8: Coasts

Impacts of Climate Change on the Coasts of Washington State

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Abstract

Climate change on the Washington coast will trigger significant physical and chemical stressors: (a) inundation of low-lying areas by high tides as sea level rises; (b) flooding of coasts during major storm events, especially near river mouths; (c) accelerated erosion of coastal bluffs; (d) shifting of beach profiles, moving the position of the Mean High Water line landward; (e) saltwater intrusion into coastal freshwater aquifers; and (f) increased ocean temperature and acidity. Similar forces will be working everywhere, but shore areas will respond differently depending upon substrate (sand versus bedrock), slope (shallow versus steep cliffs), and the surrounding conditions (exposed versus sheltered from storms). We expect substantial impacts on coastal systems from bluff erosion, shifting beach berms, shoreline armoring, and inundation of coastal lands. Further, increased ocean temperatures and acidity will negatively impact shellfish aquaculture. As beaches adjust to sea level rise, coastal property lines and intertidal aquaculture leases will need to be carefully defined through modified property laws. We anticipate relatively minor impacts on coastal freshwater aquifers. Additional research is needed to develop a more comprehensive assessment of climate impacts on all coastal features in the state.

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1. Introduction

Washington State has more than 5000 km (3085 miles) of coastline (Table 1) with very diverse characteristics. The coastline can be divided into five regions: (1) the Pacific coast south of Point Grenville, (2) the Pacific coast north of Point Grenville, (3) the coast along the north shore of the Olympic peninsula and east through the Strait of Juan de Fuca, (4) the Puget Sound region, including Hood Canal, and (5) the San Juan Islands and the US portion of the Strait of Georgia (Figure 1). Sandy beaches with shallow slopes and high-energy waves are characteristic of the ocean shore in southwestern Washington, while Willapa Bay and Grays Harbor are shallow, protected bays with extensive mudflats. The coast north of Point Grenville and along north Olympic Peninsula coast has a mixture of steep rocky shores, estuaries, and sandy beaches and spits subject to high wind and waves. According to Johannessen and MacLennan, “the most prevalent shore type in Puget Sound is the bluff-backed beach – coastal bluffs fronted by narrow mixed sand and gravel beaches” (2007, p. v). Much of the San Juan Islands coast is hard, stable bedrock.

Long-term climate change is expected to result in sea level rise (SLR), and increased ocean temperature and acidity (Intergovernmental Panel on Climate Change 2007). Further, on the Pacific coast of Washington there is evidence that shifting storm tracks and increased wave heights have begun eroding beaches south of Point Grenville (Graham and Diaz 2001, and Allan and Komar 2006). While the same basic climate forces will be changing everywhere, each region, and related human activities, will respond to climate change in specific ways depending upon substrate (sand versus bedrock), slope (shallow versus steep cliffs), and the surrounding conditions (exposed shores versus sheltered bays and sounds).

Table 1. Shoreline length for each segment of the Washington coast (adapted from Bailey et al., 1998 and ArcGIS measurements)

Coastal Segment	Shoreline Length
Puget Sound (including Hood Canal)	2411.6 km (1477.1 mi)
San Juan Islands and Georgia Strait	1302.9 km (807.8 mi)
North Olympic Peninsula Coast	325.4 km (202.4 mi)
Cape Flattery to the Point Grenville	267.1 km (166.0 mi)
Point Grenville to the Columbia R. -- “Southwest Coast”	695.3 km (432.0 mi)
Total	5002.3 km (3085.3 mi)

The physical and chemical effects of climate change will manifest themselves in five primary ways:

Inundation. As the sea level rises (Mote, et al. 2008), the lowest lying shores will be regularly flooded by high tides. Coastal inundation is a gradual process on decadal time scales due to expanding volume of ocean water (called *eustatic* SLR), melting of glaciers, and local factors such as land subsidence and tectonic uplift (Snover et al., 2007).

Flooding. During major storm events, SLR will compound the effects of storm surges, which can contribute to more extensive coastal flooding. Also, changes in the seasonal pattern of rainfall or increased peak runoff from snow melting could lead to more serious coastal flood events, especially near rivers.

Erosion and Landslides. Although erosion on beaches and bluffs is a natural, on-going process, major episodes of erosion often occur during storm events, particularly when storms coincide with high tides. SLR will exacerbate the conditions that contribute to episodic erosion events, and this will accelerate bluff and beach erosion. Increased storm strength or frequency will exacerbate this. Climate change is also likely to increase

Figure 1. Washington coastal region

winter precipitation in the Pacific Northwest, which can contribute to landslides on bluffs saturated by rainfall or run-off.

Saltwater Intrusion. As the sea level rises, coastal freshwater aquifers will be subject to increased intrusion by salt water.

Increased Ocean Surface Temperature and Acidity. As the atmosphere warms, the ocean temperatures will increase. Additionally, absorption of carbon dioxide by the oceans leads to increasing acidity (lower pH).

Because Washington's coasts are heavily utilized for ports, home sites, public recreation, and shellfish aquaculture, these physical and chemical effects of climate change will pose significant challenges. To highlight expected climate change impacts, this chapter will focus on select locations in Puget Sound, Willapa Bay on the southwest Washington coast, and the San Juan Islands. Some general predictions are made about climate impacts in these study areas, and adaptation options and research gaps are discussed.

Table 2. Relative sea level rise projections for major geograpic areas of Washington State (adapted from Mote et al 2008)

SLR Estimate	By the year 2050			By the year 2100		
	NW Olympic Peninsula	Central & Southern Coast	Puget Sound	NW Olympic Peninsula	Central & Southern Coast	Puget Sound
Very Low	-5” (-12 cm)	1” (3cm)	3” (8cm)	-9” (-24cm)	2” (6 cm)	6” (16cm)
Medium	0 “ (0 cm)	5” (12.5 cm)	6” (15 cm)	2” (4cm)	11” (29 cm)	13” (34 cm)
Very High	14” (35 cm)	18” (45 cm)	22” (55 cm)	35” (88cm)	43” (108cm)	50” (128cm)

2. Background

The scientific literature relevant to dynamics of change in Washington coastal areas describes (a) the nature and process of coastal erosion on beaches and bluffs (Shipman, 2004; Terich, 1987; Komar, 1998); (b) the roles of sea level changes and storm waves in accelerating shoreline erosion (e.g. Graham and Diaz, 2001; Allan and Komar, 2006; Mote et al., 2008; and Zhang, Douglas, and Leatherman, 2004); (c) long-term experience with saltwater intrusion into coastal freshwater aquifers, mainly as a result of excessive pumping for freshwater supply (e.g. Walters, 1971; and Jones, 1985); (d) effects of increased sea surface temperature on the frequency of harmful algal blooms (Moore et al., 2008); and (e) trends in and effects of ocean acidification (e.g. Doney, 2006 and Feely et al., 2008). The literature has also begun to document how climate change may exacerbate risks to human uses of coastal areas. A number of recent regional investigations and public workshops have addressed these issues. For example, the State of Washington has prepared documents describing the nature of climate change, regional vulnerabilities, and opportunities for adaptation (Snover et al., 2007). These sources of information, assessment, and policy investigations have been broadly surveyed and incorporated in the following sections. Based on that starting point, this chapter focuses on specific risks posed by climate change to the Washington coast.

