

Table of Contents

| | |
|--|----|
| 1. Skagit Basin Overview | 1 |
| 1.1 Overview of the Skagit River Basin | 1 |
| 1.2 Geology and Land Cover | 2 |
| 1.2.1 Geology | 2 |
| 1.2.2 Land Cover | 4 |
| 1.3 Human Settlement of the Skagit Basin | 6 |
| 1.3.1 Drainage Infrastructure | 7 |
| 1.3.2 Dams | 9 |
| 1.3.3 Highways | 10 |
| 1.4 Ecological Change | 10 |
| 1.5 Population Growth and Future Projections | 13 |
| 1.6 Summary and Conclusions | 14 |
| 1.7 References | 16 |
| 2. Climate Variability | 21 |
| 2.1 Overview of Historical Variations in Pacific Northwest Climate | 21 |
| 2.2 Global Climate Patterns Affecting Pacific Northwest Climate | 24 |
| 2.2.1 The El Niño-Southern Oscillation | 24 |
| 2.2.2 The Pacific Decadal Oscillation (PDO) | 26 |
| 2.3 Impacts of ENSO and the PDO on Pacific Northwest Climate and Hydrology | 27 |
| 2.3.1 PNW Temperature and Precipitation | 28 |
| 2.3.2 Effects of the PDO and ENSO on PNW Hydrology | 29 |
| 2.4 ENSO and PDO Impacts on the Skagit River Basin's Climate and Hydrology | 33 |
| 2.4.1 Skagit Basin Temperature and Precipitation | 33 |

| | |
|--|----|
| 2.4.2 Skagit Basin Snowpack | 34 |
| 2.4.3 Skagit Basin Streamflow | 35 |
| 2.4.4 Skagit Basin Flood Risk..... | 40 |
| 2.4.5 Skagit Basin Water Temperature | 41 |
| 2.4.6 Heating and Cooling Energy Demand | 42 |
| 2.5 Summary and Conclusions | 43 |
| 2.6 References..... | 45 |
| 3. Climate Change Scenarios..... | 50 |
| 3.1 Global Climate Models..... | 51 |
| 3.2 Dynamical Downscaling Using Regional Scale Climate Models (RCMs) | 54 |
| 3.3 Statistical Downscaling Approaches | 55 |
| 3.3.1 Delta Method..... | 55 |
| 3.3.2 Transient Bias Corrected and Statistical Downscaling (BCSD) Method..... | 56 |
| 3.3.3 Hybrid Delta Downscaling Method | 57 |
| 3.4 Climate Change Impacts on Meteorological Conditions and Sea Level Rise | 57 |
| 3.4.1 Changes in Temperature..... | 57 |
| 3.4.2 Changes in Precipitation..... | 60 |
| 3.4.3 Changes in Sea Level | 63 |
| 3.5 Summary and Conclusions | 67 |
| 3.6 References..... | 70 |
| 4. Glaciers..... | 74 |
| 4.1 Background..... | 74 |
| 4.2 Global glacier changes..... | 76 |
| 4.3 Glacial changes in the Skagit Basin and North Cascades..... | 80 |

| | | |
|-------|---|-----|
| 4.3.1 | Glaciers monitored by NCGCP | 82 |
| 4.3.2 | Glaciers monitored by the National Park Service | 84 |
| 4.4 | Summary and Conclusions | 90 |
| 4.5 | Reference | 92 |
| 5. | Hydrology | 97 |
| 5.1 | Background | 98 |
| 5.2 | Hydrologic Impacts over the Pacific Northwest | 100 |
| 5.2.1 | Implications of changes in April 1 snow water equivalent | 100 |
| 5.2.2 | Implications of changes in seasonal streamflow timing | 102 |
| 5.3 | Hydrologic impacts in the Skagit River basin | 105 |
| 5.3.2 | Changes in mean monthly streamflow | 110 |
| 5.3.3 | Changes in Hydrologic Extremes | 112 |
| 5.4 | Groundwater | 117 |
| 5.5 | Drainage and Potential Conversion to Marsh in Low-Lying Areas | 118 |
| 5.6 | Summary and Conclusions | 118 |
| 5.7 | References | 120 |
| 6. | Geomorphology | 124 |
| 6.1 | Background | 125 |
| 6.2 | Morphology of the Skagit River Delta | 125 |
| 6.3 | Sediment Supply and Transport in the Skagit River | 128 |
| 6.4 | Effects of Climate Change on Sedimentation | 129 |
| 6.5 | Potential Climate Change Impacts on Delta Morphology | 132 |
| 6.6 | Summary and Conclusions | 138 |
| 6.7 | Reference | 140 |

