

V. IMPLICATIONS FOR COASTAL NEARSHORE HABITATS & ECOSYSTEMS

Waves, currents, and sediment supply are the primary controls on coastal evolution; any changes in global climate which alter the timing and magnitude of storms and/or raise global sea level will have severe consequences for beaches, coastlines, and coastal structures.⁷⁹⁷ Based on a search of the scientific and grey literature, the following implications of climate change for coastal nearshore habitats and ecosystems in the NPLCC region have been identified:

1. Altered patterns of coastal erosion and increased coastal squeeze
2. Altered sedimentation patterns
3. Habitat loss, degradation, and conversion

Many physical processes important for determining nearshore habitat characteristics will be affected by climate change.⁷⁹⁸ Climate change will also affect biological processes important for nearshore habitat.⁷⁹⁹ The affected physical and biological processes include:

- Significant sea level rise and storm surge will adversely affect coastal ecosystems; low-lying and subsiding areas are most vulnerable.⁸⁰⁰
- Storms may also have increased precipitation intensity; this would increase both erosion and salinity stress for coastal marine ecosystems.⁸⁰¹
- Changes in salinity and temperature and increased sea level, atmospheric CO₂, storm activity and ultraviolet irradiance alter sea grass distribution, productivity and community composition.⁸⁰²
- Changes in precipitation could change nutrient loading and sediment accumulation.⁸⁰³
- Changes in water temperature, water salinity, or soil salinity beyond the tolerance of certain plants could change the mix of plant species in salt marshes and the viability of invertebrates (e.g., crab, shrimp and sponges) that play a key role in the health and functioning of nearshore systems.⁸⁰⁴

Among the most clear and profound influences of climate change on the world's oceans are its impacts on habitat-forming species such as corals, sea grass, mangroves, salt marsh grasses, and oysters.⁸⁰⁵ Collectively, these organisms form the habitat for thousands of other species.⁸⁰⁶ Projected changes would

⁷⁹⁷ *Adams and Inman. *Climate change hotspots and potential hotspots of coastal erosion along the southern California coast: Final Paper (CEC-500-2009-022-F)*. (2009, p. 1)

⁷⁹⁸ *Snover et al. (2005, p. 29)

⁷⁹⁹ *Snover et al. (2005, p. 29)

⁸⁰⁰ * Karl, Melillo and Peterson. (2009, p. 149)

⁸⁰¹ *Hoffman. (2003, p. 135)

⁸⁰² *Nicholls et al. (2007, p. 329).The authors cite Short and Neckles (1999) for this information.

⁸⁰³ *Snover et al. (2005, p. 29)

⁸⁰⁴ *Snover et al. (2005, p. 29)

⁸⁰⁵ *Hoegh-Guldberg and Bruno. (2010, p. 1526)

⁸⁰⁶ *Hoegh-Guldberg and Bruno. (2010, p. 1526)

fundamentally alter the region's coastal habitats and the species they support.⁸⁰⁷ Some species may be able to respond to changes by finding alternative habitats or food sources, but others will not.⁸⁰⁸

The following structure will be used to present information on the implications of climate change for the NPLCC region's coastal nearshore habitats and ecosystems:

- **Observed Trends** – observed changes at the global level and for each jurisdiction in the NPLCC geography (Alaska, British Columbia, Washington, Oregon, California).
- **Future Projections** – projected direction and/or magnitude of change at the global level and for each jurisdiction in the NPLCC geography
- **Information Gaps** – information and research needs identified by reviewers and literature searches.

⁸⁰⁷ *Glick, Clough and Nunley. *Sea level Rise and Coastal Habitats in the Pacific Northwest: An Analysis for Puget Sound, Southwestern Washington, and Northwestern Oregon.* (2007, p. v)

⁸⁰⁸ *Glick, Clough and Nunley. (2007, p. v)

1. ALTERED PATTERNS OF COASTAL EROSION AND INCREASED COASTAL SQUEEZE

Observed Trends

Global

Information needed.

Southcentral and Southeast Alaska

Information needed.

British Columbia

Information needed.

Washington

Natural rates of erosion vary widely among locations in Washington State: in Island County, fifty-one percent of the shoreline is classified as “unstable”,⁸⁰⁹ as opposed to twenty percent of Bainbridge Island⁸¹⁰ and only three percent of San Juan County.⁸¹¹ The Southwest Washington Coastal Erosion Project has identified several erosion “hot spots”.⁸¹² 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.⁸¹³

Examples of erosion rates (landward progression) from different areas of Washington include:

- In Island County, erosion rates have been measured from 0.30 inches (1 cm) to more than two feet (0.61 meters) per year.⁸¹⁴
- On Whidbey Island, typical erosion rates are approximately 1.2 inches per year (3 cm/yr).⁸¹⁵ 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.⁸¹⁶
- On Bainbridge Island, bluff erosion rates are generally between two and six inches per year (5-15 cm/yr), 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.⁸¹⁷ As on Whidbey Island, bluff erosion events are episodic.⁸¹⁸ After heavy rains and soil saturation, Bainbridge Island has experienced a number of bluff erosion events.⁸¹⁹

⁸⁰⁹ *Huppert et al. *Impacts of climate change on the coasts of Washington State*. (2009, p. 294). The authors cite Shipman (2004) for this information.

⁸¹⁰ *Huppert et al. (2009, p. 296). The authors cite Shipman (2004) for this information.

⁸¹¹ *Huppert et al. (2009, p. 296). The authors cite Shipman (2004) for this information.

⁸¹² *Huppert et al. (2009, p. 292)

⁸¹³ *Huppert et al. (2009, p. 292)

⁸¹⁴ *Huppert et al. (2009, p. 294). The authors cite Island County (2006) for this information.

⁸¹⁵ *Huppert et al. (2009, p. 294)

⁸¹⁶ *Huppert et al. (2009, p. 295). The authors cite Johannessen and MacLennan (2007) for this information.

⁸¹⁷ *Huppert et al. (2009, p. 296). The authors cite City of Bainbridge Island (2007) for this information.

⁸¹⁸ *Huppert et al. (2009, p. 296)

⁸¹⁹ *Huppert et al. (2009, p. 296)

- Bluff erosion rates are negligible in San Juan County.⁸²⁰
- At Washaway Beach (formerly known as Shoalwater Bay) at the north entrance of Willapa Bay, 65 feet per year (19.7 m/yr) of beach have been lost, on average, since the 1880s.⁸²¹
- High erosion rates have also been observed at Ocean Shores, just north of Cape Leadbetter (more precise data not provided).⁸²²

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 one foot (0.3 m) higher than July levels.⁸²³ 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.⁸²⁴ 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.⁸²⁵ 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.⁸²⁶

Oregon

Information needed.

