Skagit River Basin Climate Science Report

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Table of Contents

Table of Figures

Table of Tables

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.

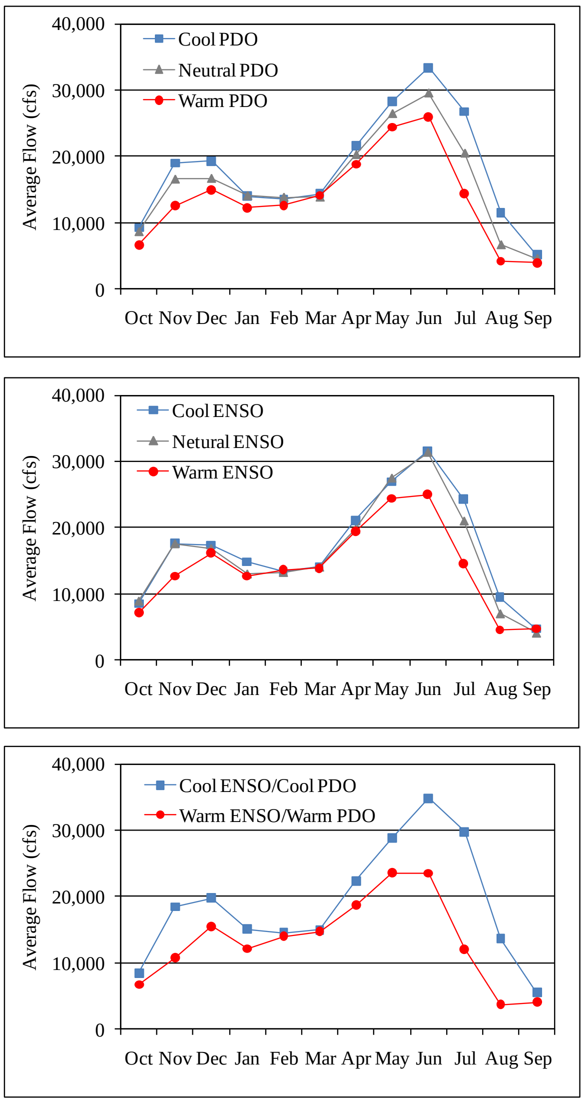

Figure ES.2 Composite monthly average simulated streamflow for the Skagit River near Mount Vernon (water years 1916 -2006) for the PDO phases based on the PDO index (top), ENSO phases based on Dec-Feb averaged Nino3.4 Index (middle) and the PDO and ENSO in phase (bottom) (see Chapter 2).

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 ^{o}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 ^{o}F for B1 and 5.8 ^{o}F for A1B in comparison to historical average temperature (see Table ES.1).

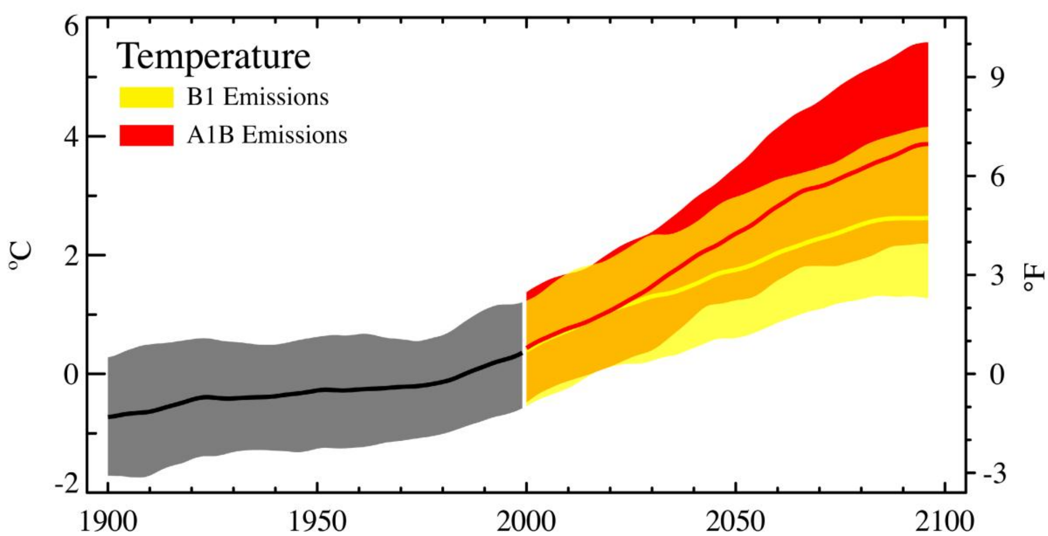

Figure ES.3 Summary of 20th and 21st century annual average temperature simulations from 20 GCMs over the PNW, relative to the 1970-99 mean, for two greenhouse gas emissions scenarios. Solid lines show the mean. The grey bands show the range (5th to 95th percentile) for the historical simulations, the 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.

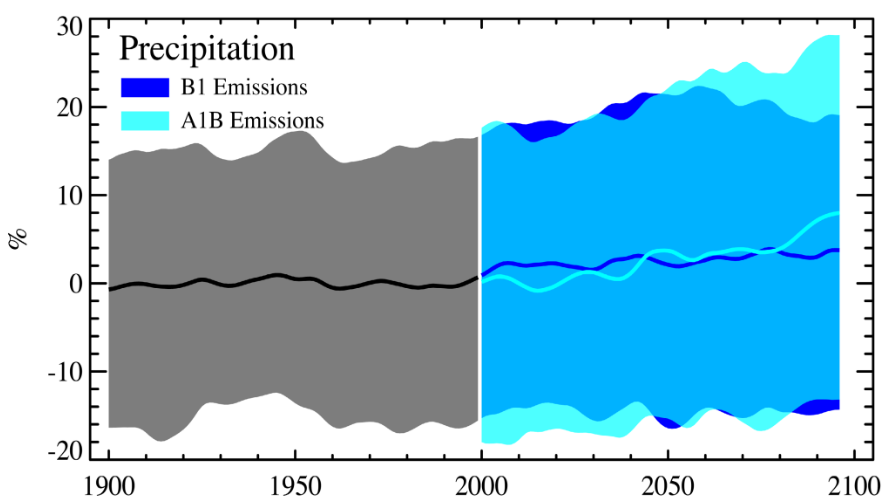

Figure ES.4 Summary of 20th and 21st century annual precipitation simulations from 20 GCMs for the PNW, relative to the 1970-99 mean, for two greenhouse gas emissions scenarios. Solid lines show the mean. The grey bands show the range (5th to 95th percentile) for the historical simulations and the colored 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.

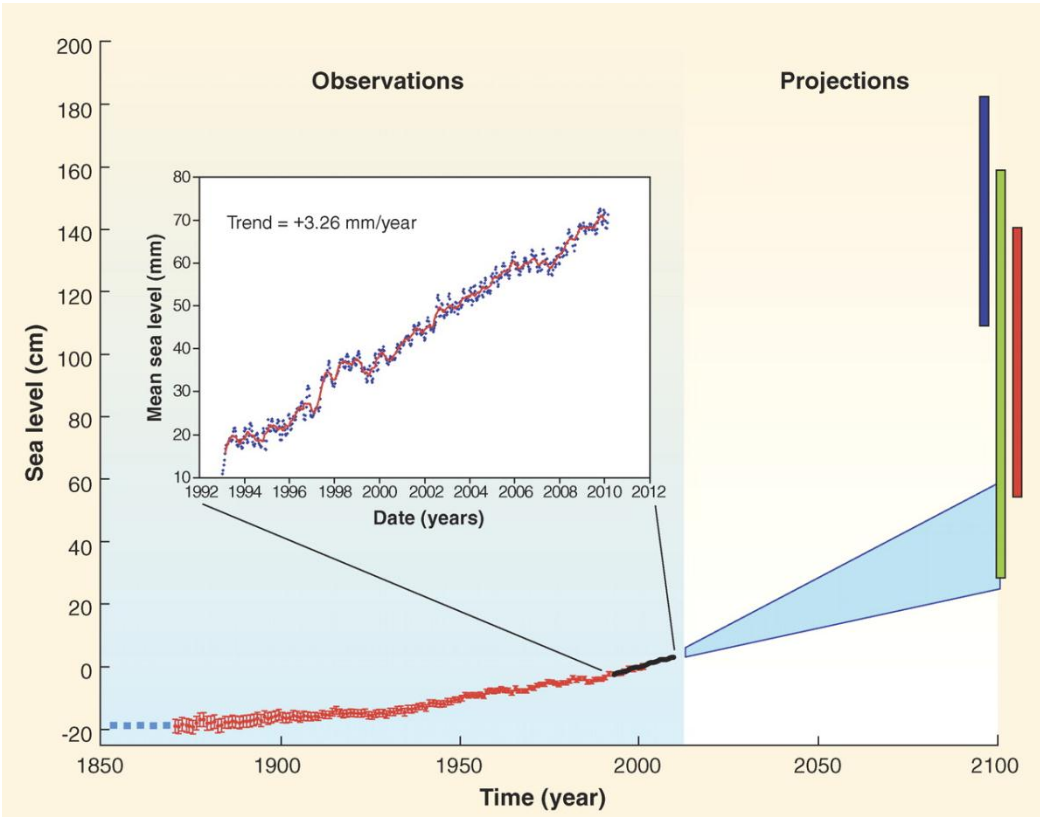

Figure ES.5 Global mean sea level evolution over the 20th and 21st centuries. The red curve is based on tide gauge measurements. The black curve is the altimetry record (zoomed over the 1993–2009 time span). Projections for the 21st century are also shown. The shaded light blue zone represents IPCC AR4 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, 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.

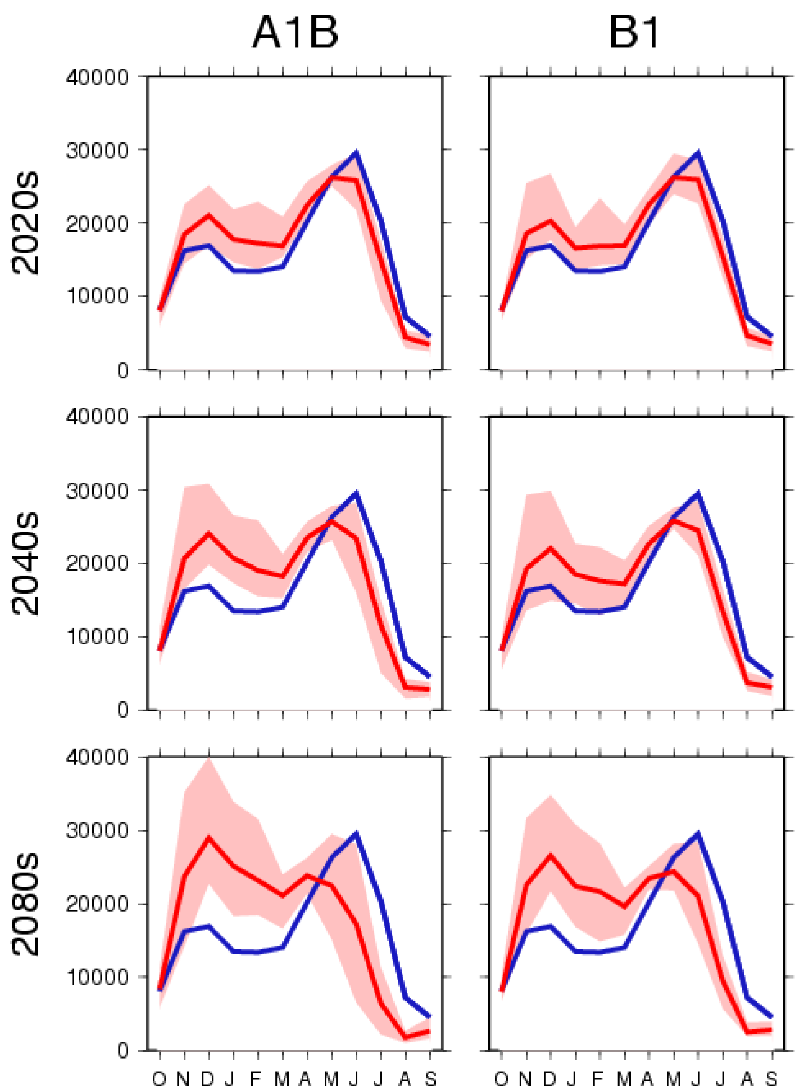

Figure ES.7 Simulated composite monthly average streamflow (in cfs) for the lower Skagit River near Mount Vernon. The blue line represents the historical mean (water years 1916-2006), while the red line represents projected monthly average streamflow across ~ 10 Hybrid Delta simulations. The red band 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.

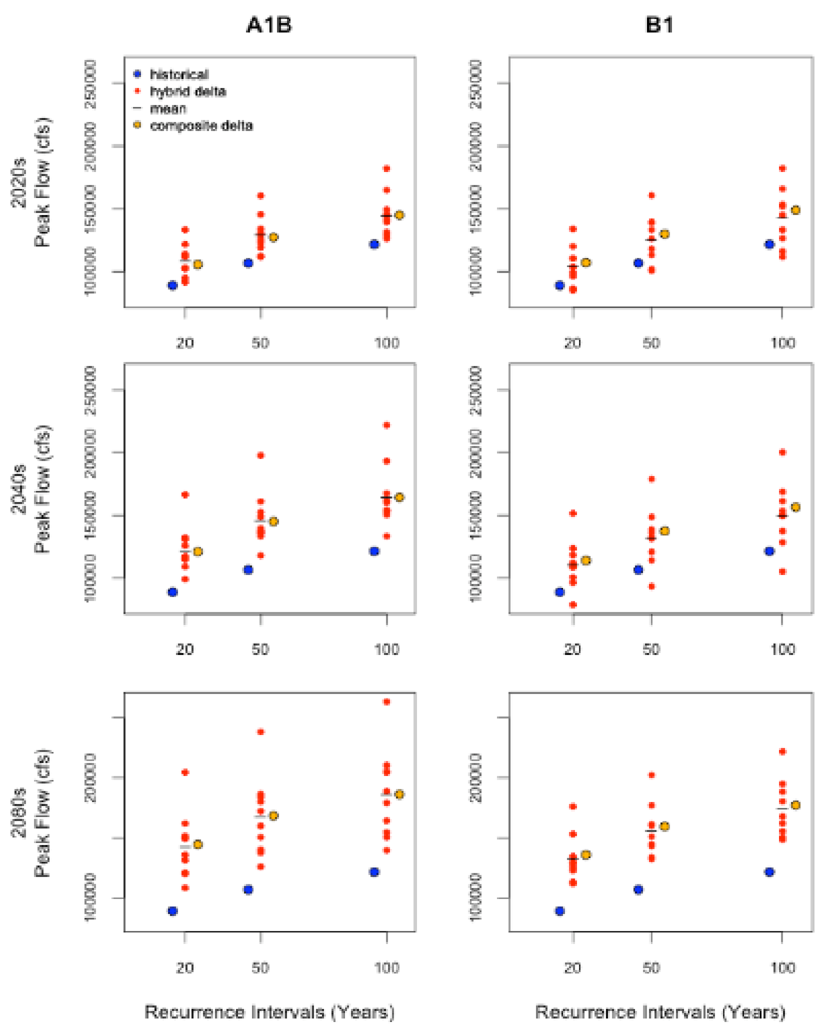

Figure ES.8 20-year, 50-year and 100-year flood statistics for the Skagit River near Mount Vernon under natural (i.e. unmanaged or unregulated) conditions for the historical(blue), Hybrid Delta runs (red), Hybrid Delta mean (horizontal tick) and Composite Delta(orange) runs (Source: http://www.hydro.washington.edu/2860/,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

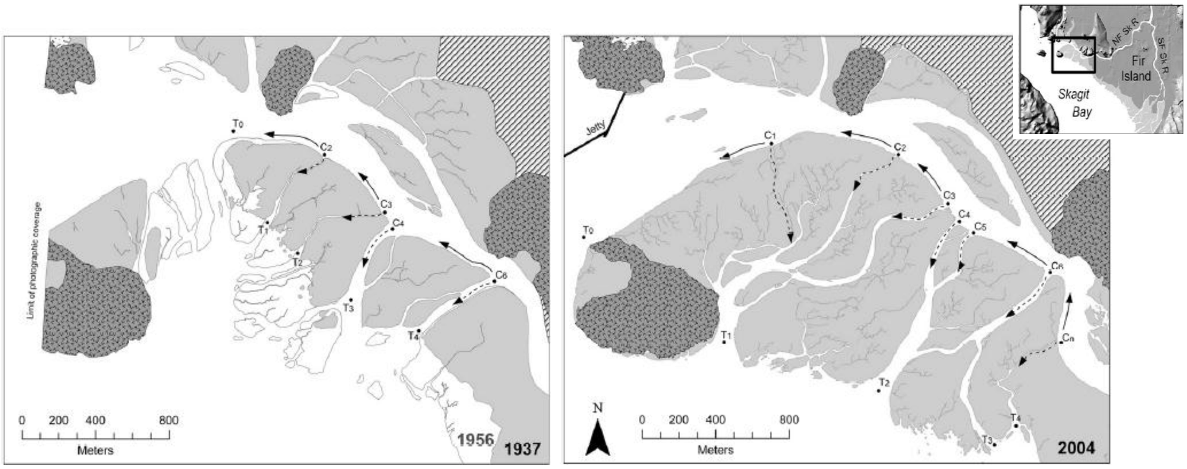

Figure ES.9 Planforms of the North Fork marsh/distributary system. Cross-hatched areas are farmland, checked areas are bedrock outcrops, light gray is tidal marsh, showing expansion from 1937 (left panel) to 2004 (right penal); gray outline in left panel indicates 1956 tidal marsh. White areas are channels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

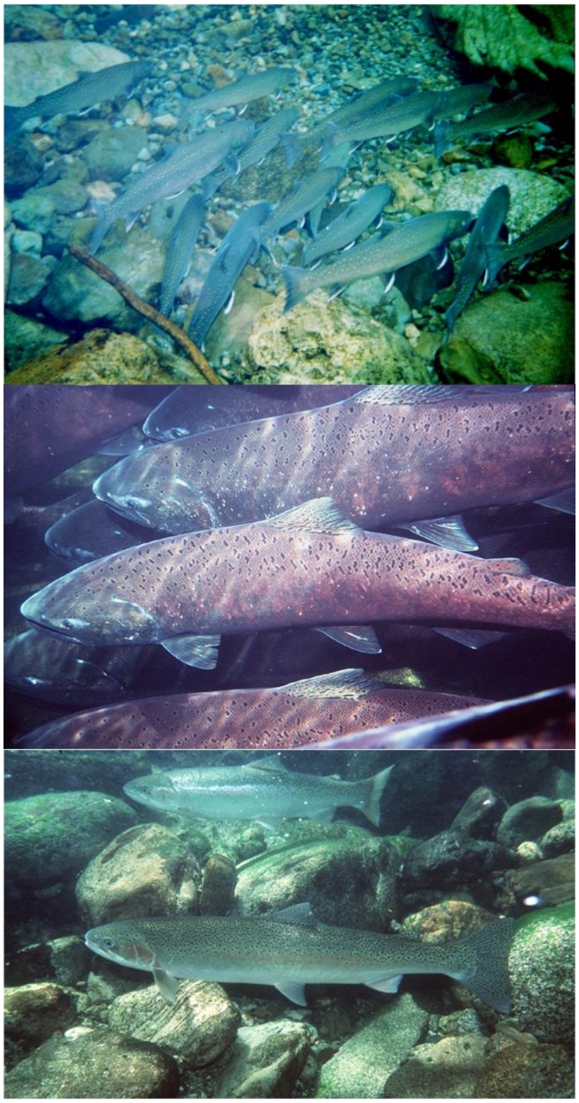

Figure ES.10 Cold water fish species in the Skagit basin likely to be impacted by climate change include bull trout (top), Chinook salmon (middle), steelhead (bottom) (Source: Ed Conner, Seattle City Light, *northcascadia.org/workshops/noca/1110_Connor_CC_Fish_0217.ppt*).

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 (Source: Donatuto, 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).

1. Skagit Basin Overview

Abstract

Since the 1850s, the Skagit River basin has been altered by human activities such as logging, diking, and the construction of dams, roads, levees, and tide gates. Logging and construction of levees and dikes converted coniferous forest and wetlands to farmland, industrial, and urban/suburban residential development. Dams constructed in the Skagit River not only generate hydropower but also provide flood control, recreation opportunities, and diverse ecosystem services. Major highways constructed through Skagit County promoted both economic and population growth in Skagit County. These human developments have dramatically impacted the hydrology and geomorphology of the basin and have impacted or reduced habitat for a wide range of species, including multiple species of native anadromous fish historically reliant on Skagit River Basin tributaries. Low-lying farms, urban development, and other lands in the floodplain are currently vulnerable to river flooding and sea level rise. The economy of the Skagit River basin in the 19th and early 20th centuries was focused primarily on logging, mining, and agriculture, but has diversified through the second half of the 20th century. Rapid increases in population in the 21st century are projected for Skagit Co., which, under the Growth Management Act and the Skagit County Comprehensive Plan, will direct future growth primarily in urban areas.

1.1 Overview of the Skagit River Basin

The Skagit River basin is located in southwestern British Columbia in Canada and northwestern Washington in the United States (Figure 1.1) and drains an area of 3,115 square miles (Pacific International Engineering, 2008). Major tributaries in the basin are the Baker River, Cascade River, and Sauk River. The Skagit River basin is approximately 110 miles long and 90 miles wide (Pacific International Engineering, 2008). Downstream of the town of Mount Vernon, the river splits into the North Fork and the South Fork before entering Skagit Bay in Puget Sound (Figure 1.1). Under low to moderate flow conditions, about 60 % and 40 % of the Skagit River flows are carried out by the North and South Forks, respectively, while at higher flows, this ratio is closer to a 50-50 split (Curran et al., in review; Pacific International Engineering, 2008). Although not considered in detail in this report, other local rivers such as the Samish and Stillaquamish also materially affect the local economy and natural resources of Skagit Co, and the ecology of the Puget Sound lowlands and Skagit Bay.

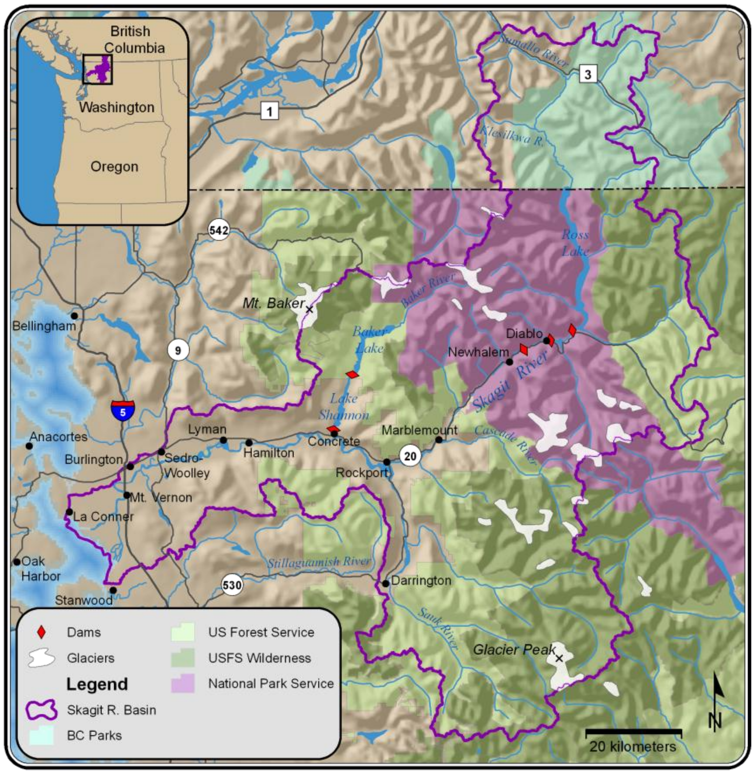

Figure 1.1 Key Geographic features of the Skagit River basin. Note that only the largest glaciers are shown on the figure (see Chapter 4 for details).

1.2 Geology and Land Cover

1.2.1 Geology

The eastern mountainous region of the basin consists of ancient metamorphic rocks, together with granitic rocks and volcanic deposits associated with Mount Baker and Glacier Peak (Pacific International Engineering, 2008). The two highest points in the basin are Mount Baker on the northern side of the basin at an elevation of 10,778 ft and Glacier Peak in the southern portion of the basin at an elevation of 10,568 ft (Pacific International Engineering, 2008). Most of the eastern portion of the basin is above an elevation of 6,000 feet (Pacific International Engineering, 2008), where nearly all winter precipitation currently falls as snow. From Rockport to Sedro Woolley, the Skagit River flows in a 1-mile to 3-mile-wide valley that was largely formed by Alpine glaciers (Waitte, 1977; Pacific International Engineering, 2008). The valley walls are moderately steep, timbered hillsides with few developments (Pacific International Engineering, 2008). Below Sedro Woolley, the valley falls to nearly sea level and widens to a flat, fertile floodplain formed by continual river sediment transport and also by historic lahars from Glacier Peak - most notably an event about 5,900 years ago, which is estimated to have deposited between 0.5 and 0.7 cubic miles of sediment extending to the present location of Samish Bay to the northeast and La Conner and Stanwood to the southeast (Pacific International Engineering, 2008). Another study also identified a large lahar event approximately 1800 years ago that deposited large amounts of material to an overlapping area (Dragovich et al., 2000).

Prior to the late 19th century diking, floodwaters from the Skagit and Samish River basins and their associated suspended sediment commonly flowed across this entire geomorphic delta comprised of the modern Samish, Padilla and Skagit floodplains (Collins, 1998). Because of their different geological origins, the lower substrate of most deep valleys in the headwaters and middle basin consists of glacial deposits and/or moraines, while that of the floodplain in the lower basin is composed of volcanic sands and laharic deposits such as muddy, gravelly volcanic rock debris. The fertile upper layers of soil in the floodplain are composed primarily of finer sediments deposited by the river such as sands, silts, and clays (Collins, 1998; Pringle and Scott, 2001; Pacific International Engineering, 2008; Haugerud and Tabor, 2009).

Under current conditions the Skagit River has been estimated to transport between 1.7 million and 4.5 million tons of sediment annually (Collins, 1998, Curran and others, in review; Pacific International Engineering, 2008). In water year 1991, which included two major floods (Pacific International Engineering, 2008), the river transported 4.4 million tons of sediment (Collins, 1998). Recent studies present evidence that sediment delivery has increased dramatically since 1850 due to a combination of land use change (e.g. logging and road building), clearing and dredging in the lower river, and channelization of flow, which reduced connectivity between river and floodplain (Grossman et al., in press) (See also chapter 6).

Largely as a consequence of these changes the Skagit River delta is currently prograding (increasing in area) (Beamer et al., 2005a). Extensive diking of the lower river has also dramatically changed where sediment is deposited, concentrating it at the mouths of the South and North Forks and on the outer face of the delta (Hood, 2004; Collins, 1998; Grossman et al., in press). Fine sediments, however, primarily bypass the delta, shoreline and tidal flats and are transported offshore (Grossman and others, 2007) (See Chapter 6 for more details).

Recent studies provide evidence that the entire Skagit tidal flats have been converted from a mud-rich system to a sand-dominated system since about 1850, which has led to habitat impacts and lost marine resources. For example, the Swinomish Tribe used to harvest soft shell clam in the delta, but this species is no longer viable in areas now dominated by sand deposition. Similarly the Swinomish Tribe used to harvest oysters in the area north of the current Jetty, but oysters are no longer viable in this area because of extensive mud accumulation since the 1940s when the jetty was emplaced (Grossman et al., in press and review; Grossman et al. 2007).

1.2.2 Land Cover

Since settlement by non-Native Americans began in the 1850s, the land cover of the Skagit River Valley (and adjoining areas in the Puget Sound Lowlands in the Samish and Stillaquamish River basins) has been changed from mostly coniferous forest and wetlands to farmland and urban or rural residential areas (Beechie et al., 2001; Cuo et al., 2009). Outside of national park and wilderness areas, forested foothills and mountains have been converted from old growth to commercial tree farms or second growth forest (Skagit County, 2007). Based on 2007 satellite images, land cover in Skagit County is 65.5% forest, 15.5% grassland or scrub/shrub (including recently cut forest), 7.3% agriculture, 3,5% developed, and 5.2% ice and rock (J. Greenberg, personal communication; see Figure 1.2). Based on current Skagit Co. zoning designations land use are classified as 48% public, 29% industrial forest, 12% secondary forest or rural, 8% agriculture, and 4% urban, including the cities of Mount Vernon, Burlington, and Sedro Woolley and the towns of Concrete, Hamilton, Lyman, and La Conner (J. Greenberg, personal communication; see Figure 1.3). The basin also includes the reservations of the Sauk-Suiattle Indian Tribe and the Upper Skagit Indian Tribe. The City of Anacortes and the Swinomish Indian Tribal Community are on Fidalgo Island, just outside of the Skagit River basin boundary (Figure 1.1). The federally recognized Samish Indian Nation is currently headquartered in Anacortes, but does not have a reservation of its own. Although the reservation is outside the basin boundary, the Swinomish Tribe maintains significant treaty interests in the Skagit River and Skagit River delta, as does the Samish Tribe.

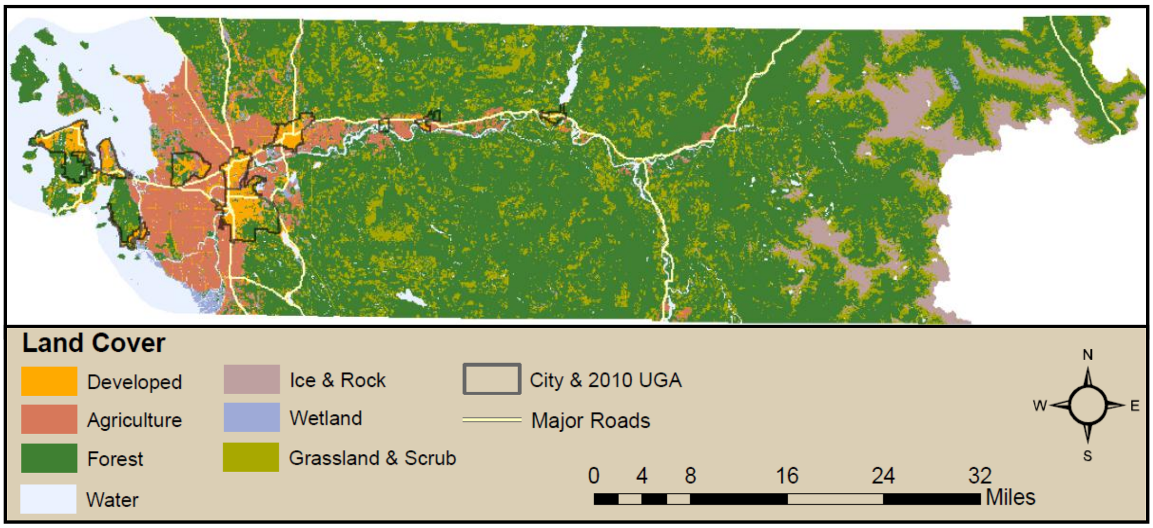

Figure 1.2 Land cover of Skagit County.

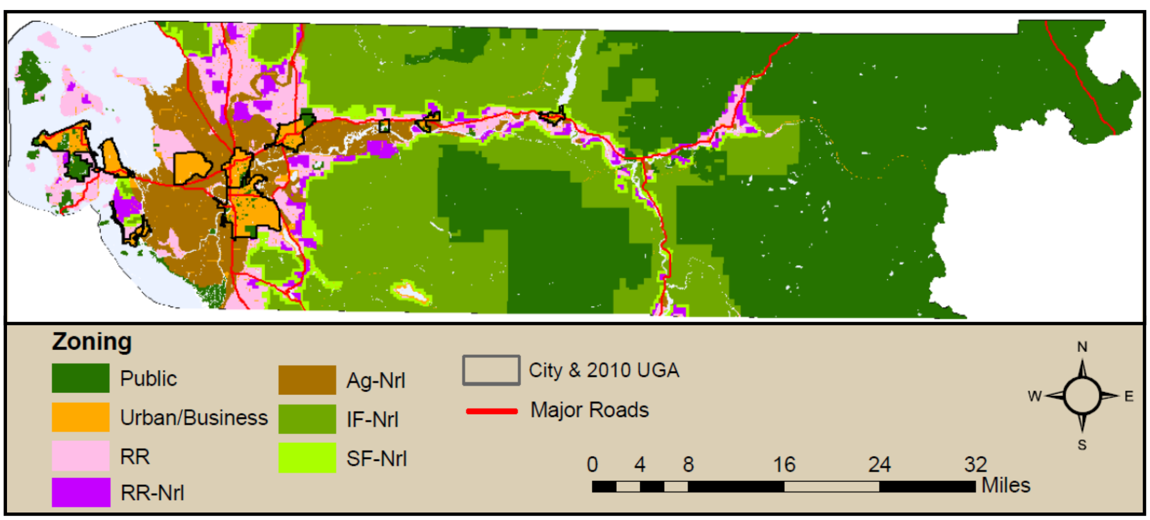

Figure 1.3 Major land use zones based on Skagit County designations. “IF-Nrl” is Industrial Forest, and “SF-Nrl” is Secondary Forest, “RR” is Rural Reserve, “RR-Nrl” is Rural Resource and “Ag-Nrl” is Agriculture. (Map produced by Skagit County GIS 2011.)

Prior to non-native settlement, at least one half of what is now the Skagit River delta was composed of perennial wetlands, including tidal marsh, freshwater marsh, or open channels (Collins, 1998). Historically, the lower Skagit River likely moved across the entire Skagit Flats, including the current Samish River Valley out to Samish Bay (Collins, 1998). A former channel of the river that led to Padilla Bay was clearly detectable in a U.S. Army Corps of Engineers analysis in 1881, for example (Kunzler, 2005).

1.3 Human Settlement of the Skagit Basin

Native Americans occupied lands within the Skagit River Basin for uncounted centuries prior to non-native settlement. Within a few years following the Oregon Treaty of 1846, which established American sovereignty below the 49th parallel, European-Americans and other ethnic groups began moving to the Puget Sound area. The first continuous non-native settlement in Skagit County was on the prairies of March Point in 1853 (Easton, 1976). The cession of tribal lands through the Point Elliott Treaty of 1855 provided the basis for granting land titles and encouraged more extensive settlement (Skagit County, 2007). The first dikes along the Skagit River are believed to have been constructed in 1863 (Breslow, 2011). La Conner was the first town established in the county. It began as a trading post in the early 1860s, benefitting from its location on a protected waterway (Easton, 1976). As was the case throughout western North America in the 18th and 19th century, ships, canoes, and other watercraft were the primary means of early transportation until clearing of upland forests made overland travel more feasible. Thus early settlement was typically near major water bodies such as the Skagit River and Puget Sound. Early agriculture in the delta focused on oats and barley, which did well in salty soils (Econorthwest, 2010). As early as 1873, the temperate microclimate of the Skagit Valley was found to be well-suited for growing cabbage and brassica seeds, which grew to be an economically important industry in the 20th century (Breslow, 2011; Econorthwest, 2010).

Before the early 1880s, two huge log jams blocked passage of steamer ships at Mount Vernon (Breslow, 2011). Until the jams were removed, they caused spring snow melt to flood across the valley downstream (Kunzler, 2005). Removal of the jams allowed Mount Vernon to grow; it became the county seat in 1884 (Easton, 1976). Logging on the delta and along the river was the county's first major industry (Kunzler, 2005). Logging advanced upriver, along with early mining operations, after the U.S. Army Corps of Engineers completed removal of the log jams at Mount Vernon and cleared additional snags and jams further upriver to improve navigation (Breslow, 2011). Railroad connections cemented Mount Vernon's role as the leading city in the county in the late 19th century. Spur lines led to the growth of Anacortes and upriver towns. Most of these towns were established in association with nearby mines (Breslow, 2011). By the early 20th century, upriver floodplains had been extensively converted to agricultural use and the riparian forest had been logged from as far upstream as the Sauk River (Beechie et al., 2001). After timber near the river was cut, railroads supported logging operations as they moved up the hillsides (Kunzler, 2005; Easton, 1976).

In the 1950s, the county economy diversified its industrial base from its historic dependence on the agricultural and forestry industries, adding two petroleum refineries on Fidalgo Island near Anacortes and establishing a pleasure boat building industry (Hovee and Company, 2003). In the 1970s and 1980s, downturns in the lumber, wood, and food processing industries led to higher unemployment in Skagit County than elsewhere in Washington. The county has broadened its employment base since then. Today, services and retail are the county's two largest economic sectors (Hovee and Company, 2003).

1.3.1 Drainage Infrastructure

By the late 19th century, an extensive system of dikes had transformed the delta into some of the richest farmland in the state (Kunzler, 2005). The growing cities of Skagit County depended on agriculture as the basis for the local economy. However, the delta remained subject to catastrophic flooding, which was exacerbated by logging, the channelization of streams and rivers, and the dike and drainage system itself, which increased the severity of downstream flooding by channeling the river's force and removing the absorptive capacity of trees and wetlands (Breslow, 2011). Much of the land surface in the delta protected by dikes is currently below the mean higher high tide (J. Greenberg, personal communication; see Figure 1.4, making it vulnerable to projected sea level rise, especially in combination with increased river flooding projected for a warmer future climate (see Chapters 5 and 8).

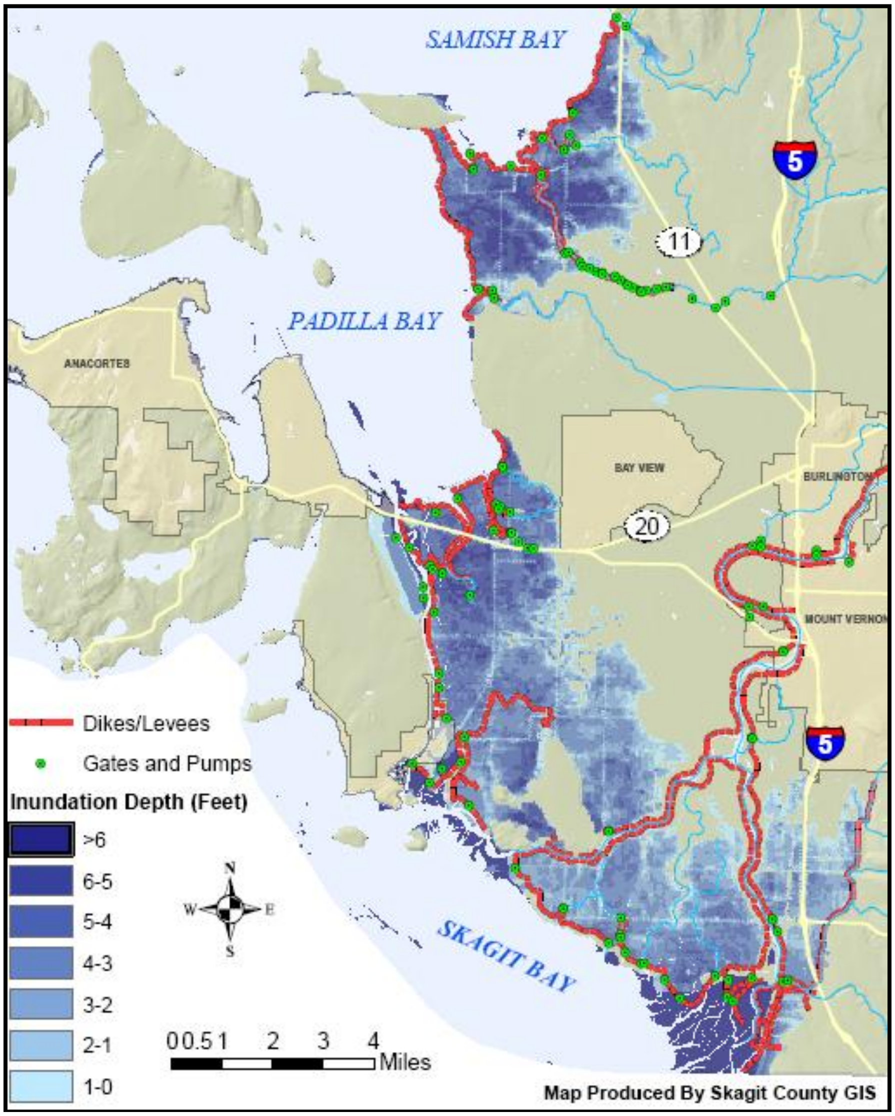

Figure 1.4 Predicted inundation extent at higher high tide in the Skagit Flats if tide gates were removed from existing dikes (J. Greenberg, personal communication). (Map produced by Skagit County GIS 2011.)

Tide gates and flood gates have been installed in low-lying land in the Skagit delta to protect against flooding and to provide adequate drainage for farming (Mitchell et al., 2005; WWAA et al., 2007). Tide gates are essentially one-way valves that allow drainage water to flow to marine waters during a low tide cycle. At high tide, tide gates close to keep saltwater out of the drainage system (WWAA et al., 2007). Flood gates also prevent water in the Skagit River from back-flowing into a drainage system when the river is at flood stage (WWAA et al., 2007). These two types of drainage infrastructure are essential for the long-term sustainability of agriculture in the Skagit delta. They have also caused declines in salmonid productivity by blocking fish passage, and have reduced sediment transport to the Skagit delta. The performance of tide gates and flood gates is likely to be influenced by sea level rise, especially in combination with increased river flooding (Chapter 8).

1.3.2 Dams

Five major hydroelectric dams were constructed in the basin between 1924 and 1959: Gorge Dam (completed as a wooden structure in 1924, then replaced with a concrete dam in 1950), Diablo Dam (completed in 1931), and Ross Dam (first completed in 1940, then raised in 1949) on the upper Skagit River and, on the Baker River, Lower Baker Dam (completed in 1925) and Upper Baker Dam (completed in 1959). The three Seattle City Light dams on the upper Skagit River produce 805 megawatts (MW) of power: 460-MW Ross, 168-MW Diablo, and 177-MW Gorge. The two Puget Sound Energy dams on the Baker River generate 170 MW of hydropower: 91-MW Upper Baker and 79-MW Lower Baker (URLs 1 & 2).

The three storage dams (Ross, Upper Baker, and Lower Baker) significantly reduced natural spring river flows originating as snowmelt and also augment summer low flows (Pacific International Engineering, 2008). Since 1954, Ross Dam has provided 120,000 acre-feet of flood control storage. Since 1980, Upper Baker Dam has provided 74,000 acre-feet of additional storage (Pacific International Engineering, 2008). During a flood event when forecasted natural flow at Concrete is above 90,000 cfs, the U.S. Army Corps of Engineers operates Ross Dam in coordination with Upper Baker Dam to reduce flood peaks in the lower Skagit River valley (Puget Sound Energy, 2006). Collectively, Ross and Upper Baker Dams control runoff from about 39 percent of the drainage area of the Skagit River basin upstream of the Skagit River near Mount Vernon (Puget Sound Energy, 2006). Nevertheless, the five dams in the basin were not built primarily for flood control and provide only limited relief from the worst river flooding, which generally occurs in late fall when warm storm systems bring heavy rainfall, which can also melt early snowpack (Kunzler, 2005).

1.3.3 Highways

Interstate 5 (I-5) was constructed through Skagit County in the 1960s. The final portion of I-5, between Everett and Marysville, opened in May 1969, connecting the county to the Seattle area and points south. This was a turning point for the local agricultural industry, cutting several hours from the time needed to move inputs, products, and labor between farms and markets, and also attracting new suppliers, processors, and resellers to the valley (Breslow, 2011). It also made commuting between Skagit County and the fast-growing central Puget Sound area much more feasible, leading to a significant and sustained increase in Skagit County's population growth rate, as discussed further in the section 1.5.

In summer 1972, the North Cascades Highway was completed, connecting the Skagit Valley to the Methow Valley east of the mountains. Combined with the creation of North Cascades National Park in 1968, this transformed Skagit County into a gateway to popular recreational areas in the mountains. The county was already a gateway to the San Juan Islands through a spur of State Routes (SR) 20 to the ferry terminal at Anacortes. Other major highways in the basin include SR 9, 538 and 536. Highways lying in the floodplain such as SR 20, 9, and 536 are susceptible to flooding and are closed during extreme high flows.

1.4 Ecological Change

The transformation of the Skagit River and its basin over the final decades of the 19th century and early decades of the 20th century involved dramatic changes to the basin's ecosystems. Figure 1.5 identifies changes just in estuarine habitat zones between the 1860s and 1991. Most of these changes had already taken place by the early 20th century (Collins, 1998). Snag removal and logging in the floodplain not only removed complex habitats used extensively by salmon and other species, they eliminated dynamic processes through which the river created and maintained habitats over time (Collins, 1998). Diking isolated more than 90% of the delta from riverine and tidal influence (Hood, 2004), leading to dramatic losses in freshwater wetlands and estuarine habitats (see Figure 1.6). Beamer et al. (2005b) calculated a net loss of 98% of freshwater wetlands and floodplain forest in the non-tidal delta to Sedro Woolley (see Figure 1.7).

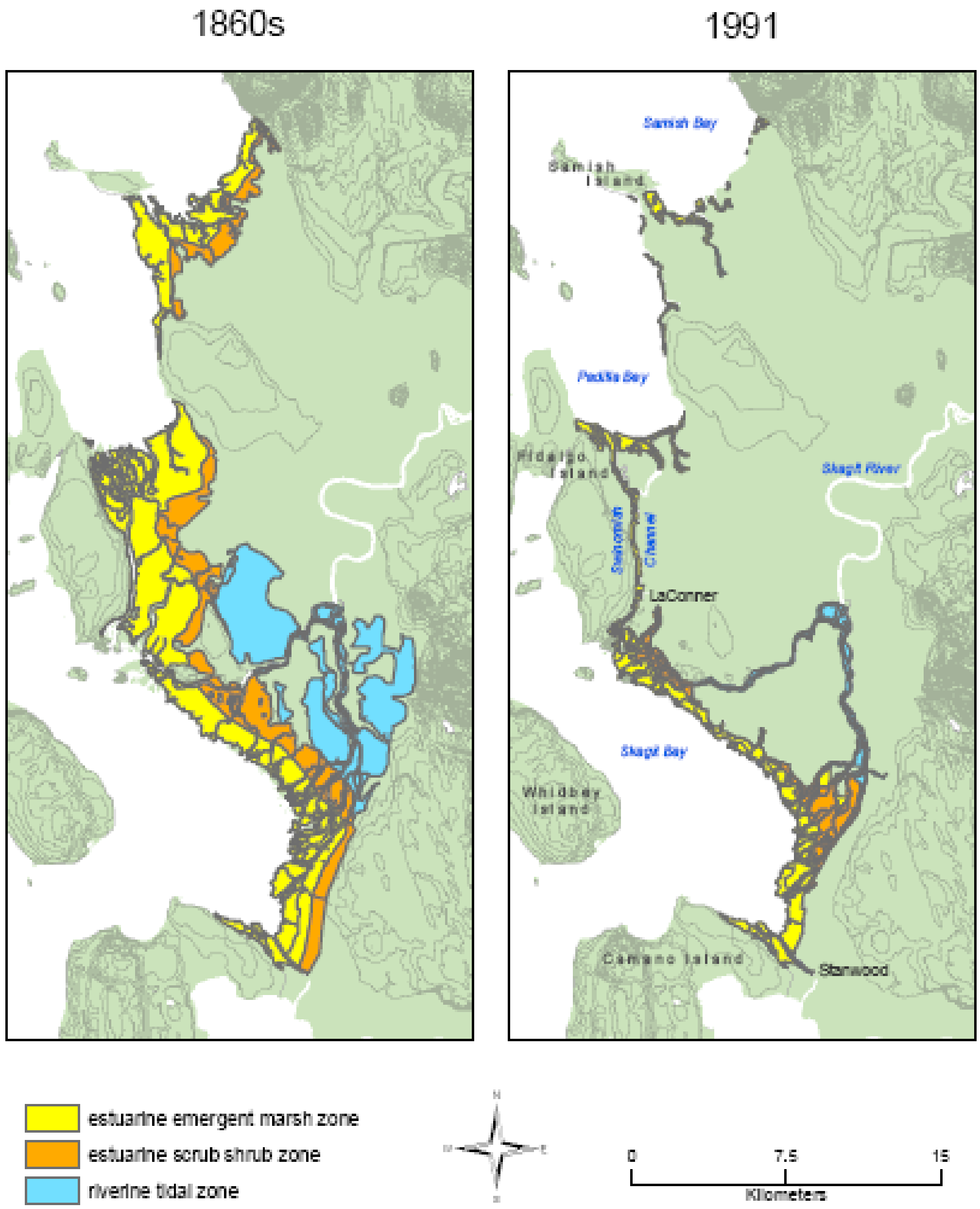

Figure 1.5 Changes to the estuarine habitat zones within the Skagit delta (Source: Beamer et al., 2005a).

