WEST COAST GOVERNORS ALLIANCE on OCEAN HEALTH
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Conversations with West Coast Subject Matter Experts: Habitat vulnerability to sea level rise and increasing wave height/energy

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Summary by Benjamin Reder

"There will be winners and there will be losers." – Interviewee

"Big waves, high tides, and past events are already revealing what SLR is going to do - it's not a big mysterious thing." – Interviewee

West Coast Governors' Alliance on Ocean Health
Climate Change Action Coordination Team

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Introduction

This report documents the findings from a series of interviews with climate change subject matter experts and conducted by the West Coast Governors' Alliance on Ocean Health (WCGA) Climate Change Action Coordination Team (CC ACT) from August through September 2011. To complete the assessment, CC ACT members interviewed 21 professionals (seven in each state) with experience and expertise related to the West Coast (Washington, Oregon, and California). A "snowball" methodology was used, starting with several key informants, to identify leading experts. Interviewees ranged in their background and expertise, but generally fell into the following categories: climate scientist, researcher, natural resource manager, geologist, geomorphologist, estuarine ecologist, or oceanographer.

This assessment focused on two specific elements of climate change: sea level rise (SLR) and increasing wave heights and energy. The main goal of the project was to identify specific habitats or areas along the West Coast likely to be vulnerable to the impacts of these forces.

The information collected was qualitative and the interviews were conversational in nature. Throughout the document, there are quotes from interviewees. The main themes that surfaced through the interviews generally fell into these main categories: information regarding general habitat impacts, vulnerability issues related to specific areas of the coast, current restoration projects, and additional relevant literature and modeling resources.

Interviewees were asked to focus their comments to address natural areas within the coastal zone, including the intertidal zone, the beach shore, cliffs, bluffs, and associated habitats such as rocky coasts, sandy beaches, estuaries, spits, marshes, deltas, bays, lagoons, barrier islands, and others. Since the discussions were structured around the theme of climate change vulnerability, it was important to develop a definition of this term. The definition used during these interviews was adapted from Nicholls et al. (2007) and Glick et al. (2011). Vulnerability was described as a function of three factors: the *sensitivity* of a particular system to climate changes, the system's *exposure* to those changes, and the system's *capacity to adapt* to those changes. These key terms were defined as follows:

- <u>Sensitivity</u>: a measure of the susceptibility of a habitat to climate change impacts, focusing on the innate characteristics of the system to tolerate the identified changes.
- <u>Exposure:</u> refers to a particular habitat's direct exposure (magnitude and rate of change) to a specific climate change impact.
- <u>Adaptive capacity</u>: considers both intrinsic (e.g. physical, ecological, biological aspects of the system) and extrinsic factors (e.g. ability for habitat to migrate, existence of dams, rates of geologic uplift) of the habitat to adjust to the projected impacts.

All Interviewees were asked to consider two main assumptions during the interviews:

- Sea level rise: there will be a global mean SLR of approximately one-meter by 2100[1].
- Increasing wave heights and energy: For all regions, assume a general trend of increased storminess and wave intensity[2]. Elevated wave heights and energy will have the largest impacts during high tides and El Niño events. The synchrony between increased storminess and elevated relative sea levels during these periods is the main issue. Interviewees were asked to consider the scenario that the combination of larger waves and higher water levels will be more frequent in the future.[3]

In regards to SLR, most subject matter experts (interviewees) interviewed felt comfortable with the approximation of one-meter rise in global sea levels, but also commented that in assessing vulnerability, local differences must be considered. In regards to increasing wave heights and energy, several interviewees commented that the assumption, there will be an increasing trend of storminess and wave intensity, does not hold true for southern California. These individuals explained, that while this particular assumption may hold true in Northern California, Oregon and Washington, it does not accurately capture what will most likely occur in southern California in the future. From their perspective, southern California will most likely see a small decrease in overall and extreme wave height as a result of a shift in storm tracks and sheltering from Point Conception and the Channel Islands. One interviewee said, "severe storms are going to be more severe because of the warming and the storm paths are going to track farther north across the Central Pacific than they do now."