| | |
|---|-----|
| 7. Ecosystems | 144 |
| 7.1 Terrestrial Ecosystem | 144 |
| 7.1.1 Forest Ecosystems | 144 |
| 7.1.2 Wildlife..... | 145 |
| 7.2 Aquatic Ecosystems | 148 |
| 7.3 Tidal Marsh Habitat | 156 |
| 7.4 Estuary and Puget Sound | 158 |
| 7.5 Summary and Conclusions | 159 |
| 7.6 Reference | 161 |
| 8. Human Systems | 166 |
| 8.1 Water Management..... | 167 |
| 8.1.1 Hydropower Resources | 167 |
| 8.1.2 Flood Control | 169 |
| 8.1.3 Stormwater Management | 174 |
| 8.1.4 Recreation..... | 175 |
| 8.2 Agriculture | 176 |
| 8.3 Flood Plain Development and Infrastructure..... | 178 |
| 8.4 Roads and Bridges | 181 |
| 8.5 Economics..... | 183 |
| 8.6 Summary and Conclusions | 185 |
| 8.7 References..... | 189 |

Table of Figures

| | |
|--|----|
| 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). | 2 |
| Figure 1.2 Land cover of Skagit County. | 5 |
| Figure 1.3 Major land use zones based on Skagit County designations. “IF-Nr1” is Industrial Forest, and “SF-Nr1” is Secondary Forest, “RR” is Rural Reserve, “RR-Nr1” is Rural Resource and “Ag-Nr1” is Agriculture. | 5 |
| 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). | 8 |
| Figure 1.5 Changes to the estuarine habitat zones within the Skagit delta (Source: Beamer et al., 2005a). | 11 |
| Figure 1.6 Historical and current vegetated tidal wetlands in the Skagit Estuary, Washington (Source: Dean et al., 2000)..... | 12 |
| Figure 1.7 Floodplain areas for the non-tidal delta portion of the Skagit River. The map shows changes to floodplain and mainstream habitats (Skagit River System Cooperative and Washington Department of Fish and Wildlife, 2005). | 12 |
| 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)..... | 22 |
| Figure 2.2 A temporally smoothed 20 th 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). | 23 |
| 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)..... | 26 |

| | |
|---|----|
| 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)..... | 27 |
| 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)..... | 29 |
| 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)..... | 30 |
| 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). | 31 |
| 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)..... | 32 |
| 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. | 34 |
| 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). | 35 |
| 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). | 37 |

| | |
|---|----|
| 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). | 38 |
| 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). | 39 |
| Figure 2.14 Observed instantaneous peak flow in the unregulated Sauk River near Sauk from 1928-2009 (Source: USGS). | 40 |
| 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). | 41 |
| Figure 3.1 Summary of the 20 th and 21 st 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). | 58 |
| Figure 3.2 Summaries of the 20 th and 21 st century monthly mean temperatures (in °F) for A1B (left) and B1 (right) scenarios for the Skagit River near 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). | 59 |
| Figure 3.3 Summary of 20 th and 21 st century annual precipitation simulations from 20 GCMs | 60 |
| 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 10 th and 90th percentiles (whiskers), 25 th and 75th percentiles (box ends), and median (solid middle bar) for each season and scenario (Source: Mote and Salathé, 2010). | 61 |
| Figure 3.5 Summaries of 20 th and 21 st century monthly mean precipitations (in inches) for A1B (left) and B1 (right) scenarios for the Skagit River near 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). | 62 |
| Figure 3.6 Regional sea-level trends from satellite altimetry from 1993 to 2009 (Source: Nicholles et al., 2010)..... | 63 |
| Figure 3.7 Global mean sea level evolution over the 20 th and 21 st 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 21 st 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). | 65 |
| 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). | 77 |
| 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). | 78 |
| 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). | 79 |
| 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). | 79 |
| Figure 4.5 Location map of North Cascade glaciers (Source: Pelto, 2006) | 81 |
| Figure 4.6 Locations of monitored glaciers and major hydrologic crests in the North Cascades National Park Complex (Source: Riedel et. al., 2008) | 81 |
| 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). | 82 |
| Figure 4.8 a) Milk Lake glacier in 1988 and b) Milk Lake in 2009 (Source: URL 1). | 83 |

