

SECTION 5

How Will Climate Change Affect Landslides, Erosion, and Sediment Transport?

The Puget Sound region is expected to experience increases in the frequency of landslides and the rate of erosion and sediment transport in winter and spring, primarily as a result of continued declines in snowpack and projected increases in the frequency and intensity of heavy rain events. In summer, these processes are expected to become less important in the future, due to diminishing streamflow and drier soils. Both natural climate variability and human modification to the landscape have a strong effect on landslide and sediment processes, and will continue to influence these processes in the future. While a lack of direct observations makes it challenging to make robust projections, communities in the Puget Sound region are preparing for changing landslide and sediment risk through targeted regulations, climate-informed design, and floodplain infrastructure aimed at mitigating anticipated impacts.

Climate Drivers of Change

DRIVERS *Climate change can alter landslides^{A,1} and sediment^{B,2} processes via increasing air temperatures, higher intensity and more frequent heavy rain events, decreasing summer precipitation, and sea level rise.^{3,4,5,6}* These effects vary with season and for different locations across the Puget Sound region,^C and are affected by non-climatic factors, such as changes in land use and land cover.

- *Observations show a clear warming trend, and all scenarios project continued warming during this century.* Most scenarios project that this warming will be outside of the range of historical variations by mid-century (see Section 2).^{7,8} Increasing air temperatures can facilitate soil breakdown, allow more water to

^A Landslides are used generally in this text to describe various types of mass movement of rock, earth and debris downslope, including debris flows, lahars, mudflows, rockslides, soil creep, shallow landslides, and deep-seated landslides.

^B Sediment is broadly defined as a collection of particles, loose or consolidated, including hillslope soils, clay, silt, sand, gravel, cobbles, and boulders. This report is focused on changes in both the rate of erosion and in the amount of sediment transported in rivers.²

^C Throughout this report, the term “Puget Sound” is used to describe the marine waters of Puget Sound and the Strait of Juan de Fuca, extending to its outlet near Neah Bay. The term “Puget Sound region” is used to describe the entire watershed, including all land areas that ultimately drain into the waters of Puget Sound (see “How to Read this Report”).

penetrate soils, reduce snow accumulation, and increase the risk of wildfire and other threats to forest health, all of which can affect the rates of erosion and sediment transport and the likelihood of landslides.

- *Heavy rain events are projected to become more intense.* Current research is consistent in projecting an increase in the frequency and intensity of heavy rain events.⁹ These changes could result in greater erosion, higher sediment transport in rivers and streams, and a higher likelihood of landslides, primarily as a result of higher soil water content.
- *Most models are consistent in projecting a substantial decline in summer precipitation.* Projected changes in other seasons and for annual precipitation are not consistent among models, and trends are generally much smaller than natural year-to-year variability.⁸ Declining precipitation in summer could result in decreased erosion, a reduced rate of sediment transport, and a lower probability of landslides.
- *Nearly all scenarios project a rise in sea level.* Sea level rise is projected for all locations except Neah Bay, where a decline in sea level cannot be ruled out due to the rapid rates of uplift in that area.^{10,11,12} Higher seas could limit the transport of sediment from rivers to Puget Sound and increase the rate of erosion in some coastal areas.
- *Although climate is a major driver of erosion, sediment transport, and landslide hazards, there are other factors that can have an important effect on these processes.* In particular, changes in land use and land cover – both due to development and forest management – can dramatically affect the likelihood of a landslide, the exposure of sediments to erosion, and the rate of streamflow and sediment transport.¹³

Mechanisms linking climate with landslides, erosion, and sediment transport.

