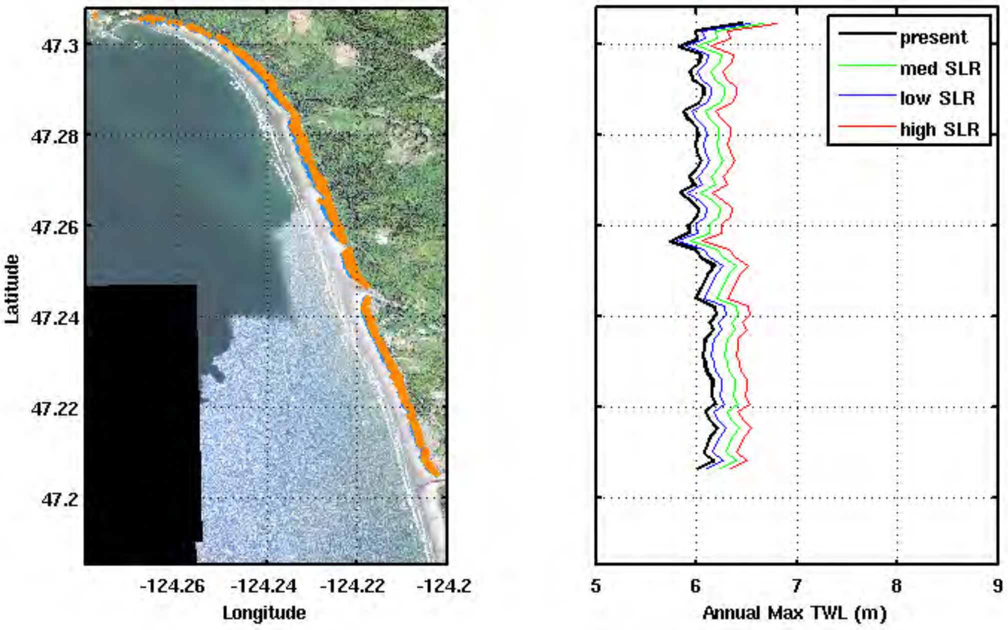


Figure 5.48 *The annual maximum TWL for the southern extent of the Quinault reservation. Bolded black lines indicate the average (across 35 simulations) annual maximum TWL computed using the present-day simulations while blue, green, and red lines indicate the average annual maxima of future simulations (12 each scenario) for low, medium, and high sea level rise, respectively.*



5.4.3 Impacts to Natural Resources

Certain species with economic and cultural significance to the Treaty of Olympia tribes may be impacted by the projected future changes in extreme total water levels described above. Here we analyze the present-day impact to specific intertidal elevation contours along the Washington Pacific coast (e.g., 2 (approximately the mean high water shoreline), 3, 4, and 5 m) and how this may change under future TWL scenarios (Figures 5.49 – 5.56).

Surf Smelt is an intertidal forage fish that lays eggs in shallow water along sand and gravel beaches. Smelt eggs have been found at Rialto Beach, Ruby Beach, and Kalaloch-area beaches. Because of the large amount of gravel/sand beaches in this area, it is likely smelt spawning exists in other locations as well. Razor clams inhabit the subtidal and intertidal zone of sandy beaches. Vertical movement of razor clams up and down the beach is common for adjusting to shifting sands, heavy surf, and predators, however the species do not typically move horizontally.

While the projected changes in TWLs by 2050 may not be severe enough to significantly threaten beach habitats, some intertidal species may shift landward. For example, across all of the locations, the 3 m contour is inundated every day of the year during the maximum daily TWL under a high SLR scenario (Figures 5.49-5.56). These changes at specific elevation contours are nonlinear and the largest change across all coastlines studied is between the 3.75 m and the 4.5 m contour (an approx. 50 – 90 DPY increase in flooding). The largest amount of change, on average, is in the southern extent of the Quinault area, where the 4.25 m contour experiences flooding during the maximum daily water level 40% of the year, when previously, it only experienced it 18% of the year. While intertidal species, like razor clams and surf smelt, may have the ability to move vertically up the beach, Snowy plovers and other back-barrier nesting species may face habitat loss as SLR continues to increase.

Figure 5.49 *Number of days a year a beach elevation contour will be under water during the average of the daily maximum TWL event for Cape Alava to Rialto Beach, under present-day, low, medium, and high SLR scenarios. The grey line represents the MHW shoreline contour at 2.1m NAVD88.*

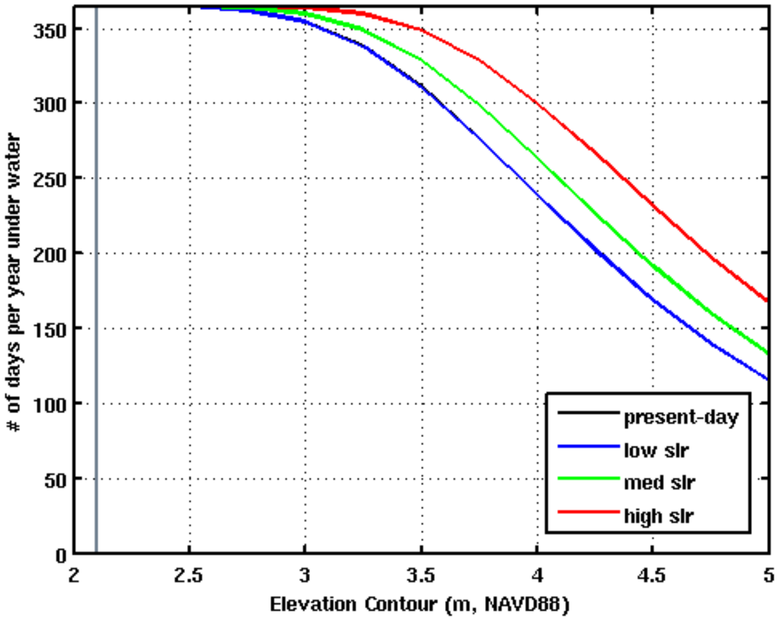


Figure 5.50 *Number of days a year a beach elevation contour will be under water during the average of the daily maximum TWL event for Quileute reservation, under present-day, low, medium, and high SLR scenarios. The grey line represents the MHW shoreline contour at 2.1m NAVD88.*

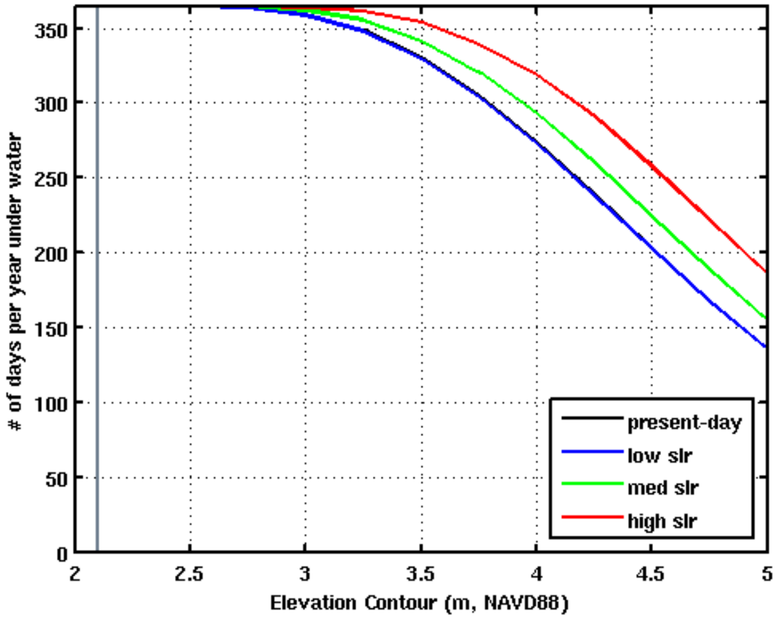


Figure 5.51 *Number of days a year a beach elevation contour will be under water during the average of the daily maximum TWL event for Second and Third Beach, under present-day, low, medium, and high SLR scenarios. The grey line represents the MHW shoreline contour at 2.1m NAVD88.*

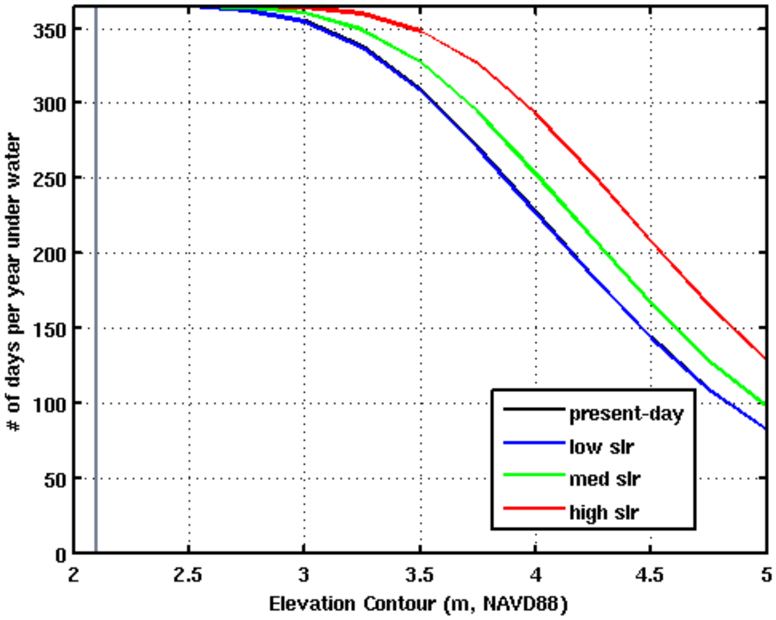


Figure 5.52 *Number of days a year a beach elevation contour will be under water during the average of the daily maximum TWL event for the Hoh reservation, under present-day, low, medium, and high SLR scenarios. The grey line represents the MHW shoreline contour at 2.1m NAVD88.*

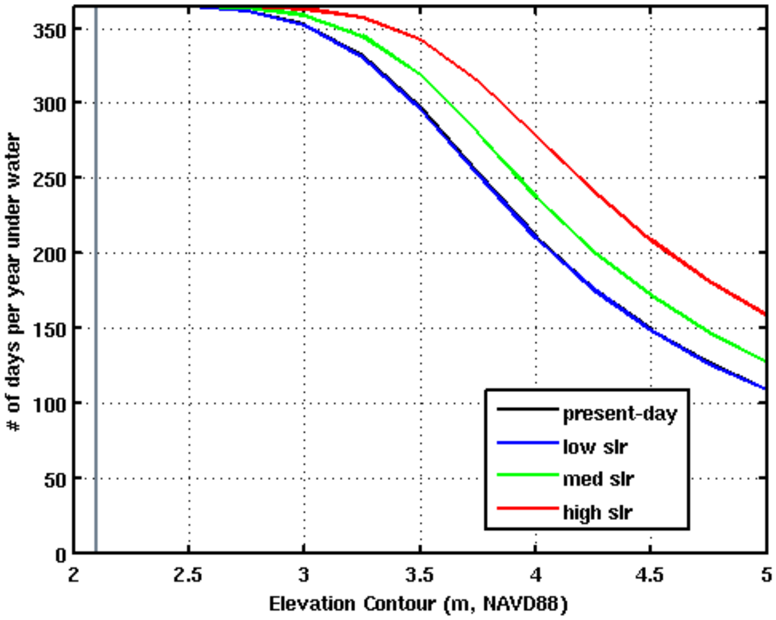


Figure 5.53 *Number of days a year a beach elevation contour will be under water during the average of the daily maximum TWL event for Ruby Beach to the Queets River, under present-day, low, medium, and high SLR scenarios. The grey line represents the MHW shoreline contour at 2.1m NAVD88.*

