Climate Change Impacts on River Flooding: State-of-the-Science and Evidence of Local Impacts

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ABSTRACT

This study looks into rainfall and river flow data throughout King County to determine whether large storm events and large flooding events are happening more often than they used to. This study also looks into results of computer modeling efforts at the University of Washington to understand whether such changes might happen in the future. This study was done to support planning efforts by King County's Rivers and Floodplain Management Section, to help ensure that flood protection efforts consider an appropriate range of flow levels based on best available information.

Overall, there is some evidence that large storms and large floods in King County are occurring more frequently than they did in the 1960s. This evidence, while still preliminary, is in line with the computer model results from the University of Washington looking at how climate change might affect Pacific Northwest rivers. Rising air temperatures and changing storm patterns are likely to lead to more rain in November than used to occur, and also a shift over time from snow to rain in the mountains in the winter. Both of these changes would result in bigger and more frequent floods, although it is unknown how many years before these changes become significant and how large these changes may be. In general, given the preliminary evidence of changes to date, and the anticipated future changes based on computer modeling, it seems reasonable to pursue management strategies that facilitate adaptation to potential future increases in the frequency and magnitude of large floods.

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EXECUTIVE SUMMARY

This report summarizes the current scientific evidence for climate change related trends in King County river flooding and implications for local flood management. Trend analyses were also conducted on representative long-term daily King County precipitation and river discharge data sets to identify evidence of trends in extreme hydrologic events. Predictions of river discharge at the same long-term river gauging locations based on two downscaled climate model simulations provided by the University of Washington for current (centered on 2000), and future (centered on 2025, 2050, and 2075) conditions were also evaluated for indications of the types of changes in the frequency and magnitude of high flows that might be expected in the future (next 25 to 75 years).

River discharge stations for trend analysis were selected based on length of continuous daily records (at least 44 years continuous through 2008) and minimal upstream flood control or water diversions during the period of record selected for analysis. Ten stations were selected: (1) Skykomish River near Gold Bar; (2) Tolt River near Carnation; (3) North Fork Snoqualmie River near Snoqualmie Falls, (4) Middle Fork Snoqualmie River near Tanner; (5) South Fork Snoqualmie River above Alice Creek; (6) Raging River near Fall City; (7) Snoqualmie River near Snoqualmie; (8) Snoqualmie River near Carnation; (9) Cedar River near Cedar Falls; and (10) naturalized Green River flow at Howard Hanson Dam. The selected river gauges represent relatively unregulated drainage areas (from a flood control viewpoint) between 83 and 1,530 km^2 and mean elevations ranging between 710 and 1,050 meters. With the exception of the Raging River near Fall City, these gauges represent runoff from so-called transient basins that have high flow in winter as a result of heavier winter rainfall and another peak in flow in spring in response to snow melt runoff from the snow pack at higher elevation.

Although of sufficient record length, flow data for the White River gauging station below the outlet of Mud Mountain Lake were not included because Mud Mountain Lake is operated as a flood control facility, thereby potentially confounding any trends induced by climate change. Unfortunately, the gauging station above Mud Mountain Lake did not begin recording discharge until the mid-1970s and has not been operating continuously since then – a gap of over 10 years occurred between early 1996 and late 2008.

Long-term daily precipitation records (up to 89 years through 2008) from 8 locations were also analyzed for trends to evaluate whether any suggested trends in river flooding were due to changes in the magnitude, frequency, duration, or timing of heavy precipitation events. These data sets were selected based on the length and completeness of daily records. The eight stations selected were: (1) Everett; (2) Monroe; (3) Startup; (4) Sea-Tac; (5) Snoqualmie Falls; (6) Buckley; (7) Cedar Lake; and (8) South Fork Tolt. These stations range in elevation from 18 to 609 m and represent a continuum from low elevation stations of the Puget Lowland to stations situated on the western flanks of the Cascade Mountains.

With the exception of downward trends in summer flow magnitude, mostly weak statistical evidence of increasing magnitude, frequency, and duration of high flows and precipitation were found. Relatively weak evidence for changes in the seasonal distribution of flow and precipitation were also found. The general trend was toward higher discharge and precipitation in November and lower discharge and precipitation during summer.

Evaluation of potential future changes in river flow was conducted using hydrologic model output provided by the University of Washington based on two global climate models (ECHAM3 and IPSL CM4) forced by the A2 Scenario, which simulates a relatively pessimistic future with respect to reductions in greenhouse gas emissions. The two model scenarios predicted future conditions that were relatively consistent with the trends observed in the historical record (i.e., increases in the magnitude and frequency of high flows, earlier timing of peak runoff, and lower summer flows).

These results are consistent with the general predictions of these two global climate models regionally – the IPSL CM4 A2 climate model scenario predicted a relatively large increase in annual mean temperature and total precipitation and the ECHAM5 A2 climate model scenario predicted a more moderate increase in temperature and precipitation. More recent climate model studies using ensemble approaches (i.e., combined results from several downscaled global climate models) are suggesting that much warmer and slightly wetter future is more likely than warming with no increase (or decrease) in precipitation.

The results of the analyses presented in this report suggest increases in the magnitude, duration, frequency, and earlier timing of extreme precipitation and river flow that is the result of some combination of decadal variation in precipitation and climate change-related shifts in precipitation (seasonal shifts and increase in extreme magnitudes), temperature (upward) and snow accumulation and melt (less snow and earlier melting).