Temperature. High temperatures contribute to slope instability by enhancing the thermal breakdown of rock,^{3,6,28} decreasing the viscosity of groundwater (i.e., more lubricating), and thawing frozen ground so more water infiltrates.^{29,30} Warm conditions can also cause increased evaporation, leading to drier soils and more stable conditions in deeper soils, especially in summer.^{6,31,32} Finally, warming can intensify the cycling between wet and dry periods, which may act to widen gaps in rock and soil, contributing to a decrease in slope stability.⁴

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Precipitation. Heavy rain events reduce slope stability by rapidly raising the water table (or groundwater elevation) and by enhancing water drainage through the soil to lower layers.⁶ In addition, intense rainfall can erode surface sediments, and higher streamflow during these events can transport more sediment downstream.⁴³ Different patterns of rainfall will affect which slopes might be destabilized, and where erosion and sediment transport are most important.^{44,45,46}

Soil Water Content. Wetter soils are heavier, can absorb less precipitation (thus increasing runoff), and have greater lubrication among soil layers. For example, analysis from the recent State-route 530 landslide (Oso, 2014) indicates that the initial conditions of the soil prior to the triggering event were an important contributor to the mobility and, as a result, the severity of the landslide.^{21,22}

Snowpack and Glaciers. Higher snowlines can lead to exposure of unconsolidated (erodible) sediment, more ground surface erosion, greater soil saturation, and higher streamflows.³ Retreating glaciers uncover loose, unvegetated sediment that is vulnerable to mobilization.^{3,40,41,42} Melting glaciers typically leave behind sediments that are then exposed to weather and erosion.³

Streamflow. Higher streamflow, which is common in winter, can erode stream banks and transport more sediment within the stream and along the stream bed. Low streamflow, which is common in summer, results in lower rates of sediment transport. In summer, the reduction in transport can increase sediment buildup within stream channels and reduce the capacity for floodwaters in subsequent events.²⁴

Vegetation. Vegetation loss from water stress, wildfire, insect attacks, or disease can lead to increased soil surface erosion and sediment transport to streams during rain events.^{25,26,27,33,34} Loss of vegetation from fire temporarily reduces the ability of soils to absorb moisture, increases surface runoff, and boosts sediment transport.³⁵ In addition, the root decay following fires can weaken slopes, especially one to three years after a fire.^{36,37,38,39}

Sea level rise. Sea level rise could trap sediment within rivers and exacerbate coastal erosion.¹⁴ Elevated sea level (for example, due to winter storm surge) could cause more sediment trapping within river and stream deltas by reducing stream velocities, which promotes sediment deposition and reduces the size of the river channel.^{15,16} Higher sea levels also allow wave energy to reach further inland, eroding unarmored^D shorelines and redistributing beach sediments.^{17,18,19,20}