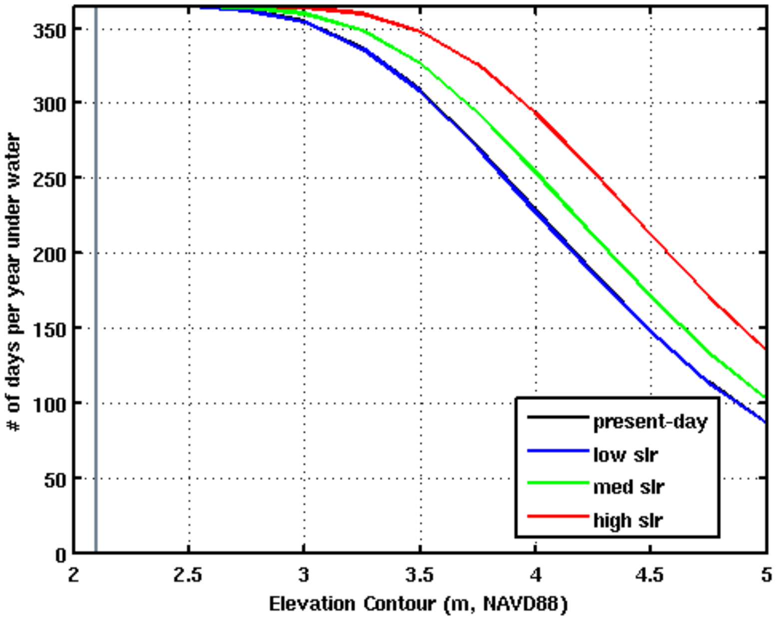


Figure 5.54 *Number of days a year a beach elevation contour will be under water during the average of the daily maximum TWL event for the northern extent of the Quinault reservation, under present-day, low, medium, and high SLR scenarios. The grey line represents the MHW shoreline contour at 2.1m NAVD88.*

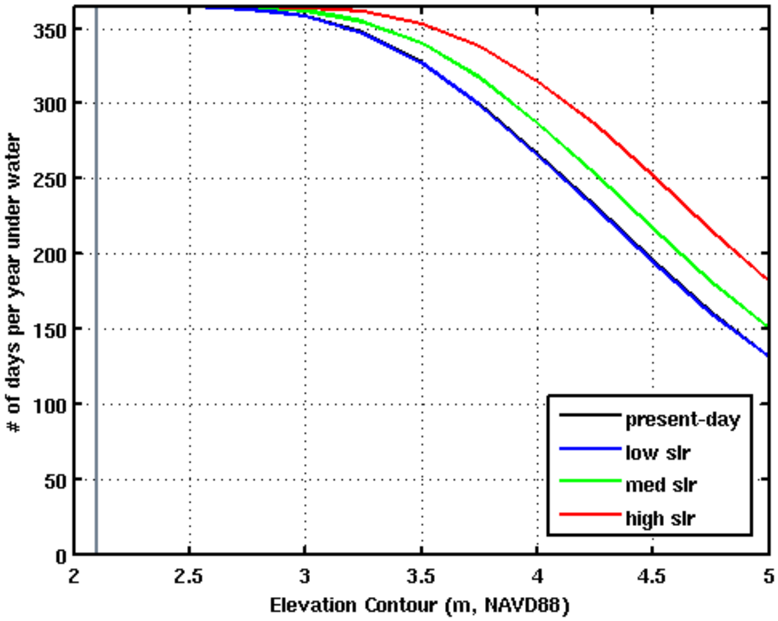


Figure 5.55 *Number of days a year a beach elevation contour will be under water during the average of the daily maximum TWL event for the middle extent of the Quinault reservation, under present-day, low, medium, and high SLR scenarios. The grey line represents the MHW shoreline contour at 2.1m NAVD88.*

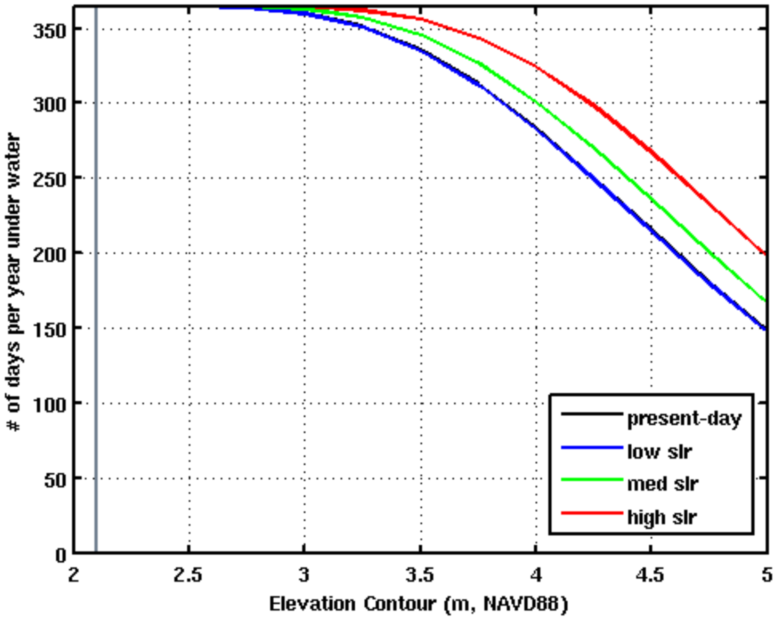
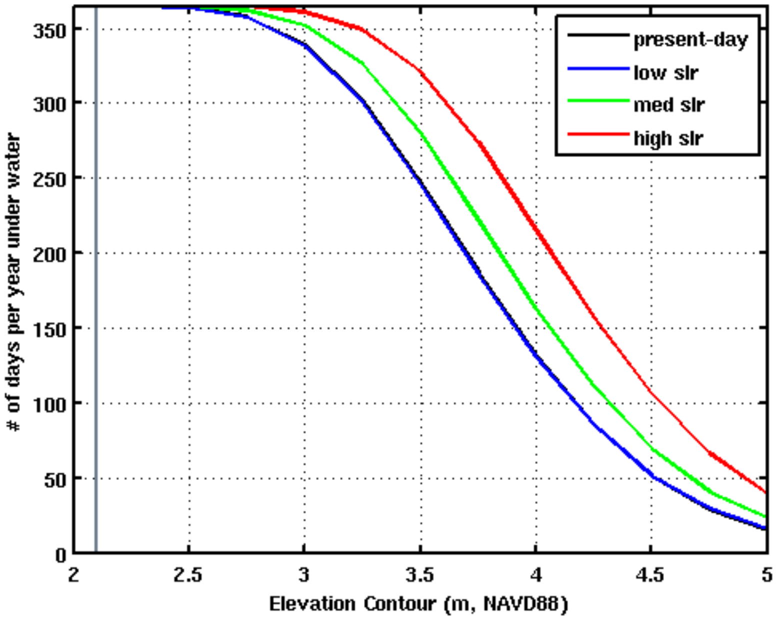


Figure 5.56 *Number of days a year a beach elevation contour will be under water during the average of the daily maximum TWL event for the southern extent of the Quinault reservation, under present-day, low, medium, and high SLR scenarios. The grey line represents the MHW shoreline contour at 2.1m NAVD88.*



5.5 Conclusions

The Hoh, Quileute, and Quinault coastlines, and surrounding beaches, are comprised of highly variable morphology which includes both sand and gravel beaches, low sloping and steep beaches, and dune and bluff/cliff backed beaches. In general, however, the most characteristic morphology includes steep cliffs and bluffs (>25 m) which occasionally are fronted by ephemeral morphological features (typically beach berms) with crests averaging around 5-7 m and cliff/dune toes averaging around 4-5 m NAVD88. These smaller fronting features (compared to the backing cliff morphology) experience alongshore variable impact and overtopping days per year and the coastlines also experience a similar alongshore variability in extreme return level events. These ephemeral features, along with logs from the destabilized conifer forests on the bluff, most likely act as a buffer to backing cliff/bluff erosion and/or critical habitat.

All SLR scenarios that were assessed increase water levels (the annual maximum event and return level events) along the coast, driving increases in IDPY and ODPY. Our analysis displays that the Hoh coastline may receive larger changes to the annual maximum TWL event than the Quileute and Quinault coastlines, likely due to the overall higher beach slopes in this region. This is also experienced by Rialto Beach in comparison to First Beach. However, even slight increases in water levels may matter more in locations with critical habitat or infrastructure (e.g., the Taholah area) rather than locations where little infrastructure and/or high backing cliff morphology exists.

This analysis provides a conservative estimate of the potential for coastal change with respect to daily maximum TWLs. While the projected changes in TWLs by 2050 are likely not severe enough to significantly threaten coastal habitat, some intertidal species may shift landward. This landward shift however, may become detrimental to snowy plovers and other back-barrier nesting species if the ephemeral berms are lost and the water levels extend more frequently to the cliff/bluff toes.

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Chapter 6: Marine Environment

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6.1 Introduction

The marine environment is culturally, economically, and ecologically important to the Treaty of Olympia tribes and a major concern is how the marine environment may change with climate change. In this chapter, we synthesize recent literature and assessments on climate change impacts to the marine environment of the West Coast of North America with special focus on the Pacific Coast of Washington and the Olympic Peninsula where such localized information exists. Limited information exists specifically for the marine environment of the Olympic Peninsula, thus much of the literature synthesized in this chapter pertains to the larger California Current System—the Pacific Ocean eastern boundary current running parallel to the West Coast of North America from British Columbia to Baja California—and the large marine ecosystem supported by the productive upwelling environment. This chapter begins with a discussion of the main climate change drivers affecting the marine environment and then, to the extent information exists, discusses how important species may respond.

6.2 Climate Change Drivers

Marine and coastal environments experience the effects of increasing atmospheric greenhouse through ocean acidification and changes in climate such as increasing sea surface temperature, altered hydrology, altered frequency and severity of storms, sea level rise, altered patterns of coastal upwelling and hypoxia zones, and harmful algal blooms (Tillmann and Siemann 2011).

6.2.1 Ocean Acidification

The global ocean has absorbed about 30% of the atmospheric concentration of carbon dioxide (CO_2) emitted by human activities resulting in lower pH (that is, more acidic seawater) and carbonate and aragonite saturation states (Hoegh-Guldberg et al., 2014) challenging calcifying marine organisms (Reeder et al., 2013). Global ocean pH has already declined by 0.1 unit and with a further doubling of atmospheric CO_2, ocean pH is projected to decrease by another 0.1 unit (Hoegh-Guldberg et al., 2014). Declines in pH in waters off the Pacific Northwest are consistent with global changes (Tillmann and Siemann 2011). Seasonal coastal upwelling and nutrient inputs combine with anthropogenic additions of CO_2 to produce some of the most acidified marine waters worldwide along the Pacific Northwest coast (Reeder et al., 2013). Ocean acidification reduces the concentration of carbonate ions that are necessary for calcifying organisms, such as zooplankton and shellfish, to build shells (in fact, recent research indicates that it may be the carbonate saturation state, and not pH per se, which has the most ecological impact (Waldbusser et al., 2014)). Reduced availability of carbonate ions is especially challenging during the larval stage of calcifying organisms (Walsh et al., 2014b). For example, the Pacific oyster larvae only have a 2-day window in which to form initial shells (Waldbusser et al., 2014). Reductions in such calcifying organisms at the base of the marine food web could have cascading effects on higher trophic marine fish, birds, mammals, and people who rely on this resource.

6.2.2 Ocean Temperature

Oceans have taken up a substantial portion (93%) of the extra heat retained by the atmosphere through the enhanced greenhouse effect during 1971-2010. Most of the warming occurred from the surface to

700 meters, though warming has also been documented at greater depths (Hoegh-Guldberg et al., 2014). The surface layer of the Pacific Ocean has warmed at a rate of 0.05°C per decade and the California Current System has warmed at a rate of 0.122 °C per decade during 1950-2009 (Hoegh-Guldberg et al., 2014). Pacific coastal waters off of Washington have also warmed, though they experience large variability in sea surface temperature (SST) (about 6°C (10.8°F) seasonally) owing to strong influences by variability in El Niño-Southern Oscillation, wind patterns, coastal upwelling, river discharge, and other factors (Reeder et al., 2013). Global ocean temperatures are projected to increase further in the future and SST off the Washington Pacific coast are projected to increase by 1.2°C (2.2°F) by the 2040s (Mote and Salathe, 2010).

6.2.3 Altered Hydrology

The near-coastal environment is influenced by freshwater inputs. Altered timing of freshwater inflow into estuaries could affect availability of nursery habitat for juvenile species (Tillmann and Siemann 2011). Rivers in the Northwest with a snowmelt component are expected to experience increased winter flows, earlier peak flows, and lower summer flows (Raymondi et al., 2013). Rivers on the west Olympic Peninsula originate at different altitudes with varying reliance on snowpack and glaciers. Forestry practices can also influence the hydrology as well as landslides contributing sediment from the increased amount of precipitation. Within the Quillayute Basin, the Dickey River originates in relatively lower elevations; however, the Sol Duc, Calawah, and Bogachiel originate in the crests of the Olympic Range, as do the Hoh, Queets, and Quinault River. These have until recently enjoyed significant snowpack to provide summer flows. Reduced snowpack in their headwaters, as well as loss of Anderson Glacier at the headwaters of the Quinault River, have altered not just hydrology (summer flows) but also temperature of these streams.