This assessment also addressed storminess, looking specifically at impacts resulting from increasing wave heights and energy. The impacts related to this aspect of the assessment focused on identifying erosion hotspots and areas subject to over-washing, predominantly along the outer coast. Several interviewees mentioned that when evaluating vulnerabilities expected to arise from storminess, precipitation should be considered. This would include potential inland factors that are likely to have an impact on coastal habitats such rivers and estuaries. For estuaries, precipitation will have a big impact on sediment delivery rates, river channel morphology, water quality, and salinity levels. However, with the current available data, it is difficult to accurately define and project how all of these variables will be affected.

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[1]Vermeer M, Rahmstorf S .2009. "Global sea level linked to global temperature". ProcNatlAcadSci USA 106:21527–21532.

[2]Barnard, Patrick L., Jonathan Allan, Jeff E. Hansen, George M. Kaminsky, Peter Ruggiero, and Andre Doria. "The impacts of the 2009-10 El Nino Modoki on U.S. West Coast Beaches". *Geophysical Research Letters* 38 ((2011) 1-7.

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Generals Impacts and Discussion

Shoreline Types

In regards to general shoreline types, interviewees often described these areas based on geomorphological features such as tidal estuaries/marshes, sandy dunes and unconsolidated coastline, and coastal bluffs of varying degrees of hardness. The impacts and risk varied for each shoreline type. From an ecosystem perspective, most agreed the greatest risk and largest impact from SLR would occur in marshes and estuaries. For these low-lying habitats, interviewees identified two main SLR-related impacts: gradual inundation and constrained habitat migration. The three main factors that contribute to constrained habitat migration are the presence of man-made levees and dikes, encroaching development, and/or naturally constraining topographic conditions.

In a general sense, the most vulnerable areas to SLR are areas that characteristically have no tectonic uplift (i.e. are not experiencing isostatic rebound), and are located at low-lying elevations, within (relatively) non-erosive watersheds. In other words, there is great concern for areas that cannot counter SLR with either tectonic uplift from erosive processes. One interviewee claimed, "isostatic rebound, in a lot of places, will be the tipping point between adaptability and vulnerability."

Estuaries

Estuaries were described in various ways, one of which invoked the comparison of *marine-dominated* estuaries to *river-dominated* estuaries (Bottom et al., 1979). In areas where the estuary is large relative to the watershed drainage, there tends to be a stronger marine influence present. River-dominated estuaries tend to be smaller with narrow inlets, and they also have a "stronger fresh water signature." The relative difference in salinity concentrations and hydrology has an effect on species presence and habitat complexity. Based on SLAMM modeling results completed for various estuaries in Oregon, researchers found that a one-meter rise in sea level prompts marine-dominated systems to become "more marine." This occurrence will likely increase the size of estuaries (if there are no man-made structures are present). In addition, the researchers found that historically river-dominated systems show a trend of transitioning to more marine-influenced systems as a result of SLR.

Estuary vulnerability is highly influenced by its morphology. Estuaries in northern California, Oregon, and Washington tend to be larger than central and southern California estuaries (Gleason 2011). Estuaries that have multiple rivers draining into their systems and feature broad flood plains demonstrate greater adaptive capacity. This is typical of marine-dominated systems. In contrast, river-dominated estuaries tend to be surrounded by steep topography with abrupt edges. River-dominated estuaries also tend to have fewer rivers feeding into their systems and have relatively less migration opportunities due to the topographical constraints.

Interviewees described various wetland types and sub-habitats such as low marsh, high marsh, and forested or scrubbed swamp. These are general categories and may not accurately describe all estuarine habitats along the West Coast. Broadly, the impacts likely expected for most estuaries are: (1) altered inundation regimes (both tidal and fluvial), and (2) changed salinity regime (this includes altered seasonality, changing peak salinities, and changing duration of exposure to salinity). One subject noted that elevation ranges do not necessarily dictate differences or boundaries between various wetland habitat types. Salinity levels are a factor in determining the distribution of these plant communities. All wetland classes are sensitive to climate change impacts in different ways. For example, even though accretion rates are much higher in low marsh than high marsh, this does not inherently mean that low marsh habitats have a greater adaptive capacity. Low marsh habitat is located so low in the tidal range and is thus more vulnerable to inundation despite higher rates of accretion. High marsh and swamp habitats have slower accretion rates, but are located higher in the tidal range and thus are less vulnerable to inundation. However, these habitats will be the fist to be eliminated if there is nowhere for to migrate. In addition, the plant communities of high marsh and swamp habitats are typically more sensitive to changes in salinity concentrations.

