Introduction to the Skagit Issue—From Glaciers to Estuary: Assessing Climate Change Impacts on the Skagit River Basin

Authors: Rybczyk, John M., Hamlet, Alan F., MacIlroy, Carol, and Wasserman, Larry

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John M. Rybczyk,[1] Department of Environmental Science, Western Washington University, Bellingham Washington 98225

Alan F. Hamlet, Department of Civil and Environmental Engineering and Earth Sciences, 156 Fitzpatrick Hall, University of Notre Dame, Notre Dame, Indiana 46556

Carol MacIlroy, Carol MacIlroy Consulting Corporation, 3715 S Hudson St #102, Seattle, Washington 98118

Larry Wasserman, Swinomish Indian Tribal Community, Environmental Policy Director, 11404 Moorage Way, LaConner, Washington 98257

Introduction to the Skagit Issue

From Glaciers to Estuary: Assessing Climate Change Impacts on the Skagit River Basin

The Skagit River, which flows from its headwaters in British Columbia to Puget Sound in northwestern Washington State, contributes more than 30% of all freshwater entering the Sound (Figure 1). It is the largest river system in the Puget Sound basin and is a tremendous economic and ecological asset to the region, providing water for the largest agricultural center in Western Washington, habitat for many important fish and wildlife populations, regionally significant hydropower resources, water resources for cities and irrigation, and extensive outdoor recreational opportunities. The Skagit basin is home to all six salmon species present in the Sound, including steelhead and the most abundant remaining run of Chinook salmon, and the lower basin is also a haven for migratory waterfowl (Lee and Hamlet 2011).

Previous research has demonstrated that the Skagit basin is highly vulnerable to climate change, and warming temperatures and changes in precipitation are projected to strongly affect both human and natural systems via a large number of impact pathways (Hamlet et al. 2010, Lee and Hamlet 2011). The estimated 394 glaciers in the Skagit's eastern headwaters provide 6–12 % of the Skagit's summer flow, and these resources are rapidly being depleted by rising temperatures (Lee and Hamlet 2011). Although detailed modeling studies are in progress, impacts on glacial resources in the Skagit are expected to continue and intensify through the 21st century in response to continued warming. Projected decreases of interannual snowpack are likely to increase winter flows and decrease summer flows, affecting both aquatic ecosystems and human systems via hydropower production and water supply (Hamlet et al. 2010, Hamlet et al. 2013, Lee and Hamlet 2011). Hydrologic extremes (floods and low flows) in the Skagit and associated water temperature and sediment source and transport regimes are profoundly affected by climate via changes in temperature, precipitation, snow cover, and loss of glaciers (Hamlet et al. 2010, Hamlet et al. 2013, Tohver et al. 2014, Salathé et al. 2014). Projected changes in flow and water temperature regimes will have implications for aquatic ecosystems, and particularly for iconic cold-water fish species like salmon (Hamlet et al. 2010, Mantua et al. 2010). The Skagit estuary and other near-coastal areas in the basin are projected to be substantially affected both by changing fluvial processes (flow, sediment transport) and by sea level rise via expected increases in coastal flooding, coastal erosion, and wave damage (Mote et al. 2008, NRC 2012). Sea level rise and changing fluvial sediment transport regimes will affect the Skagit Delta (Lee and Hamlet 2011).

In 2009, through the instrumental efforts and support of the Swinomish Tribe, a group of physical and ecological scientists from federal, state, municipal, tribal, university and non-governmental organizations currently working in the Skagit River basin formed the Skagit Climate Science Consortium (SC^2) to study the integrated effects

[1]Author to whom correspondence should be addressed.
Email: john.rybczyk@wwu.edu

