

Skagit River Basin Climate Science Report

Executive Summary

Chapter 1. Skagit Basin Overview

The Skagit River basin in the northwestern Cascades extends from headwaters in southwestern British Columbia to the mouth of the river in the Puget Sound lowlands. The basin drains an area of about 3,115 square miles. There are three major tributaries to the Skagit River: the Sauk, Cascade and Baker Rivers. The Sauk and Cascade Rivers are largely undeveloped. Native American tribes have inhabited the basin for millennia, however since European-American settlement began in the mid-19th century, the Skagit River basin has been extensively altered by human activities such as logging and conversion of floodplain areas for agriculture and urban development (Figure ES.1). These activities continued through the early 20th century, resulting in the Skagit Valley including some of the richest farmland in the world as well as a number of small cities. In the second half of the 20th century, and particularly since the completion of Interstate-5 in the mid-1960s, urban/suburban development in the Puget Sound lowlands has led to continuing development in the basin. Figure ES.1 shows an aerial view of the extensive development in the lower basin. The construction of dikes, levees, and tide gates protect farm land and small cities such as Mount Vernon, Burlington, and Sedro Woolley from flooding, but failures often occur during a current 30-year flood event. Thus flooding and floodplain management are major issues in the basin. Five major dams were constructed in the Upper Skagit River and the Baker River in the 20th century. These projects generate hydropower and provide flood control, recreation opportunities, and diverse ecosystem services. Human development in the basin has created a strong local economy, but has also dramatically impacted the hydrology of the basin as a whole, the geomorphology of the Skagit Valley, and ecosystems, primarily in the lower basin. Headwater areas of the basin, although they have been logged and developed for water resources management in the past are relatively pristine, and provide many ecosystem services and recreation opportunities which also support the local economy.



Figure ES.1 An aerial view of the extensive development in the lower Skagit River basin.

Chapter 2. Climate Variability

The decade-to-decade and year-to-year variability of climate and hydrology in the Pacific Northwest (PNW) and the Skagit River basin is strongly influenced by the El Niño-Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO). Warm phases of the PDO and ENSO generally produce warmer and drier winter/spring weather while cool phases of the PDO and ENSO produce cooler and wetter conditions. These variations in temperature and precipitation influence important hydrologic variables such as April 1 snow water equivalent (SWE), annual and seasonal streamflow, and hydrologic extremes (floods and low flows). For example, warm phases of the PDO and ENSO produce lower April 1 SWE and summer streamflows than cool phases of the PDO and ENSO (Figure ES.2). Flood risks are higher in cool ENSO years than in warm ENSO years. Variations in air temperature associated with the PDO and ENSO have also affected water temperature for the Skagit River basin. The patterns of climate variability and associated hydrologic variables and extremes are intensified when the PDO and ENSO are in phase (i.e. warm ENSO/warm PDO or cool ENSO/cool PDO). The

impacts of the PDO and ENSO on climatological and hydrological variables in the Skagit River basin are consistent with those experienced over the PNW as a whole, but because the hydrologic cycle in the Skagit is sensitive to temperature variations, the PDO and ENSO have a more pronounced influence on hydrologic variables such as snowpack and seasonal streamflow timing for the Skagit River in comparison with the region as a whole.

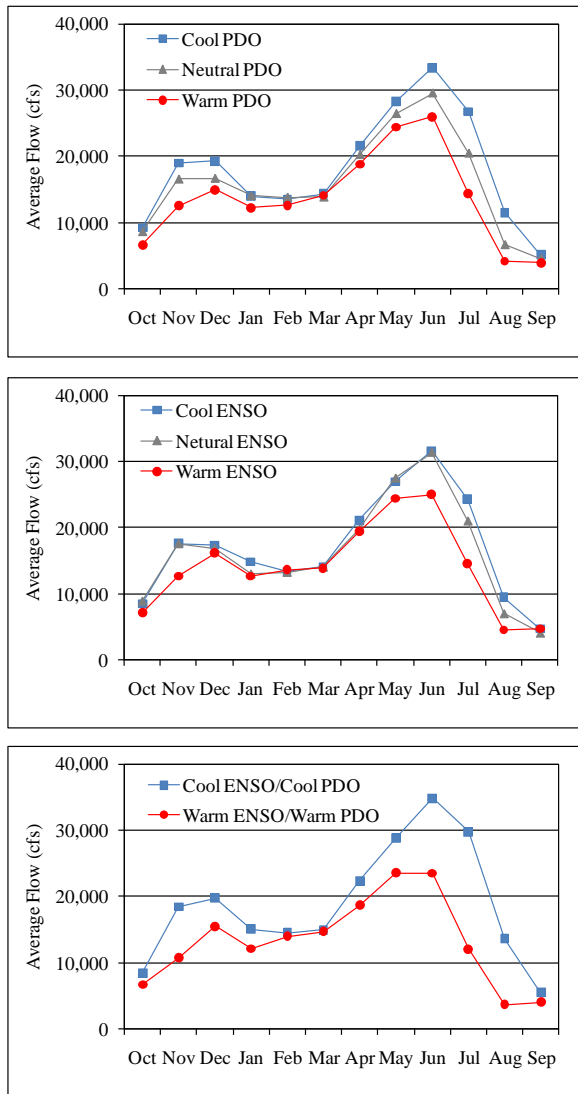


Figure ES.2 Composite monthly average simulated streamflow for the Skagit River near Mount Vernon (water years 1916 -2006) for the PDO phases based on the PDO index (top), ENSO phases based on Dec-Feb averaged Nino3.4 Index (middle) and the PDO and ENSO in phase (bottom) (see Chapter 2).

