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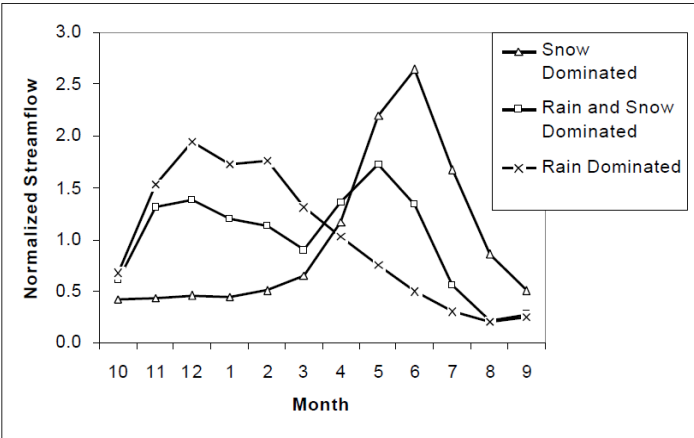
Figure 5.1 Seasonal distribution of streamflow for snowmelt-dominant, transient snow, and rain-dominant watersheds in the PNW expressed as the fraction of the monthly mean streamflow that occurs in each month (Source: Hamlet et al., 2001).

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.
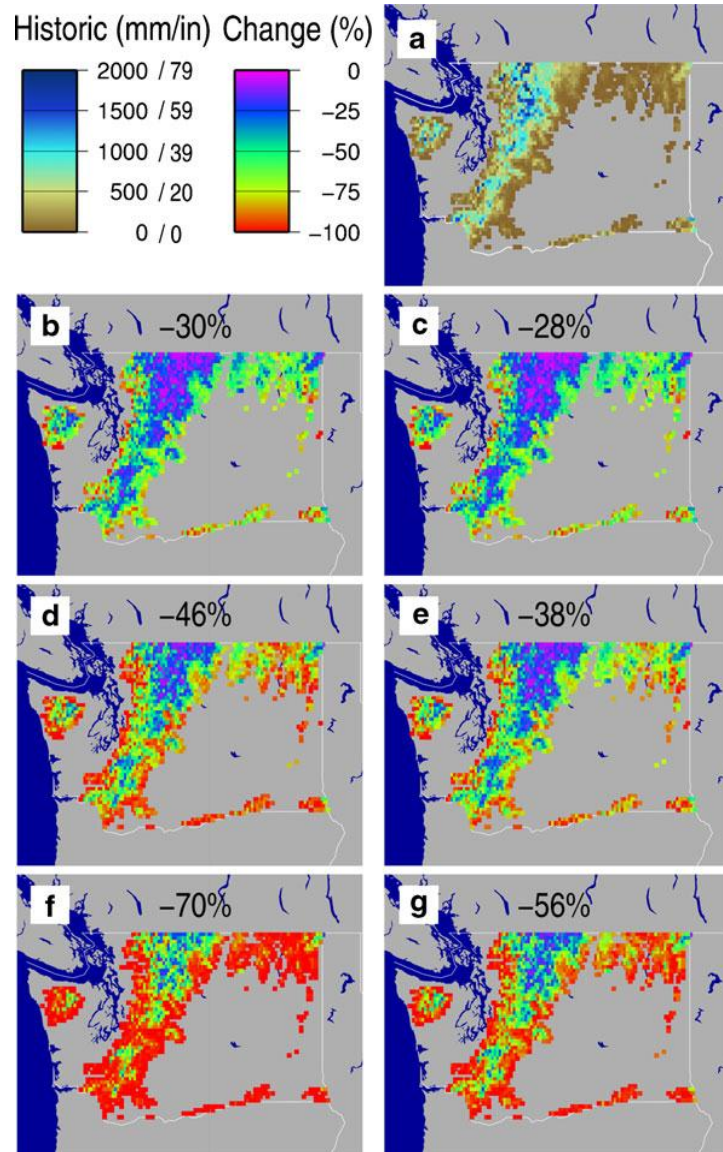
Figure 5.2 Summary of projected percent change in April 1 SWE in WA as simulated by the Variable Infiltration Capacity (VIC) hydrologic model. **a** Historical April 1 SWE (mean for water years (Oct-Sept) 1917–2006). **b**, **d**, **f** Projected change in April 1 SWE for A1B scenarios for the 2020s, 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).