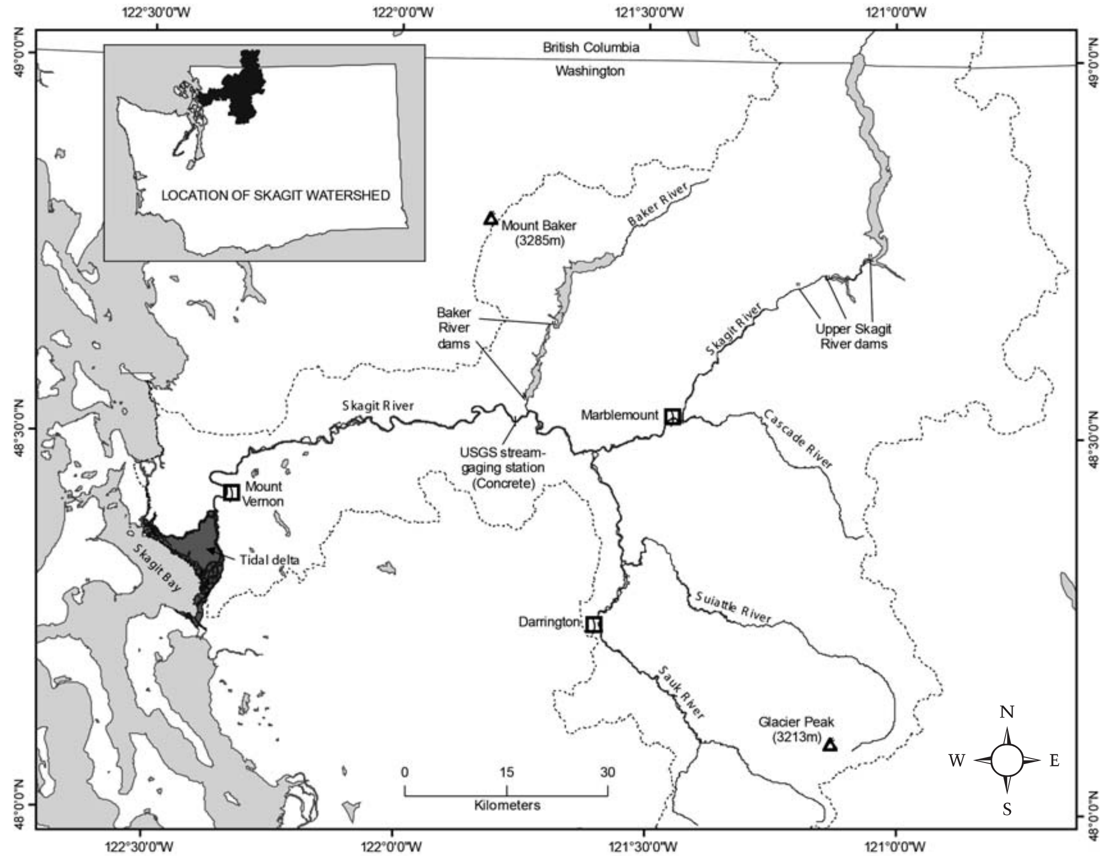

Figure 1. Map of the Skagit River watershed with major tributaries (from Greene et al., 2005).

of climate change (and other factors) on the Skagit watershed and understand how the landscape, plants, animals and people may be affected by changes in the patterns of temperature, precipitation, snow, ice, storms and tides (http://www.skagitclimatescience.org). The key objectives of the consortium are to:

- Foster collaborative, interdisciplinary research to understand and quantify the diverse impacts of climate change on the Skagit basin.
- Serve as an objective and non-politically affiliated source of scientific information, data, and services to support long-term planning and climate change adaptation by stakeholders in the basin.
- Identify new scientific products, data, or services that are needed to address climate change impacts in the basin, and generate research funding to address these needs.
- Establish and maintain long-term relationships between scientists and stakeholders in the basin in the interest of generating trust, fostering effective collaboration, and sharing information.