6.2.4 Storms

Winter storms have increased in frequency and intensity in the Northern Hemisphere since the 1950s and their tracks have generally shifted northward following the slight northward shift of the jet stream (Walsh et al., 2014b). However, on the Northwest coast, including British Columbia, the slightly positive trend from 1948-2010 in extratropical winter storm frequency is not statistically significant (Vose et al., 2014). Average wave heights in the northeast Pacific have increased since the 1970s with the largest wave heights having increased at a faster rate (Ruggiero et al., 2010). Furthermore, this trend of increasing wave heights along the NW coast may have had a larger influence on coastal flooding and erosion events than sea level changes (Ruggiero 2013). Changes in alongshore sediment transport are also a concern of the tribes.

Future climate projections suggest a continued slight poleward shift in the jet stream, but there is as yet no consensus on whether or not extratropical storms will intensify or become more frequent under a warmer climate (Vose et al., 2014). Similarly, future changes in wave heights are not yet discernible in current model projections (Reeder et al., 2013). However, in the analysis of coastal erosion and flooding hazards in Chapter 5, the observed trend in extreme wave climate is assumed to continue through mid-21st century.

6.2.5 Sea Level Rise

As the climate warms and melts glaciers and ice sheets and thermally expands seawater, sea level will continue to rise. Along the Pacific Northwest coast, sea level is projected to rise by 4-56" by 2100[9] considering uncertainties in global greenhouse gas emissions, thermal seawater expansion, melting land ice, and vertical land movements (Reeder et al., 2013; NRC 2012). Projections are similar for the Olympic Peninsula, although variations in vertical land movement and other local effects could alter this projected range by several inches (Reeder et al., 2013). Vertical land motion in Washington is dominated by regional tectonics associated with the Cascadia Subduction Zone. The average rate of uplift from both glacial isostatic adjustment and tectonics (an ongoing, not sporadic process) varies (see NRC 2012) but is on the order of a couple of mm/yr. The northwest Olympic Peninsula is uplifting at a rate similar to or greater than the rate of global sea level rise such that local sea levels may decrease under low emissions scenarios or increase at a slower rate under higher emissions scenarios (Mote et al., 2008; Miller et al., 2013). The central and southern Washington coast may experience the effects of sea level rise earlier than the northwest coast due to a lower rate of tectonic uplift and even subsidence in some areas (Miller et al., 2013). Mote et al. (2008) estimate sea level rise of 2-43" for the central and southern Washington coast. Along the Olympic Coast National Marine Sanctuary, Miller et al. (2013) suggest that a planning horizon of 1.0 meters (~39 inches) of sea level rise by 2100 is reasonable although lower and higher rates are justified. In the analysis in the Coastal Hazards chapter, sea level projections from NRC (2012) for 2050 are used, which range from -0.10 to 0.5 meters (-3.9" to 19.7"), corresponding with the projected range for 2100 (NRC 2012). Sea level rise combined with storm surge, high tide, and wave heights pose a threat to shoreline habitat, resources, and infrastructure (See Chapter 5: Coastal Hazards). While sea level rise is a gradual change, the tectonic setting of the Washington coast sets the stage for an inevitable major subduction earthquake that would almost instantly change the coastline as the land sinks.

6.2.6 Coastal Upwelling

Coastal upwelling along the California Current System (CCS) occurs seasonally beginning in early spring, when the dominant alongshore wind direction shifts southward pushing surface waters offshore allowing the transport of deeper, nutrient-rich waters on to the continental shelf, and ending in late summer or fall when wind direction shifts northward (Tillmann and Siemann 2011). With climate change, coastal upwelling-favorable winds in Eastern Boundary Upwelling Systems (EBUS), such as the CCS, are expected to intensify due to the greater heating over land than over ocean resulting in increases in spring and summer upwelling intensity (Bakun et al., 2015) and a lengthening of the upwelling season (Wang et al., 2015). In the CCS and other EBUS, coastal winds have intensified over the past 60 years consistent with this expectation of upwelling intensification (Sydeman et al., 2014). However, regional controls on CCS upwelling such as ENSO, PDO, and NPGO will continue to have large influences (Wang et al., 2015). Such an intensification of coastal upwelling could mediate the effects of coastal habitat warming, but it could also lead to more frequent hypoxic events, higher acidity, and an altered food supply impacting the marine food web (Bakun et al., 2015).

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[9] The large range is due to the uncertainty in regional effects (steric and ocean dynamics, cryosphere, fingerprinting effects, vertical land motion from tectonics, glacial isostatic adjustment, and subsidence) out to 2100. A sea level rise (SLR) scenario of 4" could be thought of as reflecting lower rates of SLR but also larger rates of uplift. NRC (2012) provides in depth analysis of these regional variations and uncertainties.

6.2.7 Coastal Hypoxia

Hypoxic conditions occur when water is nearly devoid of dissolved oxygen, generally less than two milligrams per liter of water (2.0 mg/L). Hypoxia occurs seasonally off the West Coast as a result of changing wind patterns and ocean currents, increased microbial respiration resulting in oxygen demand exceeding supply, stratification, and warm saline waters. Since 2002, Oregon and Washington have seen an uptick in severe hypoxic events, particularly in 2006 when a large area of the Washington's continental shelf was hypoxic with record low dissolved oxygen levels (Tillmann and Siemann 2011). During the 2002 hypoxic event, Dungeness crab mortality was up to 75% in some locations. In the 2006 anoxic event, fish normally present were absent from rocky reefs (Tillmann and Siemann 2011).

The likelihood of hypoxia in coastal environments could increase under future global climate change as a result of warmer water temperature, more stratified waters, altered wind and upwelling patterns, which could enhance the transport of deep, low-oxygen waters onto the productive continental shelf, and ocean acidification, which can increase oxygen demand (Tillmann and Siemann 2011). Recent severe hypoxic events are consistent with how these systems are expected to change under future climate change, however, recent events have not as yet been formally attributed to climate change (Tillmann and Siemann 2011).

6.2.8 Harmful Algal Blooms

Harmful algal blooms (HABs) occur when certain phytoplankton species experience excess population growth ("blooms") and produce high levels of biotoxins. The toxin accumulates in fish and shellfish, which when consumed at certain levels (FDA-prescribed and therefore all three tribes collect samples for regular testing and public posting of levels) can make marine mammals, sea birds, and humans ill. No amount of preparation (e.g., freezing or cooking) reduces the risk. The main marine toxins from harmful algal blooms along the West Coast include domoic acid from certain *Pseudo-nitzchia* species, paralytic shellfish poison caused by *Alexandrium catenella*, and diarrhetic shellfish poison from *Dinophysis* species (NWFSC Harmful Algal Blooms). While HABs occur naturally, they are enhanced by warmer water temperature, stronger stratification, and higher nutrient inputs expected under climate change leading to more frequent, longer lasting HABs (Lopez et al., 2008; Moore et al., 2008). Changes in ocean circulation patterns and enhanced upwelling may also increase HAB occurrence (Lopez et al., 2008). An increase in HABs has been observed worldwide (Lopez et al., 2008).

Recent increases in HABs along the Washington coast since 1991 have resulted in commercial, recreational, and subsistence shellfish harvest closures with economical and cultural losses (Lopez et al., 2008). The large harmful algal bloom along the West Coast during the summer of 2015 (Doughton, The Seattle Times, "Toxic Algae Bloom") has rendered shellfish along the Washington and Oregon coast unsafe to eat and closed the crab fishery in Washington, Oregon, and California for much of the season. Such events could occur more often in the future. These events are noted amongst the members because of the large impact, both culturally and economically. Norman Capoeman (Quinault Indian Nation) recalls:

> *"I remembered like maybe ten or maybe fifteen years ago there was a red tide, a big ocean current that came through, in front of the northwest coast and it killed a lot of crab and a lot of bottom fish and I'm sure it killed a lot of salmon too in the ocean, but that was maybe like ten or fifteen years ago, and then it killed a lot of razor clams too."*

6.3 Ecosystem and Species Responses

Marine and coastal ecosystems are likely to respond to such drivers of climate change through altered nutrient cycling, ocean productivity, and food web dynamics. Coastal and nearshore habitats and ecosystems are likely to respond to climate change through altered patterns of coastal erosion and increased coastal squeeze (loss of habitat between rising seas and fixed shorelines), altered sedimentation patterns, habitat loss, degradation, and conversion.

The shallow estuaries along Washington's outer coast are crucial habitats for many culturally and ecologically important species, including juvenile salmon and larvae of various shellfish species. Estuaries may be impacted by climate change through changes in freshwater runoff, sedimentation, upwelling, ocean acidification, and sea level rise. The combination of these factors can influence nutrient levels, stratification, salinity, productivity, and habitat (Tillmann and Siemann 2011). Altered timing of freshwater input could "lead to a decoupling of the juvenile phases of many estuarine and marine fishery species from the available nursery habitat" (Tillmann and Siemann 2011). Primary production in the small coastal plain estuaries of the Pacific Northwest is driven by freshwater inputs as well as coastal upwelling, which may increase in the future (Tillmann and Siemann 2011). High productivity can also lead to more acidified waters via degradation of organic matter (Feely et al., 2012). Sea level rise could increase the salinity of estuaries and also inundate and erode estuarine and marine beaches that are important spawning habitat for forage fish (Tillmann and Siemann 2011).

Marine and coastal species, populations, and communities are likely to respond to changes in coastal and nearshore habitats by shifting ranges and distributions, altering phenology and development, shifting community composition, competition, and survival, and altering interaction with non-native and invasive species (Tillmann and Siemann 2011).

The Treaty of Olympia tribes are concerned about climate change impacts on marine species with major food chain importance and cultural, commercial, and subsistence significance (See Appendix A for a complete list of species and importance). Shellfish (e.g., clams, crabs, mussels) and finned fish (e.g., blackcod, and a number of species of rockfish, groundfish, flatfish, salmon, and smelt) are all important for food and livelihood of the tribes including the exercise of treaty fishing rights. Marine mammals (e.g., seals, sea lions, and whales), while no longer targeted per the Marine Mammal Protection Act, are important culturally and ecologically. Marine plants and algae are important for their key ecological roles.

6.3.1 Shellfish & Other Marine Invertebrates

Ocean acidification can reduce calcification and affect growth in shellfish and certain planktonic constituents of the food chain, making invertebrate fisheries and aquaculture highly vulnerable to climate change (Wong et al., 2014). The Treaty of Olympia tribes identified important mollusks including bivalves (clams, mussels), gastropods (snails, limpets, pteropods), and cephalopods (squid, octopus). Some crustaceans (crabs, barnacles) and echinoderms (sea stars, urchins) were also considered important. Clams (razor, little necks, butter), crabs (Dungeness, red rock), and mussels (California, blue) were determined to be the most important of the marine invertebrates concerning the Treaty of Olympia tribes (See Appendix A). Of these, razor clams and Dungeness crabs are important commercial fisheries.

Razor clams and Quinalt baskets. Photo courtesy Larry Workman, QIN.

While there is limited information on the expected response of individual species to ocean acidification, survival and growth for most phyla and classes of calcifying organisms, with the exception of crustaceans, will be negatively affected. However, different species may be more resilient than others depending on phenology and other factors (Tillmann and Siemann 2011). If shellfish populations decline or become too toxic to eat from increasing harmful algal blooms, then a shift in traditional food diet may be required as shellfish is a mainstay subsistence food for all Treaty of Olympia tribes.

Mollusks

The tolerance of mollusks to ocean acidification varies within the taxa. In general, both benthic and pelagic mollusks are considered vulnerable (negative effect for >5% of species) to ocean acidification due to reduced calcification and weakened calcified structures under elevated pCO_2 (Pörtner et al., 2014). However, cephalopods are considered tolerant (no affect for >95% of species) (Pörtner et al., 2014).