| | |
|--|-----|
| 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). | 84 |
| 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). | 85 |
| 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). | 86 |
| Figure 4.12 View to the west of Silver Glacier in 1958 (left, by Post) and 2006 (right, by Scurlock) (Source: URL 2). | 87 |
| 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). | 88 |
| Figure 4.14 Average summer balance (ablation) from 1993 to 2009 (Source: URL 2). | 88 |
| Figure 4.15 Glacier area changes in Thunder Creek watershed (left) and in the Klawatti glaciers since the Little Ice Age (Source: URL 2) | 89 |
| 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). | 99 |
| 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 20 th Century baseline shown in panel a). (Source: Elsner et al., 2010). | 101 |
| 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). | 103 |
| 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). | 104 |

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. 105

Figure 5.6 Changes in unbiasedcorrected (“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..... 107

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..... 108

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). 109

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). 111

Figure 5.10 Schematic of impacts on snowpack and runoff production due to rising freezing levels associated with regional warming (Source: Hamlet, 2010). 112

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). 115

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). 116

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). 127

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 panel), gray outline indicates 1956 tidal marsh (left panel), white areas are channels and bay. T₀ is the river terminus and T₁–T₄ are the termini for distributaries of the North Fork of the Skagit River. C₁–C₆ are the distributary channel bifurcation points (Source: Hood, 2010a). 127

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). 131

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). 133

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). 135

Figure 7.1 Map of the Skagit Wildlife Area (Source: Garrett, 2005). 146

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). 150

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. 151

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). 152

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). 153

| | |
|--|-----|
| 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)..... | 154 |
| 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)..... | 155 |
| 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)..... | 157 |
| 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). | 158 |
| 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 B1 scenario (Source: Hamlet et al., 2010). | 167 |
| 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). | 169 |
| 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. | 171 |
| 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..... | 172 |
| 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..... | 173 |
| Figure 8.6 Number of optimal rafting days with streamflow above 3500 cfs per month for the Sauk River (Source: Mickelson, 2009)..... | 176 |
| Figure 8.7 Proposed flood hazard management plan (Source: Skagit County, 2008)..... | 180 |
| Figure 8.8 Photo of town of Hamilton during October 2003 flood (Source: URL 10). | 180 |

| | |
|--|-----|
| Figure 8.9 Inundation of roads near La Conner due to storm/tidal surge of February 2006 (Source: Donatuto, 2010). | 181 |
| Figure 8.10 I-5 Flooding in Samish River north of Burlington during the flood of Jan 2009 (Source: URL 12). | 182 |
| 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). | 183 |

Table of Tables

| | |
|---|-----|
| Table 2.1 Retrospective Definitions of Warm, Neutral, and Cool ENSO and PDO Years (Source: Hamlet and Lettenmaier, 2007). | 28 |
| Table 3.1 A brief summary of the main features of selected IPCC emissions scenarios (Source: NHC, 2008)..... | 52 |
| Table 3.2 Summary of ten global climate models selected for Columbia Basin Climate Change Scenarios Project (Source: Randall et al., 2007)..... | 53 |
| Table 3.3 Summaries of the 20 th and 21 st century annual and seasonal mean temperatures (in °F) for the A1B and B1 scenarios for the Skagit River near Mount Vernon. (DJF=winter, MAM=spring, JJA=summer, and SON=fall)..... | 59 |
| Table 3.4 Summaries of 20 th and 21 st century annual and seasonal mean precipitation (in inches) for A1B and B1 scenarios for the Skagit River near Mount Vernon. (DJF=winter, MAM=spring, JJA=summer, and SON=fall)..... | 62 |
| 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).. | 66 |
| 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)..... | 83 |
| 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)..... | 136 |
| 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) | 137 |
| Table 8.1 Storage characteristics of major reservoirs in the Skagit River basin (Source: FEMA, 2009)..... | 169 |