Chapter 3. Climate Change Scenarios

Human caused climate change is projected to substantially influence the climate of the PNW and Skagit basin in the 21st century. Based on currently available climate change scenarios from the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report downscaled to the PNW, average temperatures for the PNW by the 2080s for the B1 and A1B emissions scenario are projected to be 4.7 - 7.0 °F warmer than a late 20th century baseline (see Figure ES.3). These changes are very large in comparison with year to year natural variability. Even by the mid-21st century, projected 5th percentile temperatures are larger than the 95th percentile temperatures for the 20th century baseline as shown in Figure ES.3. A smaller increase in temperature is expected for the Skagit basin in comparison with the PNW as a whole, partly because of the Skagit's proximity to the coast. For example, the temperature increase for the Skagit basin by the end of the 21st century is about 4.0 °F for B1 and 5.8 °F for A1B in comparison to historical average temperature (see Table ES.1).

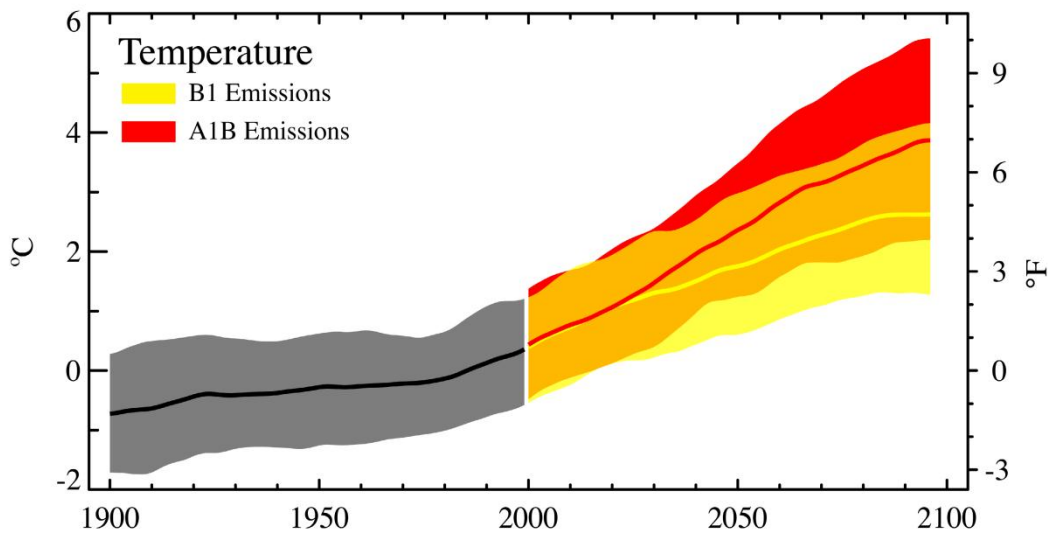


Figure ES.3 Summary of 20th and 21st century annual average temperature simulations from 20 GCMs over the PNW, relative to the 1970-99 mean, for two greenhouse gas emissions scenarios. Solid lines show the mean. The grey bands show the range (5th to 95th percentile) for the historical simulations, the colored bands show the range of future projections for each emissions scenario (Source: Mote and Salathé, 2010, see Chapter 3).

Table ES.1 Summaries of the 20th and 21st century annual and seasonal mean temperatures (in °F) for the A1B and B1 scenarios for the entire Skagit River basin upstream of Mount Vernon. (DJF=winter, MAM=spring, JJA=summer, and SON=fall, see Chapter 3).

Scenarios	Annual	DJF	MAM	JJA	SON
Historical	40.8	28.3	38.4	54.6	41.9
2020 A1B	42.6	29.9	40.0	57.0	43.4
2020 B1	42.5	29.8	40.0	56.6	43.4
2040 A1B	44.1	31.0	41.0	59.1	45.2
2040 B1	43.2	30.5	40.4	57.8	44.2
2080 A1B	46.6	32.9	43.4	62.3	47.7
2080 B1	44.8	31.7	41.9	59.6	45.8

By comparison, projected systematic changes in annual mean precipitation are relatively small in comparison with natural variability from year to year, and will therefore be difficult to detect in observations (see Figure ES.4). Projected seasonal changes in precipitation are substantial, however. By the end of the 21st century, for example, average precipitation changes for the Skagit River basin are projected to increase by 9.8 % in winter, 8.0 % in spring and 19.2 % in fall but decrease by 27.6 % in summer (see Table ES.2). As discussed in subsequent sections, these projected changes in climate have major implications for long-term planning in the basin.