The detection of these trends is difficult not only because of the relatively infrequent nature of extreme events and the limited record lengths evaluated, but difficult also because of changes in land cover (primarily forest harvest and regrowth) that have occurred over the period of analysis. Nonetheless, it seems probable that the evidence for trends in extreme flows will become stronger if the potential climate impacts on river flows in King County described in this report are any indication of future river flow conditions.

Traditionally, flood management has been based on the use of historical data to estimate flood magnitudes with specific return probabilities. However, trends in observed data and modeling of potential future conditions suggest that this approach (based on the assumption of stationarity) is no longer valid. Unfortunately, there is no other approach currently recognized by the Federal Emergency Management Agency (FEMA) for flood risk management. The issue of stationarity and the potential of a future hydrologic regime with ever greater frequency and magnitude of high flows also suggest the need for more integrated water management approaches.

In general, given the preliminary evidence of changes to date, and the anticipated future changes based on computer modeling, it seems reasonable to pursue management strategies that facilitate adaptation to potential future increases in the frequency and magnitude of large floods.

1.0. INTRODUCTION

Traditionally, water management infrastructure has been designed and operated under the assumption that historical observations of water system behavior are a reasonable basis for approximation of future variability – the so-called "assumption of stationarity." As historical records have grown longer, proxies have been developed to extend records even further back in time, and evidence for human-caused shifts in global climate has mounted; the assumption of stationarity and its usefulness to water resource management has been questioned (Milly et al., 2008). However, many practitioners (technical engineers and water resource managers) remain skeptical. Regardless, the design tools and regulatory management structure have not adapted to the notion that "The future ain't what it used to be."

In addition to natural and human-induced climate driven trends, there are also other more accepted human disturbances that affect the stationarity assumption – development of water management infrastructure (water supply, irrigation, flood control, drainage management), hydraulic channel modifications, and land cover/land use changes (particularly forest loss and creation of impervious cover). These disturbances are often recognized and incorporated into the design and management process, but not always. For example, Federal Emergency Management Agency (FEMA) flood risk maps only implicitly incorporate the effects of changes in land cover/land use and other channel and water management infrastructure through irregular flood mapping updates. Furthermore, flood risk management, at least in the U.S., has been primarily reactive rather than proactive – for example no limits are directly imposed on forest removal or urbanization to minimize flood risk in large rivers.

1.1 Report Background

Flooding is arguably the most costly natural hazard in King County. Since 1978, King County has had the most flood insurance claims and the greatest number of repetitive flood loss properties of any county in the state (Washington State Hazard Mitigation Plan, November 2007). Nationally, the annual cost of flood damage continues to rise (Pielke and Downton, 2000). Growing flood damage costs are primarily due to the intersection of naturally powerful and dynamic river floodplain interactions and the concentration and continuing encroachment of people and their infrastructure in floodplains. However, there is also mounting evidence that streamflow has generally been increasing in the United States since the 1940s, although the Pacific Northwest was noted as having a number of streamflow decreases, particularly in the lowest flow percentiles (Lins, 2005). There also appears to be some seasonality to these trends, with the increases detected most between September and December, which is consistent with observed seasonality in increases in precipitation in the U.S. (Lins, 2005).

Because King County is in the path of moist air flow coming from the Pacific Ocean and includes mountainous topography on the windward side of the Cascade Mountains, along with many other areas along the Pacific Coast, this area experiences some of the highest relative flow magnitudes in the conterminous United States and Alaska (O'Connor and Costa, 2003). Generally, the magnitude of floods in King County depends on a number of factors including: intensity and duration of rainfall, antecedent soil moisture conditions, basin area and elevations, and presence, location, and size of snowpack (Kresch and Dinicola, undated). Some of the largest recorded floods in the Pacific Northwest (e.g., floods of 1964 and 1996) were caused by substantial rain-on-snow events, which most significantly affect larger drainage basins on the order of 100 to 100,000 mi^2 (O'Connor and Costa, 2003).

Attempts to detect trends in global flood frequency have been equivocal (Milly et al., 2002; Kundzewicz et al., 2005). Kundzewicz et al. (2005) evaluated 195 long-term records from a global dataset for trends in annual maximum discharge and found 27 records with strong, statistically significant increases, but also 31 cases in which annual maximum discharge was decreasing. Milly et al. (2002) focused on evaluating trends in the frequency of extreme flows (100-yr flood) using data and coupled ocean-atmosphere-land model output for 29 large river basins (>200,000 km^2) throughout the world. They detected a significant increase in the risk of extreme flows and forecasted further increases – the historical 100-year flood was predicted to have a return frequency between 12.5 and 50 years by about 2025. Both of these studies noted the large interannual variability in maximum discharge.

Evidence of effects of climate change and interdecadal variability on flood risks in the western United States was reported by Hamlet and Lettenmaier (2007). They concluded that late 20th century warming and precipitation variability has increased flood risks in rain-dominant basins, strongly increased risks in coastal areas with transient snow, and left risks unchanged in snowmelt-dominant basins and cooler interior basins. Hamlet and Lettenmaier (2007) also emphasized the strong effect of the Pacific Decadal Oscillation (PDO) and El Niño Southern Oscillation (ENSO) on interannual variation in flood risks.