Bivalves

Clams, including razor (*Siliqua patula*), little necks (*Protothaca staminea* or *Leukoma staminea*), and butter (*Saxidomus gigantea*), and mussels, such as the California mussel (*Mytilus californianus*) are culturally important subsistence foods for the Treaty of Olympia tribes. The razor clam is also a major commercial species, especially for the Quinault Indian Nation. Bivalves are vital and have high cultural importance because of their use in regalia and other cultural items such as tools, or added to basketry or carvings. David Hudson gives an example of their importance, and use:

> *"I went a potlach party and they gave me a mussel shell. A mussel shell was used for like a harpoon, the blade part."*

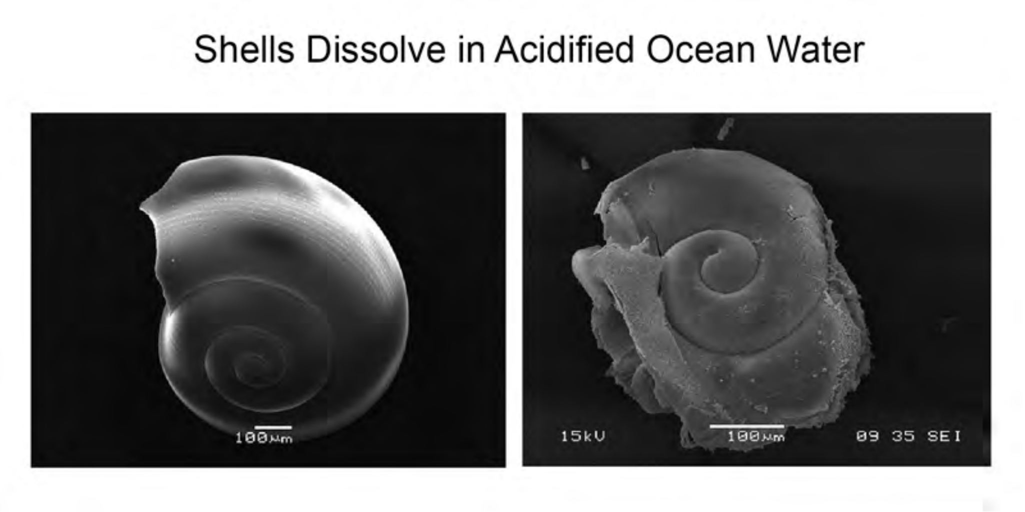
Bivalves are sensitive to elevated pCO_2, particularly during the larval and juvenile stages (Feely et al., 2012). California mussel larvae experienced slower growth under elevated pCO_2 conditions (Feely et al., 2012) and are expected to experience declines due to ocean acidification (Wootton et al., 2008).

Gastropods

Snails and limpets are traditionally gathered for food by Treaty of Olympia tribes. There is relatively limited information on climate change vulnerability of gastropods compared with bivalves. However, some adult limpets experienced higher calcification rates at moderately elevated pCO_2 levels, then falling to lower rates at higher pCO_2 levels (Pörtner et al., 2014).

Pteropods are calcifying zooplanktons (gastropods) that are important to the marine food web, especially as food for juvenile salmon. Ocean acidification reduces calcification in pteropods (Pörtner et al., 2014; Walsh et al., 2014b) (Figure 6.1). Future changes in pteropod population dynamics are unknown; however, off the coast of Vancouver Island, subarctic pteropods have declined and subtropical pteropods have increased over the past few decades (Feely et al., 2012).

Figure 6.1 *The photos show what happens to a pteropod's shell in seawater that is too acidic. The left panel shows a shell collected from a live pteropod from a region in the Southern Ocean where acidity is not too high. The shell on the right is from a pteropod collected in a region where the water is more acidic (Photo credits: (left) Bednaršek et al. 2012; (right) Nina Bednaršek). (Source: Walsh et al., 2014b)*



Cephalopods

The Treaty of Olympia tribes identified octopus and squid as important marine species. In general, cephalopods are considered tolerant (no affect for >95% of species) of ocean acidification (Pörtner et al., 2014). Another type of cephalopod, cuttlefish, grew stronger internal structures under elevated pCO_2 during the juvenile stage (Pörtner et al., 2014). The Humboldt squid is expected to extend its range northward (Sydeman et al., 2015).

Crustaceans

Crabs are a major commercial fishery for all three Treaty of Olympia tribes, especially the Dungeness crab (*Metacarcinus magister*), but also the Red rock crab (*Cancer productus*).

In general, crustaceans are considered tolerant (no effect for >95% of species) of ocean acidification (Pörtner et al., 2014), especially those that "inhabit fluctuating environments, such as estuaries and shallow coastal regions" compared with those "inhabiting more stable environments, such as deep sea regions" (Feely et al., 2012).

Calcification of crustacean carapaces (upper part of the exoskeleton) has been shown to either increase or remain unchanged in response to elevated pCO_2 levels, although maintaining this adequate calcification may require more energy (Feely et al., 2012). In larval crustaceans, however, elevated pCO_2 levels resulted in reduced calcification and weakened calcified structures (Pörtner et al., 2014). In one crab species, molting success was also reduced (Pörtner et al., 2014). Because of the high commercial importance of the Dungeness crab, more studies are underway to learn their particular response to ocean acidification (Feely et al., 2012).

Another crustaceous traditional food source for Treaty of Olympia tribes is gooseneck barnacles (*Pollicipes* spp.), which are expected to decline in abundance and mean size with declining pH (Wootton et al., 2008).

Echinoderms

On Washington's outer coast, echinoderms promote biodiversity within intertidal communities (Feely et al., 2012). The main importance to the Treaty of Olympia tribes of sea stars, such as the Sunflower sea star (*Pycnopodia helanthoides*) and the Ochre sea star (*Pisaster ochraceus*), and sea urchins, such as the Green (*Strongylocentrotus droebachiensis*), red (*S. franciscanus*), and purple (*S. purpuratus*), is ecological, however, sea urchins were traditional food sources and are still consumed currently, but to a lesser extent.

Ochre sea stars. Photo courtesy Larry Workman, QIN.

In general, echinoderms are considered vulnerable (negative effect for >5% of species) to ocean acidification because of reduced calcification and weakened calcified structures under elevated pCO_2 levels (Pörtner et al., 2014). Some sea urchins experienced greater calcification rates at moderately elevated pCO_2 levels, but lower rates at even higher levels (Pörtner et al., 2014). Sea urchins are likely to experience reduced survival and growth in response to ocean acidification, particularly for juveniles (Feely et al., 2012). Ocean acidification could also challenge reproductive success of the red sea urchin, for example (Feely et al., 2012). Changes in population dynamics from ocean acidification "could have strong domino effects on ecosystems" (Feely et al., 2012).

6.3.2 Marine Finned Fish

Marine finned fish are important economically (rockfish, commercial groundfish and trawl fisheries), ecologically (seasonality and distribution of marine fish important to the food chain of salmon, birds, and mammals), and culturally (subsistence, exercise of treaty rights) for the Treaty of Olympia tribes. Among the most important species include blackcod (sablefish), lingcod, several species of rockfish, halibut, flounder, Pacific sanddab, sardines, several species of salmon, and various species of smelt (See Appendix A for a complete list of important species).

Fisheries will exhibit varied responses to changing water conditions (e.g., temperature, hypoxia, food source) depending on differences in vulnerability and adaptive capacity (Pörtner et al., 2014). As temperatures warm, the range of many marine fishes is projected to shift poleward in the Northeast Pacific (Cheung et al., 2015). An influx of warm water species is also expected (Cheung et al., 2015), such as mackerel, Bluefin tuna, dorado, and mola mola, which have been seen off the Olympic Peninsula's Pacific coast more frequently (J. Schumacker, per. comm.). Species assemblages are projected to change potentially resulting in mis-matches between co-evolved species, which could cause cascading effects up the marine food web, and shifting of traditional fishing grounds (Cheung et al., 2015). This could mean that fishermen would have to travel longer distances to maintain traditional fisheries or establish a new fishery among the shifted species assemblage.

Recruitment of many marine fish species is influenced by ocean climate variability, which will continue to influence year-to-year fish abundance in a warming world. The Pacific Decadal Oscillation (PDO) is a major sea surface temperature index of ocean climate variability in the North Pacific. During warm phases of the PDO many fish species thrive such as sablefish (blackcod), some rockfish, halibut, arrowtooth flounder, and sardines. Future warming conditions may increase abundance and expand the territory of such species (Tillmann and Siemann 2011). However, disruption in the marine food chain from ocean acidification and other changes in ocean conditions would complicate the response. During cool phases of the PDO, other fish species thrive such as anchovies, salmon (e.g., Coho), Pacific sanddab, and Pacific herring (Tillmann and Siemann 2011).

Species that inhabit nearshore habitats, such as juvenile salmon and forage fish (e.g., Pacific herring, surf smelt, Eulachon) may experience greater impact from climate change. They may be impacted more greatly by storms and higher wave action, by sediment loads from flooding streams, by temperature increases in these shallower waters, or by enhanced ocean acidification as can occur with the addition of terrestrial inputs (Feely et al., 2012). Ocean acidification can cause neurological behavior disturbances in larvae and juvenile fish possibly threatening survival in predator-rich nearshore environments (Pörtner et al., 2014; Ou et al., 2015). Fish are an important cultural aspect for the tribes. Many members identify as fishermen, or coming from fishing families where fish are incorporated into cultural and economic identity. David Hudson explains:

> *"As a former fisherman down in Hoh River, you used to be able to see a lot of fish as you walked across the creek. Some were on their backs, there were so much fish."*

Below we summarize existing information on climate change vulnerability for the marine finned fish species of interest to the Treaty of Olympia tribes:

Salmon

Pacific salmon (*Oncorhynchus spp.*) are important culturally, economically, and for subsistence for the Treaty of Olympia tribes. The climate change vulnerability in the freshwater and marine stages is discussed in more detail in Chapter 4: Freshwater Environment, but during the ocean phase salmon can also experience climate change impacts. “Warmer waters are likely to promote increased populations of Pacific salmon in Alaska while promoting decreased populations elsewhere” along the West Coast (Tillmann and Siemann 2011). Delayed upwelling may result in lower survival of coho and Chinook salmon due to delayed plankton production (Tillmann and Siemann 2011). A reduction in pteropods, a main marine food source for salmon, due to ocean acidification could reduce salmon growth (Tillmann and Siemann 2011). Nearshore habitats for rearing juvenile salmonids, such as pink, chum, and Chinook, may decline with increasing sea levels (Tillmann and Siemann 2011). David Hudson discusses the changes he has seen in recent decades to present:

> *“I just know I have and have not seen Springers and caught like that as it used to be in the late 80’s, late 90’s.”*

Sablefish

The sablefish (blackcod) (*Anoplopoma fimbria*) is a big money fish for all in the Treaty of Olympia area and is avidly fished by all Washington outer coast tribes by management agreement. Recruitment of sablefish in Canada’s Pacific thrives in warm conditions, but not in California. Thus, warming may benefit northern stocks of sablefish (Okey et al., 2014). In addition, the sablefish’s tolerance for low oxygen conditions may help this species expand its territory (Tillmann and Siemann 2011). Sablefish is a long-lived species and thus may be more resistant to short-term climate variability, but slower to adapt to long-term changes than species with short life spans (Okey et al., 2014).

Rockfish Species

Rockfish are important commercial and subsistence fish for the Treaty of Olympia tribes. Many species are listed under the Endangered Species Act and non-listed species are limited. Below the 48th parallel, warm phases of the PDO were associated with lower rockfish abundance (Tillmann and Siemann 2011). Some rockfish may benefit during warm phases farther north, such as the Pacific Ocean perch (*Sebastes alutus*) (Okey et al., 2014). Delayed upwelling season has been associated with rockfish declines (Tillmann and Siemann 2011). Some rockfish tolerate low oxygen conditions, which may help them expand their territory under increased hypoxic conditions (Tillmann and Siemann 2011).

Halibut

Pacific halibut (*Hippoglossus stenolepis*) is a commercial fishery for all Treaty of Olympia tribes. Recruitment thrives in warm PDO conditions and thus might benefit from future climate warming, although southward migration of halibut from Alaska may be reduced (Okey et al., 2014).

Halibut fishing. Photo courtesy Katie Krueger, Quileute.

Flounder

The Hoh Tribe used to harvest the Starry flounder (*Platichthys stellatus*), but it has been diminishing. Arrowtooth flounder catch increased in the Gulf of Alaska upon the 1976/1977 shift to warm PDO conditions (Tillmann and Siemann 2011). Dave Hudson elaborates:

> *"We used to get flounder which don't happen nowadays, as well as steelhead. I don't know what it is but all I can see is, it's not there. Those are the real things that I've seen especially the flounder, over the years. So I don't know, just gut instinct tells me the ocean conditions.*

Pacific Sanddab

The Pacific sanddab (*Citharichthys sordidus*) is an important commercial fishery. Off the central Oregon coast, the sanddab was more abundant during cool PDO conditions (Brodeur et al., 2008).