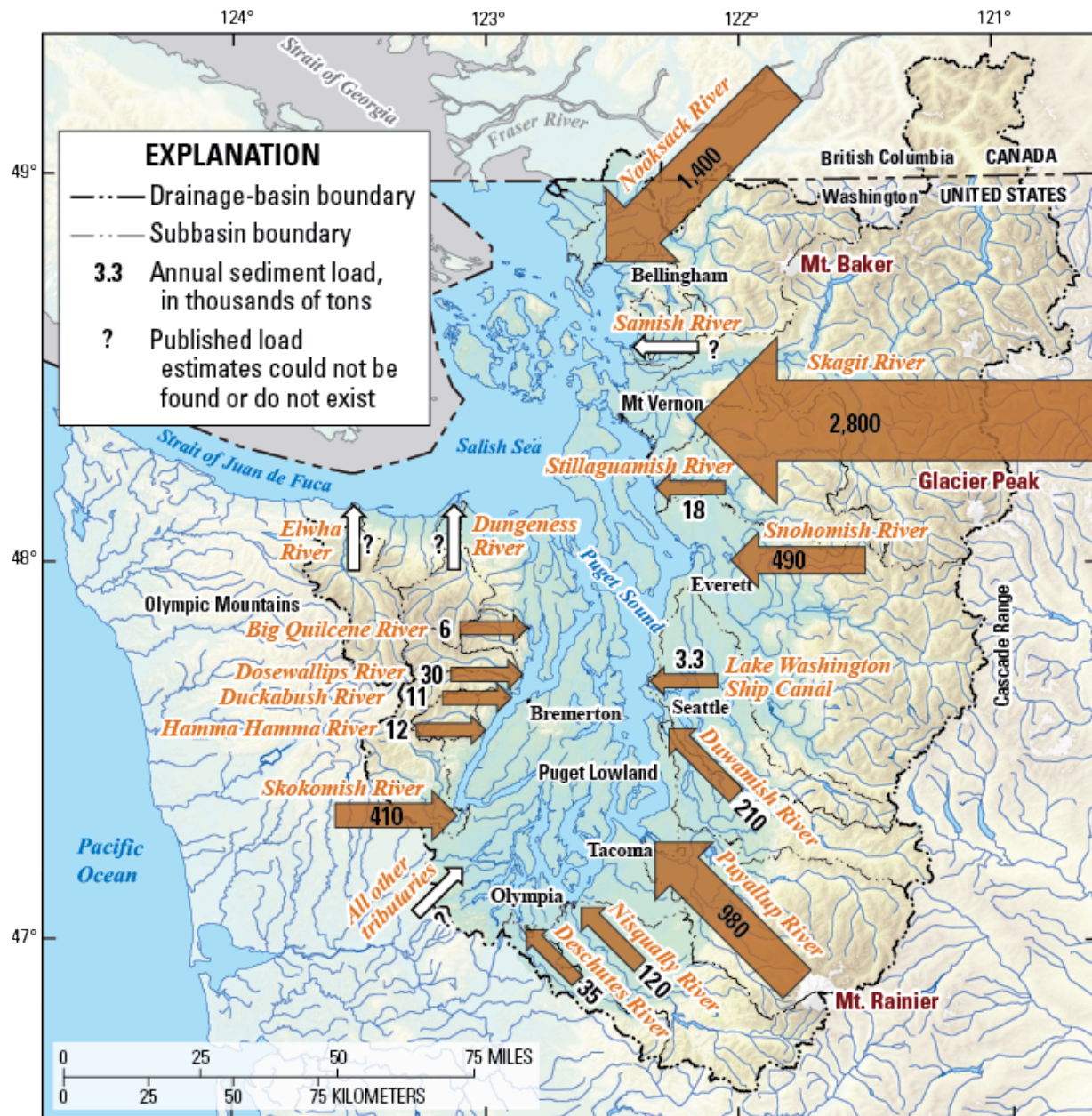


Figure 5-1. Puget Sound rivers contain massive quantities of sediment. Estimated annual sediment load (in thousands of tons) of major rivers draining into Puget Sound from measurements at or near the coast. The size of the arrow is scaled to the annual sediment load. Annually, an estimated 6.5 million tons of sediment is transported to Puget Sound; approximately 70% of the sediment is from rivers and the remaining is from shoreline erosion. *Figure Source: USGS; Czuba et al. 2011.⁴⁷*

^D Shoreline “armoring” refers to any engineered structure used to reduce the effects of coastal erosion.
http://www.psp.wa.gov/vitalsigns/shoreline_armoring.php

Observed Changes

OBSERVED *Few studies report trends in landslides and sediment processes, and even fewer have related these changes to climate.* However, some studies report climate-related increases in the vulnerability of land areas to erosion and landslides.⁸²

- *Earlier snowmelt, which allows water to infiltrate into soils earlier in spring, is making slopes less stable.* Modeling studies suggest that pre-conditioning of hillslopes to instability^E is occurring earlier than in the past. Specifically, model simulations indicate that the spring increase in soil water content is occurring earlier and April 1st soil water content is increasing in snow-influenced watersheds (1947-2003).⁸²
- *Rising river beds.* Rivers within Mount Rainier National Park have experienced aggradation (i.e., streambed rising) during the past two decades (1997-2006), indicating increasing sedimentation. Since they occur in a national park, these changes are unlikely to be a result of logging or other human development, although the increase has not been directly linked to climate drivers.^{48,49,50}
- *Higher sediment supply.* Sediment supply is greater than +1.5 times the natural rate in areas of the Skagit River basin.⁵¹ The greatest sediment load is in the lower Skagit. It is not known what proportion of this change is due to changes in climate drivers versus other human and natural processes (e.g., land development).
- *Increased sediment deposition in estuaries.* Sediment accumulation in the subtidal portions of many large Puget Sound river deltas has been extensive since the 1850s. The main factors influencing this change are most likely related to human alterations to river channels, floodplains, and other patterns of land-use.⁵²
- *Challenges in assessing trends.* There are three factors that make it difficult to interpret observed trends in landslides and sediment processes: (1) limits in the quantity and quality of observations (e.g., incomplete databases, imprecise dates), (2) the influence of non-climatic factors, including logging and development,^{53,54,55} the long timeframe of landscape changes, and the lag time between triggering events and slope or stream responses,^{4,41,56} and (3) the overall complexity of processes influencing the likelihood of landslides and the rates of erosion and sediment transport.^{6,57,58}