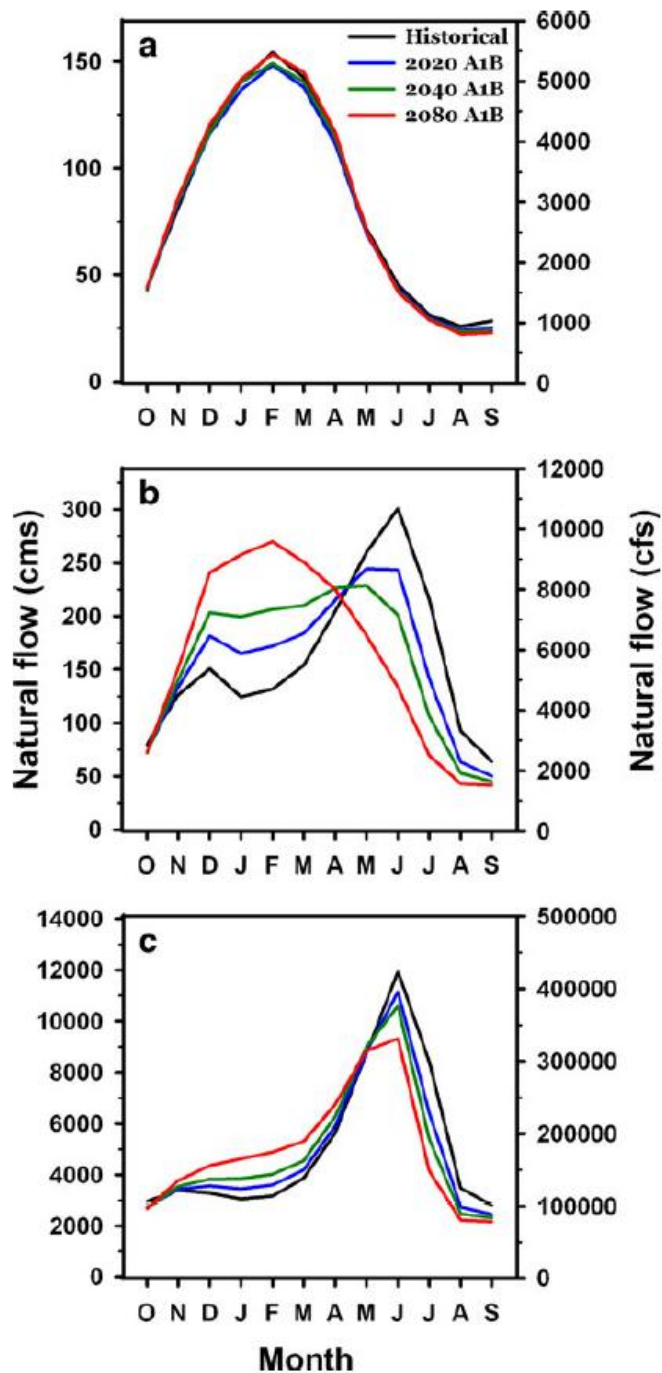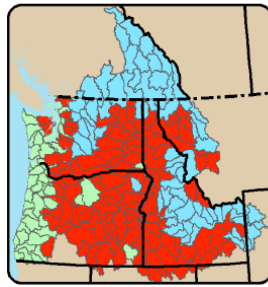
Figure 5.3 Projected average monthly streamflows for rivers draining three representative watershed types in WA: a) rain dominant (the Chehalis River at Porter), b) transient rain-snow (the Yakima River at Parker), and c) snowmelt dominant (the Columbia River at The Dalles) (Source: Elsner et al., 2010).