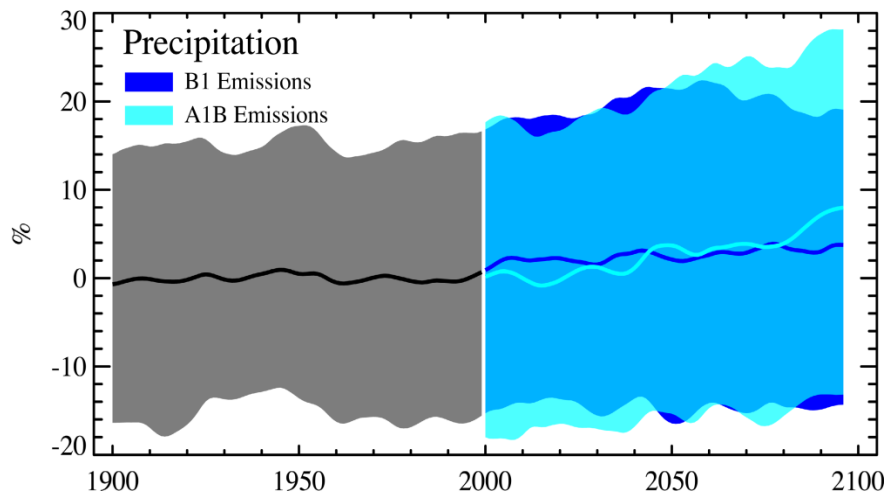


Figure ES.4 Summary of 20th and 21st century annual precipitation simulations from 20 GCMs for the PNW, relative to the 1970-99 mean, for two greenhouse gas emissions scenarios. Solid lines show the mean. The grey bands show the range (5th to 95th percentile) for the historical simulations and the colored bands show the range of future projections for each emissions scenario (Source: Mote and Salathé, 2010, see Chapter 3).

Table ES.2 Summaries of 20th and 21st century annual and seasonal precipitation (in inches) for A1B and B1 scenarios for the entire Skagit River basin upstream of Mount Vernon. (DJF=winter, MAM=spring, JJA=summer, and SON=fall, see Chapter 3).

Scenarios	Annual	DJF	MAM	JJA	SON
Historical	91.8	38.9	18.5	7.3	27.2
2020 A1B	95.2	40.9	18.9	6.0	29.4
2020 B1	94.8	39.6	19.3	6.8	29.2
2040 A1B	97.4	41.5	19.6	5.8	30.5
2040 B1	95.3	40.0	19.3	6.2	29.7
2080 A1B	100.3	42.7	19.9	5.3	32.4
2080 B1	99.0	42.2	19.4	5.8	31.6

Sea level rise is also an important concern for the Skagit River basin because the majority of human development is located in low-lying areas near sea level. Global sea level has risen through the 20th century and is currently rising at an increasing rate, though sea level at local to regional scales can differ substantially from global changes over the short-term due to normal short-term fluctuations in global circulation patterns (e.g. changes in wind patterns). Sea level is projected to increase substantially by the end of the 21st century; global sea level rise projections reported by the IPCC’s Fourth Assessment Report are between 18 and 38 cm (7.1 and 15.0 inches) for the lowest emissions scenario (B1) and between 26 to 59 cm (10.2 and 23.2 inches) for the highest emissions scenario (A1FI). The science behind sea level rise projections is progressing rapidly, and more recent global studies suggest much higher rates of sea level rise. For example, more recent projections from published studies suggest that global sea level is likely to rise by as much as 59 cm (23.2 inches), and could be as high as 179 cm (5.87 ft), by 2100 for the highest emissions scenario (A1FI) (see Figure ES.5). Projection of local sea level rise is affected by multiple factors such as atmospheric circulation and vertical land movement. For Puget Sound, sea level rise (SLR) by 2100 (based on the earlier IPCC projections) is estimated to range from about 16 cm (6 inches) for the B1 emissions scenario, to as much as 128cm (50 inches) for A1FI emissions scenario. Vertical land motion is also believed to be a significant factor contributing to relative sea level rise in the near coastal environment of Puget

Sound such as the low-lying areas of the Skagit basin, but more detailed monitoring is needed to more accurately estimate the importance of these changes. No detailed estimates of relative SLR for the Skagit lowlands are currently available, for example.