Other Wetland Habitats

Mudflats were described as “one of the richest food resources for migratory shore birds.” In particular, researchers have found that within mudflat habitat, invertebrates tend to cluster along a specific “line of inundation and salinity.” This line is located where the mudflat first dries out during a falling tide and this is where foraging birds find the highest concentration of invertebrates. The invertebrates appear to be very sensitive to salinity concentrations. A future rise in sea level may affect invertebrate distributions and the amount of time migratory shore birds can forage in mudflats.

Eelgrass beds were identified as a very important habitat for both fish and bird species. For example, eelgrass beds provide food for Chinook salmon, spawning grounds for herring. Additionally, scoters time their migration with herring spawning. Eelgrass beds are sensitive to salinity and flooding regimes. With SLR, the distribution and abundance of eelgrass beds are certain to change.

Accretion

Several of the interviewees were asked to describe the process of accretion. One person commented, accreted material is “a mix of alluvial deposition and ocean origin sediment, and in situ generated organic matter and deposited organic matter.” The premise is that low marshes, for example, exist at a dynamic equilibrium between accretion and erosion processes.

Research has shown that below-ground plant parts generate a large amount of organic matter and contribute significantly to the overall accretion process (an important component of SLR adaptive capacity). The process of generating below-ground organic matter can be affected by degraded water quality. Many of the low marsh plants have the ability to absorb nutrients through their roots and leaves. Cahoon et al. (2004) and Turner (2004) have shown that marsh plants that exist close to impacted watersheds (i.e. in close proximity to urban or intensive agricultural areas) tend to produce less root biomass. It is believed that these plants are absorbing nutrients through the leaves, and thus there is a lowered need for the development of roots. In these instances, accretion rates are greatly reduced and adaptive capacity may be threatened. An interviewee commented that water quality should be a primary consideration (in conjunction with restoration) when developing climate mitigation strategies. Maintaining clean water will "encourage" marsh plants to absorb nutrients through their root systems and subsequently produce more root biomass. It is thought that this will help maintain the accretion processes that are vital for an estuarine system to adapt to SLR.

Transition Zones and Habitat Complexity

Several interviewees were concerned that SLR may lead to reduced habitat complexity in estuarine systems where the ability to migrate has been reduced or eliminated. Notably, within estuarine systems, transition zones between wetland types are considered biological and ecological hotspots. Transition zones play an important role in determining the location and abundance of certain fish species. One researcher explained, "for salmon, the most sensitive habitats tend to be transitional wetland types, the places where you are seeing salinity changes." These areas are important during acclimation periods, when salmon shift from using freshwater to salt water, and vice versa. Similarly, tidal marsh insects are the dominant food source for juvenile Chinook salmon during the month of peak out-migration. During the time of peak pulse, as the fish come into the estuary, the primarily food source are insects that "fall" into the river channel. This example illustrates a functional relationship between tidal marsh habitat and rivers. Loss of transitional wetland habitat could affect the availability of an important food source for Chinook salmon and other anadromous fish species.

Semantics

Through the course of research and interviews for this project, it became apparent that many of the interviewees use the terms "flooding" and "inundation" interchangeably. Most dictionaries support this interchangeability. One interviewee noted that as SLR impacts become more pronounced, it will be important to differentiate between these impacts. He suggested that "flooding" should be used to describe a temporary condition or a temporal event where "something that is normally dry gets wet, but then gets dry again.", and that "inundation" should be used as a term to describe a permanent condition of flooding. The interviewee summarized the significance of this issue stating: "this is not an important distinction now because SLR has been slow, but going forward, as SLR rates increase, it is going to be important to make the distinction because there is going to be flooding that is more frequent and severe, but there is also going to be places that get inundated. These places are going to get wet, and as the sea level rises, these areas are going to stay wet."

Washington

The information for Washington is presented below divided into two geographic areas: Puget Sound and outer coastal areas. For each geographic area, general comments are listed first, followed by area-specific information.