Northwest California

Information needed.

Future Projections

Global

Global climate change may accelerate coastal erosion due to sea level rise and increased wave height.⁸²⁷ Shifts in storm tracks as a result of climate change may alter wind patterns, such that waves hit the beach with more force or from new directions (resulting in new patterns of erosion).⁸²⁸ An acceleration in sea level rise will widely exacerbate beach erosion around the globe, although the local response will depend on the total sediment budget.⁸²⁹ Specific findings include:

- **For sandy beaches**, the major long-term threat worldwide is coastal squeeze, which leaves beaches trapped between erosion and rising sea level on the wet side and encroaching development from expanding human populations on land, thus leaving no space for normal

⁸²⁰ *Huppert et al. (2009, p. 296). The authors cite Shipman (2004) for this information.

⁸²¹ Huppert et al. (2009, p. 292)

⁸²² *Huppert et al. (2009, p. 292)

⁸²³ *Huppert et al. (2009, p. 292)

⁸²⁴ *Huppert et al. (2009, p. 292)

⁸²⁵ *Huppert et al. (2009, p. 292-293)

⁸²⁶ *Huppert et al. (2009, p. 293)

⁸²⁷ Huppert et al. (2009)

⁸²⁸ Carter, L. *U.S. National Assessment of the Potential Consequences of Climate Variability and Change. Educational Resources Regional Paper: Pacific Northwest (website)*. (2003).

⁸²⁹ *Nicholls et al. (2007, p. 324). The authors cite Brown and MacLachlan (2002) for information on SLR and exacerbated beach erosion, and Stive et al. (2002) and Cowell et al. (2003a,b) for information on the sediment budget and local response.

sediment dynamics.⁸³⁰ It is not expected that predicted temperature changes will have dramatic effects on the world's beaches by 2025, but the expected rise in sea level, if coupled with an increase in the frequency and/or intensity of storms, as predicted for some regions, is likely to lead to escalating erosion and consequent loss of habitat.⁸³¹

- **Gravel beaches** are threatened by sea level rise, even under high accretion rates.⁸³² The persistence of gravel and cobble boulder beaches will also be influenced by storms, tectonic events and other factors that build and reshape these highly dynamic shorelines.⁸³³
- **Hard rock cliffs** have a relatively high resistance to erosion, while cliffs formed in softer lithologies are likely to retreat more rapidly in the future due to increased toe erosion resulting from sea level rise.⁸³⁴
- **Soft rock cliff** stability is affected by four physical features of climate change – temperature, precipitation, sea level and wave climate.⁸³⁵ For soft cliff areas with limited beach development, there appears to be a simple relationship between long-term cliff retreat and the rate of sea level rise, allowing useful predictions for planning purposes.⁸³⁶

Coastal squeeze refers to the squeeze of coastal ecosystems between rising sea levels and naturally or artificially fixed shorelines, such as beaches lacking adequate sediment supply backed by coastal bluffs and nearshore areas prohibited from upland migration by hard engineering defenses. This results in loss of shallow water habitat. For example, loss of birds from some estuaries appears to be the result of coastal squeeze and relative SLR. Adaptation activities such as creation or restoration of intertidal habitat may help to offset losses due to coastal squeeze.

Source: Nicholls et al. (2007); Parry et al. (2007)

Southcentral and Southeast Alaska

Information needed.

British Columbia

Information needed.

Washington

The severity of coastal erosion is expected to increase as a result of sea level rise and intensification of storm activity.⁸³⁷ Sea level rise will shift coastal beaches inland and increase erosion of unstable bluffs.⁸³⁸

⁸³⁰ *Defeo et al. *Threats to sandy beach ecosystems: a review*. (2009, p. 8)

⁸³¹ Brown and McLachlan. *Sandy shore ecosystems and the threats facing them: some predictions for the year 2025*. (2002, p. 62)

⁸³² *Nicholls et al. (2007, p. 325). The authors cite Orford et al. (2001, 2003) and Chadwick et al. (2005) for information on SLR and gravel beaches. The authors cite Codignotto et al. (2001) for information on high accretion rates, SLR, and gravel beaches.

⁸³³ *Nicholls et al. (2007, p. 325). The authors cite Orford et al. (2001) for this information.

⁸³⁴ *Nicholls et al. (2007, p. 325-326). The authors cite Cooper and Jay (2002) for this information.

⁸³⁵ *Nicholls et al. (2007, p. 326). The authors cite Cowell et al. (2006) for this information.

⁸³⁶ *Nicholls et al. (2007, p. 326). The authors cite Walkden and Dickson (2006) for this information.

⁸³⁷ *Bauman et al. *Impacts of climate change on Washington's economy: a preliminary assessment of risks and opportunities (pdf)*. (2006)

On Whidbey Island, future possible impacts include increased bluff erosion and landslide, and inundation.⁸³⁹ On Bainbridge Island, inundation and, to a lesser extent, bluff erosion are possible.⁸⁴⁰ Willapa Bay would see possible increases in shoreline erosion.⁸⁴¹ In the San Juan Islands, 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 bluff erosion patterns.⁸⁴²

Oregon

By the mid 21st century the projected increase in rates of SLR are expected to exceed the rates of uplift of the land all along the Oregon coast, resulting in erosion even where at present there have been little or no erosion impacts.⁸⁴³ The scenario as to when enhanced erosion and flooding begins at a specific coastal site, and the magnitude of that enhancement, depends however on the contributions by other oceanic processes and their climate controls, particularly the increase in storm intensities and the heights of their generated waves.⁸⁴⁴

Increased erosion along Oregon's ocean shore from rising sea levels and coastal storms may seriously alter beaches, and in some cases, the infrastructure necessary for safe access to and from beaches and coastal parks.⁸⁴⁵ Beach and bluff erosion will result in shoreline retreat.⁸⁴⁶ Some portions of Oregon's ocean shorelines have been armored against erosion from ocean waves, primarily in front of properties developed before 1977.⁸⁴⁷ As shorelines erode landward in response to higher sea level and storms, armored properties are at risk of becoming peninsulas, then islands, and then overtopped.⁸⁴⁸ An increase in significant wave heights is likely to damage or cause failure of some hardened shorelines, potentially resulting in damage to nearby unprotected property and infrastructure.⁸⁴⁹

Northwest California

On behalf of the Pacific Institute, Philip Williams & Associates, Ltd. assessed California's coastal erosion response to sea level rise.⁸⁵⁰ Their analysis projects dune and cliff erosion for California's coastal counties.⁸⁵¹ Del Norte, Humboldt, Mendocino, and Sonoma counties are in the NPLCC region.⁸⁵² With approximately 4.6 feet of sea level rise (1.4 meters), dune and cliff erosion across all four of these

⁸³⁸ *Littell et al. *The Washington Climate Change Impacts Assessment: Evaluating Washington's Future in a Changing Climate - Executive Summary*. (2009, p. 16)

⁸³⁹ *Littell et al. (2009, p. 16)

⁸⁴⁰ *Littell et al. (2009, p. 16)

⁸⁴¹ *Littell et al. (2009, p. 16)

⁸⁴² *Huppert et al. (2009, p. 296)

⁸⁴³ *Ruggiero et al. (2010, p. 218)

⁸⁴⁴ *Ruggiero et al. (2010, p. 218). The authors cite Ruggiero (2008) for this information.