Sardines

The Quinault Indian Nation harvests sardines (*Sardinops sagax caerulea*) commercially, though they are rare in the Quillayute River nearshore harvest area. Sardines thrive during warm PDO phases and are likely to increase in abundance under future warming conditions (Okey et al., 2014).

Lingcod

Lingcod (*Ophiodon elongatus*) is commercially harvested by all three tribes. Their eggs used to be collected from washed up kelp, but the tribes rarely see lingcod eggs now. Lingcod abundance is influenced by ocean variability (Okey et al., 2014) and they also derive a substantial portion of summer diet from herring eggs in eelgrass beds. The eelgrass beds may benefit from ocean acidification, but suffer from warmer temperatures (Tillmann and Siemann 2011).

Smelt

Smelt are forage fish that are culturally fished for food, especially surf smelt (*Hypomesus pretiosus*) and night smelt (*Spirinchus starski*), and longfin smelt (*Spirinchus thaleichthys*). Eulachon (*Thaleicthys pacificus*) is traditionally fished, but now is listed as a threatened species under the Endangered Species Act. In recent years, the tribes are seeing declines in smelt, especially surf smelt. Sea level rise could cause a loss of habitat for spawning surf smelt (Tillmann and Siemann 2011). Eulachon spawning is sensitive to shifts in spring freshets (Okey et al., 2014).

Lamprey

The Pacific lamprey (*Lampetra tridentata*) is culturally important, particularly to the Quinault Indian Nation. It has been in decline along the West Coast and climate change may exacerbate current threats through changes in water flow and stream conditions, ocean conditions, disease and predation (Tillmann and Siemann 2011).

Pacific lamprey. Photo courtesy Larry Workman, QIN.

Pacific herring

The Pacific herring (*Clupea harengus pallasi*) is a forage fish whose eggs were traditionally collected from eelgrass beds for food, but the eggs haven't been seen in years. The Pacific herring is in higher abundance with cooler water conditions. In addition to warming waters, increased predation by Pacific hake in Canada's Pacific may result in abundance declines (Okey et al., 2014).

Pacific hake

Pacific hake (*Merluccius productus*) is an open ocean fishery, but only the Makah Tribe currently exercises treaty fishery rights off Washington's outer coast. Chinook salmon bycatch are a problem with this fishery. Pacific hake could expand their range northward in warming conditions (Okey et al., 2014).

Anchovies

Anchovies (*Engraulix mordax*), another forage fish, are a current food source for people, birds, marine mammals, and juvenile fish. They are abundant in the Quillayute River nearshore environment. In many years they are found throughout the Washington coast including estuaries and lower river areas. Anchovies tend to thrive in cool conditions (Tillmann and Siemann 2011). Anchovies, because of their feeding habits, take in significant amounts of algae and, during harmful algal blooms, may adversely impact the fish or mammals that prey on them.

Pacific mackerel

The Pacific mackerel (*Trachurus symmetricus*) is an ocean fishery in the California Current and its range may expand northward in warming conditions as during warm PDO phases, thereby increasing salmon predation (Tillmann and Siemann 2011).

6.3.3 Marine Mammals

Marine mammals were historically targeted for subsistence and cultural practices, but the Marine Mammal Protection Act now generally prohibits a targeted marine mammal fishery, except for Alaskan native communities. The Treaty of Olympia tribes identified certain species of whales, seals and sea lions, porpoises, and the sea otter as ecologically and culturally important species (See Appendix A). The most important species culturally include: gray whales, orcas, harbor seal, and northern fur seal. Culturally, these species are important and play a vital role in the maintenance of culture. Richard Allen explains:

> *"There's mainly animals songs there's two songs I know about the fish in the river, there's one for the ocean for the whales."*

Climate change is likely to impact marine mammals indirectly through disruption in food availability and prey communities (Okey et al., 2014).

Cetaceans

Humpback (*Megaptera novaeangliae*) and gray (*Eschrichtius robustus*), whales are seasonally migrant to the North Pacific and Arctic to feed in the highly productive waters during the warm season (Tillmann and Siemann 2011). As the Arctic warms and sea ice declines, the whales are likely to range farther north and stay longer (Moore and Huntington 2008; Kovacs et al., 2010).

Whales are an important part of the culture, with families identifying as whalers or whaling families. Doug James states: “My family ancestors, we come from a family of whale hunters.” This enhances the cultural identity many of these tribal members know and have regarding TEK of whales and the process. Doug James explains that they are not allowed to actively go whaling, but the TEK remains intact:

> *“we don't get to. There's a lot that goes with it, like preparing, getting ready we talked with some of the whalers, my cousin talked with a lot of the guys up there getting ready, they did a lot of work, a lot bathing and a lot of eating right and changing and your mind and your body, and waiting for signs.”*

This process is clearly not lost, and the members who are not active are still participating in the knowledge, as well as supportive of the cultural attributes that accompany a whaling lifestyle. Doug James explains there are prayer and traditional storytelling that remain intact and continued:

> *“There's a few whaling songs up and down the coast, you'd have to talk with specific people because they belong to (them). One's a Wheeler song coming from Hoh River, one comes Quileute. They're usually sang for gatherings and stuff, and they have prayers and stuff, there's stories of the Thunderbird... when I was little that was one of our stories, because we'd get scared and jump under the covers (from thunder), and she'd be like it's just Thunderbird hunting for the whale, and thunder is his wings flapping, and he's just going to go get food (whale)"*

Leaping Humpback whale. Photo courtesy Larry Workman, QIN.

Humpback

Some humpback whales have remained offshore of Alaska over winter in response to availability of herring; this demonstrates their ability to adapt migration habitats (Moore and Huntington 2008).

Humpback whales have been recovering well in waters off Washington State and have been observed regularly off the coast when forage fish schools are present (J. Schumaker, pers. comm.).

Gray

Historically, gray whales were hunted for food. They are also important culturally; for example, the Quileute Tribe has a ceremony to welcome the gray whales. Increases in river runoff and turbidity could lead to decreases in benthic food sources for gray whales (Okey et al., 2014), but gray whales are generalist feeders and may be able to adapt to new food sources (Kovacs et al., 2010).

Orca

Orcas are a central part of Quileute mythology and the transients (residents are salmon eaters) are also important ecologically as a top predator of sea lions, for example. Killer whales are sensitive to variations in ocean climate and alterations to the quantity and quality of salmonids, a main food source (Okey et al., 2014). Three distinct forms, or ecotypes, of Orcas are recognized in the eastern North Pacific: resident, transient, and offshore types. The three types differ in morphology, ecology, behavior, and genetics. An important difference between the ecotypes is their preferred food source. Residents prefer fish (salmonids); transients prefer marine mammals; and offshore Orcas are presumed to prefer fish (including sharks) (Ford et al., 2000).

Orca. Photo courtesy Robert Pittman/NOAA, Public Domain.

Porpoises

The Dall's and Harbor porpoises were noted as important by the Treaty of Olympia tribes, but there is little information is available on their climate change vulnerability.

Pinnipeds & Fissipeds

Pinnipeds and fissipeds stand to be affected by climate change through changes in sea temperature, sea level, incidence of storm surge, ocean acidification, loss of glacial ice, and alterations in oceanic processes such as the frequency of El Nino events. These climatic changes can result in loss of habitat needed for resting or birthing, alterations in prey availability, and range shifts (Allen et al., 2011). Climate change is likely to shift food sources (Lurgi et al., 2012), which may result in longer travel times from usual nesting and resting grounds in order to find food. Climate change may shape the distribution of genetic diversity of pinnipeds (Phillips et al., 2011) and may put sea lions at a greater risk of disease in the future (Griffis and Howard, 2013).

Pacific harbor seals

Historically, Pacific harbor seals (*Phoca vitulina richardsi*) were hunted for food both commercially and for subsistence. They exhibit characteristics of lower vulnerability to climate change such as the currently stabilizing or increasing populations (Kovacs et al., 2012) and generalist behavior with respect to adapting to diverse habitat areas (Allen et al., 2011).

Northern elephant seal

The northern elephant seal (*Mirounga angustirostris*) has stable or increasing populations (Kovacs et al., 2012), but low genetic diversity (Davidson et al., 2012).

Northern fur seal

In contrast, the northern fur seal (*Callorhinus ursinus*) population is currently declining in the Pribilof Islands and climate change, regime shifts, and killer whale predation are considered major threats second to indirect fishery interactions (Kovacs et al., 2012). Historically, the fur seal was hunted commercially by the Quileute Tribe.

California sea lion

California sea lions (*Zalophus californianus*) exhibit generalist feeding behaviors through changing the composition of their diets from squid, anchovy, and rockfish to sardines, rockfish, and hake species (Lurgi et al., 2012). The sea lions also prey on salmon, sometimes right from the fisherman's net. California sea lions exhibit population resiliency as they have recovered quickly from declines in recent strong El Nino years (Kovacs et al., 2012). Sea lions are also susceptible to domoic acid poisoning from ingesting prey that has fed on toxic algal blooms (e.g., Seattle times article from June 2015). Such harmful algal blooms may increase with climate change.

Stellar sea lion

The native Stellar sea lion (*Eumetopias jubatus*) is protected under the Endangered Species Act. It preys on salmon, but less so than the California sea lion. Little information is available its climate change vulnerability.

Sea lion near Cape Elizabeth. Photo courtesy Larry Workman, QIN.

Sea Otter

The sea otter (*Enhydra lutris*), a fissiped, is a protected species that preys on sea urchins helping to limit the harm sea urchins can cause to kelp forests. In the scarcity of urchins, sea otters also feed on Dungeness crab and razor clams near Destruction Island. Little information is available on its climate change vulnerability, but it may be impacted by changes in food source and possibly harmful algal blooms.

Sea Otter and pup. Photo courtesy Larry Workman, QIN.

6.3.4 Marine Plants & Algae

Macroalgae

Seagrasses and macroalgae are at the bottom of the marine food web and are important for nutrient cycling processes (Koch et al., 2013). Macroalgal beds form key ecosystems in coral reefs, lagoons and other shallow habitats including intertidal and subtidal coastal areas (Wong et al., 2014). Macroalgae can be classified as calcareous (calcifying) or fleshy (non-calcifying). The Treaty of Olympia tribes are concerned with various types of fleshy macroalgae, such as brown algae (sea palm, lamineria, bull kelp, feather boa kelp, giant brown kelp, rockweed), green algae (sea lettuce), and red algae (Turkish towel) (See Appendix A). Kelp beds are a major habitat for marine fish harvested by the tribes.

Macroalgae, like all organisms, live and function optimally in specific temperature ranges (Pörtner et al., 2014). Shifts in macroalgal species due to increasing sea surface temperatures is already documented in temperate and tropical biogeographic regions (Koch et al., 2013). Temperate macroalgae species are better able to acclimatize to the large seasonal temperature changes and thus are less vulnerable to climate warming than tropical or polar macroalgae, which have adapted to limited temperature ranges (Pörtner et al., 2014).

Elevated levels of CO_2 and ocean acidification may counter some of the negative effects of warming on macroalgae by enhancing production in macroalgae through the CO_2 fertilization effect (Pörtner et al., 2014). In controlled experiments, production, growth, and recruitment increased for many fleshy seaweeds under high CO_2 conditions (Pörtner et al., 2014). Fleshy macroalgae photosynthesis and growth are generally considered to benefit from projected climate change and OA whereas calcareous macroalgae growth is considered vulnerable and threatened by OA (Pörtner et al., 2014). Kelp forests provide habitat for a number of target fish so enhanced growth in kelp forests may benefit such target fish, but the target fish also will be challenged by loss of food for juveniles, as discussed above.

Information on how individual species of macroalgae may respond to climate change is limited, but most fleshy macroalgae (e.g., Lamineria, sea lettuce) and sea grasses are likely to thrive under climate change and ocean acidification due to their low vulnerability to dissolution and ability to use additional dissolved inorganic carbon for photosynthesis and growth (Koch et al., 2013). Communities may become more dominated by fleshy macroalgae under higher OA conditions in the future (Koch et al., 2013).

Microalgae

Phytoplanktons include minute plants and other photosynthetic organisms, such as cyanobacteria, diatoms, and dinoflagellates, that form the base of marine food web. Different phytoplankton types perform different and essential functions in the marine ecosystem so changes in the phytoplankton community can lead to cascading effects on the marine food web. Excess growth of some species of phytoplankton can result in harmful algal blooms that can produce toxins harmful to the marine life and humans that consume the toxin through bioaccumulation up the food chain.

