A Simple Model that Identifies Potential Effects of Sea-Level Rise on Estuarine and Estuary-Ecotone Habitat Locations for Salmonids in Oregon, USA

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Abstract Diadromous aquatic species that cross a diverse range of habitats (including marine, estuarine, and freshwater) face different effects of climate change in each environment. One such group of species is the anadromous Pacific salmon (*Oncorhynchus* spp.). Studies of the potential effects of climate change on salmonids have focused on both marine and freshwater environments. Access to a variety of estuarine habitat has been shown to enhance juvenile life-history diversity, thereby contributing to the resilience of many salmonid species. Our study is focused on the effect of sea-level rise on the availability, complexity, and distribution of estuarine, and low-freshwater habitat for Chinook salmon (*Oncorhynchus tshawytscha*), steelhead (anadromous *O. mykiss*), and coho salmon (*O. kisutch*) along the Oregon Coast under future climate change scenarios. Using LiDAR, we modeled the geomorphologies of five Oregon estuaries and estimated a contour associated with the current mean high tide. Contour intervals at 1- and 2-m increments above the current mean high tide were generated, and changes in the estuary morphology were assessed. Because our analysis relied on digital data, we compared three types of digital data in one estuary to assess the utility of different data sets in predicting the changes in estuary shape. For each salmonid species, changes in the amount and complexity of estuarine edge habitats varied by estuary. The simple modeling approach we applied can also be used to identify areas that may be most amenable to pre-emptive restoration actions to mitigate or enhance salmonid habitat under future climatic conditions.

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Introduction

Many aquatic species traverse a range of habitats from headwater streams to the open ocean, and so will face effects of climate change in multiple environments. One such group of species is the Pacific salmon (*Oncorhynchus* spp.), which require lotic, estuarine, and marine habitats to successfully complete their life cycle (Groot and Margolis 1991). Climate change predictions indicate potential changes in ocean productivity due to a variety of factors including temperature, salinity, circulation patterns, and biogeochemical changes (Bindoff and others 2007). Ocean productivity is tied to salmonid growth and survival (Beamish and Mahnken 2001) and is known to have strong links to broader climate cycles (Mantua and others 1997). In addition, freshwater stream temperatures are predicted to increase with climate change, which may reduce habitat availability for most coldwater fishes (Eaton and Scheller 1996). Alterations in precipitation regimes and temperature are predicted to negatively affect salmonid freshwater survival at multiple life stages (Crozier and others 2008; Martins and others 2011; Waples and others 2009). Understanding the potential effects of climate change on the array of salmonid habitats is increasingly relevant to recover many at-risk populations of these socially, economically, and culturally important fish (Crozier and others 2008; Healey 2011). While the mechanisms by which climate change may affect salmon have been explored in ocean habitats (Beamish and Mahnken 2001) and freshwater habitats (Beechie and others 2012; Eaton and Scheller 1996; Mantua and others 2010; Montgomery and

others 1999; Reusch and others 2012; Wenger and others 2011), few studies have focused on estuary habitats (Bottom and others 2009; Johnson and others 2012).

The variety of marsh habitats available in the estuary and estuary-river ecotone provides for the expression of salmonid life-history diversity (Fig. 1) (Bottom and others 2005a; Hayes and others 2008; Jones and others 2008; Miller and Sadro 2003; Reimers 1973; Volk and others 2010). Estuarine areas are also a key transition zone for all migrating juveniles to shift osmoregulation from fresh to saltwater (Magnusson and Hilborn 2003; McCormick and Saunders 1987), which is necessary for ocean survival. Depending on the species or life-history strategy, rearing salmonids will occupy estuarine habitats for weeks to months at a time (Bond and others 2008; Bottom and others 2005a; Hering and others 2010; Levy and Northcote 1982). Small juveniles generally forage in nearshore habitats that include salt marshes, tidal creeks, and intertidal flats (Gray and others 2002; Jones and others 2008; Levy and Northcote 1982). Distributary channels in near proximity to wetland edge habitat are particularly important foraging and refuge areas (Bottom and others 2005a).

For a variety of reasons, recovery planning for Pacific salmon has placed less focus on estuaries than on streams or oceans. Bottom and others (2009) identified the institutional and academic boundaries that have precluded due consideration of estuarine ecosystems in the recovery of imperiled populations of salmon. With most salmon biologists studying freshwater habitat, and few investigating saline systems, the focus of restoration has been on what the science knows best, freshwater (Bottom and others 2009). Freshwater habitat in much of the Oregon Coastal Province, as in many other coastal areas, has been compromised through anthropogenic activities that reduced habitat connectivity, altered geomorphic processes, and changed natural disturbance regimes (Lichatowich 1999; Folke and others 2004; Flitcroft and others 2012; Koski 2009; Reeves and others 1995). Strong evidence of the critical importance of estuaries in maintaining life-history diversity has often been overlooked in fish population recovery planning (Bottom and others 2005b). The role of estuaries for juvenile salmonids may be as simple conduits that provide for a gradual transition between fresh and salt water. However, estuaries with diverse habitats offer rich food sources, as well as refuge from predators for juvenile salmon that may rear within them for extended periods. Regardless of the amount of time that juvenile salmon stay in an estuary, one fact is certain: all salmon will experience estuary conditions at least twice in their lifetimes.