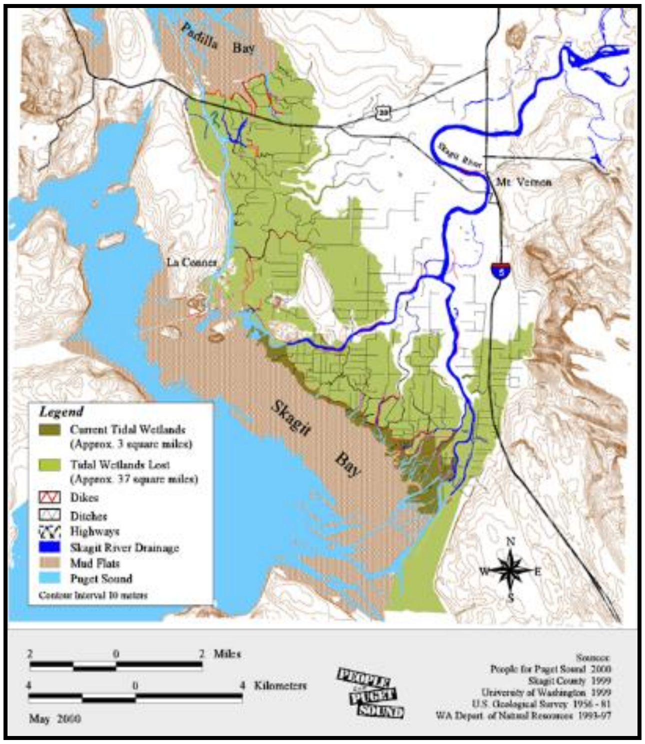

Figure 1.6 Historical and current vegetated tidal wetlands in the Skagit Estuary, Washington (Source: Dean et al., 2000)

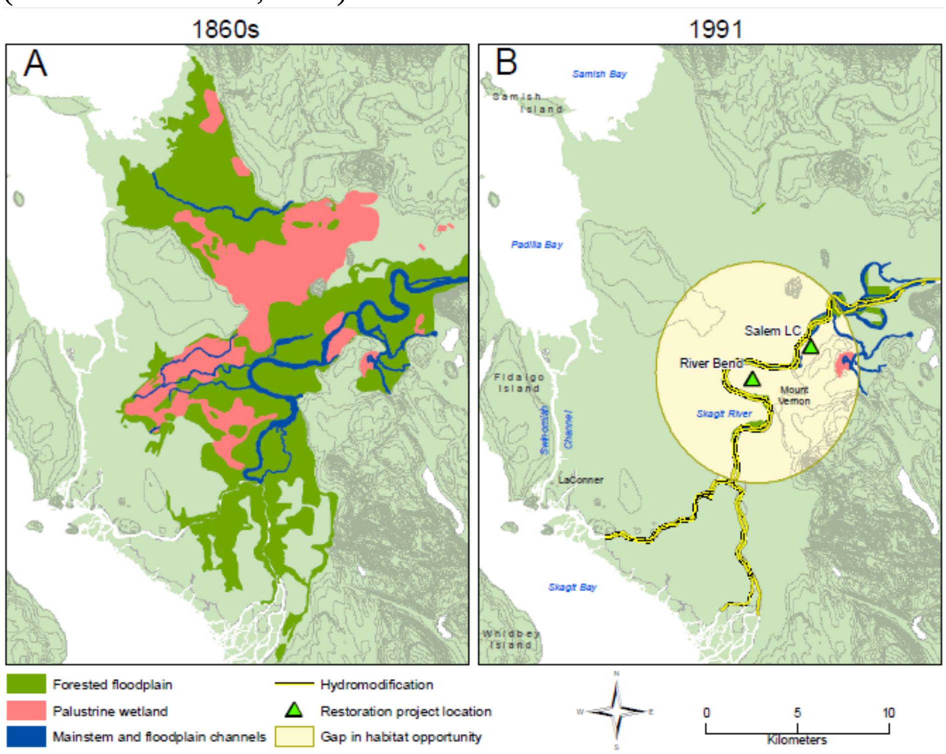

Figure 1.7 Floodplain areas for the non-tidal delta portion of the Skagit River. The map shows changes to floodplain and mainstream habitats (Source: Skagit River System Cooperative and Washington Department of Fish and Wildlife, 2005).

Diking also dramatically changed the processes that created and maintained remaining habitats. Blind tidal channels, which receive freshwater flow during floods but which regularly receive inflows from marine waters during high tides, were reduced in area by 94.6% between southern Padilla Bay and Camano Island (Beamer et al., 2005a). Distributary channels, which delivered water and sediment crucial to estuarine habitats, were cut off from the area between the North and South Forks of the river on lower Fir Island. Including other diked areas to the North, Beamer et al. (2005a) calculated a net loss of 74.6% of tidal estuarine area across the entire geomorphic Skagit delta, from Camano Island to Samish Bay. In addition to losses in total area, estuarine habitats also were disconnected from one another, becoming concentrated at the mouths of the North and South Forks of the river. These changes affected a wide range of species, including Chinook salmon, which particularly rely on estuarine habitats and which are currently listed as threatened under the Endangered Species Act. Beamer et al. (2005a) calculated that the area preferred by delta-rearing Chinook salmon has been reduced 87.9% compared to historic conditions. Upriver, dikes and roads have also dramatically reduced floodplain habitats and limited the processes that create and maintain them. Floodplains provide complex and dynamic habitats important to a wide range of species, including fish, birds, mammals, and amphibians. Between Sedro Woolley and Rockport, Beamer et al. (2005b) found that 31% of the floodplain had been isolated from hydrologic processes by dikes and roads. They found a similar amount of the floodplain was “shadowed” from river hydrology through bank hardening or roads, although these areas were not completely disconnected from the river. As discussed above, these same processes have also dramatically altered the sediment transport processes that create and maintain habitat in the delta (Chapter 6).

1.5 Population Growth and Future Projections

Skagit County’s population grew rapidly during the first half of the twentieth century, from 14,292 in 1900 to 43,273 in 1950. This approximately tripling of the population was, however, slower than average for the Puget Sound area, where the human population more than quintupled over that time (Office of Financial Management, 2007). The pace of Skagit County’s growth slowed significantly between 1950 and 1975, with population increasing less than 25% to 54,100 in 1975. With the completion of Interstate 5, the county's population increased much faster, nearly doubling to 102,979 by 2000 (Office of Financial Management, 2007). The pace of growth has slowed somewhat since then. The Envision Skagit 2060 project estimates that the county's 2010 population was probably slightly below 120,000 (K. Johnson, personal communication). The Envision Skagit 2060 project is considering low, high, and "most likely" projections for the county's population in 2060 of 192,412, 237,352 and 217,578, respectively. The high projection used by the project is an extension of the "medium" projection for the county in 2025 developed by the state Office of Financial Management. City and County planners working with Envision Skagit believed that extending the state's "high" projection for 2025 would be unrealistic over a 50-year time period. The "most likely" projection extends the 2025 planning target being used by the Skagit Council of Governments. These projections are also reasonably well aligned with currently observed growth rates. (K. Johnson, personal communication).

Under the Growth Management Act and the Skagit County Comprehensive Plan, the large majority of growth in the county's population is being directed to urban areas. While the county as a whole is projected to grow 44.8% between 2000 and 2025, the City of Mount Vernon is projected to grow 69.1%, from 28,332 to 47,900. Some urban areas are growing even faster, such as the Bayview urban growth area near the Skagit County Airport, which is projected to more than triple its population over the same period, from 1,700 in 2000 to 5,600 in 2025.

1.6 Summary and Conclusions

The Skagit River basin, which is located in northwestern Washington in the United States, drains an area of 3,115 square miles. Since European-American settlement around the 1850s, the Skagit River basin has been extensively developed. Key findings include the following:

- The formation of valleys, mountains and floodplains of the Skagit River basin has been influenced by both glaciers and volcanic activity. Therefore, geology of different areas of the Skagit River basin varies with its geological origin; the headwaters and middle basin consist of glacial deposits and/or moraines while lowlands of the Skagit River are composed of volcanic sands and laharic deposits.

- The Skagit River basin has been extensively transformed since early European-American settlement in the 19th century by logging, agriculture, urbanization and the construction of dams, dikes, levees, tide gates, channels, roads, and railroads. These human developments have dramatically affected the hydrology, geomorphology, and ecosystems of the basin (discussed in more detail in Chapters 5, 6,7).
- Levees and dikes constrain river flows, facilitating agricultural development and urban and suburban development. This infrastructure reduces flood risk, but does not eliminate the threat of catastrophic floods (discussed in more detail in Chapter 8). Levees and dikes also constrain and redirect the river's transport of sediment, which now concentrates at the mouths of the North and South Forks of the river. Most of the sediment, however, actually bypasses the delta, shore and tidal flats. Sands accumulate mostly on the delta front, while fine sediments that once accumulated in the delta as mud are now exported to distant parts of Skagit Bay and outside Deception Pass. This represents a lost resource to the delta.
- Five dams were built in the Skagit River basin primarily for hydropower generation: Ross, Diablo, and Gorge Dams on the upper Skagit River and Upper and Lower Baker Dams on the Baker River. These dams provide also flood control, recreation opportunities, and diverse ecosystem services.
- Major highways such as I-5 and SR 20 were constructed through Skagit County during the 1960s and the early 1970s and promoted economic and population growth in Skagit County.
- The location of cities in the floodplain increases their vulnerability to projected increases in river flooding due to climate change. Agricultural land and associated drainage infrastructure are vulnerable to sea level rise, especially in combination with projected increases in river flooding (discussed in more detail in Chapter 8).
- Euro-American settlement has dramatically reduced habitat for a wide range of species. As discussed in more detail in Chapter 7, these species are vulnerable to additional stresses imposed by the effects of climate change and population growth.

URL 1: http://www.hydroworld.com/index/display/article-display/350726/articles/hydro-review/volume-26/issue-1/technical-articles/predicting-effects-of-climate-changes-a-study-of-the-skagit-river-hydro-project.html
URL 2: http://www.pse.com/SiteCollectionDocuments/mediaKit/045_Baker_Hydro.pdf

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2. Climate Variability

Abstract

Long historical records of flow in the Columbia River back to about 1860 show that Pacific Northwest (PNW) climate has varied considerably on centennial (century-to-century), decadal (decade-to-decade), and interannual (year-to-year) time scales. Two large scale climate phenomena, the El Niño-Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO), explain the broad features of PNW climate variability in the 20th century (e.g. cool season temperature and precipitation variations) along with associated variations in hydrologic variables (snowpack and streamflow) and hydrologic extremes (floods and droughts) in the PNW. The patterns of climate variability, climate extremes, and associated hydrologic variables are likely to be intensified when the PDO and ENSO are in phase (i.e. warm ENSO/warm PDO or cool ENSO/cool PDO). Similarly, the PDO and ENSO strongly influence the climate and hydrology of the Skagit River basin. Variations in air temperature associated with the PDO and ENSO also affect water temperature for the Skagit River.

2.1 Overview of Historical Variations in Pacific Northwest Climate

The impacts of climate variability on hydrologic systems in the Pacific Northwest (PNW) are dominated by cool season (October to March) precipitation, which effectively "recharges" the region's water systems each year. PNW cool season precipitation and annual river flow have varied considerably on centennial (century-to-century), decadal (decade-to-decade), and interannual (year-to-year) time scales (Mote et al., 2003; Hamlet, 2011). Figure 2.1 shows reconstructed annual flow in the Columbia River at The Dalles from 1958-1998. Annual flow in the Columbia is a good proxy for cool precipitation over the region as a whole (cool season precipitation explains more than 80% of the variance in annual flow), and this relationship is very insensitive to temperature variations (Bumbaco and Mote, 2010). Although trends in annual flow and cool season precipitation in the 20th century (when most observed streamflow and climate records are available) have been relatively small, Figure 2.1 shows that the second half of the 19th century was much wetter than the 20th century in the PNW. In the last 40 years of the 19th century, for example, there were five annual high flow events that were comparable to or larger than the two wettest years on record in the Columbia basin (1974 and 1997). Water year (Oct-Sept) 1894 stands out as an extreme wet year, and produced an instantaneous peak flow in June, 1894 of 1.24 million cfs (USGS peak flow records), almost 25% higher than the highest natural peak flows observed for the Columbia River in the 20th century (May, 1948, 1.01 million cfs). For comparison, the two wettest annual water years in the 20th century, 1974 and 1997, produced estimated natural spring peak flows of about 800,000 cfs, more than 50% below the 1894 peak flow.

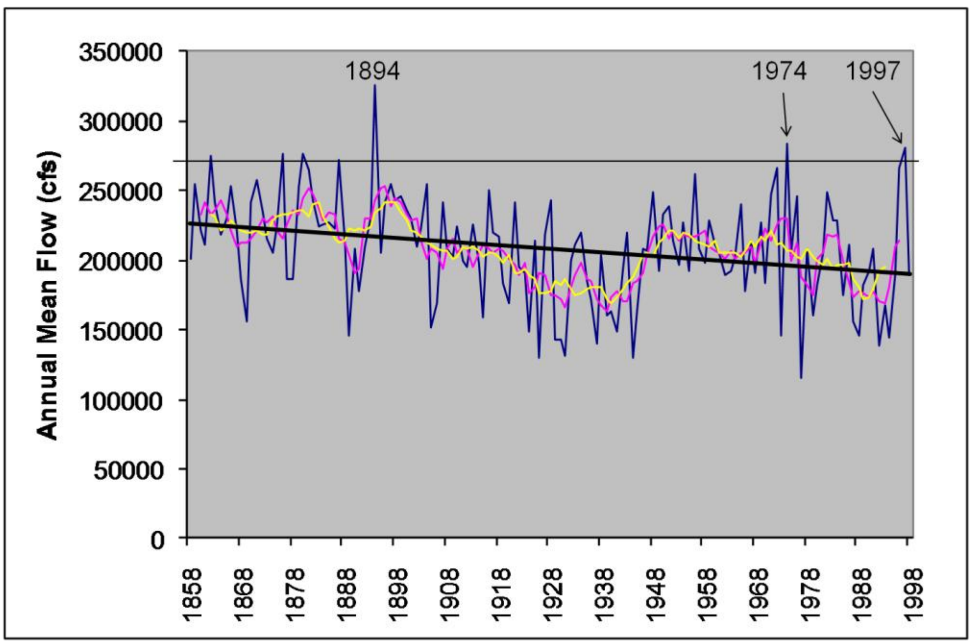

Figure 2.1 Naturalized annual flow in the Columbia River at The Dalles, OR from water years 1858-1998. Flows from water years (Oct-Sept) 1858-1877 are reconstructed from estimates of peak stage from railroad records. Flows from water years 1878-1998 are naturalized data extracted from daily gage records. Magenta and yellow traces show temporally smoothed traces using a five and ten year moving window average respectively (Source: Hamlet, 2011).

Regional summaries of observed precipitation and temperature data show strong 20th century trends in some cases (Figure 2.2). Maximum and minimum daily temperatures in cool season, for example, have exhibited relatively strong warming trends throughout the 20th century. Cool season precipitation, by comparison, has shown relatively little trend. Warm season daily maximum and minimum temperatures show similar patterns to cool season, although minimum temperatures in warm season show stronger trends. Warm season precipitation in the PNW has exhibited strong upward trends over the 20th century. Changes in temperature before about 1970 are believed to be largely related to natural climate variability, whereas changes after 1970 are a mixture of natural (40-65%) and anthropogenic (35-60%) causes (Barnett et al., 2008) (See also Chapter 3). Changes in precipitation over the 20th century have so far not been attributed to anthropogenic climate change, and the dominant hypothesis is that the observed changes are related mostly to climate variability.

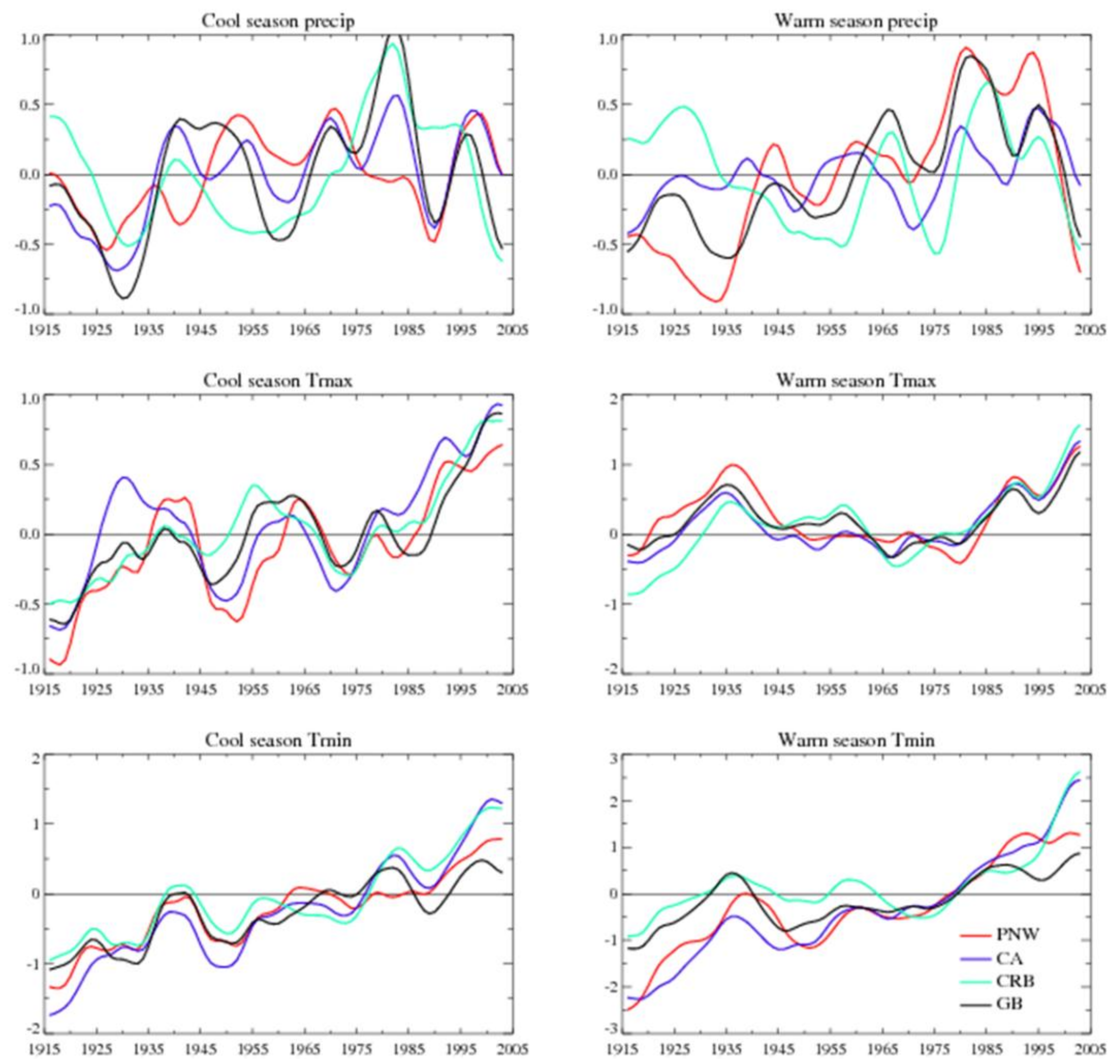

Figure 2.2 A temporally smoothed 20th century time series (1915-2003) of regionally averaged precipitation, maximum temperature, and minimum temperature for the warm and cool season over the western U.S. (Pacific Northwest, California, Colorado River Basin, and Great Basin) (units: standard deviations from the mean) (Source: Hamlet et al., 2007).

2.2 Global Climate Patterns Affecting Pacific Northwest Climate

Two global-scale patterns of climate variability, the El Niño-Southern Oscillation (ENSO) (Battisti and Sarachik, 1995) and the Pacific Decadal Oscillation (PDO) (Mantua et al., 1997), are strongly related to variations in PNW climatological and hydrological variables such as precipitation, temperature, snowpack, and streamflow in the PNW (Piechota et al., 1997; Cayan et al., 1998; Livezey and Smith, 1999; Hamlet and Lettenmaier, 1999; Mote et al., 2003). In this section, we discuss these global climate phenomena and their observed variability over the last 100-150 years.

2.2.1 The El Niño-Southern Oscillation

ENSO is a climate phenomenon directly affecting the tropical Pacific Ocean which impacts regional climate throughout the globe. ENSO is usually defined as a function of wind and sea surface temperatures (SSTs) anomalies (changes from normal conditions) in the tropical Pacific Ocean (Wallace et al., 1998; Battisti and Sarachik, 1995). El Niño (commonly referred to as the *warm phase* of ENSO), refers to the climate conditions characterized by weakened easterly trade winds and unusually warm SSTs in the central and eastern parts of the tropical Pacific. La Niña (commonly referred to as the *cool phase* of ENSO) is essentially the opposite of El Niño and is characterized by warm surface waters pushed far to the west by stronger easterly trade winds and anomalously cold SSTs in the central and easterly parts of the tropical Pacific Ocean (Vecchi and Wittenberg, 2010; Miles et al., 2000). ENSO variations are typically measured via numerical indices such as the Southern Oscillation Index (SOI), which is based on long records of the observed difference in pressure between Tahiti and Darwin, or the Nino3.4 Index (Trenberth, 1997), which is based on SST anomalies in a specific area of the tropical Pacific (covering parts of the Nino3 and Nino4 regions). It is worth noting that although these two indices are broadly equivalent in terms of characterizing historical ENSO events, they are opposite in sign, which sometimes causes confusion. A positive Nino3.4 value corresponds to a negative value of the SOI. For the Nino3.4 index an official definition of ENSO is an anomaly of plus or minus 0.5 ^{o}C (warm or cool respectively) persisting for at least five consecutive and overlapping three month periods. Years which are neither warm nor cool are considered to be ENSO neutral.

ENSO events typically persist for 6 to 18 months and peak in mid-winter (most often in January), when they typically have the greatest effect on regional climate. Warm or cool events have a return interval between two to seven years. ENSO has global impacts, although its effects are regionally specific (Hamlet and Lettenmaier, 1999; Trenberth and Jones, 2007). For instance, ENSO variations (as measured by the Nino3.4 index) are positively correlated with precipitation and streamflow in the U.S. Southwest and Central America and negatively correlated with precipitation and streamflow in the Northwestern U.S. and tropical South America (Gershunov and Barnett, 1998; Hamlet and Lettenmaier, 1999; Cayan et al., 1999; Dettinger et al., 2001; Barton and Ramirez, 2004).

The frequency and amplitude of ENSO have varied considerably over the past 130 years (Folland et al., 2001; Trenberth and Jones, 2007; Wang and Picaut, 2004; Vecchi and Wittenberg, 2010). As shown in Figure 2.3, strong warm and cool ENSO events (measured here by long records of the SOI) occurred about equally often from 1866 to 1925. Strong cool phase events dominate from the mid-1940s to the mid-1970s, after which strong warm phase events have dominated (Folland et al., 2001; Trenberth and Jones, 2007; Wang and Picaut, 2004; Vecchi and Wittenberg, 2010). Since 1976, there was an apparent climate shift to warmer conditions and strong warm ENSO events occurred more persistently (Folland et al., 2001; Trenberth and Jones, 2007; Wang and Picaut, 2004; Vecchi and Wittenberg, 2010), especially from 1990 to 1995, when several weak to moderate El Niño events occurred without alternating with La Niña events (Goddard and Graham, 1997). ENSO variability observed at the end of the 20^{th} century is unprecedented in the record back to 1866. The causes of this unusual variability in ENSO in the last 25 years of the 20^{th} century, including the exceptionally strong El Nino events of 1982/83 and 1997/98, and whether this unusual variability is linked to global warming remains key research questions as noted by Folland et al. (2001) and Trenberth and Jones (2007).

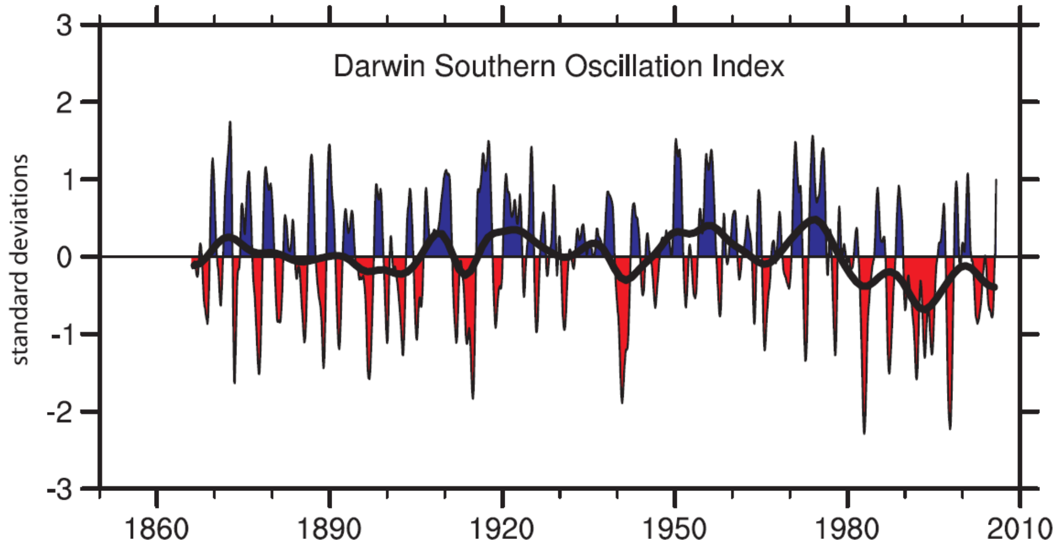

Figure 2.3 The Darwin-based SOI, in normalized units of standard deviation, from 1866 to 2005. The smooth black curve shows decadal variations. Red values indicate positive sea level pressure anomalies at Darwin and thus El Niño conditions (Source: Trenberth and Jones, 2007).

2.2.2 The Pacific Decadal Oscillation (PDO)

The PDO has been described as a long-lived ENSO like pattern of climate variability in the Pacific Basin and North America (Mantua et al., 1997; Miles et al., 2000; Trenberth and Jones, 2007) or as a low-frequency residual of ENSO variability expressing itself on multi-decadal time scales (Trenberth and Jones, 2007; Newman et al., 2003). Newman et al. (2003), for example, demonstrated that simple statistical models representing the persistence of the PDO from year to year combined with an ENSO forcing term could very closely reproduce the variability of the PDO index from one year to the next. In terms of its effects on regional climate, the PDO is different from ENSO in three ways (Miles et al., 2000; Mote et al., 2003; Moore et al., 2008). First, warm and cool PDO events show much longer temporal persistence in comparison with ENSO events. Warm or cool PDO events typically persist for 20 to 30 years while ENSO events persist for 6-18 months. Secondly, the PDO has its most pronounced climatic influence in the central and North Pacific with a more secondary climatic influence in the tropics, while the opposite is true for ENSO. Finally, the observed time series behavior of the PDO is much less well understood than ENSO in part because only a few cycles of the PDO are represented in the relatively short observed climate records available.

The PDO index is based on the Empirical Orthogonal Function (EOF) analysis, a statistical technique which decomposes the spatial and temporal patterns of SST for the Pacific basin north of 20 ^{o} N into a single time series which explains most of the variance in these patterns (Mantua et al., 1997). The PDO index is used in this report primarily to characterize decadal climate variability in the PNW (Hamlet and Lettenmaier, 1999). The PDO had five phases during the 20th century (Figure 2.4): weak warm (positive index values) and cool (negative index values) excursions were present from 1900 to 1924 then predominantly in the warm phase from 1925 to 1946, in the cool phase from 1947 to 1976, and again in the warm phase with several relatively brief excursions to the cool phase (URL 1) from 1977 to the present. It is worth noting that estimates of the PDO in the early 20th century (prior to about 1950) are more uncertain than at the end of the record due to relatively few SST measurements in the early record.

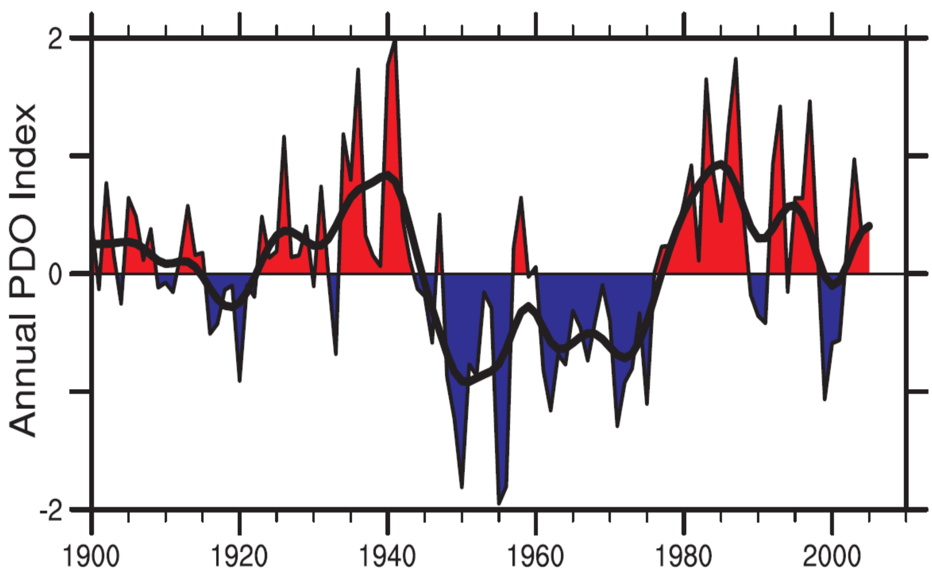

Figure 2.4 Annual time series Pacific Decadal Oscillation (updated from Mantua et al., 1997). The smooth black curve shows decadal variations (Source: Trenberth and Jones, 2007)

2.3 Impacts of ENSO and the PDO on Pacific Northwest Climate and Hydrology

In this section, we discuss regional-scale variations in climatological and hydrological variables associated with ENSO and the PDO. These relationships were created based on the PDO and ENSO definitions defined in Table 2.1. For example, in estimating temperature anomalies associated with warm ENSO years, temperature data from all the warm ENSO years (as defined in the table) were averaged and compared to the same quantities for cool ENSO and ENSO neutral years.

Table 2.1 Retrospective Definitions of Warm, Neutral, and Cool ENSO and PDO Years (Source: Hamlet and Lettenmaier, 2007).

Climate Category	Index Used	Definition
Warm ENSO	NINO 3.4	> 0.5 std. deviations above the mean for DJF mean
ENSO neutral	NINO 3.4	Neither warm nor cool
Cool ENSO	NINO 3.4	< -0.5 std. deviations above the mean for DJF mean
Warm PDO	PDO	> 0.5 std. deviations above the mean for ONDJFM mean
PDO neutral	PDO	Neither warm nor cool
Cool PDO	PDO	< -0.5 std. deviations above the mean for ONDJFM mean

2.3.1 PNW Temperature and Precipitation

Warm ENSO (El Niño) events generally produce warmer and drier winter/spring weather in the PNW (Hamlet and Lettenmaier, 1999; Miles et al., 2000; Mote et al., 2003; Moore et al., 2008), whereas cool ENSO (La Niña) events produce cooler and wetter conditions. As shown in Figure 2.5, warm ENSO years are likely to have higher cool season (Oct-Mar) temperature (about 1°C (1.8 °F) warmer) and lower cool season precipitation (by about 10%) in comparison with cool ENSO years. Cool season temperature and precipitation anomalies (i.e. changes from the mean) associated with the PDO are broadly similar to those shown for ENSO (Figure 2.5). Warm phase PDO shows higher temperature and lower precipitation than cool phase PDO in the cool season (see Figure 2.5). When the PDO and ENSO are in phase (e.g. warm ENSO/warm PDO or cool ENSO/cool PDO), these patterns of climate variability positively reinforce each other. That is, the likelihood of unusually warm and dry winter/spring weather is especially high in years when a warm ENSO event coincides with warm PDO (Gershunov and Barnett, 1998; Miles et al., 2000; Mote et al. 2003). Conversely, cool ENSO/cool PDO years are strongly associated with unusually cool and wet conditions.

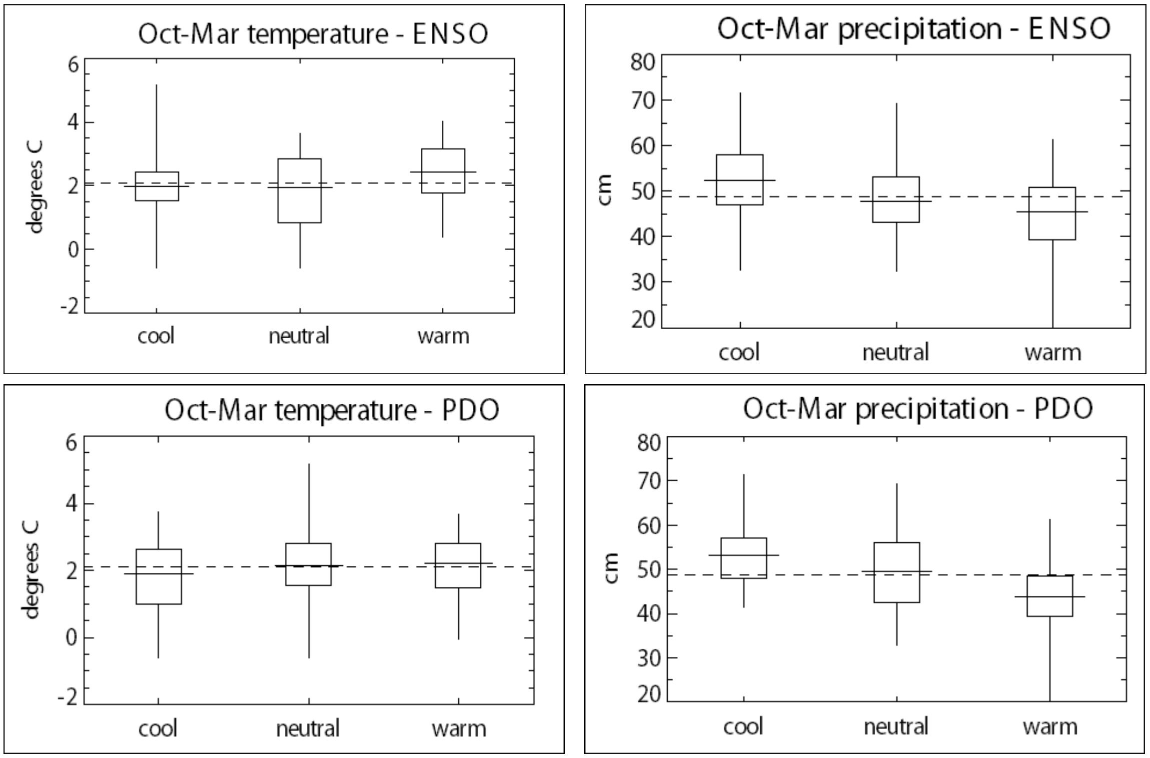

Figure 2.5 Box-and-whisker plots showing the influence of ENSO (top) and the PDO (bottom) on October-March temperature and precipitation (1899-2000) for the PNW. For each plot, years are categorized as cool, neutral, or warm phases. For each climate category, the distribution of the variable is indicated as follows: range of values (whiskers); mean value for the phase category (solid horizontal line); regional mean for all categories combined (dashed horizontal line); 75th and 25th percentiles (top and bottom of box). Area-averaged Climate Division data are used for temperature and precipitation (Source: URL 2).

2.3.2 Effects of the PDO and ENSO on PNW Hydrology

The PDO and ENSO influence temperature and precipitation patterns in the PNW (warm and dry or cool and wet) as mentioned above, and thus these patterns of climate variability also influence hydrologic variables such as snowpack and streamflow in the PNW (Piechota et al., 1997; Cayan et al., 1998; Hamlet and Lettenmaier, 1999; Livezey and Smith, 1999). The effects of climate variability on April 1 snow water equivalent (SWE) in the Western United States have been well documented in previous work (Clark et al., 2001; Hamlet et al., 2005; Mote, 2006). Hamlet et al. (2005) and Mote (2006) examined the separate roles of precipitation and temperature in producing the trends in SWE. They found that the April 1 SWE was negatively correlated with cool season temperature and positively correlated with cool season precipitation in the PNW. Because warm (cool) phases of ENSO and the PDO produce warmer and drier (colder and wetter) winters in the PNW, warm (cool) phases of ENSO and the PDO are associated with lower (higher) SWE as shown in Figure 2.6.

When the PDO and ENSO are in phase (i.e. warm PDO/ El Niño), these April 1 SWE anomalies tend to be enhanced (see Figure 2.6 right). These effects are more pronounced in relatively warm areas in the PNW such as the western slopes of the Cascades because spring snowpack in near-coastal mountain ranges is strongly affected by cool season temperature (Hamlet et al., 2005; Mote et al., 2005; Mote et al., 2007).

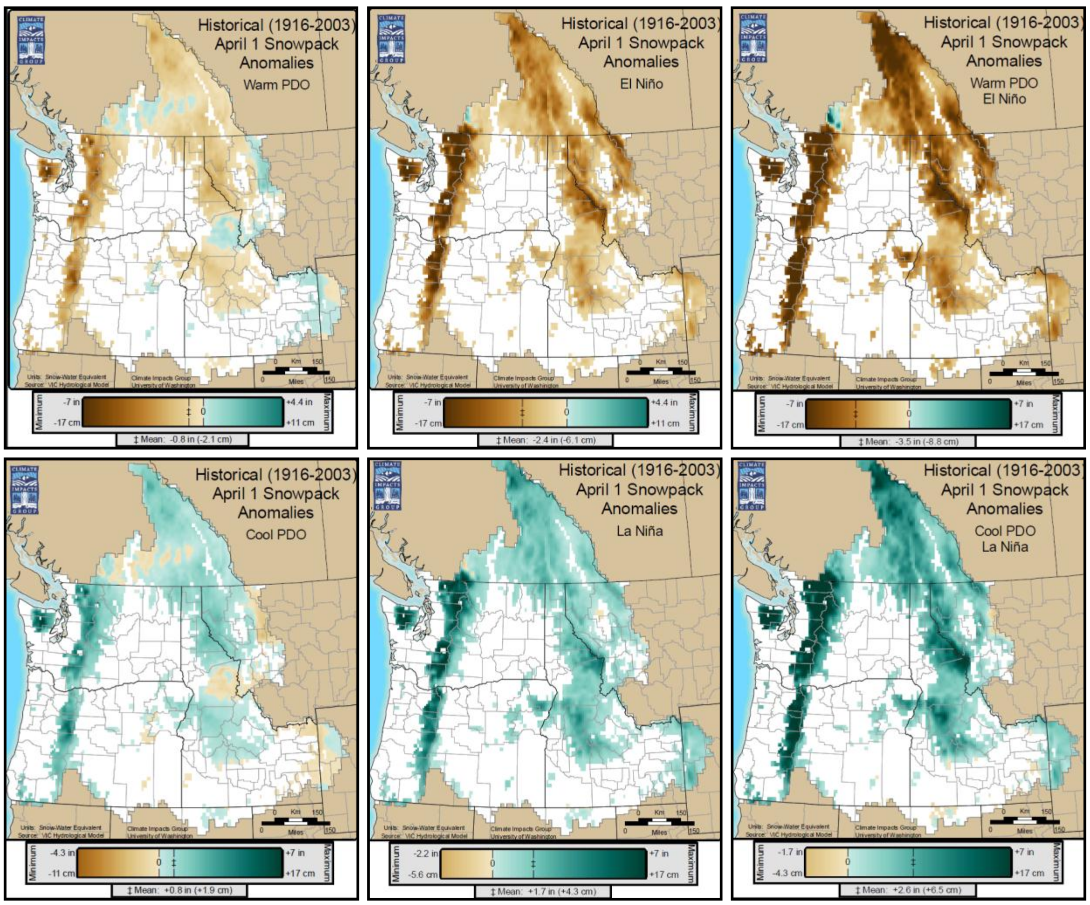

Figure 2.6 Anomalies (i.e. changes from the mean) in April 1 SWE over the 1916-2003 period of record for the Columbia River basin for the PDO phases based on historical epochs (left), for ENSO phases based on Dec-Feb averaged Nino3.4 Index (middle) and for the PDO and ENSO in phase (right). Top panels show warm phase signals, lower panels show cool phase signals (Source: URL 3).

The correlation between streamflow and the PDO and ENSO in the PNW is also well-established (Hamlet and Lettenmaier, 1999; Gershunov and Barnett, 1998; Cayan et al., 1999; Dettinger et al., 2001; Barton and Ramirez, 2004; Miles et al., 2000; Mote et al., 2003). Monthly naturalized streamflow at The Dalles, for example, shows that warm phases of the PDO and ENSO produce lower monthly streamflow in comparison with cool phases of the PDO and ENSO, with the largest response in June (see in Figure 2.7) (Hamlet and Lettenmaier, 1999; Miles et al., 2000; Mote et al., 2003). Coincidence of warm (cool) phases of ENSO and the PDO tends to enhance these streamflow anomalies: cool ENSO/cool PDO produces much higher streamflow in June in comparison with warm ENSO/warm PDO (see lower panel in Figure 2.7).

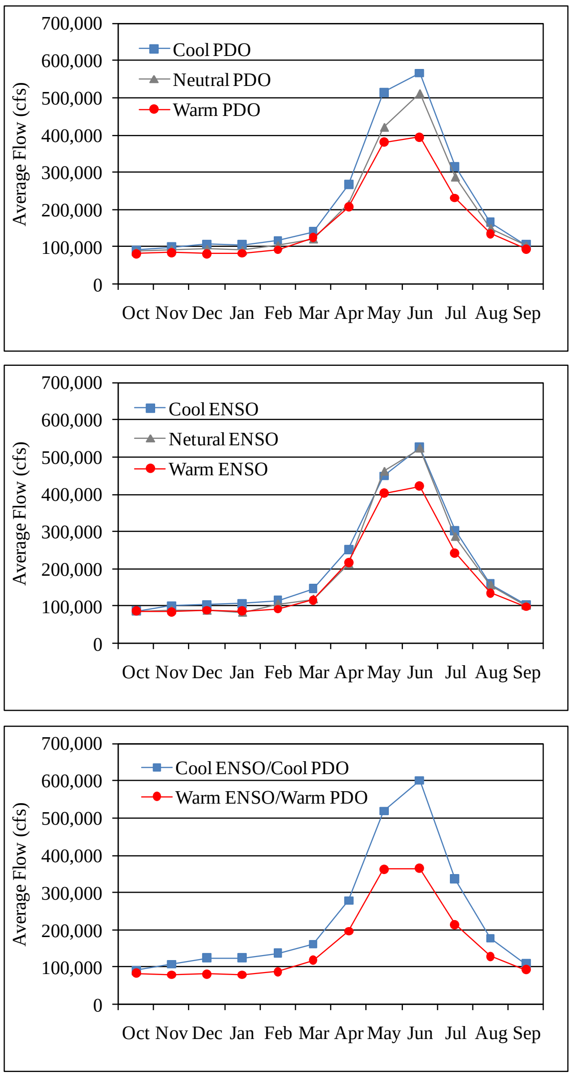

Figure 2.7 Composite monthly naturalized hydrographs for the Columbia River at The Dalles (water years 1931 -1989) for the PDO phases based on the PDO index (top), ENSO phases based on Dec-Feb averaged Nino3.4 Index (middle) and the PDO and ENSO in phase (bottom).

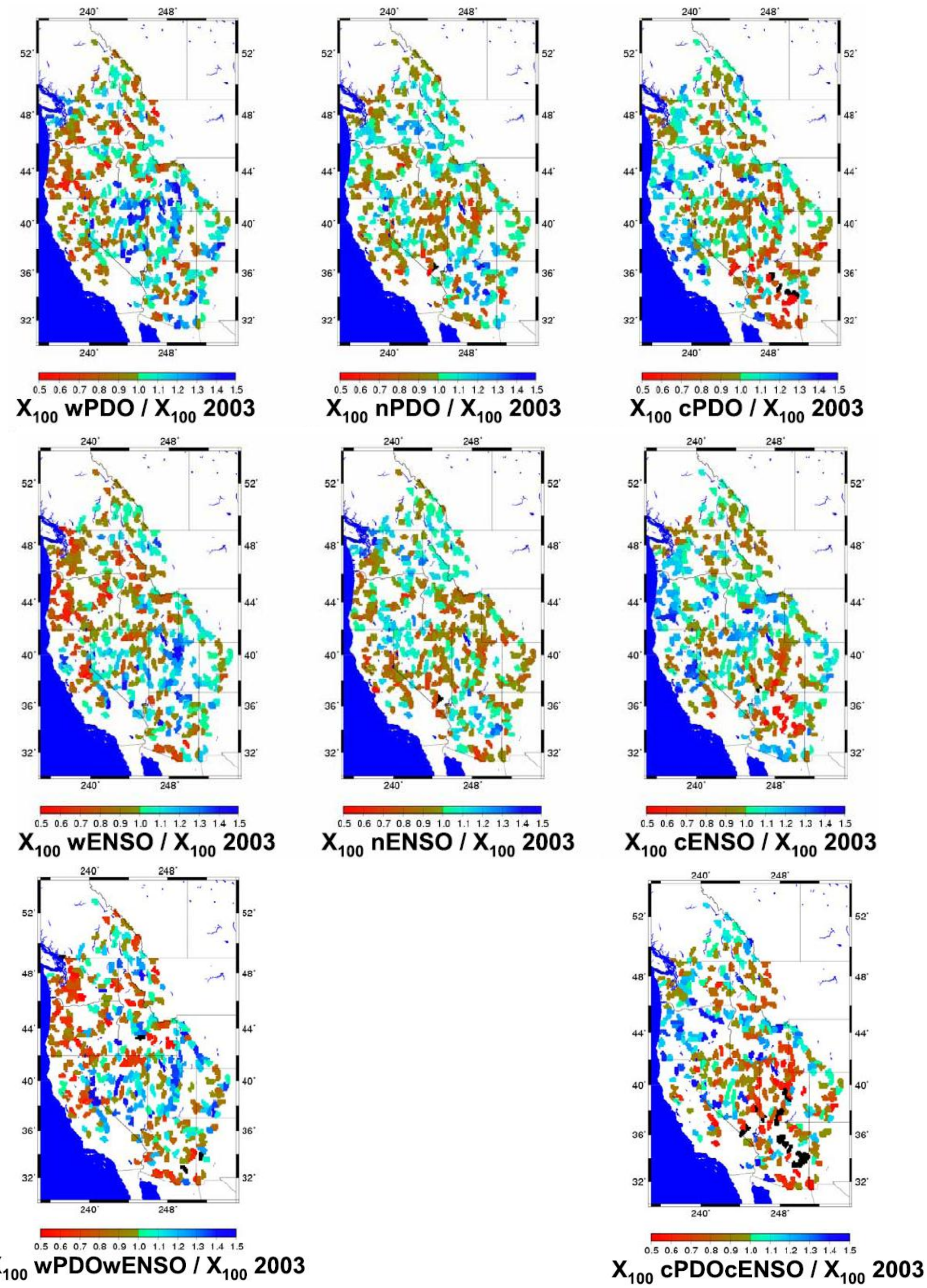

Figure 2.8 Spatial plots of change in s flood risk simulated by a hydrologic model for medium sized river basins (~1700 km^2) across the western U.S. showing the ratio of the estimated 100-year flood for the PDO (top), ENSO (middle) and combined the PDO and ENSO (bottom) to the estimated 100 year flood for all years. (Source: Hamlet and Lettenmaier, 2007).

The incidence of hydrologic extremes such as droughts and floods in the PNW is also influenced by the PDO and ENSO. For example, flood risks are generally higher in the PNW during cool phases of the PDO and ENSO and lower during warm phases of the PDO and ENSO, with large impacts in coastal area (Figure 2.8) (Hamlet and Lettenmaier, 2007). When the PDO and ENSO are in phase, the impacts on changes in flood risks are intensified as shown in the bottom panels in Figure 2.8. Since 1900, five of the six extreme multi-year droughts occurred during the warm phase of the PDO and four of the five highest flow years happened during the cool phase of the PDO (three of them when ENSO was also in its cool phase) (Mote et al., 2003). When these two oscillations are out of phase, observed streamflow tends to vary near the long-term mean (Hamlet and Lettenmaier, 1999; Miles et al., 2000; Mote et al., 2003).

2.4 ENSO and PDO Impacts on the Skagit River Basin's Climate and Hydrology

In this section, we extend the regional analysis presented above to discuss the effects of the PDO and ENSO on the climate and hydrology of the Skagit River basin alone.

2.4.1 Skagit Basin Temperature and Precipitation

Impacts of natural climate variability on temperature and precipitation for the Skagit River are shown in Figure 2.9. Following similar trends over the PNW, warm (cool) phases of ENSO and the PDO produce warmer and drier (cooler and wetter) winter in the Skagit River. When ENSO and the PDO are in phase, the climate anomalies are intensified. Averaged Oct-Mar temperature is 1.4 ^{o}F and 1.7 ^{o}F higher for warm phases of the PDO and ENSO in comparison with cool phases of the PDO and ENSO, respectively. When the PDO and ENSO are in phase, the difference of Oct-Mar temperature between warm and cool phases is significantly increased to 2.8 ^{o}F. Precipitation anomalies are also increased by about a factor of two when the PDO and ENSO are in phase.

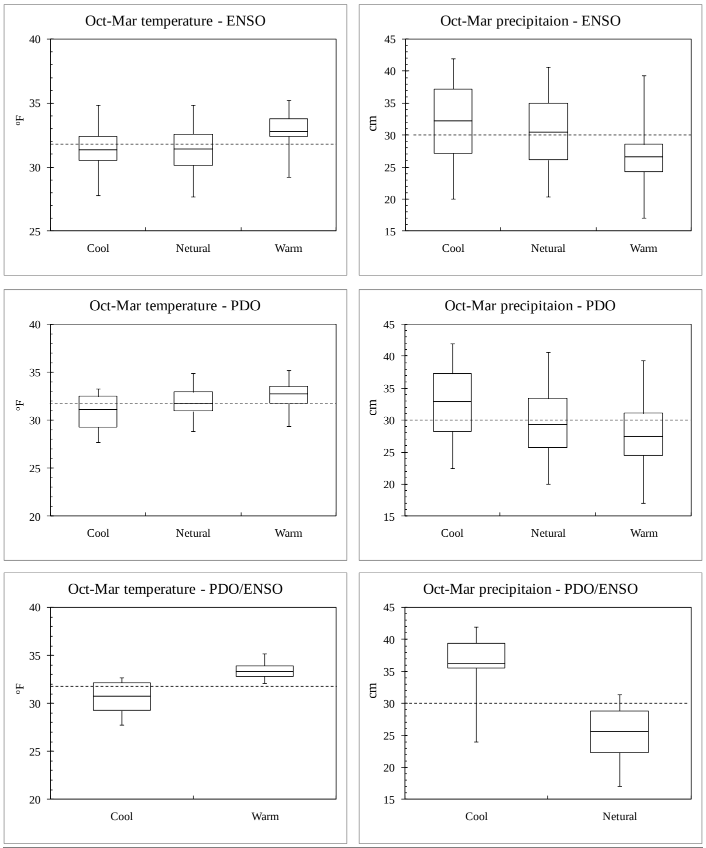

Figure 2.9 Same as Figure 2.5 but the influence of ENSO (top), the PDO (middle) and combined the PDO and ENSO (bottom) on October-March temperature and precipitation (1916-2006) for the Skagit River.