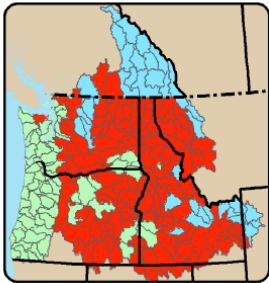
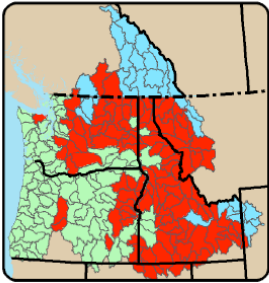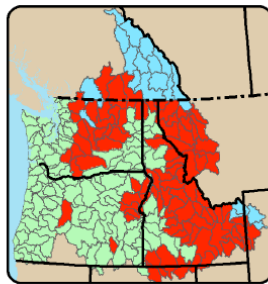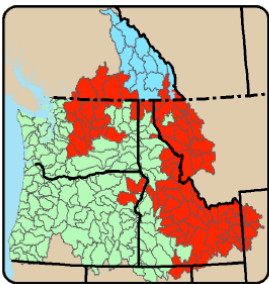Figure 5.4 Ratio of April 1 SWE to total cool-season (October-March) precipitation for the historical period (water years 1916 to 2006), for the A1B scenario (left panels) and for the B1 scenario (right panels) for three future time periods (the 2020s, the 2040s, the 2080s) (Source: Tohver and Hamlet, 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.
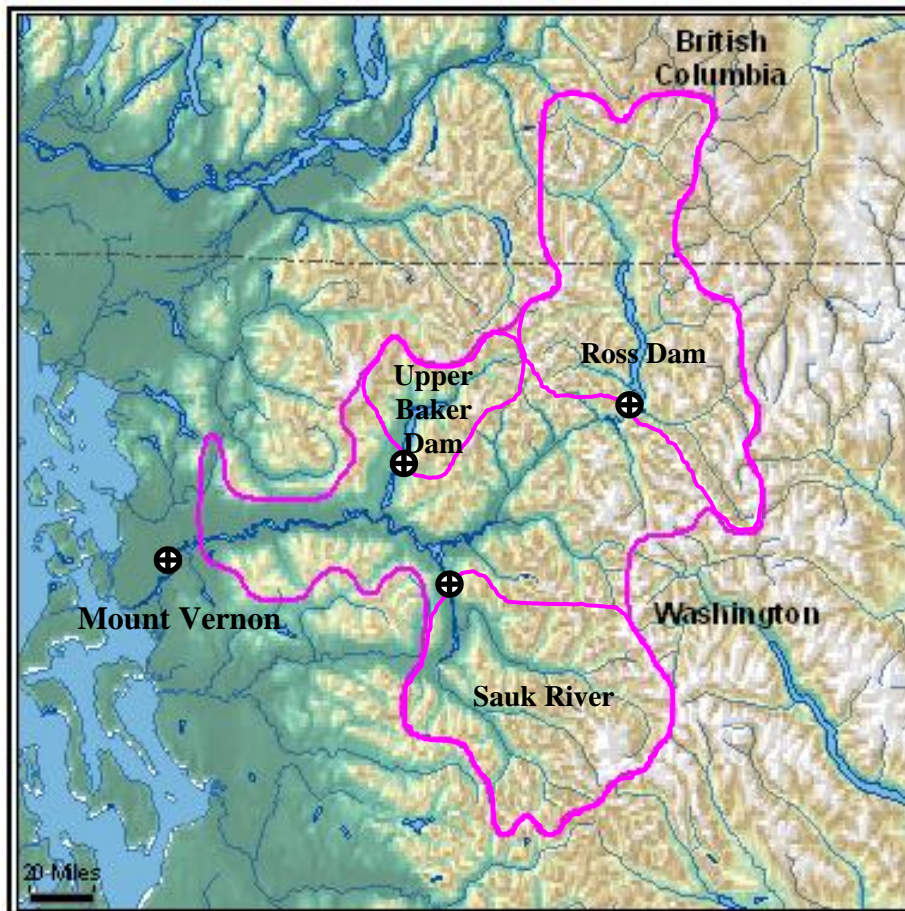
Figure 5.5 A map showing drainage area of the upper Skagit River at Ross Dam near Newhalem, the Sauk River near Sauk, the Baker River at the Upper Baker Dam near Concrete and the lower Skagit River near Mount Vernon. A black circle with cross shows the location of each river location and the pink line 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.