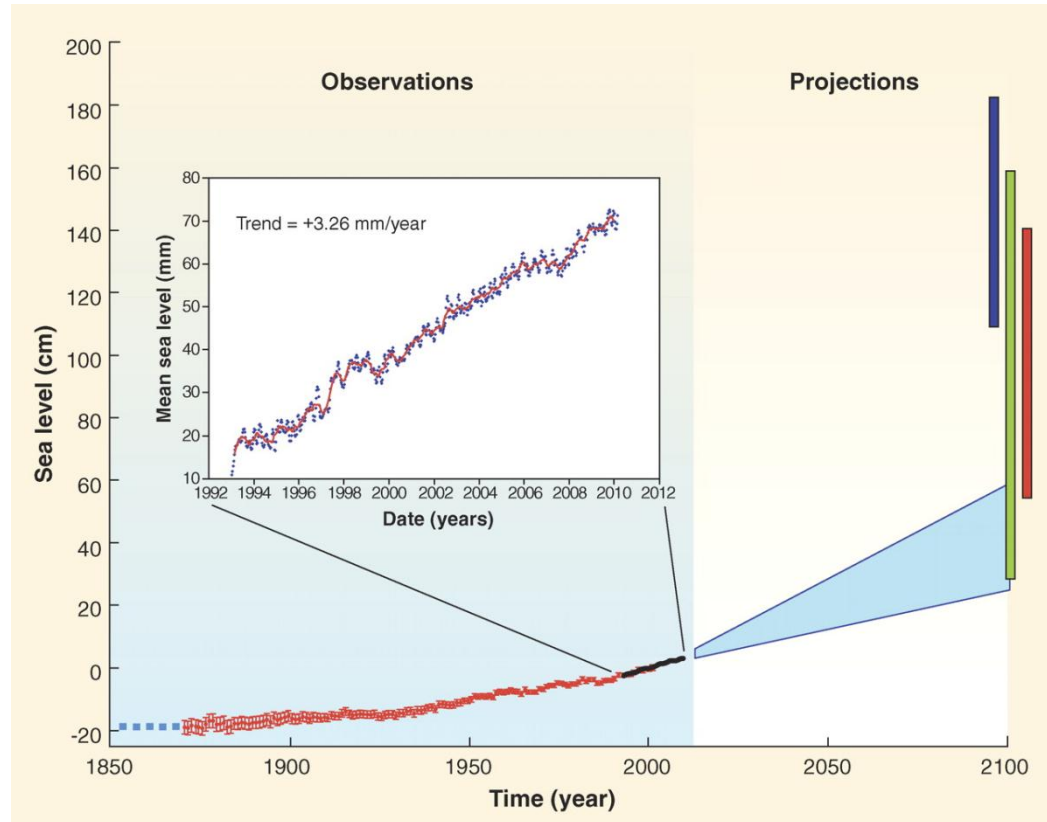


Figure ES.5 Global mean sea level evolution over the 20th and 21st centuries. The red curve is based on tide gauge measurements. The black curve is the altimetry record (zoomed over the 1993–2009 time span). Projections for the 21st century are also shown. The shaded light blue zone represents IPCC AR4 projections for the A1FI greenhouse gas emissions scenario. Bars are semi-empirical projections [red bar: (Rahmstorf, 2007); dark blue bar: (Vermeer and Rahmstorf, 2009); green bar: (Grinsted et al., 2010)] (Source: Nicholls and Cazenave, 2010, see Chapter 3).

For both the PNW and the Skagit River basin, projections of temperature and related variables such as sea level rise are higher for higher emissions scenarios (e.g. A1B or A1FI) than for a low emissions scenario (e.g. B1), showing that regional impacts of climate change on long time scales could be mitigated by reducing the concentration of greenhouse gases. The amount of warming over the next several decades, however, is insensitive to the emissions scenario,

supporting the argument that adaptation may be the only viable approach to avoiding impacts in the next several decades.

Chapter 4. Glaciers

Glaciers are an important natural resource in the Skagit basin, providing an additional supply of cold water in the warmest part of the summer to support low flows. Glacier fed streams and lakes also provide important habitat for cold water fish species such as bull trout. At both regional and global scales, many glaciers have been retreating since the end of the Little Ice Age (~1550-1850). While a few specific glaciers have advanced during intervening relatively cool and wet periods, glacier retreat and mass losses have generally accelerated in response to post-1970 global warming.

These same patterns of glacial retreat are evident in the Skagit basin. For example, Figure ES.6 shows the retreat of Silver Glacier in the Upper Skagit River near Ross Lake. In comparison with the photo taken in 1958, the glacier feeding the head of the lake has completely disappeared by 2006, and the ice mass in the higher elevation areas is dramatically reduced. (Figure ES.6). The glacial area in North Cascades National Park Complex is estimated to have decreased by approximately 7 % between 1958 and 1998. Ongoing losses of glacial ice and ice caps are projected to continue in response to the regional expressions of global climate change. The disappearance or shrinkage of glaciers is expected to exacerbate summer low flow (particularly during droughts) and result in warmer water temperatures in watersheds with significant glacial coverage, impacting cold-water fish in the Skagit basin such as salmon, steelhead, and bull trout in headwater streams. The changes in summer melt in the Skagit basin are also likely to influence water resources management via reduced hydropower generation and instream flow in the late summer.



Figure ES.6 View to the west of Silver Glacier in 1958 (left, by Post) and 2006 (right, by Scurlock) (Source: [http://northcascadia.org/workshops/noca/0955_Riedel CC Glaciers_0217.pdf](http://northcascadia.org/workshops/noca/0955_Riedel_CC_Glaciers_0217.pdf), see Chapter 4).