2.4.2 Skagit Basin Snowpack

As mentioned above, the PDO and ENSO have a pronounced influence on snowpack variability in the relatively warm mountain areas on the western slopes of the Cascades (see Figure 2.6). This enhanced sensitivity to both temperature and precipitation is shown in simulations of SWE for the Skagit River basin (Figure 2.10). On average, April1 SWE during warm phases of ENSO and PDO years is 42 % and 58 % lower than those associated with cool phases of ENSO and the PDO, respectively. When the PDO and ENSO are in phase (i.e. warm ENSO/warm PDO or cool ENSO/cool PDO), average April 1 SWE is 86% lower in warm ENSO/warm PDO phase than cool ENSO/cool PDO phase (Figure 2.10). Minor timing shifts in the date of peak SWE are also apparent for warm phase years.

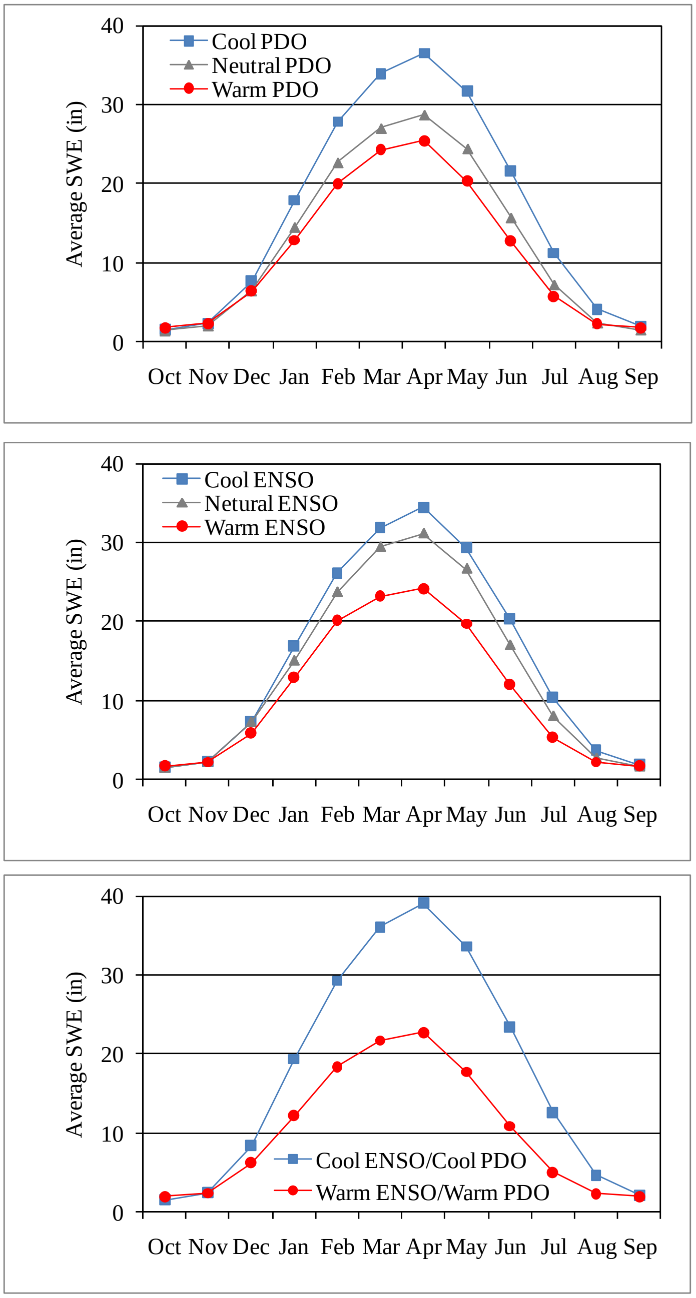

Figure 2.10 Composite monthly simulated snow water equivalent (SWE) for the Skagit River (water years 1916 -2006) for the PDO phases based on the PDO index (top), ENSO phases based on Dec-Feb averaged Nino3.4 Index (middle) and the PDO and ENSO in phase (bottom).

2.4.3 Skagit Basin Streamflow

The PDO and ENSO impacts on streamflow for the Skagit River are illustrated by composite average monthly hydrographs for Ross reservoir near Newhalem (Figure 2.11), for the Sauk

River near Sauk (Figure 2.12) and for the Skagit River near Mount Vernon (Figure 2.13). Monthly naturalized flows for water years 1916-2006 and 1929 -2006 are used for Ross reservoir and for the Sauk River, respectively. Naturalized streamflows are not available for the Skagit River near Mount Vernon, thus streamflows simulated by the Variable Infiltration Capacity hydrologic simulation model (Liang et al., 1994) for water year 1916-2006 are used for the Skagit River near Mount Vernon (URL 4). As shown in Figures 2.11 to 2.13, the responses of annual streamflow to the PDO and ENSO in the Skagit River basin are similar to those experienced in the Columbia River basin, but seasonal responses are somewhat different between the two basins. For both the Columbia River basin and the Skagit River basin, a strong hydrologic response to the PDO and ENSO is observed during summer. In comparison with the Columbia River basin (see Figure 2.7), the Skagit River streamflows show a larger hydrologic response during wintertime (see Figures 2.11 through 2.13). These differences reflect the fact that the Columbia River basin is a strongly snowmelt dominant watershed, whereas the Skagit River basin is warmer and has more temperature sensitive snowpack, which results in a larger streamflow response to precipitation falling as rain in the fall and early winter and a somewhat less pronounced snowmelt peak in spring (Elsner et al., 2010). Thus, winter precipitation anomalies in the Skagit associated with the PDO and ENSO produce a greater streamflow response in the Skagit in the fall and early winter, and warm season flow in the Skagit is more strongly coupled to temperature in cool season. Correlations between Apr-Sep streamflow and Oct-Mar temperature are helpful in quantifying the relationship between cool season temperature and warm season flow. The correlation coefficient between these two variables for the Columbia River at The Dalles is -0.09. By contrast, the correlations for the Skagit River Ross Dam, the Sauk River, and Mount Vernon are -0.38, -0.49 and -0.39 respectively. In other words, Apr-Sep streamflows for the Skagit River are more strongly correlated with cool season temperature in comparison with the Columbia River basin. (Similar relationships between cool season temperature and April 1 SWE are also present in the North Cascades (see Mote, 2006) and, in fact, the sensitivity of SWE to temperature is one of the primary causes of the warm season streamflow anomalies discussed above.) Note also that hydrographs associated with ENSO neutral and cool ENSO years are quite similar to each other.

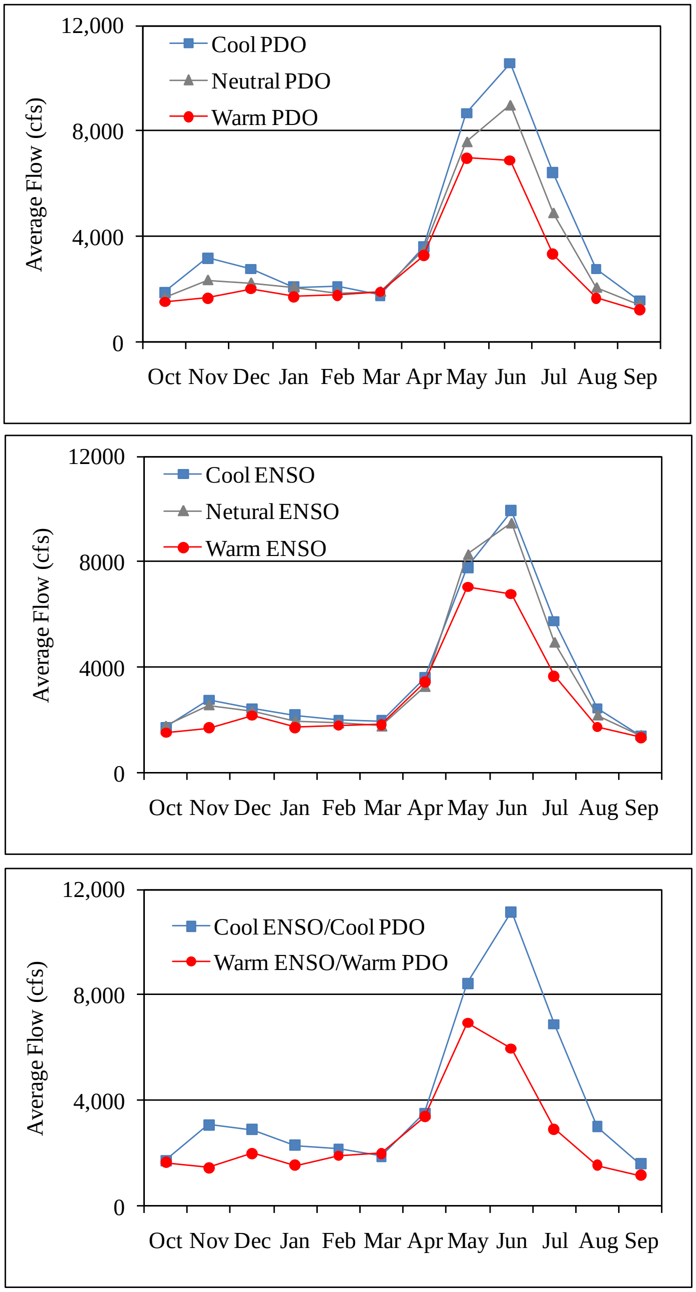

Figure 2.11 Composite monthly naturalized streamflow for Ross reservoir near Newhalem (water years 1916 -2006) for the PDO phases based on the PDO index (top), ENSO phases based on Dec-Feb averaged Nino3.4 Index (middle) and the PDO and ENSO in phase (bottom).

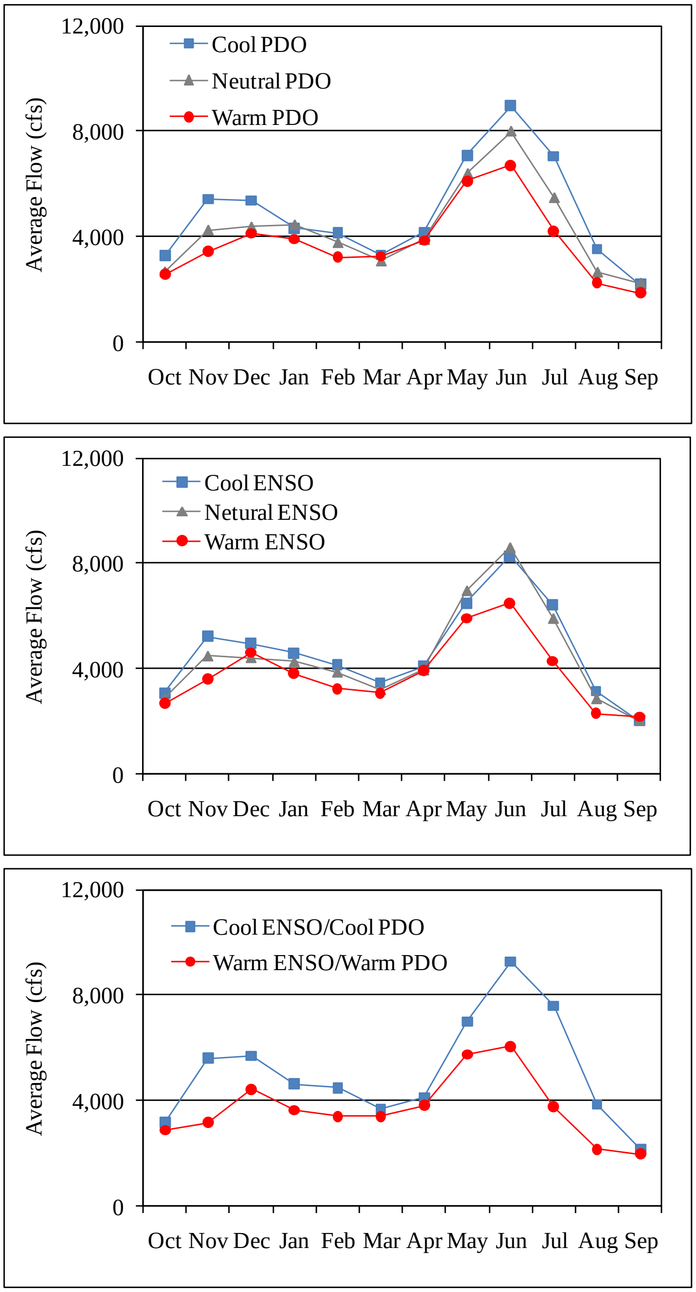

Figure 2.12 Composite monthly naturalized streamflow for the Sauk River near Sauk (water years 1929 -2006) for the PDO phases based on the PDO index (top), ENSO phases based on Dec-Feb averaged Nino3.4 Index (middle) and the PDO and ENSO in phase (bottom).

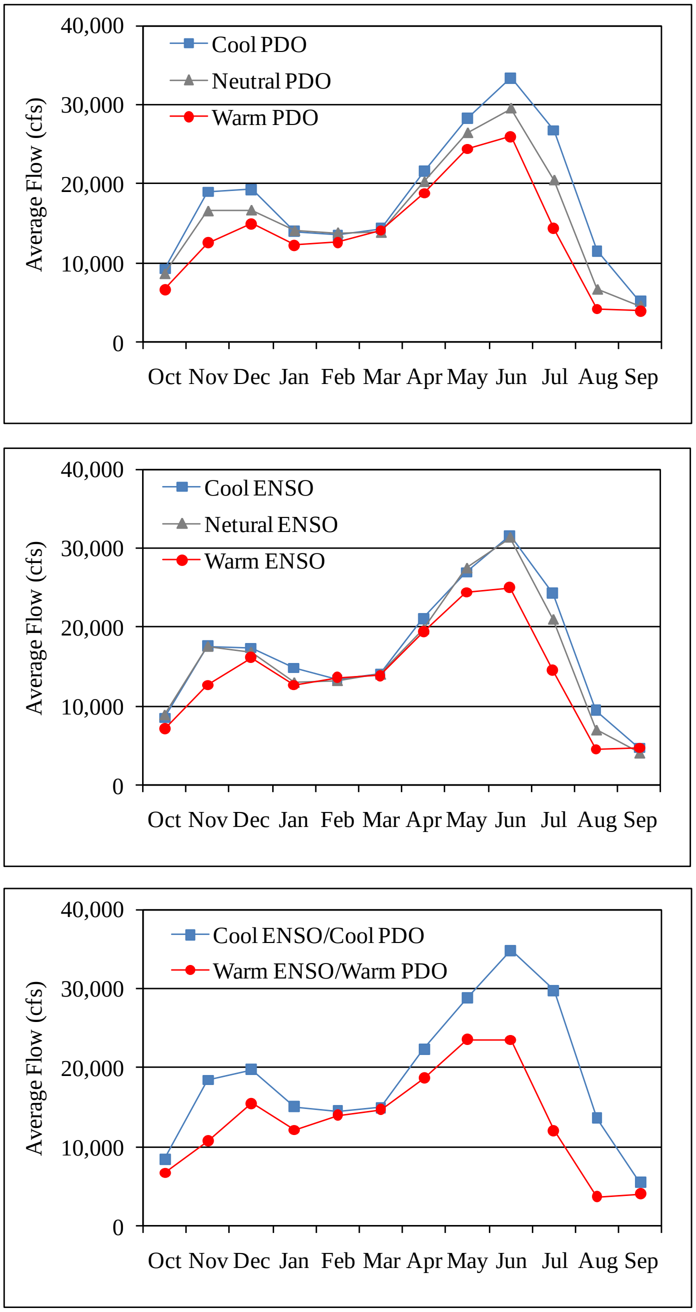

Figure 2.13 Composite monthly raw VIC simulated streamflow for the Skagit River near Mount Vernon (water years 1916 -2006) for the PDO phases based on the PDO index (top), ENSO phases based on Dec-Feb averaged Nino3.4 Index (middle) and the PDO and ENSO in phase (bottom).

2.4.4 Skagit Basin Flood Risk

Retrospective hydrologic modeling studies show that the North Cascades area typically experiences the highest flood risk in cool PDO epochs and ENSO-neutral years in (Figure 2.8) (Hamlet and Lettenmaier, 2007). The same study showed that twentieth century warming trends and increases in cool season precipitation variability that have occurred across the West since about 1975 have strongly increased flood risk in western Washington State. A long unregulated peak flow record is available for the Sauk River near Sauk, WA (a tributary to the Skagit), which shows the expanding variance of peak flows since the mid-1970s associated with the increasing cool season precipitation variance (Figure 2.14). Note also that the four highest peak flow events have all occurred in the last 30 years or so.

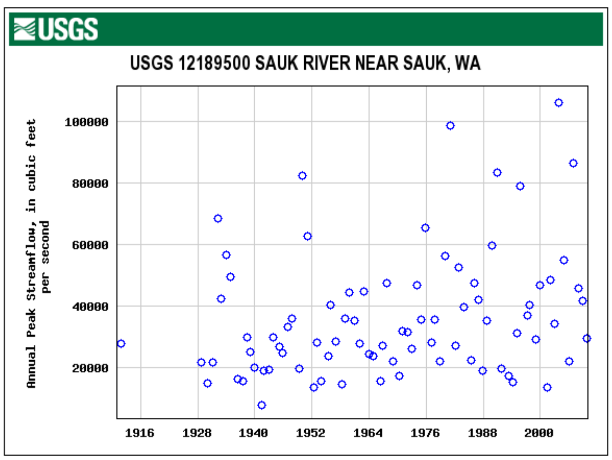

Figure 2.14 Observed instantaneous peak flow in the unregulated Sauk River near Sauk from 1928-2009 (Source: USGS).

The observed increases in precipitation variability, and the associated recent increases in flood risk are currently hypothesized to be related primarily to climate variability, but the observed changes in flood risk may also be related to changing intensity of atmospheric rivers (also called “pineapple express” storms) and warmer temperatures that may have some connection to global climate change (Chapter 3). Neiman et al. (2010), for example, show that many of the largest flood events in western WA in recent decades have been caused by intense atmospheric rivers that deliver both warm temperatures and intense precipitation to the PNW coast. Such storms are hypothesized to increase in intensity with the increased sea surface temperatures in the tropics (the primary source of moisture) and the moisture holding capacity of a warmer atmosphere.

2.4.5 Skagit Basin Water Temperature

The composite weekly water temperature for the Skagit River above Sedro Woolley is shown in Figure 2.15.

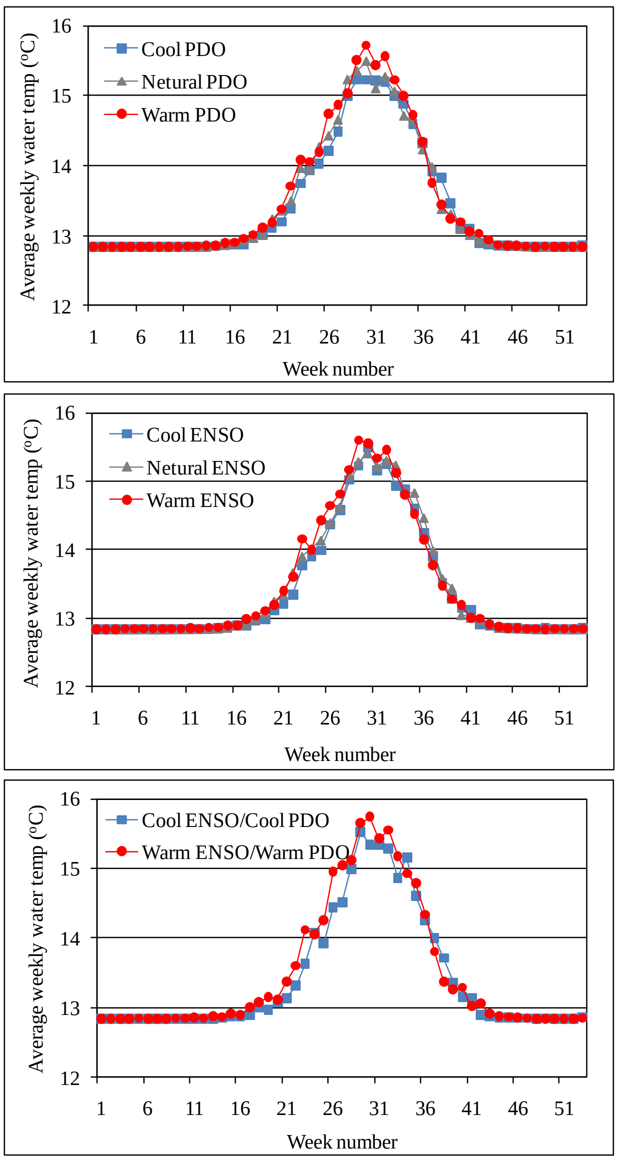

Figure 2.15 Composite weekly water temperature for the Skagit River above Sedro Woolley (water years 1916 -2006) for the PDO phases based on the PDO index (top), ENSO phases based on Dec-Feb averaged Nino3.4 Index (middle) and the PDO and ENSO in phase (bottom) (data source: Hamlet et al., 2010 a).

The warm phase of PDO and ENSO are typically associated with warmer water temperature for the Skagit River. When the PDO and ENSO are in phase, the impacts on water temperature tend to be enhanced.

2.4.6 Heating and Cooling Energy Demand

A heating (cooling) degree day is a measurement which relates a daily average temperature to an index value that is approximately proportional to the energy needed to heat (cool) a home or business (the actual energy use is a function of insulation values, etc.). Heating degree days (HDD) and cooling degree days (CDD) are calculated from the difference between a daily average temperature and a base temperature as follows:

$$HDD = \max(0, 18.33 - t_{avg}) \qquad (1)$$

$$CDD = \max(0, t_{avg} - 23.89) \qquad (2)$$

where t_{avg} is a daily average temperature in degrees Celsius, and 18.33 ^{o}C (65 ^{o}F) and 23.89 ^{o}C (75 ^{o}F) are base temperatures for HDD and CDD, respectively (Hamlet et al., 2010 b). The long term annual average HDD and CDD calculated for historical data (water years 1916 to 2006) for western WA are 3730 ^{o}C (6746 ^{o}F) and 28 ^{o}C (82 ^{o}F), respectively. Figure 2.16 shows special patterns of HDD and CDD in western WA, which vary according to proximity to the coast and elevation. For comparison, observed long-term average heating degree days at Mount Vernon are about 5330 (°F) and cooling degree days (based on the 75° F threshold above) are essentially zero. Thus, energy demand for space heating in the Skagit basin is dominated by heating degree days. Heating degree days are only moderately affected by temperature variability associated with the PDO and ENSO. A warming of 1° C (1.8° F) associated with ENSO, for example, results in about a 10% decrease in heating degree days in the Puget Sound lowlands.

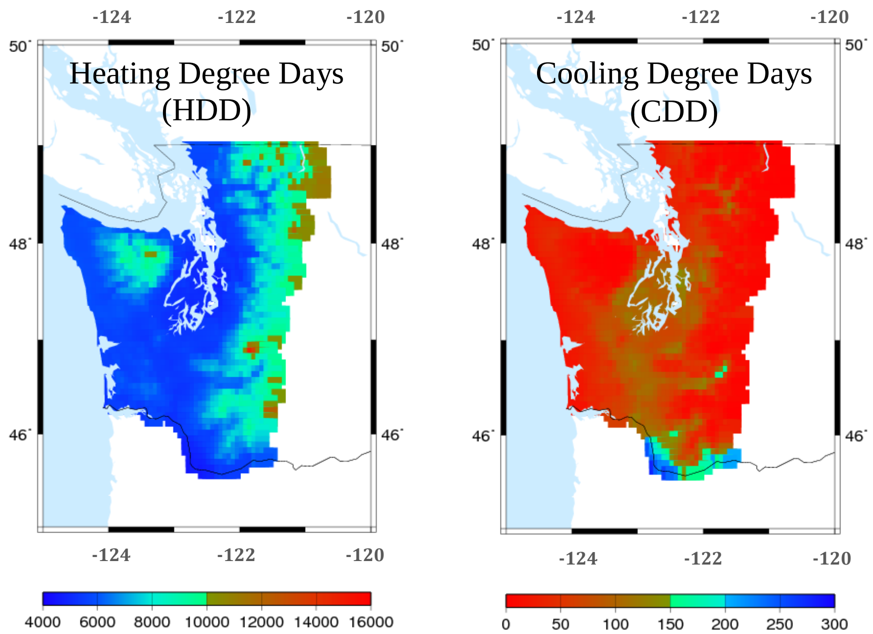

Figure 2.16 Long-term average annual total heating degree days (HDD)(right panel) and cooling degree days (CDD) (left panel) (in ^{o}F) for west Washington (1916-2006). HDD are based on a threshold of 18.33 ^{o}C (65 ^{o}F). CDD are based on a threshold of 23.89 ^{o}C (75 ^{o}F) (Adapted from HDD and CDD databases produced by Hamlet et al., 2010 b).

2.5 Summary and Conclusions

Two large-scale climate phenomena, the El Niño-Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO), influence temperature and precipitation patterns in the PNW. These patterns of climate variability also influence hydrologic variables such as April 1 SWE, streamflow, and hydrologic extreme such as droughts and floods in the PNW. Coincidence of warm (cool) phases of the PDO and ENSO tends to enhance the patterns of climate variability and associated anomalies in hydrologic variables and hydrologic extremes. Similarly, the PDO and ENSO have influenced climatological and hydrological variables in the Skagit River basin. Key findings include the following:

- Observed variations in temperature and precipitation in the PNW over the 20th century are mostly related to natural climate variability, although anthropogenic climate change has substantially influenced changes in temperature after 1970 (see also Chapter 3).

- Warm phases of the PDO and ENSO generally produce warmer and drier winter/spring weather over the PNW while cool phases of the PDO and ENSO produce cooler and wetter conditions.
- April 1 SWE is negatively correlated with cool season temperature and positively correlated with cool season precipitation. Therefore, warm phases of the PDO and ENSO are associated with lower April 1 SWE but cool phases of the PDO and ENSO are associated with higher April 1 SWE. The impacts of climate variability on April 1 SWE are pronounced in coastal Washington State which is a relatively warm area.
- Similar to the impacts of climate variability on SWE, warm phases of the PDO and ENSO produce lower streamflows than cool phases of the PDO and ENSO, with largest response in June.
- Coincidence of warm/cool phases of the PDO and ENSO tends to enhance the patterns of climate variability and subsequently the anomalies in hydrologic variables such as SWE and streamflow and the incidence of hydrologic extremes such as floods and droughts.
- Consistent with the impacts of the PDO and ENSO on climate over the PNW as a whole, temperature and precipitation along with associated hydrologic variables and hydrologic extremes for the Skagit River are strongly influenced by the PDO and ENSO.
- Hydrologic variables in the Skagit River correlate better with cool season temperature in comparison with the PNW as a whole. As a result, the PDO and ENSO have a more pronounced influence on snowpack and streamflow for the Skagit River basin in comparison with the PNW as a whole.
- The water temperature for the Skagit River above Sedro Woolley is higher for warm phases of the PDO and ENSO in comparison with cool phases of the PDO and ENSO. The coincidence of warm phases of the PDO and ENSO increases the likelihood of unfavorable summer water temperatures for cold water fish.
- Energy demand for the Skagit River basin is dominated by heating degree days. Heating degree days are only moderately affected by temperature variability associated with the PDO and ENSO.

URL 1: http://cses.washington.edu/cig/pnwc/compensopdo.shtml

URL 2: http://cses.washington.edu/cig/pnwc/clvariability.shtml

URL 3: http://cses.washington.edu/cig/maps/

URL 4: http://www.hydro.washington.edu/2860/

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3. Climate Change Scenarios

Abstract

Physically based scenarios of future climate are essential in assessing the potential impacts of climate change and supporting related long-term planning activities and policy decisions. To project future climate, global climate models (GCMs) and regional climate models (RCMs) are used. In studies assessing climate impacts, the outputs from GCMs or RCMs are used as inputs to hydrologic models. However, the outputs from GCMs or RCMs are at a relatively coarse spatial and temporal resolution. These coarse spatial and temporal scales are not matched to the hydrologic models, which are typically implemented at much finer resolution. Thus, post-processing of the GCM data, or “downscaling”, is commonly used to obtain data at a finer resolution. Climate change is projected to have a significant effect on meteorological and hydrological variables such as temperature, precipitation, and sea-level over the Pacific Northwest (PNW) and for the Skagit River. Temperature is projected to increase for both the PNW and the Skagit River basin, though a smaller increase in temperature is expected for the Skagit River basin in comparison with the PNW as a whole. Average temperatures for the Skagit basin by the 2080s are projected to be 5.8 ^{o}F (A1B scenario) and 4.0 ^{o}F (B1 scenario) warmer than the 20th century baseline. Although changes in annual mean precipitation are small in future projections, substantial seasonal changes in precipitation are projected for both the PNW and the Skagit River basin, with increasing precipitation projected in winter, spring, and fall and decreasing precipitation projected in summer. Average changes in precipitation for the Skagit River basin by the 2080s (for A1B) are projected to be 9.8 %, 8.0 % and 19.2 % increase in winter, spring, and fall precipitation, respectively, with a 27.6 % decrease in summer precipitation. Global sea level has risen through the 20th century and is currently rising at an increasing rate. Sea levels are projected to increase substantially over the 21st century in the PNW. Very conservative estimates based on projections from the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report suggest moderate expected increases in mean

sea level of at least 13 inches in Puget Sound, with a high extreme (low likelihood) estimate of about 50 inches. The science behind sea level rise projections is progressing rapidly and more recent global studies suggest much higher rates of global sea level rise. Short-term changes in sea level at local to regional scales can differ substantially (even in sign) from global changes, but are related to short-term fluctuations in climate rather than long-term trends.

3.1 Global Climate Models

Global Climate Models (GCMs) are physically based numerical models simulating key elements of the climate system. GCMs simulate a number of meteorological variables by calculating energy and moisture fluxes between the sun, atmosphere, land, ocean, and ice. GCMs are used to estimate future climate conditions associated with increasing greenhouse gas concentrations and related internal feedback mechanisms such as increases in water vapor in the atmosphere which increase the greenhouse effect, or losses of sea ice which decrease the reflectivity (albedo) of ice covered areas. The GCMs used in the 2007 Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) have been developed by a number of independent research groups. The model outputs simulated by 21 GCMs are available to other researches through the IPCC Data Distribution Center.

Future greenhouse gas emissions scenarios are one of the key forcing factors that determine future climate change. Over 40 emissions scenarios have been produced by the IPCC Special Report on Emissions Scenarios (IPCC, 2000). The emissions scenarios are based on a range of assumptions about future technological change and energy use as well as future trajectories for the global economy and population (NHC, 2008). Table 3.1 shows the most commonly used emissions scenarios for GCMs runs. Even under the lowest emissions scenario, B1, the projected global concentration of carbon dioxide (CO_2) by 2100 is higher by a factor of 1.6 (at 600 ppm) than baseline conditions in 2005 (about 380 ppm) (Table 3.1; NHC, 2008). Under the "business as usual" scenario, A2, the global CO_2 concentration is projected to increase to 1200 ppm by

2100. For purposes of comparison, B1 and A2 can be selected as a low emissions scenario and higher emissions scenario, respectively. However, the A1B emissions scenario, which projects higher emissions at the beginning of the century than A2 and lower emissions at the end of the century (a plausible response to increasing impacts over time), is often selected as an alternate emissions scenario (Mote and Salathé, 2010). If analysis is focused on the mid-21st century climate change, the A1B greenhouse gas emissions scenario represents potentially greater warming than the A2 scenario. Also, a larger number of GCMs were run with the A1B greenhouse gas emissions scenario than with the A2 scenario; they provide more information regarding the range of plausible effects. To analyze the impacts of rapid and essentially uncontrolled greenhouse gas accumulations by 2100, the A1FI emissions scenario might be the most appropriate choice, although the number of GCM simulations of this emissions scenario is limited. It is worth noting that actual greenhouse emissions have in recent years exceeded the average of the A1FI scenario family, although they have not exceeded the single representative scenario used in the IPCC GCM simulations (URL 1).

Table 3.1 A brief summary of the main features of selected IPCC emissions scenarios (Source: NHC, 2008).

Scenario	2100 CO_2 Conc.(ppm)	Economy and Population	Energy Sources
B1	600	Sustainable economy with emphasis on equity, reduced consumption, environment. Global economic convergence. 2100 population 7 Billion.	Largely non-fossil
A1B	850	Rapid growth, materialistic, market-oriented, high consumption economy. Global economic convergence. 2100 population 7 Billion.	Balanced fossil/ non-fossil
A2	1200	Moderate, uneven economic growth, regionally varied, function of culture. No global economic convergence. 2100 population 15 Billion.	Regionally mixed depending on availability
A1FI	1550	Rapid growth, materialistic, market-oriented, high consumption economy. Global economic convergence. 2100 population 7 Billion.	Fossil-intensive

Table 3.2 Summary of ten global climate models selected for Columbia Basin Climate Change Scenarios Project (Source: Randall et al., 2007).

Model ID, Vintage	Source	Atmosphere Top Resolution
UKMO-HadCM3, 1997	Hadley Centre for Climate Prediction and Research/Met Office, UK	$2.5^{o} \times 3.75^{o}$
CNRM-CM3, 2004	Météo-France/Centre National de Recherches Météorologiques, France	$\sim 1.9^{o} \times 1.9^{o}$
ECHAM5/MPI-OM, 2005	Max Planck Institute for Meteorology, Germany	$\sim 1.9^{o} \times 1.9^{o}$
ECHO-G,1999	Meteorological Institute of the University of Bonn, Meteorological Research Institute of the Korea Meteorological Administration (KMA), and Model and Data Group, Germany/Korea	$\sim 3.9^{o} \times 3.9^{o}$
PCM, 1998	National Center for Atmospheric Research, USA	$\sim 2.8^{o} \times 2.8^{o}$
CGCM3.1(T47), 2005	Canadian Centre for Climate Modeling and Analysis, Canada	$\sim 2.8^{o} \times 2.8^{o}$
CCSM3, 2005	National Center for Atmospheric Research, USA	$1.4^{o} \times 1.4^{o}$
IPSL-CM4, 2005	Institute Pierre Simon Laplace, France	$2.5^{o} \times 3.75^{o}$
MIROC3.2(medres), 2004	Center for Climate System Research (University of Tokyo), National Institute for Environmental Studies, and Frontier Research Center for Global Change (JAMSTEC), Japan	$\sim 2.8^{o} \times 2.8^{o}$
UKMO-HadGEM1,2004	Hadley Centre for Climate Prediction and Research/Met Office, UK	$\sim 1.3^{o} \times 1.9^{o}$

The uncertainty in future climate change impacts is often estimated from an ensemble (group) of GCMs simulations which provide a range of results. To reduce computational requirements, some models which perform less well in reproducing important features of the observed regional climate are often excluded from the analysis. A common method for evaluating a model's performance is to compare the model's simulation of 20^{th} century climate with observed regional temperature and precipitation (Mote and Salathé, 2010) or other important aspects of historical variability. The Climate Impacts Group, for example, selected the top 10 GCMs whose 20^{th} century simulations showed the smallest bias in temperature and precipitation and the best reproduction of North Pacific climate variability for a recent climate change study on the Pacific Northwest Columbia River Basin (Hamlet et al., 2010). Brief information on the 10 GCMs is shown in Table 3.2 (detailed information and references of all 21 models are described in Table 8.1 of Randall et al. (2007)). Among the 10 GCMs selected, UKMO-HadGEM 1 or CCSM3 tend to be the warmest in each scenario and each decade, and IPSL_CMS is the wettest. Evaluation metrics and additional details are discussed by Mote and Salathé (2010).

3.2 Dynamical Downscaling Using Regional Scale Climate Models (RCMs)

Although GCMs provide a great deal of meaningful information at the regional scale, they have many limitations, particularly for watersheds like the Skagit whose hydrologic behavior is informed by topographic variations at sub-regional scales. For example, GCMs do not explicitly resolve the topography of the North Cascades and the Skagit River basin. Regional Scale Climate Models (RCMs) provide greatly improved representation of mountain topography and important feedback mechanisms such as the snow albedo feedback, which results in more rapid warming in areas with loss of snowpack (Salathé et al., 2010). RCMs also provide explicit and more realistic simulations of storms, providing improved tools for the assessment of hydrologic extremes such as flooding at daily or even hourly timescales. RCMs are usually not run over the entire globe, but instead are typically "nested" within a GCM domain. Use of nested RCMs for climate impacts assessment is commonly referred to as "dynamic downscaling". A good description of the details of dynamic downscaling and a comparison with GCM simulations can be found in Salathé et al. (2010).

While providing many potential advantages over GCMs for regional scale assessment, RCMs are very computationally intensive to run, which frequently limits the length and number of future climate change scenarios available. Comprehensive assessment of uncertainties deriving from the different GCM simulations that could potentially provide input data to the RCMs at the outer boundaries (*large scale forcing*) is therefore generally not possible at the current time due to the computational expense associated with such efforts.

3.3 Statistical Downscaling Approaches

As noted in the previous section, some important regional topographic features such as the Cascade Mountains are not represented by GCMs, making metrological data from GCMs unsuitable as input data for hydrologic models in their raw form. In studies assessing climate impacts, a downscaling process is often applied to relate monthly time scale simulation of temperature (T) and precipitation (P) data at around 200 km resolution produced by a GCM to daily time scale data required for a hydrologic model at finer (e.g. at 6 km) resolution (Hamlet et al., 2010). Statistical downscaling methods such as Delta Method and Transient Bias Correction and Statistical Downscaling (BCSD), as well as the Hybrid Delta method (which combines the strengths of the previous two methods) are described in detail by Hamlet et al. (2010). Here we give a brief overview of three statistical downscaling approaches.

3.3.1 Delta Method

One of the simplest statistical downscaling methods is the Delta method, which applies monthly changes in large scale temperature and precipitation from a GCM to historical temperature and precipitation observations at more local scales. The advantage of the Delta method is that it preserves the observed sequence of temporal and spatial variability from gridded observations, which makes for easy interpretation and straight-forward comparison with historical observations. For example, a particular drought or flood year in the historical record can be directly compared in future projections. The other advantage of the Delta method is that bias from GCMs is automatically removed and the spatial resolution of each GCM is not very important when changes are calculated at the regional scale.

One significant weakness of the Delta method is that information about potential changes in the probability distributions of temperature and precipitation simulated by the GCMs, such as changes in the variance or extremes, is ignored. For example, increased precipitation from the GCM simulation is captured by simply multiplying the changes (or delta) of precipitation on days with precipitation in the historic record but the actual number of days with precipitation simulated from GCMs are not transformed. These simplifications are intentional, and were originally intended to avoid the profound limitations of early GCMs in simulating regional climate, but as GCMs have steadily improved, a desire to incorporate more information from them has resulted.

3.3.2 Transient Bias Corrected and Statistical Downscaling (BCSD) Method

More sophisticated statistical downscaling method is the Bias Corrected Statistical Downscaling (BCSD) (Wood et al., 2002). In comparison with the Delta method, the Transient BCSD approach extracts more information from the large scale GCM simulations. The trend in the monthly GCM simulations of temperature and precipitation is preserved in the Transient runs, making the BCSD approach an appropriate tool for assessing rates of change. The spatial variability and realizations of interannual and interdecadal variability in the GCMs are also preserved. These preserved climate trends and variability are useful for applications such as modeling ecological systems but can make the interpretation of the results more difficult for other applications such as water resources planning. The quality of BCSD results are heavily dependent on the quality of the GCM simulations from which they derive, so caution should be exercised in interpreting these results (Mote and Salathé, 2010; Hamlet et al., 2010).

3.3.3 Hybrid Delta Downscaling Method

This downscaling method combines the strengths of the two methods described above, by combining the more detailed spatial and probabilistic information extracted from GCM simulations using the BCSD method with the historically accurate time series behavior of the traditional delta method (Hamlet et al., 2010). Most of the specific results that we discuss for the Skagit River basin in subsequent sections are based on this downscaling method.

3.4 Climate Change Impacts on Meteorological Conditions and Sea Level Rise

In this section, projected climate change impacts on PNW (regional) and Skagit basin (local) temperature and precipitation are presented, and projected impacts to global and regional sea level are discussed.

3.4.1 Changes in Temperature

PNW temperatures have warmed by about 0.8 °C (1.5 ^{o}F) since 1920 (Mote et al., 2003) and are predicted to increase over the 21st century with higher certainty than the other variables (Christensen and Hewitson, 2007; Mote and Salathé, 2010). Figure 3.1 shows a summary of temperature simulations from ~20 GCMs averaged over the PNW for two emissions scenarios: the A1B (medium emissions) and B1 (a low emissions) greenhouse gas scenarios (Mote and Salathé, 2010). As shown in Figure 3.1, the changes in projected temperature by the end of the 21st century are strongly dependent on the emissions scenario: by the 2080s, the temperature increase relative to 1970-99 is almost 7.0 ^{o}F for A1B and 4.7 ^{o}F for B1. This finding shows that a reduction in the concentration of greenhouse gases will be an important factor in mitigating regional warming on long time scales.

The signal to noise ratio for temperature is very high, meaning that the magnitude of warming is very large in comparison with the observed normal variability. For example, by the 2050s the new 5th percentile value for the B1 scenario (which is the lowest value in the yellow band) is close to the 95th percentile shown for end of the 20th century (the upper range of the grey band). This result supports the argument that statistically significant increases in temperatures will be readily apparent in future observations.

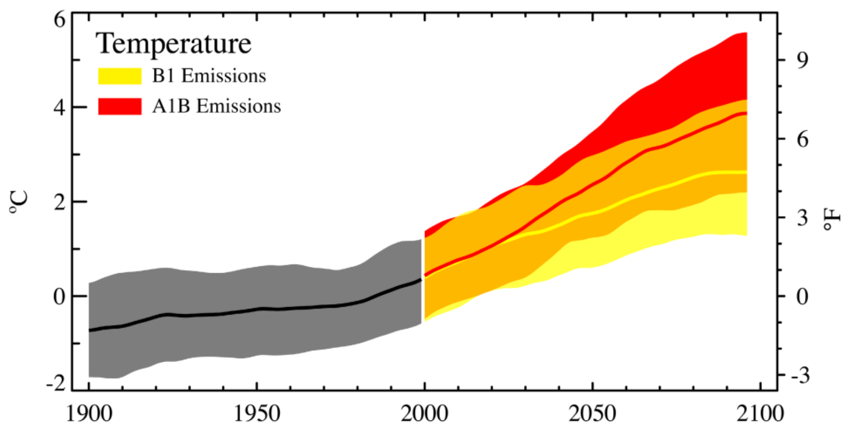

Figure 3.1 Summary of the 20th and 21st century annual average temperature simulations from 20 GCMs over the PNW, relative to the 1970-99 mean, for two greenhouse gas emissions scenarios. Solid lines show the mean. The grey bands show the range (5th to 95th percentile) for the historical simulations, the colored bands show the range of future projections for each emissions scenario (Source: Mote and Salathé, 2010).

Figure 3.2 and Table 3.3 show a summary of the 20th and 21st century monthly mean temperature simulations from ~10 GCMs averaged for the Skagit River basin near Mount Vernon for the A1B and B1 emissions scenarios. By the end of the 21st Century, the temperature increase is about 5.8 °F for A1B and 4.0 °F for B1 in comparison to historical average temperature (water years 1916-2006) (see Table 3.1), which is a somewhat smaller change compared to the PNW as a whole. This is explained primarily because the Skagit basin is relatively close to the coast, which warms more slowly than the interior due to proximity to the ocean. The projected monthly mean temperature also shows a seasonal pattern; the changes in projected temperature are largest in summer with largest increase in August. This seasonal pattern essentially increases in strength as projections move toward the end of the 21st century (Mote and Salathé, 2010).

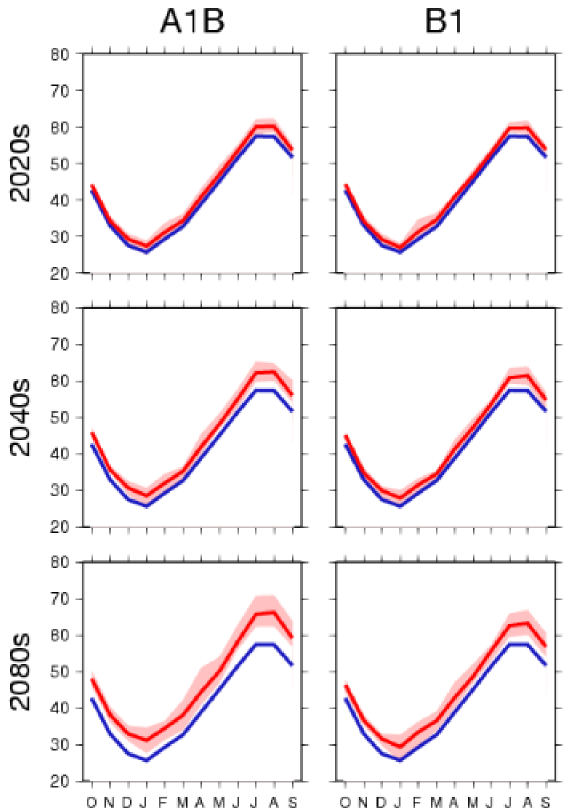

Figure 3.2 Summaries of the 20th and 21st century monthly mean temperatures (in ^{o}F) for A1B (left) and B1 (right) scenarios for the Skagit River basin upstream of Mount Vernon. The blue line represents historical monthly mean temperature (water years 1916-2006), while the red line represents projected monthly mean temperature across ~ 10 Hybrid Delta simulations for the A1B and B1 scenarios. The red band represents the range of individual scenario (Source: URL 2).

Table 3.3 Summaries of the 20th and 21st century annual and seasonal mean temperatures (in ^{o}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).

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

3.4.2 Changes in Precipitation

In contrast to temperature, the signal to noise ratio for annual precipitation is very low, meaning that changes in mean precipitation from GCM simulations are not statistically significant (see Figure 3.3). Although systematic changes in annual precipitation are small, substantial seasonal changes in precipitation are projected for the 21st century as shown in Figure 3.4. The ensemble means show the precipitation increasing in winter, autumn and spring, and decreasing in summer in comparison with the 1970-99 average climate. These patterns of seasonal change increase in intensity as the projections move toward the end of the 21st century.

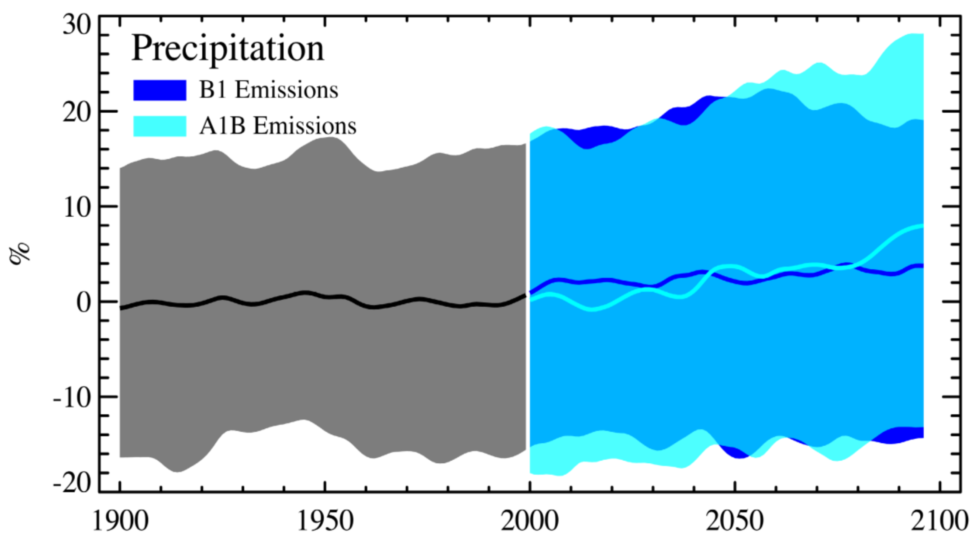

Figure 3.3 Summary of 20th and 21st century annual precipitation simulations from 20 GCMs over the PNW, relative to the 1970-99 mean, for two greenhouse gas emissions scenarios. Solid lines show the mean. The grey bands show the range (5th to 95th percentile) for the historical simulations and the colored bands show the range of future projections for each emissions scenario (Source: Mote and Salathé, 2010).

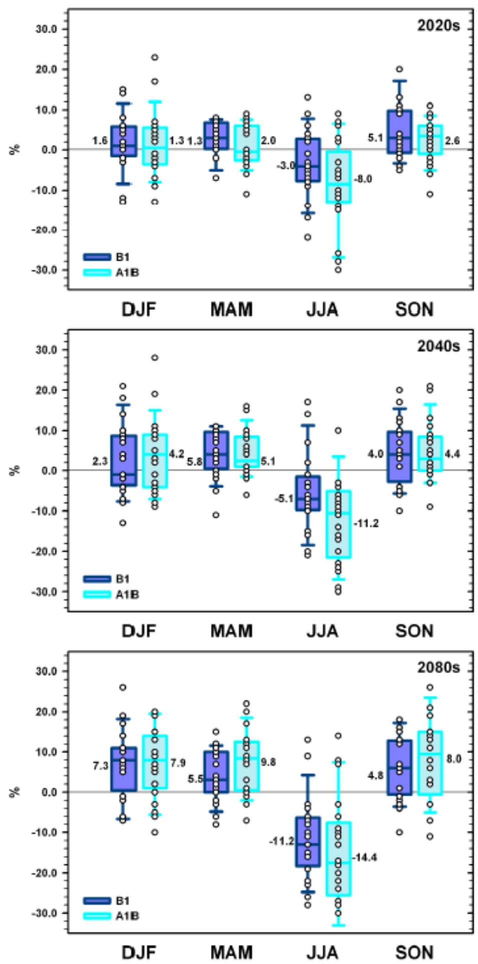

Figure 3.4 Range of projected changes in precipitation for each season (DJF=winter, MAM=spring, JJA=summer, and SON=fall), relative to the 1970-99 mean. Circles are individual model values. Box-and-whiskers plots indicate 10th and 90th percentiles (whiskers), 25th and 75th percentiles (box ends), and median (solid middle bar) for each season and scenario (Source: Mote and Salathé, 2010).