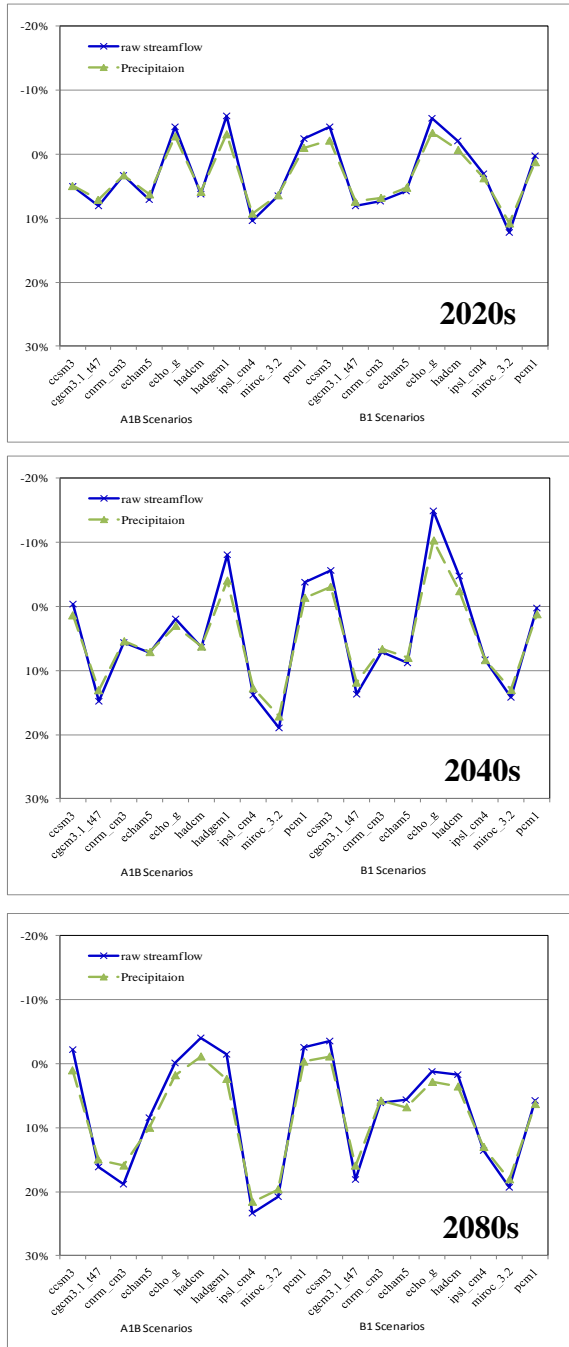
Figure 5.6 Changes in unbiascorrected ("raw") annual streamflow and basin-average cool-season precipitation relative to historical baseline (water years 1916 to 2006) for the Skagit River near Mount Vernon for the 2020s, 2040s, and 2080s. Climate change scenarios are identified on the X axis.

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

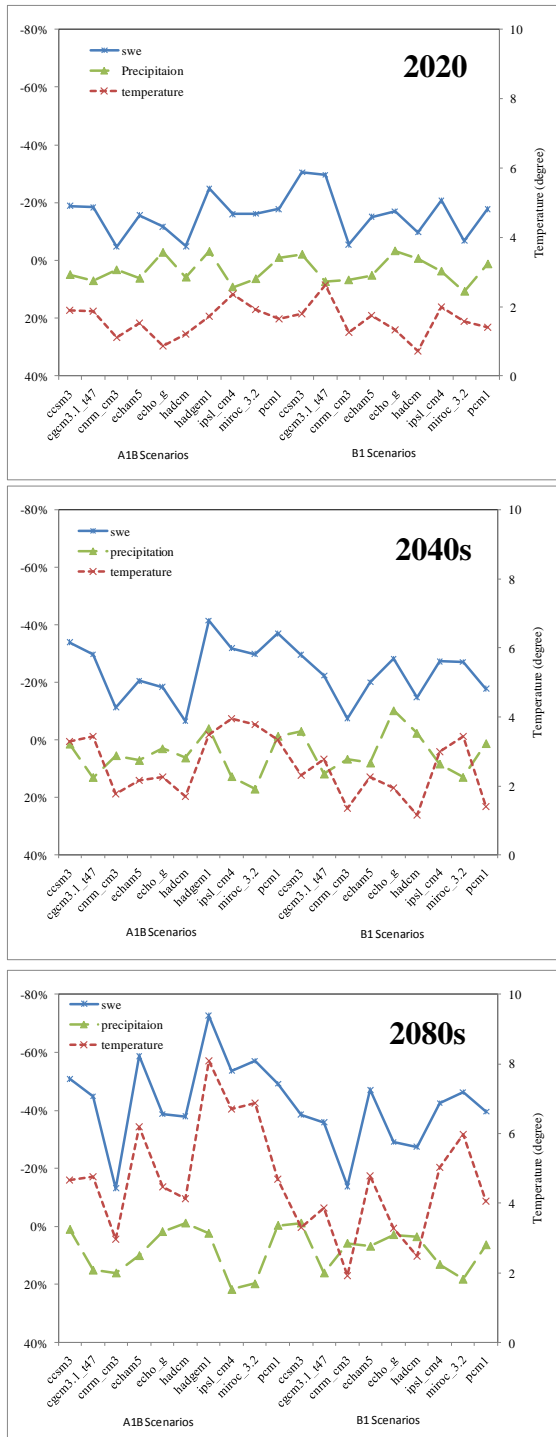Consistent with SWE projections over the PNW and WA as a whole, basin average SWE for the upstream areas associated with the Skagit River at Ross Dam and Skagit River at Mount Vernon are projected to decline (Figure 5.8). Reduction of SWE is more pronounced for the A1B than B1 emissions scenario, due 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.