Rising sea levels are a key process by which climate change may affect estuarine habitats for salmon. Climate change may alter mean sea level through changes in global temperature and precipitation regimes (Bindoff and others 2007). The International Panel on Climate Change has estimated increases in global mean sea level to range from 0.18 to 0.59 m by the year 2100 (Bindoff and others 2007). Although the predictions of potential changes in global mean sea level have varied, recent studies that include models of predicted thermal changes (Mote and Salathé 2010; Vermeer and Rahmstorf 2009) or changes in ice flow and glacial conditions (Pfeffer and others 2008) propose that increases of up to 2.0 m are possible. It is also possible that tectonic changes along some coastlines may occur at rates that mitigate for rising sea level, or potentially exacerbate its effect (Committee on Sea Level Rise in California, Oregon, and Washington, prepublication 2012). Sea-level rise associated with climate change has the potential to alter the availability, configuration, and location of habitats in the estuary and estuary-river ecotone by flooding current habitats and pushing the edge of saltwater intrusion further upstream (Craft and others 2009; Glick

Fig. 1 Generalized anomadrous salmonid life-history diversity facilitated by available estuarine habitat
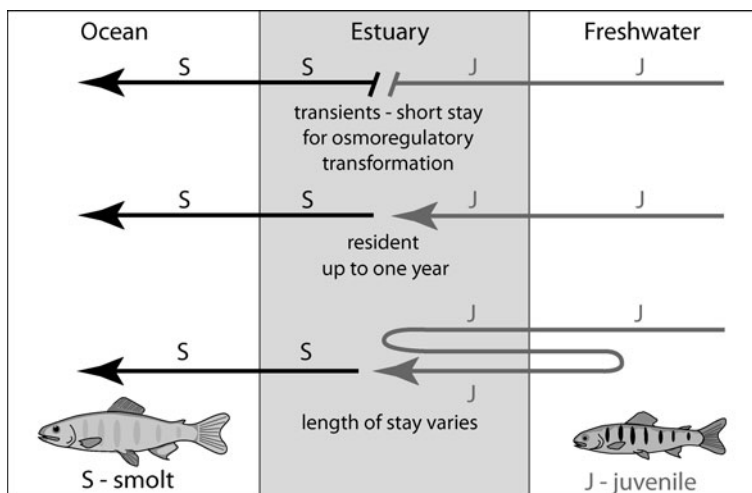
and others 2007). These locations supply habitat critical to rearing salmonids (Koski 2009).

Over the geologic record, the extents of tidal vegetation communities have expanded and contracted with changes in overall global temperatures and sea levels (Fletcher and others 1993), but documentation about how these changes affected salmon or their habitats is lacking. Plant species that colonize estuaries are adapted to diverse conditions, thereby allowing vegetation distributions to flex with changing conditions over time. Due to their extreme mobility, salmon may also be able to shift distributions when conditions change. As with other systems, the resilience of the estuarine ecosystem to assimilate changes from sea-level rise may be complicated by human modifications of the environment that constrain the ability of vegetation communities, and possibly salmonid communities, to move with alterations in tidal and freshwater regimes (Folke and others 2004). The effect of sea-level rise on the configuration and classification of estuarine wetland habitats has been explored by coastal wetland ecologists and geomorphologists (Morris and others 2002; Reed 1995). They have developed a variety of models, ranging from simple to complex, to predict local, regional, and global effects of sea-level rise on estuarine geomorphology, salinity levels, and vegetation communities of coastal regions (Mcleod and others 2010). However, clearly defined methods or accepted procedures that allow managers to plan preemptive actions to mitigate for the potential effects of climate change are not currently available for well-studied estuarine components (Mcleod and others 2010), much less for salmon.

The primary objective of this study is to explore potential changes in salmon habitat in the estuary and estuary-river ecotone with sea-level rise in coastal Oregon. In this project, we hope to provide managers and salmon biologists with a starting point for considering the potential effects of sea-level rise on estuarine habitats. To accomplish this, we chose a simple, mechanistic model using available and spatially comprehensive geospatial data sets. First, we compared three different elevation data sets to determine their merits and limitations for simple modeling work, such as ours, that uses estuarine topography. Next, we examined the effect of potential sea-level rise (SLR) by modeling a suite of physical and biological metrics for two inundation scenarios in five selected estuaries on the Oregon Coast for three species of anadromous salmonids. The two scenarios, a mean SLR of 1 and 2 m above the current mean sea-level, encompass currently projected increases in mean sea level by the year 2100 (Pfeffer and others 2008; Vermeer and Rahmstorf 2009). Ultimately, our goal is to increase the understanding of the effect of climate change on habitats critically important for maintaining life-history diversity for at-risk salmonids.

Materials and Methods

Study Area

Of the seven species of Pacific salmon, three are present in self-sustaining populations along the Oregon Coast; Chinook salmon (*Oncorhynchus tshawytscha*), steelhead (anadromous *O. mykiss*), and coho salmon (*O. kisutch*) have supported recreational and commercial fisheries. These anadromous salmonids have complicated habitat requirements that include the continuum of freshwater, estuarine, and marine habitats (Fig. 2). Oregon coastal coho salmon are currently listed as Threatened under the US federal Endangered Species Act (Federal Register 2011). Populations of fall-run Chinook salmon and steelhead are also declining in the coastal Oregon. These three salmonid species appear to be resistant to current restoration efforts, and strong popular support for their recovery, makes all the three species of conservation interest.

Estuaries selected for the study currently provide habitat for Chinook salmon, steelhead, and coho salmon, and were meant to represent a range of sizes, types, and locations. Five Oregon estuaries were chosen: Salmon River (194 km^2), Alsea River (1,228 km^2), Smith River (900 km^2), Elk River (243 km^2), and Chetco River (911 km^2) (Fig. 3). The four northern-most estuaries drain catchments with headwaters in the Oregon Coast Range, while the Chetco River estuary has higher elevation headwaters at the junction of the Oregon Coast Range and Klamath Mountains. For all estuaries, dominant land uses are related to forestry at higher elevations and to agriculture or rural residential development in river floodplains at lower elevations. The climate throughout the Oregon Coast Range is temperate maritime, with precipitation falling predominantly as rain during winter. Underlying geology for the Salmon and Alsea Rivers is sandstone. Smith River geology is characterized by volcanic rock, while the Elk River and Chetco River are contained within a metamorphosed geology.