Recently, a number of studies have been conducted to assess the potential effect of future climate change on the hydrology of the Pacific Northwest (Mote et al., 1999; Elsner et al., 2009; Hamlet et al., 2010). All of these studies have concluded that the region will become warmer and wetter in response to changes in global climate, with most of the precipitation increase occurring in winter. In transient rain-snow dominated basins, more winter precipitation is expected in the form of rain, along with a decline in total snow pack and earlier timing of spring runoff. Higher flows are expected during winter and lower flows are expected in spring and summer. Hamlet et al. (2010) included an analysis of the effects of climate change on flood risk in the Columbia River, Puget Sound and coastal basins and concluded that warming and precipitation changes will likely increase flood risks in transient snow-rain dominant basins as more precipitation in these basins falls as rain rather than snow in winter. In snow dominant basins, flood risk may even decline as the amount of winter snowpack declines and in rain dominant basins flood risk may rise only slightly due to increased winter precipitation. However, in any particular basin where snow plays some part in controlling river flow, flood risk will depend on tradeoffs between the timing and form of winter precipitation (rain or snow) and changes in snow pack cover, with warmer basins having a higher future flood risk as snow is replaced by runoff contributing areas (Hamlet and Lettenmaier, 2007).

1.2 Goals and Objectives

The overall goal of this study is to contribute to a better understanding of the magnitude and likelihood of large flood flows in King County in the future that can be applied to local flood hazard reduction efforts. The specific objectives of this study are to evaluate:

- historical King County flow data provided by USGS for trends in magnitude, frequency, duration, and timing of high flows

- future climate-impacted hydrologic model output provided by the University of Washington for trends in high flows
- precipitation data related to high flows to identify potential causes of any identified trends in high flows

2.0. BACKGROUND

Polebitski and Palmer (2006) evaluated many of the same precipitation gauge records analyzed in this report and found that although November precipitation has fluctuated from decade to decade since the 1930s, November totals at the 7 stations they analyzed were higher than they had ever been in the latest decade they reported (Figure 1). Madsen and Figdor (2007) evaluated trends in the frequency of occurrence of daily precipitation events greater than the 1-yr return frequency of the record and found a statistically significant 45 percent increase in these precipitation events in the Seattle metropolitan area.

Hamlet and Lettenmaier (2007) have conducted modeling and data analyses that suggest changes in cool season precipitation since about 1973 have increased flood risk over much of the western U.S. They also suggest that global warming thus far may have played only a minor role in this trend. They also point out that the interannual variability of cool season precipitation has increased over that same time period. Hamlet and Lettenmaier (2007) also show that increasing temperature throughout the western U.S. has also resulted in substantial increases in flood risk, particularly in warm transient basins along the coast. Their analysis also indicates that years when PDO and ENSO are "in phase" are associated with increased flood risk.

Cuo et al. (2009) conducted a modeling study using DHSVM that evaluated the effect of land cover and climate change on the hydrology (monthly flows) of the Puget Sound basin. Based on their results, Cuo et al. (2009) suggested that in upland Puget Sound basins (like the ones analyzed in this study), both land cover and climate change have been important factors controlling hydrologic change – primarily due to the effects of climate change-related temperature increases on snow accumulation and melt and changes in forest cover affecting evapotranspiration, snow accumulation, and rain-on-snow events.

In general, there has been some debate regarding climate change related trends in extreme precipitation (Kunkel et al., 2003; Michaels et al., 2004) and the apparent paradox of increasing trends in precipitation and the lack of broad trends in increasing high river flows (Small et al., 2006). However, more recent studies have detected upward trends in the frequency of very heavy precipitation events that are consistent with future climate model simulations (Groisman et al., 2005) and increases in streamflow (Groisman et al., 2001). Groisman et al. (2001) also suggested that the decline in snow cover in the western U.S. has complicated the relationship between precipitation and streamflow to explain the lack of observed increasing trends in peak flow magnitudes.

Regonda et al. (2005) emphasize that the lower elevations of the Pacific Northwest are the most sensitive to temperature changes that in turn result in a relatively larger hydrologic response. They also note the general decline in snow pack and increase in winter precipitation in the western U.S. The combination of increasing winter precipitation and increasing severity of rain-on-snow events has significant implications for flood prediction, risk assessment, and management (McCabe et al., 2007).

Recent attribution studies have established a likelihood that much of the recent increase in temperature and reduction in winter snow pack in the western U.S. are the result of greenhouse gas forced global climate change (Bonfils et al. 2008; Pierce et al., 2008), which has resulted in changes in the hydrology of western rivers (Barnett et al., 2008; Das et al., 2009; Hidalgo et al., 2009).

