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Estuarine response to river flow and sea-level rise under future climate change and human development

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ABSTRACT

Understanding the response of river flow and estuarine hydrodynamics to climate change, land-use/land-cover change (LULC), and sea-level rise is essential to managing water resources and stress on living organisms under these changing conditions. This paper presents a modeling study using a watershed hydrology model and an estuarine hydrodynamic model, in a one-way coupling, to investigate the estuarine hydrodynamic response to sea-level rise and change in river flow due to the effect of future climate and LULC changes in the Snohomish River estuary, Washington, USA. A set of hydrodynamic variables, including salinity intrusion points, average water depth, and salinity of the inundated area, were used to quantify the estuarine response to river flow and sea-level rise. Model results suggest that salinity intrusion points in the Snohomish River estuary and the average salinity of the inundated areas are a nonlinear function of river flow, although the average water depth in the inundated area is approximately linear with river flow. Future climate changes will shift salinity intrusion points further upstream under low flow conditions and further downstream under high flow conditions. In contrast, under the future LULC change scenario, the salinity intrusion point will shift downstream under both low and high flow conditions, compared to present conditions. The model results also suggest that the average water depth in the inundated areas increases linearly with sea-level rise but at a slower rate, and the average salinity in the inundated areas increases linearly with sea-level rise; however, the response of salinity intrusion points in the river to sea-level rise is strongly nonlinear.

1. Introduction

Increasing human population and global climate change are challenges common to coastal areas worldwide. Complex coastlines, tidal wetlands, soils, rivers, and climate support a rich array of life in marine waters, watersheds, and tributaries, and provide a prosperous and appealing home for millions of people. However, the integrity of the ecosystems and the livelihood of the human residents are threatened by the twin forces of climate change and human development. While climate change and increased human development will have direct effects on marine and freshwater organisms and habitats, strong impacts will also be felt on the fresh and marine waters that support the overall function and health of estuarine systems. Human development can be measured by the surrogate of land-use/land-cover (LULC) change. Understanding the response of river flow and estuarine hydrodynamics to future climate change, LULC change, and sea-level rise is essential to managing water resources and stress on living organisms under these changing conditions, particularly in basins where development pressures are highest. These management challenges depend on accurate estimates of the freshwater flow delivered from snowpack and precipitation, and its effect on the estuarine hydrodynamics and nearshore habitats.

The future integrity of the Snohomish River basin in US northwestern Washington State is of particular concern with respect to maintaining river flows for Pacific salmon. Salmon populations are under pressure from many aspects of climate change, including ocean acidification, changes in flow timing and retention in the river and lower estuary, changes in water temperature, and changes in food availability resulting from ecosystem alteration (Hare and Francis, 1995; Beamish and Mahnken, 2001; McDaniels et al. 2010). Future climate predictions and pressure from LULC changes are likely to add additional burdens that will further stress the fish.

Tidal circulation, mixing, and salinity intrusion in estuaries are complex processes based on the geometry of the estuary and the multiple forcing mechanisms that include river flows. This paper presents a modeling study that evaluates the hydrodynamic response of the estuary to expected changes in river flows, inferred

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from predictions of LULC change and climate change. With the addition of global changes in climate and specific atmospheric and oceanic changes that are magnified in the North Pacific, the Puget Sound region of the northwestern United States is under stress that threatens to degrade and destroy many features that make it a desirable home for humans and other organisms. Management of stormwater, coastal and river flooding, and nutrient stress on salmon have been defined as management priorities within the watersheds and estuaries of Puget Sound (PSP, 2010). We applied the modeling framework to the Snohomish River estuary in Puget Sound as a function of river flow under climate change, LULC change, and sea-level rise scenarios, using a high-resolution three-dimensional (3D) coastal ocean model for the Snohomish River estuary and its floodplain.

The immediate impacts of sea-level rise on the coastal zone are well known, including increased flooding of coastal wetlands and saltwater intrusion in the estuaries (Nicholls et al. 2007; Nicholls and Cazenave, 2010). Some studies have been conducted to investigate the impacts of sea-level rise and river flow on the estuarine hydrodynamics and salinity intrusion (French, 2008; Rice et al. 2012; Hong and Shen, 2012; Liu and Liu, 2014). However, estuarine response to river flow from the combined effects of climate change and LULC change receive less attention because LULC change is commonly considered a local problem (Osterkamp et al. 2001; Roberts et al. 2009; Estes et al. 2014). There are few studies of the impact of sea-level rise and river flow under climate change and LULC change scenarios on variables important to nearshore habitats and floodplains, such as water depth and salinity in intertidal wetlands during periods of inundation. In the study reported here, we examined the responses of salinity intrusion in a multi-branch estuary, and water depth and salinity in the intertidal zone, to sea-level rise and river flow as a result of climate change and LULC change, using a Distributed Hydrology-Soil-Vegetation Model (DHSVM; Wigmosta et al. 1994) and an unstructured-grid Finite Volume Community Ocean Model (FVCOM; Chen et al. 2003). A series of numerical experiments were carried out using the DHSVM to simulate a broad range of river flow conditions under different climate (historical and 2050) and LULC change (2002 and 2050) scenarios. Monthly statistics of river flow results from DHSVM simulations were used to drive the estuarine hydrodynamics model to simulate the flooding and salinity intrusion processes in the Snohomish River estuary, under current and future sea-level conditions. Salinity intrusion in all of the distributaries of Snohomish River estuary and the average water depth and salinity in the river floodplain and intertidal zone, were determined. The next section describes the Snohomish River estuary. Modeling approaches and data inputs used for the study are given in Section 3. Results/discussion and conclusions are provided in Sections 4 and 5, respectively.