Locally, *relative* SLR -- the combined effect of global SLR and local rates of vertical land movement -- drives many coastal impacts. Mote, et al (2008) explain that Western Washington is located on the edge of the North American continental plate with the Juan de Fuca oceanic plate subducting underneath, which produces gradual uplift in the northwestern part of the region. The northwestern Olympic peninsula has been rising at about 2 mm/yr. On the other hand, South Puget Sound has been subsiding at a rate of 2 mm/yr. Vertical land movement on most of Washington’s coast and the rest of Puget Sound has been found to be less than 1 mm/yr. If these trends continue, relative SLR will be greatest in south Puget Sound and least on the northwest tip of the Olympic peninsula (See Table 2). Substantial and reliable scientific models do not back up these trends, which is a major reason for the wide range of projected SLR. As noted by Mote el al (2008), (1) they have not formally quantified the probabilities, (2) SLR cannot be estimated accurately at specific locations, and (3) these SLR projections are for advisory purposes and are not actual predictions.

Clearly, the regional impacts of climate change depend upon the patterns of coastal land use and development. The predominant land use in the Puget Sound is low-density housing (91% of shoreline properties classified as single-family homes), often located at the top of bluffs, which are typically protected by a form of shoreline defense (such as concrete bulkheads or riprap) (Gabriel and Terich, 2005). On the southwest Washington coast there are local, dense developments of beach homes and tourist businesses. Because the Puget Sound region is most densely inhabited region, human impacts are expected to be greatest there and least on the Olympic peninsula north of Point Grenville and in the San Juan Islands. Between those extremes lie the Strait of Georgia and southwest Washington coasts.

3. Approach/Methods Used

The background information identified above has been reviewed and assessed in the five Key Findings summarized in the following section. In addition, we include information gathered through conversations and interviews with personnel at State and local agencies who are dealing with some of the potential impacts of SLR, elevation of sea temperature and acidity, and saltwater intrusion of coastal aquifers. Our basic approach is (a) to select specific locales and impacts for study, (b) to characterize the understanding of the local circumstances and concerns related to these impacts, and (c) to note how the impacts on the local population, structures, public facilities, and economy depend upon how people adapt to the physical changes. We characterize the adaptation responses in three categories: (1) *accommodation*, which means continuing with current uses of the coastline despite the changes in coastal oceans and environments – for example, to accommodate to SLR by raising the height of piers and placing shoreline buildings on pilings; (2) *protection*, which involves building structures like seawalls and dikes that keep the sea from intruding on coastal areas; and (3) *retreat*, which involves abandoning coastal sites and moving to higher ground. Each of these adaptive responses is likely to be adopted within the Washington coastal areas.

Because available information is not adequate to examine climate impacts on the entire Washington coast, this study focuses on a few cases to illustrate the nature of the impacts and to highlight specific areas of the coast where these impacts will be a significant concern. his case study approach is necessarily somewhat anecdotal and incomplete. The principal outcome of this study is to push the existing knoledge a bit further in the direction of useful, integrated understaning of the threats posed by climate change on the Washington coast**.**

4. Key Findings

4.1. Impacts on Beaches and Sand Spits

Beach erosion is an on-going natural process. Beaches are nourished by sediment eroded from bluffs or provided by rivers. Sand eroded from beaches moves along the coast or is pushed offshore by high-energy waves. There is a constant dynamic tension between the natural processes of accretion and erosion. Here, we focus on the role of SLR in processes affecting beaches of Puget Sound and Willapa bay.

Figure 2. Seawalls protecting Bainbridge Island homes, which have been found to degrade nearshore habitat (The Seattle Times, 2008)

4.1.1. Washington Beaches and Sea Level Rise (SLR)

Puget Sound's shoreline, estimated at 2411 km (1477 mi) in length, has many facilities and residential developments that will be affected by SLR (Shipman 2004). SLR will increase erosion rates and coastal flooding on Washington's beaches and bluffs. Erosion tends to occur largely through infrequent, episodic events, such as high-energy storm waves coming on a high tide. Wave-induced erosion of the uplands can occur when waves reach the junction between the beach face and its backing feature, such as a sea cliff, dune, or shore armoring (Ruggiero et al., 1997). SLR will cause the landward migration of the shoreline as waves break higher on the beach profile.

Coastal development could be threatened by increased vulnerability of coastal property as SLR shifts shorelines and tides closer to homes and infrastructure. In the Puget Sound region, approximately 90% of Puget Sound's shorelines have single-family residences or are available for residential development (Taylor et al., 2005). In recent years, the Washington State Department of Fish and Wildlife has approved numerous residential bulkheads to armor the shoreline of Puget Sound (particularly around Tacoma, Olympia, and the coasts of Whidbey Island), despite the documented damage to nearshore habitats. (Johannessen and MacLennan 2007, p.15)

Ironically, shoreline armoring by sea walls, riprap, or revetments typically decreases the volume of sediment available to sustain beaches. Because wave energy reflected off coastal armor carries sediment offshore, and the armoring itself reduces erosion of protected bluffs, protected shores gradually lose sediment and shallow water habitat (Johannessen and MacLennan, 2007, p.13.). The resulting increased water depths and greater wave energy tends to weaken the protective structures. In addition,

Figure 3. Housing on Point Monroe, Bainbridge Island (Washington Department of Ecology, Washington Coastal Atlas)

the beaches of Puget Sound are critical habitat for juvenile fish (including salmonids) and shorebirds, and they support shellfish and epibenthic zooplankton, among other species. Aquatic vegetation dominates the base of the food web in these habitats and provides forage, refuge, and other functions for many marine species (Zelo et al., 2000). Beach erosion rates will vary depending on wave environment, geology, beach characteristics, and extent of shoreline armoring (Finlayson, 2006).

4.1.2. Expected Impacts on Washington Beaches

4.1.2a. Bainbridge Island

Bainbridge Island contains 85.2 km (53.3 mi.) of shoreline with 82% of the shorelines currently in residential, recreational, commercial, or industrial use. Bainbridge Island's shorelines are quite diverse, with conditions ranging from polluted urban waterfronts, to residential developments, to fairly uninhabited areas of shoreline with intact riparian habitats (NOAA, 2004). The majority of development is for single-family residences, but also includes parks, a fish-pen aquaculture center, a ferry terminal, and mixed-use developments. About 48% of the shoreline is armored (mostly vertical rip rap or concrete structures). Figure 2 illustrates a bulkhead protecting homes along Bainbridge Island's shoreline. About 27% of the shoreline has armoring that extends into the intertidal zone (NOAA, 2004). Where shoreline modification is extensive, the slope is gauged as unstable, while the areas with little shoreline modification have stable slopes.