Predicting the response is challenging for several reasons, but one reason is that there are several thousand species of phytoplankton and each one responds a little differently. The makeup of phytoplankton communities is projected to change substantially due to warming, with an average poleward shift in phytoplankton range, and differing responses to ocean acidification spurring competition among species (Dutkiewicz et al., 2015).

The tolerance of phytoplankton to ocean acidification varies between and within taxa. In general, however, ocean acidification is considered beneficial (positive effect for most species) for nitrogen-fixing cyanobacteria (Pörtner et al., 2014). Coccolithophores, calcifying phytoplankton, are considered vulnerable (negative effect for >5% of species) to ocean acidification due to their need to form shells, though the response among species is highly varied (Pörtner et al., 2014). Diatoms and dinoflagellates are considered tolerant (no affect for >95% of species) of ocean acidification (Pörtner et al., 2014).

Many of the phytoplankton species responsible for harmful algal blooms (certain species of diatoms and dinoflagellates) are sensitive to ocean acidification and can produce higher toxin levels under elevated dissolved carbon dioxide (pCO_2) (Pörtner et al., 2014). Increasing ocean temperatures can also result in more frequent harmful algal blooms (Reeder et al., 2013).

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Chapter 7: Conclusions

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7.1 Key Findings

Climate change will affect tribal quality of life in a number of ways. Changes across the landscape (including the marine and freshwater environments) will necessitate changes in cultural practices; tribal economies (which include natural resource based industries) will need to adapt to new conditions; and subsistence living practices will be impacted. In this assessment, we addressed the climate change vulnerability of the forests and prairies, freshwater resources (such as wetlands, streams, and lakes), coastline, and ocean within the Treaty of Olympia area on the western Olympic Peninsula, along with the associated plant and animal species most important to the Quinault Indian Nation and the Hoh and Quileute tribes. Identification of key climate change vulnerabilities can help guide natural resource managers in developing the best strategies for managing and conserving the landscape and resources in light of both climate change and existing stressors (Glick et al., 2011). It will also serve to develop projects for implementation. Here, we highlight key findings within the terrestrial, freshwater, coastal, and marine environments.

Key findings in the Terrestrial Environment chapter include:

- Forests are sensitive to temperature and precipitation changes as well as changes in disturbance regimes such as increasing wildfire activity, increasing insect and disease outbreaks, and competition with invasive species.
- Bogs, fens, wet meadows, isolated ponds and wetlands near headwater streams and alpine ecosystems are more vulnerable to climate change than wetlands with sustained water sources (assuming no degradation in the quality of these sources).
- Prairies—traditional gathering areas and foraging grounds—are vulnerable to climate change through changes in hydrology and increased pressure from invasive species.
- Limited dispersal ability and high sensitivity to disturbance regimes were the most common factors contributing to the climate sensitivity of identified trees species.
- Changes in disturbance regimes will be major factors as to where western hemlock grows in the future.
- A species' vulnerability to climate change is not the same as its sensitivity to climate change.
- Big leaf maple and red alder were least sensitive to climate change due to their wide climatic range and good dispersal ability; their vulnerability was also low.
- Sitka spruce was most sensitive to climate change due to its restricted coastal range, physiological sensitivity to temperature and precipitation, poor dispersal ability, and high sensitivity to disturbances; but its vulnerability was low.
- Understory vegetation could increase as a result of overstory die-offs; however, pressure from invasive species will limit habitat quality and the effect on individual species (e.g., berries) is largely unknown.
- Elk, black bear, and black-tailed deer had the largest projected declines in current habitat assessed over their entire range, but on the Olympic Peninsula suitable habitat is projected to remain stable for black-tailed deer, increase at high elevations east of the Olympics for black

bear, and decline for elk. Cervids browsing on forbs of the prairie or forest floor may be adversely impacted by any decline in these native plant species.
- Suitable habitat on the Olympic Peninsula is projected to remain stable or increase for the birds assessed. The birds of greatest importance to the tribes (e.g., bald eagle, raven) were considered least vulnerable to climate change due to their large range and projected stable or increasing suitable habitat on the Olympic Peninsula.
- Migratory birds had the highest climate change sensitivity due to specific food and habitat requirements.

Key findings in the Freshwater Environment chapter include:

- Pacific salmon will be affected by warmer streams, lower summer flows, and higher winter flows in the Treaty of Olympia area watersheds. It is likely that changes in the marine environment will also present a major challenge for the salmon.
- Warmer, more acidic marine waters will disrupt the marine food web and thermal habitat supporting salmon resulting in fewer and smaller returning adults hindering reproductive success.
- Warmer stream temperatures in summer could reduce growth of juveniles and survival over winter, but increased growth rates under warmer waters in other seasons could offset this. Warmer water could also increase predation by and competition with warm-water fish, and increase susceptibility to pesticides and disease.
- Reduction of pools of cool water for holding and migrating may diminish reproductive potential and increase pre-spawning mortality, especially for spring Chinook and summer steelhead.
- High quality habitat area for Chinook salmon in the Queets River and Quillayute River basin is most vulnerable to projected summer water temperature increases.
- Lower summer flows could affect smolt migration and delay spawning migration.
- High quality habitat area for Coho and Chinook salmon in the Hoh River, and for Chinook in the Quillayute River basin is most vulnerable to reduced summer flows.
- Depending on the stream characteristics, higher winter flows could increase risk of scouring of eggs and juveniles, especially for summer steelhead.
- Medium and high quality habitat areas for Coho, Chinook, and Steelhead in the Quillayute River basin are most vulnerable to increases in winter flows.

Key findings in the Coastal Hazards chapter include:

- Sea level rise and increasing wave heights combined with storm surge, high tide, seasonal and interannual variability will create erosion and flooding hazards to varying degrees along the Treaty of Olympia coastline.
- By 2050, sea level is projected to increase by up to nearly 20” under the high scenario and decrease by almost 4” under the low scenario taking into account uncertainty in regional tectonics.
- The beach segments from south of Ozette Lake to Rialto Beach, along the Quileute reservation, and Ruby Beach to the Queets River experience erosion regime during the majority of the year largely due to steep beach slopes and low dune toes.

- The beach segment from Ruby Beach to the Queets River and areas within the Cape Alava to Rialto Beach segment experience the largest increases in impact days per year (erosion regime).
- The overtopping (or inundation) regime is rarer, but is most common near Kalaloch and some parts of the Taholah area where it occurs about 100 days per year.
- The Cape Alava to Rialto Beach segment and the Hoh Reservation coastline experience the largest increases in overtopping days per year, but the overtopping regime remains infrequent due to the preponderance of cliffs and bluffs backing the coastline.
- The highest yearly total water level event increases annual maximum TWL event increases under all SLR scenarios for the Hoh, Quileute, and Quinault coastlines, but
- Extreme high water events increase all along the coastline, but the Hoh coastline may receive the largest increases in the annual maximum total water level event due to the overall steeper beaches.
- The three-meter beach contour is inundated every day of the year during the maximum daily total water level under the high sea level rise scenario, the largest change being in the southern extent of the Quinault area, forcing some intertidal species to shift landward.

Key findings in the Marine Environment chapter include:

- The combination of ocean acidification, warming waters, altered freshwater hydrology, rising seas, increasing storminess, upwelling, hypoxia, and harmful algal blooms will substantially change the marine and coastal nearshore environment leading to changes in marine species ranges, abundances, phenology, and community composition.
- Many species' ranges will shift northward with warming waters increasing competition between native and invasive species.
- Rising seas and increased storminess will increase risks of coastal erosion and flooding leading to coastal habitat loss.
- Ocean acidification will increasingly challenge the calcifying organisms at the base of the marine food web causing cascading effects on marine fish, birds, and mammals.
- The combination of ocean acidification, altered upwelling, sea level rise, and changes in freshwater runoff (including increased sedimentation and pollutant loads, which are not strictly climate related) could substantially alter the quality of crucial estuarine habitat.
- Harmful algal blooms are expected to increase in frequency in the future leading to greater risks to marine mammals, birds, and humans who harvest or consume shellfish or anchovies for subsistence or commercially.
- Survival and growth for most calcifying organisms will be negatively affected by ocean acidification, though the response varies by species and life stage. In general, calcifying mollusks and echinoderms are more vulnerable to ocean acidification than crustaceans.
- Marine fisheries will exhibit varied responses to changing water conditions, food sources, and new species assemblages, but in general, future warming may favor fisheries that currently thrive during warm periods such as sablefish, halibut, and sardines.
- Marine mammals may range farther north with warming waters, lose habitat from sea level rise, but the biggest impact will likely be from changes in marine food supply. Most mammals may be able to adjust migration or feeding habits to adapt to changes.

- Kelp forests may benefit from climate change through enhanced growth due to the fertilization effect of increased dissolved carbon dioxide (ocean acidification).
- Phytoplankton communities are likely to change substantially due to warming and, while the response is species dependent, ocean acidification is likely to challenge calcifying phytoplankton (coccolithophores), benefit cyanobacteria, and have minimal effect on diatoms and dinoflagellates. Many of the phytoplankton species responsible for harmful algal blooms can produce higher toxin levels under elevated dissolved carbon dioxide.

7.2 Knowledge & Data Gaps

The research on climate change impacts and vulnerability of species and ecosystems and localized areas is accelerating, but several knowledge and data gaps remain. Filling the gaps in understanding how the species and ecosystems important to the culture and economy of the Treaty of Olympia tribes will respond will be important for building resiliency to climate change impacts. Here, we list knowledge and data gaps encountered throughout this project.

Data and knowledge gaps in the Terrestrial Environment chapter include:

- Range projections for certain key species such as salmonberry, huckleberry, native blackberry, strawberry, cranberry, and other traditional foods and snowshoe hares, seagulls
- Lack of climate change sensitivity information for yellow cedar, black cottonwood, snowshoe hares, black tailed deer, black bear, cougar, seagulls
- Localized wildfire projections for the Olympic Peninsula
- Role climate change plays in invasion of particular non-native species in particular areas (Burgiel et al., 2014)
- Role of climate change in exacerbating diseases among animal species (e.g., tularemia in beavers, hoof disease in elks)
- Role of climate change in exacerbating tree pests and pathogens (especially for big leaf maple, Pacific yew, Western white pine, western hemlock, western red cedar, salal)
- Limited knowledge about the climate sensitivity of Sitka spruce, Western white pine, Western red cedar, Pacific Yew, lodgepole pine, Western hemlock, big leaf maple, and red alder in light of climate change
- Limited understanding of how wind storms might change as important disturbance agents for Pacific yew and Sitka spruce
- Competition among tree species following disturbances in light of climate change
- Limited knowledge about physiological sensitivity of Canada goose, brown pelican, and Harlequin ducks to changing temperatures and precipitation
- Climate change effects on spread of avian diseases among migrating birds (Fuller et al., 2012)
- Lack of information on climate change vulnerability of understory species, for example huckleberries, salmonberries, native blackberry, strawberry, cranberry, beargrass, Indian tea (a native rhododendron), skunk cabbage, forbs, devil’s club, Nootka rose, cascara, and mushrooms compared with tree species.

Data and knowledge gaps in the Freshwater Environment chapter include:

- Projections of stream water temperatures during fall, winter, and spring and the potential impacts on salmon
- Limited understanding of the relationship between streamflow changes and growth and survival of salmonids (Bradford and Heinonen 2008)
- Data on the variability in preferred spawning location during low and high winter flow years and the potential scouring or sediment loading risks
- Limited knowledge about the role of genetic variation and the ability of natural populations to respond adaptively to current and future environmental change (Gienapp et al., 2005)
- Uncertainty in how steelhead may respond to climate change due to the two life-history expressions (anadromous and resident)
- Unclear role of hatcheries in helping to meet the challenges of climate change
- Comprehensive analysis of climate change impacts on each Pacific salmon run in the study area
- Projected impacts of climate change on lakes in the study area
- How new assemblages of native and non-native species will interact (Montoya and Raffaelli 2010)

Data and knowledge gaps in the Coastal Hazards chapter include:

- Lack of consensus about how modes of climate variability (e.g., El Niño-Southern Oscillation) will respond to climate change
- Lack of lidar data at some inlet mouths or bluffs that lead to gaps in shoreline information
- How terminal fishing grounds will be affected by sea level rise, stream inflow and river mouth geomorphology, which is beyond the scope of this project
- Verification of beach type and backshore features since a site visit for ground surveys was beyond the scope of this project
- Locations dominated by exposed, bedrock, wave-cut platforms were not analyzed
- Local sea level rise estimates accounting for local vertical land motion, also beyond the scope of this project
- How changes in the erosion and inundation regimes from climate change will affect specific shorebird, forage fish, and shellfish (razor clams) habitat
- Prediction of actual erosion rates (a complex task never proposed as a deliverable for this project); estimation of changes in impact days per year is used as a proxy for erosion potential along the coastline

Data and knowledge gaps in the Marine Environment chapter include:

- Limited information on how individual species important to the Treaty of Olympia tribes will respond to ocean acidification (e.g., Dungeness crab, forage fish) and other climate related changes in the ocean
- How the marine food web might be altered
- How species assemblages (both native and non-native) will shift
- How the distribution of traditional marine fisheries (e.g., shellfish, finned fish) may change and the implications for tribal treaty fishing rights

- Lack of consensus regarding future changes in storms and wave heights
- Future projections of regional changes in ocean circulation, coastal upwelling, hypoxia, nutrient cycling, and ocean productivity in the California Current system (Tillmann and Siemann 2011)

7.3 Next Steps in Climate Change Preparation

Adapting to climate change involves reducing vulnerability to expected impacts. It is an iterative and collaborative process that begins with identifying and understanding key vulnerabilities. The next step is to plan strategies to respond to existing and future climate change impacts (Bierbaum et al., 2014). The key vulnerabilities identified in this report will serve as priority areas for the Treaty of Olympia tribes to begin investigating options to reduce vulnerabilities and enhance resilience to climate change.