Puget Sound

Puget Sound is unique compared to other areas addressed through this project, in that it is geographically separated from the outer coast. The Strait of Juan de Fuca extends roughly 95 miles in the east-west direction, connecting Puget Sound to the Pacific Ocean. Wave action generated from the outer coast quickly dissipates as it enters the strait. In interviews, the Puget Sound climate was characterized as "locally generated." Although the effects of SLR will undoubtedly be felt in this area, the scenario of increasing wave heights and energy (from the outer coast) is not applicable because wave action in the Puget Sound is generated by local windstorms. In regards to climate change, is very difficult to accurately predict how the local storm patterns will change.

The Puget Sound shoreline includes more than 1,800 miles of beaches, bluffs, estuaries, lagoons, river deltas, and rocky coastlines (Shipman 2008). Shipman further classifies the various Puget Sound shoreline habitats into two major categories: exposed shorelines (rocky coasts and beaches) and protected shorelines (embayments and river deltas).

In regards to protected shorelines, Puget Sound has two main wetland types: (1) big river deltas and (2) small lagoons and estuaries. Big river deltas account for 10-15% shoreline and tend to exist in areas where medium to large rivers reach the shore, forming wide, expansive, low gradient, fine-grained deltas. Salt marsh is the dominant habitat within the deltas, and the gradation of the system is dependent on elevation and salinity. Big river deltas are vulnerable to SLR because of they exist at low elevations, occupy broad areas, and are relatively shallow. A small rise in water level would have a significant impact in these areas. Effects resulting from salinity changes will alter the extent and location of existing salt marshes. If these river deltas exist in an area where they have the ability to migrate, habitat diversity and complexity may increase as sea levels rise.

Small lagoons and estuaries range in size, ranging from10 to 100 acres. There are thousands of these habitat types scattered around Puget Sound, and each one is morphologically unique. These habitats typically exist at entrances of small streams and rivers. One interviewee commented that small lagoons and estuaries have not received enough attention in climate change vulnerability assessments.

Interviewees noted that resilience and vulnerability, for all wetland habitats, will depend on their area and "what goes on behind them." Topographic and infrastructure constraints will prevent habitat migration resulting in "coastal squeeze." Bigger systems may be less vulnerable because there will be room to migrate within the existing boundaries of the ecosystem.

Northern Puget Sound was identified as a high "opportunity" zone for habitat restoration. Interviewees commented that **Whatcom**, **Skagit**, and **Snohomish** Counties were the historic wetland habitat "hotspots" relative to other areas in Puget Sound. Much of the historic wetland habitat has been lost due to agricultural practices. The fact that this area is expected to be dominated by agriculture, as opposed to urban development, is seen as a positive. Conservation-wise, if SLR does degrade the viability of this land, then dikes and levees can be removed and restoration can occur. Maintaining the dominance of agriculture in this area is a strategic move that allows for greater management flexibility in the future.

<u>Specific Areas</u>

In **Bellingham Bay,** development has led to the significant loss of habitat and this is likely to continue. Nooksack Delta was identified as an area with a fair amount of diking. Conservation groups are actively looking for marginal agricultural land to identify potential areas for transitional restoration projects (e.g. dike removal) through easements. Tidal and fresh marsh and swamps in this area were noted as very vulnerable to SLR. **Lummi Island** has relatively less coastal wetlands, but in general is vulnerable to erosion. Changes in the morphology of the coastline are very uncertain.

Commencement Bay was characterized as fairly degraded habitat, being "completely channelized" and having only a few remnant marshes left. The watershed that feeds into the bay is erosive and there will be a lot of sediment delivered. Unfortunately, there are almost no marshes to maintain.

There are probably many areas in Puget Sound where coastal squeeze or topographic constraints will hinder habitat migration in the future. Interviewees identified **Padilla Bay**, **Stillaguamish Delta**, and **Nisqually Delta** as example areas of where this scenario may occur. Interviewees also noted several relatively large wetland restoration projects either underway or likely to be underway soon, these include the **Stillaguamish Delta**, **Skagit Delta**, **Nisqually Delta** and **Nooksack Delta** (proposed).

Restoration in **Nisqually Delta** is by far the largest undertaking in regards to wetland restoration projects in the Puget Sound. Much of the work has focused on dike removal, reconnecting historic flood plains, and increasing potential salt marsh habitat. The restoration project referred to as "the largest tidal marsh restoration project in the Pacific Northwest," includes 900 acres of land in the Nisqually National Wildlife Refuge and on the Nisqually Indian Tribe lands.