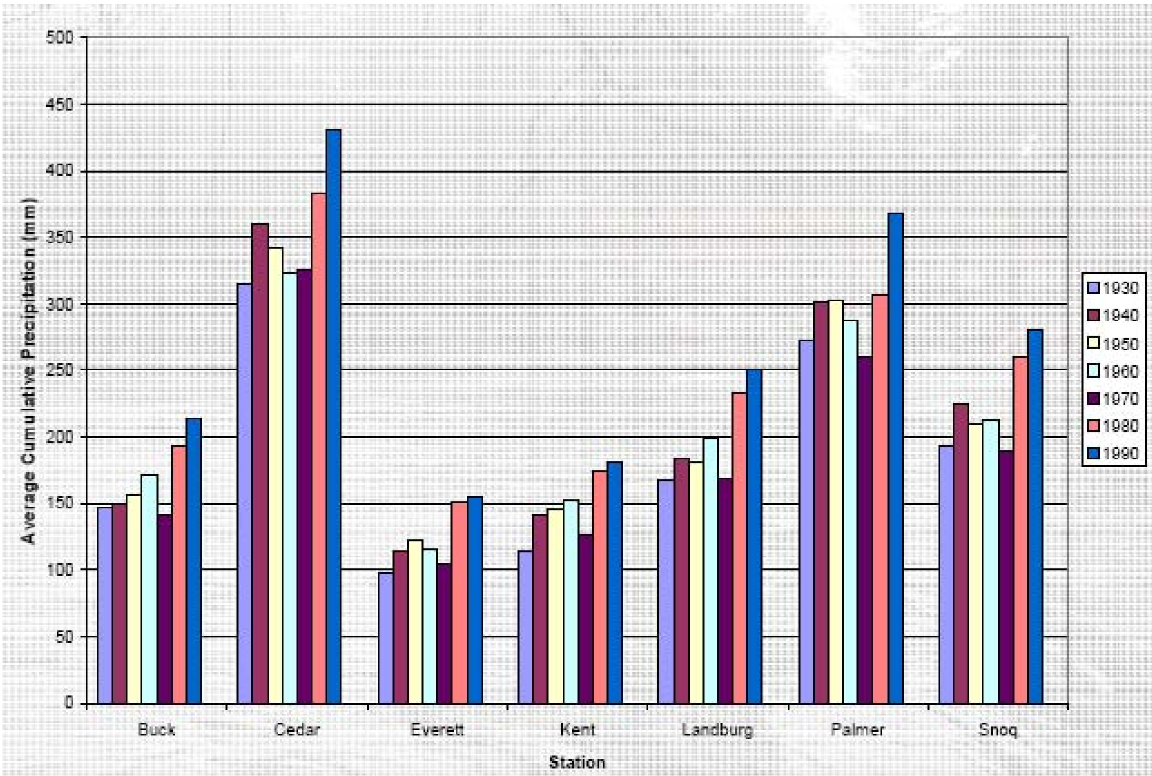

Figure 1. Decadal trends (1930-1990) in total precipitation in November for 7 long term station records (Polebitski and Palmer, 2006).

In addition to documented climate change impacts on temperature, winter snow pack, and hydrology there appears to be a developing interest in the influence of atmospheric rivers (Dettinger, 2004; Ralph et al., 2006; Neiman et al., 2008). Atmospheric rivers are another way to describe the local phenomenon known as the “pineapple express.” These rivers form from the intense mid and lower tropospheric winds that bring heat and water vapor from the tropics toward the west coast of North America. These events bring heavy amounts of rain to concentrated areas of the coast producing about twice as much winter precipitation as all other storms (Neiman et al., 2007). These atmospheric rivers also appear to be most pronounced when the PDO is positive and ENSO is neutral or near-neutral conditions (Dettinger, 2004). Salathé (2006) presented an analysis of historical data and future climate simulations that indicated the potential for climate change to shift the North Pacific stormtrack northward along the coast of North America and produce more intense precipitation in the future, particularly along the coast of British Columbia and northern Washington.

3.0. DATA

Historical USGS gauging records for river stations in King County were reviewed to identify stations with relatively long, uninterrupted daily records and minimal upstream flow control or water diversions. Daily records were used in this analysis because higher frequency data (e.g., 15-minute) typically contain periods of missing data that would introduce another level of uncertainty in the analysis of trends in the frequency, magnitude, duration, and timing of river discharge and precipitation described in this report. In these relatively large river systems, any identified trends based on daily data are very likely to be good indicators of changes in annual extreme flows of greatest concern from a flood management perspective.

Ten stations were selected for trend analysis based on station descriptions in the USGS 2008 Annual Water Data Report, which did not indicate significant upstream flow control or diversions that might affect high flows (Table 1). Remarks made in the USGS 2008 Annual Water Report for each gauge, which include information about the quality of the data and information about upstream regulation, are provided in Table 2. A daily time series of inflow to Howard Hanson Dam on the upper Green River provided by the U.S. Army Corps of Engineers (Ken Brettman, pers. comm., 20 October 2008) was also incorporated into the analysis.

The 10 stations selected were:

- Skykomish River near Gold Bar (12134500)
- Tolt River near Carnation (12148500)
- North Fork Snoqualmie River near Snoqualmie Falls (12142000)
- Middle Fork Snoqualmie River near Tanner (12141300)
- South Fork Snoqualmie River above Alice Creek (12141300)
- Raging River near Fall City (12145500)
- Snoqualmie River near Snoqualmie (12144500)
- Snoqualmie River near Carnation (12149000)
- Cedar River near Cedar Falls (1211500)
- Green River inflow to Howard Hanson Dam (natural flow at 12105900)

Although of sufficient record length, flow data for the White River gauging station below the outlet of Mud Mountain Lake were not included because Mud Mountain Lake is operated as a flood control facility, thereby potentially confounding any trends induced by climate change. Unfortunately, the gauging station above Mud Mountain Lake did not begin recording discharge until the mid-1970s and has not been operating continuously since then – a gap of over 10 years occurred between early 1996 and late 2008.

The locations of the 10 stations selected for analysis are shown in Figure 2. Two of these stations (Skykomish River near Gold Bar and the Snoqualmie River near Snoqualmie) are part of the U.S. Hydro-Climatic Data Network (HCDN) selected by the USGS to study the effects of climate on regional hydrologic trends. Stations included in the HCDN are not considered to necessarily be pristine, but are considered to be relatively unaffected by human activities such as water impoundments, diversions, or extractions; or significant land cover change (i.e., large-scale conversion of forest to agricultural or urban uses).