Often the first approach to climate adaptation involves gathering information and building capacity (Tillmann and Siemann 2011). Conducting a vulnerability assessment is a key component in this stage, but other actions include gathering or conducting additional research to fill key knowledge gaps such as those outlined in the previous section, increasing organizational capacity through enhancing technological resources and job training, and building partnerships and engaging the community (Tillmann and Siemann 2011). Shared coastlines and competition for common resources increases the motivation for tribes to work cohesively on the impacts that are occurring within the tribal regions.

Another approach to climate adaptation includes monitoring key components of the ecosystem by developing climate change indicators (see discussion in Chapter 4: Freshwater Environment) and planning for climate change by incorporating expected climate change impacts into existing and proposed management and development plans (Tillmann and Siemann 2011), such as the proposed Upland and Riparian Forest Management Corridors forest management approaches on the Quinault Indian Reservation. The uncertainty inherent in climate projections need not preclude their incorporation into existing plans, but can be accommodated through scenario-based planning and adaptive management (Tillmann and Siemann 2011).

Increasing resilience of infrastructure and development, particularly on the shoreline, is a critical adaptation approach (Tillmann and Siemann 2011). Infrastructure risks from sea level rise and coastal hazards were not examined in this vulnerability assessment, however, they will be investigated in a separately-funded, subsequent project involving the authors of Chapter 5: Coastal Hazards.

Adapting governance, policies, and laws is another approach for increasing community resilience to climate change (Tillmann and Siemann 2011). Salient examples of this process already underway include: the Quinault Indian Nation is considering moving its main village away from the encroaching seas; the Quileute Tribe is in the process of moving its village to higher ground after federal legislation doubled the size of its reservation (PL 1112-97 of 2/27/12); and the Hoh Tribe had similar federal legislation adopted in December of 2010. Other actions include developing preparedness plans that include risks from climate change and reviewing and enhancing existing laws and regulations or creating new ones to reduce barriers to implementing adaptation actions (Tillmann and Siemann 2011).

Finally, conservation, restoration, protection, and natural resource management of species and habitats in light of projected climate change is perhaps the most important adaptation approach for the Treaty of Olympia tribes. Common adaptation actions include maintaining shorelines, sediment, and water quality, preserving habitat for vulnerable species, managing invasive species, and reducing non-climate stressors that climate change is likely to exacerbate (Tillmann and Siemann 2011).

7.4 Traditional Ecological Knowledge

A comprehensive understanding of the climate change vulnerability of the landscape, surrounding waters, and plant and animal species is important for maintaining traditional culture and lifestyle. David Hudson summarizes it well when he stated:

> *"Our traditional uses - that has to do with the ocean, from waterways, to our highways. All the foods that we eat and I know its not just the tribes but the communities as well. We all use the resources out there. So, it's all important to each one of us, I believe, in their own different ways, that we utilize the resources, food or regalia."*

The TEK of the tribal members of all three Treaty of Olympia tribes is expansive, and not fully documented yet. The Quileute Tribe is under a separate EPA program researching its TEK. This project did not undertake a full TEK study, but provided references to it when available and applicable. Western science is a critical component in understanding future climate change impacts, however, it is limited. More fully conducting and integrating TEK interviews of the tribal members themselves would produce a more comprehensive vulnerability assessment. Some of the knowledge gaps noted in the report could have been better articulated with more extensive TEK information. This would provide the tribes with an expansive list of resources, places, seasonal shifts, and cultural adaptations, which western scientific methodologies cannot accurately provide comprehensibly. Such an in-depth assessment of TEK, however, can be costly, and is time-intensive due to the cultural sensitivities and the oral interviews that would need to be scheduled and then conducted, along with the transcriptions.

Many of the individuals who participated and have TEK knowledge, are active within the tribal land bases, and are interacting on a near-daily basis with resources for expanses of time. This provides a depth and breadth of knowledge that can be utilized within multiple tribal departments as well as inter-tribally if the tribes choose to do so. One example of this is David Hudson's comment regarding salmon fishing timing:

> *"Well I just know growing up, I guess it's the elderberries, I guess it is, the white little leaves or whatever you see on it, on the trees, when it starts blooming out and that lets you know that the spring salmon are in. Just by, without looking at fishing schedules. Its mother nature, tells yah what should be coming."*

Some of the more profound statements have been about how the resources are cherished, and the recognition that not just Natives are utilizing these. The economic benefit of natural resources is important for the tribes' survival, but cultural survival is equally important, and tied to the marine as well as terrestrial species. One cannot be easily separated from the other, as they are intricately interwoven into cultural fabrics of the tribes.

> *"All of our songs have to do with Mother nature the plants and animals. Everything out here is real important to us"   - David Hudson*

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Appendix A. Species Ranking by Economical, Cultural, Ecological, and Subsistence Importance

COMMON NAME	SPECIES NAME	VALUE/IMPORTANCE	ECON			CULT			ECOL	SUBS			AVE		
Trees			QL	H	QN	QL	H	QN	All	QL	H	QN	QL	H	QN
Western red cedar	*Thuja plicata*	All: $; cultural (canoes, basketry)	1	1	1	1	1	1	2	NA	NA	NA	1.3	1.3	1.3
Red alder	*Alus rubra*	All: $; cultural (smoking fish)	2	1	1	1	1	1	1	NA	NA	NA	1.3	1.0	1.0
Big leaf maple	*Acer macrophyllum*	QL: $; cultural (leaves used for cooking) QN: cultural (music wood, burls, firewood)	1	3	3	2	2	2	3	NA	NA	NA	2.0	2.7	2.7
Western hemlock	*Tsuga heterophylla*	QN: $	1	1	1	2	2	2	1	NA	NA	NA	1.3	1.3	1.3
Douglas fir	*Pseudotsuga menziesii*	All: $	1	1	1	3	3	3	2	NA	NA	NA	2.0	2.0	2.0
Yellow cedar	*Supressus nootkatensis*	All: $; cultural (canoe paddles)	2	3	3	2	2	2	2	NA	NA	NA	2.0	2.3	2.3
Pacific yew	*Taxus brevifola*	All: cultural (carving, paddles, spears)	3	3	3	1	1	2	2	NA	NA	NA	2.0	2.0	2.3
Sitka spruce	*Picea sitchensis*	All: $; large woody debris; Eagle nests	2	2	2	3	3	3	1	NA	NA	NA	2.0	2.0	2.0
Lodgepole pine	*Pinus contorta*	All: $	1	2	2	3	3	3	2	NA	NA	NA	2.0	2.3	2.3
Western white pine	*Pinus monticola*	All: $	2	2	2	3	3	3	3	NA	NA	NA	2.7	2.7	2.7

Cottonwood	*Populus trichocarpa*	All: eagle nests; large woody debris	3	3	3	3	3	3	1	NA	NA	NA	2.3	2.3	2.3
Pacific silver fir	*Albies alba*	All: $	3	3	3	3	3	3	2	NA	NA	NA	2.7	2.7	2.7
COMMON NAME	**SPECIES NAME**	**VALUE/IMPORTANCE**	**ECON**			**CULT**			**ECOL**	**SUBS**			**AVE**		
Berries, Shrubs, & Mushrooms			**QL**	**H**	**QN**	**QL**	**H**	**QN**	**All**	**QL**	**H**	**QN**	**QL**	**H**	**QN**
Blue huckleberry	*Vaccinium ovalifolium*	All: food	3	3	3	1	1	1	1	1	1	1	1.5	1.5	1.5
Red huckleberry	*Vaccinium parvifolium*	All: food, medicine	3	3	3	1	1	1	1	1	1	1	1.5	1.5	1.5
salmonberry	*Rubus spectabilis*	All: food	3	3	3	1	1	1	1	1	1	1	1.5	1.5	1.5
salal	*Galtheria shallon*	All: decorative; food (historically) H: $	3	2	3	1	3	3	2	1	2	3	1.8	2.3	2.8
Cascara		All: $	3	3	3	2	2	2	3	NA	NA	NA	2.7	2.7	2.7
bear grass	*Xerophyllum tenax*	All: cultural (weaving baskets); $; food (bulbs)	2	1	1	1	1	1	1	2	NA	NA	1.5	1.0	1.0
native blackberry	*Rubus ursinus*	All: food	3	3	3	2	2	2	2	1	1	1	2.0	2.0	2.0
Indian (labrador) tea	*Rhododendron spp.*	All: cultural	3	3	3	1	1	1	2	2	2	2	2.0	2.0	2.0
mushrooms	various spp	All: $; food; medicine	2	2	2	3	3	3	1	2	2	2	2.0	2.0	2.0
strawberry	*Frageria species*	All: food	3	3	3	2	2	2	2	2	2	2	2.3	2.3	2.3

Cranberry	*Vaccinium oxycoccus ovalifolium*	All: food	3	3	3	2	2	2	2	2	2	2	2.3	2.3	2.3
skunk cabbage	*Lisochitum americanum*	All: food (traditionally, leaves used for wraps in cooking)	3	3	3	3	3	3	1	NA	NA	NA	2.3	2.3	2.3
forbs (shrubs & tree seedlings)	many species	food for elk; reduced by invasives	3	3	3	3	3	3	1	NA	NA	NA	2.3	2.3	2.3
Devil's club	*Oplopanax horridus*	?													
Nootka rose	*Rosa nutkana*	All: medicine (formerly)	3	3	3	3	3	3	3	2	2	2	2.8	2.8	2.8
COMMON NAME	**SPECIES NAME**	**VALUE/IMPORTANCE**	**ECON**			**CULT**			**ECOL**	**SUBS**			**AVE**		
Terrestrial Mammals			**QL**	**H**	**QN**	**QL**	**H**	**QN**	**All**	**QL**	**H**	**QN**	**QL**	**H**	**QN**
Roosevelt elk	*Cervus canadensis roosevelti*	food, cultural (ceremonial)	3	3	3	1	1	1	1	1	1	1	1.5	1.5	1.5
black bear	*Ursus americanus altifrontalis*	food, commercial hunting (guiding), culturally important for some clans; top predator	2	2	2	2	2	2	1	2	2	2	1.8	1.8	1.8
beaver	Castor canadensis	pelts	2	2	2	3	3	3	1	NA	NA	NA	2.0	2.0	2.0
Blacktailed deer	*Odocoileus hemionus columbianus*	food	3	3	3	2	2	2	1	2	2	2	2.0	2.0	2.0
river otter	*Lutra candensis*	pelts (rare), eats salmon (human competitor)	2	2	2	3	3	3	1	NA	NA	NA	2.0	2.0	2.0
cougar	*Puma concolor*	food; natural predator control	3	3	3	3	3	3	1	3	3	3	2.5	2.5	2.5
Snowshoe hare	*Lepus americanus*	food; prey for mammals and birds	3	3	3	3	3	3	1	3	3	3	2.5	2.5	2.5
COMMON NAME	**SPECIES NAME**	**VALUE/IMPORTANCE**	**ECON**			**CULT**			**ECOL**	**SUBS**			**AVE**		