^E “Pre-conditioning” refers to factors that increase the chance of a slope failure (or landslide) given a triggering event, such as a rainstorm.

Projected Changes

PROJECTED *Climate change is expected to increase the likelihood of landslides in winter and early spring and decrease the likelihood in summer.* Although there are no published projections for changing landslide hazards in the Puget Sound region, changes in the climate drivers of landslides point to changes in the frequency and size of landslides. Landslide-prone areas are expected to become less stable in winter as more precipitation falls as rain rather than snow, temperatures rise, soil water content increases, and as heavy rainfall events become more intense.⁵⁹

- *In winter, landslide risk is expected to increase in response to declining snowpack.* Average spring snowpack in the Puget Sound region is projected to decline by –37 to –55% by the 2080s (2070-2099, relative to 1970-1999), on average, for a low and a high greenhouse gas scenario (see Section 3).^{F,G,H,60} Snow cover protects soils from raindrop erosion and can also absorb rain.⁶¹ Projected losses in mountain snowpack will reduce the protective effect of snow and frozen ground and lead to increased soil water content, both of which could increase the probability of landslides and the rate of sediment input into streams during winter.
- *In summer, landslide risk is expected to decrease as a result of declining streamflow and soil water content.* For the 12 major Puget Sound watersheds analyzed,^I the spring peak in streamflow is projected to occur two to six weeks earlier, on average, by the 2080s (2070-2099, relative to 1970-1999, see Section 3).^{J,K,60} Earlier snowmelt could lead to decreased soil water and an increase in slope stability. Sediment transport will also likely decrease as runoff from snowmelt declines, although glacier meltwater may temporarily offset this effect in glacier-fed streams (Figure 5-2).

^F Greenhouse gas scenarios were developed by climate modeling centers for use in modeling global and regional climate impacts. These are described in the text as follows: "very low" refers to the RCP 2.6 scenario; "low" refers to RCP 4.5 or SRES B1; "moderate" refers to RCP 6.0 or SRES A1B; and "high" refers to RCP 8.5, SRES A2, or SRES A1FI – descriptors are based on cumulative emissions by 2100 for each scenario. See Section 1 for more details.

^G These numbers indicate changes in April 1st Snow Water Equivalent (SWE). SWE is a measure of the total amount of water contained in the snowpack. April 1st is the approximate current timing of peak annual snowpack in the mountains of the Northwest. Changes are only calculated for locations that regularly accumulate snow (historical April 1st SWE of at least 10 mm, or about 0.4 inch, on average).

^H Projected change for ten global climate models, averaged over the Puget Sound region. Range spans from a low (B1) to a moderate (A1B) greenhouse gas scenario.

^I Projected changes in streamflow were calculated for 12 Puget Sound watersheds. Listed in clock-wise order, starting at the US-Canadian border, they are: the Nooksack R. at Ferndale (USGS #12213100), Samish R. Nr. Burlington (USGS #12201500), Skagit R. Nr. Mt Vernon (USGS #12200500), Stillaguamish R. (Flows were obtained for the NF Stillaguamish R. Nr. Arlington, USGS #12167000, then scaled to the river mouth based on the ratio of basin area and total precipitation), Snohomish R. at Snohomish (USGS #12155500), Cedar R. at Renton (USGS #12119000), Green R. at Tukwila (USGS #12113350), Nisqually R. at McKenna (USGS #12089500), Puyallup R. at Puyallup (USGS #12101500), Skokomish R. Nr. Potlach (USGS #12061500), Dungeness R. at Dungeness (USGS #12049000), and Elwha R. at McDonald Bridge Nr. Port Angeles (USGS #12045500).