Chapter 5. Hydrology

Changes in temperature and precipitation, as simulated by global climate models for future greenhouse gas emissions scenarios (discussed above), are projected to significantly influence the hydrology of the PNW and Washington State (WA) as a whole. Despite increasing cool season (Oct-Mar) precipitation in many climate change scenarios, reductions in April 1 snow water equivalent (SWE) are projected over the PNW and WA. These reductions in natural storage are largest in the simulations for moderate elevation areas that are near freezing in mid-winter. Hydrologic model simulations show that warmer temperatures, more precipitation falling as rain in winter, and the resulting loss of snowpack will cause substantial shifts in streamflow timing and changes in flood and low flow risk. For the Skagit basin, these changes in streamflow timing are projected to be relatively small in the colder headwater areas (e.g. Skagit River at Ross Dam), and larger for sites in the lower river (e.g. Skagit River at Mt Vernon). Watershed characteristics for all sites in the Skagit River are likely to shift toward more rain dominant behavior by the end of the 21st century. In the lower basin, the changes in streamflow timing are very large, with peak flows shifting from June to December in the simulations (Figure

ES.7). An examination of the sensitivity of changes in SWE to projected temperature and precipitation changes shows that temperature plays a dominant role in comparison with precipitation in producing changes in SWE throughout the 21st century.

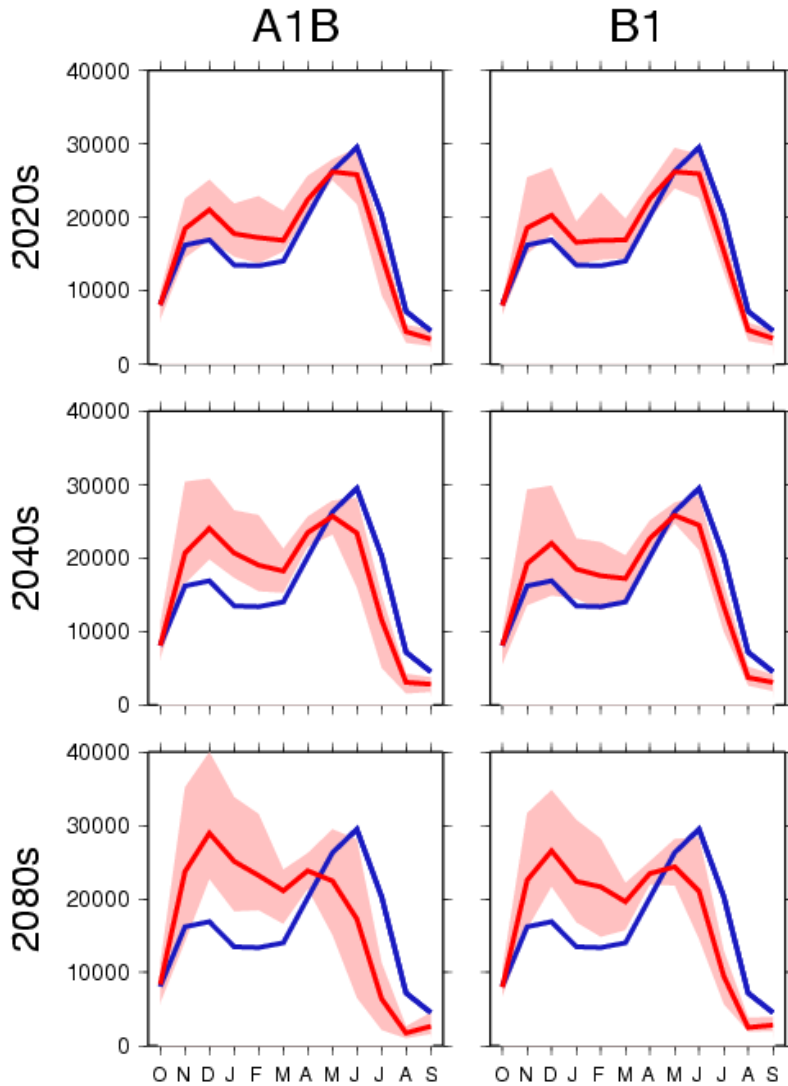


Figure ES.7 Simulated composite monthly average streamflow (in cfs) for the lower Skagit River near Mount Vernon. The blue line represents the historical mean (water years 1916-2006), while the red line represents projected monthly average streamflow across ~ 10 Hybrid Delta simulations. The red band represents the range of individual Hybrid Delta method scenario (Source: <http://www.hydro.washington.edu/2860/>, see Chapter 5).