Each of these estuaries has experienced some level of human impact. However, over the past four decades, most of the saltwater marsh that had been diked for agriculture in the Salmon River estuary was restored through dike removal and vegetation plantings to facilitate saltwater wetland recovery. Hardscape, needed to protect Oregon State Highway 101, is the most constraining anthropogenic feature remaining in the Salmon River estuary. This contrasts with the Alsea River estuary, which has significant human impacts, including dredging to support navigation, as well as diking and draining of floodplains (Oregon Estuary Plan Book 1987). The community of Waldport is located along the Alsea estuary margin. Agriculture, primarily grazing, and low-density housing predominate in

Fig. 2 Salmonid habitat use and distribution extend from the mountains to the sea. Examples of estuarine habitats include low marshes (**a**), brackish marsh (**b**), and tidal freshwater habitats (**c**). These are linked along the stream network to spawning habitats, and headwater refuge habitats (**d**)
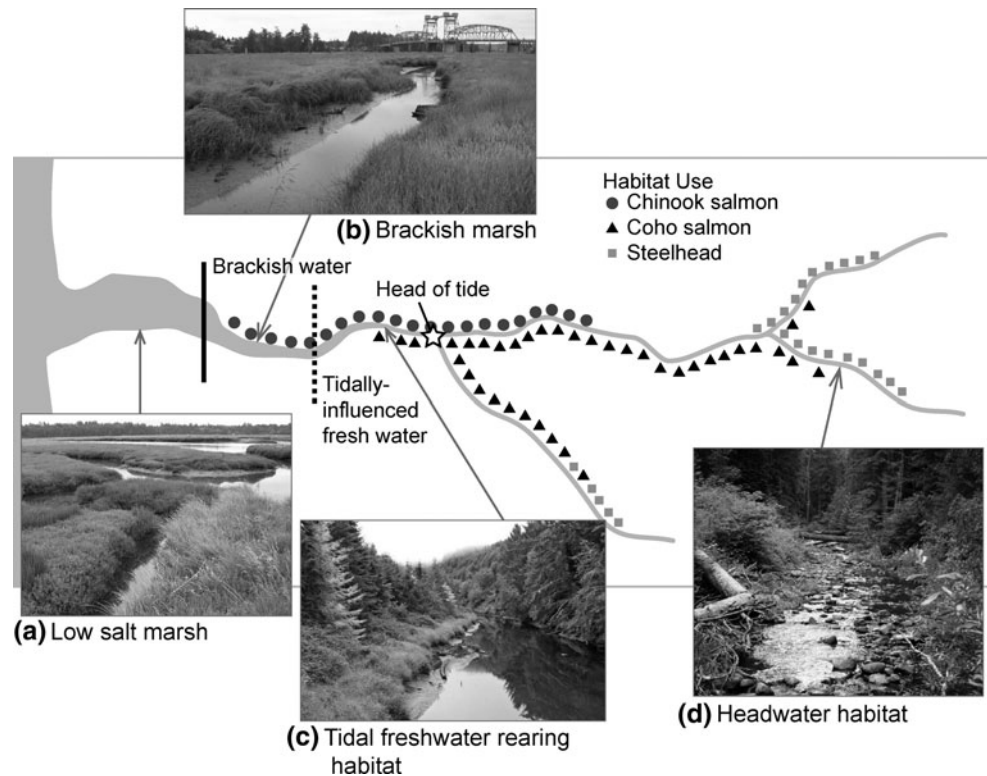
the tidal floodplain. Estuaries of the Smith, Elk, and Chetco Rivers also have extensive diking and floodplain drainage (Oregon Estuary Plan Book 1987). The Chetco River estuary supports a boat basin associated with the community of Brookings. The Smith River is the only estuary in this study that does not drain directly into the Pacific Ocean, but into the estuary of the larger Umpqua River.

Elevation Datasets

Our ability to model the potential effects of SLR on salmonid estuary habitats depends on the resolution of the digital elevation data and how well the land–water interface can be determined from it. We chose the Salmon River estuary to evaluate the utility of different sources of elevation data for modeling the potential effects of SLR on salmon habitat. At Salmon River, three digital data sets are publicly available: LiDAR (light detection and ranging) flown specifically to capture low-tide conditions at a 1 × 1 m resolution (hereafter referred to as low-tide LiDAR); LiDAR flown as part of a comprehensive coast-wide data set; and 10-m digital elevation models (DEMs) (obtained at http://www.fsl.orst.edu/clams/index.html).

Salmon River is the only Oregon estuary where low-tide LiDAR is available. This data set was collected under contract with the Siuslaw National Forest, with the specific intent of capturing the lowest possible tidal conditions. The LiDAR effectively captures the bathymetry of the Salmon

River estuary, and represents the best available digital information. We compared the two coast-wide geospatial data sets (coast-wide LiDAR and DEMs) to the low-tide LiDAR to determine the best option, among currently available imagery, to model multiple estuaries along the Oregon Coast.

The coast-wide LiDAR data was funded by a consortium of federal, state, and county agencies, with the goal of acquiring high-resolution imagery for the Oregon coastal region. Most of this imagery was obtained by aircraft for areas west of Highway 101 in flights between May and October 2008, and was flown at a resolution of 0.9 × 0.9 m. This LiDAR was flown using the infrared visual spectrum, and therefore could not penetrate through water. The coast-wide LiDAR data set was collected to support road infrastructure maintenance and was not designed to capture low-tide conditions along the coast.

Contour Intervals

Our analysis included two parts; first, we compared the effectiveness of three digital data sets (low-tide LiDAR, coast-wide LiDAR, and 10-m DEMs) to detect changes in the mean sea-level at Salmon River Estuary; and second, we estimated mean SLR for each of the five Oregon study estuaries. For both of these analyses, the initial step was to determine a baseline elevation contour interval, meant to represent the current mean high tide. Techniques are
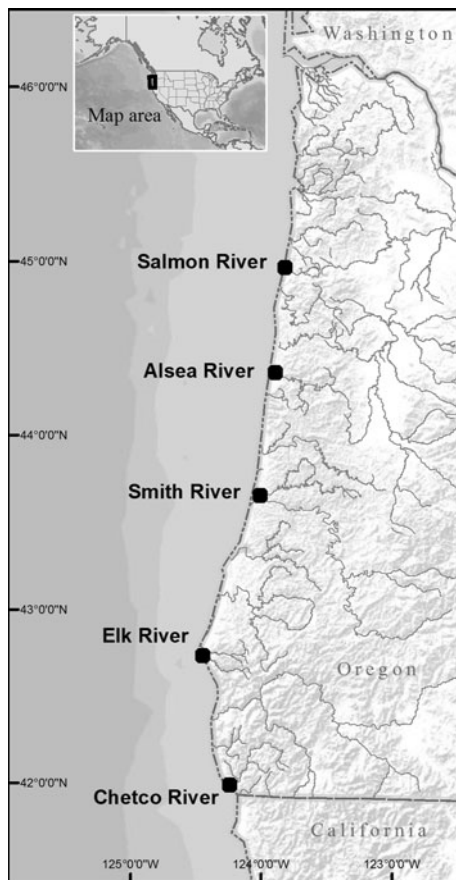
Fig. 3 Estuaries investigated for the potential effects of increase in mean sea-level on the Oregon Coast