Similar patterns are observed for the precipitation projections for the Skagit River basin (see Figure 3.5 and Table 3.4). Average changes in precipitation for the Skagit River basin by the 2080s (for A1B) are projected to increase by 9.8 % in winter, 8.0 % in spring and 19.2 % in fall but to decrease 27.6 % in summer. Because GCM precipitation projections for the 21st century are much more uncertain than temperature projections, greater caution is required when using changes in precipitation in planning and policy decisions.

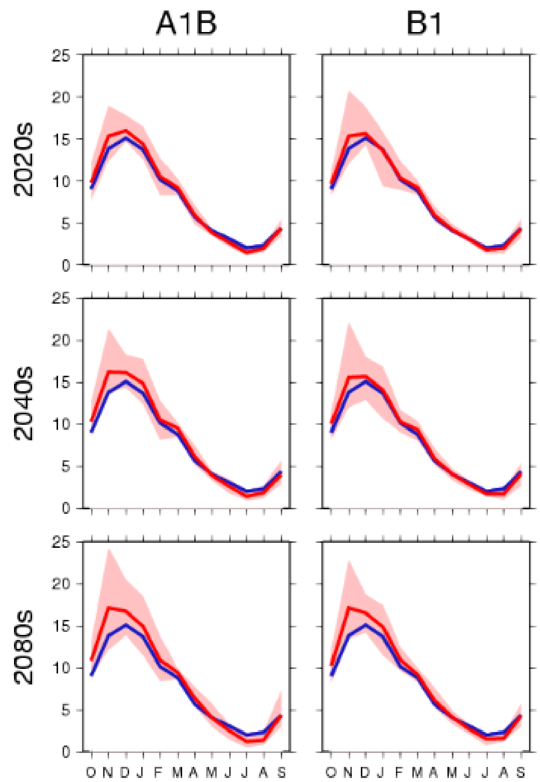

Figure 3.5 Summaries of 20th and 21st century monthly mean precipitations (in inches) for A1B (left) and B1 (right) scenarios for the Skagit River basin upstream of Mount Vernon. The blue line represents historical monthly mean precipitation (water years 1916-2006), while the red line represents projected monthly mean precipitation across ~10 Hybrid Delta simulations for A1B and B1 scenarios. The red band represents the range of individual scenario (Source: URL 2).

Table 3.4 Summaries of 20th and 21st century annual and seasonal mean 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).

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

3.4.3 Changes in Sea Level

Global sea level has risen through the 20th century and is currently rising at an increased rate (Nicholles et al., 2010; IPCC, 2007). For example, the mean rate of global sea level rise (SLR) from 1993 to 2009 was about 3 mm/year, which is significantly higher than the average during the previous half century (Figure 3.7) (Nicholles et al., 2010; IPCC, 2007). However, sea-level is not rising uniformly around the world as shown in Figure 3.6 (IPCC, 2007; Nicholles et al., 2010). In some regions such as the western Pacific and eastern Indian Oceans, sea level has risen up to five times faster than the global mean rise, while in other regions such as the eastern Pacific (i.e. the west coast of the United States) and the Western Indian Oceans, sea level has been falling (Figure 3.6) (IPCC, 2007; Nicholles et al., 2010). Spatial variability of the rates of sea level rise, however, likely reflects decadal fluctuations rather than long-term trends (IPCC, 2007; Nicholles et al., 2010).

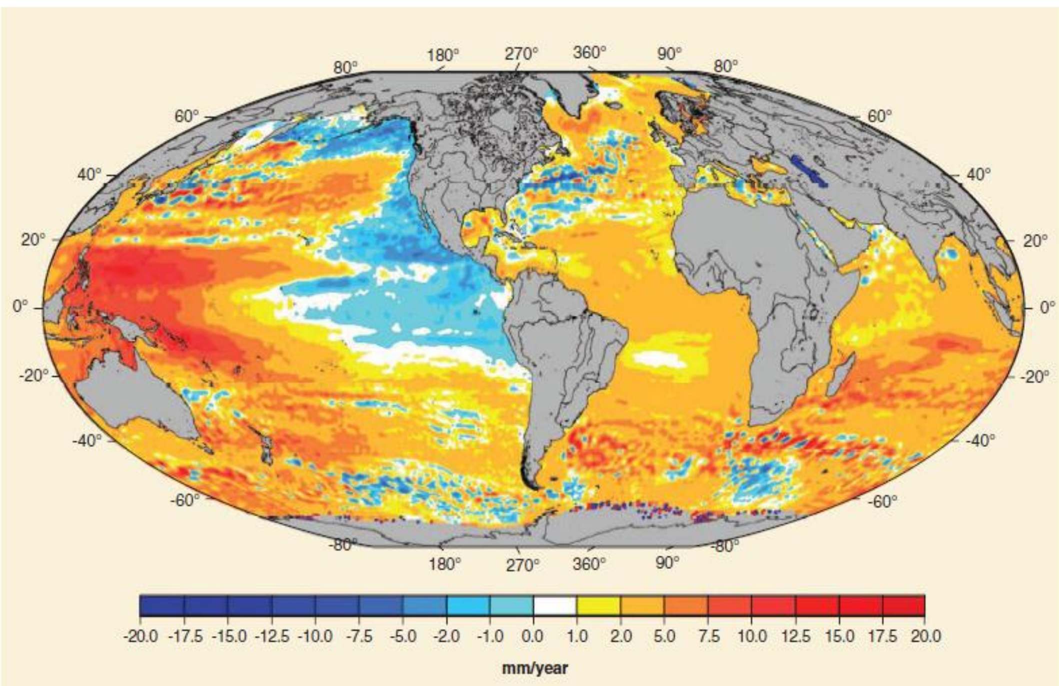

Figure 3.6 Regional sea-level trends from satellite altimetry from 1993 to 2009 (Source: Nicholles et al., 2010).

The IPCC's Fourth Assessment Report (AR4) projected that global sea level rise will be between 18 and 38 cm (7.1 and 15.0 in) for the lowest emissions scenario, and between 26 to 59 cm (10.2 and 23.2 in) for the highest emissions scenario (IPCC, 2007). These estimates of sea level dynamics were based on published studies of glacial dynamics available at the time the IPCC report was being prepared. More recent monitoring and modeling studies, which were not included in the IPCC process, have shown much more rapid loss of ice mass. When rapid glacial dynamics are included, projected SLR will be much higher than the IPCC AR4 projection (Rahmstorf, 2007; Horton et al., 2008; Pfeffer et al., 2008; Vermeer and Rahmstorf, 2009; Grinsted et al., 2010; Nicholls and Cazenave, 2010). For example, semi-empirical approaches linking SLR to temperature change showed that the range of global sea level projection will be 0.34 to 1.79 m (1.12 to 5.87 ft) by 2100 (Rahmstorf, 2007; Horton et al., 2008; Vermeer and Rahmstorf, 2009; Grinsted et al., 2010). Global sea level projections also vary considerably depending on the assumptions used in these empirical relationships--such as which IPCC projection (IPCC TAR or AR4), which emissions scenarios, or which GCMs are used. Figure 3.7 shows the IPCC AR4 SLR projections as well as three more recent semi-empirical SLR projections. Rahmstorf (2007) assumed a linear relationship between the rate of SLR and temperature, reporting 0.5-1.4 m (1.64 – 4.59 ft) of SLR by 2100 for A1FI scenarios of the IPCC Third Assessment Report. For the IPCC AR4 A1FI scenario, Vermeer and Rahmstorf (2009) and Grinsted et al. (2010) reported 1.13-1.79 m (3.71 – 5.87 ft) and 0.34 – 1.6 m (1.12-5.25 ft) of SLR for the 21st century, respectively. Vermeer and Rahmstorf (2009) and Grinsted et al. (2010) modified the linear relationship by considering more rapid response.

Projected 21st century local SLR in the PNW was estimated by Mote et al. (2008) by combining the estimates of global SLR from the 2007 IPCC report and local factors such as atmospheric circulation and vertical land movement due to tectonic movement (e.g. isostatic rebound). The very low, medium, and very high SLR projections for Puget Sound for 2050 and 2100 are shown in Table 3.5. The end-of-century very low estimates for global SLR are based on the IPCC's B1 emissions scenario. For the medium global SLR estimate, an average of six emissions scenarios is used. The very high estimate of global SLR includes the IPCC's A1FI emissions scenario and a rough estimate of the upper limit of ice sheet contributions of 34 cm (13.4 in) for 2100.

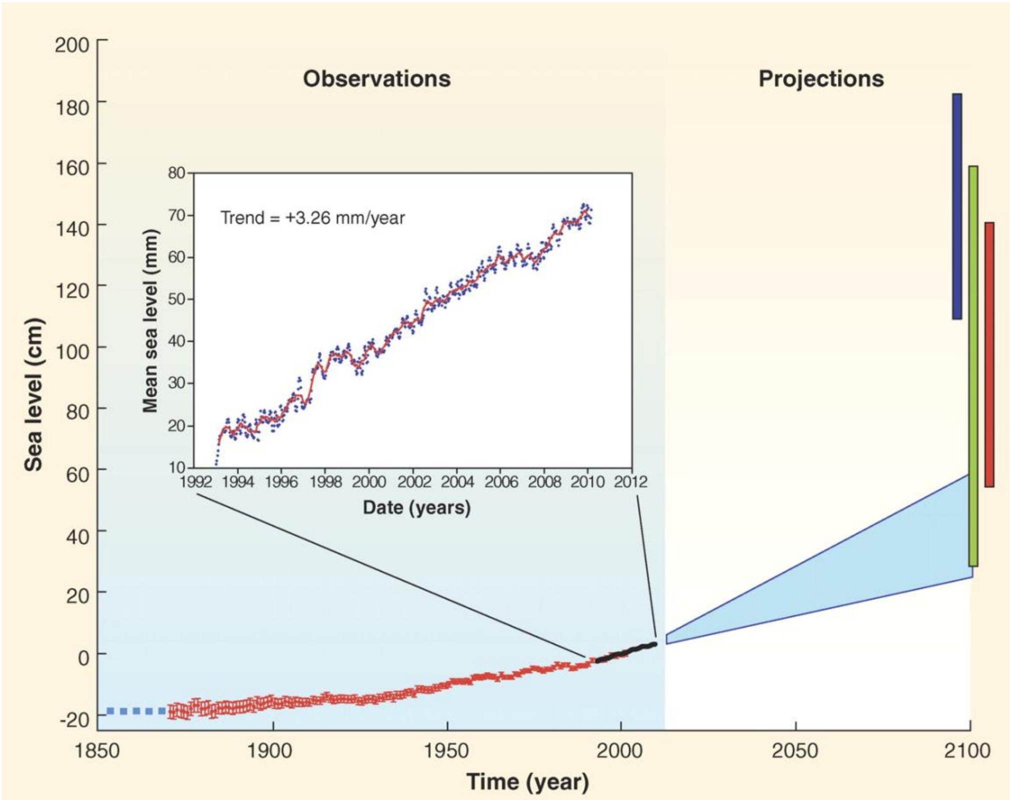

Figure 3.7 Global mean sea level evolution over the 20th and 21st centuries. The red curve is based on tide gauge measurements. The black curve is the altimetry record (zoomed over the 1993–2009 time span). Projections for the 21st century are also shown. The shaded light blue zone represents IPCC AR4 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).

Averaged sea level rise projection over 18 models for the moderate IPCC A1B emissions scenarios suggests that sea level along the coast of western North America is likely to be about 2-3 cm below the global average possibly due to northward wind (Mote el al., 2008; IPCC, 2007; Nicholles et al., 2010). The local atmospheric circulation impacts on SLR are estimated in the very low SLR scenarios by subtracting 1 cm (0.4 in) by 2050 and 2 cm (0.8 in) by 2100 from the very low SLR estimates and are assumed to be negligible for the medium scenarios (Table 3.5).

However, several models project increases in wintertime southerly (i.e. from the south) winds. The very high SLR scenarios consider this component by adding 7 cm (2.8 in) by 2050 and 15 cm (5.9 in) by 2100 into the very high SLR estimates, respectively (Table 3.5).

Table 3.5 Calculation of very low, medium and very high estimates of sea level changes in Puget Sound for 2050 and 2100 relative to 1980-1990 (Adapted from Mote et al., 2008).

SLR Estimate	Components	2050	2100
Very Low	Global SLR (Thermal Expansion and Melting of Global Ice)	9 cm (3.5 in)	18 cm (7.1 in)
	Local Atm. Dynamics	-1 cm (-0.4 in)	-2 cm (-0.8 in)
	Local Vertical Land Movement	0 cm (0.0 in)	0 cm (0.0 in)
	Total	8 cm (3.1 in)	16 cm (6.3 in)
Medium	Global SLR (Thermal Expansion and Melting of Global Ice)	15 cm (5.9 in)	34 cm (13.4 in)
	Local Atm. Dynamics	0 cm (0.0 in)	0 cm (0.0 in)
	Local Vertical Land Movement	0 cm (0.0 in)	0 cm (0.0 in)
	Total	15 cm (5.9 in)	34 cm (13.4 in)
Very High	Global SLR (Thermal Expansion and Melting of Global Ice)	38 cm (15.0 in)	93 cm (36.6 in)
	Local Atm. Dynamics	7 cm (2.8 in)	15 cm (5.9 in)
	Local Vertical Land Movement	10 cm (3.9 in)	20 cm (7.9in)
	Total	55 cm (21.7 in)	128 cm (50.4 in)

An earlier study of vertical land movement (VLM) in the PNW suggested that south Puget Sound was subsiding at a rate of about 2 mm/yr (Holdahl et al., 1989; Mote et al., 2008; Schweiger, 2007). Recent studies found that little or some small uplifts occurred in southern Puget Sound and VLM in further north Puget Sound was less than 2 mm/yr (Verdonck, 2006; Schweiger, 2007; Mote et al., 2008). Because estimates of VLM in Puget Sound are not consistent among studies, VLM in Puget Sound was assumed to be negligible for very low and medium SLR estimates (Mote et al., 2008). Subsidence of 10 cm (3.9 in) by 2050 and 20 cm (7.9 in) by 2100 is assumed for the very high SLR estimate in Puget Sound (Table 3.5) (Mote et al., 2008). For the Skagit River basin, Schweiger (2007) used VLM of -7 cm (-2.4 in) by 2050 and -9 cm (-3.5 in) by 2100. Mote et al. (2008) estimated that the very high SLR in Puget Sound by 2100 would be 128 cm (50.4 in). It is noted that Mote et al. (2008) used IPCC's SLR projection for A1FI, which is 59 cm (23.2 in). Even though Mote et al. (2008) considered future contributions to SLR from the melting glaciers of Greenland and Antarctica (34 cm), their highest global SLR estimate of 93 cm (36.6 in) is much lower than the 179 cm (70.5 in) reported by Vermeer and Rahmstorf (2009). When considering a global SLR estimate of 179 cm (70.5 in), the approach taken in Mote et al. (2008) would suggest that PNW sea-level could increase as much as 214 cm (84.3 in) by the end of the 21st century.

3.5 Summary and Conclusions

Future climate is projected using physically based models such as global climate models (GCMs) and regional climate models (RCMs). These projections are used to assess the potential impacts of climate change and to support related long-term planning activities and policy decisions. Projected future climate and other key findings include the following:

- Different GCMs show different future climate projections depending on greenhouse gas emissions scenarios and their unique sensitivity to these forcings. Among the top 10 GCMs, which are selected based on each GCM's performance, UKMO-HadGEM 1 or CCSM3 tend to be the warmest in each scenario and each decade, and IPSL_CMS is the wettest.
- In comparison with GCMs, RCMs provide greatly improved representation of regional topographic features such as the Cascade Mountains and consequently simulate more realistic storms at daily or even hourly timescales. Because they are very computationally

intensive to run, the length and number of future climate change scenarios are limited in RCMs.

- To assess hydrologic impacts, the outputs from GCMs or RCMs are used as inputs to hydrologic models but spatial and temporal resolution of the outputs from GCMs are not matched to those required for hydrologic models. Thus, downscaling is commonly used to transform monthly time scale data at a coarse special resolution reproduced by GCMs to daily time scale data at finer special scales required for hydrologic model simulation.
- Projected changes in temperature for the Skagit River basin are broadly consistent with the PNW temperature projections, though the changes in temperature are somewhat smaller for the Skagit River basin relative to those over the PNW as a whole. For both the PNW and the Skagit River basin, temperature projections are higher for higher emissions scenarios (A1B) than for low emissions scenarios (B1), showing that regional warming on long time scales could be mitigated by reducing the concentration of greenhouse gases. The amount of warming over the next several decades is insensitive to the emissions scenario, supporting the argument that adaptation may be the only viable approach to avoiding impacts in the near term.
- Precipitation projections both for the PNW and for the Skagit River basin show wetter winters and drier summers relative to historical climate, though the changes in annual mean precipitation are not statistically significant. Greater caution is required when precipitation projections are used in planning and policy decisions, because precipitation projections are much more uncertain than temperature projections.
- Global sea level has risen through the 20th century and is currently rising at an increased rate, though there is spatial variability of the rates of sea level rise: sea level in some regions has been rising several times faster than the global mean rise, while sea level in other regions has been falling.
- Without the efforts of reducing the concentration of greenhouse gases, SLR in the PNW is estimated to increase dramatically. For highest emissions scenarios (A1FI), SLR of 128 - 219 cm (50.4 – 86.2 in) is estimated for Puget Sound by 2100. For the low

emissions scenarios (B1) only 16 cm (6.3 in) of SLR is projected for the same time period. 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, but more detailed monitoring is needed to more accurately estimate the importance of these changes. No detailed estimates of relative SLR for the Skagit River basin lowlands are currently available, for example.

URL 1: http://www.realclimate.org/index.php/archives/2010/06/recent-trends-in-co2-emissions/
URL 2: http://www.hydro.washington.edu/2860/products/sites/?site=6021

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4. Glaciers

Abstract

On a global scale, many glaciers have been retreating since the end of the Little Ice Age (~1550-1850) while some glaciers have advanced during intervening relatively cool and wet periods. Recent studies have demonstrated that widespread negative mass balance and the resulting accelerated glacier retreat over the last two or three decades is largely a response to increasing anthropogenic greenhouse gases which has caused accelerated global warming since the 1970s. Following trends for the North Cascades as a whole, the Skagit's 394 glaciers (which provide 12-18 % of May-September summer flow--120-180 B gallons) have been retreating in response to observed warming and changes in precipitation. Estimates of total loss of glacial area in the Skagit Basin since 1900 are on the order of 50%. Glacial retreat has been more rapid on the wetter western side of the Skagit River Basin than on the more arid eastern side. Projected warming for the 21st century is likely to accelerate glacier retreat, resulting in exacerbated summer low flows (particularly during droughts) and higher summer water temperature in watersheds with significant glacial coverage.

4.1 Background

Globally, glaciers are an important natural water resource, providing water for agriculture, water supply, hydropower generation, recreation, and fish flow augmentation, particularly during warm and dry periods (Barry, 2006; Moore et al., 2009; Pelto, 2010). Glaciers fluctuate depending on the amount of snowfall (accumulation) and the amount of snow and ice lost by melting and sublimation (called ablation) (Myrna et al., 2003). When the ablation exceeds accumulation, a glacier is said to have negative mass balance and the glacier decreases in mass and volume. Changes in atmospheric conditions such as precipitation, wind, temperature, radiation fluxes, and cloud cover affect the surface energy, mass balance, and terminus (or end) location of a glacier (Zemp et al., 2006 & 2009). Glacial ice also gradually moves downslope to the terminus of the glacier. Below the terminus, all snow and transported ice mass from higher elevations melts each year. Unlike animals and plants, glaciers are not capable of adaptation to mitigate the impacts of climate change; they react physically to the surrounding conditions (Hall and Fagre, 2003). Thus, mountain glaciers provide some of the most tangible evidence of climate change and are essential variables for early detection strategies in global climate related observation (Hall and Fagre, 2003; WGMS, 2008; Barry, 2006).

The mass balance of a number of glaciers has been monitored since the mid-20th century. These observations provide direct evidence of climate change effects without any time lag (Josberger et al., 2007; Pelto and Riedel, 2001; Krimmel, 1999; Moore et al., 2009; WGMS, 2008; Zemp et al., 2006; Pelto, 2010). However, most of the mass balance observations do not have long records available. Only about 20% of world's glacial mass balance observations have continuous records more than 20 years long (Dyurgerov and Meier, 1997; Barry, 2006). The longest continuous record of glacial mass balance is for the period from 1946 to present for Storglaciären, Sweden (Dyurgerov and Meier, 1997). Several glaciers in the North Cascades have relatively long mass balance records, and long-term monitoring in the region has provided a rich data resource for the Pacific North West. Sound Cascade Glacier has been monitored by the USGS since 1957 (55 years at the time of this writing), for example, and the North Cascade Glacier Climate Project (NCGCP) has monitored 3 glaciers for 31 years. The National Park Service has monitored three glaciers for 19 years.

The terminus behavior of glaciers (i.e. changes in the location of the lower end of the glacier), by comparison, is an indirect and delayed proxy for climate change signals but generally has much longer records available (Barry, 2006). In comparison with mass change measurements (reported in cubic meters of water lost or as thickness averaged over the entire area of the glacier), the location of the terminus of the glacier is relatively easy to monitor. So, changes in the length of the glacier are most commonly used to monitor the response to climate change (Pelto and Hedlund, 2001; Oerlemans, 1994).

Glaciers are influenced not only by climate variables such as temperature and precipitation but also by regional factors such as topography and geography (Huybers and Roe, 2009). Therefore, it is important to review how glaciers have historically responded to climate change at both global and regional scales.

4.2 Global glacier changes

Worldwide collection of information about ongoing glacier changes was initiated as early as 1894, in some cases (WGMS, 2008). International glacier monitoring has produced some 36,000 length change observations for 1,800 glaciers and about 3,400 mass balance measurements for about 300 glaciers (IPCC, 2007; WGMS, 2008). The observations are located around the world but most (90%) are located in the Northern Hemisphere (NH) and many of these (40% of the NH observations) are in Europe (Zemp et al., 2009). Figure 4.1 shows glacier length changes since the late 19th century for about 1800 glaciers worldwide (WGMS, 2008).

The length change observations show that glaciers have been retreating since the end of the Little Ice Age that lasted from about 1550 to 1850 in North America (Mann, 2002; Hall and Fagre, 2003). Within this general trend, glacial extent has fluctuated in response to climate variability; strong glacier retreats were observed in the 1940s and 1950s, followed by stable or advancing conditions until the end of the 1970s, followed by rapid rates of ice loss since the mid-1980s (WGMS, 2008). Though there are some deviations from these global trends such as the advance of glaciers in coastal Scandinavia (in Atlantic) and the New Zealand (in the Southern Hemisphere) during the 1990s (See Figures 4.1 and 4.2), smoothed mean terminus data averaged over large regions back to 1700, based on 169 glacier length records compiled by Oerlemans (2005) shows unambiguous declines since about 1850 as shown in Figure 4.2 (IPCC, 2007).

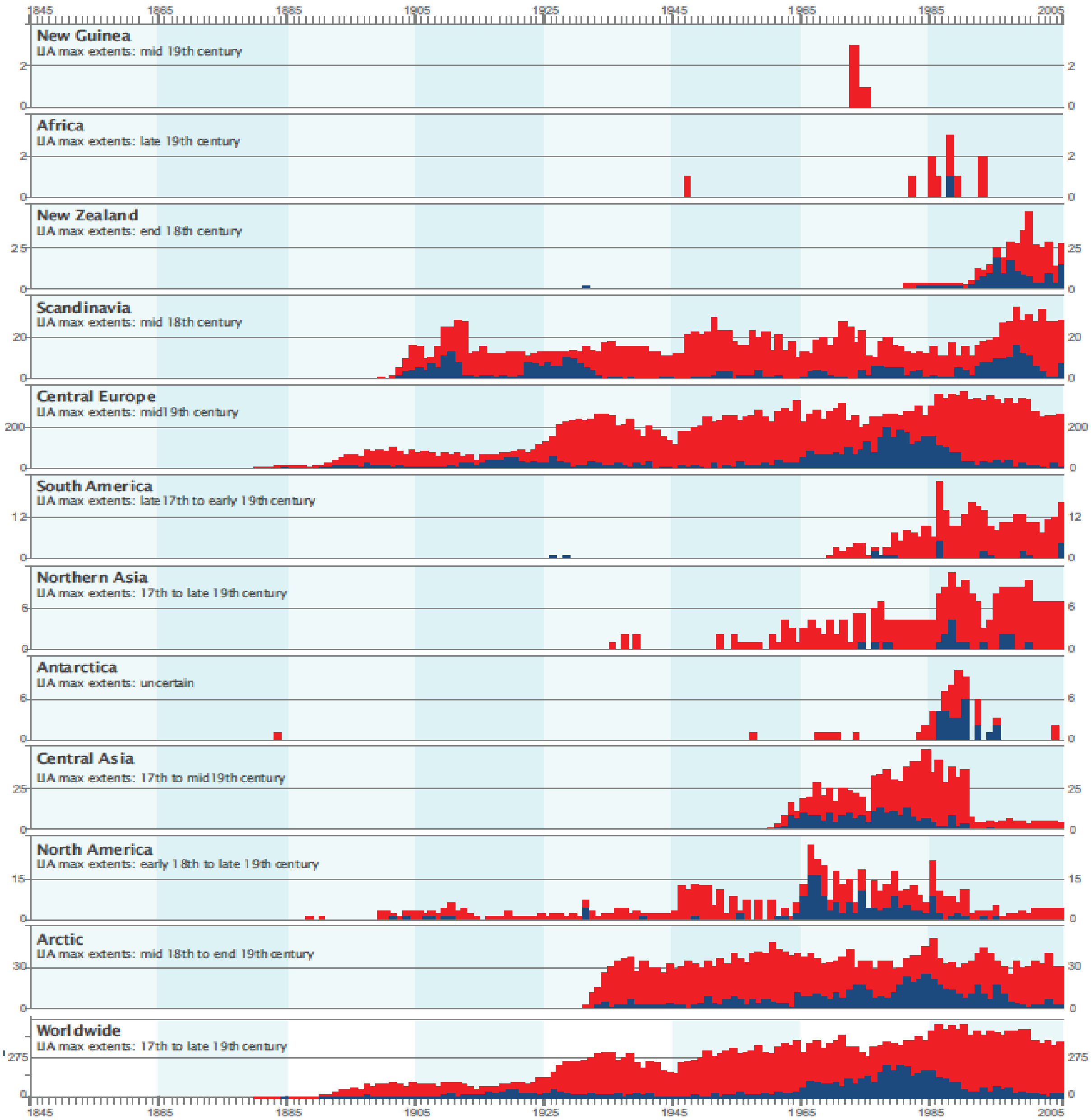

Figure 4.1 Glacier length changes - Temporal overview on short-term glacier length changes. The number of advancing (blue) and retreating (red) glaciers are plotted as stacked columns in the corresponding survey year. Note that the scaling of the number of glaciers on the y-axis changes between the regions (Source: WGMS, 2008).

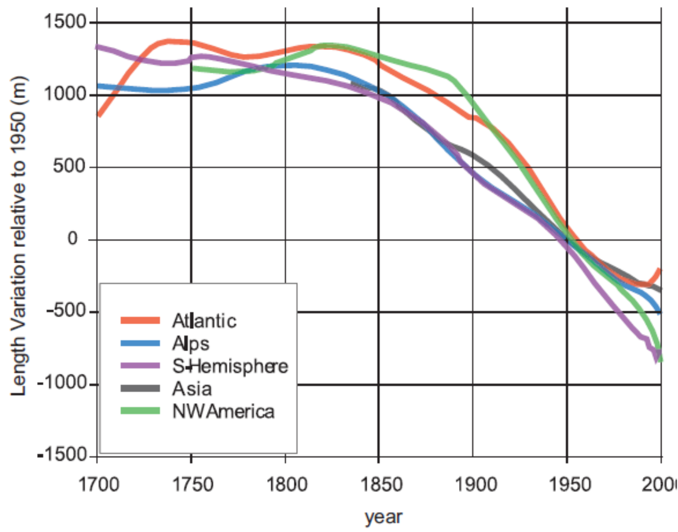

Figure 4.2 Large-scale regional mean length variations of glacier tongues. Glaciers are grouped into the following regional classes: SH (tropics, New Zealand, Patagonia), Northwest America (mainly Canadian Rockies), Atlantic (South Greenland, Iceland, Jan Mayen, Svalbard, Scandinavia), European Alps and Asia (Caucasus and central Asia) (Source: IPCC, 2007).

Seasonal and annual mass balance data from 228 glaciers around the globe have been collected since 1946 by the World Glacier Monitoring Service (WGMS) (IPCC, 2007; WGMS, 2008). Of these glaciers, only 30 which have ongoing and continuous date series since 1976 were used for reference glaciers by the WGMS (WGMS, 2008; Zemp et al., 2009). Glaciologists often express the change in a glacier's mass in terms of the "specific mass balance", which is the total change in ice mass divided by the surface area of the glacier (units in kg m^{-2}) or meters of water equivalent (m w.e.) (Note 1 m w.e. = 1000 kg m^{-2}) (WGMS, 2008). Thus, the mass changes in different glaciers of any size and elevation range can be directly compared using the specific mass balance, and runoff can be easily calculated by multiplying the specific mass balance with the corresponding glacier area (WGMS, 2008).

The cumulative specific mass balance curves for the mean of all glaciers and 30 'reference' glaciers show that the mean specific mass balance was close to zero (near equilibration condition) around 1970, supporting the argument that the glacier mass loss in the late 20th century is related most strongly to post-1970 global warming (see Figure 4.3) (Rignot et al., 2003; Arendt et al., 2003; Meier et al., 2003; Greene, 2005; Haeberli et al. 2005; Barry, 2006; Zemp et al., 2006; Kaser et al., 2006; Pelto, 2006; IPCC, 2007).

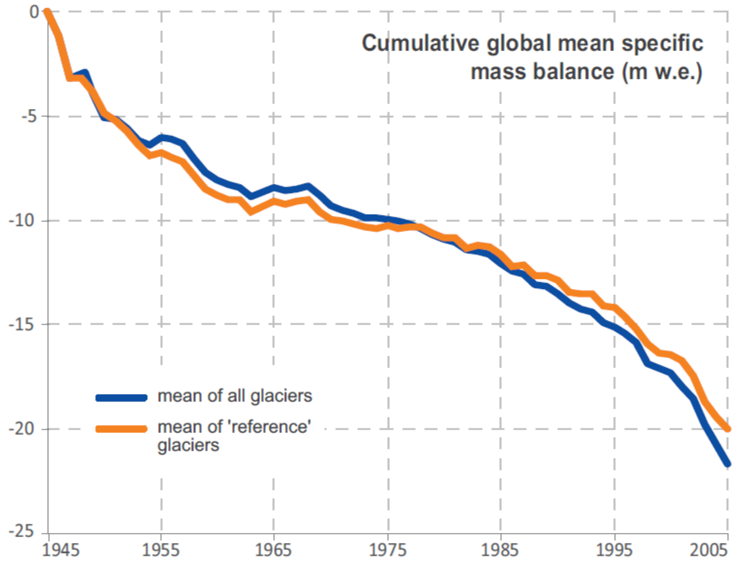

Figure 4.3 The cumulative specific mass balance curves are shown for the mean of all glaciers and 30 ‘reference’ glaciers with (almost) continuous series since 1976 (Source: WGMS, 2008).

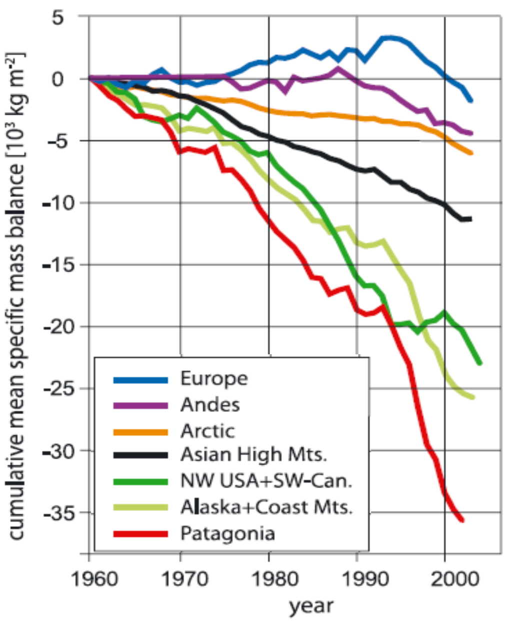

Figure 4.4 Cumulative specific mass balances of glaciers and ice caps since 1960, calculated for large regions [Dyurgerov and Meier, 2005]. Specific mass balances signalize the strength of the glacier response to climatic change in each region (Source: Kaser et al., 2006).

Dyurgerov and Meier (2005) combined individual mass balance values into averages for large regions which were weighted by the surface area of each glacier (Figure 4.4). Generally, negative trends in area-weighted specific mass balance were observed for all of the regions except Europe. The most markedly negative mass balance values were observed for Patagonia, Alaska and Northwest U.S. and Southwest Canada until the early 1990s (Kaser et al., 2006; IPCC, 2007). Thereafter, greatly accelerated loss rates in Patagonia and Alaska were observed, while modest mass gain was observed for Northwest U.S. and Southwest Canada in the late 1990s to early 2000s (Dyurgerov and Meier, 2005; Kaser et al., 2006; IPCC, 2007). For glaciers in the European Alps regional mass gains were observed in the late 1970s to early 1980s and the early 1990s (Figure 4.4).

4.3 Glacial changes in the Skagit Basin and North Cascades

Since the importance of monitoring glacier behavior was acknowledged during the International Geophysical Year in 1957 (Pelto, 2008a), the U.S. Geological Survey has been studying South Cascade Glacier as one of several benchmark glaciers (Krimmel, 1999; Bidlake et al., 2005; Moore et al., 2009). Because a single glacier cannot represent the behavior of all glaciers in response to climate change (Fountain et al., 1991 & 2009), the North Cascade Glacier Climate Project (NCGCP) has been monitoring more than 10 representative glaciers in the North Cascade Range since 1983 (see Figure 4.5) (Pelto, 2006 & 2008a). Beginning in 1993, the National Park Service (NPS) began long-term monitoring of seasonal mass balance on four glaciers in North Cascades National Park Complex (NOCA), which is the crest of the northern section of the North Cascade Range and includes parts of the Skagit River Basin (see Figure 4.6) (Pelto and Riedel, 2001; Granshaw and Fountain, 2006; Riedel et. al., 2008; Riedel and Larrabee, 2011). NPS mass balance monitoring focuses on representative four glaciers out of 394 glaciers in the Skagit River Basin (Granshaw and Fountain, 2006; Riedel et. al., 2008; Post et al., 1971) and follows typical methods in estimating annual net mass balance by summing winter accumulation (mass gained) and summer ablation (mass lost) (discussed below). On the other hand, the study of glaciers by NCGCP measures the residual snow left on a glacier at the end of summer to assess mass balance. This approach is somewhat different from the method discussed above, but is valuable because it covers spatially wider range in the region and temporally longer data set. Therefore we introduce both glacial studies conducted by NCGCP and NPS.

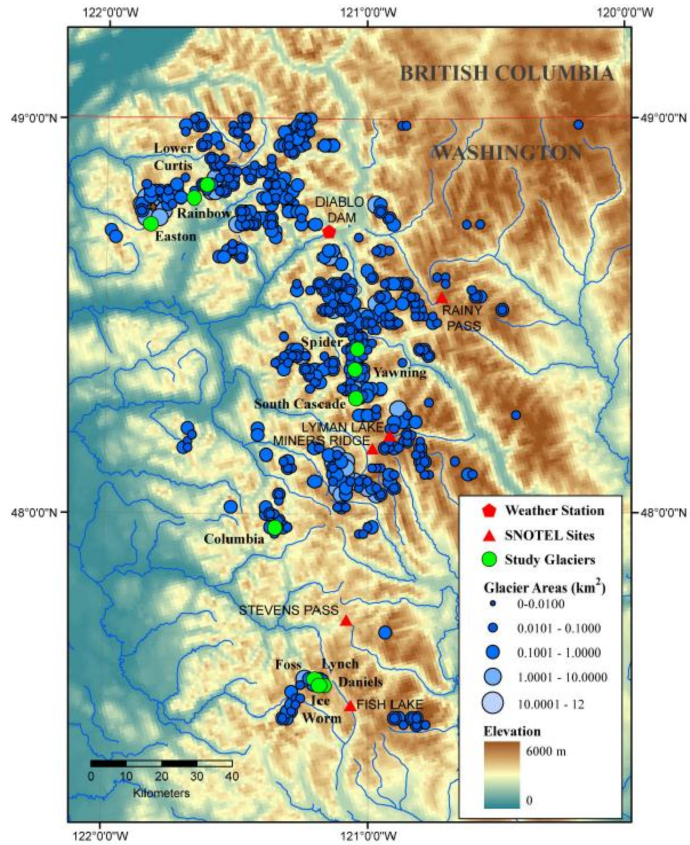

Figure 4.5 Location map of North Cascade glaciers (Source: Pelto, 2006)

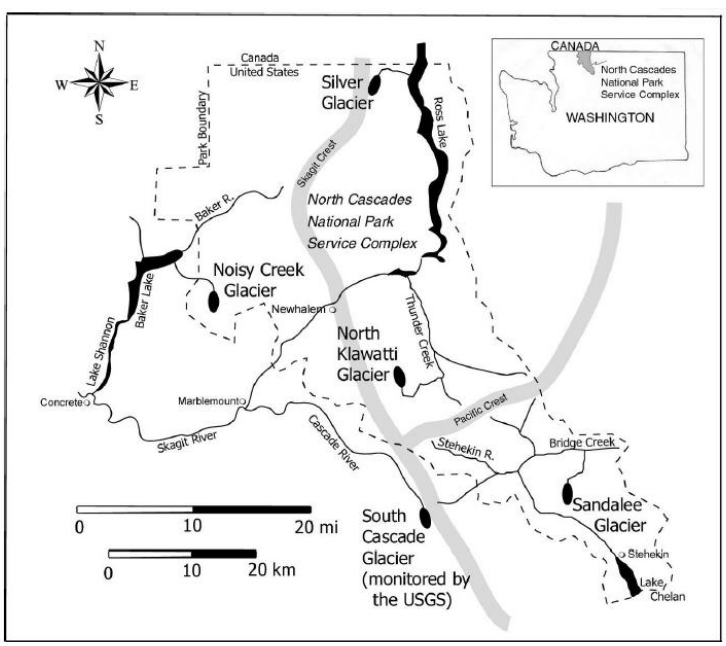

Figure 4.6 Locations of monitored glaciers and major hydrologic crests in the North Cascades National Park Complex (Source: Riedel et. al., 2008)

4.3.1 Glaciers monitored by NCGCP

Following the global patterns discussed above, North Cascade glaciers have generally retreated since the end of the Little Ice Age, though glacier retreat has also fluctuated from decade to decade in response to climate variability (Pelto and Hedlund, 2001). Based on monitoring of the terminus location, three distinctive periods have been identified. Rapid retreat of North Cascade glaciers occurred between 1890 and 1944 due to a progressive temperature rise (Pelto and Hedlund, 2001; Burbank, 1981; Pelto, 2010). The average retreat of the 38 North Cascade glaciers monitored by NCGCP was 1215 m (Pelto and Hedlund, 2001). During the second period which began in 1945, many North Cascade glaciers and all 11 Mount Baker glaciers advanced in response to cooler and wetter weather (Pelto and Hedlund, 2001; Meier and Post, 1962; Pelto, 2006). The third period began in 1977, and rapid retreat from that date forward continues, due to a drier, warmer climate (Pelto and Hedlund, 2001; Pelto, 2010). For example, all 11 Mount Baker glaciers had receded by an average of 197 m by 1984 (Pelto and Hedlund, 2001). Thirty-five of the 47 North Cascade glaciers observed by NCGCP had retreated during 1979-1984 (Pelto and Hedlund, 2001) and, by 1992, a retreat was observed for all 47 glaciers (Pelto, 1993). A dramatic retreat was observed in the White Chuck glacier as shown in Figure 4.7. By 2003, the north branch of the White Chuck glacier was entirely gone. Since 1958, the White Chuck glacier has lost approximately 70% of its area (Pelto, 2009). By 2006, four of the monitored glaciers had disappeared entirely: David, Lewis, Spider and Milk Lake glaciers (Pelto, 2006). Milk Lake glacier in the North Cascades had melted away between 1988 and 1996, creating Milk Lake (see Figure 4.8).

Figure 4.7 White Chuck glacier, the North Cascades 1973 (left) and 2006 (right) from Glacier gap at the head of the north branch of the glacier. The north arm of White Chuck glacier was completely gone by 2003 (Source: Pelto, 2008b).

Figure 4.8 a) Milk Lake glacier in 1988 and b) Milk Lake in 2009 (Source: URL 1).

Table 4.1 Cumulative mass balance measured during 1984-2007 (Easton and Sholes glaciers during 1990-2007) and change in area extent of the 10 North Cascade glaciers monitored by NCGCP (data adapted from Pelto, 2008b).

Glacier	Cumulative Mass Balance (in meters in water equivalent)	Area in 1958 (km^2)	Area in 2005 (km^2)	% Areal Reduction 1958-2005
Columbia	-12.7	1	0.9	10
Daniels	-14.4	0.5	0.35	30
Easton	-10.5	2.9	2.7	7
Foss	-12.4	0.5	0.2	60
Ice Worm	-15.8	0.1	0.06	40
Lower Curtis	-13.0	0.8	0.7	13
Lynch	-10.4	1	0.6	40
Rainbow	-8.8	1.9	1.7	11
Sholes	-11.5	0.9	0.8	11
Yawning	-13.3	0.2	0.16	20

Table 4.1 shows cumulative mass balance for the 10 North Cascade glaciers monitored by NCGCP. Substantial mass loss has occurred in Ice Worm glacier since 1984. The largest area reduction since 1958 was observed in Foss glacier. These two glaciers are recognized as endangered and are not expected to survive long in the current climate (Pelto, 2008a). As shown in Figure 4.9, the cumulative mean mass balance of the 10 glaciers from 1984-2006 was -12.28 m w.e., which is equal to a minimum of 14 m of glacier thickness lost. Considering that the

average thicknesses of North Cascade glaciers are between 30 and 60 m (Pelto and Hedlund, 2001), North Cascade glaciers have lost 20-40 % of their volume since 1984 (Pelto, 2008a). Some caution should be used in interpreting these results because this volume loss estimate is based on surface mass balance measurements which tend to underestimate overall changes in glacier mass and volume (personal communication with Jon Riedel).

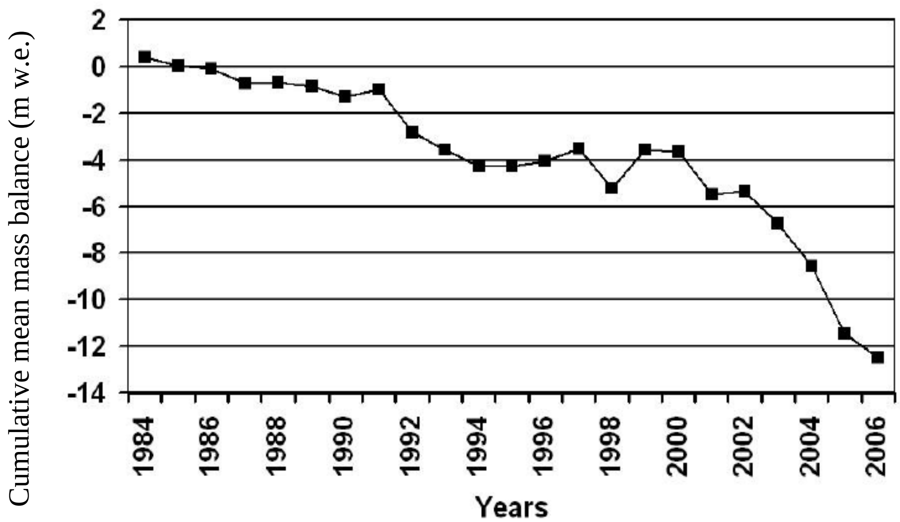

Figure 4.9 Cumulative mass balance record of North Cascade glaciers, 1984–2006, in meters of water equivalent. The increasingly negative trend is evident (Source: Pelto, 2008a).

Pelto (2010) also examined 12 glaciers in the North Cascades to forecast glacier survival based on accumulation zone observations. Based on this analysis, most of the glaciers except Easton, Rainbow and Yawning glaciers are out of equilibrium with current climate. Without a consistent accumulation zone these glaciers are predicted not to survive current climate or future warmer climate.

4.3.2 Glaciers monitored by the National Park Service

In 1958, the North Cascades National Park Complex (NOCA) had 321 glaciers which covered approximately 117.3 ± 1.1 km^2. By 1998, the total glacier population had decreased to 316 (loss of 5) and the total glacier area had reduced to 109.1 ± 1.1 km^2, a reduction of 8.2 ± 0.1 km^2 (7 %) (Granshaw and Fountain, 2006), and unpublished estimates of total loss of glacial area in the

Skagit Basin since 1900 are on the order of 50% (personal communication Jon Riedel). The volume of melt water from the net glacier mass loss over the 40 years was estimated to 0.8 ± 0.1 km^3 of ice which contributes up to 6 % of the late summer (August –September) streamflow of the four watersheds in NOCA such as Thunder Creek, Stehekin River, Cascade River and Newhalem Creek (Granshaw, 2002; Granshaw and Fountain, 2006).

Four representative glaciers in NOCA were monitored by the National Park Service since 1993: Noisy Creek, Silver Creek, and North Klawatti Glaciers in the Skagit River Basin and one glacier outside of the Skagit Basin, Sandalee Glacier as shown in Figure 4.6. The National Park Service has estimated annual net mass balance of four NOCA glaciers (see Figure 4.10) (Riedel et al., 2008; Riedel and Larrabee, 2011). Generally, the four NOCA glaciers have shown a negative long-term trend in response to climate change, although the glacier net mass balance at NOCA has fluctuated in response to climate variability. For example, 5 out of 7 water years had positive mass balance between water years 1996 and 2002 in response to the last cool phase of the Pacific Decadal Oscillation (PDO), although the volume gains were modest and glaciers did not advance (Riedel and Larrabee, 2011). After a short period of positive mass balance, all four NOCA glaciers have resumed a consecutive negative net mass balance (Figure 4.10).

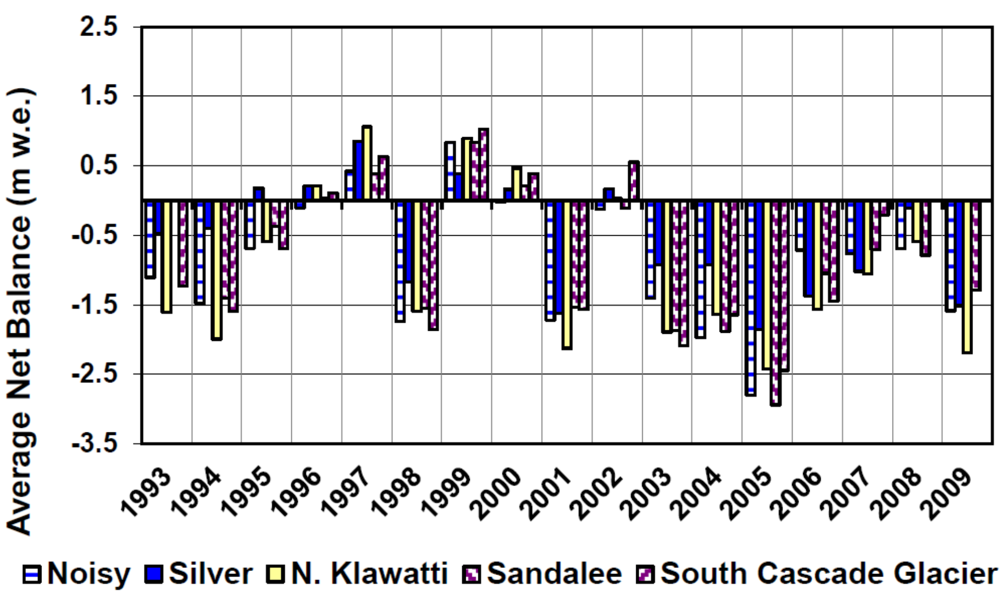

Figure 4.10 Net annual mass balances comparison for four glaciers monitored by NPS and South Cascade Glacier monitored by USGS (Source: Riedel and Larrabee, 2011).

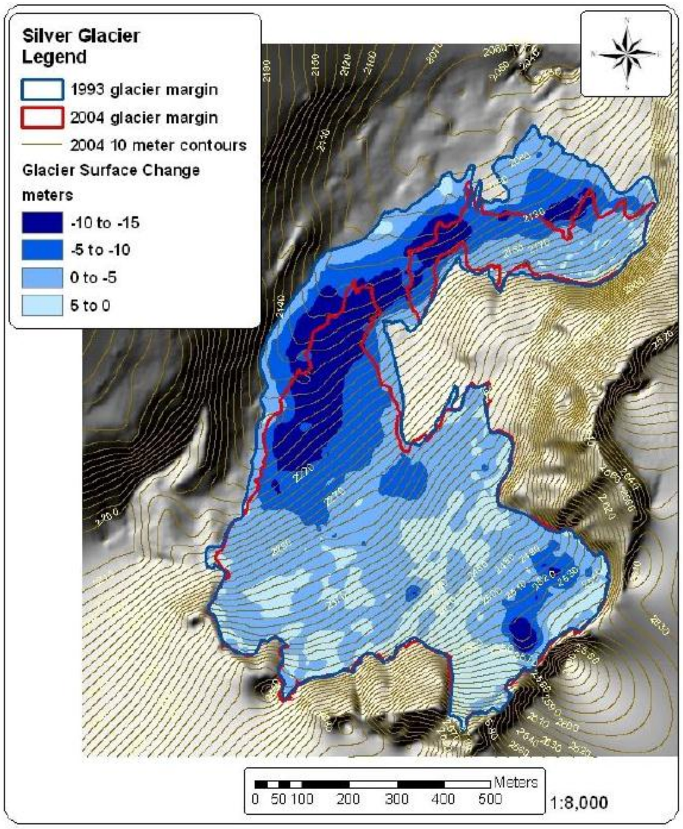

Figure 4.11 Silver Glacier comparison of 1993 adjusted reference map and 2004/2005 balance map. Glacier surface elevation change is the difference between the 1993 surface (photogrammetry) and 2004/2005 surfaces from photogrammetry and GPS (Source: Riedel and Larrabee, 2011).