More severe hydrologic extreme events (floods and low flows) are projected for the Skagit River basin. Floods are shown to become more intense due to increasing winter precipitation and

higher freezing elevations during winter storms that increase runoff production in moderate elevation areas. Estimates of flood risk under natural (i.e. unmanaged or unregulated) conditions at Mount Vernon averaged over 10 climate change scenarios, for example, show about a 30% increase in the 100-year flood by the 2040s (Figure ES.8). Low flow risks also increase in intensity in the simulations, due to loss of snowpack, drier summers, and resulting reduced late summer soil moisture that supplies baseflows. Projected loss of glaciers (which were not included in the analysis discussed above) is expected to result in even greater impacts to low flows in sub-basins with significant glacial coverage.

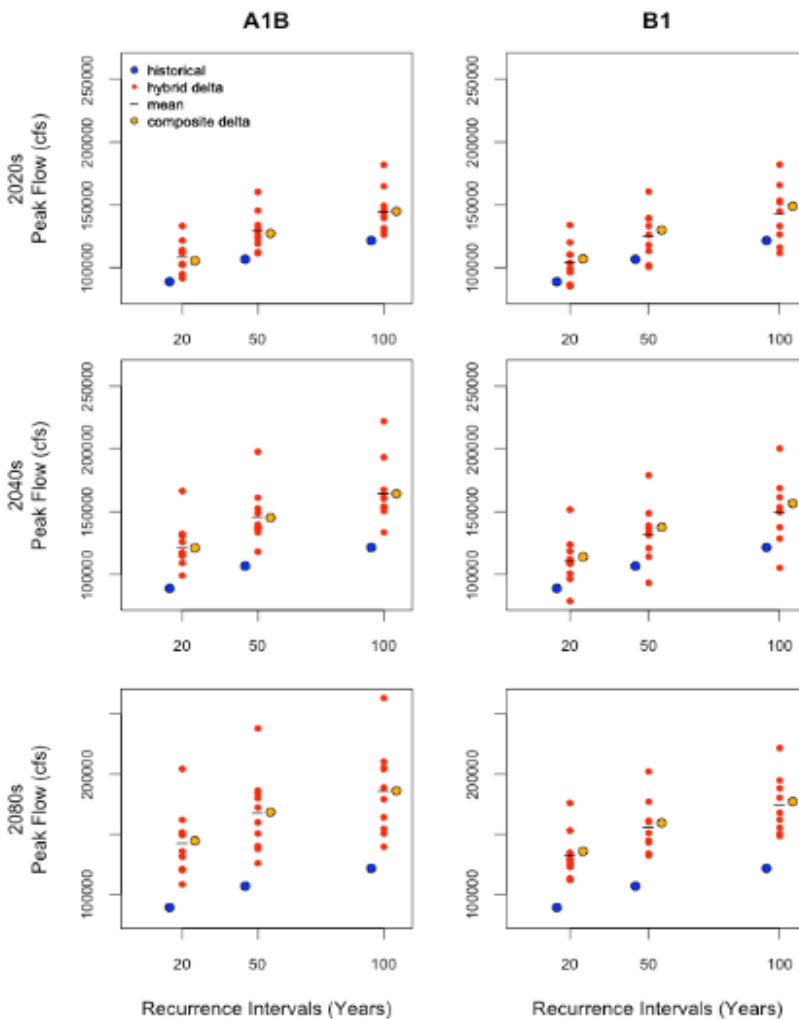


Figure ES.8 20-year, 50-year and 100-year flood statistics for the Skagit River near Mount Vernon under natural (i.e. unmanaged or unregulated) conditions for the historical(blue), Hybrid Delta runs (red), Hybrid Delta mean (horizontal tick) and Composite Delta(orange) runs (Source: <http://www.hydro.washington.edu/2860/>, see Chapter 5).

Chapter 6. Geomorphology

The Skagit River delta has evolved over time due to both human and natural processes. Human activities such as construction of dikes and levees have influenced the formation of distributaries (dominant flow paths) that deliver most of the sediments and river flow to the delta, isolating numerous large historical distributaries in the Skagit River from riverine and tidal influence. As a result, more than 90 % of the Skagit delta has been isolated from riverine and tidal influence and the remaining distributaries are located at the outlet of the North and South Forks of the Skagit River. Sediment transported to the outlet of the North and South Forks has resulted in marsh accretion and the development of new (or altered) distributaries (see Figure ES.9). Marsh accretion has shifted to the North Fork after the dominant flow was shifted from the South Fork to the North Fork around 1937. Sediment supply to the basin has also been influenced by human activities: clearing of log jams, logging and road construction have increased sediment loads in the Skagit River while dams have trapped sediments originating in the headwaters, reducing overall sediment supply and transport to the basin from these areas. Human modification of the river channel has also altered sediment transport to the delta. Sediment reaching the delta largely bypasses the shoreline and tidal flats and accumulates on the face of the delta in deeper waters. Fine sediments mostly bypass the delta and are transported offshore (predominantly to the north) by surface currents. The offshore transport of fine sediments impacts important nearshore habitats through abrasion, fragmentation, substrate burial, and the effects of increased turbidity in the water column. Sediment loads would be expected to increase in the Skagit River due to climate change-related changes in glacier retreat, loss of interannual snowpack, projected increases in flooding, and increased coastal erosion due to sea level rise. A key uncertainty in projecting future conditions is whether expected increases in sediment loads and resulting marsh accretion will be able to keep pace with projected sea level rise, or whether sea level rise will ultimately result in a net loss of tidal marsh. Initial studies estimating net loss of salt marsh and estuarine beaches due to several competing factors suggest net losses in these near shore features.