Areas most susceptible to inundation are the uplifted beach terraces on the southern third of the island, and the majority of the bays and coves on the island (City of Bainbridge Island, 2007). Rolling Bay-Point Monroe on the northeastern shore runs 9.0 km (5.6 miles) encompassing Point Monroe, Point Monroe Lagoon, and Rolling Bay to Skiff Point. Areas like Point Monroe (Figure 3), where houses are situated on a small strip of beach with water on two sides, are especially at risk. While Point Monroe is primarily residential, its shore does include Fay Bainbridge State Park, which is a stretch of relatively undeveloped sandy beach with access for recreation. Many homes along the spit at Point Monroe are built on fill material (NOAA, 2004). A total of 291 modifications were recorded along the Point Monroe shorelines, at an average of 10 modifications per 1000 ft. (NOAA, 2004). These include protective structures at the waterline (112), docks (33), and overwater structures (28). NOAA (2004) recommends that unnecessary armoring structures, especially those that intrude into the intertidal zone, be modified or removed.

4.1.2b. Impacts on the Southwest Washington Beaches

The southwest Washington coast covers the northern three quarters of the Columbia River littoral cell, which stretches from Point Grenville south to Tillamook Head, Oregon. The Washington segment of the littoral cell contains three sub-cells stretching from the Columbia River to the entrance to Willapa Bay, from Willapa Bay to the Grays Harbor entrance, and from the Grays Harbor entrance to Point Grenville. The coast here is of two principle types, sandy beach and berms along the outer coast, and mudflats within the two bays. The ocean beaches and dunes reflect a high-energy coast that shifts seasonally as wave energy and direction vary. After jetties were constructed at the entrances to the Columbia River and Grays Harbor in the early 1900s, sediments were trapped behind the jetties, causing rapid beach accretion in the first half of the 20th century. But development of 11 major, mainstem dams on the Columbia River has reduced peak river flows and sediment discharges to the coast. Substantial recent evidence suggests a shifting regional trend towards erosion (Kaminsky, et al. 1998), which may be related to lower sediment budget and/or shifting storm tracks with larger, more energetic winter storm waves.

The Southwest Washington Coastal Erosion Project has identified several erosion “hot spots”. These are located at the south end of Ocean Shores; near the southern jetty at the Grays Harbor entrance north of Westport; at the north end of the Long Beach peninsula (Leadbetter Point); and just north of the Columbia River entrance near Fort Canby. Recently, the highest erosion rates occur at the north entrance of Willapa Bay (formerly known as Shoalwater Bay) the fastest-eroding beach on the Pacific coast, locally referred to as Washaway Beach (Daniels et al., 1998). Since the 1880s, it has been losing 19.7m (65ft) of beach a year on average. High erosion rates have also been observed at Ocean Shores, just north of Cape Leadbetter. Beach erosion appears to occur when large waves approach at a steeper angle from the south, especially during El Niño conditions, when winter sea level is as much as 0.3 m higher than July levels. Researchers also suspect that higher storm waves are reaching the southwest Washington coast due to a northward shift in the storm track as a consequence of broader global climate changes. Hence, there are at least three possible factors contributing to erosion along the beaches of southwest Washington, (a) reduced sediment supply; (b) gradual SLR as a longer-term factor, and (c) northward shift in Pacific winter storm tracks. Increased storm intensity may be an additional climate-related factor, but there is less than broad agreement among the climate scientists about the relative importance of these factors.

Economic impacts of episodic erosion events are illustrated by the events at Washaway Beach. Despite official warnings, and a decade-old building moratorium, people still continue to buy property there. More than 100 homes have fallen into the ocean in the last 20 years, including the entire town of North Cove (Martin, September 2007). Current residents of Washaway Beach are resigned to the fact that their homes will most likely be gone within a decade and that they will have to retreat due to the wave action and erosion, but they say that the view and location is worth the risk (Martin, September 2007). More than $24 million has been spent to protect nearby Highway 105 and $12 million has been spent to protect the Shoalwater Bay Indian reservation, which has seen a reduction of tribal lands and shellfish resources due to the rapid retreat of Cape Shoalwater. There are currently no plans to protect the property at Washaway Beach (Morton et al., 2007).

Ocean Shores has been actively eroding since the 1995/96 winter season. A temporary structure was emplaced to protect condominiums and infrastructure valued at more than $30 million (Kaminsky, 1998). While these examples of shoreline erosion occur without significant climate change, they illustrate the kinds of erosion events that may occur more frequently as SLR and increased winter storm waves attack other shoreline segments on the southwest Washington coast.

Within the shallow bays, the shorelines are relatively well protected from high-energy waves and major episodes of erosion. Extensive mudflats in both Willapa Bay and Grays Harbor have long been utilized for shellfish aquaculture, primarily oyster culture, which contributes significantly to the local economy. In Grays Harbor, the mudflats have been eroding and shrinking, perhaps due to higher currents flowing through the dredged and jettied entrance, which permits greater wave energy to enter the Bay. Again, higher sea levels and increased wave action due to shifting storm tracks, driven by global climate changes, could be a contributor to reduced habitat for shellfish in the Bay. (Kaminsky, personal communication 2009).

4.2. Bluff Erosion in Puget Sound

Bluff erosion is an on-going natural process that feeds sediment for beach formation, but also threatens property and human lives when buildings are close to the eroding bluffs (Figure 4). We examine the role of wave action and tides, and how this may change with SLR. Three case studies illustrate some of the different types of bluffs present in the Sound.

4.2.1. Sea Level Rise and Bluff Erosion

Wave action creates unstable bluff profiles through toe erosion, which "results in the loss of lateral support" for the bluff, and may lead to large slabs of the bluff failing (Baum, 1998). The steepening of bluff slopes increases the probability of bluff failure (Thurston County, 2005), and