Hydrologic model output for the same locations generated by researchers at the University of Washington as part of a recent water supply planning process (http://www.govlink.org/regional-water-planning/) was also compiled. The hydrologic model output was from the Distributed Hydrology Soil Vegetation Model (DHSVM) based on 2001 land cover derived from Landsat data and calibrated to long-term historical flow gauge data (Polebitski et al., 2007a). The calibrated model was then forced with statistically-downscaled meteorological output from 3 global circulation model (GCM) runs selected from a set of 10 GCMs and future economic and greenhouse gas emission scenarios made available through the Fourth Assessment Report by the Intergovernmental Panel on Climate Change (Mote et al., 2005; IPCC, 2007; Palmer, 2007; Polebitski et al., 2007a).

The 3 GCM runs selected for use by Polebitski et al. (2007a) in the DHSVM simulations represent output from combinations of the 3 GCMs with 2 emissions scenarios, which are highlighted in Figure 3. The GCMs primarily differ in the algorithms used to simulate interactions among oceans, land, and the atmosphere, including feedback mechanisms. The 2 greenhouse gas emission scenarios (A2 and B1) represent upper and lower bounds of future greenhouse gas changes, especially beyond 2050 when scenario model results begin to dramatically diverge.

The 2 emissions scenarios are characterized by the IPCC as follows (http://www.grida.no/climate/ipcc/emission/094.htm):

- "The A2 scenario family represents a differentiated world. Compared to the A1 storyline it is characterized by lower trade flows, relatively slow capital stock turnover, and slower technological change. The A2 world "consolidates" into a series of economic regions. Self-reliance in terms of resources and less emphasis on economic, social, and cultural interactions between regions are characteristic for this future. Economic growth is uneven and the income gap between now-industrialized and developing parts of the world does not narrow, unlike in the A1 and B1 scenario families."
- "The central elements of the B1 future are a high level of environmental and social consciousness combined with a globally coherent approach to a more sustainable development. Heightened environmental consciousness might be brought about by clear evidence that impacts of natural resource use, such as deforestation, soil depletion, over-fishing, and global and regional pollution, pose a serious threat to the continuation of human life on Earth. In the B1 storyline, governments, businesses, the media, and the public pay increased attention to the environmental and social aspects of development. Technological change plays an important role. At the same time, however, the storyline does not include any climate policies, to reflect the Special Report on Emissions Scenarios' terms of reference. Nevertheless, such a possible future cannot be ruled out."

The 3 GCM models were:

- Goddard Institute for Space Studies model (GISS ER) and Emissions Scenario B1 as the "warm" regional change scenario (nearly the smallest increase in temperature, nearly the largest decrease in precipitation)

- Max Planck Institute for Meteorology's ECHAM5 model and Emissions Scenario A2 as the "warmer" regional change scenario (mid-range increases in temperature and precipitation)
- Institut Pierre Simon Laplace model (IPSL CM4) and Emissions Scenario A2 as the "warmest" regional change scenario (large increase in temperature, nearly the largest increase in precipitation).

A statistical downscaling approach described by Polebitski et al. (2007b and 2007c) was used to translate monthly GCM output at about a 200 km^2 grid scale to daily time series at a 12 km^2 grid and meteorological station scale appropriate for development of inputs to DHSVM. Daily discharge predictions for current and potential future climate conditions for the Snoqualmie River and tributaries were provided by Austin Polebitski (University of Washington) and the remaining data were obtained from the Climate Variables Database (http://www.climate.tag.washington.edu/). The development and calibration of the DHSVM models is documented in Polebitski et al. (2007a).

However, following the regional water supply planning study, the Washington legislature funded a state-wide climate assessment through House Bill 1303 – The Washington Climate Change Impacts Assessment (Climate Impacts Group, 2009). As part of this assessment, a larger set of 20 models were evaluated for their ability to represent features of Pacific Northwest climate observed in the latter portion of the 20th century (Mote and Salathé, 2009). These features included the ability of each model to represent the spatial distribution of temperature, precipitation, and sea level pressure (Mote and Salathé, 2009). Sea level pressure was chosen as a measure of the ability of each model to represent the predominant North Pacific storm track that delivers heavy winter precipitation to the Pacific Northwest. Of interest to this study is their finding that the GISS ER model performed much more poorly than any of the other 20 models in its ability to reproduce sea level pressure patterns resulting in the GISS ER model to be ranked last among all 20 models evaluated in overall performance. The IPSL CM4 model ranked next to last in their study Mote and Salathé, 2009).

In a more recent study, a similar evaluation identified the top 10 of the 20 models for a climate change assessment conducted of the Columbia River, Puget Sound, and coastal basins (Hamlet et al., 2010). The top 10 models selected did not include the GISS ER model, but did include the ECHAM5 and IPSL CM4 models (Hamlet et al., 2010). Within the these 10 models, ECHAM5 was among the top 5 and the IPSL CM4 model ranked lowest due in part to poorer performance in reproducing the North Pacific storm track (Hamlet et al., 2010). Based on the documented poor performance of the GISS ER model, we only report the downscaled hydrologic model results from the ECHAM5 and IPSL CM4 GCMs forced by the A2 Scenario.

Table 1. USGS gauging stations with long-term records selected for use in this study. Gauge locations selected for analysis are highlighted in yellow.