National Park Service has been remapping the NOCA glaciers after ~10 years to assess area changes, advance/retreat of termini, surface elevation/volume changes and recalculated mass balance based on updated maps to provide more accurate and consistent mass balance results (Riedel and Larrabee, 2011). Updated maps were created for Silver and Sandalee glaciers in 2009 (Figure 4.11) and used to adjust mass balance of Silver and Sundalee glaciers for water years 2001-2009 (Figure 4.12). New maps for North Klawatti and Noisy glaciers will be finalized in 2011 (Riedel and Larrabee, 2011). Comparison of old and new maps (or photos) illustrates that the glacial area in NOCA has declined due to observed warming and precipitation change and that most of the loss occurred in the ablation zone (Riedel and Larrabee, 2011). For instance, comparison of 1993 adjusted reference map and 2004/2005 balance map for Silver Glacier illustrated that the area of Silver Glacier decreased 16 % and Silver Glacier has lost as much as 15 m in depth near its terminus (Figure 4.11) (Riedel and Larrabee, 2011). Photos of Silver Glacier taken in 1958 and 2006 (Figure 4.12) show extensive loss of ice mass on the slopes feeding the lake and an enlargement of the lake area. Furthermore, comparison with an earlier map from 1913 shows that ice that completely covered the current location of the lake in the early 20^{th} century had essentially disappeared by 1958 (Jon Riedel, personal communication).

Figure 4.12 View to the west of Silver Glacier in 1958 (left, by Post) and 2006 (right, by Scurlock) (Source: URL 2).

The cumulative balance for the four NOCA glaciers has been negative although there were slight volume increases between 1996 and 2002 (Figure 4.13) (Riedel and Larrabee, 2011). After a short period of slight volume increase, the negative cumulative balance trend was strengthened due to the seven consecutive years of negative net mass balance for all four glaciers. In general, large glaciers on the wetter west side of NOCA such as Noisy and North Klawatti Glaciers show more negative cumulative balance in comparison with those on the more arid eastern part of the park such as Silver and Sandalee Glaciers (Riedel and Larrabee, 2011). This is due to the fact that the eastern glaciers are relatively small, exist at higher elevations and receive solar shading from nearby mountains (Riedel and Larrabee, 2011). In water year 2009, cumulative net mass balance was most negative for North Klawatti Glacier (– 16.7 m w.e.) and least for Silver Glacier (-9.5 m w.e.) (see Figure 4.13). Between water years 1993 to 2009, the average annual melt rate for all four NOCA glaciers has increased by about 12 % (1 m w.e.) (Figure 4.14), increasing glacial contribution to summer (May – September) runoff (Granshaw and Fountain, 2006). In the Thunder Creek watershed, the most heavily glaciated basin in the North Cascades (Chennault, 2004), North Klawatti Glacier contributed about 32 % of total summer (May-September) streamflow, while in the more arid, less glaciated Ross Lake basin Silver Glacier provided about 6 % of total summer streamflow (Riedel and Larrabee, 2011). Glacier contribution to summer runoff on the Skagit River Basin is about 12-18 % (120-180 B gallons) (personal communication Jon Riedel).

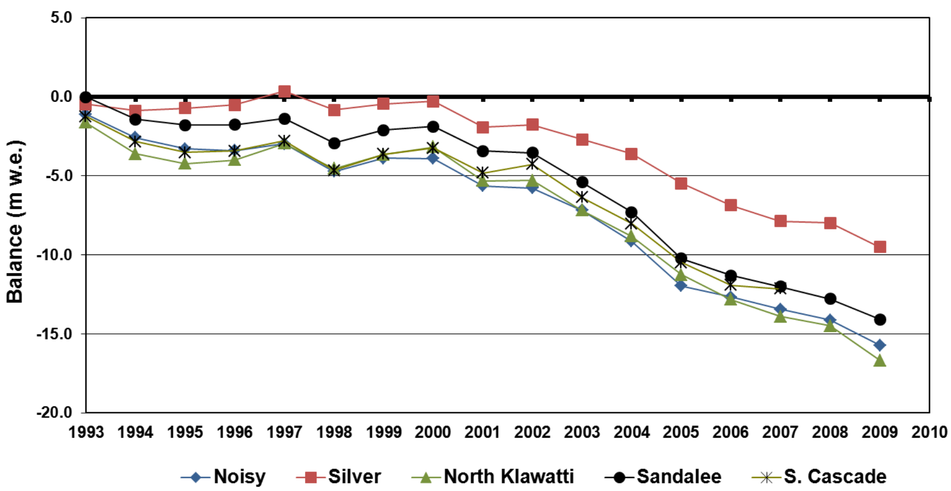

Figure 4.13 Cumulative mass balances for four glaciers monitored by NPS and South Cascade Glacier monitored by USGS. Silver and Sundalee glacier curves are map-adjusted (Source: Riedel and Larrabee, 2011).

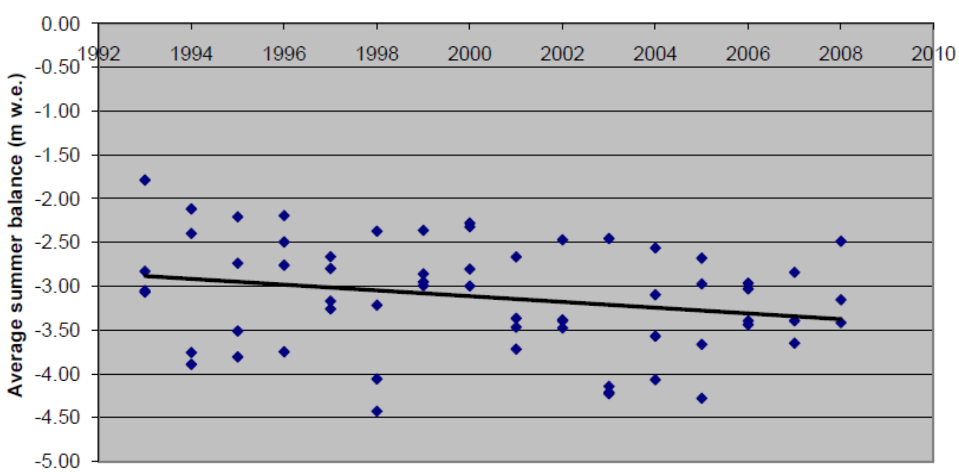

Figure 4.14 Average summer balance (ablation) from 1993 to 2009 (Source: URL 2).

Chennault (2004) evaluated the impact of projected future climate change on glacial hydrology in Thunder Creek using the Distributed Hydrology Soils Vegetation Model (DHSVM). The glacier coverage of Thunder Creek watershed had dropped from about 22.5 % to 12.8 % between the Little Ice Age (1850) and 1998 (Figure 4.15) (Chennault, 2004). Based on the glacier retreat rate from the Little Ice Age to 1998, a decrease to 7.1 % glacier coverage is expected by 2100 and could result in a 31% decline in late summer streamflow in Thunder Creek (Chennault, 2004).

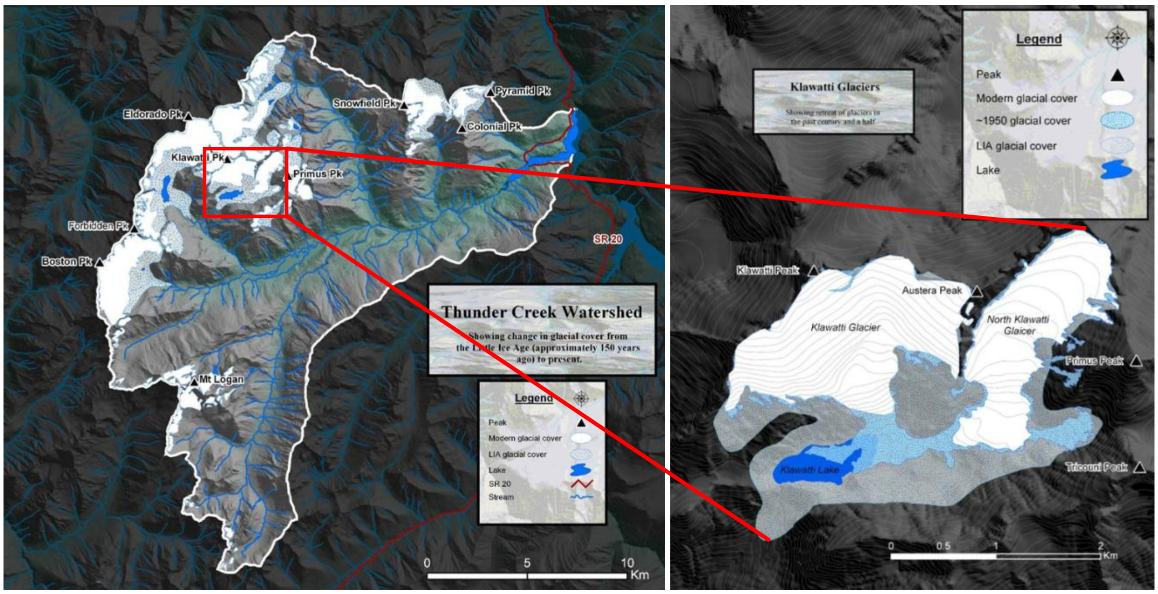

Figure 4.15 Glacier area changes in Thunder Creek watershed (left) and in the Klawatti glaciers since the Little Ice Age (Source: URL 2)

The shrinking or disappearance of glaciers and the resulting decrease in glacial contribution to summer runoff influence hydropower generation, instream flow augmentation in late summer, sediment and nutrient loadings, and water temperature. These impacts may in turn create socioeconomic impacts related to municipal and industrial water supply, agriculture, energy supply, fluvial and marine ecosystems, recreation, and tourism (Fountain and Tangborn, 1985; Granshaw and Fountain, 2006; Mantua et al., 2010). The disappearance or shrinkage of glaciers is expected to exacerbate reductions in annual minimum flows and projected increases in water temperature due to warmer air temperature, impacting cold water fish such as salmon and bull trout (Mantua et al., 2010).

4.4 Summary and Conclusions

Glacier retreat and mass losses occurred locally, as well as globally and regionally have accelerated in response to post-1970 global warming and are projected to continue in response to global climate change. The changes in summer melt in the Skagit Basin are likely to influence water resources management of hydropower generation, agriculture, and instream flow augmentation in the region during the summer months. The disappearance or shrinkage of glaciers is expected to exacerbate summer low flow and result in warmer water temperatures, impacting cold-water fish in the Skagit basin such as salmon and bull trout in headwater streams. Key findings are summarized below:

- Worldwide records of glacier length changes and mass balance measurements show that glaciers have been generally retreating since the end of the Little Ice Age (~1550-1850) but rates of glacier changes have fluctuated corresponding to climate variability; strong glacier retreats were observed in the 1940s and 1950s, followed by stable or advancing conditions until the end of the 1970s, and then rapid rates of ice loss since the mid 1980s.
- Glacier recession rates have increased due to rapid global warming since the 1970s, although different regions have shown somewhat different rates of change. Mass losses per unit area were strongest for Patagonia, followed by Alaska and U.S. and Canada. Unlike the other regions, glaciers in the European Alps showed small regional mass gains mostly due to increased precipitation. Similar effects were observed for glaciers in coastal Scandinavia and New Zealand.
- Following global trends, North Cascades glaciers have been retreating, although glaciers in the North Cascades have also fluctuated in response to the 20th century climate variability. Rapid retreat occurred between 1890 and 1944, glaciers slightly advanced from 1945 to 1976 and then have again retreated rapidly since about 1977.
- Based on 1958 and 1998 inventories, reductions of the glacier population (loss of 5) and area (8.2 ± 0.1 km^2) were observed in the North Cascades National Park Complex (NOCA). The estimated volume loss for the same periods was 0.8 ± 0.1 km^3 of ice which contributes up to 6 % of the late summer (August –September) runoff.

- Glaciers in the Skagit River Basin have also shown a strongly negative long-term trend corresponding to climate change since monitoring began in 1957 on South Cascade Glacier. This trend was slowed by cool-wet periods in 1970-76 and 1996-2002 in response to climate variability (the cool phase of the PDO). Estimates of total loss of glacial area in the Skagit Basin since 1900 are on the order of 50%.
- More rapid losses of glacial resources were observed on the wetter west side of the Skagit Basin such as Noisy and North Klawatti Glaciers than on the more arid east side of the park such as Silver Glacier: cumulative net mass balance was most negative for North Klawatti Glacier (– 16.7 m w.e.) and least for Silver Glacier (-9.5 m w.e.). This is due to the fact that the eastern glaciers are relatively small, exist at higher elevations and receive solar shading from nearby mountains.
- Glacier contribution to summer (May-September) runoff on the Skagit River Basin is about 12-18 % (120-180 B gallons).
- All glaciers in the Skagit River Basin are expected to continue to decrease rapidly in volume. Ongoing losses of glacial ice and ice caps are projected to continue in response to the regional expressions of global climate change. Some glaciers in the North Cascades are already in disequilibrium with the current climate, and are expected not to survive either the current climate or future (warmer) climate.

URL1: http://www.nichols.edu/departments/glacier/glacier_retreat.htm
URL2: http://www.nps.gov/noca/naturescience/glacial-mass-balance8.htm

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5. Hydrology

Abstract

Changes in temperature and precipitation, as simulated by global climate models for future greenhouse gas emissions scenarios, are projected to significantly influence the hydrology of the Pacific Northwest (PNW) and Washington State (WA). Despite increasing cool season (Oct-Mar) precipitation in many scenarios, reductions in April 1 snow water equivalent (SWE) are projected over the PNW and WA. These reductions in natural water storage are largest in the simulations of moderate elevations that are near freezing in mid-winter. Hydrologic model simulations show that warmer temperatures, more precipitation falling as rain in winter, and loss of snowpack cause a shift in runoff timing. As for changes in snowpack, the largest shifts in runoff timing are projected in transient snow (mixed rain and snow) watersheds at moderate elevations. Shifts in runoff timing due to climate change are projected for the Skagit River basin but, in comparison with Washington State (WA) as a whole, the Skagit River basin would experience less reduction in April 1 SWE; high-elevation, snowmelt dominant areas in the headwaters of the Skagit River basin (e.g., upstream of Ross Dam) are among the areas in WA least sensitive to climate change. Watershed characteristics throughout the Skagit River basin are likely to shift toward more rain dominant behavior by the end of the 21st century. An examination of the sensitivity of changes in SWE to projected air temperature and precipitation changes shows that temperature plays a dominant role in comparison with precipitation in producing changes in SWE throughout the 21st century. More severe extreme hydrologic events (floods and low flows) are projected for the Skagit River basin using hydrologic models. Floods are projected to increase in magnitude for all return intervals due to increasing winter precipitation and higher freezing elevations during winter storms that increase runoff production in moderate elevation areas. Extreme low flows also decrease in magnitude in the simulations, due to reduced late-summer baseflows in the hydrologic simulations. Projected loss of glaciers is expected to result in even greater impacts to low flows in sub-basins with significant glacial coverage.

5.1 Background

In the Pacific Northwest (PNW), most of the annual precipitation comes in the cool season (Oct-Mar). Whether the precipitation falls as rain or snow depends primarily on air temperature, which is determined by proximity to the coast, elevation, and other factors. Based on the dominant form of cool-season precipitation and the amount of natural storage as snowpack, PNW watersheds are frequently classified into three regimes; rain-dominant watersheds, transient snow (mixed rain and snow) watersheds, and snowmelt-dominant watersheds (Hamlet et al., 2001; Hamlet and Lettenmaier, 2007; Elsner et al., 2010). Low-lying coastal watersheds, such as the Chehalis River basin in western WA, are rain-dominant basins. Streamflow in these basins responds quickly and directly to the precipitation that falls on the basin because most of precipitation falls as rain. Long-term monthly average streamflow in rain-dominant basins has one peak in winter coincident with the peak in seasonal precipitation, as shown in Figure 5.1. Watersheds lying at moderate elevation where winter temperatures fluctuate around freezing level are classified as transient snow (mixed rain and snow) basins. In these watersheds, a substantial portion of the cool-season precipitation in mid-winter falls as snow, but at the lower elevations in the basin the accumulated snow often melts a few days or weeks after it falls (hence the label “transient” snow). At the higher elevations, however, there is considerable snow accumulation in mid-winter, which ultimately melts in the spring/summer. These characteristics of transient snow watersheds result in two seasonal streamflow peaks as shown in Figure 5.1; one in the early winter generated primarily by precipitation falling as rain, and a second which is caused by rain and melting snow.

In snowmelt-dominant basins, air temperatures are below freezing for most of the cool season and cool-season precipitation accumulates primarily as snow, which then melts in the spring and early summer. Therefore, the hydrographs of the snowmelt-dominant basins show low flows during winter months and high flows during late spring/early summer, as shown in Figure 5.1. Because major tributaries in the Columbia and Snake River basins drain snowmelt-dominant watersheds, the hydrograph of the Columbia River at The Dalles, OR (USGS # 14105700) in the lower Columbia River basin) shows strong snowmelt-dominant behavior.

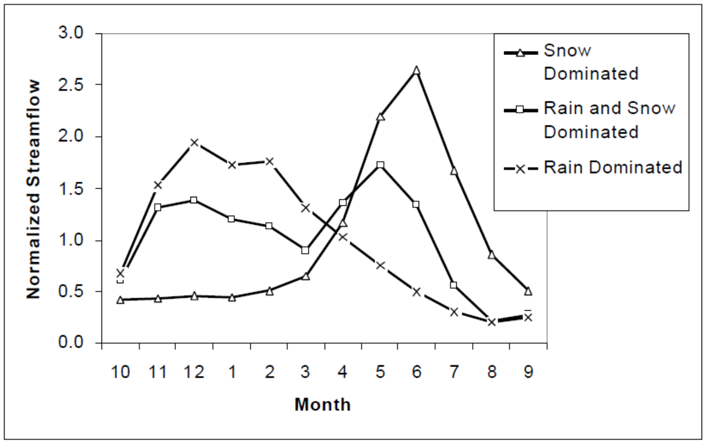

Figure 5.1 Seasonal distribution of streamflow for snowmelt-dominant, transient snow, and rain-dominant watersheds in the PNW expressed as the fraction of the monthly mean streamflow that occurs in each month (Source: Hamlet et al., 2001).

Each of the three types of watersheds responds in a different way to climate change. For instance, warmer climate may cause freezing levels to rise as illustrated in Figure 5.10. In rain dominant basins, such changes are not very significant, since the dominant portion of the basin experiences conditions above freezing already. By comparison, transient snow basins are more sensitive to warming because of loss of snowpack and increasing basin area subjected to rainfall. Thus, relatively large changes in natural storage (less snowpack, reduced late-summer soil moisture) and runoff timing (more winter flow, less summer flow), and increasing flood intensity are expected in those areas which currently have substantial snowpack, but which are near freezing in mid-winter (Hamlet et al., 2005 and 2007; Hamlet and Lettenmaier, 2007; Elsner et al., 2010). Large areas of the Skagit River basin have transient-snow hydrologic characteristics. Snowmelt-dominant basins show the same basic response of transient basins (less snow, greater flow in winter, reduced summer flows), but the effects are not as pronounced (Elsner et al., 2010). Many headwater areas in the Skagit River basin have snowmelt-dominant hydrologic characteristics.

5.2 Hydrologic Impacts over the Pacific Northwest

5.2.1 Implications of changes in April 1 snow water equivalent

Snowpack is a major component of the hydrologic cycle in the western United States and the PNW (Serreze et al., 1999; Hamlet et al., 2005), providing large amounts of natural storage and dramatically increasing water availability in the warm season. In the WA part of the Cascade Mountains alone, April 1 snowpack stores, on average, approximately 5.9 trillion gallons of water. Loss of snowpack is a primary impact pathway associated with regional warming in the PNW (Mote et al., 2005; Hamlet et al., 2005 and 2007).

Figure 5.2 shows projected percent change in April 1 snow water equivalent (SWE) reported by Elsner et al. (2010) for the Intergovernmental Panel on Climate Change (IPCC) A1B and B1 emissions scenarios (A1B is a medium high emissions scenario, and B1 is a low emissions scenario. For more details on emissions and climate change scenarios, see Chapter 3). Consistent with past studies (Hamlet et al., 2001; Mote et al., 2003), projections using A1B emissions scenarios show greater reduction in April 1 SWE than those using B1 emissions scenarios, especially for the 2080s simulations. The largest reductions in April 1 SWE are projected at moderate elevations in the Cascade Mountains (Central WA), the Olympic Mountains (western WA), and Okanogan highlands (northeastern WA); and in the southern part of WA. Snowpack at high elevations is less affected. For the two IPCC emissions scenarios that were simulated, April 1 SWE in WA is projected to decrease by 28 to 30 % by the 2020s, 38 to 46 % by the 2040s and 56 to 70 % by the 2080s in comparison with the historical mean for water years (Oct-Sept) 1917-2006.

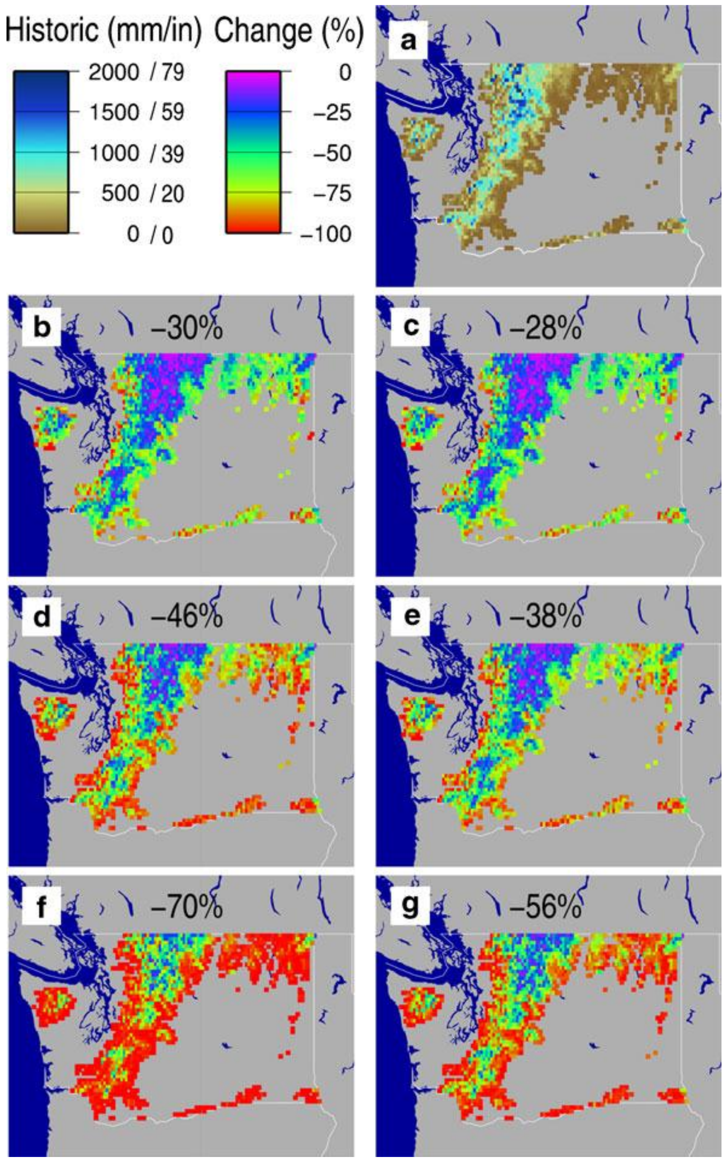

Figure 5.2 Summary of projected percent change in April 1 SWE in WA as simulated by the Variable Infiltration Capacity (VIC) hydrologic model. **a** Historical April 1 SWE (mean for water years (Oct-Sept) 1917–2006). **b**, **d**, **f** Projected change in April 1 SWE for A1B scenarios for the 2020s, 2040s and 2080s, respectively. **c**, **e**, **g** Projected change in April 1 SWE for B1 scenarios for the 2020s, 2040s and 2080s, respectively. Inset numbers in panels b-f show the percent change in April 1 SWE in comparison with the 20th Century baseline shown in panel a). (Source: Elsner et al., 2010).

5.2.2 Implications of changes in seasonal streamflow timing

Figure 5.3 shows projected mean monthly hydrographs for rivers in three representative watersheds in the PNW reported by Elsner et al. (2010). Because temperature increases primarily influence snow accumulation and melt processes, rain-dominant basins have relatively few impacts due to warming and respond primarily to changes in precipitation (Figure 5.3a). Changes in mean hydrographs are more apparent in snowmelt dominant watersheds. In these watersheds, higher winter temperature causes the precipitation to fall as rain, resulting in increased winter streamflow relative to historical mean streamflows. Warmer temperature causes less snow accumulation during winter and earlier snow melt during spring and summer. As a result, earlier spring peak flow and lower summer peak flow are projected for snowmelt-dominant watersheds (Figure 5.3 c) (Hamlet et al., 2001; Mote et al., 2003; Elsner et al., 2010). The most significant changes in mean hydrographs are projected in the transient snow (mixed rain and snow) watersheds. In these areas, the transient snow zone would move to higher elevations as the freezing level rises with warming (Figure 5.10). Thus, watersheds that have been transient snow watersheds under historical (1917-2006) climate conditions would become rain-dominant watersheds by the 2080s (Figure 5.3 b) (Hamlet et al., 2001; Mote et al., 2003). The widespread transformation from snowmelt-dominant and transient systems to rain-dominant systems is one of the most fundamental impacts of regional warming on the PNW (Figure 5.4).

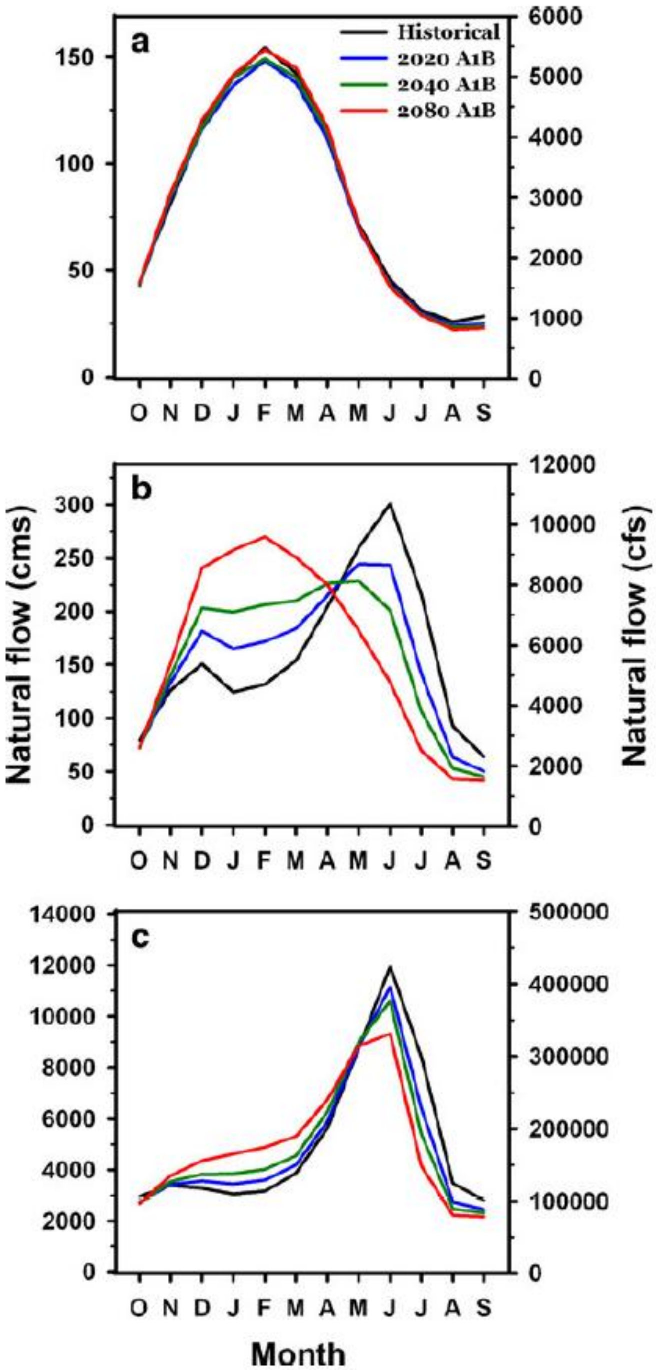

Figure 5.3 Projected average monthly streamflows for rivers draining three representative watershed types in WA: a) rain dominant (the Chehalis River at Porter), b) transient rain-snow (the Yakima River at Parker), and c) snowmelt dominant (the Columbia River at The Dalles) (Source: Elsner et al., 2010).

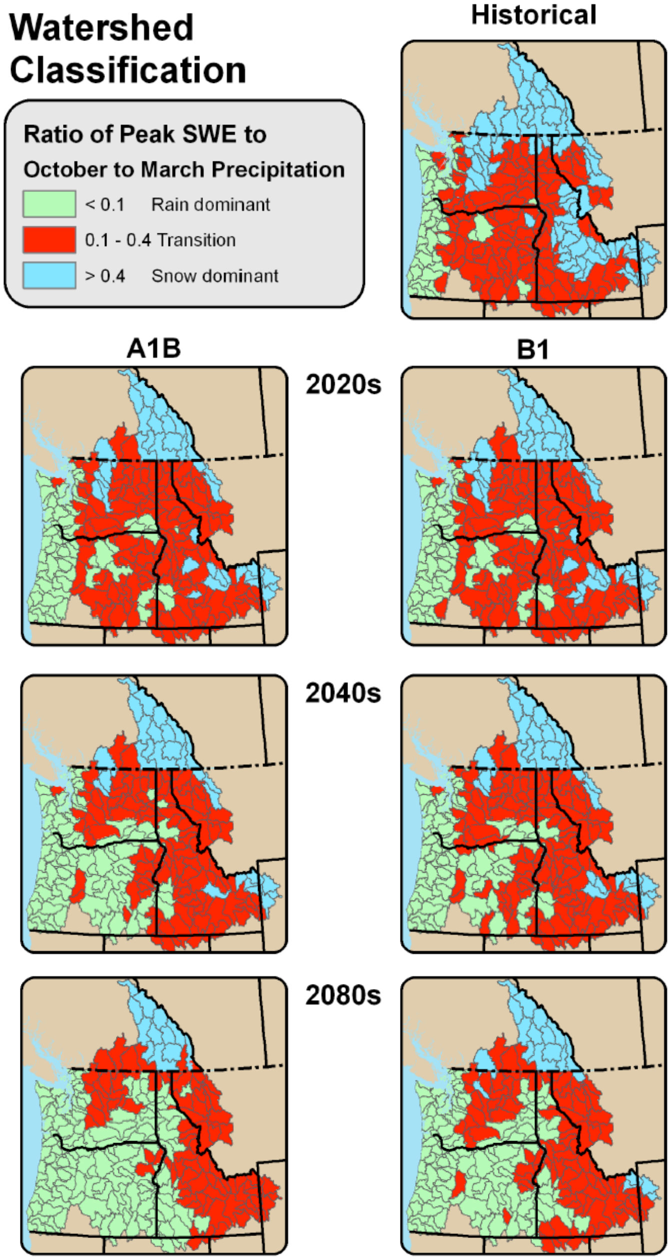

Figure 5.4 Ratio of April 1 SWE to total cool-season (October-March) precipitation for the historical period (water years 1916 to 2006), for the A1B scenario (left panels) and for the B1 scenario (right panels) for three future time periods (the 2020s, the 2040s, the 2080s) (Source: Tohver and Hamlet, 2010).

5.3 Hydrologic impacts in the Skagit River basin

The analysis of hydrologic impacts in the Skagit River basin focuses on several specific streamflow locations and their upstream contributing basin areas (Figure 5.5). Moving from the headwaters to the lower basin, these river locations are: The Skagit River a Ross Dam near Newhalem, the Sauk River near Sauk, the Baker River at Upper Baker Dam, and the Skagit River near Mount Vernon.

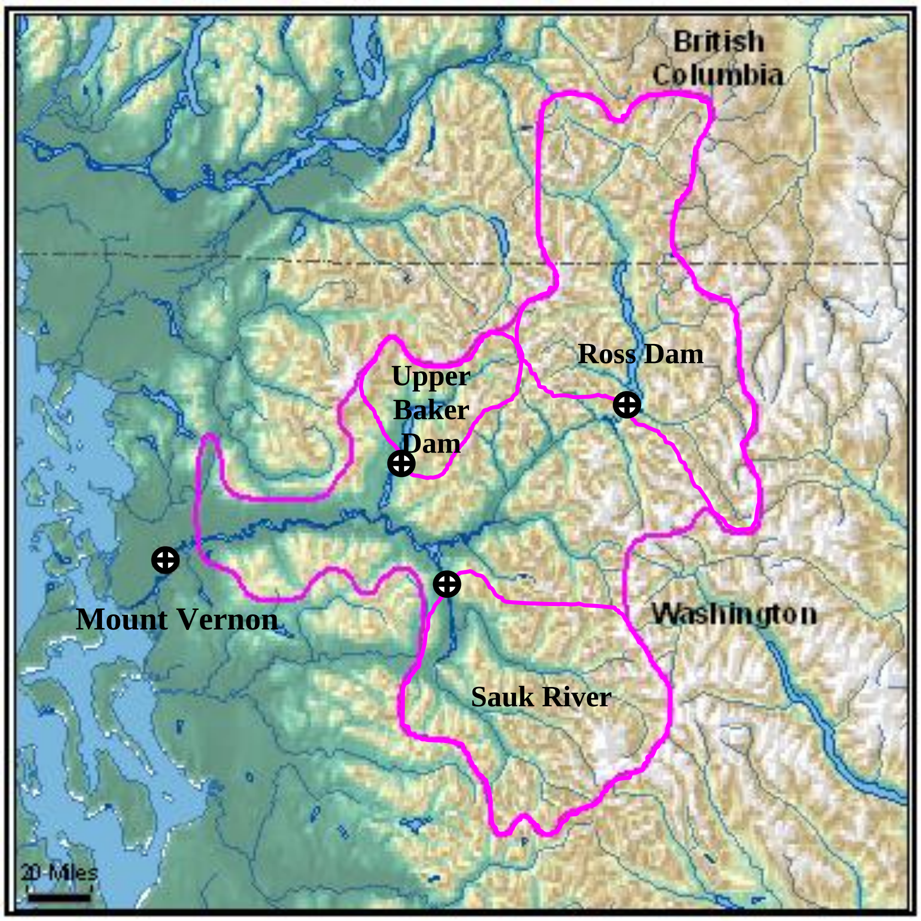

Figure 5.5 A map showing drainage area of the upper Skagit River at Ross Dam near Newhalem, the Sauk River near Sauk, the Baker River at the Upper Baker Dam near Concrete and the lower Skagit River near Mount Vernon. A black circle with cross shows the location of each river location and the pink line shows the drainage area of each site.

The projections of future temperature and precipitation changes upon which projected changes in hydrology are based are different for different global climate models (GCMs) (Mote and Salathé, 2010). All GCMs, however, project increasing trends in temperature through the 21st century. Increases in winter, spring and fall precipitation coupled with summer drying are also a common feature of the GCM simulations for the PNW (See Chapter 3). The sensitivities of the streamflow and peak SWE in the Skagit River basin to projected temperature and precipitation are examined here for ten GCM simulations downscaled using the Hybrid Delta downscaling method for A1B and B1 emissions scenarios (See Chapter 3).

Figure 5.6 shows changes in annual streamflow for the Skagit River near Mount Vernon (Figure 5.5) and cool-season precipitation averaged over the associated upstream basin area for each climate change scenario relative to the historical simulation (water years 1916 to 2006). Changes in annual streamflow at this location correspond well with changes in cool-season precipitation averaged over the corresponding upstream basin area in terms of both magnitude and direction.

Changes in SWE are affected primarily by temperature, but precipitation also plays a substantial role in determining SWE impacts, particularly in the earlier part of the 21st century. Figure 5.7 shows percentage changes in peak SWE and cool-season precipitation plotted with changes in cool-season mean air temperature (averaged over the upstream basin area) relative to the historical simulations (water years 1916 to 2006) for the Skagit River near Mount Vernon. Temperature plays a substantial role in determining changes in SWE over all projected periods, and changes in the Skagit River basin SWE are negative for all scenarios and time periods despite increasing basin-average precipitation in many cases. This demonstrates that reductions in basin-average SWE are directly related to the substantial warming in all the scenarios. As warming intensifies through the 21st century, temperature becomes an increasingly important driver of changes in peak SWE: the correlation coefficients (R) between changes in peak SWE and changes in temperature are -0.67, -0.82, and -0.92 for the 2020s, 2040s and 2080s, respectively. By contrast, basin-average precipitation has less influence on changes in SWE in comparison to temperature and this influence declines through the 21st century: $R = 0.28$ for the 2020s, 0.12 for the 2040s and -0.07 for the 2080s. These relationships reflect the fact that dramatic temperature changes continue through the 21st century in the scenarios, whereas precipitation changes only increase slightly. Another way to state this is that GCM-projected increases in precipitation that would, in isolation, tend to mitigate losses of snowpack will not be able to keep pace with the losses of snowpack due to projected warming.

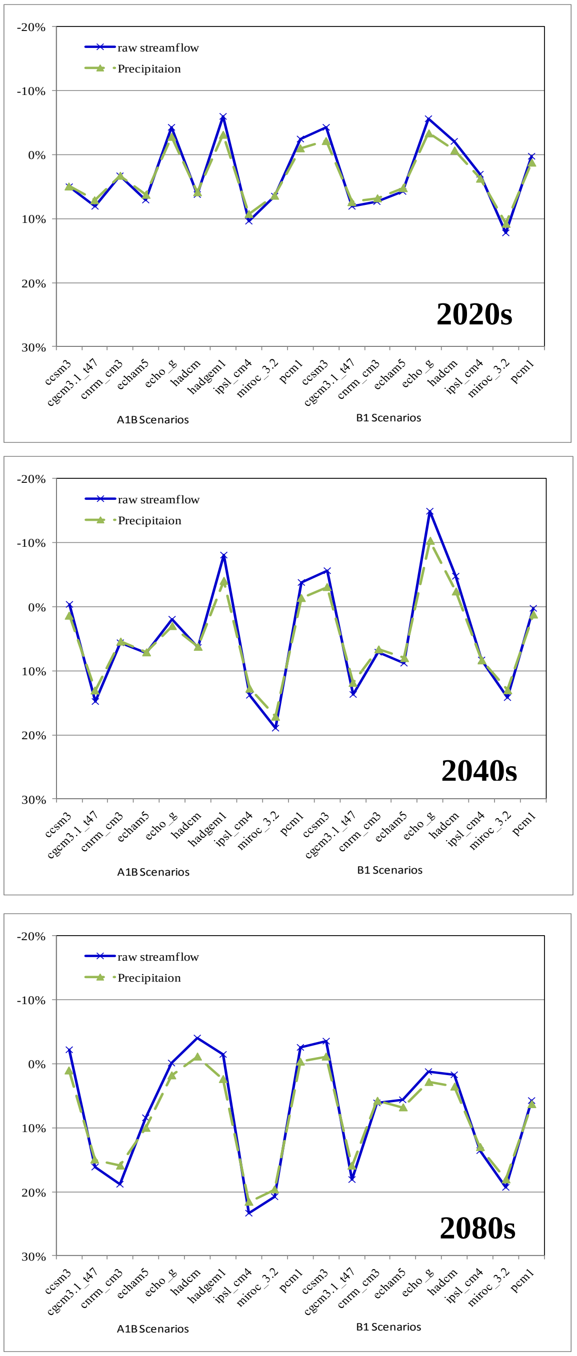

Figure 5.6 Changes in unbiascorrected ("raw") annual streamflow and basin-average cool-season precipitation relative to historical baseline (water years 1916 to 2006) for the Skagit River near Mount Vernon for the 2020s, 2040s, and 2080s. Climate change scenarios are identified on the X axis.

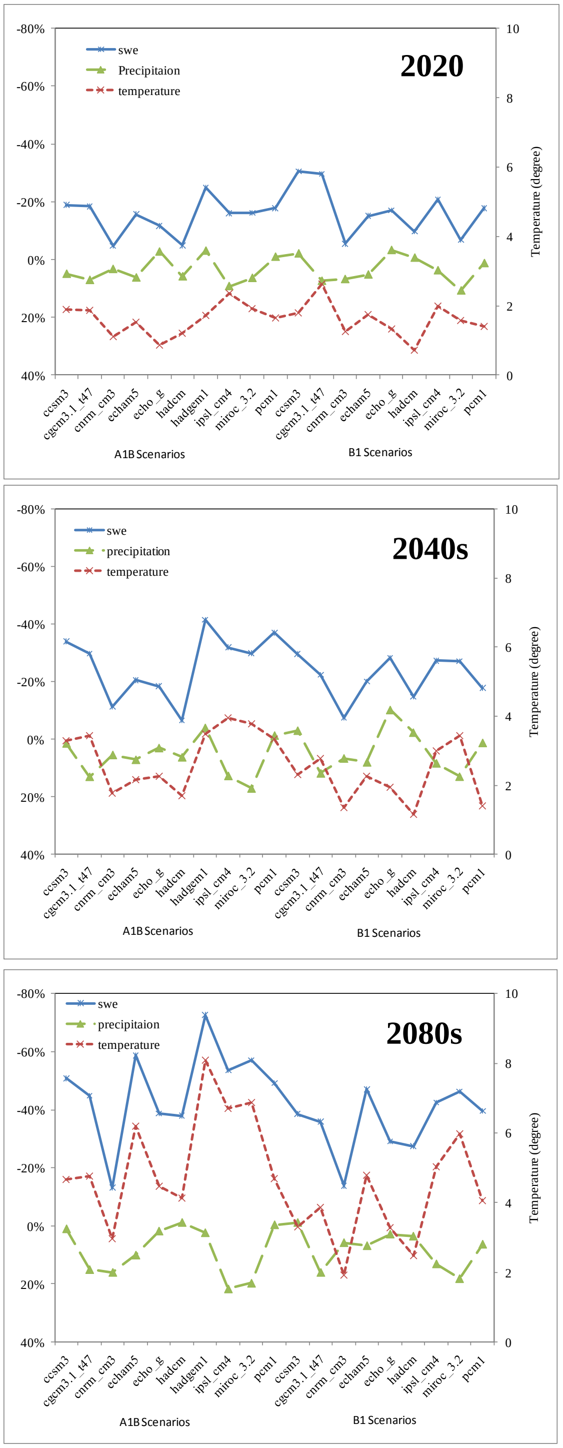

Figure 5.7 Changes in peak SWE, and basin-average cool-season precipitation and air temperature for each climate change scenario relative to a historical baseline (water years 1916 to 2006) for the Skagit River near Mount Vernon for the 2020s, 2040s, and 2080s. Climate change scenarios are identified on the X axis.

5.3.1 Changes in snow water equivalent in the Skagit River basin

Consistent with SWE projections over the PNW and WA as a whole, basin average SWE for the upstream areas associated with the Skagit River at Ross Dam and Skagit River at Mount Vernon are projected to decline (Figure 5.8). Reduction of SWE is more pronounced for the A1B than B1 emissions scenario, due to greater warming. Projections using the A1B scenario show a decline of April 1 SWE of 19 and 26 % by the 2040s for Ross Dam and for Mount Vernon, respectively, in comparison with the historical means for water years 1916-2006. Less SWE reduction is projected for Ross Dam because this portion of the Skagit River basin is at higher elevation and is colder in the winter than the portion of the basin upstream of Mount Vernon. The change in April 1 SWE for the Skagit River basin is less than the average change in SWE for WA (Figure 5.2). This is also consistent with Figure 5.4, which shows that the northern Cascade Range is likely to be one of only a few remaining transient snow areas in WA by the end of the 21st century.

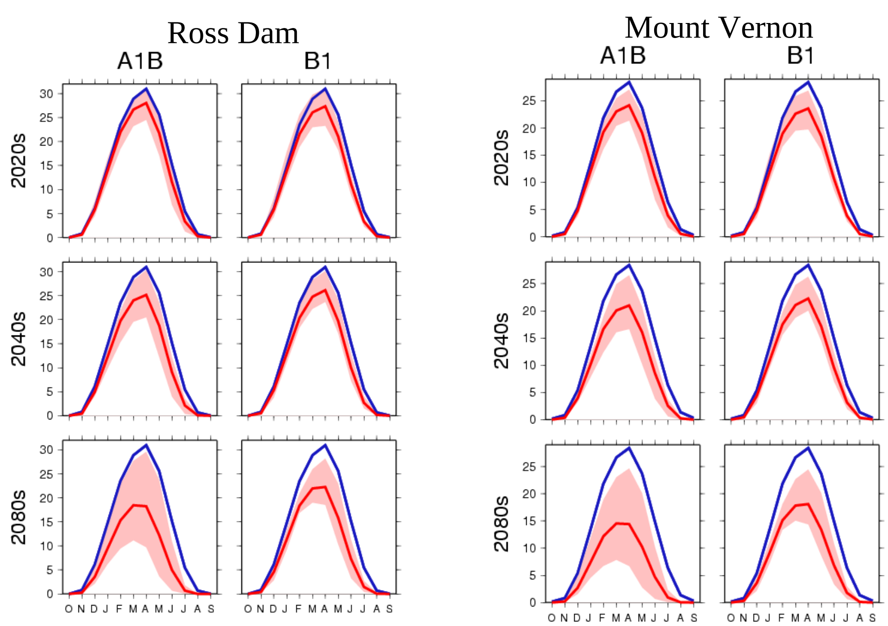

Figure 5.8 Seasonal cycle of basin-average SWE (in inches) for the basin area upstream of the Skagit River at Ross Dam near Newhalem (left) and the Skagit River near Mount Vernon (right) for three future time periods (rows) and two emissions scenarios (columns). The blue line represents the historical mean SWE (water years 1916-2006), and the red line represents projected monthly mean SWE across ~10 Hybrid Delta scenarios. The pink band represents the range from ithe ensemble of Hybrid Delta scenarios (Source: URL 2).

5.3.2 Changes in mean monthly streamflow

Figure 5.9 shows projected mean hydrographs for the Skagit River main stem and its major tributaries: the upper Skagit River at Ross Dam near Newhalem, the Sauk River near Sauk, the Baker River at the Upper Baker Dam near Concrete, and the lower Skagit River near Mount Vernon (Figure 5.5). Monthly hydrographs for the Skagit River near Mount Vernon in the lower basin shows a transient (mixed rain and snow) characteristic whereas the hydrograph for the Skagit River at Ross Dam in the headwaters shows a snowmelt-dominant characteristic (Figure 5.9). The differences in the response of each watershed are determined primarily by mid-winter temperatures rather than strictly by elevation. For instance, the hydrographs for the Baker River at lower Baker Dam and Upper Baker Dam show a more transient snow watershed characteristic than those at the Sauk River near Sauk (Figure 5.9), despite the fact that upstream basin area associated with Baker River site is at a higher elevation than the upstream basin area associated with the Sauk River site. Mid-winter temperature regimes also largely determine the sensitivity of snowpack and the resulting streamflow timing shifts to warming as discussed above. The hydrograph at Ross Dam shows the typical response of a snowmelt-dominant watershed to climate change: increase in winter flow, earlier peak flow, and decrease in summer average and peak flow (Figure 5.9). By the 2080s, the hydrograph for the Skagit River at Ross Dam shows a clear shift toward a dual-peak transient snow hydrograph. The Sauk River near Sauk, the Baker River at Upper Baker Dam, and the Skagit River near Mt. Vernon are currently transient snow watersheds. Increased winter streamflow and streamflow timing shifts in those areas are therefore more dramatic than those at Ross Dam. For all sites streamflows increase in the winter months and decrease in summer months as time moves toward the end of the 21st century. In some cases dramatic shifts in the seasonal timing of peak flows are also apparent in the simulations. For the Sauk River and Mount Vernon sites, for example, average November flows for the Hybrid Delta simulations for the 2080s are near historical flows in June. For the Upper Baker Dam, average winter peak flows for the 2080s are higher than summer peak flows for the historical simulations: a shift in the timing of peak seasonal streamflow of more than six months.