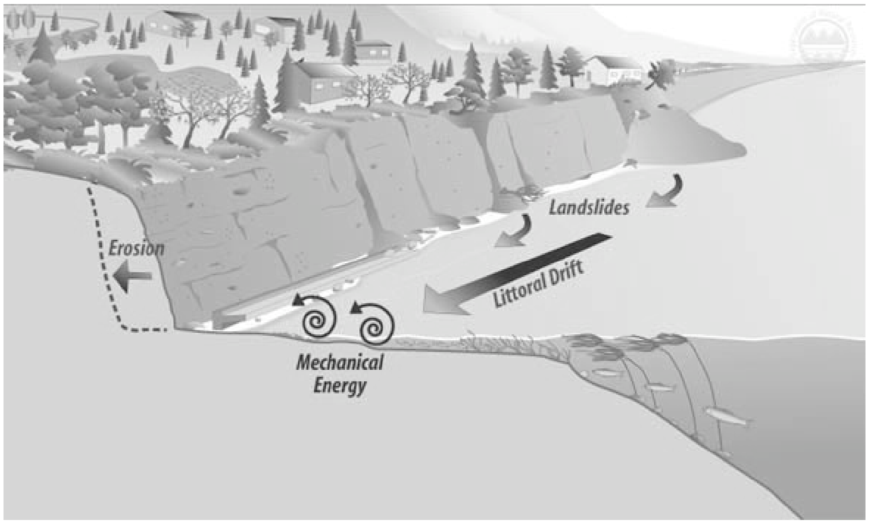

Figure 4. Bluff erosion process (Williams et al., 2006)

accelerates the long-term retreat of the bluff. Steeper, unstable bluffs are more susceptible to small landslides, which are often triggered by heavy rainfall and drainage failures (Terich, 1987). Elevated groundwater levels or seismic activity may also trigger large landslides (Shipman, 2004.). Therefore, bluff toe erosion "sets the stage" for slope failure, but rarely is it the direct cause of a coastal bluff landslide (Thurston County, 2005).

Among key factors in bluff erosion are storms with large waves, especially when combined with high tides or elevated sea levels associated with El Niño events (Shipman, 2004). The length of the fetch --the distance over which waves develop-- and wind speed during storms increases wave energy. For example, western Whidbey Island is subject to a very long fetch along the Strait of Juan de Fuca (Shipman, 2004). Furthermore, when storms occur at high tide, the wave action on bluffs is magnified. Increasing the sea level raises the high tide level. As a result, waves will be able to directly erode the toe of the bluff in its current position more often, increasing the frequency of landslides (Shipman, 2004). These factors could lead to complex changes in shorelines as SLR shifts the bluff/sea interface further inland. Eventually, the sediment supply from eroding bluffs should maintain the elevation of beaches as beach and bluff profiles move landward.

4.2.2. Examples of Bluff Erosion

4.2.2a. Western Whidbey Island

Island County is comprised of six islands with 354 km (221 mi) of shoreline, of which 51% is classified as "unstable" (Shipman, 2004). Whidbey Island is the largest and most populated island in Island County. Erosion rates in the county have been measured from a centimeter to more than 61 cm (2 ft) per year (Island County, 2006). The western shore of Whidbey Island has experienced many landslides. There is a large prehistoric landslide that extends about 2 km (1.25 mi) along the shoreline, which sometimes reactivates during wet weather (Shipman, 2004). Typical erosion rates are about 3 cm (1.2 in)/yr, which involves the loss of 1 meter of bluff or bank in a landslide every 33 years. Areas that have greater exposure and higher wave energy may exhibit erosion rates of several inches per year or more

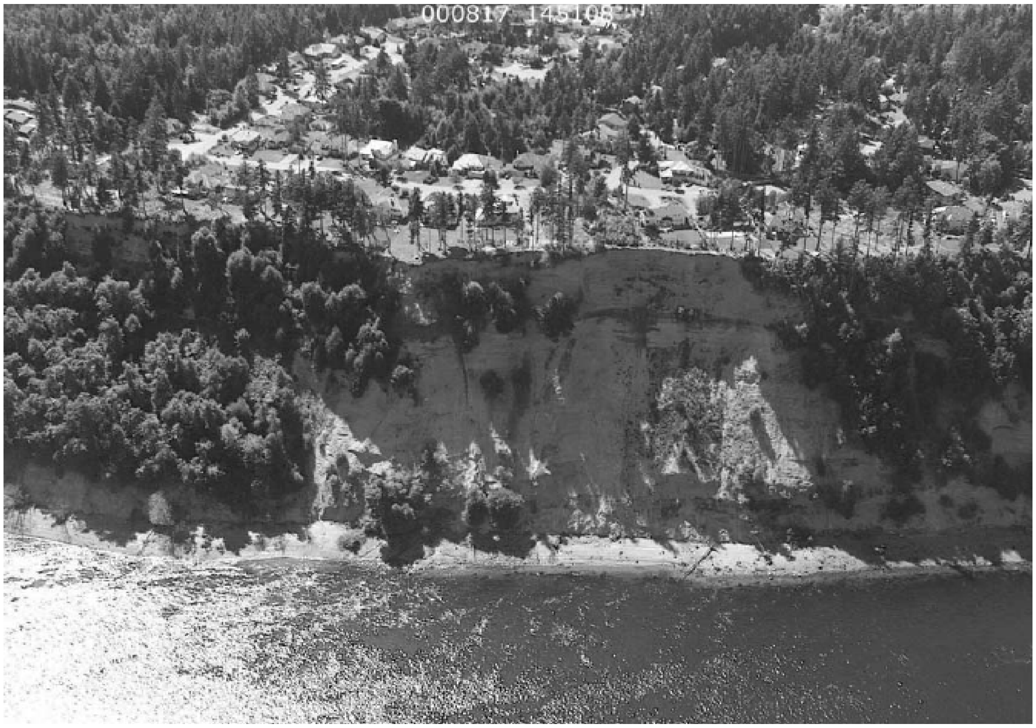

Figure 5. Houses on a bluff on western Whidbey Island. (http://apps.ecy.wa.gov/shorephotos/scripts/bigphoto.asp?id=ISL0354)

(Zelo et al., 2000). Recently, high waves have caused large amounts of erosion on Whidbey Island, particularly in drift cells on the southeastern portion of the island and on large spits on Cultus Bay (Johannessen and MacLennan, 2007). A recent risk assessment has shown that there is a 100% probability of a landslide somewhere, of some magnitude in a given year, though most will be small (Island County, 2006). As in most of Puget Sound, Whidbey Island bluffs are attractive sites for residential development (Shipman, 2007). As a result, when major bluff slides occur, homes are on the front lines, and residents may be forced to protect, accommodate, or retreat from their homes (Figure 5).

Many residential developments built on Whidbey Island in the 1950s and 1960s included construction of bulkheads at the base of high bluffs. These practices would not be allowed today, but the structures that are currently standing are allowed to remain. Regulation of construction on residential sites is not very restrictive, because the Shoreline Management Act (1971) exempts the construction of single-family residences and "normal protective bulkheads" from a Shoreline Substantial Development Permit (Zelo et al., 2000). There have been regular conversions of small houses into large homes, which are at greater risk of slide damage when they reside on unstable slopes (Shipman, 2004).

As SLR causes increased bluff erosion and landslides, these locations will be subject to increased hazards of damage. A preliminary analysis using Zillow (a web-based tool for estimating home value based upon tax assessments and home improvements, among other factors) shows that along a one mile long stretch of bluff along West Beach Road on northwest Whidbey Island, approximately $32 million worth of property could be involved (Barton and Frink, 2007). Many of these homes are less than a hundred feet from the current bluff edge, and are at risk for severe structural damage resulting from accelerated bluff erosion.