Description	Site Number	Drainage Area km^2 (mi^2)	Mean Basin Elevation meters (feet)	Period of Continuous Complete Water Year Daily Records	National Weather Service Flood Stage	Flood Warning Level
Skykomish River near Gold Bar	12134500	1,386 (535)	1050 (3450)	10/1/1928 to 9/30/2008	15 feet	NA
Tolt River near Carnation	12148500	210 (81)	720 (2360)	10/1/1937 to 9/30/2008	4,500 cfs	Phase 1: 1,500 cfs Phase 2: 2,500 cfs Phase 3: 4,500 cfs Phase 4: 7,000 cfs
North Fork Snoqualmie River near Snoqualmie Falls	12142000	166 (64)	930 (3060)	10/1/1929 to 9/30/1949 10/1/1961 to 9/30/2008	NA	Sum: North, Middle, South Phase 1: 6,000 cfs Phase 2: 12,000 cfs Phase 3: 20,000 cfs Phase 4: 38,000 cfs
Middle Fork Snoqualmie River near Tanner	12141300	399 (154)	1040 (3400)	10/1/1961 to9/30/2008	NA	
South Fork Snoqualmie River above Alice Creek	12143400	108 (41.6)	1040 (3410)	10/1/1960 to 9/30/2008	NA	
Raging River near Fall City	12145500	83 (32)	710 (2340)	10/1/1964 to 9/30/2008	NA	NA
Snoqualmie River near Snoqualmie	12144500	971 (375)	870 (2,860)	10/1/1958 to 9/30/2008	20,000 cfs	NA
Snoqualmie River near Carnation	12149000	1530 (590)	710 (2340)	10/1/1929 to 9/30/2008	54 feet	NA
Cedar River near Cedar Falls	12115000	105 (40.7)	1000 (3280)	10/1/1945 to 9/30/2008	NA	NA
Green River at Howard Hanson Dam (naturalized flow)	12105900	105 (40.7)	1000 (3280)	10/1/1931 to 9/30/2008	NA	NA

NA = Not applicable

Table 2. USGS station remarks from the USGS 2008 Annual Water Data Report.

Description	Site Number	Remarks
Skykomish River near Gold Bar **a**	12134500	No estimated daily discharges. Records good. No regulation. Several small diversions upstream from station.
Tolt River near Carnation	12148500	No estimated daily discharges. Records good. Some regulation by South Fork Reservoir, capacity, 57,830 acre-ft, and by Seattle City Light hydroelectric project, upstream from station. During the current water year City of Seattle Water Department diverted an average daily discharge of about 80 ft^3/s upstream from station for municipal use.
North Fork Snoqualmie River near Snoqualmie Falls	12142000	No estimated daily discharges. Records good. No regulation or diversion upstream from station.
Middle Fork Snoqualmie River near Tanner	12141300	Records good except estimated daily discharges, which are fair. No regulation or diversion upstream from station.
South Fork Snoqualmie River above Alice Creek	12143400	No estimated daily discharges. Records good. No regulation or diversion upstream from station.
Raging River near Fall City	12145500	Records good except for estimated daily discharges, which are fair. Some small diversions for irrigation and domestic use upstream from station. No regulation.
Snoqualmie River near Snoqualmie **a, b**	12144500	No estimated daily discharges. Records good. Medium and low flows affected by power plant 0.1 mi upstream from station. Prior to September 1999, gauge located at site on opposite bank, at same datum.
Snoqualmie River near Carnation **b**	12149000	Records good, except for estimated discharges, and periods of Nov. 16–Dec. 5, 2006 and Feb. 20–21, 2007, which are fair due to uncertainty as to proper application of corrections due to the float tape coming off the pins. During the current water year, Seattle Water Department diverted an average daily discharge of 80 ft^3/s upstream from station from South Fork Tolt River for municipal use. Several small diversions for irrigation and domestic use upstream from station. Low flow diverted for operation of power plant at Snoqualmie Falls but returned to river upstream from station. Some pondage at Snoqualmie Falls and some diurnal fluctuation caused by power plant.
Cedar River near Cedar Falls	12115000	No estimated daily discharges. Records good. All diversions are returned to river upstream from station. Flow regulated by Chester Morse Lake (station 12115900) and Cedar Lake (station 12116060).
Green River at Howard Hanson Dam (naturalized flow)	12105900	Not applicable

[a] Station part of the U.S. Hydro-Climatic Data Network (HCDN) which is a compilation of streamflow data that are unaffected by artificial diversions, storage, or other works of man in or on the natural stream channels or in the watershed that can provide an account of hydrologic responses to fluctuations in climate.

[b] Modeling studies have determined that the during certain high flows, the Snoqualmie can backwater above the confluence with the Skykomish River, affecting the accuracy of the rating curves at these two Snoqualmie River gauges (NHC, 2006). Other concerns associated with these gauges include potential local superelevation during high flows at the Snoqualmie River near Snoqualmie guage in the years before it was moved to the opposite bank in 1999 and potential split flow channels across the broad floodplain at the Carnation gage affecting gauge reliability at higher flows. As an example, the November 1990 peak flows for the Snoqualmie River near Snoqualmie gauge (upstream) and at the Snoqualmie River at Carnation gauge (downstream) were 78,000 and 65,200 cfs respectively. This is the only recent high flow event on the Snoqualmie River between Carnation and Snoqualmie to show decreasing flows between these two guages. A decrease in flow downstream of the Snoqualmie gauge during a flooding event is suspect. It is not clear if flow at the upstream gauge was overestimated or if the flow downstream was underestimated. Both flow records are considered approved data by the USGS.