A representative from Nisqually National Wildlife Refuge commented that despite the restoration effort, with SLR they are expecting to see "big changes in plant communities." The tidal marsh plants have been "observed in a very narrow elevation range." Potential impacts from SLR include changes in flooding times and frequencies, and change in salinity concentrations. These impacts will have a profound affect on habitat and plant community distribution.

An interesting point was raised during the interview with the Nisqually National Wildlife Refuge representative: there is a certain degree of vulnerability to SLR when restoring tidal marshes and removing dikes. The interviewee noted that a lot of land has subsided during the time it was diked. With the removal of dikes, these areas are "starting off low," at a lower elevation than the surrounding areas that were not diked. SLR may inhibit the restoration of the intended habitat.

Outer Coast and Strait

Interviewees noted several vulnerable habitats along Washington's outer coast, these include unconsolidated sediment beaches, barrier beaches, and barrier estuaries. It was noted that barrier and unconsolidated beaches are relatively erosive "until you get up to the southern Olympic Peninsula." These areas are vulnerable if wave height and energy increase. Barrier estuaries (e.g. Willapa Bay) in Washington tend to have very narrow spits and are comprised of fine sediment (similar habitats in Oregon, like Netarts and Tillamook Bay, have more coarse sediment and thus less vulnerable to erosion).

Specific Areas

If wave energy and intensity were to increase, the **Strait of Juan de Fuca** would expectedly move a greater amount of sediment to the eastern portion of the strait and northern Puget Sound.

Dungeness Spit and **Ediz Hook** are both sand spits that are potentially vulnerable to erosion and over washing. The removal of Elwha Dam may increase sediment accumulation in these areas and thereby reduce vulnerability to these impacts. Ediz Hook is artificially maintained and historically, sediment delivery from Elwha River (and erosion from nearby bluffs), helped to sustain the spit. Coastal armoring of the bluffs and construction of the dam has greatly reduced sediment loads. Removal of the dam will increase sediment delivery, but interviewees were unsure if the sediment delivered as a result will be enough for the spit to start accreting again and remain stable. In the **Columbia River,** sediment input, especially sand, has been greatly reduced due to the presence of dams.

Willapa Bay and **Grays Harbor** were noted as extremely vulnerable to SLR and erosion. These areas were described as "a big flat system" that will likely get drowned out over time. The tidal flats in Willapa Bay and Grays Harbor run up against a steep and abrupt shoreline.

Topographic constraint of wetland habitat is a big issue. The tidal flats were also noted as a very important habitat for shorebirds**.**

Long Beach Peninsula was identified as an erosive hotspot. Interviewees stated there has been no historic overwash, but erosion will be an issue in the future. Specifically, **Washaway Beach**/**Cape Shoalwater** were identified as historic erosion hotspots.

Washington Resources

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For more information about restoration around the **Nisqually Delta** visit:
http://nisquallydeltarestoration.org/

For more information about erosion **Washaway Beach**/**Cape Shoalwater** visit:
http://www.ecy.wa.gov/programs/sea/coast/erosion/washaway.html

Oregon

There are 21 major estuaries in Oregon, many of which are "defined by sand spits that only provide a thin margin of protection against ocean forces." These are obvious areas of concern when considering impacts from SLR and increasing wave heights and energy. With SLR, there is a good chance that some of these barrier spits will be lost completely and this will profoundly alter the ecosystem. Specific areas of concern include **Rockaway**, **Tillamook**, **Manzanita**, **Oceanside**, **Pacific City**, and **Netarts**. Interviewees characterized Oregon's south coast estuaries as mostly "riverine," and not having many tidal lands (e.g. **Chetco** and **Rogue** rivers). Marine dominated estuaries tend to have more tidal lands and diverse wetland habitats (e.g. **Coquille River**, **Coos Bay**, **Tillamook Bay**, and **Nestucca Bay**). These areas also tend to have large diked areas. One subject stated, "with many diked areas in Oregon, water gets right up there…there's very little free-board on the highest tides of the year…they're built by just piling up mud and something is going to give as sea levels rise."

Oregon Coast

Elk River is another example of a river-dominated system typical of the south coast. The watershed is "tightly constrained" by steep topography. SLAMM results that modeled a one-meter SLR scenario indicated this system will change to a marine-dominated system. The impacts that result from this scenario are unclear. The lower portion of Elk River is currently used for grazing livestock and is owned by a couple of families who are "interested in conservation," and are willing to explore mitigation and adaptation-related projects. The spit at nearby **Sixes River** was identified as an area vulnerable to overwashing.