^J Calculations are based on the change in streamflow "Center Timing" (CT). CT is defined as the day of the water year (starting on October 1st) when cumulative streamflow reaches half of its total annual volume.

^K Projected change for ten global climate models for a moderate (A1B) greenhouse gas scenario.

- *Winter soil water content, an indicator of landslide hazard, is projected to increase.* December 1st soil moisture, used as an indicator of landslide risk, is projected to increase up to +35% in the 2040s (2030-2059) relative to 1970-1999 along the slopes of the Cascade Mountains.^{K,62}
- *Heavy rainfall events, which can trigger landslides, are expected to become more intense.* Global models project that the heaviest 24-hour rain events in the Pacific Northwest will intensify by +19%, on average, by the 2080s (2070-2099, relative to 1970-1999, see Section 2).^{L,63} Combined with the projected increase in winter soil water content, the projected increase in heavy rain events is expected to result in more frequent landslides.^{60,64,65}
- *“Rain-on-snow” events^M are expected to become less frequent.* Landslides in the Puget Sound region are often triggered by rain-on-snow events.^{66,67,68} Although little research has specifically evaluated projected future changes in these events, increasing air temperatures are likely to result in less frequent rain-on-snow events as winter snowpack and the length of the snow season decreases.^{27,69}
- *Modeling studies confirm that projected changes in precipitation and air temperature will increase landslide hazards in winter.* Although there are no published estimates of landslide hazard for the Puget Sound region, one study projected a +7% to +11% increase in areas with high landslide susceptibility^N for the Queets Basin (west slope of Olympic Peninsula),^O by 2045 relative to 1970-1999.^{P,70}

PROJECTED *Climate change is projected to lead to increased rates of erosion and sediment transport in winter and spring and lead to a decrease in summer.* Along the coast, sea level rise is expected to increase the rate of erosion for unprotected beaches and bluffs.

- *As heavy rain events become more intense, the rates of both erosion and sediment transport are expected to increase.* More intense rainfall (see above) can erode

^L Based on an analysis of 5 global climate model projections and a high greenhouse gas scenario (RCP 8.5).

^M “Rain-on-snow” events are warm rainfall events that occur in winter, after some amount of snow accumulation. During these warm events, rain falling on snow triggers rapid snowmelt, thereby increasing soil water content and streamflow.

^N This study categorized landslide susceptibility by using a set of weights calculated by Van Westen (1997) for specific landslide controlling factors (e.g., slope, land cover, elevation). Weights receive negative values when landslide susceptibility is low, and positive values when susceptibility is high. A landslide susceptibility map was developed by summing the weights over each pixel of the Basin. The range of susceptibility values for the Queets Basin spanned -3.24 to 2.21, and was divided into three susceptibility classes using thresholds of 33% and 67% of the cumulative susceptibility. This resulted in three susceptibility classes: low (<0.05), medium (0.06 to 0.79), and high (>0.79).

^O Many characteristics of Puget Sound’s climate and climate vulnerabilities are similar to those of the broader Pacific Northwest region. Results for Puget Sound are expected to generally align with those for western Oregon and Washington, and in some instances the greater Pacific Northwest, with potential for some variation at any specific location.

^P Estimates were obtained using the Distributed Hydrology Soil Vegetation Model (DHSVM) with a landslide (“mass wasting”) algorithm. Projections were obtained from two global climate models (CGCM_3.1t47 and CNRM-CM3), each based on a low (B1) and a moderate (A1B) greenhouse gas scenario, respectively.