⁸⁴⁵ *OCMP. (2009, p. 14)

⁸⁴⁶ *OCMP. (2009, p. 17)

⁸⁴⁷ *OCMP. (2009, p. 14)

⁸⁴⁸ *OCMP. (2009, p. 14)

⁸⁴⁹ *OCMP. (2009, p. 14)

⁸⁵⁰ Philip Williams and Associates, Ltd. *California Coastal Erosion Response to Sea level Rise - Analysis and Mapping*. (2009, Table 4, p. 17)

⁸⁵¹ Philip Williams and Associates, Ltd. *California Coastal Erosion Response to Sea level Rise - Analysis and Mapping*. (2009)

⁸⁵² California State Association of Counties. *CA County Map*. Available at <http://www.counties.org/default.asp?id=6> (accessed 6.10.2011).

counties is projected to total 21.1 square miles (54.7 km²), with 6.9 square miles (18 km², 33%) attributable to dune erosion and 14.1 square miles (36.4 km², 67%) attributable to cliff erosion.⁸⁵³ Table 19 lists projected dune and cliff erosion by county.

Table 19. Erosion area with a 4.6 ft (1.4 m) sea level rise, by county. <i>Source: Table modified from Philip Williams and Associates, Ltd. (2009, Table 4, p. 17) by authors of this report.</i>			
County	Dune erosion miles² (km²)	Cliff erosion miles² (km²)	Total erosion miles² (km²)
Del Norte	1.9 (4.9)	2.6 (6.7)	4.5 (11.7)
Humboldt	3.7 (9.6)	2.4 (6.2)	6.1 (15.8)
Mendocino	0.7 (1.9)	7.5 (19.4)	8.3 (21.5)
Sonoma	0.6 (1.6)	1.6 (4.1)	2.2 (5.7)
Total	6.9 (18)	14.1 (36.4)	21.1 (54.7)

Information Gaps

Information is needed on regional trends and projections for coastal erosion throughout the geographic extent of the NPLCC, particularly quantitative data for the extent of current and projected erosion at different locations with the NPLCC geography. Information is also needed on global trends and projections for coastal erosion.

⁸⁵³ Philip Williams and Associates, Ltd.. *California Coastal Erosion Response to Sea level Rise - Analysis and Mapping*. (2009, Table 4, p. 17)

2. ALTERED SEDIMENTATION PATTERNS

Observed Trends

Global

Deltas, some of the largest sedimentary deposits in the world, are widely recognized as highly vulnerable to the impacts of climate change, particularly sea level rise and changes in runoff, as well as being subject to stresses imposed by human modification of catchment and delta plain land use.⁸⁵⁴ Most deltas are already undergoing natural subsidence that results in accelerated rates of relative sea level rise above the global average.⁸⁵⁵ Many are impacted by the effects of water extraction and diversion, as well as declining sediment input as a consequence of entrapment in dams.⁸⁵⁶ Dikes built in river deltas to “reclaim” marsh areas impact physical processes associated with sediment, water, and organic material movement, both inside and outside of the diked area.⁸⁵⁷

Southcentral and Southeast Alaska

Information needed.

British Columbia

Information needed.

Washington

Information needed.

Oregon

Information needed.

Northwest California

Information needed.

Future Projections

Global

Climate change and sea level rise affect sediment transport in complex ways and abrupt, non-linear changes may occur as thresholds are crossed.⁸⁵⁸ In situations where the area of intertidal environments has been reduced by embanking or reclamation, the initial response will be a lowering of remaining tidal flats and infilling of tidal channels.⁸⁵⁹ Depending on tidal characteristics, the availability of marine sediment,

⁸⁵⁴ *Nicholls et al. (2007, p. 327)

⁸⁵⁵ *Nicholls et al. (2007, p. 327)

⁸⁵⁶ *Nicholls et al. (2007, p. 327)

⁸⁵⁷ Hood. (2004)

⁸⁵⁸ *Nicholls et al. (2007, p. 320). The authors cite Alley et al. (2003) for this information.

⁸⁵⁹ *Nicholls et al. (2007, p. 328)

and the rate of sea level rise, the remaining tidal flats may either be further drowned, or their relative level in the tidal frame may be maintained.⁸⁶⁰

If sea level rises slowly, the balance between sediment supply and morphological adjustment can be maintained if a saltmarsh accretes, or a lagoon infills, at the same rate.⁸⁶¹ An acceleration in the rate of sea level rise may mean that morphology cannot keep up, particularly where the supply of sediment is limited, as for example when coastal floodplains are inundated after natural levees or artificial embankments are overtopped.⁸⁶² Exceeding the critical sea level thresholds can initiate an irreversible process of drowning.⁸⁶³

An indirect, less-frequently examined influence of sea level rise on the beach sediment budget is due to the infilling of coastal embayments.⁸⁶⁴ As sea level rises, estuaries and lagoons attempt to maintain equilibrium by raising their bed elevation in tandem, and hence potentially act as a major sink of sand which is often derived from the open coast.⁸⁶⁵ This process can potentially cause erosion an order of magnitude or more greater than that predicted by the Bruun model (which suggests shoreline recession is in the range of 50 to 200 times the rise in relative sea level), implying the potential for major coastal instability due to sea level rise in the vicinity of tidal inlets.⁸⁶⁶

Southcentral and Southeast Alaska

Information needed.

British Columbia

Information needed.

Pacific Northwest

Information needed. Inundation of tidal flats in some areas would reduce stopover and wintering habitat for migratory shorebirds.⁸⁶⁷ It could also have a major impact on the economically-important shellfish industry.⁸⁶⁸

Northwest California

Information needed.

Information Gaps

Information is needed on observed sedimentation patterns in the NPLCC region, as well as projected sedimentation patterns throughout the NPLCC region.

⁸⁶⁰ *Nicholls et al. (2007, p. 328). The authors cite Dronkers (2005) for this information.

⁸⁶¹ *Nicholls et al. (2007, p. 320)

⁸⁶² *Nicholls et al. (2007, p. 320)

⁸⁶³ *Nicholls et al. (2007, p. 320). The authors cite Williams et al. (1999), Doyle et al. (2003), and Burkett et al. (2005) for this information.