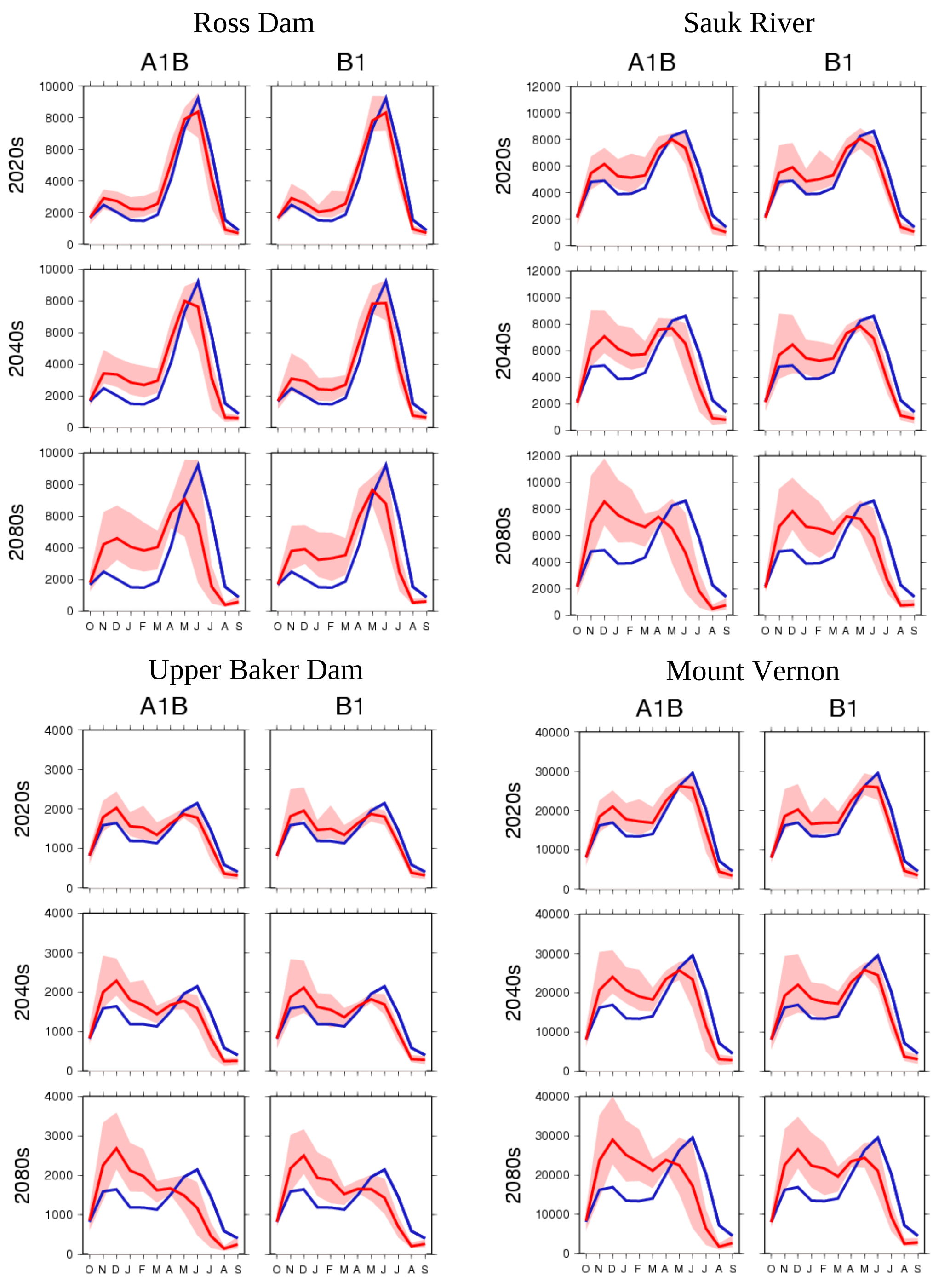

Figure 5.9 Simulated monthly average streamflow (in cfs) for the Skagit River at Ross Dam near Newhalem (upper left panel), for the Sauk River near Sauk (upper right panel), for the Baker River at Upper Baker Dam near Concrete (bottom left panel) and for the Skagit River near Mount Vernon (bottom right panel). The blue line represents historical mean (water years 1916-2006), while the red line represents projected monthly mean streamflow across ~ 10 Hybrid Delta simulations. The red band represents the range from the ensemble of Hybrid Delta scenarios (Source: URL 2).

5.3.3 Changes in Hydrologic Extremes

In snowmelt-dominant watersheds, flooding usually occurs in spring when the accumulated snowpacks melt. The largest floods occur when unusually large snowpacks melt rapidly due to warm temperatures or when large snowpacks melt simultaneously with heavy rain (Hamlet et al., 2007). For warmer temperatures observed in the late 20th century (without increases in storm intensity), the magnitude of the 20-year and 100-year flood in many snowmelt-dominant watersheds has decreased in hydrologic model simulations (Hamlet and Lettenmaier, 2007). In the absence of increases in precipitation, projected future warming would be expected to decrease flood magnitude in snowmelt-dominant basins. Projected increases in cool season precipitation in many climate change scenarios, however, tend to mitigate these effects, and many snowmelt dominant basins show modest increases in flood risk in future projections (Tohver and Hamlet, 2010).

In contrast to these flood risk projections for snowmelt-dominant watersheds, increased flood magnitude is projected for many transient (mixed rain and snow) snow watersheds (Hamlet and Lettenmaier, 2007). For a warmer climate, freezing levels rise and the effective area contributing to runoff production from rainfall increases (Figure 5.10). For basins in which this factor dominates (e.g. much of western WA), the same storm produces much more runoff in a warmer climate, which increases the magnitude of flooding (Mantua et al., 2010; Tohver and Hamlet, 2010). Projected increases in cool season precipitation tend to exacerbate these effects.

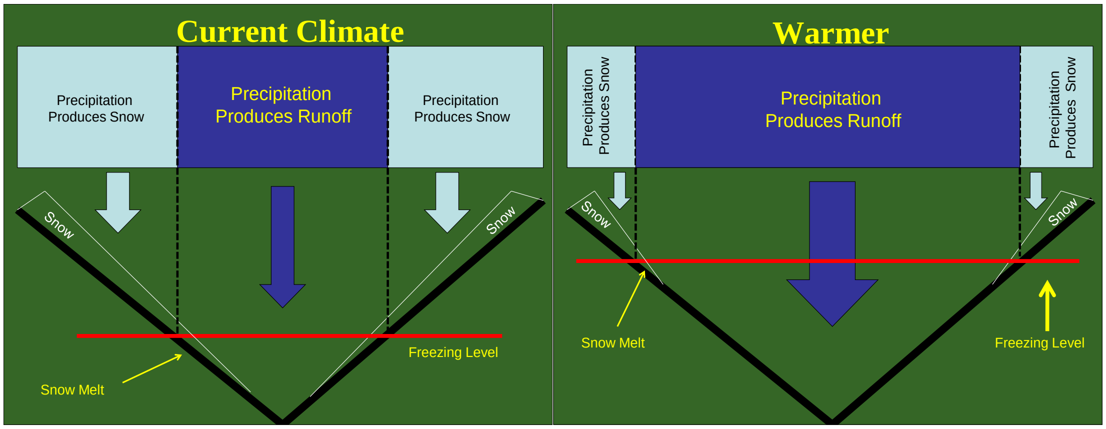

Figure 5.10 Schematic of impacts on snowpack and runoff production due to rising freezing levels associated with regional warming (Source: Hamlet, 2010).

A warmer climate would also typically cause antecedent snowpack to decrease, potentially decreasing the importance of rain-on-snow events in some basins. In basins where these factors dominate, flood risk may decline due to warming alone (Hamlet et al., 2007). Projected increases in cool season precipitation, however, tend to mitigate these effects.

Climate change impacts on the extreme flows for the Skagit River are reported by Hamlet et al. (2010). Figure 5.11 shows projected flood magnitude for the 20-, 50-, and 100-year return intervals at four representative locations in the Skagit River system: the Sauk River near Sauk, the Baker River at Upper Baker Dam, and the Skagit River at Ross Dam and Mount Vernon. For the 2020s, the hydrograph at the Skagit River at Ross Dam still shows snowmelt-dominant watershed characteristics (Figure 5.8). The central tendency of the projected 100-year flood at Ross Dam is near the historical number, as shown in Figure 5.11 (some of the projections show lower flood magnitude than the historical values, some higher). By the 2080s, following a dramatic shift to transient (mixed rain and snow) behavior (Figure 5.8), flood magnitude increases dramatically, especially for the A1B emissions scenario (Figure 5.11). The central tendency of the projected 100-year flood for the A1B emissions scenario for the 2080s at Ross Dam is 49% higher than the historical baseline.

For three other transient snow watersheds in the Skagit River basin, the flood magnitude is projected to increase for all three time periods (Figure 5.11). In transient snow watersheds, warmer climate causes higher freezing levels and increased effective basin areas (Figure 5.10), which, coupled with increasing cool-season precipitation, dramatically increases flood risk even for the relatively small temperature increases projected for the 2020s. Increasing flood risk is expected to appear first in the warmer lower basin and later in the century in the colder headwater areas.

Although glaciers and the groundwater system are not included in the simulations, changes in extreme low flows are projected by Hamlet et al. (2010) due to loss of snowpack, earlier snowmelt, increased evaporation, and projected drier summers alone. The lowest consecutive 7-day flows with a 10-year return interval (7Q10) are used as a metric to evaluate extreme low flows (Figure 5.12). As warming and loss of precipitation in summer intensifies through the 21st

century, more severe low flows are projected for all sites in the Skagit River basin. By the 2080s, projected 7Q10 values are 75% and 60% of the historical value (water years 1916 -2006) for the Skagit River at Ross Dam and Mount Vernon, respectively. For the Baker River at Upper Baker Dam and the Sauk River at Sauk, projected 7Q10 values are about half of the historical values by the end of the 21st century. In areas with significant glacial melt contribution to summer streamflow, impacts to low flows are expected to be more severe as glaciers continue to retreat. However, additional research will be needed to quantify these impacts.

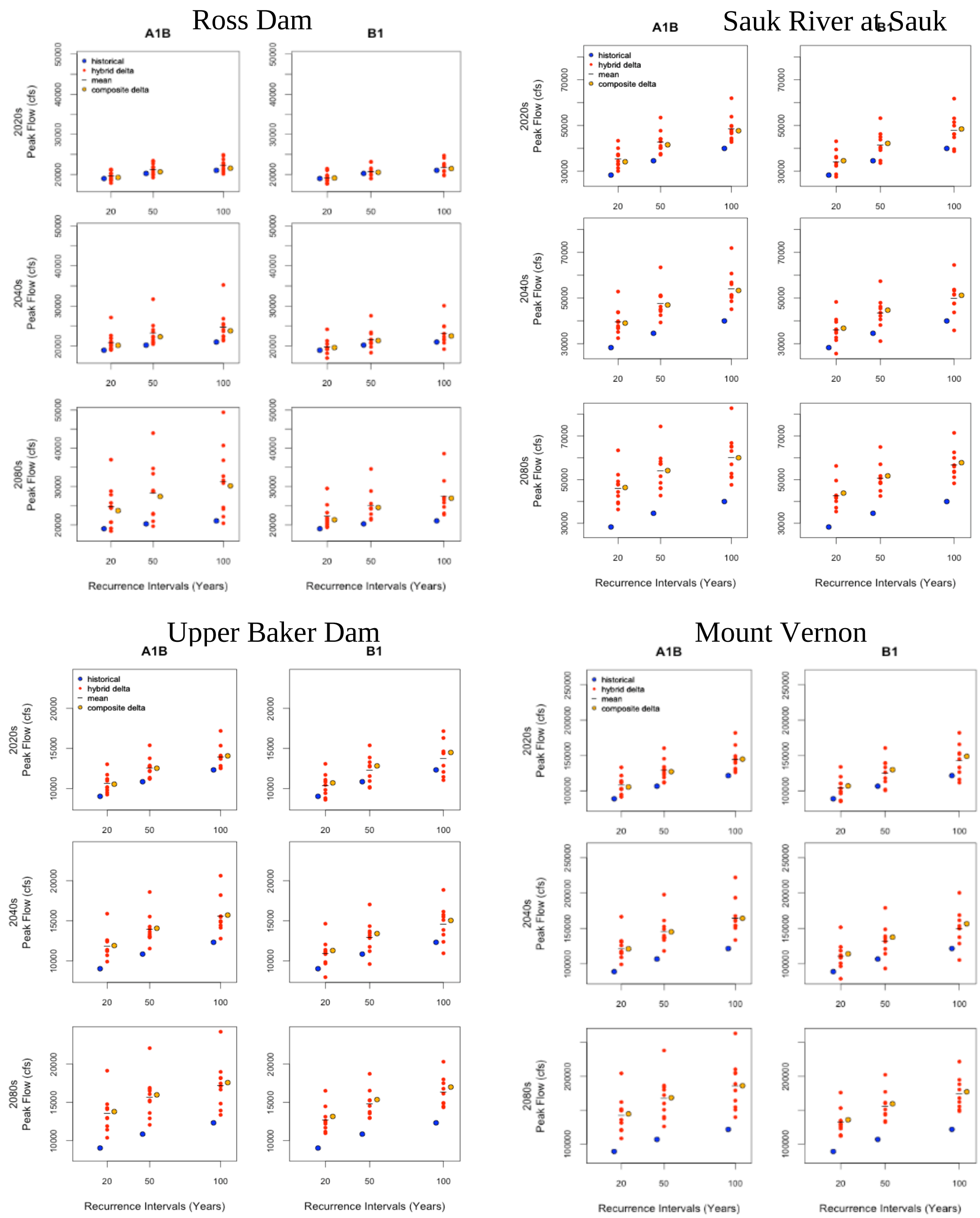

Figure 5.11 The 20-, 50-, and 100-year flood statistics for the Skagit River at Ross Dam near Newhalem (upper left panels), the Sauk River near Sauk (upper right panels), the Baker River at Upper Baker Dam near Concrete (bottom left panels) and the Skagit River near Mount Vernon (bottom right panels) for the historical (blue dots), Hybrid Delta runs (red dots), and Composite Delta runs (orange dots) (Source: URL 1).

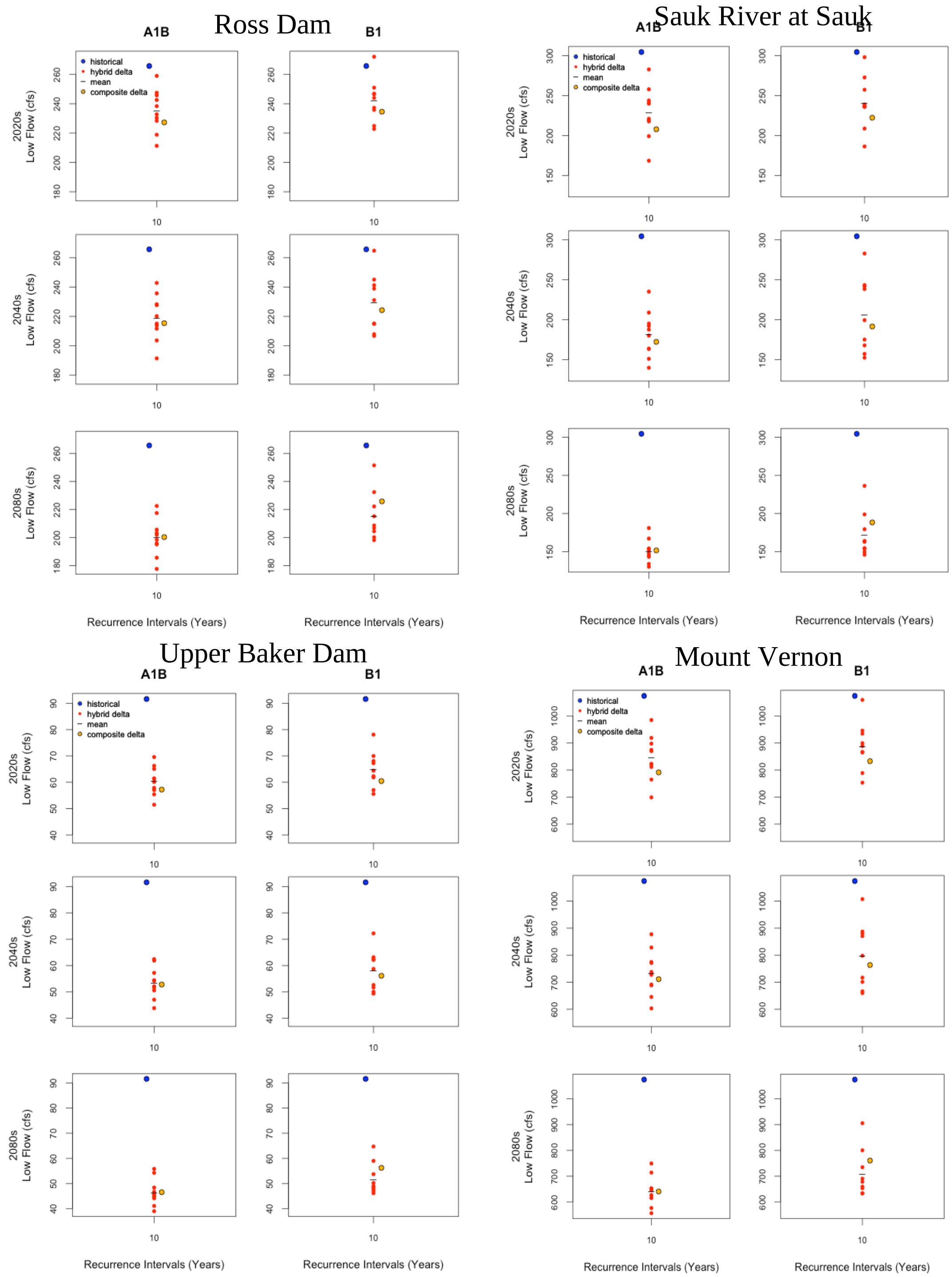

Figure 5.12 The 7-day minimum low flow statistics with a 10-year return interval (7Q10) for the Skagit River at Ross Dam near Newhalem (upper left panels), for the Sauk River near Sauk (upper right panels), for BakerRiver at Upper Baker Dam near Concrete (bottom left panels) and for the Skagit River near Mount Vernon (bottom right panels) for the historical baseline (blue dots), Hybrid Delta runs (red dots), and Composite Delta runs (orange dots) (Source: URL 1).

5.4 Groundwater

Recently, an assessment of groundwater resources in the Skagit River was conducted by the U.S. Geological Survey (Fasser and Julich, 2009; Johnson and Savoca, 2010; Savoca et al., 2009a and 2009b). The assessment focused on the groundwater system in and around four subbasins tributary to the lower Skagit River during water years 2007 and 2008: East Fork Nookachamps Creek, Nookachamps Creek, Carpenter Creek, and Fisher Creek. For the years examined, approximately one-third of precipitation enters the groundwater system in the subbasins and the estimated groundwater recharge from precipitation is about 18 inches per year (Savoca et al., 2009b). During the study period, withdrawals from wells were only 3% of the recharge. Most of the recharge (65%) discharges to creeks. The remaining 32% of the recharge flows towards the northwest and west in the direction of the Skagit River and Puget Sound. The U.S. Geological Survey also developed a groundwater-flow model to evaluate the potential groundwater withdrawals and consumptive use in the study area (Johnson and Savoca, 2010). However, there was no discussion of the potential impacts of climate change on groundwater resources in the study area.

Climate change is likely to affect groundwater recharge (Kundzewicz and Doll, 2009). Precipitation increases during the cool season will likely increase groundwater recharge, but increased evapotranspiration associated with warming may increase losses to the groundwater system during the warm season, particularly if groundwater use for irrigation increases over time (e.g. water demand could increase due to both warming and population growth). Other factors affecting groundwater recharge, such as changing precipitation intensity or interarrival time of storms, changes in land-use (changes in vegetation cover or impervious surface), and hydrologic soil conditions may also affect the outcomes (Zhou et al., 2010). Saline intrusion into groundwater systems due to sea level rise may be a problem in coastal areas (Barlow, 2003; Titus et al., 2009).

In comparison with surface water systems, the climate impacts on groundwater systems have received much less attention. More detailed and comprehensive studies will be required to assess the potential impacts of climate change on the groundwater system in the Skagit River basin. Several studies have reported the potential impacts of climate change on groundwater at global and regional scales (Allen et al., 2004; Scibek and Allen, 2006; Hiscock and Tanaka, 2006; Deyle et al., 2007; Kundzewicz and Döll, 2009; Döll, 2009). However, to date (2011), no published information is available related to the potential effects of climate change on groundwater resources in the Skagit River basin.

5.5 Drainage and Potential Conversion to Marsh in Low-Lying Areas

As discussed in Chapter 1, dikes, levees and tide gates were installed in many low-lying areas in the Skagit River delta to provide a suitable environment for agriculture. The need for drainage, however, may be an important vulnerability for coastal farmland due to projected sea level rise (Poulter et al., 2008), increased river flooding, and increased precipitation (Titus et al., 2009). For instance, one would expect tide gates (see Chapter 1) to be closed more often with projected sea level rise and increased river flooding (Titus et al., 2009), resulting in less drainage capacity, while the need for drainage may *increase* with increasing cool-season precipitation. Some farmland in low-lying areas not protected by dikes may be converted to marsh or non-tidal wetland (Riggs and Ames, 2003; Titus et al., 2009) as has occurred in other areas of the U.S. (Poulter et al., 2008; Titus et al., 2009).

5.6 Summary and Conclusions

Projected changes in temperature and precipitation for the 21st Century are likely to have profound effects on the hydrology of the PNW, including loss of natural water storage as snowpack, changes in runoff timing from summer to winter, and increasing intensity of floods and extreme low flows. Key findings include the following:

- April 1 SWE in Washington State is projected to decrease by approximately 38% to 46% by the 2040s in comparison with the historical mean for water years 1917-2006. The largest influence of climate change on April 1 SWE is projected for moderate elevations in the mountains, particularly in the southern part of Washington. Snowpack at high elevations is less affected by climate change. Although significant change is projected in SWE, the Skagit River basin headwaters are projected to be one of the least affected areas in WA.

- Warming and loss of snowpack is projected to cause widespread transformation from snowmelt-dominant watersheds to transient snow watersheds (the upper Skagit River basin), and from transient snow watersheds to rain-dominant watersheds (the Baker, Sauk, and lower Skagit River basins). Changes in mean hydrographs are most apparent in the transient snow watersheds with smaller impacts in snowmelt dominant watersheds. Warmer winter temperatures would raise freezing levels, moving the transient snow zone to higher elevations. Rain-dominant and transient watersheds would be predominant in the Skagit River basin by the end of the 21st century, with essentially no snowmelt-dominant areas remaining.
- Projected changes in SWE are strongly associated with temperature; however, precipitation also plays a substantial role in the earlier part of the 21st century. Towards the end of the 21st century, the relative influence of temperature change on changes in SWE increases and the influence of precipitation change decreases.
- Warmer winter temperatures will cause more precipitation to fall as rain instead of snow. As freezing levels increase with warming, the effective basin area contributing to runoff from rainfall increases. Combined with increases in cool-season precipitation, these changes are projected to increase flooding in the Skagit River basin.
- Due to reductions in snowpack, earlier snowmelt, and increased evapotranspiration, more severe low flows are projected during late summer throughout the Skagit River system. Reductions in, and losses of, glaciers are expected to exacerbate these impacts in affected basins.
- No published studies are currently (2011) available that address the potential impacts of climate change on groundwater resources of the Skagit River basin. Drainage of low-lying cropland is likely to be impacted by sea level rise and increased river flooding, which will render tide gates less effective. Projected increases in cool season precipitation will likely exacerbate these impacts.

URL 1: http://www.hydro.washington.edu/2860/products/sites/?site=6021

URL 2: http://www.hydro.washington.edu/2860/

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6. Geomorphology

Abstract

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 spatial location, distribution, and function of distributaries that deliver most of the sediments and river flow to the delta, disconnecting numerous large historical distributaries in the Skagit River from riverine and tidal influence. Today, 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 in these areas and the development of new (or altered) distributaries, though marsh accretion shifted to the North Fork after the dominant flow was shifted from the South Fork to the North Fork due to channel adjustments in 1937. Sediment supply and transport in the basin has been influenced by human activities such as logging and road construction that have increased sediment loads in the Skagit River. Clearing of large log jams have increased sediment transport capacity in the lower river, and dams have trapped sediments, reducing overall sediment supply from the headwaters. 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, and projected increases in flooding. Climate change is also expected to increase coastal erosion due to sea level rise, although it is uncertain whether these effects would deliver additional sediment to the Skagit River delta or not. A key uncertainty in projecting future conditions is whether expected increases in sediment loads will lead to sufficient marsh accretion 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 using relatively simple models suggest net losses in these nearshore features.

6.1 Background

Geomorphology is the study of changing landforms, including how landscapes have evolved historically, and the biophysical processes that shape or control such changes (Woodroffe, 2002). Understanding these changing processes is important in the context of managing coastal resources that are vulnerable to climate change due to sea level rise, changes in rivers, or other factors (Woodroffe, 2002). River deltas in particular are affected by changing sea level, rising or falling land surface, changing river flow, retreating glaciers, changing sediment transport regimes, changing delivery of nutrients, debris, and related biological interactions among vegetation and animal behavior (Hood 2007 & 2010a). One of the most important factors controlling or shaping delta landforms is the geometry of the distributaries (river channels which cut through the delta and deliver flow and sediment) (Hood, 2007 & 2010a). In addition to delivering sediments and fresh water, river distributaries deliver nutrients, debris, and other aquatic organisms to estuarine and coastal wetlands along the distributaries (Hood, 2007 & 2010a).

6.2 Morphology of the Skagit River Delta

As mentioned in Chapter 1, more than 90 % of the Skagit delta has been isolated from riverine and tidal influence by dikes and converted to farmland or other uses following non-native settlement in the 19th century. As a result of these changes, numerous large historical distributary channels have been disconnected from the river (Collins et al., 2003). These changes have continued sporadically through the 20th century. Historical distributary sloughs across Fir Island, between the North and South Forks for the Skagit River, for example, were disconnected from the river as recently as the 1950s in order to reduce dike maintenance costs and breaching risk (see Figure 6.1) (Collins, 1998; Collins et al., 2003; Hood, 2007 & 2010a). The remaining two distributaries in the Skagit delta are located at the outlet of the North and South Forks

(Figure 6.1). Due to these changes in the delta, direct fluvial delivery of freshwater and sediment to the bay fringe of Fir Island no longer occurs, although nearshore circulation may at times convey limited freshwater and sediment to the bayfront (Erik Grossman, personal communication). Consequently the bay fringe area is largely sediment starved and is experiencing marsh erosion, resulting in significantly lower tidal channel density in the bay fringe marshes (Collins, 1998; Hood, 2007 & 2010a; Beamer et al., 2005).

In contrast, the deltas near the outlets of the North and South Forks (which currently receive more flow and sediment) have substantially prograded (increased in area) since at least 1889 (Collins, 1998; Hood, 2007). As a result, new marsh and minor distributaries have developed in the outlets of the North and South Forks. Between 1889 and 1937, for example, significant amounts of marsh had accreted in the South Fork while there was little change in the North Fork marsh. After the dominant flow of water and sediment was shifted from the South Fork to the North fork around 1937 (due to human changes to the river channel), marsh accretion shifted from the South Fork to the North Fork (Collins, 1998; Hood 2010a) (Figure 6.2). As sediment was deposited at the outlet of the North Fork, smaller distributary tidal channels were also formed at the outlet of the North Fork (Hood, 2006 & 2010a). Some of the distributaries were blocked by more sediment at the upstream end of the channel to form blind tidal channels (typically tidal channels with an open downstream channel but no upstream inlet) (Hood, 2006 & 2010a). For example, the channel labeled C_1 in Figure 6.2 is one of several blind tidal channels that have formed (Hood, 2010a). Tidal channels (particularly blind tidal channels) provide important rearing habitat for juvenile Chinook salmon, and other aquatic species (Hood, 2007). It is important to note, however, that these recently formed areas of favorable delta habitat are very small in comparison with the salmon habitat lost due to historical isolation of the river from its floodplain. Also, recent formation of blind channels has been quite localized, whereas historically these kinds of habitat were spread evenly across a much larger area with a range of salinity gradients, thereby creating diverse habitat for the continuum of early life-history stages for Chinook.

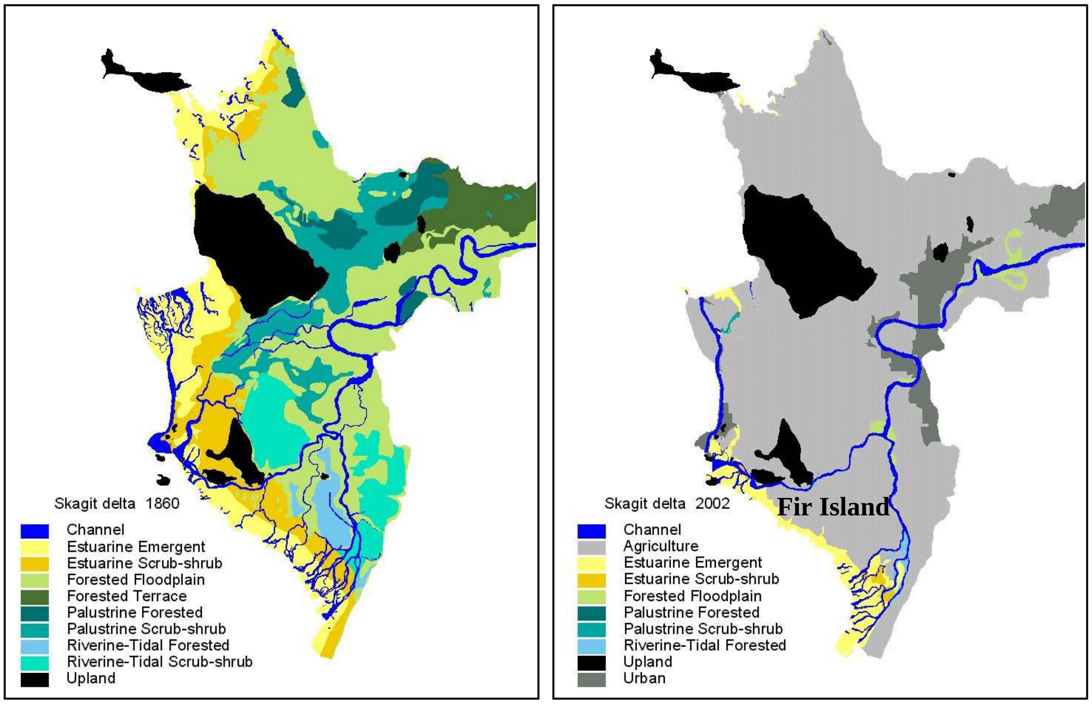

Figure 6.1 The mid-19th century (1860, left panel) and current (2002, right panel) channel conditions in the Skagit delta (Source: Collins et al. 2003; Hood, 2009).

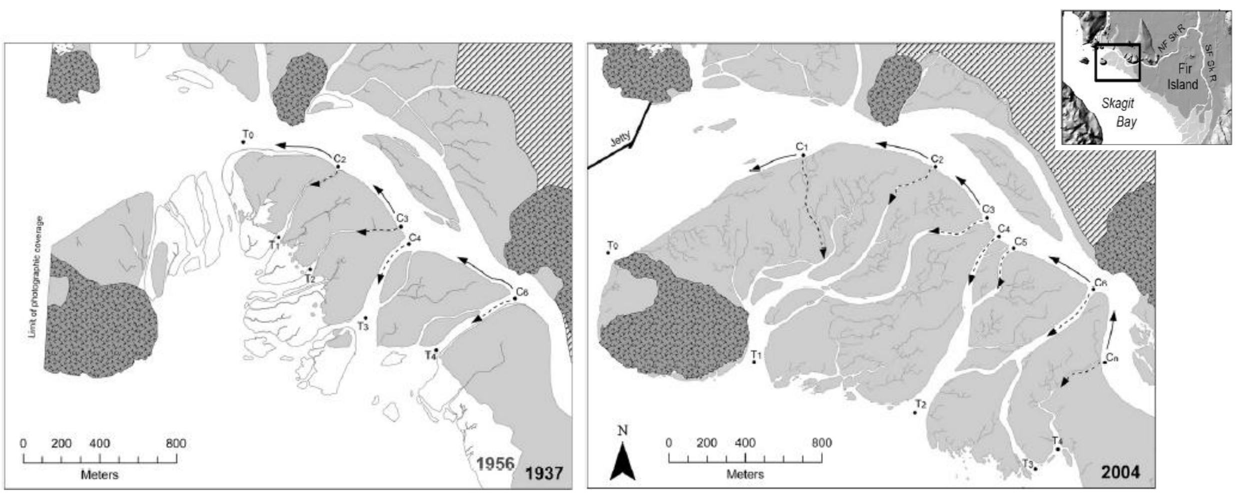

Figure 6.2 Planforms of the North Fork marsh/distributary system. Cross-hatched areas are farmland, checked areas are bedrock outcrops, light gray is tidal marsh in 1937 (left panel) and 2004 (right penal), gray outline indicates 1956 tidal marsh (left panel), white areas are channels and bay. T_0 is the river terminus and T_1–T_4 are the termini for distributaries of the North Fork of the Skagit River. C_1–C_6 are the distributary channel bifurcation points (Source: Hood, 2010a).

Channelization of the lower Skagit river, disconnection from the natural floodplain, and a reduction in the number of distributaries in the Skagit delta have resulted in strongly altered sediment transport processes in the Skagit delta. Channelization of the entire flow of the river through its two present outlets of the North and South Forks focused freshwater and sediment and likely increased flow velocities and sediment carrying capacity in the lower river. Bathymetric change analyses across the Skagit tidal flats and examination of sediment cores indicate that a significant change in substrate and habitat occurred beginning in 1850 as the entire tidal flats that were once muddy were replaced by 1-2 m thick sand (Grossman et al., in press). The sands show evidence of cross-bedding which is indicative of sediments bypassing the delta and suggest that tidal flats also changed from a relatively calm environment where muds used to accumulate to a more energetic tidal flat characterized by braided, meandering, sand-filled channels (Grossman et al., in press).

Several recent studies have established that sediments delivered to the delta (primarily sands, which constitute 50-60% of the total sediment load—Curran et al. in review) mostly bypass the shoreline and tidal flats and are instead accumulating along the delta front (Grossman et al. in press and in review). The fine sediments that in pre-settlement times were deposited in the delta as mud, are now largely lost from the delta, swept away by surface currents that show a net northward transport direction (Grossman et al. 2007). These fine sediments that bypass the delta also impact near-shore habitats and eelgrass beds through abrasion, fragmentation, burial, and by increasing turbid conditions that block light and may affect fish gills.

6.3 Sediment Supply and Transport in the Skagit River

Sediment supply and transport in the Skagit River basin has also been significantly influenced by human activities. The clearing of log jams up to a mile long in the Mount Vernon area, logging of streamside forests, forest road construction, and dredging of the lower river have been identified as probable causes of increased sediment supply to the Skagit River and sediment transport to the delta (Collins, 1998; Beamer et al., 2005). At the same time, dam construction on the Baker River and Skagit River, which impound flow and sediment from about 47% of the basin, have both reduced natural peak flood flows in the lower river (by about 50%) and trapped sediments. However, because of different geology and sediment production regimes, the contribution of sediment to the Skagit River from the watersheds above these impoundments in comparison with undammed tributaries (particularly the Sauk and Cascade Rivers that drain Glacier Peak) remains uncertain. It also remains uncertain as to whether there has been a net increase or reduction of sediment delivery to the delta due to the cumulative effect of these different historical changes.

Much of the sediment in the Skagit River basin is glacial in origin, and the estimated sediment transport rate is between 1.7 and 4.5 million tons per year (Collins, 1998; Curran et al., in review; Pacific International Engineering, 2008). As noted above, sediments deposited to the delta have provided important habitat for salmon by creating new distributary channels in some areas. On the other hand, increased sediment supply in some tributaries, mostly due to logging and road construction, has caused an increase in scour and fill of the channel bed in some areas, affecting salmon egg to fry survival as well as freshwater rearing (see Chapter 7) (SRSC and WDFW, 2005). This problem is exacerbated by accelerated sedimentation from glacial recession on Glacier Peak which exposes unstable slopes to erosion, and is observed to produce large quantities of fine sediment. For instance, glacier melt from Glacier Peak has deposited large amounts of silt downstream of the Suiattle River since 1991, reducing incubation survival (SRSC and WDFW, 2005). Beamer et al. (2000) reported that sediment supply is greater than 1.5 times the natural rate in many areas of the Skagit River basin. The area with the greatest sediment load is the lower Sauk River, which doesn't have any dams and is also impacted by receding glaciers (SRSC and WDFW, 2005).

6.4 Effects of Climate Change on Sedimentation

Sediment loads are likely to increase under climate change due to loss of snowpack and continued glacial recession (Chapter 4), which may expose additional and highly mobile sediment sources (Knight and Harrison, 2009; Lu et al., 2010), and increasing extreme peak flows (Chapter 5), which would move sediments downstream more rapidly. There is also evidence that sediment loads in glacial-fed watersheds could be elevated by geomorphic hazards associated with glacial retreat such as rock avalanche, debris flows and moraine dam failures (Moore et al., 2009; Lu et al., 2010; URLs 1, 2, & 3).

Thus continued glacier recession is hypothesized to result in increasing sediment loads in glacial-fed rivers at the time scales of years to decades, though the sediment loading rate could be reduced temporarily if glacial lakes trap and store sediment discharged by a glacier (at least until the lakes fill) (Moore et al., 2009; Lu et al., 2010). Fine, subglacial sediments would be flushed with meltwater resulting from strong summer ice mass loss from glaciers. Rapid glacier retreat also releases sediments stored in the ice near the terminus, near the bed of the glacier, and from recently deglaciated moraines and forefield deposits. These sources of fine sediment in late summer would presumably decrease with ongoing loss of glacial ice mass and reduced late summer melt water.

These hypothesized impact pathways related to changes in glaciers are supported by historical changes in other PNW rivers on the west slope of the Cascades, such as the Nisqually and White Rivers, which have experienced dramatic increases in sediment production and accretion in the headwaters (Lu et al., 2010; PALS, 2008). In the Nisqually and White River case studies, large amounts of sediment have been transported from steep, unvegetated slopes exposed by retreating glaciers. These sediments are then deposited downstream, increasing river bed elevation (a process called aggradation) and/or making a shallow, braided river system with multiple (and potentially more mobile) flow channels (Lu et al., 2010; PALS, 2008). For example, aggradation in glacial-fed rivers in Mount Rainier National Park has occurred at a rate of 6 to 14 inches per decade (URL 1). In the last decade, the rate of sediment buildup at Mount Rainier has dramatically increased (URL 2) due in part to high flow events and resulting debris flows, such as the flood of November 6 and 7, 2006. During that event, Mount Rainier received 18 inches of rain in 36 hours. Debris flows, which began with glacial outburst floods, increased the elevation of the riverbed near Nisqually Road by more than four feet (URL 1). The Nisqually River bed has in certain areas been elevated by 38 feet since 1910 (URLs 1 & 4). Debris flows have also increased damage to Mount Rainier National Park (URLs 1 & 3). Figure 6.3 shows some of the flood damage that occurred at Mount Rainier National Park during the 2006 flood. Impacts to the lower basin in the Nisqually case study are not clear, in part because intervening dams have trapped sediments before they reach the Nisqually delta. A current USGS study of sediments stored behind Alder dam in the Nisqually basin since about 1950 calculates that sediment loading at the delta has been reduced by about a factor of ten by the dam (E. Grossman, personal communication).

Physical drivers are similar in the glaciated headwaters of the Skagit River basin, and increased sediment loads are expected to accompany projected continued glacial recession (see Chapter 4) and loss of snowpack (Chapter 5), especially in undammed rivers like the Sauk.

Figure 6.3 The flood damage at Mount Rainier National Park in November 2006: the Nisqually River at Sunshine Point (left panel) and the broken edge of the Nisqually road (right panel) (URL 5).

In coastal environments, sediment loads are also expected to increase due to accelerated bluff erosion under climate change. Bluff erosion or collapse is usually caused by storms with large waves, especially when combined with high tides (Laevelle et al., 1986; Huppert et al., 2009). Projected sea level rise (Chapter 3) will increase the high tide level (Shipman, 2004; Huppert et al., 2009), potentially accelerating rates of erosion on unstable bluffs and increasing the frequency of landslides (Lavelle et al., 1986; Shipman, 2004; Huppert et al., 2009). It remains uncertain, however, whether sediment sourced from bluff erosion will be retained on beaches to help mitigate further effects of sea-level rise or be transported offshore by increased wave exposure near the shore under higher water levels.

6.5 Potential Climate Change Impacts on Delta Morphology

Fully integrated modeling studies that would result in a more comprehensive understanding of the impacts of climate change on the Skagit River delta are currently unavailable, however a number of well-formed hypotheses have developed based on historical impacts related to sea level rise and potential changes in sediment transport. Initial studies estimating net loss of salt marsh and estuarine beaches due to several competing factors suggest net losses in these near shore features.

As mentioned above, the salt marshes in both the South and North Forks of the Skagit River have prograded (increased in area due to sediment accumulation) until about 1980. Analysis of progradation rates in the Skagit delta as a whole using remote sensing techniques indicates that rates have been gradually slowing since 1937. The South Fork region has experienced more rapid declines in progradation rates than the North Fork (see Figure 6.4) (Hood, 2005) and in fact the South Fork marshes have probably been eroding since about 1980 (Beamer et al., 2005). This steady decline in progradation rates in the North Fork and the shift to steadily increasing erosion rates in the South Fork marshes may be the result of sea level rise over the past century (estimated to be about 20 cm in the global mean) or changes in the relative distribution of sediments between the N and S Forks. Therefore one hypothesis is that further declines in the progradation of the marsh (and/or increases in current erosion rates) would accompany projected sea level rise for the 21st century, and would also result in associated decreases in the network of distributary channels and the habitat they provide. This hypothesis is supported by long-term geological records which show that regression (marsh translation landward) was the norm between 5,000 yr BP and 1850s in most areas of the world when sea level rise was 0.5 to 1.0 mm/yr (Stanley and Warne, 1994).

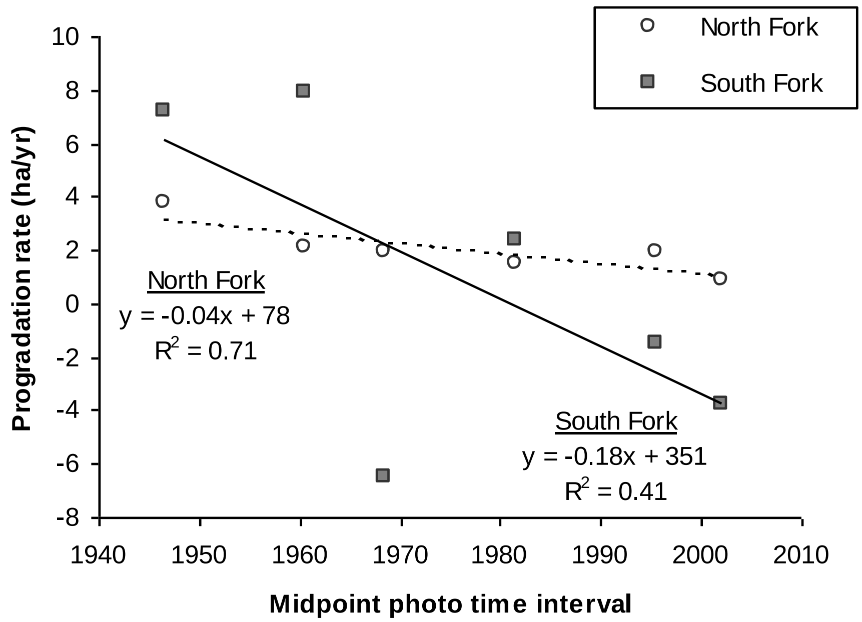

Figure 6.4 Average marsh progradation rates, calculated from GIS analysis of historical aerial photos. The North Fork trend is represented by a dashed line, the South Fork trend by a solid line. Negative values represent net marsh erosion rather than progradation (Source: Hood, 2005).

An alternate hypothesis, however, is that possible rapid increases in sediment deposition in the Skagit delta due to climate-change-related changes in glacial recession, increased flooding, erosion of bluffs due to sea level rise, or along-shore transport of sediment originating from other near-shore areas could result in accelerated rate of accretion and the development of new (or altered) distributaries. Thus a key question remains as to whether sea level rise will ultimately result in a net loss of tidal marsh or whether marsh accretion due to changes in these factors will ultimately be able to keep pace with an accelerating rate of sea level rise associated with global warming (Schweiger, 2007).

Based on the recent studies quantifying sediment transport processes in the delta cited above, establishing a physical environment where net accretion can take place will likely require re-connection of distributary channels to a larger area of the delta in order to spread sediments and river flow more evenly across areas being inundated by sea level rise. This is because a substantial portion of sediment delivered to the delta currently bypasses the shoreline and tidal flats and most fine sediments are lost offshore (Grossman et al., in press; Grossman et al., in review).

Without such structural changes, initial studies (using relatively simple models) support the first hypothesis that sea level rise will result in net loss of tidal marsh. Schweiger (2007) estimated the loss of tidal marshes and estuarine beaches for two sea level rise scenarios - 28 and 69 centimeters (11.2 and 27.3 inches) of sea level rise as shown in Figure 6.5, concluding: "Much of the dry land for this site is protected by dikes and is not subject to inundation. This means that brackish marshes and beaches that are trapped against seawalls may be especially subject to loss, largely through conversion to saltmarsh or tidal flat. By 2100, brackish marsh is projected to decline by 77 percent, and estuarine beach by 91 percent." (see Table 6.1 and upper panel in Figure 6.5). It should be noted that while the study considered changes in elevation of the delta due to estimates of current sedimentation and accretion rates as well as tectonic processes (subsidence and uplift) when investigating the impacts of sea level rise on tidal marsh habitats in the Skagit delta, potential systematic changes in sediment supplies, nutrient supplies, and other biological factors associated with climate change that may influence the delta were not considered. For reasons already discussed above, marshes in the South Fork were projected to be more vulnerable than those in the North Fork (Hood, 2005; Schweiger, 2007).

Lower panels in Figure 6.5 and Table 6.2, however, show simulations of the effects of removing the existing dikes. In this scenario there is a dramatic conversion of undeveloped dry land to salt marsh, transitional marsh, and tide flats. Thus one adaptive response to the losses of delta habitat projected in Table 6.1 and upper panels in Figure 6.5 may be to remove some of the existing diking (as has been done in the Nisqually Delta, for example). (This scenario also highlights the vulnerability of existing dry land areas to potential dike failures under conditions of elevated sea level).

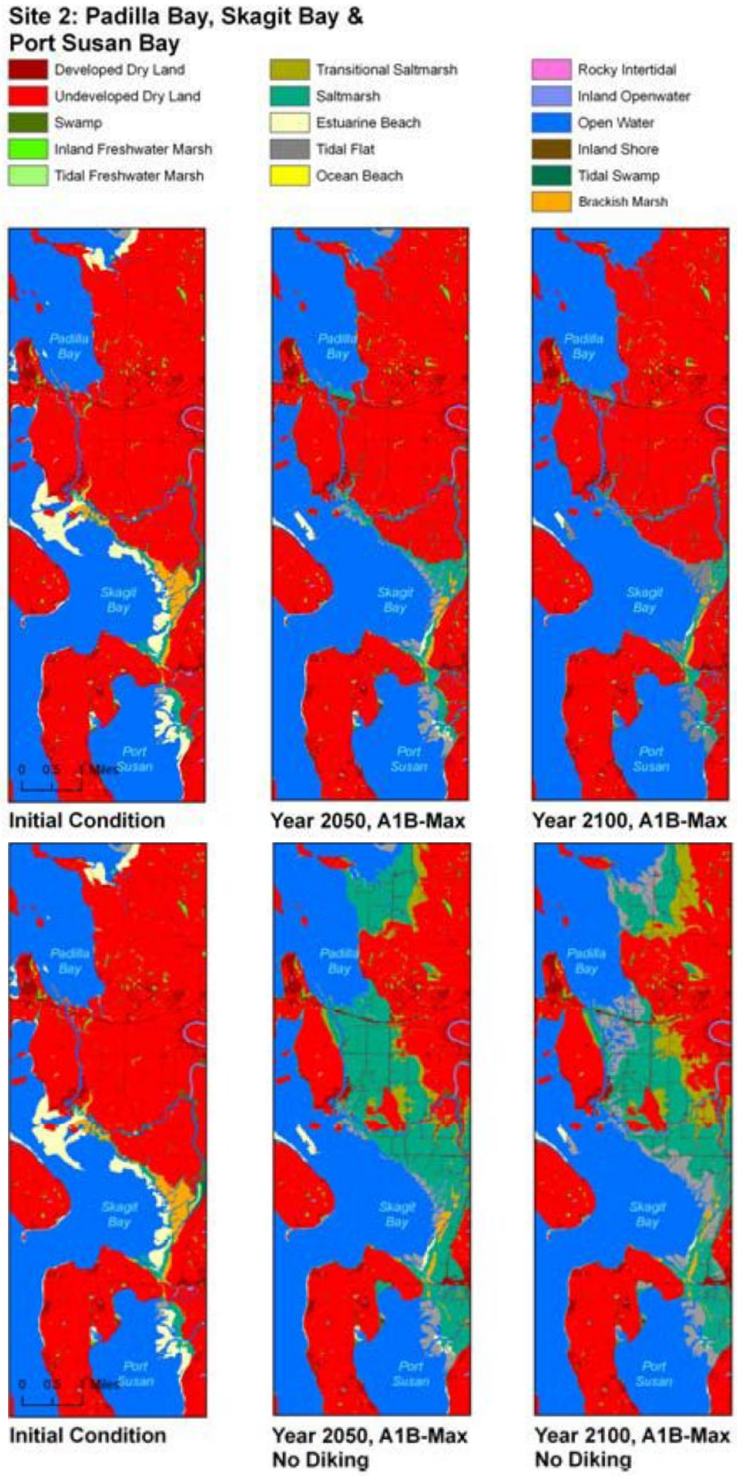

Figure 6.5 Projections of Habitat Changes for a projected 29 cm (2050) and 69 cm (2100) of sea level rise, accounting for current sediment deposition rates and vertical motion with diking (upper panels) and without diking (lower panels) (Source: Schweiger, 2007).

Table 6.1 Changes in the near coastal environment resulting from estimated sea level rise for 2050 and 2100 in the Skagit Delta and surrounding near-shore areas with existing dikes intact (see upper panels Figure 6.5). (Source: Table 10, Schwieger, 2007).