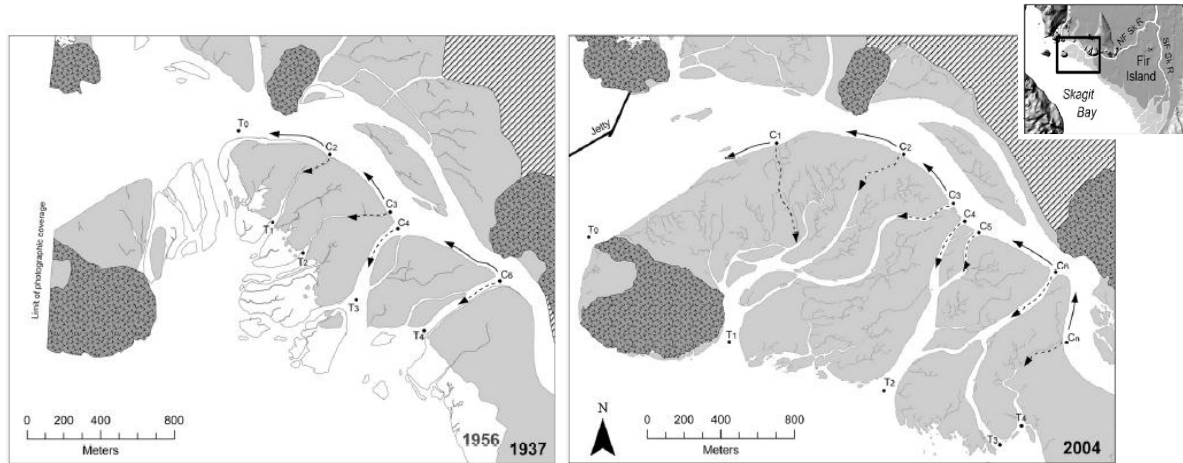


Figure ES.9 Planforms of the North Fork marsh/distributary system. Cross-hatched areas are farmland, checked areas are bedrock outcrops, light gray is tidal marsh, showing expansion from 1937 (left panel) to 2004 (right panel); gray outline in left panel indicates 1956 tidal marsh. White areas are channels and bay (Source: Hood, 2010a, see Chapter 5).

Chapter 7. Ecosystems

Climate change is likely to result in profound impacts to terrestrial, freshwater, and marine ecosystems in the Skagit basin. Hydrologic changes such as increasing water temperature and hydrologic extreme events (floods and low flows) are likely to cause changes in water quantity (timing) and decreases in water quality, disturbing food webs and preventing access to habitat. Increased forest disturbance (e.g. from fire and insect impacts) is projected for a warmer 21st century climate, which often provides a competitive advantage for invasive species after disturbance. There are many uncertainties about the projection of sea level rise and its impacts on coastal habitats but there is little doubt that coastal habitat will be profoundly influenced by sea level rise. Such changes in fish and wildlife habitat are expected to have significant impacts on cold water fish such as salmon, steelhead, and bull trout (Figure ES.10), migratory birds, and other species.