⁸⁶⁴ *Nicholls et al. (2007, p. 324)

⁸⁶⁵ *Nicholls et al. (2007, p. 324) The authors cite van Goor et al. (2001), van Goor et al. (2003), and Stive (2004) for this information.

⁸⁶⁶ *Nicholls et al. (2007, p. 324) The authors cite Woodworth et al. (2004) for information on the Bruun model projections in comparison to infilling of coastal embayments. The definition of the Bruun model is also on p. 324.

⁸⁶⁷ *Glick, Clough and Nunley. (2007, p. v)

⁸⁶⁸ *Glick, Clough and Nunley. (2007, p. v)

3. HABITAT LOSS, DEGRADATION, AND CONVERSION

Observed Trends

Global

Coastal wetland ecosystems are among the most altered and threatened natural systems.⁸⁶⁹ Important impacts include increased nutrient loading leading to eutrophication, direct loss through habitat destruction, changes in hydrology, introduction of toxic materials, and changes in species composition due to over-harvest and introduction of new species.⁸⁷⁰

During periods of sea level rise, coastal wetlands can persist only when they accrete soil vertically at a rate at least equal to water-level rise.⁸⁷¹ A number of studies have shown that coastal marshes are indeed able to accrete at a rate equal to the historical rate of sea level rise (0.04-0.08 inches per year; 1-2 mm/year) and persist for hundreds to thousands of years.⁸⁷² However, many rivers emptying into coastal estuaries now carry only a fraction of the inorganic sediment that they did historically.⁸⁷³

Southcentral and Southeast Alaska

Information needed.

British Columbia

Information needed.

Washington

Information needed.

Oregon

Information needed.

Northwest California

Information needed. Most coastal wetland loss has been due to draining and filling.⁸⁷⁴ In some coastal states, such as California, almost all coastal wetlands have been lost.⁸⁷⁵

⁸⁶⁹ *Poff, Brinson and Day. (2002, p. 23)

⁸⁷⁰ *Poff, Brinson and Day. (2002, p. 23-24). The authors cite Day et al. (1989), Mitsch and Gosselink (1993), and Neumann et al. (2000) for this information.

⁸⁷¹ *Poff, Brinson and Day. (2002, p. 25). The authors cite Cahoon et al. (1995a) for this information.

⁸⁷² *Poff, Brinson and Day. (2002, p. 26). The authors cite Gornitz et al. (1982) for the historical rate of SLR and Redfield (1972), McCaffey and Thompson (1980), and Orson et al. (1987) for information on wetland persistence.

⁸⁷³ *Poff, Brinson and Day. (2002, p. 26)

⁸⁷⁴ *Poff, Brinson and Day. (2002, p. 24)

⁸⁷⁵ *Poff, Brinson and Day. (2002, p. 24)

Future Projections

Global

Coastal vegetated wetlands are sensitive to climate change and long-term sea level change as their location is intimately linked to sea level.⁸⁷⁶ Global mean sea level rise will generally lead to higher relative coastal water levels and increasing salinity in estuarine systems, thereby tending to displace existing coastal plant and animal communities inland.⁸⁷⁷ Instead of migrating inland, estuarine plant and animal communities may persist as sea level rises if migration is not blocked and if the rate of change does not exceed the capacity of natural communities to adapt or migrate.⁸⁷⁸ Climate change impacts on one or more “leverage species,” however, can result in sweeping community level changes.⁸⁷⁹

Climate change will likely have its most pronounced effects on brackish and freshwater marshes in the coastal zone through alteration of hydrological regimes,⁸⁸⁰ specifically, the nature and variability of hydroperiod and the number and severity of extreme events.⁸⁸¹ Other variables – altered biogeochemistry, altered amounts and pattern of suspended sediments loading, fire, oxidation of organic sediments, and the physical effects of wave energy – may also play important roles in determining regional and local impacts.⁸⁸² Specific impacts include:

- Modeling of all coastal wetlands (but excluding sea grasses) by McFadden et al. (2007) suggests global losses from 2000 to 2080 of thirty-three percent and forty-four percent given a 14 inch (0.36 m) and 28 inch (0.72 m) rise in sea level, respectively.⁸⁸³
- Sea grasses appear to be declining around many coasts due to human impacts, and this is expected to accelerate if climate change alters environmental conditions in coastal waters.⁸⁸⁴
- Increases in the amount of dissolved CO₂ and, for some species, bicarbonate (HCO₃⁻) present in aquatic environments, will lead to higher rates of photosynthesis in submerged aquatic vegetation, similar to the effects of CO₂ enrichment on most terrestrial plants, if nutrient availability or other limiting factors do not offset the potential for enhanced productivity.⁸⁸⁵ Please see Chapter VII Section 5 for more specific information on the impacts of climate change in seagrasses.

⁸⁷⁶ *Nicholls et al. (2007, p. 328)

⁸⁷⁷ *Nicholls et al. (2007, p. 328)

⁸⁷⁸ *Nicholls et al. (2007, p. 328)

⁸⁷⁹ *Nicholls et al. (2007, p. 328). The authors cite Harley et al. (2006) for this information.

⁸⁸⁰ *Nicholls et al. (2007, p. 329). The authors cite Burkett and Kusler (2000), Baldwin et al. (2001), and Sun et al. (2002) for this information.

⁸⁸¹ *Nicholls et al. (2007, p. 329)

⁸⁸² *Nicholls et al. (2007, p. 329)

⁸⁸³ *Nicholls et al. (2007, p. 328)

⁸⁸⁴ *Nicholls et al. (2007, p. 329). The authors cite Duarte (2002) for this information.