4.2.2b. Bainbridge Island

Bainbridge Island has 394 km (246 mi) of shoreline, 20% of which is classified as “unstable” (Shipman, 2004). Unlike Whidbey Island, where substantial waves arrive through the Strait of Juan de Fuca, Bainbridge Island is nestled inside Puget Sound where waves do not gather the same magnitude of energy. However, the bluffs on Bainbridge Island are still vulnerable to erosion. Bluff erosion rates average between 5.1 cm (2 in) and 15.2 cm (6 in) per year, depending on physical characteristics such as beach profile, substrate, and slope angle, as well as the presence or absence of human-built protective structures such as bulkheads (City of Bainbridge Island, 2007). As on Whidbey Island, bluff erosion events are episodic. After heavy rains and soil saturation, Bainbridge Island has experienced a number of bluff erosion events.

Rolling Bay Walk has been the site of a number of large bluff erosion events, including one in the spring of 1996 that pushed a house off of its foundation, and a series of slides in 1997 that overturned one house into the water, and damaged at least three more (Baum et al., 1998). Another area that has experienced bluff erosion is near Harvey Road. In the past decade, homeowners have reported a 2.5-3 m (8-10 ft) retreat at the base of the bluff. At least one of the homes is now within 6.1 m (20 ft) of the edge of the bluff, with others 12.1 m or 24.2 m (40 or 80 ft) from the retreating bluff line. Additionally, many auxiliary structures such as septic systems are threatened by bluff erosion (Shoreline Hearings Board, 2007).

4.2.2c. The San Juan Islands

The San Juan Islands, in contrast to the previous two cases, have very little bluff erosion. Although there is moderate fetch and storm wave energy in the north and south, the islands are comprised predominately of exposed bedrock coast (Shipman, 2004). This landscape was formed when glaciers scoured knobs and hills, exposing the bedrock. Only 3% of San Juan County’s 602 km (376 mi) of shoreline is classified as “unstable” (Shipman, 2004). Therefore, due to “their resistant lithologies and the modest wave energy of the sound” in these areas, bluff erosion rates are negligible (Shipman, 2004). While there are some unstable bluffs vulnerable to erosion and landslides, the resistance of bedrock bluffs to wave action erosion makes it unlikely that an increase in SLR will significantly affect the bluff erosion patterns in the San Juan Islands.

4.3. Impacts on Ports and Harbors

Major ports and harbors in the State of Washington include the Ports of Seattle, Tacoma, Everett, Olympia, Grays Harbor, and Port Angeles. In addition, there are many smaller ports and marinas designed mainly for private pleasure craft. Because such facilities are adjacent to the shore, SLR will affect them all. The magnitude of impacts to the operation of ports and harbors due to SLR will depend upon a variety of factors. These include: the geomorphology of the land surrounding the port, whether the port is located near a river whose flow may be affected by climate change, the degree to which the transportation system surrounding the port will be impacted, and whether re-construction of piers and other structures can accommodate the expected level of SLR.

Most ports in Washington State are operated by local Port Authorities, organized at the county level, which can encompass a variety of administrative units. Due to limitations on time and resources available for this study, only the two large ports of Seattle and Tacoma are specifically considered below. Both of these are "landlord ports," meaning that they lease terminals and shore-based equipment (e.g. container cranes) to shipping lines that operate the terminals. These two large ports handle most of the State's freight and cruise ship traffic, and much of the commercial fishing fleet operating out of Puget Sound. The likely impacts depend upon the strategies adopted by the ports for adapting to SLR. Finally, it should be noted that the broader effects of SLR on the transportation networks would impact ports. Both the Seattle and Tacoma ports serve as points of freight transfer between ocean ships and land-based cargo carriers serving distant markets. Roughly 50% of the cargo moving through the Port of Seattle is destined for markets east of the Mississippi River. The ability of the ports to continue operation in the face of SLR depends upon the continued operation of trucking lines and railroads. Hence, we can broaden the concept of impacts to include any disabling of links in the transportation system that disconnects the ports from distant markets they are serving.

4.3.1. Port of Seattle

Freight terminals in the Port of Seattle line the edges of Elliot Bay and the Duwamish River estuary. Much of the land on which the piers and facilities reside was created by fill dirt brought from upland sites early in the history of Seattle. These sites are all within a few feet of the extreme high water mark. Hence, higher levels of forecasted SLR (> 0.91m or 3 ft) will pose a significant hazard to the continued operation of the port facilities. According to key staff at the port, they are considering a variety of strategies to accommodate to SLR, such as raising existing docks and designing floating terminals with ramps to the upland railroad yards. Some docks and cranes have already been raised in elevation to accommodate to SLR and the increasing size of ships. The main port complex in Elliot Bay is adjacent to railroad yards and the south Seattle industrial district which is located on very low elevation land. A significant rise in sea level would threaten to inundate the entire area, cutting the Port off from the requisite inland transportation facilities. Adding to this potential problem is the nearshore position of the Burlington Northern-Santa Fe railway line on the Puget Sound north of Seattle. Even if the Port were able to protect its current facilities from SLR, a break in the rail network could threaten its viability as a major container and bulk freight center.

Further, the Port's Shilshole marina is just seaward of a significant bluff on the west side of the Sunset Cliffs neighborhood. It is surrounded by very low elevation land that could be inundated by just a few feet of SLR. There is little prospect of adapting this facility to significant SLR, short of installing a few feet of new fill dirt to raise the elevation of the adjacent land.

4.3.2. Port of Tacoma

The Port of Tacoma is a major freight transfer facility, bounded on the south by the Puyallup River and on the north by the Hylebos waterway. Just north of that waterway is a steep bluff topped by extensive housing developments. Current pier maintenance and re-construction plans will increase pier elevations by roughly 1.3 m (4.3 ft) to accommodate the higher levels of SLR predicted for the next century. Hence, the facilities operated by the Port and most of the Port's tenants will accommodate to SLR over the next century unless the actual levels of SLR exceed the predictions. However, the Port planners are aware that SLR, in combination with high river run-off, raises the threat of flooding along the Puyallup River to the south of the main body of freight terminals. This could inundate the intermodal rail yards upon which the transportation network depends. Additional protective structures, such as dikes along the riverbanks, may be needed under the high SLR scenarios.

4.4. Saltwater Intrusion in Coastal Aquifers

4.4.1. Hydrological Dynamics of Aquifers and Seawater

Under normal conditions, the movement of freshwater towards the sea prevents saltwater from contaminating the water in coastal aquifers, and the interface between freshwater and saltwater is below the land surface near the coast (USGS, 2004). Since freshwater is slightly less dense, it tends to float on top of saltwater when both are present in an aquifer. The bottom of the freshwater body floating on seawater within an aquifer is typically about 40 times as far below sea level as the top is above sea level. When freshwater is pumped from the aquifer, the underlying saltwater tends to rise 40 ft for every foot that the water table is lowered (Walters, 1971). The boundary between the freshwater and saltwater zones, known as the zone of diffusion or the zone of mixing (Kelly, 2005), will be pushed landward and upward as sea level rises, potentially making coastal aquifers more vulnerable to saltwater intrusion (Barlow, 2003).