2. Study site – Snohomish River estuary

The Snohomish River is located in the Whidbey Basin of Puget Sound, Washington, USA. The estuary connects to the Puget Sound Main Basin through Possession Sound in the west and the Saratoga Passage and Port Susan Bay in the north (Fig. 1). The Snohomish River is the second largest river in Puget Sound and accounts for about 30% of the freshwater discharge to Whidbey Basin. The long-term annual average river flow, measured at the U.S. Geological Survey (USGS) stream gage at the city of Monroe, is approximately 270 m^3/s. The flow of Snohomish River varies seasonally, with a recorded minimum monthly flow of 32 m^3/s and maximum monthly flow of 838 m^3/s, based on 50 years of stream records from 1963 to 2012.

The Snohomish River discharges into Possession Sound through several large distributaries, including Ebey Slough along the north side of Snohomish delta, Steamboat Slough and Union Slough through the middle of the delta, and the main stem river along the south side of the delta and Everett Peninsula (Fig. 1). These distributary sloughs provide important fish-rearing habitat for juvenile salmon before they migrate from the freshwater to the saltwater environment (Greene and Beechie, 2004; Scheuerell

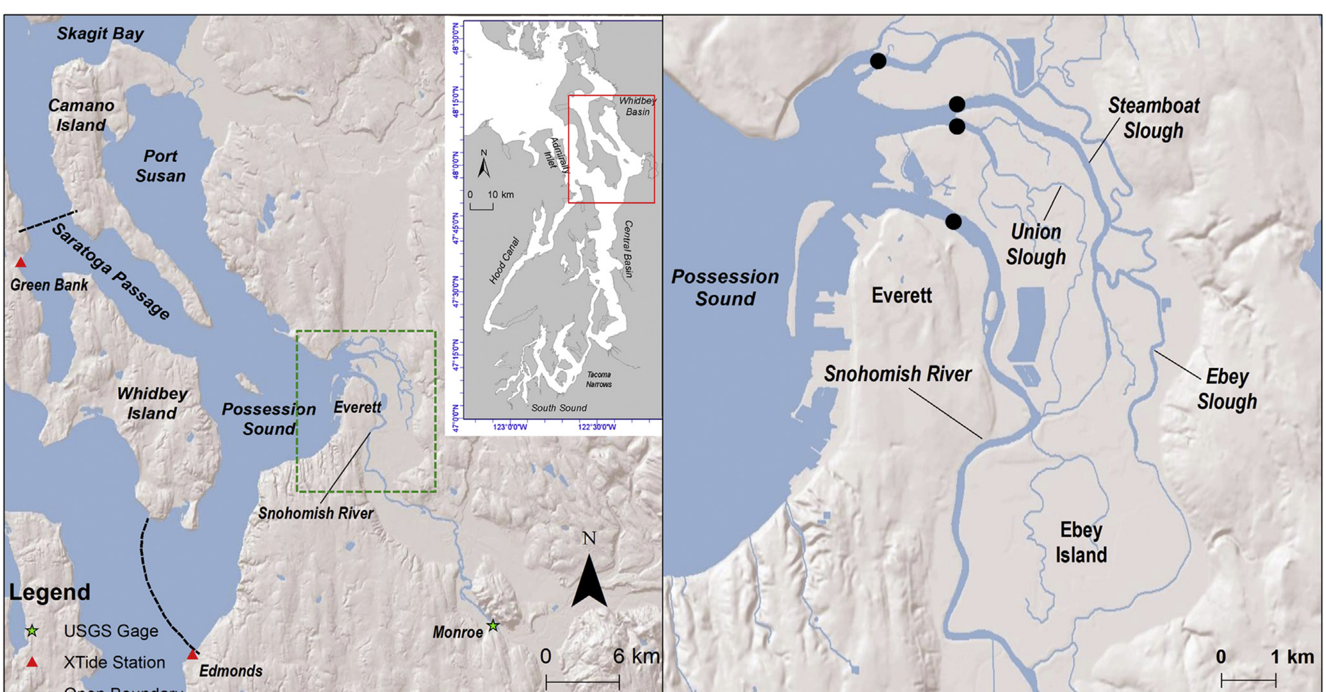

Fig. 1. Snohomish River estuary in Puget Sound (left) and detail of the distributary sloughs in the lower estuary at a larger scale (right). The black circles on the right-hand panel indicate the locations of the river mouths for the main stem, Union Slough, Steamboat Slough and Ebey Slough of the Snohomish River.