⁸⁸⁵ *Nicholls et al. (2007, p. 329)

Southcentral Alaska

In Alaska, changes in sea level and increases in storms and erosion could result in the following habitat impacts:

- Low-lying habitats critical to the productivity and welfare of coastal dependent species could be lost.⁸⁸⁶
- Low-lying coastal staging areas that support millions of shorebirds, geese, and ducks during spring and fall staging could degrade.⁸⁸⁷ This includes areas in the Stikine Delta, Cook Inlet marshes, and the Copper River Delta and barrier islands.⁸⁸⁸
- If brackish/salt intrusion is restored to the Copper River Delta, reversion to graminoid sedge marsh from current shrub/forest succession could occur.⁸⁸⁹ Positive changes for dusky Canada geese may result.⁸⁹⁰

A study using the Sea level Affecting Marshes Model (SLAMM, version 6, see Box 16) projects widespread changes to coastal habitats in Cook Inlet.⁸⁹¹ SLAMM 6 was run using the A1B-mean scenario, which predicts approximately 1.3 feet (0.40 m) of global sea level rise (SLR) by 2100.⁸⁹² SLAMM was also run assuming 3.28 feet (1 m), 4.92 feet (1.5 m), and 6.56 feet (2 m) of eustatic SLR (sea level rise due to changes in ocean mass and volume) by the year 2100 to accommodate the recent literature suggesting that the rate of sea level rise is likely to be higher than the 2007 IPCC projections.⁸⁹³ Six sites in Cook Inlet were evaluated, four on the Kenai Peninsula and two near Anchorage.⁸⁹⁴ The study results underscore the fact that Alaska poses unique challenges for sea level rise modeling (e.g. significant data gaps, especially high quality elevation data, and coarse quality of some other data inputs).⁸⁹⁵

For the Kenai study region as a whole, less than one percent of dry land is predicted to be lost to the effects of sea level rise.⁸⁹⁶ Between zero and two percent of the total study area swamp lands are predicted to be lost across all scenarios.⁸⁹⁷ While the site is predicted to lose fourteen percent of its tidal flat, some of this may have occurred since the late 1970s.⁸⁹⁸ Substantial losses of ocean beach seem to be triggered at eustatic (due to changes in ocean mass/volume) rates of sea level rise above 4.92 feet (1.5 m).⁸⁹⁹

⁸⁸⁶ *AK State Legislature. (2008, p. 91). Report by the Alaska State Legislature, available online at http://www.housemajority.org/coms/cli/cli_final_report_20080301.pdf (last accessed 12.14.2010).

⁸⁸⁷ *AK State Legislature. (2008, p. 91)

⁸⁸⁸ *AK State Legislature. (2008, p. 91)

⁸⁸⁹ *AK State Legislature. (2008, p. 92)

⁸⁹⁰ *AK State Legislature. (2008, p. 92)

⁸⁹¹ Glick, Clough and Nunley. (2010)

⁸⁹² Glick, Clough and Nunley. (2010, p. 3)

⁸⁹³ *Glick, Clough and Nunley. (2010, p. 3). The authors cite Grinstead et al. (2009), Vermeer and Rahmstorf (2009), and Pfeffer and O'Neel (2008) for information suggesting the rate of SLR is likely to be higher than the 2007 IPCC projections.

⁸⁹⁴ Glick, Clough and Nunley. (2010)

⁸⁹⁵ *Glick, Clough and Nunley. (2010, p. 1)

⁸⁹⁶ *Glick, Clough and Nunley. (2010, p. 8)

⁸⁹⁷ *Glick, Clough and Nunley. (2010, p. 8)

⁸⁹⁸ *Glick, Clough and Nunley. (2010, p. 8)

⁸⁹⁹ *Glick, Clough and Nunley. (2010, p. 8)

At the four sites on the Kenai Peninsula, the following changes are projected:

- Erosion of tidal flats and reformulation of ocean beach at Fox River Flats, Eastern Kachemak Bay.⁹⁰⁰
- Conversion of freshwater swamps to transitional salt marsh as the south portion of the study site in Chickaloon Bay falls below the salt boundary.⁹⁰¹

Box 16. SLAMM: Alternatives & Limitations.

SLAMM simulates dominant processes involved in wetland conversions and shoreline modifications during long-term sea level rise (SLR). Within later versions of SLAMM (5.0, 6.0, 6.0.1 Beta), five primary processes can affect wetland fate under different scenarios of SLR: inundation, erosion, overwash, saturation, and salinity.

Key limitations include no mass balance of solids, no models of seagrasses or marine flora, it is not a detailed bathymetrical model, there is no concept of “marsh health,” accretion rates are based on an empirical relationship, feedbacks among variables are not modeled, and it lacks a socioeconomic component for estimating the costs of SLR.

Alternatives to SLAMM include the Kirwan marsh model, the USGS Coastal Vulnerability Index, BTEISS, the more straight-forward “bathtub” models, and support tools such as the Dynamic Interactive Vulnerability Assessment Tool and SimCLIM. See Appendix 4 for further information.

Sources: *Clough, Park & Fuller. (2010); Glick, Clough & Nunley (2010); Glick, Clough & Nunley (2007); Kirwan & Guntenspergen. (2009); Mcleod et al. (2010); Warren Pinnacle Consulting, Inc. (2010a); Warren Pinnacle Consulting, Inc. (2010b).*

- The freshwater swamps along the Kenai River near the Town of Kenai are predicted to start to show salinity effects, especially under the highest rate of sea level rise estimated (6.56 feet, or 2 meters by 2100).⁹⁰²

- Some saline intrusion of the dry lands and swamps to the east of the river at the Northern Coho/Kasilof site are predicted, especially under higher eustatic scenarios of sea level rise.⁹⁰³

For the Anchorage study site as a whole, results show only minor susceptibility to the effects of sea level rise.⁹⁰⁴ Dry land, which comprises slightly more than one-third of the study area, is calculated to lose between two and three percent of its initial land coverage across all SLR scenarios.⁹⁰⁵ Swamp lands – which comprise roughly four percent of the study area – are predicted to lose between four and ten percent of their initial land coverage across all SLR scenarios.⁹⁰⁶ Projections for the two sites in the Anchorage area include:

- North of Chugiak, near Birchwood Airport, the dry lands and swamps at the north end of the study area are predicted to be subject to saline inundation, especially under the highest scenarios run.⁹⁰⁷

- At the Anchorage sub-site, the most substantial predictions seem to be the potential inundation of developed land at the northern portion of the study site in the Ship Creek/Port of Anchorage area and the potential vulnerability of the tidal swamp northwest of Potter Marsh, under the more aggressive prediction of a eustatic sea level rise of 6.56 feet (2 m).⁹⁰⁸

⁹⁰⁰ *Glick, Clough and Nunley. (2010, p. 9)

⁹⁰¹ *Glick, Clough and Nunley. (2010, p. 10)

⁹⁰² *Glick, Clough and Nunley. (2010, p. 11)

⁹⁰³ *Glick, Clough and Nunley. (2010, p. 12)

⁹⁰⁴ *Glick, Clough and Nunley. (2010, p. 13)

⁹⁰⁵ *Glick, Clough and Nunley. (2010, p. 13)

⁹⁰⁶ *Glick, Clough and Nunley. (2010, p. 13)

⁹⁰⁷ *Glick, Clough and Nunley. (2010, p. 14)

⁹⁰⁸ *Glick, Clough and Nunley. (2010, p. 15)

British Columbia

Information needed.