Seawater typically contains about 35,000 mg/L of dissolved solids, including approximately 19,000 mg/L of chloride. Uncontaminated groundwater in most areas of coastal Washington usually contains less than 10 mg/L of chloride, and the EPA recommends that the chloride concentration of drinking water supplies be less than 250 mg/L (Dion and Sumioka, 1984). If saltwater intrusion into coastal aquifers occurs, the waters may not be suitable for drinking and irrigation, the high mineral content of the saltwater could cause corrosion of pipelines and well pumps, and the aquifer and its wells could become unusable if the intrusion becomes too severe (Island County Water Resources Management Plan, 2005).

In some areas of Washington State saltwater intrusion is already a concern due to excessive pumping of the aquifers. On Whidbey Island 72% of its residents rely on the groundwater (Island County Water Management Plan, 2005). In a study by Island County Environmental Health in 2005, areas containing wells were designated as low risk, medium risk, or high risk. Low risk wells within 0.8 km (½ mile) have chloride concentrations less than 100 mg/L; medium risk wells have chloride concentrations between 100 and 200 mg/L; and high risk areas have chloride concentrations greater than 200 mg/L. Out of 379 wells surveyed, 242 showed no evidence of intrusion, 101 showed inconclusive indications of intrusion, and 36 showed positive indications of intrusion. In preventing saltwater intrusion, the important factor is the water level in the area between the well and the shoreline, because saltwater intrusion would first occur along the shoreline and then move inland as the situation worsened. In addition, aquifers that are at critically low water elevation are at risk of saltwater intrusion if there is continued groundwater withdrawal (Kelly, 2005).

4.4.2. Likely Impacts of Sea Level Rise

While projected SLR could cause increased saltwater intrusion into coastal aquifers, expert opinion suggests that SLR will have only a minor effect. Aquifers act as a gradient to the sea, and the amount of water recharge from the surface will likely remain about the same. Hence, the amount of freshwater available is not expected to change. In the very near coastal areas, a rise of 0.3 - 0.9 m (1-3 ft) in the sea level will reduce the depth of the freshwater lens floating above the seawater by 0.3 – 0.9m (1-3 ft). Nearshore wells that already have intrusion problems may have trouble with more saline water, so those wells may need to be moved or reconstructed. But this will be a serious concern only in a very narrow range along the coast, where the freshwater lens is already very shallow, and there are few wells. Based upon our review of the saltwater intrusion problem on Whidbey Island, we conclude saltwater intrusion is not a major risk for Washington State aquifers.

4.5. Impacts on Shellfish Aquaculture

Washington currently has 106 commercial shellfish-growing areas and is the leading producer of commercially farmed bivalve shellfish in the United States, including 86% of the West Coast's production in 2000. Washington's shellfish farmers and harvesters sell shellfish products around the world, and support the economies of many rural western Washington communities ("Treasures of the Tidelands," 2003). Table 3 shows that the sale value of oysters, mussels, small clams, and geoduck clams from aquaculture in Washington is roughly $75 million a year.

4.5.1. Impacts of Sea Level Rise and Increased Sea Surface Temperature

SLR and increased sea surface temperature could impact the shellfish aquaculture industry in several ways. Negative effects of increased temperature could include reduced shellfish growth, reproduction, distribution, and health (Cheney and Dewey, 2006). SLR may affect

Table 3. Shellfish production in Washington State in 2006 (Cheney and Dewey, 2006)

	Oysters	**Clams**	**Mussels**	**Geoduck**	**Total**
Production (mil. lbs.)	77	7	1.5	.4	85.9
Sales Value (mil. $)	$57.75	$14	$1.73	$2.5	$75.98

coastal habitats in the Puget Sound through the inundation and shift of habitat types on existing beaches. SLR would have a minimal impact on mussel and oyster culture on rafts or other floating structures (Pacific Coast Shellfish Growers Association, 2008).

Most shellfish culture occurs on the intertidal substrate, where SLR will directly affect access to these lands through changes in the high and low tide ranges (Pacific Coast Shellfish Growers Association, 2008). If the aquaculture sites do not migrate landward, SLR reduces access to aquaculture beds because of increased water coverage. A 0.16 m (0.53 ft) rise in sea level could lead to an increase in water coverage and a reduction in harvest time of 13%, while a 0.31 m (1 ft) rise in sea level could lead to an increase in water coverage and a reduction in harvest time of 31% (Cheney and Dewey, 2006). The increased water coverage will reduce workdays for shellfish growers because they typically work at low tide. It is very difficult to plant, harvest, or tend partially or completely submerged oysters (Gordon et al., 2003). A further complexity is the issue of shoreline armoring, which affects the availability of tidelands for shellfish farming, as shoreline armoring tends to increase beach erosion and change the characteristic of the beach sediment.

Since SLR will shift beach profiles landward, there may be no reduction in sub-tidal habitat overall, but the optimal growing areas may be shifted off of the farmer's property or lease (Cheney and Dewey, 2006). At present, "average high tide" or "ordinary high water" is treated as a stable boundary line that separates upland property from inter-tidal areas used for shellfish aquaculture. In the future, however, SLR may create ambiguity in the definition of the property rights due to a shift in where the actual high tide occurs. The high tide with SLR will be further inland. One option would be to retain the definition of tidelands and shoreline property boundaries, but recognize explicitly that these boundaries are moving upland as sea level rises – an option entitled "rolling easements" (Titus, 1986).

4.5.2. Likely Impacts of Sea Surface Temperature and Harmful Algal Blooms

Harmful Algal Blooms (HABs) are blooms of algae that can produce potent natural toxins that cause harmful physiological effects (including illness or death) when they are concentrated within filter feeding shellfish and fish. Humans and other animals are exposed to the HAB toxins by ingesting the contaminated fish or shellfish and by consumption, aerosol inhalation, or skin contact with contaminated water. Paralytic shellfish poisoning (PSP) from dinoflagellates in the genus *Alexandrium* and amnesiac shellfish poisoning, caused by domoic acid created by diatoms *Pseudo-nitzschia,* are the primary problems on the West Coast (Horner et al., 1997). Other species of dinoflagellates can cause a range of illnesses, such as neurotoxic shellfish poisoning, diarrheic shellfish poisoning, and ciguatera fish poisoning. These also cause fish, bird, and marine mammal die-offs (Patz et al., 2006).