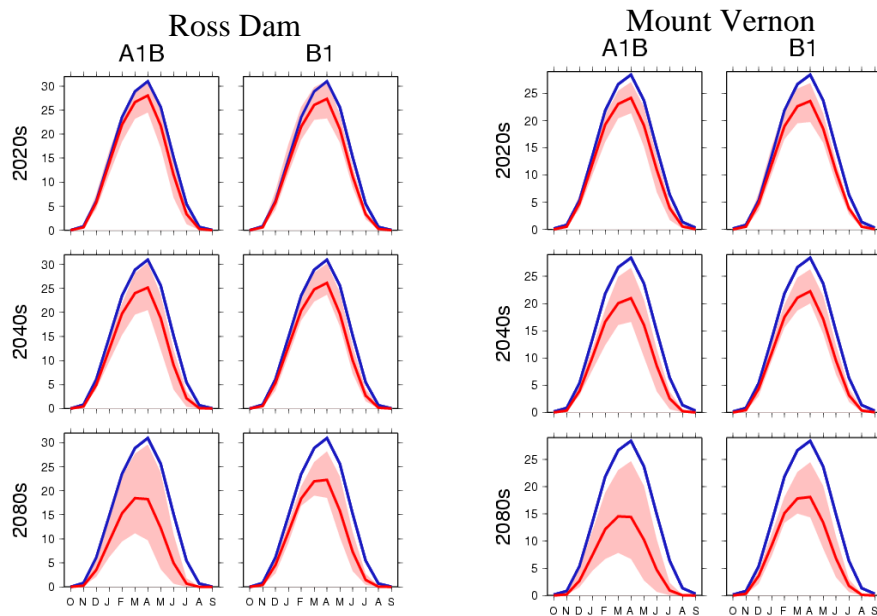
Figure 5.8 Seasonal cycle of basin-average SWE (in inches) for the basin area upstream of the Skagit River at Ross Dam near Newhalem (left) and the Skagit River near Mount Vernon (right) for three future time periods (rows) and two emissions scenarios (columns). The blue line represents the historical 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.