Alsea Bay, which drains out at Waldport, was described as being very low lying and shallow. There has been no dredging within the bay.

The **Siletz River** sand bar is highly urbanized. The spit has been breeched in the past and is likely to breech again in the future. This is a concern for the existing developed areas. Similarly, **Netarts** and **Tillamook** have spits that are developed. **Tillamook Bay** (at the mouth of Miami River) is particularly low-lying (approximated at 8-10 feet above sea level). There is a lot of diked agricultural land in Tillamook valley. Many wetlands in this region are topographically constrained.

Neskowin, in Tillamook County, has had a substantial amount of sand loss from its beaches over the last several years and it has not been replenished. The Neskowin community is concerned because the elevation of their town is near current sea level. A community group has formed, and they are looking at possible mitigation actions.

South Slough, Coos Bay has many "pocket fringe" marshes that are topographically constrained, running up against elevated forested areas. This is also an important commercial oyster area. A representative from the South Slough Estuary mentioned that there is a NOAA SLR monitoring station onsite. They have collected over 30 years of data, indicating that local sea level is rising at a rate of 1.3 mm/yr. There was a significant dike removal effort that occurred between 1996 and 2003, resulting in the removal of many dikes within the South Slough National Estuarine Research Reserve, except within Hayward Creek. **Joe Ney Slough Dam,** a secondary drinking source, will likely be overtopped by storm surges in the future. The South Slough spit is eroded along the northern edge of the river mouth. When the recent Tsunami from Japan hit the west coast, damage occurred in the **Charleston harbor**. In addition, there were eyewitness accounts of surges in the upper reaches of the slough.

Sea level rise, and greater storm surge/wave energy in the **South Slough** and **lower Coos estuaries**, will likely cause a significant shift in the location and possibly the density of eelgrass beds in intertidal and subtidal zones. The intertidal zone in the estuary is wide and the majority of it includes suitable intertidal elevation range for the native *Zostera marina* (eelgrass). Higher energy in the estuary, and more intense precipitation events, have the potential to scour some of these beds, and create increased or more prolonged periods of water column turbidity that will likely reduce the amount of light these plants receive while submerged underwater. Longer periods of tidal inundation, due to SLR, will also cause eelgrass bed to migrate up the intertidal zone. Subtidal eelgrass beds will be affected by anything that reduces their ability to get enough light.

Sea level rise and greater storm surge/wave energy in the **South Slough** and lower **Coos estuaries** will likely affect tidal wetland restoration and compensatory mitigation projects. Public and private investments in these projects over the years have been significant.

In **Nestuca Bay,** there is a management program for dusky Canada geese and Aluetian Canada geese. Nestuca Bay is used by 18 percent of the world's population of Canada geese, approximately 6,000 to 7,000 birds. To maintain the goose populations, managers must also maintain diked pastureland. In the future, the ability to continue this management is "probably minimal" due to SLR.

Bandon Marsh just completed a large tidal marsh restoration project, the largest in Oregon (August 2011). The work will ultimately restore more than 400 acres of tidal wetlands, nearly doubling the amount of tidal wetlands in the estuary. This area had tremendous historic fish value and the restoration is expected to boost Chinook and Coho salmon populations. Diking and agriculture has contributed to a major loss of acreage of tidal marsh (50-95% habitat already gone). Bandon Marsh has the highest percentage loss of tidal marsh habitat of any estuary in Oregon. An interviewee noted this project was strategic in that there was a "large chunk of land with relatively few owners" to work with in developing the plan to restore the tidal marshes.

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For more information about restoration at **Bandon Marsh** visit:
http://www.fws.gov/oregoncoast/bandonmarsh/restoration/

California

For the purpose of this document, the California section has been divided into two geographic regions: northern and southern California. The northern California section contains information about areas located between the Oregon-California Border, south to Monterey. The southern California section contains information about areas south of Monterey to the Mexico Border.

Several Interviewees referenced current models, and predicted that southern California will not be subject to increasing wave heights. One interviewee expressed the view that SLR has been suppressed along the West Coast for the past 30 years as a result of prevailing wind stress and ocean circulation patterns (Bromirski et al., 2011). This individual stated: “sea level has been static along the west coast since 1980, but that’s not going to last much longer.”