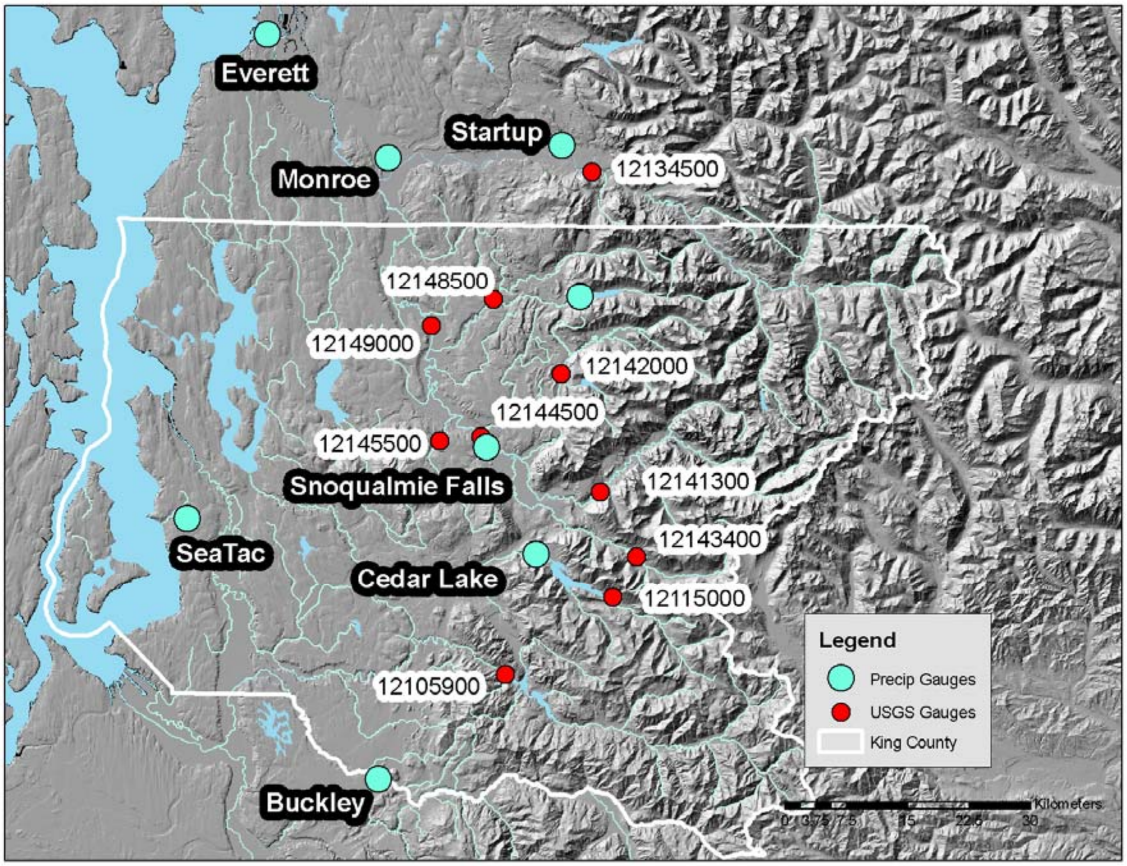

Figure 2. Locations of USGS gauging stations selected for trend analysis.

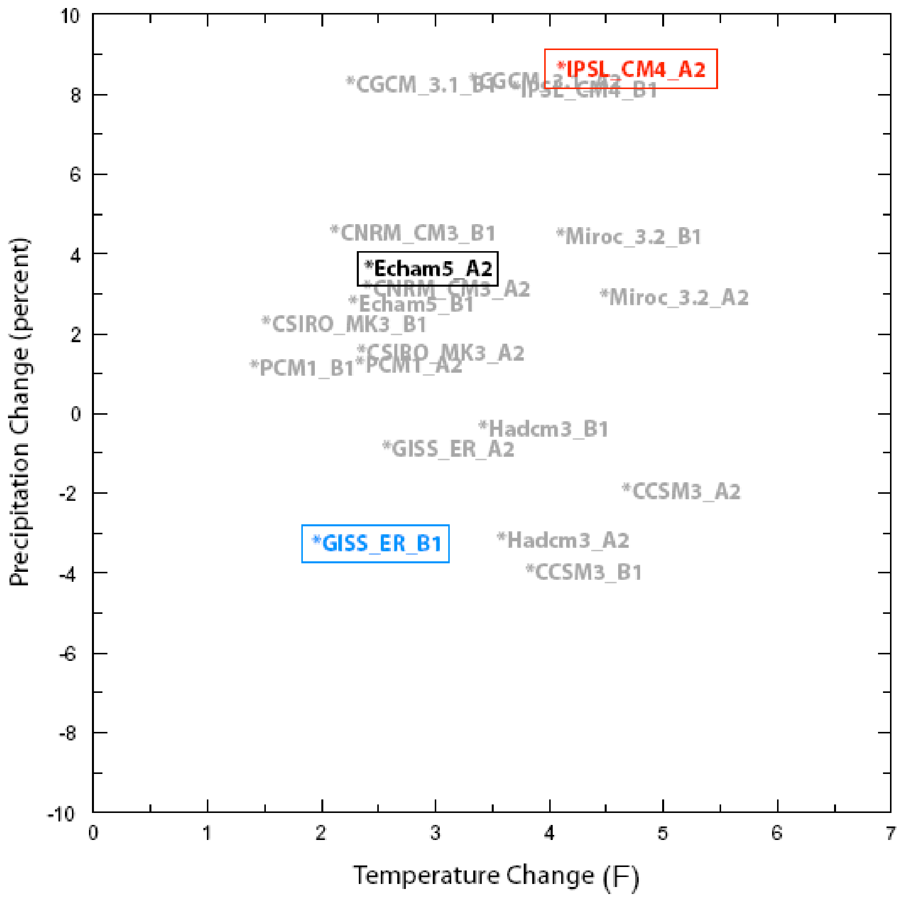

Figure 3. Comparison of general circulation model predictions of changes in future Pacific Northwest precipitation and temperature based on combinations of GCMs and future economic and greenhouse gas emission scenarios.