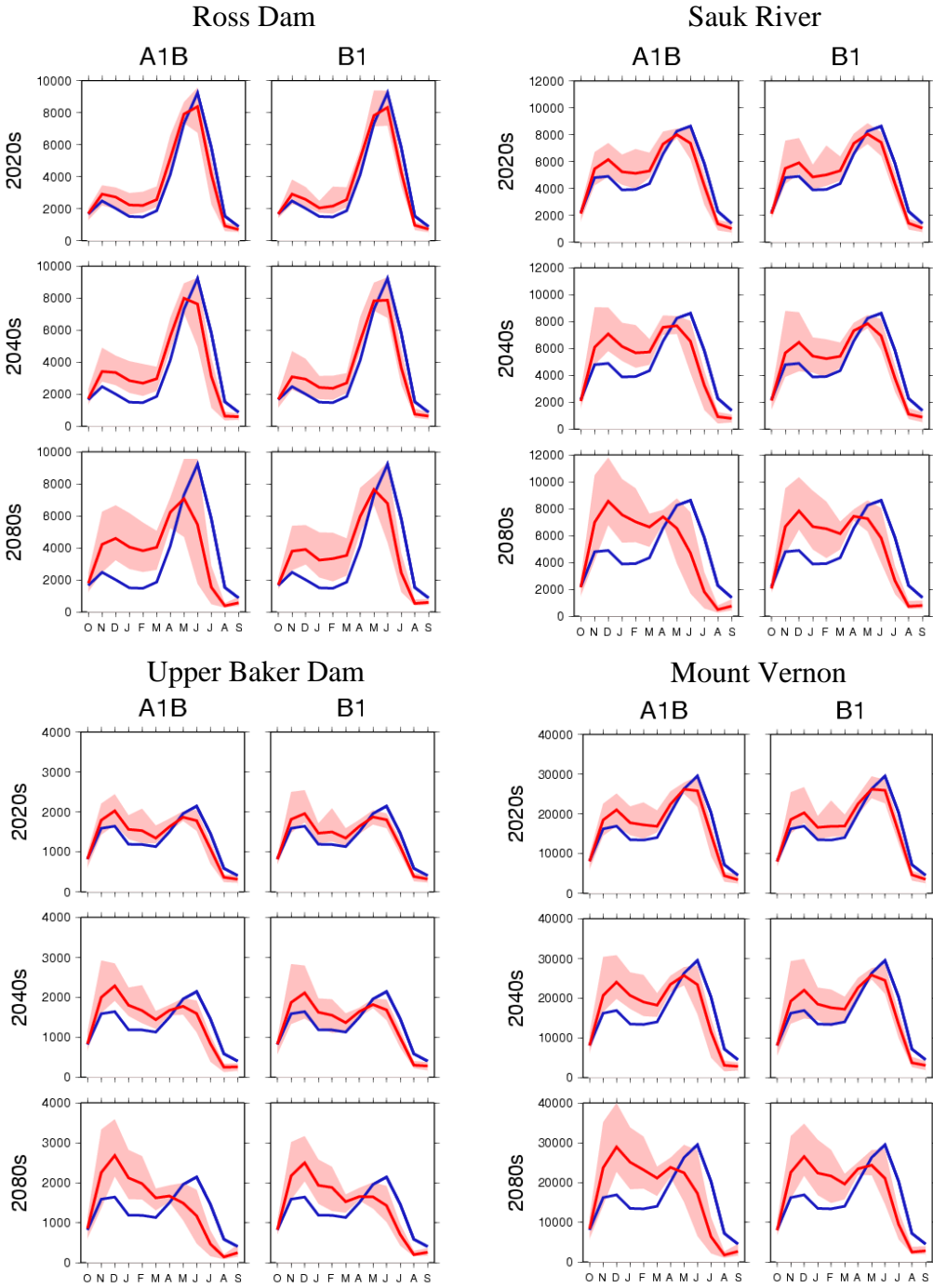
Figure 5.9 Simulated monthly average streamflow (in cfs) for the Skagit River at Ross Dam near Newhalem (upper left panel), for the Sauk River near Sauk (upper right panel), for the Baker River at Upper Baker Dam near Concrete (bottom left panel) and for the Skagit River near Mount Vernon (bottom right 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).

111

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.
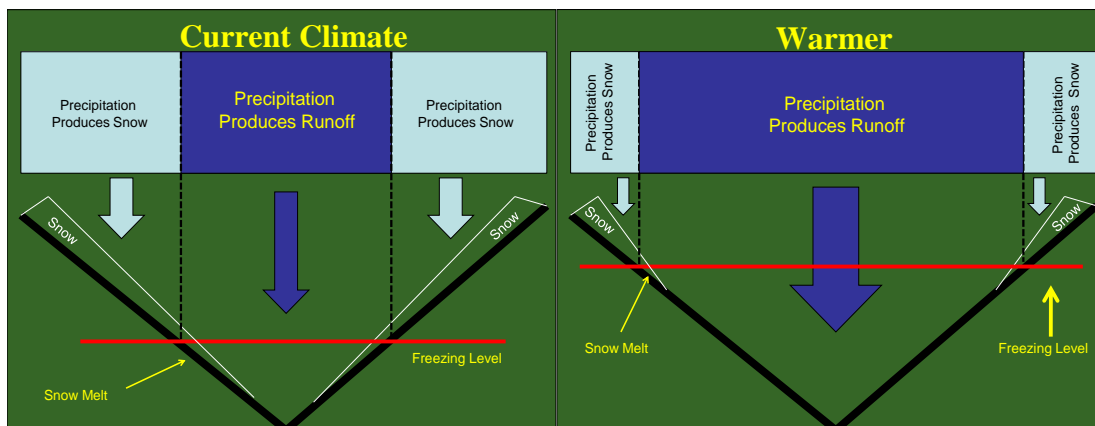

Figure 5.10 Schematic of impacts on snowpack and runoff production due to rising freezing levels associated with regional warming (Source: Hamlet, 2010).