currently unavailable to connect terrestrial dataset such as LiDAR or DEMs (for the Salmon River estuary comparison study) with the currently available Pacific tidal datums (Gill and Schultz 2001). Therefore, we accessed other spatial data to determine the mean high-tide contour interval. Several spatial data sets were used to inform the selection of this baseline elevation contour, including digital aerial photography, digital topographic maps, and a mean head-of-tide geospatial point coverage that the Oregon Division of State Lands (DSL) that was developed based on empirical surveys of tidal inundation (State of Oregon Division of State Lands 1989).While not ideal, the DSL data set provided access to surveyed points in each estuary that documented tidal movement inland. Once the baseline contour interval was identified, we then calculated a 1- and 2-m elevation contour interval above baseline to simulate a 1- and 2-m rise in mean sea-level.

The coast-wide LiDAR posed some processing challenges when developing contour intervals. We found that the land–water interface was often difficult to identify from LiDAR in heavily vegetated areas. Further, because flight times did not coincide with low tides, adjacent bands of

LiDAR data may have a different water signature depending on the height of the tide during the flight. This produced spurious "stair-steps" in the water signature delineated with the LiDAR. To generate continuous contour intervals from the LiDAR dataset, we hand-corrected edge signatures associated with vegetation by referencing high-resolution aerial photography, and removed inconsistencies in open water caused by different tide levels.

Potential Effects of Sea-Level Rise on Salmonid Freshwater Habitat Availability

We anticipated that varying estuarine topographies would affect accessibility of tidal flows into floodplain areas. The degree of constraint by hill slopes also may influence the response of estuaries to higher sea level through floodplain expansion, or by flooding into freshwater habitats. To capture the effect of SLR on the amount of estuary habitat and the complexity and extent of estuarine edge habitat, we calculated the total estuary perimeter, estuary area, and fractal dimension, for the current baseline and for the 1- and 2-m SLR scenarios. Estuarine margins that include tidal channels are important foraging and refuge areas for rearing salmonids (Hering and others 2010; Levy and Northcote 1982). Estuary perimeter is meant to capture the potential available edge habitat for rearing juveniles. Estuary area offers another dimension of habitat. However, we cannot predict the actual habitat area without models of estuarine bathymetry, vegetation, salinity, or flow. These types of models are not currently available throughout the Oregon Coast. Therefore, we estimated estuary area as a means of describing the potential change in available habitat area throughout the estuary.

Fractal dimension quantifies the sinuosity of a linear feature and has been used to describe potential habitat complexity in terrestrial systems (Irme and Bogaert 2004). We calculated fractal dimension of the estuarine edge to quantify edge complexity. For salmon habitat, we considered estuaries with fractal dimensions that are closer to a linear shape (fractal dimension of <2) to have less potential for complex edge habitat than estuaries with a higher fractal dimension (fractal dimension ≥ 2). To estimate estuary area and perimeter, contour intervals were converted into closed polygons in GIS. The fractal dimension of contour lines was calculated using Hawths Tools (Beyer 2004) in ArcGIS 9.3.1 (ESRI 2008).

To capture the effect of SLR on the estuary-river ecotone, the length of upstream migration by the estuary contour was also calculated by overlaying the contour on 1:100,000 stream hydrography using ArcGIS 9.3.1 (ESRI 2008). For each estuary, we measured the number of meters of freshwater habitat with potential to be inundated between 0 and 1 m of SLR and between 1- and 2-m SLR.

We then calculated the percent of currently available freshwater salmon habitat that this inundation would effect. This allowed us to compare which river systems might experience more inundation than others, and which ones might experience the majority of change between 0- and 1-m SLR or 1- and 2-m SLR. The hydrography that was selected for this study contains salmon habitat by species as designated by the Oregon Department of Fish and Wildlife (ODFW). These habitat designations for native salmonids were created by ODFW by synthesizing information from field surveys and consulting staff biologists. Stream segments on the 1:100,000 hydrography include classifications of spawning or rearing habitat for Chinook, coho salmon, or steelhead. The maps are publicly available online (StreamNet GIS Data 2003).

Results

Comparisons of Elevation Datasets

The three elevation data sources [coast-wide LiDAR, low-tide LiDAR (LiDAR intentionally flown to capture low-tide conditions), and 10-m DEMs] yielded different estimates of current conditions, and the two SLR scenarios at Salmon River estuary (Table 1). An important difference among the data sets is the location of the current mean high-tide contour (Fig. 4). It appears that the coast-wide LiDAR was collected over Salmon River estuary during a tidal phase higher than mean high tide. Because the coast-wide LiDAR does not penetrate water, the first contour interval in this data set to enter the estuary was associated with a height of 2.6 m elevation (datum is NAD83). This contour was above the estimated mean high tide under both the low-tide LiDAR and the 10-m DEMs (Fig. 4). However, it was the first contour interval available and had to be used as the baseline contour.

Estuary perimeter values were considerably higher when estimated with both the LiDAR data sets than with the coarser 10-m DEMs (Table 1). For all the three sources of digital elevation data, values of estuary perimeters in both the 1- and 2-m SLR scenario were lower than current estimates (Table 1). However, the estimate of estuary perimeter (km) from the 10-m DEMs was considerably lower, at all stages, than either the low-tide or coast-wide LiDAR estimates.

In the two SLR scenarios, upstream migration of the estuary into currently identified salmonid freshwater habitat varied among the three elevation data sets (Table 2). The coast-wide LiDAR data set identified the greatest extent of estuarine upriver migration into areas currently classified as freshwater salmon habitat with a 1-m SLR (Table 2). The 10-m DEM dataset identified the smallest extent of freshwater inundation among the three data sets with a 2-m SLR (Table 2). The low-tide LiDAR consistently identified the largest effect of SLR, with more upstream movement of the mean high-tide contour line at both the 1- and 2-m levels of SLR (Table 2).