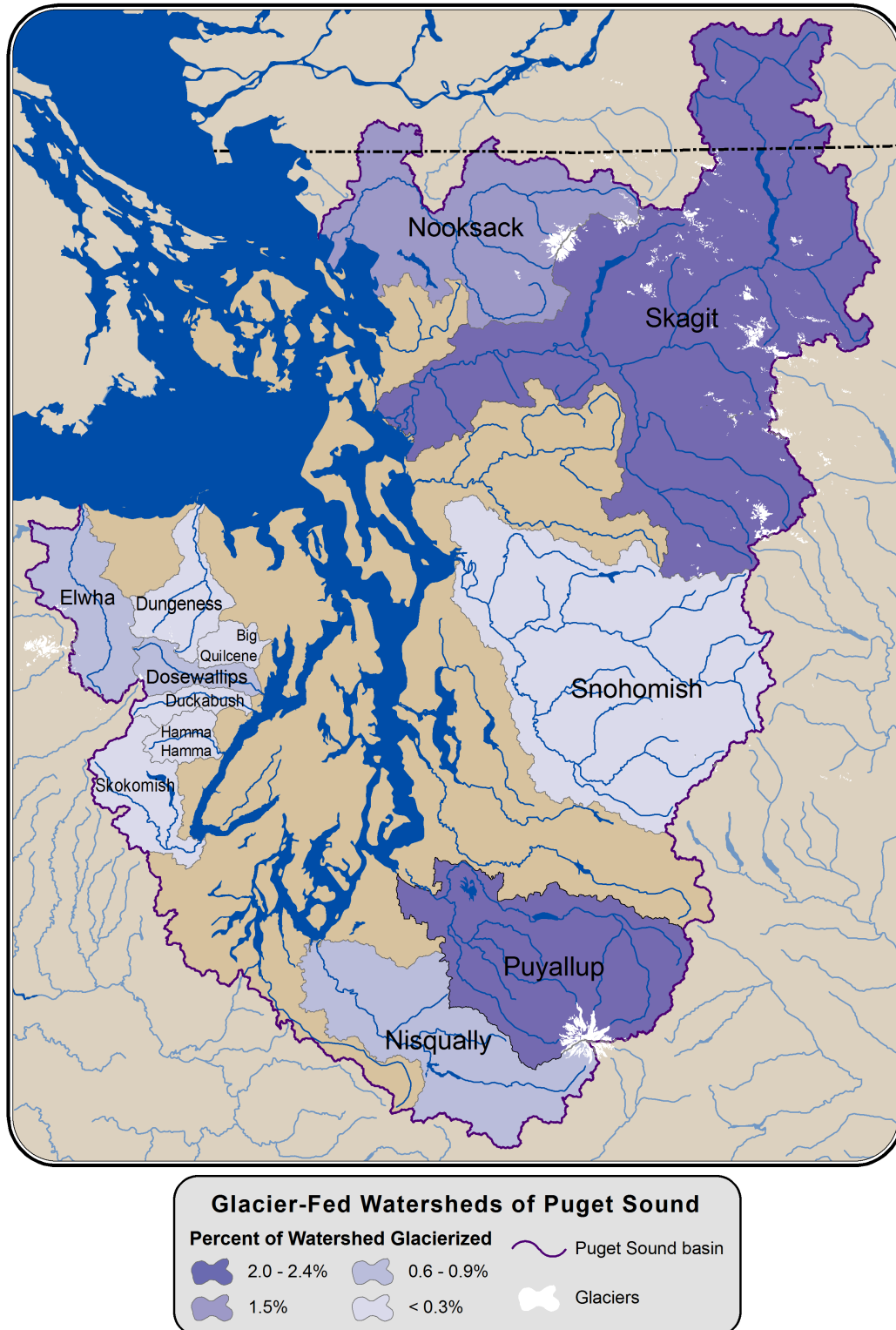


Figure 5-2. Glacially-influenced watersheds in the Puget Sound region. This map indicates Puget Sound watersheds with streamflow originating from glacier meltwater. Purple shading indicates the percentage of the watershed area covered by glacier, ranging from <0.3% to 2.4%. *Figure Source: Robert Norheim, Climate Impacts Group.*

surface sediments, contributing more sediment to streams.³⁴ Higher streamflow during these events can transport more sediment downstream.^{40,71} Peak river flows in 12 Puget Sound watersheds are projected to increase by +18% to +55%, on average, by the 2080s (2070-2099, relative to 1970-1999), based on a moderate greenhouse gas scenario.^{I,K,60}