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.

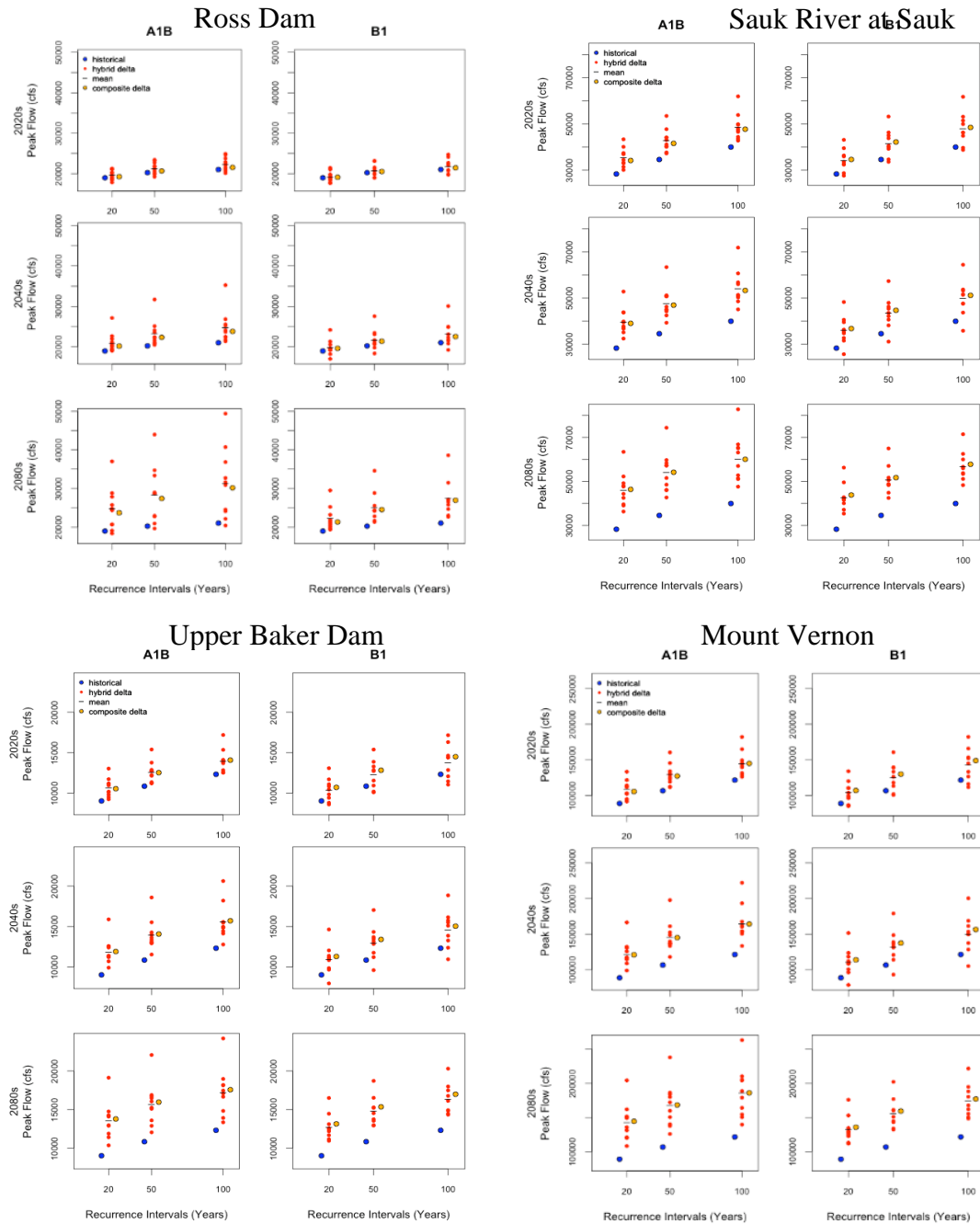Figure 5.11 The 20-, 50-, and 100-year flood statistics for the Skagit River at Ross Dam near Newhalem (upper left panels), the Sauk River near Sauk (upper right panels), the Baker River at Upper Baker Dam near Concrete (bottom left panels) and the Skagit River near Mount Vernon (bottom right panels) 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).