Washington and northwest Oregon

Estimates of sea level rise for the Puget Sound suggest that on beaches with armored shoreline substantial surf smelt spawning habitat might be lost in the next few decades and most spawning habitat might be lost by 2100.⁹⁰⁹ A Puget Sound study suggests sea level rise is likely to cause substantial loss of surf smelt spawning habitat on beaches with armored shorelines because armoring prevents beach migration inland, thereby reducing the area of beach with elevations preferred for spawning.⁹¹⁰

Using the SLAMM 5.0 model, widespread changes to coastal habitats in eleven sites around the Puget Sound (WA), southwest Washington, and northwest Oregon have been projected.⁹¹¹ Model results vary considerably by site, but overall the region is likely to face a dramatic shift in the extent and diversity of its coastal marshes, swamps, beaches, and other habitats due to sea level rise.⁹¹² For example, if global average sea level increases by 27.3 inches (0.69 m), the following impacts are predicted by 2100 across the sites investigated:

- Estuarine beaches will undergo inundation and erosion to total a sixty-five percent loss.
- As much as forty-four percent of tidal flat will disappear.⁹¹³
- Thirteen percent of inland fresh marsh and twenty-five percent of tidal fresh marsh will be lost.⁹¹⁴
- Eleven percent of inland swamp will be inundated with salt water, while sixty-one percent of tidal swamp will be lost.⁹¹⁵
- Fifty-two percent of brackish marsh will convert to tidal flats, transitional marsh and saltmarsh.⁹¹⁶
- Two percent of undeveloped land will be inundated or eroded to other categories across all study areas.⁹¹⁷

Localized impacts of 27.3 inches (0.69 m) of SLR by 2100 across six sites illustrate the variability in these results:

- **Ediz Hook near Port Angeles (WA), through the Dungeness Spit and Sequim Bay:** Tidal flats at this site are extremely vulnerable, as is Dungeness Spit itself, especially to higher sea level rise scenarios in which complete loss of the spit is predicted.⁹¹⁸ Additionally, over fifty-eight percent of area beaches (estuarine and ocean together) are predicted to be lost by 2100 under all scenarios.⁹¹⁹

⁹⁰⁹ *Krueger et al. *Anticipated effects of sea level rise in Puget Sound on two beach-spawning fishes.* (2010, p.176)

⁹¹⁰ *Krueger et al. (2010, p.171). The authors cite Griggs and others (1994) for information on SLR, armoring, beach migration inland, and habitat loss.

⁹¹¹ *Glick, Clough and Nunley. (2007)

⁹¹² *Glick, Clough and Nunley. (2007, p. iii)

⁹¹³ *Glick, Clough and Nunley. (2007, p. iii)

⁹¹⁴ *Glick, Clough and Nunley. (2007, p. iii)

⁹¹⁵ *Glick, Clough and Nunley. (2007, p. iii)

⁹¹⁶ *Glick, Clough and Nunley. (2007, p. iii)

⁹¹⁷ *Glick, Clough and Nunley. (2007, p. iii)

⁹¹⁸ *Glick, Clough and Nunley. (2007, Table 1, p. iv)

⁹¹⁹ *Glick, Clough and Nunley. (2007, Table 1, p. iv)

- **Dyes Inlet, Sinclair Inlet, and Bainbridge Island (WA):** Most dry land in this portion of Puget Sound is of sufficient elevation to escape conversion even in the more aggressive sea level rise scenarios.⁹²⁰ Over half of beach land is predicted to be lost, however, primarily converted to tidal flats.⁹²¹ Saltmarsh and transitional marsh increase, primarily due to loss of dry land.⁹²²
- **Elliott Bay and the Duwamish Estuary (WA):** Limited effects are predicted for the Seattle area due to a higher density of development and high land elevations overall.⁹²³ However, 300 to 400 hectares (741-988 acres; 3-4 km²) of dry land are predicted to be at risk of being converted to transitional marsh, saltmarsh, and tidal flats.⁹²⁴ In addition, fifty-five percent of estuarine beach at this site could be lost by 2100 under this scenario.⁹²⁵ Understandably, the assumption that developed areas will be protected from the effects of sea level rise is significant at this site which is nearly fifty percent composed of developed land.⁹²⁶ If the protection of developed land was not assumed, regions along the Duwamish Waterway and Harbor Island would be subject to additional inundation effects, especially under scenarios with higher rates of sea level rise.⁹²⁷
- **Annas Bay and Skokomish Estuary (WA):** High land elevations for dry land and swamp make this site less likely to be influenced by sea level rise than many of the other sites studied.⁹²⁸ The most significant change is loss of estuarine beaches, which decline by about one-third under all scenarios.⁹²⁹
- **Commencement Bay, Tacoma, and Gig Harbor (WA):** The Tacoma area is well protected by dikes around the Puyallup River, so results of sea level rise are limited near that river.⁹³⁰ Three to four percent of undeveloped land is predicted to be lost at this site overall, though, converting to transitional marsh and saltmarsh.⁹³¹ Over two-thirds of area beaches are predicted to be lost by 2100 due to erosion and inundation.⁹³²
- **Olympia, Budd Inlet, and Nisqually Delta (WA):** The largest predicted changes for this site pertain to the loss of estuarine beach and the inundation of some dry lands.⁹³³ Estuarine beach, in particular, declines by eighty-one percent.⁹³⁴ As with the other sites, all developed lands (including Olympia) are assumed to remain protected.⁹³⁵

Impacts on the remaining sites (Bellingham Bay, Skagit Bay, Willapa Bay, and the Lower Columbia River; see Figure 19) have been re-analyzed by Ducks Unlimited using LiDAR (Light Detection And Ranging, a technology for assessing elevation using lasers) and a newer version of SLAMM (version

⁹²⁰ *Glick, Clough and Nunley. (2007, Table 1, p. iv)

⁹²¹ *Glick, Clough and Nunley. (2007, Table 1, p. iv)

⁹²² *Glick, Clough and Nunley. (2007, Table 1, p. iv)

⁹²³ *Glick, Clough and Nunley. (2007, Table 1, p. iv)

⁹²⁴ *Glick, Clough and Nunley. (2007, Table 1, p. iv)

⁹²⁵ *Glick, Clough and Nunley. (2007, Table 1, p. iv)

⁹²⁶ *Glick, Clough and Nunley. (2007, p. 57)

⁹²⁷ *Glick, Clough and Nunley. (2007, p. 57)

⁹²⁸ *Glick, Clough and Nunley. (2007, Table 1, p. v)

⁹²⁹ *Glick, Clough and Nunley. (2007, p. 60)

⁹³⁰ *Glick, Clough and Nunley. (2007, Table 1, p. v)

⁹³¹ *Glick, Clough and Nunley. (2007, Table 1, p. v)

⁹³² *Glick, Clough and Nunley. (2007, Table 1, p. v)

⁹³³ *Glick, Clough and Nunley. (2007, Table 1, p. v)