- *Suspended sediments in the Skagit River are projected to increase substantially in winter.* The amount of sediment transported downstream past Mt. Vernon is projected to be nearly five times larger, on average in winter (+380%, range: +140 to +730%) for the 2080s (2070-2099, relative to 1970-1999) and a moderate (A1B) greenhouse gas scenario. Annual sediment transport is projected to more than double (+149%, on average) by the 2080s.^{Q,72}
- *Sediments resulting from glacier melt will likely increase in the near future.* Glacier retreat is expected to initially cause an increase in sediment loads, as retreating ice uncovers new soil and meltwater increases. Over time, fine sediments carried by glacier meltwater will decrease as glaciers decline in mass and disappear, although other processes may continue to erode glacier sediment deposits thereafter.⁴⁰
- *Shifts in vegetation and increased wildfire risk (see Section 9) could lead to more soil erosion and sediment transport.*³⁶ Vegetation changes and wildfires can reduce root reinforcement leading to increased landslide activity and greater erosion, increasing sediment supply to rivers.⁷³
- *Unprotected coastal bluffs are projected to erode more rapidly.* Over one quarter of Puget Sound's shorelines are armored.^D Increased erosion is expected to affect many of the remaining coastal areas as sea level rises, although the effects depend on the geology and exposure of each location. Coastal bluffs are projected to be particularly sensitive. One study projects that coastal bluffs in San Juan County will recede by – 75 to –100 ft. by 2100 (relative to 2000).^{R,74} This corresponds to a doubling, on average, of the current rate of recession. Another study projected that bluff erosion rates will increase by up to +4 inches per year by 2050 (relative to 2000).^{S,75} As waters rise and cover more land, this additional erosion is expected to cause the shoreline to migrate inland in some places.^{76,77}

^Q Results are based on an integrated daily time step reservoir operations model built for the Skagit River Basin. The model simulated current operating policies for historical streamflow conditions and for projected flow for the 2040s and 2080s associated with five global climate model simulations. Sediment loading was estimated based on an empirical relationship between suspended sediment loading and flow rate.

^R Projections are based on an empirical model that assumes that the equilibrium rate of shoreline erosion is proportional to the rate of sea level rise. Projections are based on the NRC (2012) report and a moderate (A1B) and high (A1FI) greenhouse gas scenario.

^S Projection is based on an empirical model of bluff erosion, based on a high (A1FI) scenario of sea level rise.

- *It is not known if the sediment supply to Puget Sound will increase or decrease.* In the Strait of Juan de Fuca, sediments are typically transported out of estuaries. In Puget Sound, sediment is most often deposited in river deltas.^{47,78} Rising sea levels could cause even more sediment to be deposited within Puget Sound estuaries.⁷⁸ Given the combination of increased erosion for coastal bluffs and increased deposition in estuaries, it is not known if the net effect will be an increase or a decrease in coastal land area.

PROJECTED Year-to-year and decade-to-decade variability in the region's climate influences landslide and sediment.⁷⁹ This climate variability is expected to continue into the future (see Section 2). Soil water content, vegetation composition, erosion rates, and sea level can all be directly influenced by longer-term (up to several decades) climate variability driven by El Niño/La Niña and the Pacific Decadal Oscillation (PDO; see Section 2).^{80,81,82}

Climate Risk Reduction Efforts

CLIMATE RISK REDUCTION Puget Sound communities, government agencies, and organizations are preparing for the effects of climate change on erosion, sediment transport, and landslide hazards. Many communities have a long history of actively managing historical sediment and landslide patterns. Several communities have begun to assess the impacts of climate change, and a few are implementing adaptive responses geared towards sediment management. No adaptation efforts have been identified that address changing landslide hazards in the Puget Sound region.