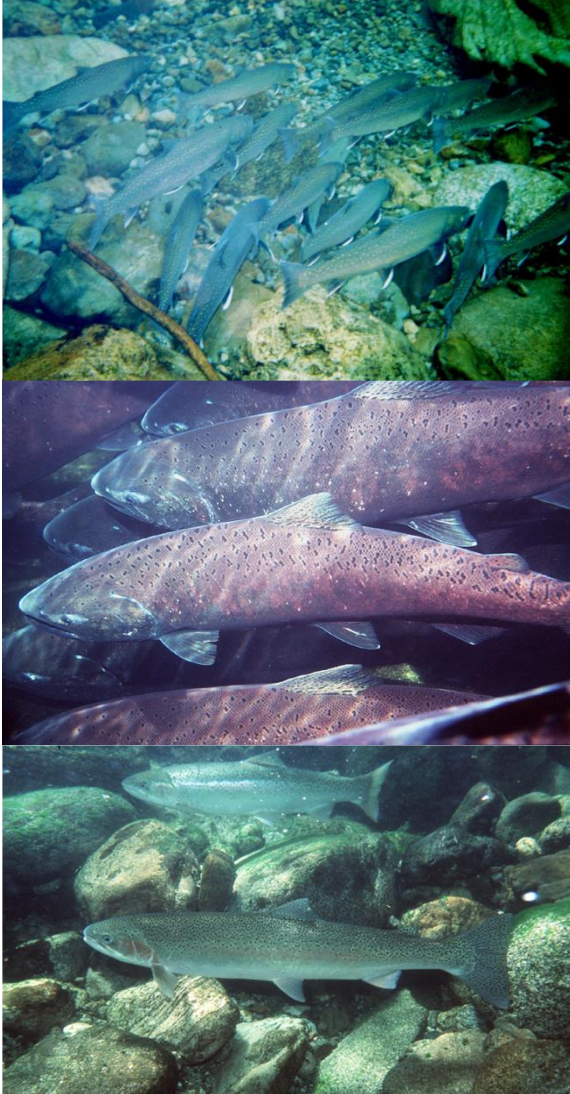


Figure ES.10 Cold water fish species in the Skagit basin likely to be impacted by climate change include bull trout (top), Chinook salmon (middle), steelhead (bottom) (Source: Ed Conner, Seattle City Light, northcascadia.org/workshops/noca/1110_Connor_CC_Fish_0217.ppt).

Climate change and its consequences are likely to alter the species composition in the Skagit's forests. Drier and warmer summers would cause decreases in drought-susceptible species such as western red cedar and even drought-tolerant species such as Douglas fir, which is an economically important species in the Skagit basin. It is difficult to translate the potential habitat changes into specific impacts on individual species, but generally these changes are likely to have negative impacts on terrestrial and aquatic species in the Skagit River basin, exacerbating impacts relating to human activities. Potential declines of economically valuable fish species

such as salmon and steelhead, and tree species such as Douglas fir would likely have negative impacts on the Skagit's current economy.

Chapter 8. Human Systems

Climate change is likely to substantially impact human systems and many elements of the local economy in the Skagit basin. As mentioned above, warmer temperatures and changes in the seasonality of precipitation are projected to significantly alter the hydrology of the Skagit River on which water resources systems depend. Due to the altered hydrology of the Skagit basin, the seasonality of hydropower production is projected to change, increasing in winter and decreasing in summer. For the projected 2040s climate, for example, a 20% increase in winter power generation was simulated for the Seattle City Light (SCL) hydropower projects in the upper Skagit River. By the 2080s, peak hydropower generation in the SCL system shifts from July to January. The seasonal timing of peak flows in the Skagit River is also projected to shift from spring to fall/winter due to a warmer climate and associated rise in freezing level, increasing the risk of flooding in the Skagit basin. Dams in the upper Skagit River basin and Baker River can only impound the relatively small fraction of total flow from the headwaters above Ross Dam and Upper Baker Dam. Preliminary results from daily time step reservoir operations modeling (based on a single climate change scenario) suggest that the regulated 100-year flood will increase substantially in the future in comparison with historical baselines (20% by the 2040s and 24% by the 2080s). Proposed increases in flood storage are simulated to decrease the magnitude of the regulated 100-year flood by a small amount in comparison with current operations (3% reduction in the 100-year flood by the 2040s, and 7% reduction by the 2080s). Increasing flood storage would also likely result in important tradeoffs with other system objectives such as hydropower production and instream flow. Thus potential increases in flood storage would ultimately need to be weighed in the context of tradeoffs with other system objectives. Increasing winter precipitation will likely impact urban stormwater management systems, increase landslide risks, and impact public safety in the transportation sector. Decreasing mountain snowpack will likely impact both winter recreation opportunities such as skiing and white water recreation opportunities that depend on summer flow in rivers. These

combined impacts are likely to pose formidable challenges for water resources managers, utilities, and municipalities, particularly in the context of floodplain management.

Increased flood risks from the combination of sea level rise and projected increases in river flooding has the potential to cause major damage to low-lying farms and urban development in the floodplain, impacting homes, businesses, water treatment plants, and transportation infrastructure such as bridges and roads. For example, Figures ES.11 shows inundation of roads near La Conner during the flood of February 2006, impacting homes and businesses. Estimates of flood inundation based on combined sea level rise and increased river flows are needed to better quantify these impacts. Sea level rise may also impact the ability to drain low-lying farmland using traditional tide gates. Warmer water temperatures, more severe and prolonged low summer flows, and potential habitat loss associated with projected sea level rise are projected to negatively impact coldwater fish species such as salmon, steelhead, and trout.



Figure ES.11 Inundation of roads near La Conner due to storm/tidal surge of February 2006 , photos courtesy of John Doyle (Source: SITC, 2010, see Chapter 8).

Agriculture is the leading industry in Skagit County. About \$300 million worth of crops, livestock, and dairy products are produced in approximately 100,000 acres of Skagit County (see Figure ES.12) Agriculture in Skagit County is expected to be influenced by climate change via longer growing seasons, warmer, drier summers, wetter winters, warmer temperatures, and changing risks for pests, invasive plants (weeds), and diseases. Warmer temperatures (in isolation) are expected to result in degraded quality and/or decreased productivity of some crops such as spinach seeds, raspberries, blueberries and potatoes. Elevated carbon dioxide levels, however, may compensate for these impacts by increasing net productivity in some crops in a warmer climate.



Figure ES.12 Major crops, livestock and dairy products produced in Skagit County (Source: Washington State University, 2007).