⁹³⁴ *Glick, Clough and Nunley. (2007, Table 1, p. v)

⁹³⁵ *Glick, Clough and Nunley. (2007, Table 1, p. v)

6.0).⁹³⁶ Grays Harbor was also analyzed.⁹³⁷ Given a global average sea level rise of 27.3 inches (0.69 meters) under the A1B scenario, preliminary results from this ongoing project indicate that, across the study sites, substantial increases in transitional marsh (+12,101 acres, or 266%), and decreases in saltmarsh (-533 acres, or 2%), freshwater tidal areas (-3953 acres, or 24%), and low tidal areas (-60,766 acres, or 58%) are likely by 2100 (Table 20).⁹³⁸

Significant local results include loss of two-thirds of low tidal areas in Willapa Bay and Grays Harbor, and a loss of eleven to fifty-six percent of freshwater tidal marsh in Grays Harbor, Puget Sound, and Willapa Bay (see Figure 18 for Willapa Bay results).⁹³⁹ Much of these habitats are replaced by transitional marsh.⁹⁴⁰ The Lower Columbia River may be the most resilient site of those studied because losses to low tidal, saltmarsh, and freshwater tidal habitats are minimized, while gains in transitional areas are substantial (Figure 19).⁹⁴¹

Changes in the composition of tidal wetlands could significantly diminish the capacity for those habitats to support salmonids, especially juvenile Chinook and chum salmon.⁹⁴² A significant reduction in the area of estuarine beaches, for example, would affect important spawning habitat for forage fish, which make up a critical part of the marine food web.⁹⁴³ Unless species are able to find alternative spawning areas, their populations could decline.⁹⁴⁴ Further, loss of coastal marshes would affect habitat for thousands of wintering waterfowl that visit the region each year.⁹⁴⁵

⁹³⁶ Ducks Unlimited, Inc. (DU). *Update of Puget Sound SLAMM Analysis*. (2010d); DU. *SLAMM Analysis of Willapa Bay, Washington*. (2010c); DU. *SLAMM Analysis of the Lower Columbia River, Washington and Oregon*. (2010b). All reports are unpublished technical reports.

⁹³⁷ DU. *SLAMM Analysis of Grays Harbor, Washington (unpublished technical report)*. (2010a)

⁹³⁸ The DU analysis grouped habitat types as follows. *Low tidal* areas include estuarine beach, tidal flats, vegetated tidal flats, ocean beaches, and ocean flats. *Saltmarsh* includes saltmarshes. *Transitional marsh* includes irregularly flooded marsh and scrub/shrub areas. *Freshwater tidal areas* include tidal swamps and tidal/fresh marshes.

⁹³⁹ DU. (2010a); DU. (2010c); DU. (2010d)

⁹⁴⁰ DU. (2010a); DU. (2010c); DU. (2010d)

⁹⁴¹ DU. (2010b)

⁹⁴² *Glick, Clough and Nunley. (2007, p. v)

⁹⁴³ *Glick, Clough and Nunley. (2007, p. v)

⁹⁴⁴ *Glick, Clough and Nunley. (2007, p. v)

⁹⁴⁵ *Glick, Clough and Nunley. (2007, p. v)

Table 20. Changes to the Area of Four Coastal Habitats in Washington & Oregon.

	Current Area (acres)	Projected Area (acres)	Total Change (acres)	Percent Change
Whatcom, Skagit Bay, and Snohomish, WA				
Low tidal areas	10623	8723	-1900	-18
Saltmarsh	5701	5836	135	2
Transitional areas	637	2133	1496	235
Freshwater tidal areas	1569	937	-632	-40
Grays Harbor, WA				
Low tidal areas	37646	12271	-25375	-67
Saltmarsh	2758	3716	958	35
Transitional areas	1135	6373	5238	461
Freshwater tidal areas	6993	5317	-1676	-24
Willapa Bay, WA				
Low tidal areas	50268	16889	-33379	-66
Saltmarsh	7806	7307	-499	-6
Transitional areas	1972	6046	4074	207
Freshwater tidal areas	1653	724	-929	-56
Lower Columbia River, WA/OR				
Low tidal areas	5545	5433	-112	-2
Saltmarsh	5975	4848	-1127	-19
Transitional areas	810	2103	1293	160
Freshwater tidal areas	6370	5654	-716	-11
All Study Sites				
Low tidal areas	104082	43316	-60766	-58
Saltmarsh	22240	21707	-533	-2
Transitional areas	4554	16655	12101	266
Freshwater tidal areas	16585	12632	-3953	-24

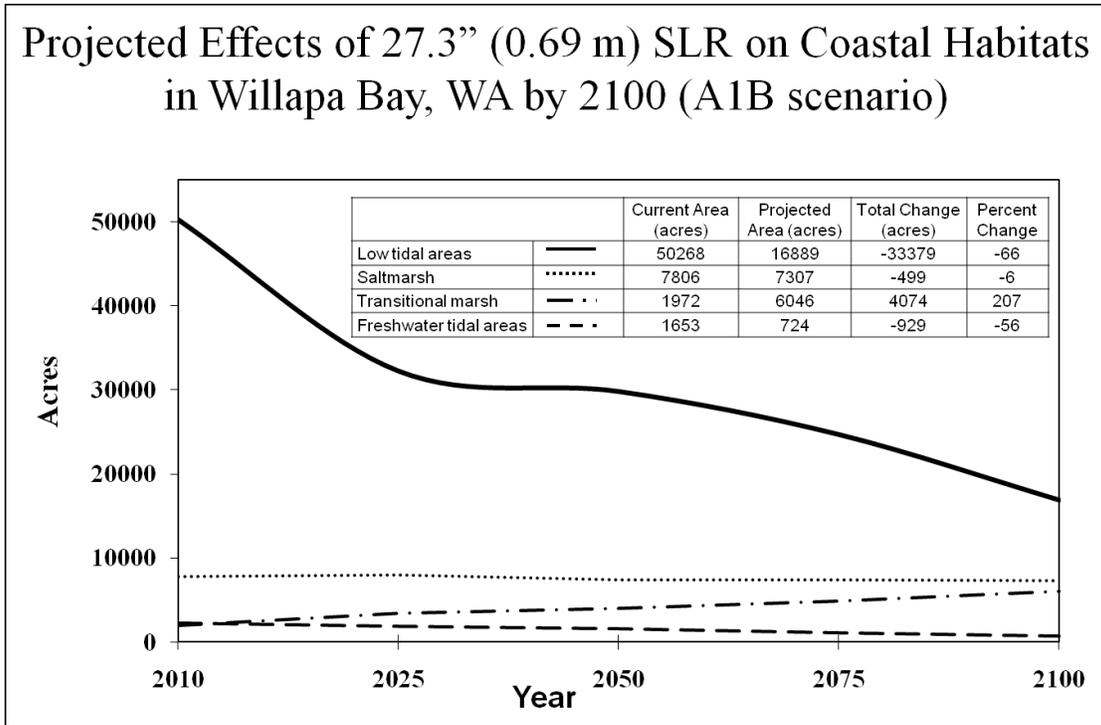


Figure 18. Projected effects of 27.3 inches (0.69 meters) sea level rise on coastal habitats in Willapa Bay, WA by 2100 (A1B scenario). *Data Source: Ducks Unlimited (figure created by authors of this report)*