- *New regulatory guidance on shoreline erosion.* Washington State Department of Ecology provides guidance to local government jurisdictions on addressing sea level rise along shorelines in Appendix A of their Shoreline Master Program Handbook.⁸³ The guidance includes: anticipated sea level rise and sediment impacts; coastal landform inventory and vulnerability; public participation, access, and use; shoreline environmental designations, modification, and restoration policies, and some specific jurisdictional examples.
- *Redesigning the Anacortes Water Treatment Plant.* Climate change projections for increased flooding and sediment loading in the Skagit River led to design changes for the City of Anacortes' new \$65 million water treatment plant, including more effective sediment removal processes.⁸⁴
- *Lower White River Countyline Levee Setback project.* In order to accommodate sediment, increase flood-conveyance capacity, and alleviate flooding, King and Pierce counties are planning to build a setback levee in spring 2016 along the White River that is designed to accommodate a 10% increase in sediment delivery in the future.⁸⁵

Additional Context on Landslide and Sediment Processes

Landslides and sediment processes are governed by climate, geology, soils, land cover, land use, topography, and streamflow.

- **Landslides** are ubiquitous in mountain and hilly environments, which are found in the Puget Sound region from the slopes of the Cascade Mountains to the coastal bluffs.⁸⁶
- **Timing:** Most landslides in the Seattle area have occurred between November and April, with the highest percentage occurring in January (45%).^{87,88,89,90,91}
- **Climate:** Precipitation, both prolonged and intense, is the most common trigger of landslides.^{92,93} Storms have triggered a significant numbers of landslides in the Puget Sound region over the past century⁹⁴ (1933, 1972, 1986, 1990, 1996, 1997, 1998, 2003, 2006, 2009, 2011, 2012, and 2014).^{29,19,95,96,97,98,99,100,101,102} In Seattle, rainfall in excess of 1.6 in (40 mm) in 24 hours is typically sufficient to cause landslides when prior soil wetness is high.^{87,89} Approximately 85% of precipitation-related landslides have occurred on days when maximum air temperature was between 46° and 56°F.²⁹
- **Geology:** In the Puget Sound region, ice age glaciers and volcanoes have created a terrain with varying slopes, strength, layering (or “stratigraphy”), permeability, and depth – these factors all create regional diversity in vulnerability to landslides and erosion.^{30,103}
- **Topography:** The Puget Sound region is characterized by steep, narrow watersheds that rapidly convey runoff through watersheds to lower elevations and the coast.
- **Land cover and use:** Vegetation cover and human modifications to the landscape – including development, logging, and other factors – affect landslide hazard and sediment transport by modifying soil properties and the way water is absorbed and conveyed.^{104,105,106}
- **Sediment Supply:** Rivers flowing into Puget Sound receive sediment from (1) shallow landsliding and debris flows into tributary streams, (2) sediment transport within tributary streams, (3) erosion of debris-flows fans and streambanks, (4) soil creep and erosion of adjacent hillsides, (5) landslides from hollows adjacent to the river, (6) volcanism and lahars (i.e., mudflows), (7) glaciers, (8) weathering, and (9) land use practices.^{47,107} Landslides are the dominant source of sediment to Puget Sound rivers.^{53,57} Puget Sound receives sediment from streams and rivers as well as erosion of coastal bluffs.¹⁰⁸

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- **Sediment Pulses:** Sediment inputs often arrive in pulses from landslides triggered by precipitation or ground disturbance (e.g., fire, earthquake, logging).³⁴
- **Transport:** Sediment is carried by streams and rivers as suspended or “wash load” within the water column or as “bedload,” moving along the bottom of the water channel.¹⁰⁹ Watersheds transport different amounts of sediment depending on the watershed climate, geology, tectonics, human development, volcanism, glaciers, and river channel slope (Fig. 5-1).⁴⁷ On the coast, sediment moves in and out of river deltas and also along the shoreline, driven by currents, tides, and waves.⁸¹

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