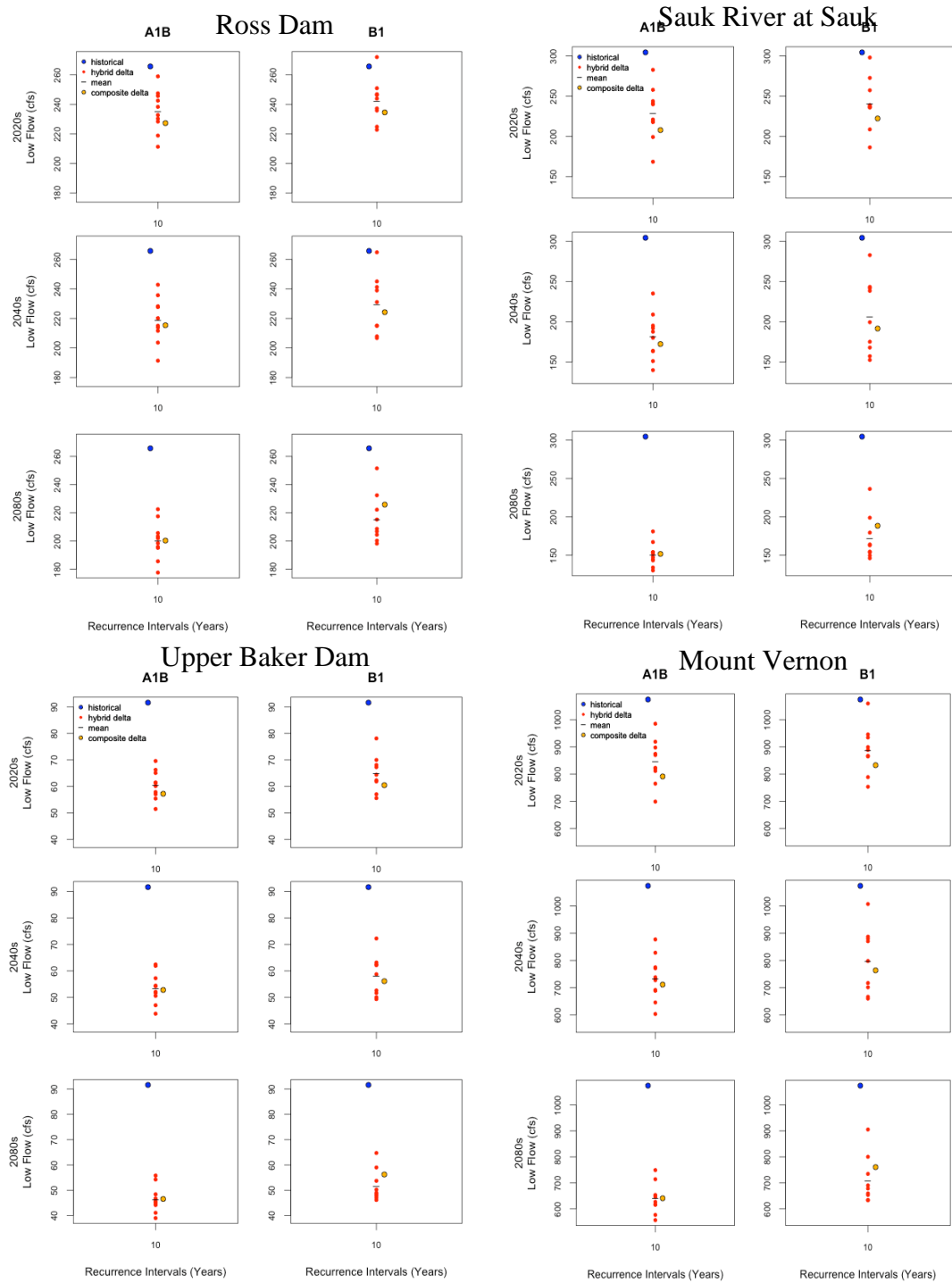
116

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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