Over the past decade, evidence of a relationship between climate and the magnitude, frequency, and duration of HABs has suggested that the seasons when HABs occur may expand as a result of climate change. Sea surface temperature and upwelling have both been linked with HABs (Patz et al., 2006). Due to their physiological and ecological diversity HAB species will not exhibit a uniform response to changes in climate. Phytoplankton growth is typically influenced by temperature, light, and the availability of nutrients (Moore et al., 2008). Most marine HAB dinoflagellates are expected to be favored over other phytoplankton under future climate scenarios, because their ability to swim allows them to reach nutrients in the deeper parts of the upper stratified layer of the water column that diatoms and other phytoplankton cannot reach. It is not known if blooms originate at one or several sites, or whether isolated blooms develop in separate locations at the same time in response to similar hydrographic conditions. It is also difficult to determine if blooms develop offshore before they are detected in coastal waters (Horner et al., 1997).

The frequency and distribution of HABs has increased over the last 30 years, and human illness from algal sources has increased. In fact, the present variability and occurrence of HABs is unrivaled from those in the past 60 years (Patz et al., 2006). In Puget Sound *Alexandrium* species occur primarily in the late summer and early fall when the water temperatures reach their seasonal peak. Blooms of the dinoflagellates *Ceratium* species and *Akashiwo sanguinea* generally occur during the same period in shallow areas of southern Puget Sound. Increased mortality of oyster larvae and adults has been associated with these dinoflagellates, but there is no indication of a chemical toxin. The increased mortality could be due to mechanical damage or oxygen depletion caused by a bloom decay (Horner et al., 1997).

By the year 2100, surface air temperatures in the Puget Sound region could increase by as much as 6°C (10.8°F). Surface water temperatures are expected to follow this closely. This increase is a concern because water temperatures greater than 13°C (56.7°F) have been found to promote blooms. The rising air and water surface temperatures may also promote earlier and longer lasting HABs. The growth responses of HABs could also be influenced by interactions with other physical and biological aspects of the marine ecosystem, such as wind-driven upwelling at coastal margins.

Some toxic blooms are triggered by nutrients supplied by land runoff. Hence, shifts in the timing of runoff into coastal estuaries fed by snowmelt rivers could lead to changes in the timing and magnitude of stratification related to freshwater inputs and to nutrient loading and turbidity related to freshwater supplies, which could increase the frequency of blooms in coastal waters. Studies in Sequim Bay on the Strait of Juan de Fuca suggest that paralytic shellfish poisoning toxicity increases when the climate is warm and dry, and decreases when the climate is cold and wet (Horner et al., 1997). Even though there is a need for more data assessing the impacts of different climate change stressors on HAB species, current research findings suggest that HABs will occur more frequently and over wider ranges as a result of climate change.

4.5.3. Ocean Acidification

The oceans have absorbed approximately 127 billion metric tons (140 billion short tons) of carbon as carbon dioxide (CO_2) since the beginning of the industrial era. Hydrographic surveys and modeling studies have confirmed that the uptake of CO_2 by the oceans has resulted in a lowering of seawater pH by about 0.1 since the beginning of the Industrial Revolution (Feely et al., 2008). A drop by one pH unit corresponds to a ten-fold increase in the concentration of hydrogen ions, thus making the water more acidic (Doney, 2006). Lower pH levels have been found to decrease calcification rates in mussels, clams, and oysters because the reaction of CO_2 with seawater reduces the availability of carbonate ions that are necessary for $CaCO_3$ skeleton and shell formation for a number of marine organisms. Many species of juvenile shellfish may be highly sensitive to lower-than-normal pH levels, resulting in higher rates of mortality directly correlated with the higher CO_2 levels (Feely et al, 2008). A growing number of studies have shown that the survival of larval marine species, including commercial shellfish, is reduced by ocean acidification.

The range and magnitude of biological and socio-economic effects are not certain enough to quantify at this time, but they are thought to be substantial (NOAA, 2008). Acidity levels in upwelled waters off the Pacific Coast have already begun increasing faster than anticipated (Feely et al., 2008). Because these changes will be large and will occur quickly, and because human development has fragmented species into small and vulnerable populations, there is concern that future climate changes will be more stressful to species than past changes (Tangley, 1988). Hence, while there is great uncertainty about the future path of acidification and resulting impacts, there are also potentially great risks of significant changes in the species composition and vulnerability of ocean ecosystems that support shellfish.

An indication of the potential risks of increased ocean acidification and related water quality changes was recently documented in commercial and research shellfish hatcheries in Washington and Oregon. These facilities experienced poor egg survival and massive mortalities of larval and juvenile oysters during an extended period when low pH (7.5 to 7.8) water was entering their seawater intake lines. The mortalities are still unexplained, but the pH shift is one of a number of possible causal factors (personal communication with Dan Cheney, 2008).

5. Adaptation to Climate Change on the Coast

As noted earlier, adaptation to climate change can involve: (1) accommodation -- continuing, but altering, current uses of the coastline in response to changes in coastal oceans and environments; (2) protection -- fending off the impacts by building structures like seawalls and dikes that keep the sea at bay; and (3) retreat -- abandoning coastal sites and moving to higher ground. This section outlines some adaptations that could be adopted in response to SLR, increased storm strength, beach and bluff erosion, and increased temperature and acidity of ocean waters.

5.1. Beaches, Bluffs, and Sand Spits

Because flooding will be an increasing problem on river deltas, points, spits, barrier beaches, pocket beaches, and berms with low backshores, building on these properties will be increasingly risky. The greatest risk exists for structures located on top of beach berms since they can be hit by storm waves and beach debris. The Department of Ecology recommends

Figure 6. Failed bulkheads and large slide on Whidbey Island (Washington Department of Ecology http://www.ecy.wa.gov/programs/sea/pugetsound/building/bulkhead.html)

that anyone thinking of purchasing property in coastal regions should check with the local planning/zoning office to see if the area is a flood zone (Washington Department of Ecology, 2007). Further, to adapt to forecasted SLR, flood zone designations could be modified to incorporate the expected SLR of 0.15m to 0.36m (0.49 to 1.24 ft) by 2100 but which could reach an extreme of 1.4 m (4.6 ft) by 2100 if the accelerated melting of the Antarctic ice shelf and Greenland ice cap continues.

An estimated 1/3 of the total Puget Sound shoreline contains bulkheads and other hard coastal structures. As noted above, these can temporarily reduce upland erosion caused by wave action, but they can do little to prevent continued erosion of the seaward beaches, since wave reflection can enhance offshore sediment transport. This can undermine the bulkheads. Figure 6 depicts failed bulkheads and a large slide on Whidbey Island (Department of Ecology, 2007). Ultimately, owners of structures within the higher mean tide level generated by SLR may find that the best course of action is to retreat upland from their current location as the sea level rises or to build further from the edge of the bluffs.