The coincidence of runup from big storm waves with peak high tides, along with a smaller contribution from storm surge, will continue to be the primary drivers of coastal flooding, beach and structure overtopping, and beach erosion in California. The areas that will be vulnerable to high-tide and wave runup flooding in the future are generally the same low-lying areas that are vulnerable now, with new ones progressively added as sea level creeps or jumps up. Flooding at these places will increase in intensity and duration as time goes on, and new places at higher elevations will then become vulnerable. The anticipated future resumption and likely acceleration of sea level rise, which has been static along the west coast for 30 years, will cause net shoreline retreat, and more frequent and severe coastal flooding, which will likely prompt property and environmental damages, including loss of beaches and wetlands.

In northern California, particularly between Crescent City and Cape Mendocino the watersheds were characterized as “non-erosional,” accretion is occurring because of “massive sediment discharge” from these systems. Generally speaking, beaches south of San Francisco were described as being relatively narrow and “thin” (between 2 to 20 feet in depth) as a result of being “cut into coastal terraces.” These beaches are susceptible to erosion and vulnerable to impacts resulting from SLR.

Northern California

Near Crescent City, **Lake Earl** was described as a “big dune area” where development is increasing. This area is prone to flooding and overwashing will be an issue.

Interviewees with knowledge of **Humboldt Bay** stated that “perimeter levees” are currently at 10 feet in height. The highest tides measure approximately 8 feet 8inches, and if a one-meter rise in sea level were to occur, many of these levees could potentially fail or be overtopped. Subsidence behind dikes was also noted as a critical issue. Interviewees stated that land subsidence behind dikes occurs because once there is no longer salt water input, the fresh water table subsides, and aeration, compaction, and decomposition processes result in land subsidence. Interviewees also noted that king tides bring water into upper slough areas that are not diked. Current research indicates that sediment accumulation rates in Humboldt Bay are very low.

Interviewees discussed several key areas near **Humboldt Bay** that are particularly vulnerable to erosion and overtopping. The **Eel River Delta Dunes** (south bay) currently act as a natural levee. These dunes have been breached in the past. There is pastureland behind the dunes that is slowly transitioning to salt marsh habitat. The **South Spit** was characterized as "thin with less developed dunes" and susceptible to overwashing. The north spit is wider, has higher elevation sand dunes with some areas stabilized by forests.

The **Eel River Delta** was identified as an area with high adaptive capacity. The Eel River is known to be a huge sediment source and have very high rates of sediment discharge into the coastal neashore, exact rates remain undetermined. It is thought that this area will be able to keep up with predicted sea level changes. **Fortuna**, a nearby agricultural area, is low lying and prone to flooding.

In regards to habitat migration constraints, **Table Bluff** was identified as a major topographic feature, in the south portion of the bay, which will prevent salt marsh migration. **Mad River Slough** is also constrained due to topographic features.

South of Humboldt Bay, the bluffs near **Centerville** (near Ferndale) were identified as landslide prone. Similarly, **Shelter Cove** was noted as an erosion/landslide hotspot. In this area, there has been significant bluff development. The development was constructed on top of steep cliffs. Shelter Cove is a known high wave energy hotspot as well.

Near San Francisco, **Drakes Estero** was described as "natural and pristine." This area is low-lying but has a higher adaptive capacity then nearby Bolinas lagoon because of habitat migration potential. **Bolinas lagoon** was described as one of the most vulnerable sites in northern California. The wetlands are "pinched off" by surrounding mountains and encroaching development. **Tomales Bay** is also facing potential topographic constraints. Wetlands scattered around **San Francisco Bay** are also constrained by widespread development.

Ocean Beach (San Francisco) is a known hotspot for focused wave energy and erosion. The bluffs are prone to landslides. The nearby wastewater treatment facility was identified as a potential problem. The wastewater infrastructure is buried "in the back of the beach in low-lying dune habitat. The system is gravity-fed, and without re-engineering, SLR will eventually cause a "catastrophic failure of the sewage system."