Across-Estuary Comparisons

Based on the reasons detailed below, we compared across the estuaries using the coast-wide LiDAR. The magnitude and direction of change in estuary area, perimeter, and fractal dimension, between current condition and either a projected 1-m or 2-m SLR, varied among the estuaries in this study. The estimated estuary area increased between current, 1- and 2-m SLR for all estuaries (Fig. 5). The magnitude of that increase varied. For all the estuaries except Elk River, the increase under each of the SLR scenarios was less than twice the original estuary area (Table 3). For Elk River, under the 1- and 2-m SLR scenarios respectively, estuary area was greater than 2.7 and 5.7 times the current area (Table 3). The estimated length of estuary perimeter increased with SLR for the Smith, Elk, and Chetco River systems. Perimeter length decreased with the rising sea level for the Salmon River estuary between current condition and both the 1- and 2-m SLR scenarios. In the Alsea, perimeter initially increased between current and 1-m, and then decreased between 1- and 2-m SLR (Table 3). The calculated fractal dimension decreased for the Salmon and Alsea River systems with SLR. Fractal dimension remained the same in the Smith River and

Table 1 Predicted changes in available anadromous salmonid habitats in the Salmon River Estuary using three digital elevation datasets, LiDAR flown at low-tide (low-tide LiDAR), LiDAR flown without regard for tidal stage (coast-wide LiDAR), and 10-m digital elevation models (10-m DEMs)

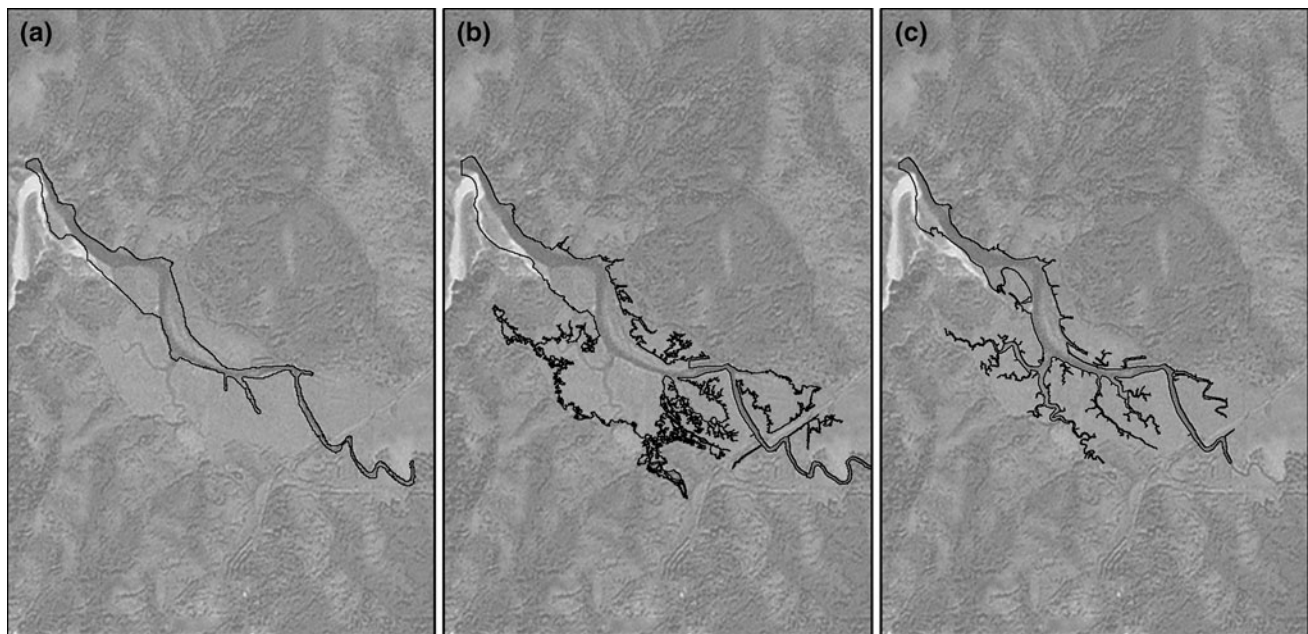| Dataset	Mean high tide		
	Current	1-m rise	2-m rise
Low-tide LiDAR			
Estuary area (km^2)	0.8	2.6	3.8
Estuary perimeter (km)	41.8	68.0	34.3
Fractal dimension	2.3	2.1	1.8
Coast-wide LiDAR			
Estuary area (km^2)	2.2	3.7	4.3
Estuary perimeter (km)	103.7	41.5	43.4
Fractal dimension	2.1	1.8	1.8
10-m DEMs			
Estuary area (km^2)	0.9	1.7	2.5
Estuary perimeter (km)	15.7	14.7	13.1
Fractal dimension	2.8	2.3	2.0

Fig. 4 Difference in baseline-current mean high-tide contour among: **a** 10-m digital elevation models (DEM), **b** LiDAR flown without considering tide level (coast-wide LiDAR), and **c** LiDAR flown specifically targeting low tide and associated low-water topography (low-tide LiDAR)

Table 2 Comparison of predicted decreases in length (m) of salmonid freshwater habitat in Salmon River Estuary using three different digital datasets for two sea-level rise scenarios (1-m and 2-m)

	Freshwater habitat included in mean sea-level contour (m) (percent of available freshwater habitat in the watershed)					
	Low-tide LiDAR		Coast-wide LiDAR		10-m DEM	
	1-m	2-m	1-m	2-m	1-m	2-m
Coho Salmon	3,610	4,566	633	2,106	1,180	1,587
	(4 %)	(5 %)	(1 %)	(2 %)	(1 %)	(2 %)
Steelhead Trout	3,250	5,722	361	1,738	882	1,199
	(3 %)	(5 %)	(1 %)	(2 %)	(1 %)	(1 %)
Fall Chinook Salmon	3,372	3,955	317	1,609	1,126	1,478
	(6 %)	(7 %)	(1 %)	(3 %)	(2 %)	(2 %)

increased at Elk River (Table 3). Fractal dimension at the Chetco River initially decreased slightly between current and 1-m, and then returned to a value of 2.0 at 2-m SLR. (Table 3).