Table 10. Projections of Habitat Changes for Site 2
[A1B Max for 2050, 2100 and 1.5 Meters for 2100]

	Area of Habitat Type in Hectares (Acres)				Percentage Change (Relative to Totals for This Site)		
	Initial Condition	2050 (+0.28 meters/11.2 inches)	2100 (+0.69 meters/27.3 inches)	2100 (+1.5 meters/59.1 inches)	2050 (+0.28 meters/11.2 inches)	2100 (+0.69 meters/27.3 inches)	2100 (+ 1.5 meters/59.1 inches)
Undeveloped Dry Land	45,482 (112,388)	43,800 (108,232)	43,606 (107,753)	43,480 (107,441)	4% loss	4% loss	4% loss
Developed	4,215 (10,415)	4,215 (10,415)	4,215 (10,415)	4,215 (10,415)	No change	No change	No change
Swamp	485 (1,198)	362 (895)	328 (811)	283 (699)	25% loss	32% loss	42% loss
Inland Fresh Marsh	665 (1,643)	504 (1,245)	491 (1,213)	481 (1,189)	24% loss	26% loss	28% loss
Tidal Fresh Marsh	76 (188)	12 (30)	11 (27)	10 (25)	84% loss	85% loss	87% loss
Transitional Marsh	29 (72)	406 (1,003)	468 (1,156)	243 (600)	1,313% expansion	1,531% expansion	747% expansion
Saltmarsh	931 (2,301)	2917 (7,208)	1,854 (4,581)	1,315 (3,249)	213% expansion	96% expansion	41% expansion
Estuarine Beach	3,670 (9,069)	597 (1,475)	329 (813)	44 (109)	84% loss	91% loss	99% loss
Tidal Flat	289 (714)	1,618 (3,998)	2,061 (5,093)	2,801 (6,921)	460% expansion	613% expansion	869% expansion
Ocean Beach	0 (0)	3 (7)	0 (0)	0 (0)	NA	NA	NA
Inland Open Water	342 (845)	291 (719)	281 (694)	269 (665)	15% loss	18% loss	21% loss
Estuarine Open Water	33,546 (82,894)	35,976 (88,899)	36,892 (91,162)	37,695 (93,146)	7% expansion	10% expansion	12% expansion
Open Ocean	875 (2,162)	1,178 (2,911)	1,482 (3,662)	1,500 (3,707)	35% expansion	70% expansion	71% expansion
Brackish Marsh	1,414 (3,494)	432 (1,067)	332 (820)	41 (101)	69% loss	77% loss	97% loss
Inland Shore	30 (74)	27 (67)	27 (67)	27 (67)	10% loss	10% loss	10% loss
Tidal Swamp	202 (499)	34 (84)	22 (54)	10 (25)	83% loss	89% loss	95% loss
Rocky Intertidal	1 (2)	<1 (<2)	<1 (<2)	<1 (<2)	4% loss	12% loss	27% loss
Riverine Tidal	278 (687)	155 (383)	126 (311)	114 (282)	44% loss	55% loss	59% loss

Table 6.2 Changes in the near-coastal environment resulting from estimated sea level rise for 2100 in the Skagit Delta and surrounding near-shore areas without existing dikes (see lower panels in Figure 6.5). (Source: Table 11, Schwieger, 2007)

Table 11. Projections for Habitat Changes for Site 2 with No Dikes (A1B Max for 2100)			
	Area of Habitat Type in Hectares (Acres)		Percentage Change (Relative to Totals for This Site)
	Initial Condition	2100 (+0.69 meters/27.3 inches)	2100 (+0.69 meters/27.3 inches)
Undeveloped Dry Land	45,482 (112,388)	27,361 (67,611)	40% loss
Developed	4,215 (10,415)	4,215 (10,415)	No change
Swamp	485 (1,198)	315 (778)	35% loss
Inland Fresh Marsh	665 (1,643)	476 (1,176)	28% loss
Tidal Fresh Marsh	76 (188)	11 (27)	85% loss
Transitional Marsh	29 (72)	4,147 (10,247)	14,346% expansion
Saltmarsh	931 (2,301)	11,331 (28,000)	1,115% expansion
Estuarine Beach	3,670 (9,069)	329 (813)	91% loss
Tidal Flat	289 (714)	4,793 (11,844)	1,559% expansion
Ocean Beach	0 (0)	3 (7)	NA
Inland Open Water	342 (845)	270 (667)	21% loss
Estuarine Open Water	33,546 (82,894)	37,371 (92,346)	11% expansion
Open Ocean	875 (2,162)	1,483 (3,665)	70% expansion
Brackish Marsh	1,414 (3,494)	332 (820)	77% loss
Inland Shore	30 (74)	27 (67)	10% loss
Tidal Swamp	202 (499)	22 (54)	89% loss
Rocky Intertidal	1 (2)	1 (2)	12% loss
Riverine Tidal	278 (687)	41 (101)	85% loss

6.6 Summary and Conclusions

Human activities such as clearing of log jams, logging, diking, and construction of levees, dams and roads, and dredging have influenced the flow and sediment transport of the Skagit River, changing distributary channels and related sediment transport processes in the Skagit estuary. The delta area is likely to be influenced by human induced climate change due to impacts on sea level, glacial recession, changing flood magnitude, and resulting changes in sediment sources and transport processes, but many uncertainties about the direction of change are present. Key findings on historical and projected changes in geomorphology in the Skagit River include the following:

- Dikes and levees have isolated numerous distributaries in the Skagit River from the riverine environment. As a result, the remaining distributaries are located at the outlet of the North and South Forks of the Skagit River. Sedimentation in the outlet of the North and South Forks has resulted in progradation and the formation of new (or altered) tidal channels, although since the 1940s it appears the a majority of the sediment delivered to the delta has largely bypassed the shore and tidal flats, This represents a lost resource to the delta that would help to mitigate the impacts of sea level rise. The redirection of fine sediment offshore has impacted habitats via offshore burying, formation of fragmenting sea grass complexes and changing substrate conditions for invertebrates, plants and fish.
- Following a shift in the dominant flow path from the South to the North Fork, the progradation rate of the South Fork declined in comparison with the North Fork. Since about 1980, the South Fork marshes may have actually started to erode. The cause of this decline of progradation rates is not clear but one suspected cause is sea level rise associated with post-1970 climate change.
- Human activities have influenced sediment supply to the Skagit River. Sediment supply and transport in the basin has been increased by the clearing of logjams, dredging, logging, and road construction. Dam construction has trapped sediments in the headwaters. Sediment loads have also increased due to glacier retreat, particularly in the Sauk and Cascade River basins.

- Increased sediment loads would be expected in the Skagit River due to ongoing glacier retreat and associated geomorphic hazards such as rock avalanche, debris flows and moraine dam failures. Sediment loads would also be increased by accelerated bluff erosion or collapse resulted from storms with large waves especially when combined with high tides, although it is unclear if these increased sediment resources would ultimately contribute to delta formation or be redirected offshore.
- These historical impacts and case studies simulating the effects of sea level rise with current diking in place suggest future decreases in the areal extent of freshwater and tidal marsh. An alternative hypothesis, however, is that rapidly increasing sediment supply from glacier recession and more intense peak flows could potentially mitigate some of these losses by rebuilding the delta as sea levels rise. Results from one case study also show that removal of existing dikes has the potential to dramatically increase transitional and salt marsh habitat under sea level rise scenarios due to flooding of undeveloped land. These changes also highlight the vulnerability of the near-shore environment behind the dikes to sea level rise.

URL 1: http://www.nps.gov/mora/parknews/upload/TahomaSum07pgs5,6.pdf

URL 2: http://www.theolympian.com/2010/12/05/1463622_rocks-on-the-move.html

URL 3: http://www.thenewstribune.com/2008/07/21/418472/scientists-study-impact-of-glacier.html

URL 4: http://climatesolutions.org/news/mt.-rainiers-melting-glaciers-create-hazard

URL 5: http://www.nps.gov/mora/parknews/upload/flooddamagev3.pdf

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7. Ecosystems

Abstract

Warmer water temperatures and more frequent and severe extreme events (floods and low flows) are expected in western Washington as a consequence of climate change. Sea level rise is likely to reduce near-coastal habitat for fish and influence the many plant and animal species they support. Changes in water quantity (and timing) and quality associated with climate change are projected to disturb food webs and prevent access to habitat, impacting both terrestrial and aquatic species. Increased forest disturbance (e.g. from fire and insect attack) is projected for a warmer 21st century climate, which often provides a competitive advantage for invasive species. Changes in temperature and precipitation would also likely alter the species composition of trees and vegetation in the Skagit forest. In general these changes are likely to have negative impacts on terrestrial and aquatic species in the Skagit River basin which have already been impacted by human activities.

7.1 Terrestrial Ecosystem

7.1.1 Forest Ecosystems

Changes in temperature and precipitation associated with climate change are likely to alter the species composition of trees and vegetation in the Skagit River basin (SITC, 2009). Projected drier and warmer summers would cause a significant decline in drought-susceptible species such as western red cedar (SITC, 2009). In some places, drought-susceptible species are already responding to climate change. For example, the tops of many tall western cedar trees in the Skagit County are dead due to less moisture during the drier and warmer summers (URL 1). Even relatively drought-tolerant species, particularly growing in lowland forest, would also be influenced by climate change if drier and warmer summers persist as projected (URL 1; Littell et al., 2010). Douglas fir, for example, an economically important drought-tolerant species, is projected to decrease by the end of the 2060s (Littell et al., 2010). On the other hand, warmer temperatures could help some species in high elevation grow more by decreasing snow cover which buries the trees in winter (URL 1). Tree lines may climb higher due to warmer climate (URL 1). Understory and ground vegetation species are likely to experience similar impacts of climate change to those projected for trees (SITC, 2009).

Hotter and drier summers are likely to contribute to the spread of forest pests and diseases such as mountain pine beetle, spruce budworm, and various fungi and blights that would previously have been suppressed by colder climatic condition (SITC, 2009; Littell et al., 2010). These changes in insect activities and diseases would presumably increase stress on trees, in some cases exacerbating impacts related to drought (URL 1). For example, mountain pine beetle populations in the Skagit County have been growing explosively in recent years (URL 1). The widespread mountain pine beetle attacks on high elevation white bark pine forests near White Pass (URL 1) in the Skagit basin killed about 17,000 trees in 2006 (URL 1). Although the Skagit mountain pine beetle impacts are substantial and growing rapidly, so far tree mortality has been much more serious in Eastern Washington and British Columbia (URL 1).

Warmer, wetter winters combined with warmer, drier summers and increased moisture stress are likely to cause increases in wintertime vegetation and larger summertime accumulations of woody and leafy debris on the forest floor, suggesting elevated risk of more frequent and large wildfires (URL 1; SITC, 2009; Littell et al., 2010). The average number of acres burned each year in Washington State (WA) has increased from 6,000 in the 1970s to about 30,000 in 2001 (URL 1) and is projected to increase further under climate change (SITC, 2009; Littell et al., 2010).

7.1.2 Wildlife

Shorebirds and migratory waterfowl such as snow geese, tundra swans, and ducks rely on the shallow waters and marsh habitats in the Skagit River basin to feed and rest (URL 2; Schweiger, 2007). These areas are also important habitat for other migratory bird such as bald eagles. The Skagit Wildlife Area shown in Figure 7.1 provides important habitat not only for waterfowl and shorebirds but also for marine mammals and other aquatic species (URLs 2, 3 & 4; Garrett, 2005; Skagit Watershed Council, 2005; Schweiger, 2007). The common terrestrial mammals living in the Skagit Wildlife Area are black-tailed deer, coyotes, raccoons, opossum, skunk, beaver and muskrats (URLs 4 & 5; Garrett, 2005). River otter, red fox, and harbor seals are also commonly seen (URL 5; Garrett, 2005). Small rodents such as mice, shrews, voles, and moles and reptiles such as the garter snake and painted turtle use the habitat in the Skagit Wildlife Area (URL 5; Garrett, 2005). Birds of prey in this area include osprey, bald eagles, peregrine falcon marsh hawks, red-tailed and rough-legged hawks, short-eared and barn owls, and the occasional golden eagle (Garrett, 2005; URL 5). Estuarine beaches provide spawning area for forage fish, which in turn provide food for birds, marine mammals and other wildlife (Schweiger, 2007). Invertebrates such as oysters and clams thrive in the mud flats and gravel beds of the Skagit delta and play a key role in the health of marsh habitats (Snover et al., 2005; Schweiger, 2007).

Figure 7.1 Map of the Skagit Wildlife Area (Source: Garrett, 2005).

The upper Skagit River hosts one of the largest and most visible populations of wintering bald eagles (URLs 6 & 7). Bald eagles migrate during winter (peaking in early January about two weeks after the peak of salmon spawning and dying) to eat the dead salmon carcasses that abound in the Skagit River and its tributaries (URLs 6 & 7). Other birds and wildlife that can be seen in the upper Skagit River are ducks, geese, ravens, blue herons, deer, black beer, cougar, beaver, otter, and raccoons (URL 6).

Coastal habitats that support wildlife are projected to be reduced due to sea level rise and other factors associated with human-enhanced global warming (discussed in section 7.3) (Schweiger, 2007; CCWAPWG, 2009). Losses of marsh habitats are likely to decrease water quality because marsh habitats have an ability of regulating nutrients and filtering pollutants (Schweiger, 2007). The excess nutrients such as nitrogen and phosphorus would enhance harmful algal blooms and hypoxia events (low oxygen), resulting in negative impacts on the overall food web and on individual species such as Chinook salmon. Potential reductions in salmon, forage fish and other food sources would cause a decline in many seabirds and marine mammals (Schweiger, 2007). For example, decline of chum salmon would result in the reduction in a major food source for the Bald Eagle.

Potential habitat losses are one consequence of global warming that impacts terrestrial ecosystems. Other changes associated with global warming also will have an impact on the ecosystem (Schweiger, 2007; CCWAPWG, 2009) including more frequent or severe extreme events such as floods, droughts and wind storms. Other kinds of disturbance such as increased wildfire, pests, and diseases may alter available habitat for many species (CCWAPWG, 2009; Running and Mills, 2009; Littell et al., 2010). Increases in air temperature are likely to alter seasonal temperature thresholds, i.e. earlier springs and later autumns are expected under climate change (CCWAPWG, 2009). These changes may affect the migration patterns of birds and migratory insects, resulting in potential misalignment of food availability. Amphibians may be affected by changes in the timing and extent of small scale ponding that affect breeding potential.

Some terrestrial species may be able to respond to climate change by finding more suitable habitats or food sources (Schweiger, 2007; CCWAPWG, 2009; Running and Mills, 2009). For example, cold temperature species may migrate to northward and/or higher elevations to escape warming conditions (CCWAPWG, 2009). On the other hand, some species (or individual populations) may not be able to move to acceptable habitat (or may be prevented from doing so by physical barriers to migration such as human development). Species which cannot migrate to more suitable habitat may not be able to adapt to the rapid rate of change of environmental conditions. In such cases these species or specific populations may become extinct in response to warming (Schweiger, 2007; CCWAPWG, 2009; Running and Mills, 2009).

7.2 Aquatic Ecosystems

Various species of predominantly freshwater fish (including kokanee salmon and lake, cutthroat, rainbow, brook and bull trout) are common in the Skagit basin's lakes and streams (URL 8). ESA listed bull trout, which require very cold water (below about 48°F) for spawning mostly reproduce in headwater streams (particularly those fed by groundwater or glacial melt) and the upper Skagit River. The Skagit provides habitat for the largest bull trout population in western Washington (URL 8).

Anadromous (migrating from fresh to salt water and back again during their life cycle) species such as salmon and steelhead and some predominantly freshwater species such as cutthroat trout and bull trout originating from the freshwater habitats of the Skagit River basin use freshwater, tidal delta, bay and ocean habitats during their life cycle (Beamer et al., 2005; Greene et al., 2005). For example, ocean-type Chinook salmon, a primarily of wild stock in the Skagit River basin (and comprising on the order of 60% of the total wild Chinook population in Puget Sound), use fresh water for spawning (July-October), incubating and hatching (December to March) and then migrate to the delta and the tidally dominated fjord systems of Skagit bay during February to October (Greene et al., 2005).

Salmonid productivity is strongly influenced by both water temperature and hydrologic extremes (McCullough, 1999; Rand et al., 2006; Beechie et al., 2006; Farrell et al., 2008; Crossin et al., 2008; Mantua et al., 2010; Hamlet et al., 2010). The salmonids originating in the Skagit River system are all cold-water species, requiring relatively cool water temperatures through their entire life cycle (McCullough, 1999; Hamlet et al., 2010). Under excessively warm temperatures, these cold water species experience increased metabolic rates (which they cannot control) and loss of available energy for physical activities such as swimming.   Under such conditions they may seek refuge in cooler water, delaying upstream migration, or failto spawn altogether (Farrell et al., 2008; Crossin et al., 2008). Increases in water temperature also cause changes in incubation duration of eggs, time of emergence, and migration behavior of juveniles that ultimately affect survival. When water temperatures exceeding a specific threshold (which varies by species and phase of life) are encountered over a long period (i.e. several days), thermal stresses on juveniles and adults can be fatal (McCullough, 1999; Mantua et al., 2010; Hamlet et al., 2010).

Streamflow extremes such as more severe low flows and larger floods also have a negative impact on these species during their freshwater life cycles. Severe or prolonged low flows in spring or summer may impact juvenile salmon migrating to the ocean (via increased exposure to predation or other factors) or adult salmon attempting to move upstream to spawn. More extreme low flows may also exacerbate water temperature impacts (Hamlet et al., 2010; Mantua et al., 2010).

Higher flood flows during incubation have been shown to decrease Chinook salmon return rates in the Skagit River basin (Greene et al., 2005). There are several possible mechanisms that explain the negative correlation of freshwater survival with flood magnitude. Peak flows during incubation increase mortality by scouring of redds (salmon "nests"), which crushes the eggs (Montgomery et al., 1996; DeVries, 1997) or increasing fine sediment deposition that reduces available oxygen (Lotspeich and Everest, 1981). Extreme high flows also can reduce the availability of preferred or suitable slow water habitats, resulting in reduced freshwater survival rates for juveniles (Greene et al., 2005; Mantua et al., 2010).

Both factors discussed above are projected to change under climate change scenarios, with impacts to Pacific Northwest salmonid populations. Mantua et al. (2010) evaluated climate change impacts on freshwater habitats in WA. They found that projected increases in water temperature will produce steadily increasing thermal stresses on Washington's salmon populations moving from the beginning to the end of the 21st century. In the study these impacts are tied directly to increasing air temperature. As expected, the warmer A1B emissions scenarios produces more thermal stress on salmon than the somewhat cooler B1 emissions scenarios (see Figure 7.2). The potential impacts of climate change on salmon due to thermal stress in the freshwater environment are less in the Skagit River basin in comparison to more sensitive areas such as the interior Columbia River Basin (Figure 7.2).

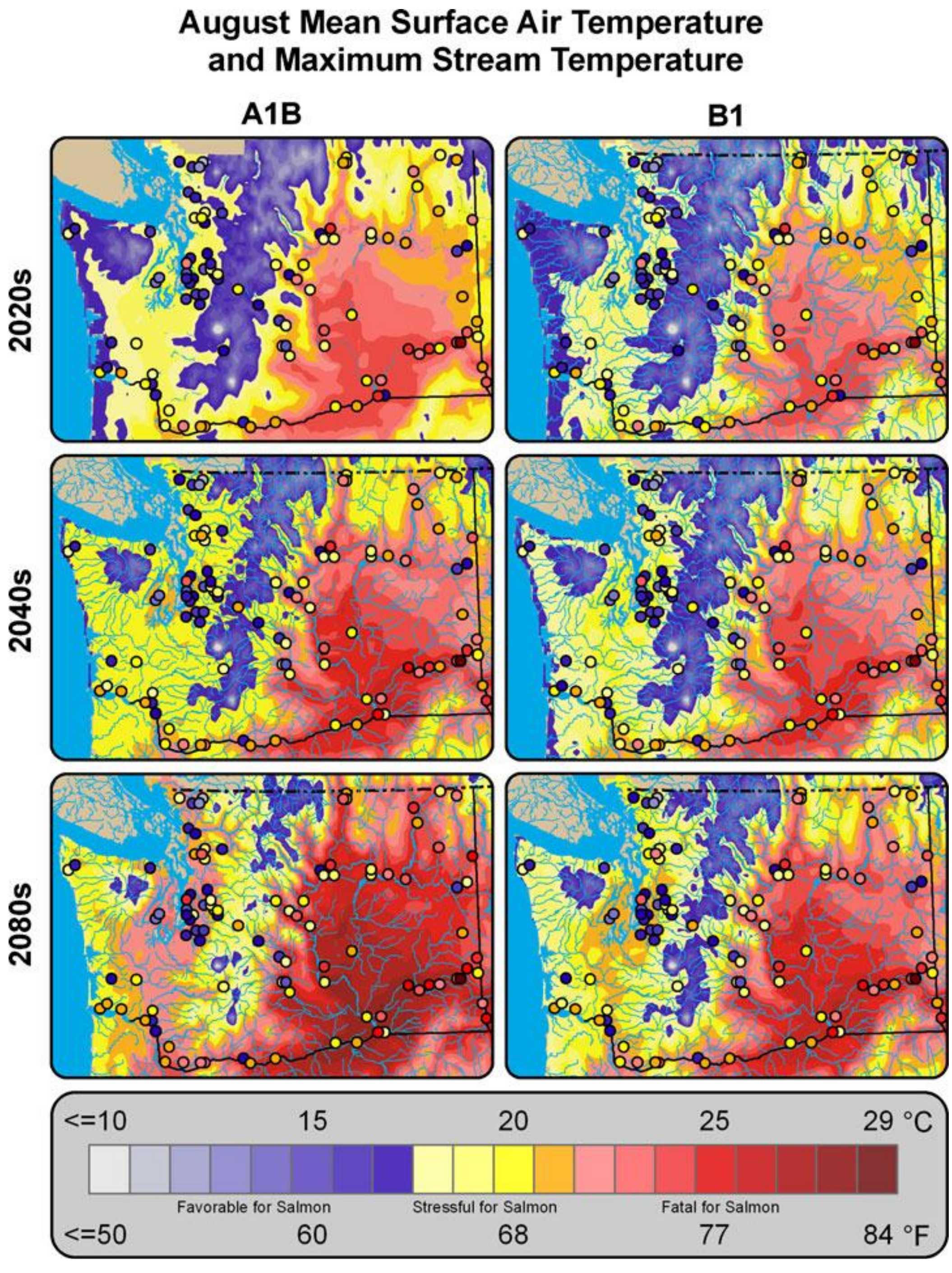


Figure 7.2 Color shading shows mean surface air temperature for August for future climate scenarios for the 2020s, 2040s and 2080s. Shaded circles show the simulated mean of the annual maximum for weekly water temperature for select locations. Multi-model composite averages based on the A1B emissions are in the left panels, and those for B1 emissions are in the right panels (Source: Mantua et al., 2010).

Recently Hamlet et al. (2010) evaluated climate change impacts on the Skagit River habitat for fish. They found that water temperature projections are differentiated by location. The east side tributaries of the Skagit River (Figure 7.3) are projected to exceed (or closely approach) thermal thresholds of 13 ^{o}C (55.4 ^{o}F) and 16 ^{o}C (60.8 ^{o}F) (see Figure 7.4), while the west side tributaries of the Skagit River (Figure 7.3) and the mainstem of the upper Skagit River remain below thermal thresholds of 13 ^{o}C (55.4 ^{o}F) (see Figures 7.5 and 7.6). The downstream site on the Skagit, at Sedro Woolley, is projected to exceed thermal threshold of 13 ^{o}C (55.4 ^{o}F) and 16 ^{o}C (60.8 ^{o}F) as shown in Figure 7.7. Seattle City Light (2010) pointed out that future climate could put more thermal stress on salmonids than what is predicted in Hamlet et al. (2010) if glacial runoff, which is not included in the study of Hamlet et al. (2010),decreases or disappears in late summer.

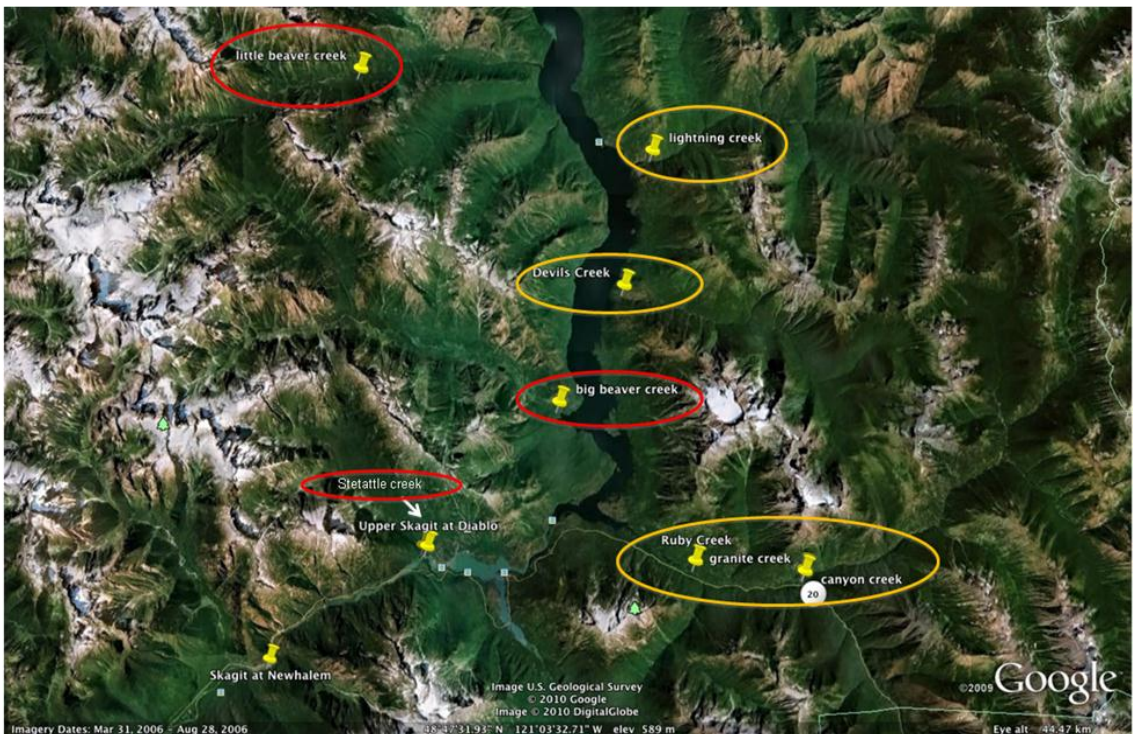


Figure 7.3 Map of study sites by Hamlet et al. (2010). Orange and red circles are the east and west side tributaries of the Skagit River, respectively.

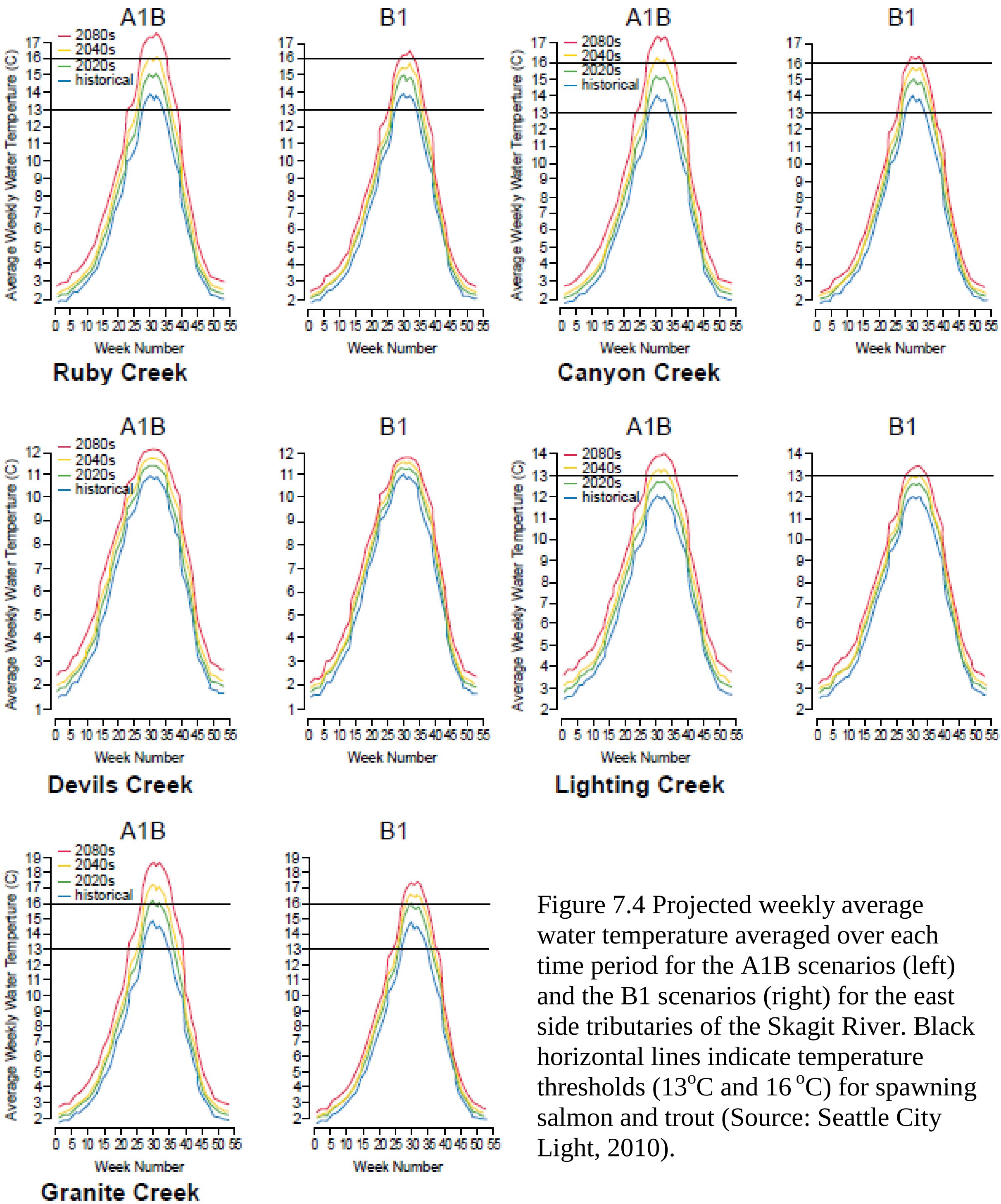


Figure 7.4 Projected weekly average water temperature averaged over each time period for the A1B scenarios (left) and the B1 scenarios (right) for the east side tributaries of the Skagit River. Black horizontal lines indicate temperature thresholds (13°C and 16 °C) for spawning salmon and trout (Source: Seattle City Light, 2010).

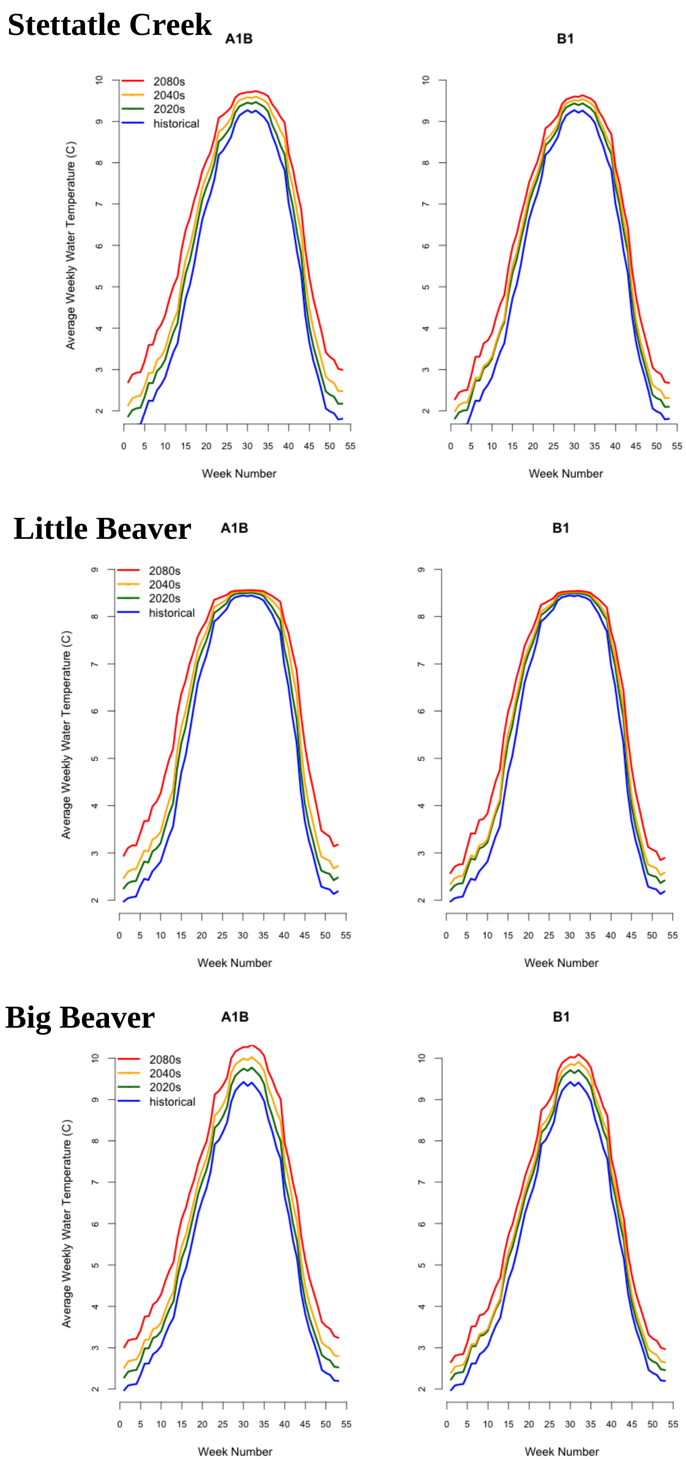
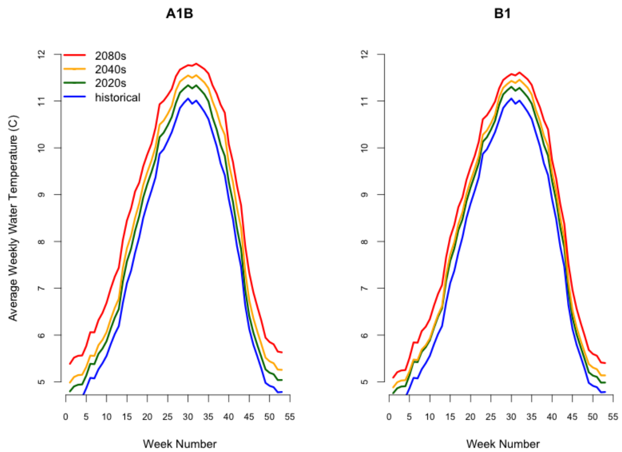
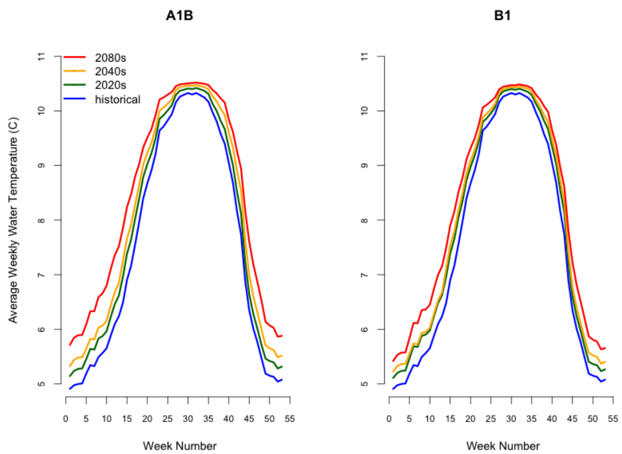


Figure 7.5 Projected weekly average water temperatures averaged over each time period for the A1B scenarios (left) and the B1 scenarios (right) for the west side tributaries of the Skagit River (Source: Hamlet et al., 2010).

Marblemount



Newhalem



Diablo

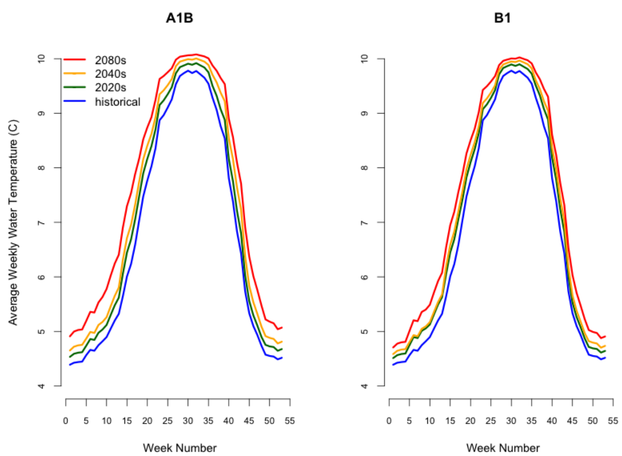


Figure 7.6 Projected weekly average water temperatures averaged over each time period for the A1B scenarios (left) and the B1 scenarios (right) for the main stem of the Skagit River (Source: Hamlet et al., 2010).

Sedro Woolley

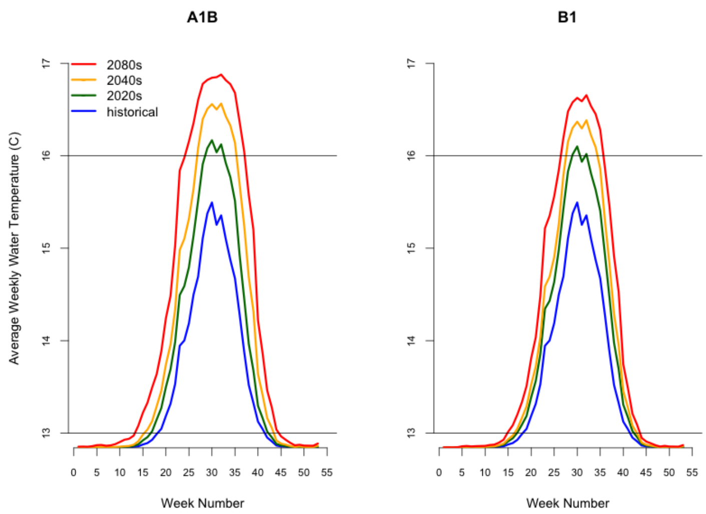


Figure 7.7 Projected weekly average water temperatures averaged over each time period for the A1B scenarios (left) and the B1 scenarios (right) for the Skagit River at Sedro Woolley (Source: Hamlet et al., 2010).

As discussed in Chapter 5, Hamlet et al. (2010) evaluated how climate change influences extreme events such as floods and low flows in the Skagit River basin. The flood risk as defined by 20, 50, and 100 year return intervals is projected to increase first in the warmer lower basin such as Mount Vernon and only later in the century in the colder headwater areas such as Ross Dam. The lowest consecutive 7-day flows with a 10-year return interval (7Q10) are projected to decrease for all sites in the Skagit River, exacerbating thermal stresses on salmon populations. Therefore, the productivity of salmonids in the Skagit River basin is expected to decline due to expected hydrologic changes and increased thermal stresses (Mantua et al., 2010; Hamlet et al., 2010; CCWAPWG, 2009).

Sea level rise is likely to reduce available habitat for juvenile chum and Chinook salmon in the Skagit estuary, resulting in a declines in these populations (URL 9; Hood, 2005; Beamer et al., 2005; Schweiger, 2007). Hood (2005) investigated the possible impacts of sea level rise on salmon habitat in the Skagit delta (discussed in following section) and then on smolt capacity. He estimated that Juvenile Chinook salmon would decline by 211,000 and 530,000 fish, respectively, for a 45 and 80 centimeters (18 and 32 inches) of sea level rise. The projected sea level rise is also likely to affect other fish species that depend on coastal habitats during their life cycle such as coho salmon, pink salmon, cutthroat trout, and bull trout (Schweiger, 2007).

7.3 Tidal Marsh Habitat

As discussed in Chapters 1 and 6, since post European-settlement began in the second half of the 19th century, estuarine habitat zones in the Skagit delta have been changed due to human actions such as diking, ditching, draining and logging (Collins, 1998; Beamer et al., 2005). Beamer et al. (2005) compared 1991 habitat conditions with reconstructed historic conditions in the 1860s to estimate the changes in the estuarine habitats in the Skagit River delta. As shown in Figure 7.8, 74.6 % of tidal delta estuarine habitat area has been lost in the entire geomorphic Skagit delta, which extends from Camano Island northward and includes Samish Bay. Swinomish Channel historically connected Skagit Bay with Padilla Bay through a wide estuarine emergent wetland and slough corridor and thus the delta area between southern Padilla Bay and Camano Island was contiguous and directly connected to the Skagit River in the 1860s. However Swinomish Channel is now a narrow dredged navigation channel. More than 90 % of the Skagit delta has also been lost from riverine and tidal influence due to dikes (Hood, 2004). As a result, the contiguous estuarine habitat area is much reduced from the mid-19th century values and is now mostly confined to the delta area near Fir Island.

As discussed in Chapter 6, sea level rise and other factors associated with climate change pose a significant threat to coastal habitats in the Skagit delta which have already been impacted by human actions. Hood (2005) used a computer model to estimate the possible impacts of sea level rise on intertidal marsh habitat within the Skagit tidal delta as shown in Figure 7.9. A 45 cm (18 inch) rise in sea level, (which was estimated to have a greater than 50 % chance of occurring based on projections available at that time), would lead to a 12 % loss (235 ha) of the tidal marshes and a 51 % loss of the estuarine shrub marsh (a middle panel in Figure 7.9). An 80 cm (32 inch) of sea level rise would result in a 22 % loss (437 ha) of the tidal marsh habitat and a 76 % loss of the estuarine shrub marsh (a right panel in Figure 7.9) (Hood, 2005; Beamer et al., 2005). Hood (2005) noted that these estimates of marsh loss due to sea level rise are preliminary and based only on direct inundation effects, i.e. the analysis didn't include the potential effects of sea level rise on the other factors which affect persistence in tidal marshes such as sediment accumulation or marsh erosion from storm-generated waves, etc. Schweiger (2007) also estimated the loss of tidal marshes and estuarine beaches for sea level rise of 28 cm (11.2 inches) by 2050 and 69 cm (27.3 inches) by 2100 as discussed in Chapter 6. Unlike the work of Hood (2005), Schweiger (2007) considered changes in land elevation due to geological factors, such as uplift and subsidence, and ecological factors, such as sedimentation and marsh accretion. Although two models by Hood (2005) and Schweiger (2007) predicted somewhat different ranges of change in the tidal marshes, both models showed that a) the area of the tidal marshes would be reduced due to sea level rise and b) the South Fork is more vulnerable to sea level rise than the North Fork.

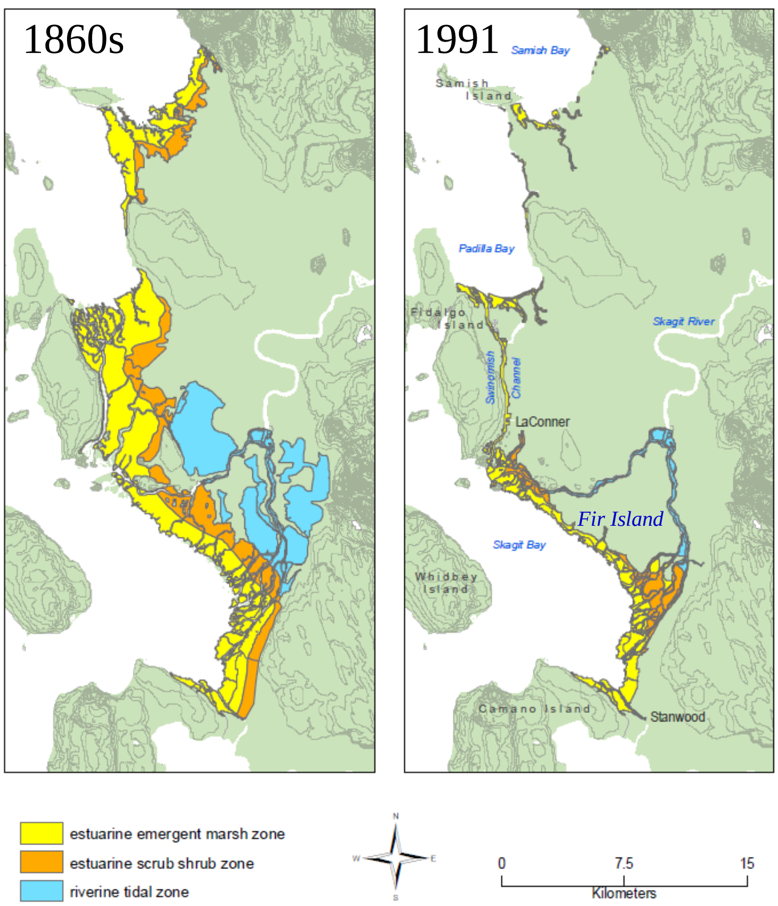


Figure 7.8 Changes to the estuarine habitat zones within the geomorphic Skagit delta. Historic (circa. 1860s) conditions were reconstructed by Collins (2000). Current habitat zones were mapped by Beamer et al. (2000) (Source: Beamer et al., 2005).

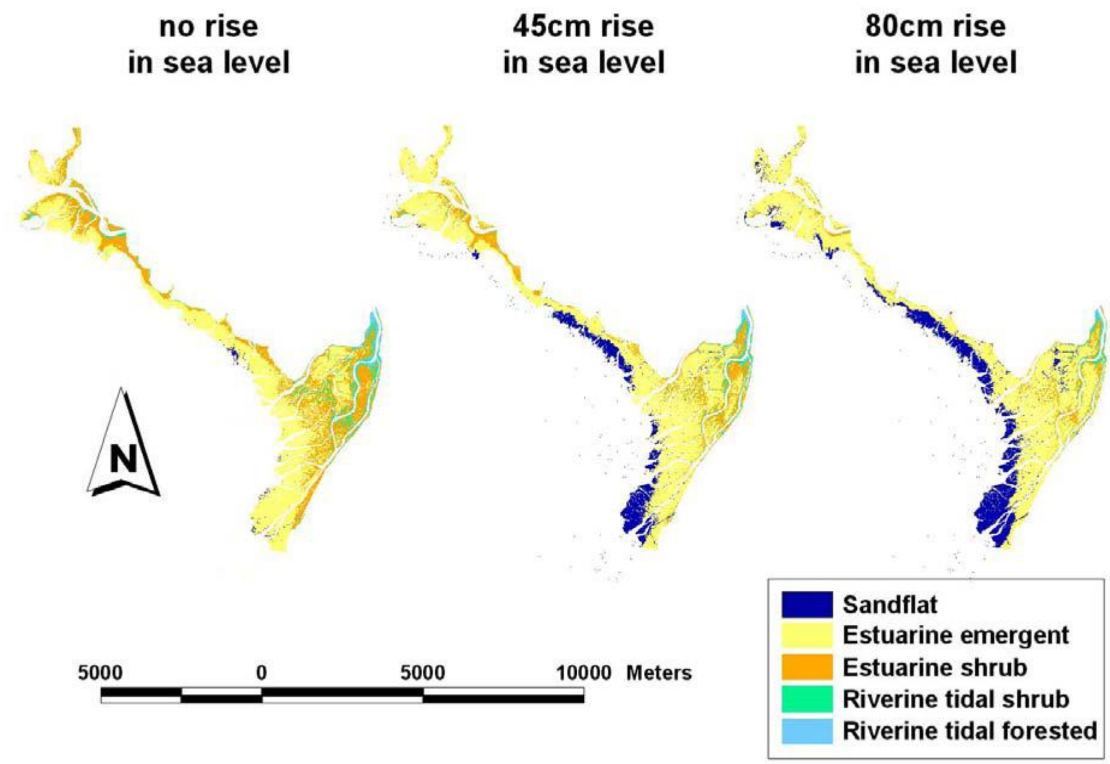


Figure 7.9 Projected estuarine habitat under two sea level rise scenarios. The marshes shown here include the North Fork mouth (NW), the South Fork mouth (SE) and bayfront marshes in between. Farmed land is to the NE of each figure, Skagit Bay to the SW (Source: Beamer et al., 2005).

7.4 Estuary and Puget Sound

Puget Sound estuaries including tidal influenced wetlands and the outer of the delta provide habitats for thousands of plant and animal species (Snover et al., 2005; Schweiger, 2007). 73 % of tidal influenced wetlands in Puget Sound have been damaged or destroyed by diking, dredging, filling, industrial and agricultural activities, and urbanization (Fresh et al., 2004; Snover et al., 2005; Schweiger, 2007; Borde et al., 2003). About one-third of Puget Sound's shoreline has been modified by seawalls, bulkheads, and other structures (Schweiger, 2007).

The remaining habitats in Puget Sound will be further threatened by climate change. Sea-level rise is one primary consequence of climate change that affects the region's coastal habitats through salt water inundation, increasing the salinity of the surface and groundwater (Schweiger, 2007). Projected sea level rise would cause further losses of Puget Sound estuaries, particularly where land areas are already sinking (i.e. central and southern Puget Sound), and/or where sediment transport is reduced (i.e. the South Fork of the Skagit River (Chapter 6)), or where upland migration of the habitats is prevented by human activities such as dikes, seawalls, and other armoring (Snover et al., 2005; Schweiger, 2007).

Higher water temperature (Figure 7.2) and the losses of pollutant-filtering coastal habitats are hypothesized to exacerbate the impact of excess nutrient runoff into coastal waters, enhancing harmful algal blooms and hypoxia events (Snover et al., 2005; Schweiger, 2007). Enhanced algal blooms and hypoxia events are likely one of the biggest threats to habitats in south Hood Canal due to relatively slow circulation in comparison with the rest of the Sound (Snover et al., 2005; Schweiger, 2007). Shifts in seasonal precipitation patterns, reduced snowpack, and the streamflow timing shifts they imply are likely to alter salinity, water clarity, stratification, and oxygen levels, resulting in additional impacts on the region's coastal habitats (Schweiger, 2007). Another emerging threat associated with increasing greenhouse gasses (e.g. CO_2) is ocean acidification (i.e. declining pH of ocean water) (Snover et al., 2005; Orr et al., 2005; Feely et al., 2009& 2010; Doney et al., 2009), which is expected to impact shellfish viability in Puget Sound (Snover et al., 2005; URLs 10 & 11). Oyster production near Olympia, WA, for example, has already declined substantially in recent years (URLs 10 & 11), and these impacts are projected to intensify (URL 10).