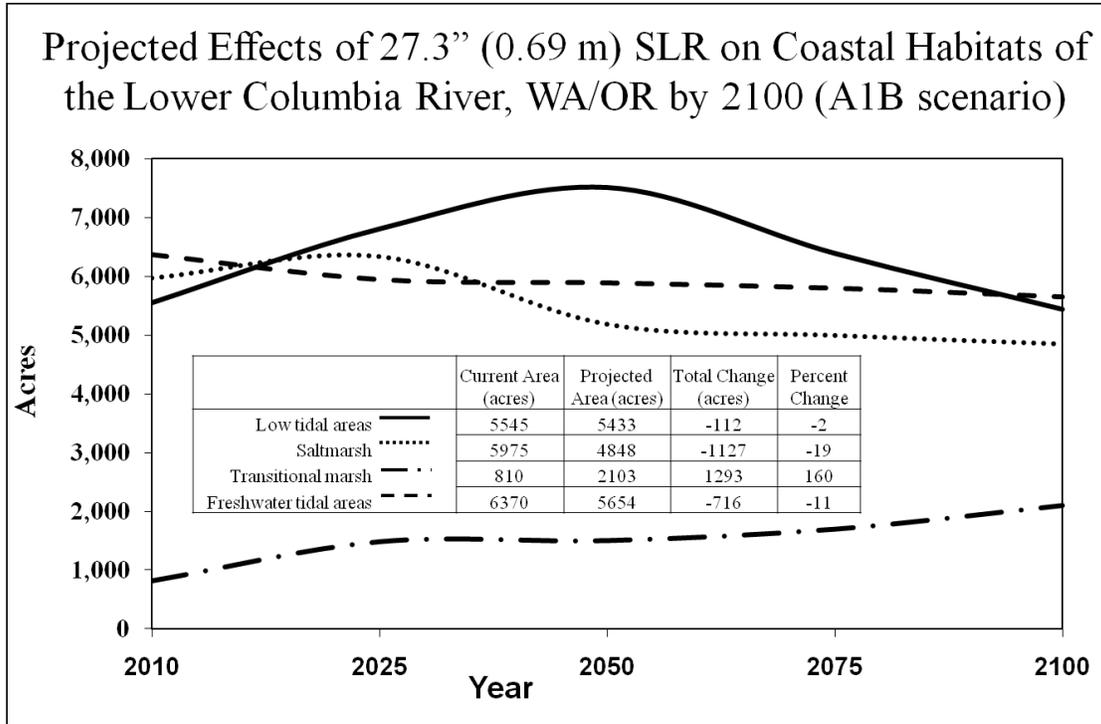


Figure 19. Projected effects of 27.3 inches (0.69 meters) sea level rise on coastal habitats in the Lower Columbia River (WA and OR) by 2100 (A1B scenario).

Data Source: Ducks Unlimited (figure created by authors of this report)

Northwest California

In a study using SLAMM 4.0 under three sea level rise scenarios, current and projected future percent changes in intertidal and upland habitat at Humboldt Bay were assessed.⁹⁴⁶ One reviewer from California noted LiDAR data was not used in this analysis.⁹⁴⁷ The three scenarios are:

- The historical rate of sea level change (based on actual past sea level changes at the site),⁹⁴⁸
- A higher-probability scenario of approximately 13 inches (34 cm) of sea level rise by 2100 (assumes 3.6°F or 2°C of warming), and
- A lower-probability scenario of approximately 30 inches (77 cm) of sea level rise by 2100 (assumes 8.5°F or 4.7°C of warming).⁹⁴⁹

By 2050 and 2100, the following habitat changes in Humboldt Bay are projected:⁹⁵⁰

- **Tidal flats in 2050:** Compared to the 2005 value of approximately 2664 acres, losses of approximately 2.7 acres (-0.1%) under the historic scenario, 346.3 acres (-13.0%) under the high-probability scenario, and 1129.5 (-42.4%) acres under the low-probability scenario are projected.
- **Tidal flats in 2100:** Compared to the 2005 value of approximately 2664 acres, losses of approximately 2.7 acres (-0.1%) under the historic scenario, 761.8 acres (-28.6%) under the high-probability scenario, and 2432.2 acres (-91.3%) are projected.
- **Salt marsh in 2050:** Compared to the 2005 value of approximately 99 acres, gains of approximately 71.9 (+72.6%) under the historic scenario, 87.9 acres (+88.9%) under the high-probability scenario, and 226.9 acres (+229.2%) are projected.
- **Salt marsh in 2100:** Compared to the 2005 value of approximately 99 acres, gains of approximately 71.9 acres (+72.6%) under the historic scenario, 173.6 acres (+175.6%) under the high-probability scenario, and 1867.1 acres (+1,886%) under the low-probability scenario are projected.
- **Upland and other habitat types in 2050:** Compared to the 2005 value of approximately 31,506 acres, losses of 63.0 acres (-0.2%) under the historic scenario, 94.5 acres (-0.3%) under the high-probability scenario, and 220.5 acres (-0.7%) under the low-probability scenario are projected.
- **Upland and other habitat types in 2100:** Compared to the 2005 value of approximately 31,506 acres, losses of approximately 63.0 (-0.2%) under the historic scenario, 189.0 (-0.6%) under the high-probability scenario, and 1890.4 acres (-6.0%) are projected.

Information Gaps

Information is needed on observed trends throughout the NPLCC and globally. Updated projections for the northern California coast, as well as information on projected habitat loss, degradation, and/or conversion in coastal British Columbia, are also needed. Lastly, additional projections throughout the NPLCC region would be helpful, as this section presents results from single studies.

⁹⁴⁶ Galbraith et al. (2005, p. 1121). Information obtained from Table 1 in the cited report.

⁹⁴⁷ Personal communication, Reviewer (January 2011)

⁹⁴⁸ *Galbraith et al. (2005, p. 1121). Information obtained from Table 1 in the cited report.

⁹⁴⁹ *Galbraith et al. (2005, p. 1120).

⁹⁵⁰ Galbraith et al. (2005).