According to the habitat mapping by ODFW, each study estuary currently borders freshwater habitat for coho salmon, steelhead, and Chinook salmon during at least one life-history stage (spawning, rearing, or both). Varying amounts of habitat for all the three salmonids in each of the five study estuaries would be included in the mean high-tide estuary contour under both SLR scenarios (Table 4). The majority of inundated freshwater habitat occurred in the first 1-m rise of sea level for the Smith River (63 %) and Alsea River (56 %) systems. The majority of inundated freshwater habitat occurred between 1- and 2-m SLR for the Salmon River (76 %), Elk River (60 %), and Chetco River (61 %) systems. In most of the estuaries, the proportion of all freshwater habitat (spawning, rearing, or both) within the watershed that would be effected by SLR was low (<3 %) (Table 4). However, coho salmon in the Elk River system would experience inundation of approximately 5 % of all the available freshwater habitats in the watershed with 1-m SLR, and 13 % inundation with SLR of 2 m (Table 4).

Discussion

In this study, we found that sea-level rise as a likely consequence of climate change has the potential to affect estuarine habitats critical in the life histories of imperiled populations of Pacific salmon. Based on our simple model
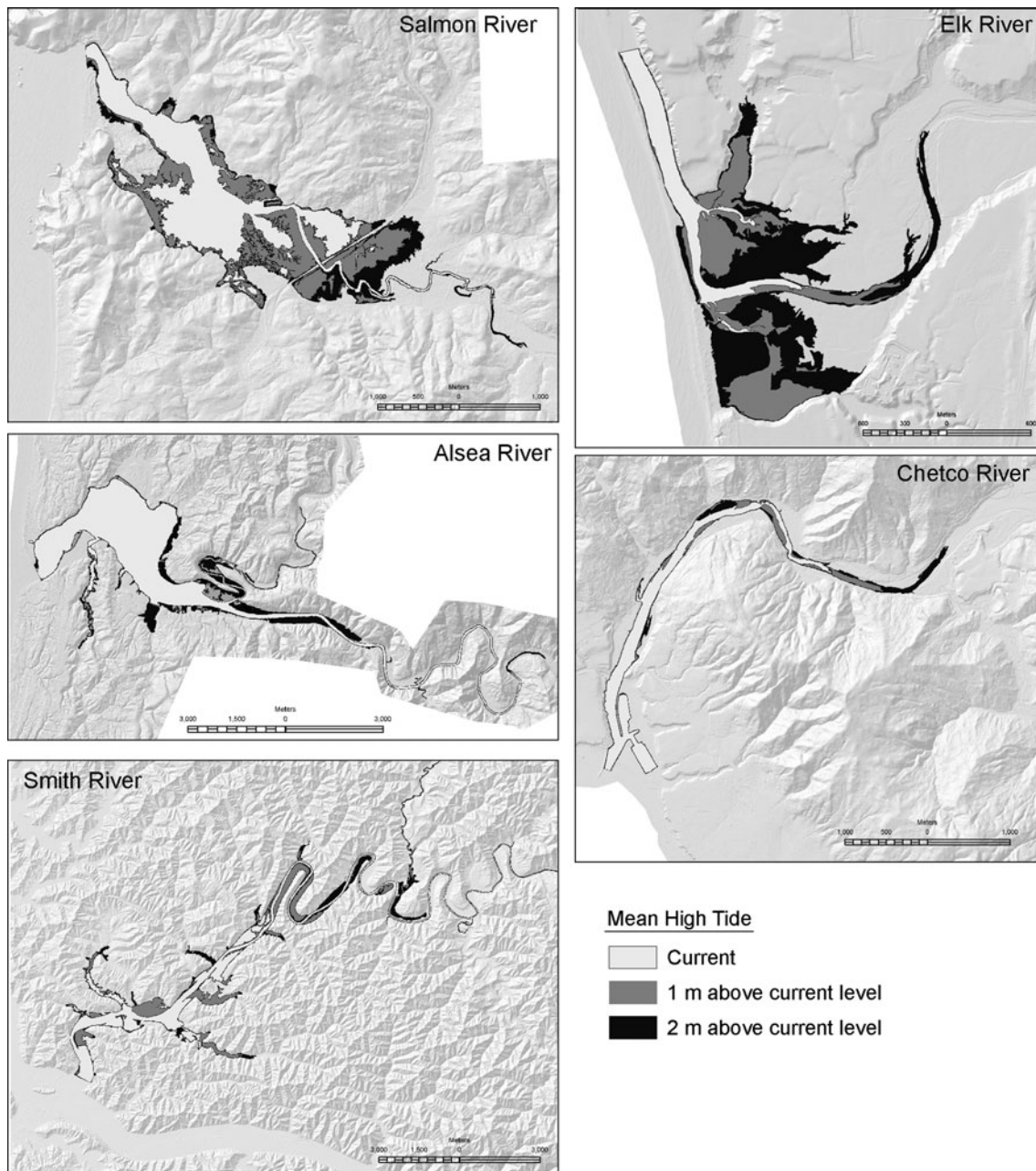
Fig. 5 Estimated estuary margin at current mean high tide, with a 1-m increase in mean sea-level, and with a 2-m increase in mean sea-level for: Salmon River, Alsea River, Smith River, Elk River, and the Chetco River

of mean high tide, we found that each estuary exhibited a different combination of responses to SLR. Some systems appeared to have more potential resilience to changes in sea level, while others appeared to be constrained by geomorphic setting and land use. All species of Pacific salmon investigated in this project would experience changes from current conditions in all of the estuaries that we modeled.

We recognize that our relatively simple topographic modeling approach excludes many important processes that can influence sea-level rise and associated effects in estuaries. However, our intent was to perform a rapid, initial analysis to examine the potential of sea-level rise to affect the estuary habitats for salmon, and if so, then quickly raise this as an issue that may merit additional research and consideration by policy-makers. Any effects of sea-level rise on salmon habitats in estuaries are in addition to other anticipated effects of climate change on food availability and habitat quality for salmon in marine and freshwater environments.