7.5 Summary and Conclusions

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) will affect many fish and wildlife species. There are many uncertainties about the projection of sea level rise and its impacts on coastal habitats but there is little doubt that coastal habitats will be influenced by sea level rise. Such changes in fish and wildlife habitat will have a significant impact on the salmon, migratory birds, and other species. It is difficult to translate the potential habitat changes into specific impacts on individual species, but generally the losses of habitats would cause a decline in terrestrial and aquatic species. Other key findings include the following:

- Climate change and its consequences are likely to alter the species composition of trees and vegetation in the Skagit forest. Drier and warmer summer would cause decrease in drought-susceptible species such as western cedar trees and even drought-tolerant species such as Douglas fir. Changes in temperature and precipitation would also create more favorable conditions for forest pests, diseases and wildfire. On the other hand, warmer climate is likely to cause some species in high elevation to grow more and tree lines to climb higher by decreasing snow cover that buries trees in winter.
- More severe and prolonged summer low flow, increased flooding, and warmer air temperatures are likely to impose steadily increasing stress on cold water fish species, resulting in declining salmon and trout populations.
- Sea level rise is likely to cause losses of habitat that support terrestrial and aquatic species. The loss of pollutant-filtering habitats would decrease water quality, disturbing the overall food web and consequently impacting many species.
- Overall coastal habitats in Puget Sound are likely to decrease due to sea level rise and other factors associated with climate change, though the impacts of sea level rise on coastal habitats vary with uncertain, site-specific factors.
- The algal blooms and hypoxia events are likely to be enhanced due to warmer water temperature and the losses of pollutant-filtering habitats. The enhanced algal blooms and hypoxia events would threaten some of habitats in Puget Sound, particularly in south Hood Canal which is most susceptible to algal blooms and hypoxia events in Puget Sound.
- Ocean acidification is likely to be intensified due to increasing carbon dioxide concentration, threatening shellfish variability in Puget Sound.

URL 1: http://www.goskagit.com/home/article/climate_change_poses_threat_to_regional_icons/
URL 2: http://en.wikipedia.org/wiki/Fir_Island_%28Washington%29
URL 3:
http://wdfw.wa.gov/lands/wildlife_areas/skagit/unit.php?searchby=unit&search=Skagit%20Bay%20Estuary
URL 4:
http://www.nature.org/wherewework/northamerica/states/washington/files/skagitvisitorsguideweb_06_07.pdf
URL 5: http://en.wikipedia.org/wiki/List_of_wildlife_of_the_Skagit_River_Basin
URL 6: http://www.skagiteagle.org/IC/IC-EagleViewingTips.htm
URL 7: http://www.wildlifeviewingareas.com/wv-app/ParkDetail.aspx?ParkID=378
URL 8: http://www.outstandingwaters.org/seattle_citylight.html
URL 9:
http://www.goskagit.com/home/article/warming_shifts_odds_away_from_salmon_survival/
URL 10: http://seattletimes.nwsource.com/html/localnews/2012338264_acidification13m.html
URL 11: http://www.theolympian.com/2010/07/20/1309700/acidic-water-no-surprise-to-shellfish.html

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8. Human Systems

Abstract

Climate change is likely to substantially impact many human systems and the local economy in the Skagit basin. In this chapter we discuss a number of impact pathways affecting human systems in the basin and their potential socioeconomic implications. 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, resulting in changes in the pattern of seasonal hydropower production, increases in the 100-year flood magnitude, and reduced summer instream flow. These changes will pose formidable challenges for water resources managers, utilities, and municipalities, particularly in the context of floodplain management. 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 and white water recreation opportunities that depend on summer flow in rivers. Agriculture in Skagit County will 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 productivity in some crops. Increased flood risks from sea level rise and projected increases in river flooding would 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. 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. With a few possible exceptions, climate change and its direct and indirect consequences are expected to have substantial negative impacts on the Skagit's current economy.

8.1 Water Management

8.1.1 Hydropower Resources

Hamlet et al. (2010) evaluated the potential effects of climate change on the demand for electric power and on hydropower generation for the Columbia River Basin and Washington State. They projected that per capita energy demand will increase in summer due to increased cooling degree days and more use of air conditioners, but decrease in winter due to warmer winters with fewer heating degree days. At the same time, projected system-wide hydropower generation for the Columbia River Hydro system increased in winter and spring but decreased in summer (Figure 8.1) corresponding to streamflow shifts associated with climate change (Chapter 5). By the 2080s, hydropower generation is projected to increase by 7.7-10.9 % in winter but decrease by 17.1-20.8 % in summer.

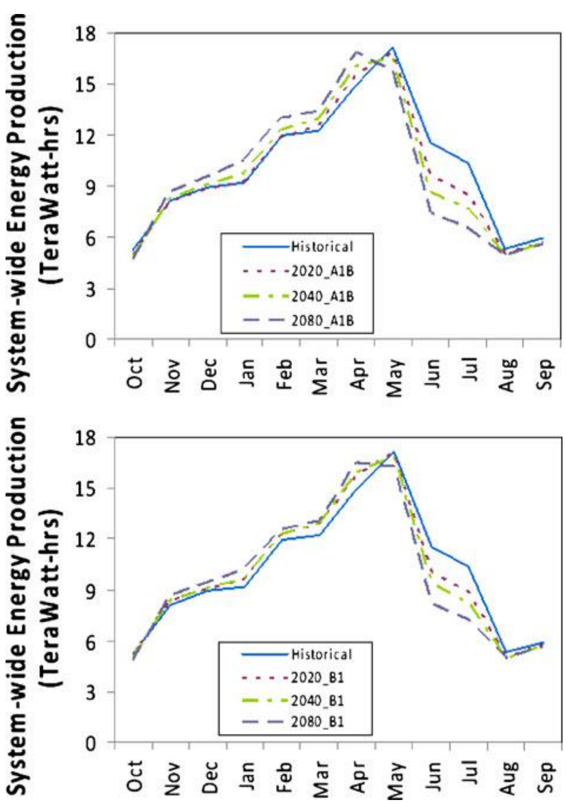

Figure 8.1 Simulated long-term mean, system-wide hydropower production from the Columbia River Basin for six climate change scenarios. Top panel shows results for the A1B scenario. Bottom panel shows results for the B1scenario (Source: Hamlet et al., 2010).

A recent study by Seattle City Light (2010) examined projected changes in hydropower generation for Seattle City Light (SCL) hydropower projects in the Skagit Basin under six climate scenarios, as shown in Figure 8.2. Seattle City Light (2010) used a Skagit Project operations model that maximizes the value of power while simultaneously adhering to regulatory requirements to maintain flood control pocket during the winter and early spring, refill Ross Reservoir by the end of June for National Park Service recreation season, and stay within allowable instream flows for fisheries downstream of Newhalem. The model does not include a summer low-flow criterion for fish. Annual power generation for the Skagit Project is projected to increase approximately 3 % by the 2020s, 5 % by the 2040s, and 9 % by the 2080s (Seattle City Light, 2010). The increased annual power generations are partly due to 1-2% of increased total annual inflow into Ross Lake (increased cool season precipitation in the scenarios) and dam operations that keep reservoirs at higher levels, creating higher efficiency (Seattle City Light, 2010). In comparison with the Columbia River Basin, the seasonality of Skagit River hydropower production is much more sensitive to streamflow timing shifts caused by warming and loss of snowpack (Chapter 5) (Figure 8.1). For the projected 2040s climate, for example, a 20 % increase in winter power generation was simulated for the SCL hydro system (Seattle City Light, 2010), whereas the same climate conditions produced about a 5 % increase in winter hydropower production for the Columbia River Basin (Hamlet et al., 2010). By the 2080s, peak hydropower generation in the SCL system shifts from July to January, which better matches existing Seattle electricity demand peaks. This projected increased generation is based on monthly flow data and may overstate increases. It assumes that Seattle City Light would be able to operate the three reservoirs in a manner that results in minimal spill events. In actual operations, large peak flow events could substantially reduce the cool season generation. Summer generation is projected to decline by 30% and could be problematic for meeting demand if use of air conditioning increases.

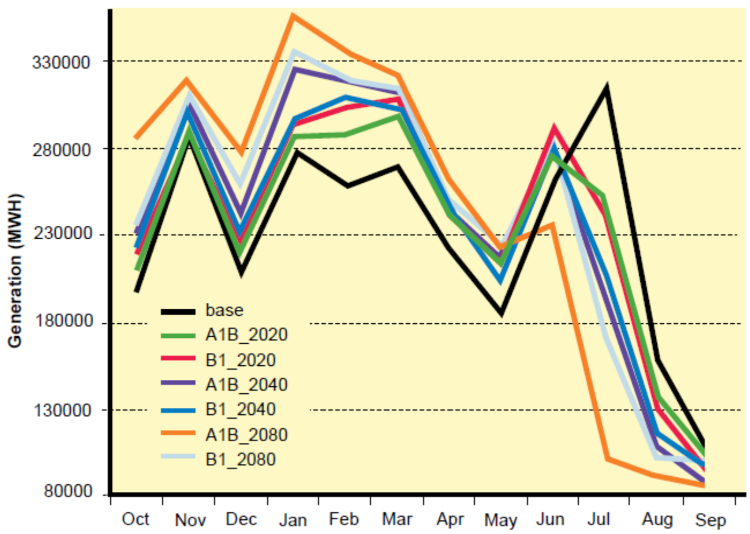

Figure 8.2 Effect of climate change on Skagit generation. Each line shows simulated ensemble median values for six climate change scenarios (Source: Seattle City Light, 2010).

8.1.2 Flood Control

The authorized storage space for flood control in the Skagit River is 194,000 acre-feet: 120,000 acre-feet at Ross Dam on the Upper Skagit River and 74,000 acre-feet at Upper Baker Dam on the Baker River (Table 8.1) (Chapter 1; FEMA, 2009). Lower Baker Dam, which has 116,700 acre-feet of usable storage (Table 8.1), can also provide additional flood protection on an on-call basis, but otherwise has no specific flood control requirements under normal conditions (Steward and Associates, 2004).

Table 8.1 Storage characteristics of major reservoirs in the Skagit River basin (Source: FEMA, 2009).

Reservoir	Flood Control Storage	Maximum Usable Storage
Ross	120,000 acre-ft	1,052,300 acre-ft
Diablo	0	76,220 acre-ft
Gorge	0	6,770 acre-ft
Upper Baker	74,000 acre-ft	180,128 acre-ft
Lower Baker	0	116,700 acre-ft

Currently, flood storage at Ross Dam is required from October 1 to March 15. Ross Reservoir is gradually drawn down to produce at least 20,000 acre-ft of storage by October 15, 43,000 acre-ft by November 1, and 60,000 acre-feet of flood storage by November 15. The full 120,000 acre-feet is required by December 1 (source: Seattle City Light). Similarly, Upper Baker Dam is required to provide 16,000 acre-feet of flood storage by November 1 and 74,000 acre-feet of flood storage by November 15 (Steward and Associates, 2004; Puget Sound Energy, 2006). If a flood event pushes forecasted runoff at Concrete to 90,000 cfs or higher, the U.S. Army Corps of Engineers operates Ross Dam in coordination with Upper Baker Dam to reduce flood peaks in the lower Skagit River valley (Puget Sound Energy, 2006; FEMA, 2009).

In an effort to increase flood protection in the Lower Skagit valley, Skagit County recently proposed increasing flood storage in Upper Baker Dam to 150,000 acre-feet and starting drawdown of the dam earlier in the fall, completing full drawdown by October 15 (one month earlier than current operations) (URL 1; Steward and Associates, 2005; Skagit County, 2008). The increased storage at Upper Baker Dam would likely be achieved by integrating Lower Baker Dam into the formal flood control system. An evaluation of the proposed Baker River flood control modifications by Steward and Associates (2005) showed that the proposed operations would provide lower peak flows on average, particularly for severe flood events, but would probably not reduce the magnitude of more frequent, moderately high flow events in comparison with current flood control operations. Steward and Associates (2005) also noted that refill timing needs to be adjusted to reach full storage by end of flood season because of the deeper reservoir drafting. Other alternatives being considered by Skagit County include increasing flood storage in Ross Reservoir from 120,000 to 180,000 acre-feet (URL 2). Actual flood storage in Ross Dam is also very dependent on hydropower operations, which typically evacuate the storage reservoirs below their required flood rule curves, resulting in more storage available for flood control by mid winter

Climate change is likely to shift the seasonal timing of peak flows in the Skagit River from spring to winter and increase the likelihood for more frequent and severe floods under natural (i.e. unmanaged or unregulated) conditions. For example, Figure 8.3 shows comparison of unregulated daily peak flows at the Skagit River near Mount Vernon for historical runs with those for the 2040s and for 2080s for Echam5 A1B scenario (a global climate model scenario which approximates the average conditions simulated by all models, see Chapter 3). For historical runs, daily peak flows occur 71 % (65 of 91 water years) in fall/winter, 21 % in spring and 8 % in summer (see Figure 8.3). For climate change, magnitude and frequency of fall/winter peak flows increase but those of spring and/or summer peak flows decrease substantially especially for the 2080s (see Figure 8.3). Cumulative distribution function (CDF) of unregulated daily peak flows (Figure 8.4) also shows that magnitude of unregulated peak flows increases as warming intensifies through the 21st century. The largest unregulated daily flood shows a 12% increase by the 2040s, and a 24% increase by the 2080s relative to the historical unregulated flood (Figure 8.4).

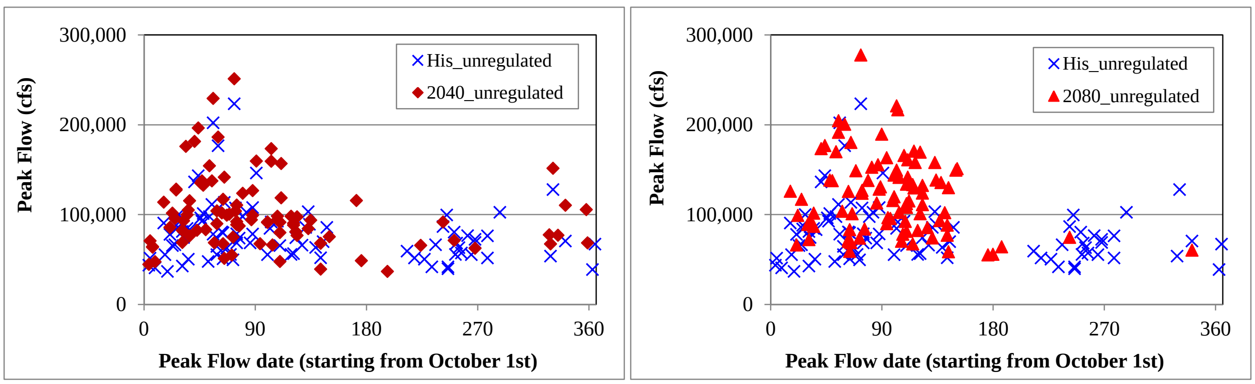

Figure 8.3 Comparison of unregulated daily peak flow dates and magnitude at the Skagit River near Mount Vernon for echam5 A1B scenarios for the 2040s (left) and 2080s (right) with those for historical runs.

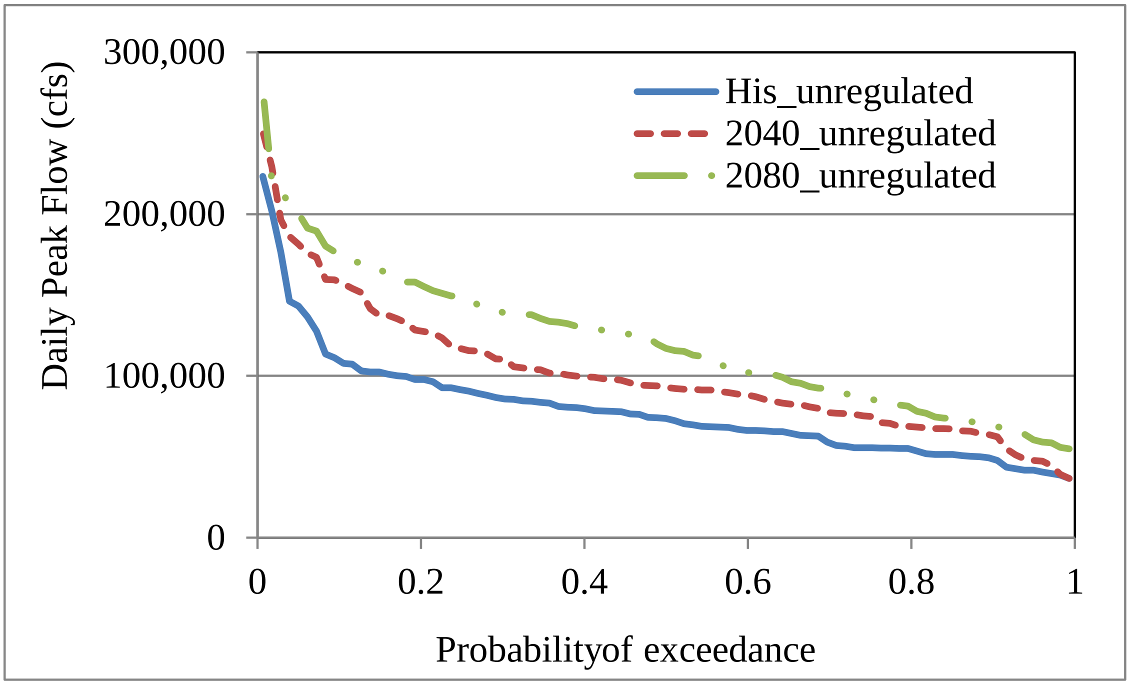

Figure 8.4 Cumulative distribution functions (CDFs) of unregulated (or natural) daily peak flows for the Skagit River near Mount Vernon for historical run and for echam5 A1B scenarios for the 2040s and 2080s.

To assess the combined effects of increasing natural flood risks and dam operations that determine impacts to regulated flow, a new integrated daily time step reservoir operations model was built for the Skagit River Basin. The model simulates current operating policies for historical flow conditions and for projected flow for the 2040s and 2080s associated with the Echam5 A1B scenario (see Chapter 3). By simulating alternative reservoir operating policies that provide increased flood storage and starting flood evacuation one month earlier, prospects for the adaptation are considered.

Regulated 100-year floods are less than natural floods in all time periods, however relative to the regulated baseline condition (the historical regulated 100-year flood under current flood control operations), the future regulated 100-year flood increased by 20% by the 2040s and 24% by the 2080s (Figure 8.5). Although increasing flood storage under the proposed alternative operations reduces 100-year flood risks, the reduction is only 3% for the 2040s and 7% for the 2080s (Figure 8.5). The alternative flood control operations are largely ineffective in mitigating the increased flood risks in the lower basin because inflows to the headwaters are a relatively small fraction of the total flow in the lower basin, and even fully capturing these inflows does not compensate for overall increases in flooding in the lower basin. It should also be noted that increasing flood storage would also entail many tradeoffs with other system objectives such as hydropower production, lake recreation, and instream flow for T & E fish species (Steward and Associates, 2004). Thus potential increases in flood storage would ultimately need to be weighed in the context of tradeoffs with other system objectives.

While these preliminary results for a single GCM scenario will need to be extended to include more GCM scenarios before final conclusions can be made, the preliminary results support the argument that climate change adaptation efforts will need to focus primarily on improving management of the floodplain to reduce vulnerability to increasing flood risk and sea level rise, rather than on increasing flood storage in existing headwater projects.

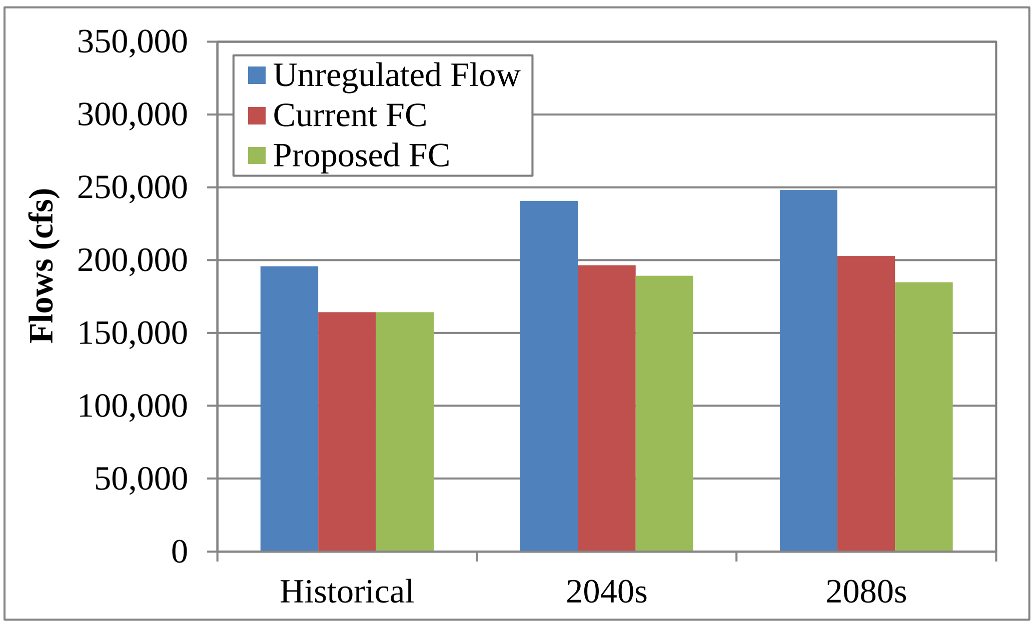

Figure 8.5 The magnitude of 100-year floods at the Skagit River near Mount Vernon for unregulated flows and for regulated flows under current flood control operations (CurFC) and alternative operations (AltFC). Historical run and echam5 A1B scenarios for the 2040s and the 2080s are considered.

Changing reservoir operating policies as an adaptation to climate change may also need to focus on altering the timing of refill so that reservoirs reach full storage during summer in order to meet the flow demands for T&E fish species and recreation needs. Lee et al. (2009), for example, showed that re-optimized flood rule curves for the Columbia River basin for a climate change scenario improved reservoir refill statistics and lowered flood risks by altering the timing of refill and decreasing the amount of flood storage. More detailed flood regulation studies are needed to explore potential adaptation strategies to the increased flood risk projected for the Skagit under warming scenarios. Although the hydrology of the Skagit and its climate sensitivity is considerably different from Columbia, the use of optimization to evaluate flood control alternatives (Lee et al., 2009) is likely a viable approach.

8.1.3 Stormwater Management

Although changes in average annual precipitation from global climate models (GCMs) show a very low signal to noise ratio (e.g. the systematic changes are small relative to the observed year-to-year variability), most GCMs project substantial increases in precipitation during the winter season (Chapter 3). Simulations by two regional climate model (RCMs) (Chapter 3) also showed substantial increases in the extreme rainfall magnitude for the next 50 years (Salathé et al. 2010). However, the magnitude of projected changes varies substantially by region and by model and future changes may be difficult to distinguish statistically from natural variability (Miles et al., 2010; Rosenberg et al., 2010). Despite these uncertainties, the general projections for more intense rainfall raise the concern that stormwater infrastructure designed using historical rainfall records may not perform adequately if extreme precipitation substantially increases. Additional RCM studies are currently underway to attempt to better characterize future storm intensity and flood responses, but results have not yet been published.

Sea level rise may also affect stormwater management. Stormwater outfalls in low-lying areas may be inundated (or provide inadequate drainage due to low slope) and may need to be relocated to higher locations, resulting in the potential need for some systems to be completely redesigned (SITC, 2009). A similar issue exists for tide gates used for agricultural drainage, as discussed in section 8.2

8.1.4 Recreation

The Skagit River offers opportunities for camping, fishing, picnicking, hiking, horseback riding, mountain biking, and pack and saddle trips (National Park Service, 2009). For example, Baker Lake is famous for trout fishing and Ross Lake also offers high quality sport fishing in summer (National Park Service, 2009). River recreation activities in the Skagit basin include river floating, kayaking, canoeing, and motor boating (National Park Service, 2009). Boat ramps are located at Baker Lake, Gorge Lake, Diablo Lake, and the north end of Ross Lake at Hozomeen (National Park Service, 2009). Winter recreation such as skiing, snowmobiling, snowshoeing, cross-country skiing, and sledding is available in the Mt. Baker National Recreation Area (National Park Service, 2009). The Skagit River also offers excellent wildlife viewing opportunities (National Park Service, 2009).

Increased temperature and changes in precipitation are likely to cause less snowfall, less snow accumulation, earlier snowmelt, and reduced summer flow (Chapter 5). These changes could have negative impacts on winter recreation and some water-related recreation (Morris and Walls, 2009; Econorthwest, 2009, 2010; Mickelson, 2009). Opening and closing dates for winter recreation depend on snow levels each year. Therefore less snowfall and reduced snow accumulation would likely shorten the winter recreation season (Morris and Walls, 2009). Low quality snow associated with climate change would also affect the demand for winter recreation days, particularly for ski days (rain during the ski season) (Morris and Walls, 2009; Econorthwest, 2009, 2010). Reduced summer flow could cause summer streamflow levels to fall below critical levels for some water-related recreation, such as river rafting and kayaking, and consequently have impacts on water-related recreation industry (Morris and Walls, 2009; Econorthwest, 2009, 2010; Mickelson, 2009). For example, a streamflow of about 3,500 cfs is required for rafting in the Sauk River (Mickelson, 2009). As shown in Figure 8.6, reduced summer flow would not adversely affect rafting early in the season (May) but is likely to reduce the possibility of rafting in July, particularly by the 2080's (Mickelson, 2009).

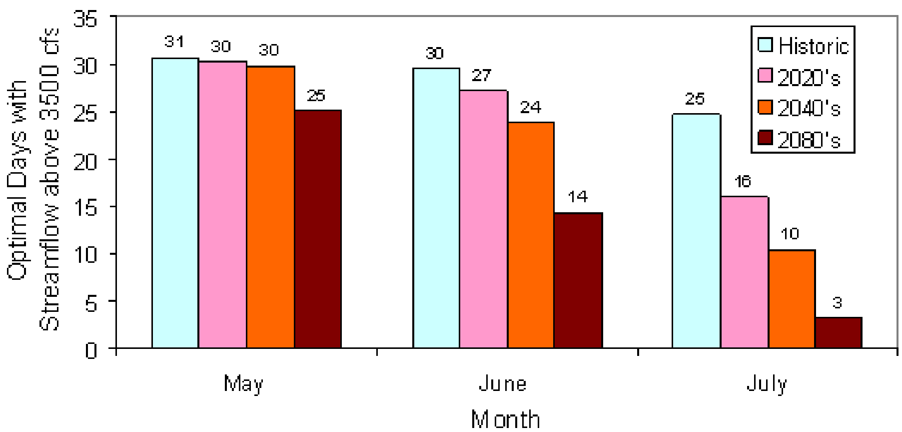

Figure 8.6 Number of optimal rafting days with streamflow above 3500 cfs per month for the Sauk River (Source: Mickelson, 2009).

The hypothesized reduction of salmon and steelhead populations (Chapter 7) would have an impact on the fishing industry in the Skagit River (Morris and Walls, 2009). Additionally, more frequent forest closures due to increased wild fire (Chapter 7) could reduce opportunities for outdoor activities such as hiking, mountain biking, wildlife watching and scenic tours (Morris and Walls, 2009; Econorthwest, 2009, 2010).

8.2 Agriculture

Agriculture is the leading industry in Skagit County (URLs 3 & 4; Hovee and Company, 2003). About $300 million worth of crops, livestock, and dairy products are produced in approximately 100,000 acres of Skagit County (URL 3). Over 90 different crops are grown in the County. Major crops include blueberries, raspberries, potatoes, sweet corn, cauliflower, broccoli, squash, pumpkins, tulips, and Jonagold apples (URLs 3 & 4; Washington State University, 2007; Hovee and Company, 2003). Skagit County produces about half of the spinach seed, table beet seed and cabbage seed for the United States (URL 4; Washington State University, 2007; Hovee and Company, 2003). Skagit County agriculture also provides habitat for thousands of migrating water birds such as swans, snow geese, and ducks (URL 3).

The effects of climate change on crop productivity has been evaluated at the global and regional scale in several large scale studies (IPCC 2007; Tubiello et al., 2002; Thomson et al., 2005; Stöckle et al., 2010). At the most basic level, crop production is impacted by climate change via water availability, temperature, and changing atmospheric carbon dioxide (CO_2) concentrations. Indirect impacts may include increased pests, invasive plants (weeds), or diseases. Tubiello et al. (2002) and Thomson et al. (2005) showed that projected warmer temperatures would (in isolation) decrease overall US agricultural productivity, but elevated CO_2 concentrations compensates for these losses by increasing productivity in some crops. Stöckle et al. (2010) found similar results for Washington State. Yields of winter wheat and apples in eastern Washington, for example, were projected to decrease in the 21st century without the effects of elevated atmospheric CO_2 concentrations; however, yields of these crops are projected to increase overall when projected CO_2 concentrations are considered (assuming no change in the availability of irrigation supply) (Stöckle et al., 2010). Tubiello et al. (2002) and Thomson et al. (2005) also noted, however, that the response of crop yield to climate change has to be evaluated at a local scale because agricultural impacts varies depending on local crop types, local weather, and especially local precipitation. As discussed below, impacts to drainage may also be an important factor.

Climate change is expected to influence local agriculture in Skagit County via longer potential growing seasons, drier summers, wetter winters, increased temperature, and changing risks for pests, invasive plants (weeds), and diseases (URL 5). Increased day time temperature is likely to degrade the quality and decrease the productivity of some crops such as spinach seed and raspberries (URL 5). Wetter winters with more frequent and severe rainfall events could cause root rot for some small fruiting plants such as raspberries, resulting in decreases in yield (URL 5). The quality of blueberries would likely be diminished due to increased nighttime temperatures (URL 5). Increasing temperatures and wetter winters are likely to create more favorable conditions for diseases, weeds, and pests (Stöckle et al., 2010), resulting in significant risks to economically important crops in Skagit County, particularly potatoes (URL 5). Projected warmer, drier summers could result in increased irrigation demand or increased moisture stress in areas without irrigation.

Most of the cropland and pasture land in Skagit County is located in the floodplain-delta area (Washington State University, 2007). The floodplain areas are protected by dikes and levees (Chapters 1 and 7) but these flood control structures are not able to protect agricultural areas from large floods (URL 6; Skagit County, 2007). Projected sea level rise and increased river flooding are likely to exacerbate the flood risk to Skagit County agriculture. Likewise drainage of low lying cropland is likely to be impacted by sea level rise, which will reduce the effectiveness of tide gates for draining the land. Without alternative measures (e.g. pumps), the viability of existing crop types and/or planting schedules may be compromised.

8.3 Flood Plain Development and Infrastructure

The Skagit flood plain, covering 90,000 acres, includes the entire floor of the Skagit River valley, the deltas of the Samish and Skagit Rivers and reclaimed tidelands adjoining the Skagit and Samish River Basins (URL 7; City of Anacortes, 2004), and is primarily agricultural but includes most of the County’s urban development, manufacturing plants and major transportation routes (URL 7). More than 30,000 Skagit County residents live in the 100-year flood plain and would need to be evacuated in a current 100-year flood (Skagit County, 2007). During the flood of October 2003 (estimated to be a 100-year event), for example, residents from Fir Island, Clear Lake and Gages Slough area of Burlington, west Mount Vernon, and the Nookachamps basin were asked to evacuate, and homes in the flood plain were destroyed or damaged, with property damage estimated at $30 million (Skagit County, 2007; URL 8). Wastewater treatment, sewage collection system and major storm water pumping are also located in the flood plain and could be severely damaged during a major flood event (City of Anacortes, 2004; Skagit County, 2007; URL 9). As a result these facilities could be shut down for weeks, creating major human health risks and costing millions of dollars to repair (Skagit County, 2007). The Anacortes Water Treatment Plant could be inoperable for 45 days or more following 100-yr flood, cutting off safe drinking water to the cities of Anacortes and Oak Harbor, the town of La Conner, both petroleum refineries and NAS Whidbey for an extended period of time (URL 9; City of Anacortes, 2004; Skagit County, 2007).

Flood control structures such as dikes and levees protect development during small floods (at about the current 30-year return interval) but are not adequate for large floods (URL 6; Skagit County, 2007; FEMA, 2009). Events at the current 30-year return interval are projected to become more frequent in the future (Mantua et al., 2010; Hamlet et al., 2010). Dike and levee breaches, which are common during large floods, cause more damage to lands and structures behind them than would occur under natural flooding conditions (URL 6). For example, floods the size of those occurring in 1917 and 1921 would have breached the levees installed between Burlington and Mount Vernon, potentially causing loss of human life and a predicted 1.3 billion dollars in damage (Skagit County, 2007). More than 80 major dikes have failed in the basin since 1900 (City of Anacortes, 2004). These impacts are a major source of vulnerability for those living in the lower basin.

Projected sea level rise (Chapter 3) could increase the risk of tidal inundation for a significant number of properties in low-lying areas (SITC, 2009). Severe storm surges and resulting debris flows would cause major damage to existing property, infrastructure, and facilities (SITC, 2009). Areas most likely to be affected are gently sloping shoreline areas, or where surge would overtop banks, seawalls and dikes. Sea level rise when combined with tidal storm surges will almost certainly exacerbate the impacts of flooding and its associated effects (SITC, 2009). Increased winter precipitation combined with sea level rise would increase soil saturation and undermine slope stability, causing erosion of banks where shoreline banks are steeper than about a 3:1 ratio (slope height to slope length) (SITC, 2009). To reduce the property damage from inundation, relocation of future development or additional protection for existing infrastructure and facilities are both possible adaptive strategies (SITC, 2009).

Several flood damage reduction measures are currently being evaluated by the U.S. Army Corps of Engineers (USACE) and Skagit County (Figure 8.7) (URL 1). One of these measures (also discussed above) is to increase flood storage of the Skagit/Baker River reservoirs system and modify reservoir operations (URL 1; Steward and Associates, 2005; Skagit County, 2008). Other proposed flood hazard management plans are a) upgrading or modifying to existing levee system along the I-5 Corridor and b) constructing by-pass of extreme flows near the I-5 Bridge as illustrated in Figure 8.7 (URL 1; Skagit County, 2008). In extremely high-risk areas, relocation of existing development has been proposed. In the last century, for example, the town of Hamilton that has flooded more than 17 times and now floods every three years or so. Relocation of Hamilton to the other side of highway 20 is now underway (Figure 8.8, URL 11).

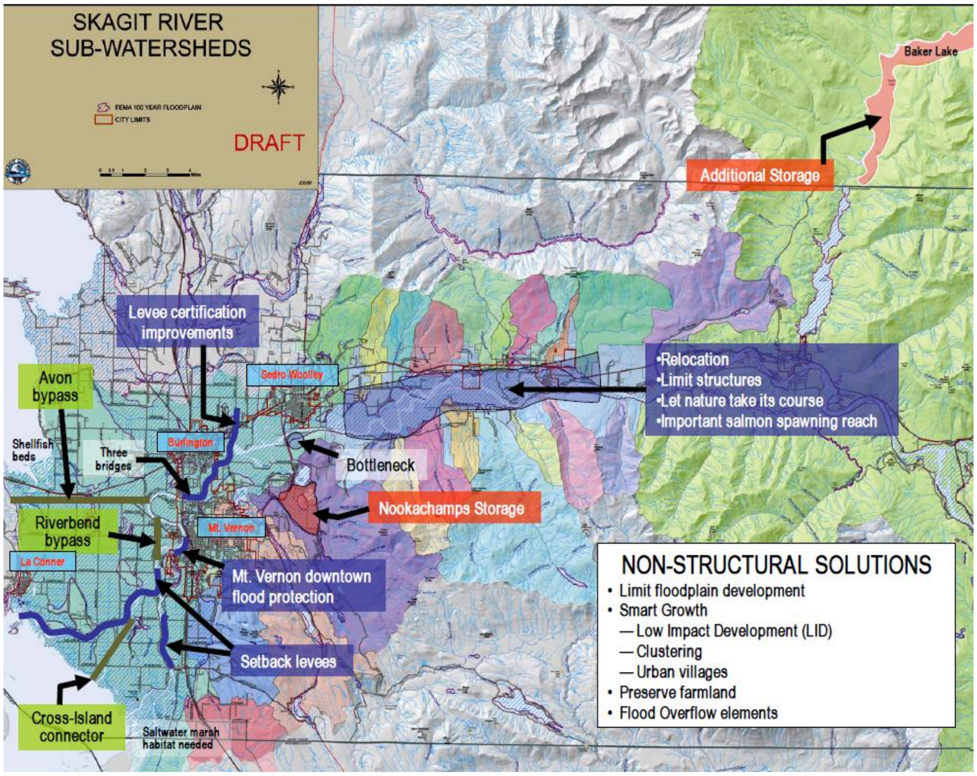

Figure 8.7 Proposed flood hazard management plan (Source: Skagit County, 2008).

Figure 8.8 Photo of town of Hamilton during October 2003 flood (Source: URL 10).

8.4 Roads and Bridges

Major highways in the Skagit are Interstate 5(I-5), State Routes 20, 9, 530 and 536 and would be closed in a 100-yr flood (Skagit County, 2007; URL 9). For instance, I-5 would be closed between Conway, to the south and Bow Hill, to the north during a 100-year flood (Skagit County, 2007; WSDOT, 2008). A railroad operated by Burlington Northern Santa Fe (BNSF) and Amtrak would also be devastated during a 100-year flood event. Projected changes in hydrologic extremes (Chapters 5 and 7) combined with sea level rise is expected to cause more frequent inundation of roads and bridges, impacting the transportation network and the local and regional economy (Skagit County, 2007; WSDOT, 2008). For example, Figures 8.9 and 8.10 show inundation of roads near La Conner and I-5 in Samish River north of Burlington during the flood of February 2006 and Jan 2009, respectively.

Figure 8.9 Inundation of roads near La Conner due to storm/tidal surge of February 2006 (Source: Donatuto, 2010).

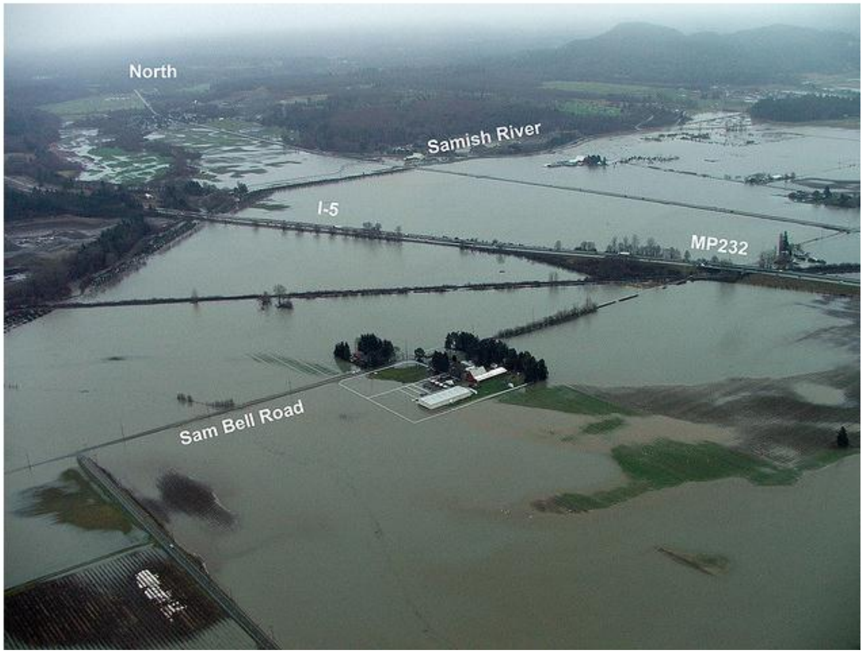

Figure 8.10 I-5 Flooding in Samish River north of Burlington during the flood of Jan 2009 (Source: URL 12).

Temporary inundation may not cause damage to roads and bridges but frequent and prolonged inundation would exacerbate erosion and pavement weathering from loosening of aggregate due to water saturated road base, possibly resulting in road or bridge failures (URL 6; SITC, 2009). For example, about 1,000 ft of the Sauk River Road just outside of the town of Darlington was eroded during the flood of October 2003 when a 100 year flood occurred in the Upper Skagit (FEMA, 2005; Lautz and Acosta, 2007). Intensified flooding during winter and resulting log jams increase the risk of damage to bridges (Figure 8.11). Debris flows, and rock fall could also damage bridges and pylons via increased scour or accelerate the deterioration of paved road surfaces, resulting in potential road and bridge failures (SITC, 2009). Increased and prolonged exposure to heat could cause more rapid break-down of asphalt seal binders and pavement softening, damaging paved roads and/or shortening road life (SITC, 2009).

Figure 8.11 Log jams behind the Burlington Northern Railroad Bridge in November 1995 flood (left panel) and in October 2003 flood (right panel) (Source: URL 10).

8.5 Economics

Potential economic costs in Washington to climate change have been evaluated by the Climate Leadership Initiative at the University of Oregon (2006) and Econorthwest (2009, 2010). Local economic impacts for the Skagit basin, however, are not available from these reports. There are probably significant differences between economic impacts for the Skagit basin (and Skagit County) and those estimated for Washington State as a whole. However, we use the Washington State economic analysis to broadly discuss analogous economic impacts in the Skagit basin and Skagit County.

Climate change and its consequences are likely to have negative impacts on Skagit's economy in several ways. In some cases, the economic harm comes from a change in climate itself, e.g. through changes in temperature, precipitation and extreme events (Econorthwest, 2009). Increased flood risks from more severe storms and sea level rise, for example, are likely to damage property, disrupt business and take lives (discussed above). Higher temperatures would reduce the productivity or quality of some crops (discussed above). In other cases, climate change indirectly influences the local economy by inducing changes in ecosystems. Warmer temperatures and increased summer moisture stress, for example, are expected to increase epidemic outbreaks of insects that kill pine trees (Littell et al., 2010) and other crops, resulting in reduced productivity (discussed above). Sea level rise is likely to cause habitat losses in low-lying areas and the Skagit delta (Chapter 6), causing reduction of economically valuable salmon and trout populations (Chapter 7). The possible negative impacts of climate change on the Skagit basin's economy are summarized as follows (Econorthwest, 2009, 2010):

- Water Resources: The water supply during summer may be insufficient to meet the combined demands for irrigation, municipal and industrial water demand, instream flow for fish and recreation (Mickelson, 2009). Diminished summer water supply has the potential to create economic impacts due to reduced access to (or increased cost of) water supply, reduced development potential in sub-basins already experiencing water stress, loss of recreation opportunities, or loss of environmental services that create impacts in other sectors (e.g. reduced salmon populations).
- Salmon Populations: Salmon populations are likely to decrease due to higher water temperature in the Skagit River and tributaries, more severe and prolonged low flow during summer, more intense flooding during winter and habitat losses due to sea level rise (Chapter 7). Because the salmon are a very important part of the Skagit basin economy, particularly for the Native American Tribes (Garibaldi and Turner, 2004; SITC, 2009), impacts to this resource would result in a relatively large impact to the local economy.
- Power Generation and Energy Demand: The mismatch between energy demand and local/regional hydropower generation (as discussed above) may result in economic losses due to the need to replace relatively inexpensive renewable hydropower resources with more expensive alternative energy sources (Hamlet et al., 2010) Although local utilities are expected to experience increased energy demand in all seasons due to population growth, individual consumers may see reduced heating bills due to lower heating degree days, a benefit of warmer winter temperatures.
- Agricultural Impacts: Climate change and its consequences may decrease the economic benefits associated with agricultural industry in Skagit County by degrading quality and the productivity of economically important crops in Skagit County (as discussed above). Poor drainage associated with sea level rise may limit the growing season or reduce the number of crop types that can be successfully grown (as discussed above). Although detailed studies are lacking, decreased summer water supply for irrigation may potentially reduce agricultural output in Skagit County. Because agriculture is the largest

industry in Skagit County, potential impacts to agriculture would result in relatively large economic impacts to the basin.

- Flood and Storm Damage: Increased tidal inundations from frequent, intense storms and sea level rise are likely to damage coastal property as well as inland areas reached by the tides. Flooding and associated impacts such as debris flows would cause damages to transportation infrastructure such as roads and bridges (Chapter 6). Major highway closures and resulting traffic delays related to a single 100-year flood event are estimated to cause economic losses estimated at over $15million (URLs 9 & 10).
- Recreation: Climate change is likely to reduce the economic benefits associated with the ski industry and some water-related recreation opportunities such as river rafting and kayaking as discussed above. More frequent forest closures due to increased forest fire would reduce opportunities available for activities such as hiking, mountain biking, wildlife watching and scenic driving (as discussed above). Winter access to some recreation areas such as bald eagle watching (Chapter 7) may improve, however, due to better driving conditions and less frequent road closures in moderate elevation areas (less snow). The hiking season would also be extended by reduced snow at lower elevations and earlier melt out of the spring snowpack at higher elevations.

8.6 Summary and Conclusions

Climate change and its consequences may influence human systems such as water management and agriculture and subsequently affect the local economy in the Skagit basin. Key findings on the implications of climate change for human systems and the local economy in the Skagit River include the following:

- Climate change is likely to cause a shift in streamflow timing, changing the seasonality for the Seattle City Light (SCL) Skagit hydropower system. Hydropower generations in the SCL Skagit system are projected to increase in winter but decrease in summer. By the end of the 21st century, the seasonal timing of maximum hydropower generation in the SCL system is likely to shift from summer to winter. Because per capita demand of electric power is projected to increase during summer for cooling but decrease during winter for heating, the seasonal timing shift of maximum hydropower generation could pose a challenge to hydropower operations. This mismatch between energy demand and local/regional hydropower generation may require replacing relatively inexpensive renewable hydropower resources with more expensive alternative energy sources, resulting in economic losses.

- A warmer climate and associated freezing level rise are likely to shift the seasonal timing of peak flows in the Skagit River from spring to fall/winter and increase the risk of flooding. Current and/or proposed flood control operations are projected not to be effective at mitigating these increased flood risks because current and increased flood storages on headwaters mitigate the impacts of natural floods only for the headwaters during high flow events, which is relatively small portion of the total flow in the lower Skagit River Basin. These results suggest that climate change adaptation efforts will need to focus primarily on improved management of the floodplain to reduce vulnerability to increasing flood risk and sea level rise, rather than on increasing flood storage on headwaters intended to reduce floods.
- The extreme rainfall magnitude is projected to increase during winter for the Skagit River, although actual changes in winter precipitation may be difficult to distinguish statistically from natural variability. Due to projected sea level rise, stormwater outfalls in low-lying areas may be inundated or provide inadequate drainage due to slope, requiring redesign and replacement.
- Climate change and its consequences are likely to influence recreation opportunities in Skagit County. Projected summer low flow is likely to reduce opportunities for some water-related recreation such as river rafting and kayaking. More frequent forest closures due to increased wildfires would reduce opportunities available for out-door activities such as hiking, mountain biking, wildlife watching and scenic driving. Less snowfall, reduced snow accumulation and earlier melt may improve winter access to some recreation areas by providing better driving conditions and less frequent road closures in moderate elevation areas and extend the hiking season at lower elevations but are likely to shorten ski season and degrade skiing conditions.

- Drier summers, wetter winters, and increased temperature may degrade the quality and the productivity of economically important crops such as spinach seeds, blueberries and raspberries. Increased disease, invasive plants (weeds), and pests due to warmer temperature are likely to reduce productivity of valued crops such as potatoes. Increased flood risk from the combined effects of sea-level rise and river flooding may also reduce agricultural productivity. Because agriculture is the leading industry in Skagit County, potential impacts to agriculture would result in relatively large economic impacts to the basin.
- Projected sea level rise and more frequent, intense flooding would increase flood risk at properties, infrastructures and transportation systems in the flood plain area. Failure of flood control structures such as dikes and levees during a flood event would further increase flood risk. The increased flood risks could cause major damages to low-lying farms and urban development in the floodplain, traffic delays due to major roads closures, and loss of human life, resulting in negative impacts on the Skagit's economy.
- Frequent and prolonged inundation as well as increased and prolonged exposure to heat could undermine the bridges or exacerbate deterioration of paved road surfaces, possibly resulting in road and bridge failures.
- In addition to economic impacts mentioned previously, climate change is likely to have negative impacts on Skagit's economy by causing changes in ecosystems. For example, economically valuable salmon and trout population is likely to decrease due to higher water temperature, more severe and prolonged summer low flow, more intense flooding during winter and habitat losses associated with sea level rise. Because salmon are a very important part of the Skagit's economy, a reduction in the salmon population would result in a relatively large impact to the local economy.
- Because current resource management strategies may not be adequate to meet the challenges caused by climate change as illustrated in flood control management, new strategies may be needed to adapt to future changes in climate. For example, increasing flood storage is proposed by Skagit County as one of the flood damage reduction strategies. Because changes in flood control operations will have an impact of other system objectives such as power generation, fish flow augmentation and recreation, more

detailed flood regulation studies are needed to explore the feasible dam operations under climate change to meet flood control requirement as well as other objectives.

URL 1:
http://www.skagitriverhistory.com/Skagit%20County%20Docs/SC%20FCZD/FCZD%20Planning%20Memo.pdf
URL 2:
http://www.skagitriverhistory.com/Skagit%20County%20Docs/Flood%20Control%20Storage.pdf
URL 3: http://skagit.wsu.edu/agriculture/index.htm
URL 4: http://www.skagit.org/edasc-skagit-county-agricultural-links.php
URL 5:
http://www.goskagit.com/home/article/climate_change_could_have_dramatic_impact_on_local_agricultural_scene/
URL 6:
http://www.co.snohomish.wa.us/documents/Departments/Public_Works/SurfaceWaterManagement/Flooding/floodissues0910.pdf
URL 7:
http://www.skagitcounty.net/Common/Asp/Default.asp?d=Flood&c=General&p=hazard.htm
URL 8:
http://www.skagitriverhistory.com/PDFs/2010-01-10%20Skagit%20CFHMP%20Chapter%206%20-%20LJK%20Draft.pdf
URL 9:
http://www.skagitcounty.net/Common/Asp/Default.asp?d=Flood&c=General&p=100yrflood.htm
URL 10: http://www.skagitriverhistory.com/Photo_Gallery.htm
URL 11: http://getdowntoearth.blogspot.com/2006_11_01_archive.html
URL 12: http://www.flickr.com/photos/wsdot/3192128998/

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