Birds			**QL**	**H**	**QN**	**QL**	**H**	**QN**	**All**	**QL**	**H**	**QN**	**QL**	**H**	**QN**
bald eagle	*Haliaeetus leucocephalus*	cultural (Quinault, Quileute use feathers); scavenger, preys on fish and some birds; ecological indicator	3	3	3	1	1	1	1	NA	NA	NA	1.7	1.7	1.7
raven	*Corvus corax*	mythology; scavenger & predator; likely to be robust	3	3	3	1	1	1	1	NA	NA	NA	1.7	1.7	1.7
pollinating birds		ecological function; hummingbirds (Anna's and Rufus hummers)	3	3	3	2	2	2	1	NA	NA	NA	2.0	2.0	2.0
Seagulls	several coastal species	scavenger and fish predator; likely to be robust	3	3	3	3	3	3	1	NA	NA	NA	2.3	2.3	2.3
brown pelicans	*Pelicanus occidentalis californicus*	numbers vary annually	3	3	3	3	3	3	1	NA	NA	NA	2.3	2.3	2.3
Northwestern crow	*Corvus caurinus*	scavenger & predator; likely to be robust	3	3	3	3	3	3	1	NA	NA	NA	2.3	2.3	2.3
Great blue heron	*Ardea herodias*	predators competing for juvenile aquatic animals	3	3	3	3	3	3	1	NA	NA	NA	2.3	2.3	2.3
migratory ducks & geese	Many different species.	traditionally food though limited by Migratory Bird Act	3	3	3	3	3	3	1	3	3	3	2.5	2.5	2.5
seagull eggs		traditionally food gathered on islands (now protected by USFWS); likely to be robust	3	3	3	3	3	3	3	3	3	3	3.0	3.0	3.0
COMMON NAME	**SPECIES NAME**	**VALUE/IMPORTANCE**	**ECON**			**CULT**			**ECOL**	**SUBS**			**AVE**		
Salmonids (more than one run for each species, four rivers)			**QL**	**H**	**QN**	**QL**	**H**	**QN**	**All**	**QL**	**H**	**QN**	**QL**	**H**	**QN**

Chinook (king)	*Oncorhynchus tshawytscha*	food: commercial, cultural, subsistence; ceremony: major celebration for first springer; hatchery (Quileute)			1			1	1			1			1.0
coho (silvers)	*Oncorhynchus kitsutch*	food: commercial, cultural, subsistence; hatchery (Quileute)			1			2	1			1			1.3
Sockeye (red, or blueback)	*Oncorhynchus nerka*	food: commercial, cultural, subsistence			1			2	1			1			1.3
Steelhead (anadromous relative of rainbow trout)	*Oncoyrhynchus mykiss*	food: commercial, cultural, subsistence; may return to spawn more than once			1			2	1			2			1.5
Cutthroat trout	*Onchorhynchus clarki clarki*	food: subsistence; prey on juvenile salmon			3			3	1			3			2.5
COMMON NAME	**SPECIES NAME**	**VALUE/IMPORTANCE**	**ECON**			**CULT**			**ECOL**	**SUBS**			**AVE**		
Terrestrial Invertebrates			**QL**	**H**	**QN**	**QL**	**H**	**QN**	**All**	**QL**	**H**	**QN**	**QL**	**H**	**QN**
insects - aquatic macroinvertebrates	Many genera of insect larvae	primary food for juvenile salmon; indicators of sufficient dissolved oxygen	1	1	1	3	3	3	1	NA	NA	NA	1.7	1.7	1.7
COMMON NAME	**SPECIES NAME**	**VALUE/IMPORTANCE**	**ECON**			**CULT**			**ECOL**	**SUBS**			**AVE**		
Marine Invertebrates (major food chain importance)			**QL**	**H**	**QN**	**QL**	**H**	**QN**	**All**	**QL**	**H**	**QN**	**QL**	**H**	**QN**
razor clams	Class of Mollusk: Pelecypoda. *Siliqua patula*	top tier food: commercial (mainly Quinault), ceremonial, and subsistence			1			1	1			1			1.0

Dungeness crab	Crustacean. *Metacarcinus magister*	food: commercial (major cash crop for all three tribes, particularly Quileute); cultural: exercise treaty rights			1			1	1			1			1.0
Little necks (clams)	Pelecypoda. *Protothaca staminea (or Leukoma staminea)*	food: ceremonial/cultural, subsistence; vulnerable to OA; tidal zone			3			1	1			1			1.5
Butter clams	Pelecypoda. *Saxidomus gigantea*	food: ceremonial/cultural, subsistence; vulnerable to OA; tidal zone			3			1	1			1			1.5
Red rock crab	Crustacean. *Cancer productus*	food: commercial, harvested locally in estuaries for commerce			2			3	1			1			1.8
blue (California) mussels	Pelecypoda. *Mytilus californianus*	food: ceremonial/cultural, subsistence; vulnerable to OA			3			2	1			2			2.0
snails and limpets	Class of Mollusk: Gastropoda. Many shoreline species: considering tidal zone species here.	Limpets traditionally gathered for food			3			3	1			2			2.3
gooseneck barnacles	Crustacean. Several kinds. *Pollicipes spp*.	more of a food source traditionally than presently			3			3	1			2			2.3
Green sea urchins	Echinodermata*:* *Strongylocentrotus droebachiensis*	food: traditionally and currently enjoyed as food, more so traditionally; ecological function: major threat to kelp forests, controlled by marine otters			3			3	1			2			2.3

Red sea urchins	*S. franciscanus*	food: traditionally and currently enjoyed as food, more so traditionally; ecological function: major threat to kelp forests, controlled by marine otters			3			3	1			2			2.3
Purple sea urchins	*S. purpuratus*	food: traditionally and currently enjoyed as food, more so traditionally; ecological function: major threat to kelp forests, controlled by marine otters			3			3	1			2			2.3
Sunflower seastar	Echinodermata: *Pycnopodia helanthoides*	ecological function: preys on sea urchin, clams, snails, sea cucumbers, other sea stars; occupies deeper water than tidal zone			3			3	1			NA			2.3
Ochre seastar	Echinodermata: *Pisaster ochraceus*	ecological function: preys on shellfish (mussels, barnacles, snails, limpets, chitons); tidal zone			3			3	1			NA			2.3
aggregating sea anemone	Coelenterata. *Anthopleura elegantissima*	rocky intertidal zone; hosts photosynthetic algae; some still gather as food, but more important historically			3			3	1			3			2.5
octopus, squid	Class of Mollusk: Cephalopoda.	food?			3			3	1			3			2.5
COMMON NAME	**SPECIES NAME**	**VALUE/IMPORTANCE**	**ECON**			**CULT**			**ECOL**	**SUBS**			**AVE**		
Marine Finned Fish (All are culturally important for treaty right ocean fishery. All part of food chain.)			**QL**	**H**	**QN**	**QL**	**H**	**QN**	**All**	**QL**	**H**	**QN**	**QL**	**H**	**QN**

blackcod (sablefish)	*Anoplopoma fimbria*	Cultural: exercise treaty rights, all four coastal tribes avidly fish by management agreement; big money fish for all in Treaty of Olympia area			1			1	1			1			1.0
rockfish	Many different species.	Cultural: exercise treaty rights, no ceremonies; can't fish for ESA listed species, non-listed species limited, reduced numbers; commercial and subsistence fish (Quileute)			1			1	1			1			1.0
halibut	*Hippoglossus stenolepis*	food: commercial for all tribes; also an ocean treaty right fish. (ground fish)			1			1	2			1			1.3
Starry flounder	*Platichthys stellatus*	food			1			2	1			1			1.3
Pacific sanddab	*Citharichthys sordidus*	food (flatfish): commercial			1			3	1			1			1.5
Eulachon (candlefish)	*Thaleicthys pacificus*	food (anadromous forage fish); considered for ESA listed, but Quillayute not part of EFH			3			1	1			1			1.5
sardines	*Sardinops sagax caerulea*	food: commercial harvest (Quinault), rare in Quillayute nearshore harvest area			1			3	1			1			1.5
lingcod	*Ophiodon elongatus*	food (groundfish): commercial harvest by all three tribes; cultural: exercise of ocean treaty rights			2			1	1			2			1.5
surf smelt or day smelt	*Hypomesus pretiosus*	food (forage fish): culturally fished a lot			3			2	1			1			1.8
Night smelt	*Spirinchus starski*	food (forage fish): culturally fished a lot			3			2	1			1			1.8
Longfin smelt	*Spirinchus thaleichthys*	food (anadromous forage fish found in estuaries and lakes)			3			3	1			1			2.0
lamprey	*Lampetra tridentata*	cultural (Quinault); EFH not in the Quillayute System.			3			2	1			3			2.3

herring	*Clupea harengus pallasi*	forage fish, eggs used to be food			2			3	1			3			2.3
whiting, more correctly, Pacific hake	*Merluccius productus*	open ocean fishery, only Makah exercises treaty fishery off WA (others are placeholders), Chinook bycatch are a problem with this fishery			3			3	1			3			2.5
lingcod eggs	*Ophiodon elongatus*	food: rare to find them on washed up kelp now.			3			3	1			3			2.5
anchovies	*Engraulix mordax*	current food for people, birds, juvenile fish; abundant in Quillayute River			3			3	1			3			2.5
mackerel	*Trachurus symmetricus*	ocean fishery in CA current.			?			?	?			?			--
COMMON NAME	**SPECIES NAME**	**VALUE/IMPORTANCE**	**ECON**			**CULT**			**ECOL**	**SUBS**			**AVE**		
Marine Mammals (MMPA generally prohibits target fishery except for Alaskan native communities)			**QL**	**H**	**QN**	**QL**	**H**	**QN**	**All**	**QL**	**H**	**QN**	**QL**	**H**	**QN**
Gray whales	*Eschrichtius robustus*	cultural (Quileute has ceremony welcoming them); historically food			3			1	1			NA			1.7
Orcas	*Orcinus orca*	ecological: top predator (sea lions); cultural: big part of Quileute mythology			3			1	1			NA			1.7
Harbor seal	*Phoca vitulina richardsi*	historically, was food (commercial & subsistence)			3			1	1			NA			1.7
hair seal (N. fur seal)	*Callorhinus ursinus*	food: historically hunted by Quileute for $			3			1	1			NA			1.7
Dall's Porpoise	*Phocenoides dalli*				3			3	1			NA			2.3
Harbor porpoise	*Phocoena phocoena*				3			3	1			NA			2.3

Elephant seal	*Mirounga angustirostris*				3			3	1			NA			2.3
Humpback whales	*Megaptera novaeangliae*	present, but rarer than gray whales			3			3	1			NA			2.3
Sea lion-California	*Zalophus californianus*	only males come up here; salmon predator (sometimes from the fisherman's nets)--NOAA allows protection of nets, gear, lives.			3			3	1			NA			2.3
Sea lion--Stellar	*Eumetopias jubatus*	Native, still ESA protected, lesser predator of salmon			3			3	1			NA			2.3
marine otter	*Enhydra lutris*	Protected, introduced from AK after extirpated in WA (keeps in check sea urchins that harm kelp)			3			3	1			NA			2.3
COMMON NAME	**SPECIES NAME**	**VALUE/IMPORTANCE**	**ECON**			**CULT**			**ECOL**	**SUBS**			**AVE**		
Marine Plants & Algae (All part of the ecosystem, food chain)			**QL**	**H**	**QN**	**QL**	**H**	**QN**	**All**	**QL**	**H**	**QN**	**QL**	**H**	**QN**
Sea Palm	*Postelsia palmaeformis*	can survive exposure at low tide; harvested for cash crop?			2			3	1			NA			2.0
Sea lettuce	*Ulva lactuca*	Edible green alga; also eaten by marine animals.			3			2	1			2			2.0
Lamineria	*Laminaria playtmeris, L. saccharina*	kind of brown alga, edible; harvested for cash crop?			2			2	1			3			2.0
Bull kelp	*Nereocystis leutkeana*	brown alga, major contributor to the kelp forests, very rapid growth, marine fish habitat			3			3	1			NA			2.3
feather boa kelp	*Egregia menziesii*	rocky intertidal and kelp forest			3			3	1			NA			2.3

Giant brown kelp	*Macrocystis integrifolia*	Brown alga, kelp forests, fish habitat			3			3	1			NA			2.3
Turkish towel	*Gigartina exasperata*	red seaweed; potential facial gel (not sure if tribes are engaging in this economy)			3			3	1			NA			2.3
Rockweed	*Fucus furcatus*	Brown alga, common in intertidal zone.			3			3	1			NA			2.3