Comparisons of Elevation Datasets

An ideal elevation data set to model potential effects of sea-level rise on estuaries would represent all surfaces, including bathymetric and topographic relief, be of high resolution, and be comprehensive. At the Salmon River estuary, only the low-tide LiDAR essentially captured estuarine bathymetry. Consequently, the low-tide LiDAR provided a basis for evaluating how well the effect of SLR on salmonid habitats might be modeled elsewhere using coast-wide LiDAR or 10-m DEM datasets. Our analysis

identified important considerations for characterizing potential effects of sea-level rise using these two readily available digital elevation data sets.

The type of LiDAR that was obtained coast-wide for Oregon absorbs near-infrared light and so cannot characterize any channels that may be submerged. The first contour that we could generate for Salmon River using the coast-wide LiDAR characterized the complexity of the land–water interface above mean high tide. However, the coast-wide LiDAR also omitted many channels that would be exposed at lower tides. Compared to the coast-wide LiDAR, the resulting estuary model underestimates of the effect of SLR on estuary area, sinuosity of the estuary edge (fractal dimension), and salmonid freshwater habitat effects, because the base-level condition identified from the coast-wide LiDAR is at high tide, rather than at the lower elevation of mean high tide. However, the coast-wide LiDAR is of high enough resolution to identify the changes in perimeter that are more similar to the low-tide LiDAR than are the perimeter estimates calculated from 10-m DEMs.

At Salmon River estuary, the mean high-tide contour interval identified by the 10-m DEMs appears to be cut off at the mouths of the estuarine marsh channels. When investigating the source information for the Salmon River DEMs, we found that the estuary configuration identified from the mean high tide matched the underlying 1:24,000 topographic maps, which are the base data for the DEMs. These topographic maps were created using aerial photography collected in 1979 (USGS 1985). The mean high tide of the Salmon River estuary, identified by the DEMs, includes levee structures that have since been removed. Therefore, mean high tide identified on the DEMs represents site conditions from 1979 rather than current conditions in the estuary. Also, the coarse resolution of the DEMs, as compared to the low-tide LiDAR, produced low estimates of estuary perimeter.

Ideally, LiDAR flown at low-tide, or LiDAR that is sensitive to a light spectrum that penetrates water (i.e., Irish

Table 3 Summary of estuary characteristics for study systems based on the coast-wide LiDAR under current sea level conditions and with an estimated 1-m and a 2-m increase in mean high tide

River system (watershed area)	Mean high tide		
	Current	1-m rise	2-m rise
Salmon River (194 km^2)			
Estuary area (km^2)	2.2	3.7	4.3
Estuary perimeter (km)	103.7	41.5	43.4
Fractal dimension	2.1	1.8	1.8
Alsea River (1,228 km^2)			
Estuary area (km^2)	10.3	11.4	13.7
Estuary perimeter (km)	122.2	161.6	123.0
Fractal dimension	1.9	1.9	1.7
Smith River (900 km^2)			
Estuary area (km^2)	0.7	1.0	1.3
Estuary perimeter (km)	153.5	173.1	180.9
Fractal dimension	1.8	1.8	1.8
Elk River (243 km^2)			
Estuary area (km^2)	0.3	0.8	1.7
Estuary perimeter (km)	9.9	21.3	24.0
Fractal dimension	1.8	1.9	2.0
Chetco River (912 km^2)			
Estuary area (km^2)	0.7	0.8	1.0
Estuary perimeter (km)	16.8	17.7	20.2
Fractal dimension	2.0	1.9	2.0

Table 4 Estimated length (m) of freshwater salmonid habitat included in the estuary contour for two scenarios of sea-level rise

Habitat	Freshwater habitat included in mean sea-level contour (m) (percent of available freshwater habitat in the watershed)									
	Salmon River		Alsea River		Smith River		Elk River		Chetco River	
	1-m	2-m	1-m	2-m	1-m	2-m	1-m	2-m	1-m	2-m
Coho Salmon	633	2,106	3,866	6,669	7,035	8,572	1,284	3,387	660	1,683
	(1 %)	(2 %)	(1 %)	(1 %)	(1 %)	(1 %)	(5 %)	(13 %)	(1 %)	(1 %)
Steelhead Trout	361	1,738	3,866	6,669	4,468	6,883	1,285	3,388	660	1,683
	(1 %)	(2 %)	(1 %)	(1 %)	(1 %)	(1 %)	(1 %)	(3 %)	(1 %)	(1 %)
Fall Chinook Salmon	317	1,609	2,690	5,250	100	231	942	2,105	660	1,683
	(1 %)	(3 %)	(1 %)	(2 %)	(1 %)	(1 %)	(1 %)	(3 %)	(1 %)	(1 %)

and Lillycrop 1999; McKean and others 2009) would be available for coast-wide assessments of sea-level rise along the entire Pacific Coast. Unfortunately, such a data set is currently not available for Oregon, or many other coastal areas. Managers and researchers interested in modeling SLR throughout the Oregon Coast, and elsewhere, generally have two data sets from which to choose: LiDAR flown without regard to tidal height or 10-m DEMs. The coast-wide LiDAR at Salmon River characterized edge complexity, but did not reflect current mean high tide. Because, the current condition was defined by a higher than mean tide, the modeled effects of SLR on estuary morphology (estuary area, fractal dimension) showed less change than with the other digital data sets. This compares to the coarseness of 10-m DEMs, which resulted in poor assessments of available edge habitat (perimeter), and also contained legacy conditions that are no longer relevant.

Rationale for Choice of Spatial Data for Across-Estuary Comparisons

When choosing an elevation data set for comparing the effects of SLR across estuaries, we considered spatial resolution and accuracy. Both digital elevation data sets available coast-wide for Oregon were spatially continuous. However, the coast-wide LiDAR was of higher resolution and collected more recently than the 10-m DEMs, and so more accurately represented current conditions. The greatest limitation that we identified with the coast-wide LiDAR for modeling sea-level rise is the variable tidal elevations at the time of data collection. Connecting flight times with the tidal level could inform researchers as to the tidal level represented in the LiDAR. However, not all estuaries on the Oregon Coast have NOAA tide gauges (http://tidesandcurrents.noaa.gov/gmap3/index.shtml?type=PreliminaryData&region=Oregon). Also, the LiDAR was pieced together from multiple flights, and references to the date and time of specific flights are not readily available. These limitations reduce the potential to identify the mean high-tide contour above the actual mean high-tide level, as we saw at Salmon River. Essentially, Salmon River illustrates the worst-case scenario when using coast-wide LiDAR to define mean high tide.