5.2. Adaptation in Ports and Harbors

As noted in Section 4.3, Washington's ports and harbors will be impacted by the slow rise in sea level over the next century. In the Puget Sound, a port manager with low risk tolerance might want to plan for the higher 0.55m (1.8 ft) SLR by 2050 and the 1.28 m (4.2 ft) SLR by 2100. For most port facilities, the speed of SLR in combination with 30-40 year rebuilding cycles gives them the flexibility to adapt via raising and shifting piers and docks over time in response to observed and forecasted SLR. But, preserving shoreline facilities may be an inadequate adaptive response. As noted earlier, the Port of Seattle and surrounding lands would have to be elevated via additional fill dirt or protected via diking in order to adapt to significant SLR. Because property ownership in the port region is complex, a solution to the SLR threat would require a broad, well-coordinated plan of action by the Port authorities, railroads, city, county, State, and Federal agencies (especially the Department of Transportation and Army Corps of Engineers).

Another complication is in preserving the port's ability to function in the freight transportation network if SLR causes flooding of lands currently devoted to highways, railroads or storage areas. There would most likely need to be construction of new dikes and/or heightening of existing riverside dikes to prevent significant flooding of the lands needed by the freight handling facilities. No specific adaptation approaches have been developed here, but the need for organizing broader sets of interests (local, State, Federal, and industry) in designing port and transportation systems is strongly emphasized.

5.3. Saltwater Intrusion in Coastal Aquifers

Because we do not anticipate significant impacts of SLR on the coastal aquifers, there will be little adaptation needed in response to climate change here. A few wells may be located in the narrow band near the shore that could be affected by SLR. These wells will undoubtedly be abandoned and new wells drilled further inland.

5.4. Shellfish Aquaculture

Shellfish aquaculture will need to adapt to the three basic threats outlined earlier: (a) SLR causing a shift of shallow tidelands towards the upland shore, which is typically owned by shoreline property owners; (b) increased sea surface temperatures and acidification which may affect shellfish survival and growth; and (c) increased frequency of harmful algal blooms. One adaptive response to shifting tidelands has been identified as shifting of shoreline property lines as the mean high water mark moves inland. In fact, some US States already follow this principle. In Texas, when large hurricane or other events cause significant erosion of shorelines, the private property lines are shifted upland to preserve the public beaches and tidelands. This sort of adaptive response might be feasible in parts of Puget Sound and in the bays of southwestern Washington.

Increased temperatures and acidification present potentially difficult challenges to the rearing of current species and strains of shellfish. However, there may be sufficient genetic variability and tolerance for changes in water temperature and pH among shellfish to allow some room for adaptation. Specifically, shifting to more tolerant strains could be a successful strategy for maintaining shellfish production. We do not have sufficient information regarding these factors to confidently predict whether this approach would be successful.

Regarding increased HAB outbreaks, the State Department of Health may need to close recreational shellfish fisheries more often and monitor commercial shellfish harvests more closely in order to prevent adverse health impacts from HABs. If reliable, qualitative predictions of HAB risks can be developed then managers can be more prepared to respond quickly if HAB risks are "high" (Moore et al., 2008). This approach to adaptation is being discussed currently among scientists.

6. Research Gaps and Recommendations for Future Research

6.1. Beaches and Sand Spits

This report reviews potential climate change impacts at select sites within Washington's coastal region. Given that Washington has about 5,002 km (3085 mi) of coastline, however, it would be prudent to initiate broader monitoring and research on beaches in the future. Beach profiles should be monitored to contribute to better understanding of the dynamics of beach accretion and erosion. The sites mentioned in this paper should also be monitored closely. For instance, Whidbey Island's western shore could be monitored to determine if it does exhibit the predicted changes due to climate change. Over the years other shoreline segments within the Willapa Bay and Grays Harbor regions (and other shorelines with similar beach characteristics) should be assessed for shoreline erosion. For those areas where unnecessary armoring structures have been removed or modified, it should be determined whether reflective wave energy has been reduced and if natural sediment processes have been allowed to restore normal beach profiles. Both applied and basic research into movement of sediments and shifts in beach profiles should be priority research topics.

6.2. Puget Sound Bluffs

Shipman (2004) notes that, "Little systematic study of bluff recession rates has been carried out within the Puget Sound region, limiting knowledge of actual rates and understanding of the relative importance of different factors in determining rates" (p. 89). As with Washington's beaches, additional Puget Sound bluff sites should be incorporated into future studies in order to gain a more comprehensive look at the effects of climate change. More research could examine how auxiliary structures will be and are being threatened by beach and bluff erosion and the possible actions that can be taken in response. A comparison of erosion rates (historic and future projections) could then be used in choosing when and where to retreat from vulnerable bluff sites.

6.3. Ports and Harbors

Since our paper focuses on climate change at the ports of Seattle and Tacoma, additional research could focus on the ports of Everett, Olympia, Grays Harbor, and Port Angeles, as well as the smaller ports and marinas designed mainly for recreational purposes. Ideally, additional interviews would be conducted at each port and marina and a comparative study would be written detailing the effects of climate change on their infrastructure and potential responses and adaptations for each location.

6.4. Shellfish Aquaculture

As with the beaches and bluffs, there should be increased monitoring to gauge the extent that shellfish aquaculture sites follow inland tidelands with SLR. Further legal research and analysis could determine the extent of subsequent issues regarding property laws between shellfish farmers and shoreline property owners. More research should focus on climate change stressors that could have an impact on shellfish growth and mortality. For instance, the effects of increased sea surface temperature and ocean acidification on various strains of shellfish are not clearly understood. More research is also recommended on how HABs originate and develop, along with the impact of different climate change stressors on HAB species and on the physiology and ecology of HABs.

7. Conclusions

Overall, this brief survey of climate impacts on the coasts of Washington State has identified numerous possible routes by which climate can interfere with historical uses of the coast and has raised many questions requiring additional research. One conclusion is that SLR will cause shifts in the coastal beaches and increased erosion of unstable bluffs, and these effects will endanger housing and other structures built near the shore or near the bluff edges. State and local governments, as well as property owners, will need to engage in longer term planning and decision-making to determine whether to retreat from the endangered shores and bluffs or to invest in structural protection or adaptation projects. These conclusions extend to the numerous ports and marinas in the Puget Sound region, which must accommodate to SLR or retreat to higher ground if they are to continue to function as major transshipping points for US-Asia trade.

We found indications that shellfish may be harmed by increasing ocean temperatures and acidity, due to shifts in disease and growth patterns, and to more frequent HABs. Further, inter-tidal habitat for shellfish aquaculture will likely be slowly shifting shoreward as sea level rises. Adapting to these effects may involve both genetic research to select more resilient sub-species of shellfish and altered property boundaries to accommodate the shifting high tide lines. All of these conclusions are tentative, based upon current understanding of the underlying phenomena. Further research will be a necessary element of any longer-term, adaptive strategy for climate change in the region.

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