In the set of papers presented in this issue, authored or co-authored by SC^2 scientists, we present a system-wide approach to modeling and projecting the effects of climate change on the Skagit River watershed. In particular we examine the impacts of climate change on headwater processes in the basin (i.e., changes in glaciers and snowpack), stream flow generated in the main stem and its tributaries (i.e., seasonal patterns of stream discharge, flooding, extreme low flows), impacts to important human systems such as water supply, hydropower production and flood control and, ultimately, integrated impacts to the Skagit floodplain, estuary, and other near-coastal areas associated with both fluvial and marine processes.

Beginning at the Skagit watershed's highest reaches, Riedel and Larrabee (2016, this issue), document a 19% decrease in glacial area in the Skagit Basin since 1959 corresponding to a 24% decrease in the surface melt component to the Skagit River. The authors further note that this is of critical concern in that surface melt from the remaining glaciers provide 6–12% of the Skagit's total summer runoff, and roughly twice that fraction during the critical low flow months of August and September. These effects will likely have important implications for both headwater areas and the Skagit main stem. To further explore the effects of climate change on low flows, Stumbaugh and Hamlet (2016, this issue) use the Distributed Hydrology Soil Vegetation Model, forced by downscaled global climate models, to simulate the effects of projected climate change on low-flow conditions on specific lowland tributaries in the Skagit watershed. Lee et al. (2016, this issue) expanded integrated hydrologic modeling efforts to the entire basin and include human water management effects by coupling a new reservoir operations model to streamflow simulations from the VIC hydrologic model to simulate the projected effects of climate change on regulated extreme flows (high and low), hydropower production, and sediment discharge in the Skagit Basin. Hamman et al. (2016, this issue) extended this effort using projected increases in sea level rise and a suite of storm surge and hydrodynamic models to simulate the combined effects of climate change on flood inundation and extreme high water levels in the Skagit floodplain. The Skagit Climate Science Consortium turned this modeling effort into an interactive map (http://www.skagitclimatescience.org/flood-scenario-map/) for use by both the scientific community and stakeholders such as flood managers. At the coast, Hood et al. (2016, this issue) show that riverine sediment delivery to the coastal marshes of the Skagit delta may not be enough to counteract wave energy given predicted rates of sea level rise under a regime of global warming. Finally, Khangaonkar et al. (2016, this issue) use a finite volume coastal ocean model (FVCOM) to assess the effects of climate change (i.e., reduced summer flows and sea level rise) on estuarine circulation, salinity and turbidity distributions in the greater Skagit River estuary.

Although it is often difficult to rigorously distinguish between climate change and climate variability at regional scales, a growing body of evidence suggests that we have entered a new era of unprecedented warming. In March of 2015 (a year ago at the time of this writing), atmospheric carbon dioxide levels averaged 400 ppm for the first time since direct measurements began in the late 1950's. Global temperature anomalies over land have been overwhelmingly positive over the past 40 years. Water year 2015 in the Pacific Northwest exhibited warming and loss of mountain snowpack comparable to projections of climate for the mid-21st century. Glaciers in the North Cascades have lost 50% of their mass since the start of the 20th century. The average freezing elevation in the Skagit River basin has risen more than 180 meters since 1958, increasing the potential for destructive fall and winter flooding and decreasing potential water storage in the snowpack. Mean sea level at Friday Harbor has increased by 10 centimeters from 1934 to 2006 and is projected to increase by another 70 cm over the next 100 years.

It is the view of the Skagit Science Consortium that the assessment of climate change impacts in coastal watersheds is currently impeded by the lack of an appropriately integrated assessment framework and the development of integrated physical and ecological models that can generate the detailed products and services needed to support long-term planning and climate change adaptation. It is our hope that the efforts of the Skagit Climate Science Consortium and the resultant integrated studies will provide key inputs and impetus to a wide range of related investigations, including ecological studies in the Skagit estuary and delta, more detailed water quantity and quality investigations, and assessment of human impacts and development choices in the Skagit River floodplain, estuary, and near coastal environment. It is also the hope that the work of

SC^2 will inspire further investment in the critical research and data collection necessary, and raise awareness about the effort it takes to make this information available to an increasingly concerned public and the decision-makers who act on their behalf.

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