Limitations of the 10-m DEMs that were relevant for modeling sea-level rise are associated with the presence of legacy conditions in delineated contour intervals, and the coarseness of the contour margins. These limitations combined to produce a low estimate of estuary perimeter, a variable we considered important when assessing habitat availability. At Salmon River estuary, we needed to refer to only one underlying topographic image for the estuary. For larger estuaries, more than one image may be needed. Not all the topographic maps are developed from aerial

photography taken at the same time. The historical provenance of each topographic image on the coast will be unique. Therefore, the 10-m DEMs represent landscape conditions at different times. Further, we wanted our modeling to reflect current conditions, not some unknown range of historic conditions. We considered the potential of coast-wide LiDAR to capture higher than mean high tide for the base contour to be less critical to the objective of this project than contours that capture legacy conditions and are insensitive to changes in the amount of edge habitat (estuary perimeter). With this conclusion, we chose to use the coast-wide LiDAR to model potential changes in SLR on salmon habitat.

Across-Estuary Comparisons

Our findings suggest that the effects of SLR on salmonid habitat will be mixed and will reflect local conditions unique to each estuary that we examined. In the Salmon River estuary, a focus of salt-marsh restoration for decades, SLR indicates a shorter estuarine perimeter. This narrow estuary has limited areas of floodplain. As the contour interval increases with potential SLR, the estuary begins to abut the edges of the surrounding valley. Complex marsh habitat, similar to the configuration of current complex tidal channels, may develop around the edges of the estuary. However, the narrow valley may constrain development of additional tidal marshes. Changes in sedimentation rates, and patterns of water circulation within the estuary due to SLR, are unknown and will strongly affect the configuration of marsh habitats that may develop into the future. This compares to the Elk River estuary, another small estuarine system, for which increased estuary area and perimeter with SLR project inundation of lowland areas. It appears that the lowland floodplain of the Elk River system may have been estuarine in the geologic past. Additional analysis of soil cores could elucidate the history of the Elk River floodplain. This system may offer the greatest potential for estuarine habitat to expand with sea-level rise. Elk River has high-gradient and constrained channels in the freshwater portion of the drainage. The system also supports fall Chinook: an expanded role of the estuary through development of more complex marsh habitats may offer an important restoration opportunity for native salmonids.

For most of the estuaries we studied (Alsea, Smith, Elk, and Chetco), habitat complexity (Fractal D) changed little, but estuarine edge habitat (perimeter) expanded. However, the Salmon River showed a decrease in edge habitat complexity (Fractal D) and the potential for a substantial decline in salt-water edge habitat (estuary perimeter). The decline in estuary perimeter is associated with the inundation of currently accessible distributary channels that

may provide important rearing and refuge habitat for juvenile salmonids (Bottom and others 2005a).

All the river systems in this study showed estuarine expansion with SLR into currently available freshwater habitat for all three species of salmon. While the amount of inundation of freshwater habitat was generally a small percentage of all available freshwater habitats, the freshwater at the estuary-freshwater ecotone is unique within the river network because of its location. This portion of the river network is the only place where salt-water transitions may occur for salmonids, and it may be disproportionately more important than the amount of stream length affected would indicate. It is possible that the movement of the estuary into freshwater may constitute an expansion of the estuary-freshwater ecotone for migrating fish. Further work that quantifies the salinity gradient in these important portions of the river network is needed to assess the potential effect on migrating and rearing salmonids of the upstream shift in the estuary mean high-tide contour interval.

A purely geomorphic approach, such as we used in this study, excludes many important processes that could influence models addressing potential effects of SLR. Including climate-induced changes to processes, such as sediment transport and vegetation succession, or human responses to climate change, such as hard-scaping with jetties or sea walls, will undoubtedly further refine approaches to predict the effect of SLR. Additionally, models of future human population growth and development in the Oregon Coastal Province should improve predictions of potential water movement within estuaries and into freshwater. Because we did not randomly select estuaries, and had a small sample size, we did not complete formal statistical tests to compare systems. However, we were able to utilize a newly available high-resolution technology to quickly assess potential effects of estuary inundation on multiple coastal estuaries.

Studies that assess the potential effect of sea-level rise on estuarine vegetation identify a variety of vegetative responses depending on estuarine characteristics and anthropogenic alterations of the estuary-upland margin (Callaway and others 1996; Craft and others 2009; Olff and others 1997). Future analysis that synthesizes potential changes in sedimentation rates, salinity, and vegetation may allow for a better quantification of changes in available estuary habitat for rearing salmonids. A larger sample of estuaries, evenly distributed across geomorphologies throughout the Pacific Northwest, would provide a robust data set for additional analysis. Our purpose in this work was to conduct initial analysis to examine whether sea-level rise would affect estuary habitats for salmon, and if so, then allow us to quickly raise this as a potential issue and one that might merit additional research.

Conclusions

The effect of SLR on ecosystem processes and current species assemblages in estuaries is an important element to consider in the wider effort to understand the effect of climate change on coastal riverscapes. Many estuaries have already been extensively modified for human uses, thereby reducing their capacity to maintain the variety of habitats most conducive to healthy salmonid populations (Koski 2009). Predicting the potential of estuaries to assimilate and respond to climate change is a critical element of planning efforts that seek to mitigate unwanted aspects of climate change (Gleason and others 2011; Glick and others 2007; Kennedy 1990). In our analysis, it appears that changes in estuarine and estuary-river ecotone habitat have potential to affect multiple salmonid species. Additional reductions in habitat and the associated decrease in capacity of estuaries to support life-history diversity, reduce the long-term survival potential of Pacific salmon. For salmon conservation and recovery programs (Bottom and others 2005a) to succeed, a focus on maintaining what remains of natural estuarine areas seems a prudent tactic. Increasing habitat diversity throughout river systems, including the estuary, bolsters the potential to maintain life-history diversity that will contribute to population resilience of salmonids into the future (Bisson and others 2009; Bottom and others 2009; Koski 2009; Simenstad and Cordell 2000).

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