Pacifica Bluffs and **Sharp Park** are also erosion hotspots. The soft soil, characteristic of this area, has some of the highest erosion rates in the state. There is an "old marsh" just east of **Pacifica State Beach**. The topography drops in elevation as you go from the beach to the marsh. The beach wall at the state park has been overtopped during storm events. There is a low-lying sewage pump station nearby as well. Other erosion hotpots include the headlands near **Mavericks** and **Moss Beach** located near **Half Moon Bay**.

In several areas, interviewees noted that roads (Highway 101) and railroad tracks are acting like a sediment trap. **Pescadero Salt Marsh** has a lot of sediment coming into the system, but it is not getting flushed out. Highway 101 has caused extra sediment to be "stuck" in the system. This is a flood prone area. **Waddell Creek** and **Scott Creek** face similar sediment trap issues. **Laguna Creek** (near Wilder Ranch State Park) is "pinched by railroad tracks."

In Santa Cruz, **Corcoran Lagoon** and **21st Avenue State Beach** are facing severe erosion due to coastal armoring. **Twin Lakes State Park** is a flood prone area. South of Santa Cruz, **Potero River** has substantial dune and low bluff habitat. This is a big agricultural zone (near Watsonville) where some areas are already converting to marginally productive land (from an agricultural perspective). This area is subject to ground water intrusion and floods during high tides and extreme storm events.

Prior to the construction of the harbor, **Elkhorn Slough** was seasonally shut off from marine water input. It was permanently "opened up" when the harbor was constructed and the jetties have altered the tidal prism within the slough, causing increased erosion. Increased tidal flow has reduced the amount of wetlands further inland.

Near Monterey, **Sand City** was identified as having low-lying dune habitat that is likely to be impacted by SLR. California's last remaining beach sand mining operation exists near here. Local sand budgets have been calculated and the deficit is approximately equal to what the mining operation is extracting. **Marina** and **Seaside** were noted as having very high rates of shoreline retreat. However, the beaches in this area are relatively "healthy" because there is little armoring nearby.

Southern California

No information was collected for areas between Monterey and Los Angeles. For much of Los Angeles and Orange County, development abuts the coastline. Beach loss and coastal armoring is an issue for many areas in southern California. **Newport Beach** and **Seal Beach** were identified as two particularly low-lying areas. In Seal Beach, flooding during extreme high tide events is a known occurrence. Land subsidence in **Long Beach** and **Huntington Beach** historically resulted from water and oil extraction from underground aquifers.

San Diego's coastal lagoons were described as "tidal wetlands and flats" having low slopes and being easily inundated. There is a trend of decreasing sediment supply to these wetlands and several interviewees commented that most will not be able to keep up with SLR. These coastal lagoons include **Buena Vista Lagoon**, **Agua Hedionda**, **Batiquitos Lagoon**, **San Elijo**, **San Deguito**, and **Torrey Pines State Reserve Estuary**. **Tijuana River Estuary** was noted as a larger system that may be vulnerable because it has "more frontal area." Most coastal lagoons in San Diego are linear, running in the east west direction. Tijuana River Estuary is relatively wide (in the north-south direction).

California Resources

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Discussion

This report captures a wide variety of information relating to coastal vulnerability to climate change impacts on the West Coast. The information presented here provides an indication of potentially vulnerable areas in Oregon, Washington, and California, as well as offers the reader a compilation of relevant and current literature.

One unintended result of this project was the identification of key research gaps that will and should be incorporated with future climate change vulnerability studies. In regards to understanding vulnerability of wetland habitats to SLR, there is a substantial need for site-specific data on sediment accumulation, erosion, and accretion rates. Also, carbon sequestration data for the west coast was described as "undeveloped." Much of the carbon sequestration work to date has occurred on the east coast salt marsh systems. West coast salt marshes are more diverse compared to east coast systems in terms of species diversity. Carbon sequestration data from the east coast will not accurately translate to the west coast. Interviewees also commented that there is a great need to better understand erosion and sediment deposition patterns.

Finally, in regards to predicting flood damage, interviewees stated that better quantitative "predictions," or at least improved development of possible future flooding and damage scenarios is possible. Currently, this is hindered by the lack of actual measurements of wave-driven runup from major events in the past. Interest and funding for this relatively simple, yet crucial data collection still seems to be generally lacking. This was noted as the single biggest impediment to developing more robust maps of likely future flooding and damage scenarios. As a remedy, "efforts should be made to institute routine local and quantitative flood height observations whenever there are large coastal storm events."

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