Note: *Model output shown is the annually averaged temperature and precipitation change for each of 20 scenarios (combination of 10 GCMs and 2 emission scenarios), for the "2040s" (i.e., 2030-2059 minus 1970-1999). The two GCM-climate scenarios combinations that were used to generate the hydrologic model output evaluated in this report are highlighted in red (IPSL CM4 A2) and black (ECHAM5 A2). Figure reproduced from Mote et al. (2005).*

Regional daily precipitation records were also reviewed and ultimately eight station records were compiled for trend analysis. A significant portion of the data used was already compiled as part of the water supply planning process mentioned above and available from the Climate Variables Database. However, these records only extended through September 2003. Additional data for these stations were downloaded from the National Climatic Data Center (NCDC) and the United States Historical Climatology Network (USHCN) (Williams et al., 2006). The analyses presented in this report focused on eight precipitation stations located in or near the basins where the majority of the relatively unregulated river gauges are located. The precipitation stations analyzed in this report are listed in Table 3 and their location in relationship to the selected flow gauges is shown in Figure 2.

Table 3 Eight precipitation gauging stations with long-term records evaluated in this study.

Station	COOP_ID	Elevation (meters)	Period of Continuous Complete Water Year Daily Records
Everett [a b c]	452675	18	10/1/1920 to 9/30/2008
Monroe [b c]	455525	37	10/1/1929 to 9/30/2008
Startup [b c]	458034	52	10/1/1927 to 9/30/2008
SeaTac [b c]	457473	122	10/1/1948 to 9/30/2008
Snoqualmie Falls [a b c]	457773	134	10/1/1931 to 9/30/2008
Buckley [a b c]	450945	209	10/1/1920 to 9/30/2008
Cedar Lake [a b c]	451233	476	10/1/1920 to 9/30/2008
South Fork Tolt [b c]	458508	609	10/1/1963 to 9/30/2008

[a] U.S. Historical Climatology Network station
[b] National Climatic Data Center station
[c] University of Washington Climate Variables Database (http://www.climate.tag.washington.edu)

4.0. METHODS

4.1 Discharge

Observed daily discharge data and DHSVM daily discharge predictions driven by historic precipitation data were summarized and analyzed in a number of ways to assess the possibility that secular[1] trends in flow magnitude, frequency, duration, and timing had occurred over the period of continuous records at each gauge. The non-parametric Mann-Kendall (MK) trend test was used to test for trends in the following measures of flow magnitude:

- Annual (Oct-Sept) average discharge (MK test)
- Annual (Oct-Sept) maximum discharge (MK test)
- Monthly average discharge (MK test for each month series)
- Monthly maximum discharge (MK test for each month series)
- Annual percentile category trends (MK test on 10-percentile increments from 0 to the 100^{th}-percentile)

The trend tests focused on trends in annual and individual monthly flow magnitudes, due to an interest in looking at the seasonal distribution of trends in flows. The MK trend test was performed using a FORTRAN program available from the USGS (Helsel et al., 2006).

Of particular concern in any statistical analysis is the avoidance of Type I and Type II errors. These errors are illustrated in Table 4. Trend analysis Type I error is when the test fails to identify a real trend in the data due to the weakness of the trend, the methodology, or the shortness of the record. Type I errors can be controlled by the selection of the statistical significance level (*p*). In general, the lower the value of *p* used to determine statistical significance, the less likely Type I errors will occur. Typically, a significance level of <0.05 is selected to identify "statistically significant" trends. However, many researchers have argued against the use of rather arbitrary definitions of statistical significance (Newman, 2008). In this report, the following definitions are used to qualify the evidence for the presence of a trend:

- **$p \geq 0.10$**: No reliable statistical evidence against the null hypothesis that a trend exists
- **$0.05 \leq p < 0.10$**: Weak evidence against the null hypothesis that a trend exists
- **$0.01 \leq p < 0.05$**: Strong evidence against the null hypothesis that a trend exists
- **$p < 0.01$**: Very strong evidence against the null hypothesis that a trend exists

[1] Secular or monotonic trends are long term underlying upward or downward movements in some measurement or indicator, which may vary both upward and downward over shorter time intervals.

Table 4. Description of statistical trend testing errors.

		Does a trend exist?	
		Yes (H_0 false)	No (H_0 true)
Has a trend been detected?	Yes (Reject H_0)	Power = 1-β	**Type I Error (α):** False trend detected when none exists.
	No (Fail to reject H_0)	**Type II Error (β):** Failure to detect an existing trend due to weakness of the trend, of the methodology, or the short length of the record.	Probability = 1-α

α = Probability (reject $H_0|H_0$ true) and $1 - \beta$ = Probability (reject $H_0|H_0$ false)

It is more difficult to avoid Type II errors. Trend test Type II errors are when the statistical trend test does not suggests a trend, but a trend really exists. Type II errors are also difficult to quantify because they require prior knowledge that a trend in the data exists. Nonetheless, one approach to minimizing Type II errors is to use relatively long records for analysis.

In order to evaluate trends in the frequency of occurrence and duration of high flows, flood frequency analyses were performed on the observed and modeled daily discharge records. The program PeakFQ for Windows (version 5.1) available from the USGS (Flynn et al., 2006) was used to estimate annual (Oct-Sep) peak flows from each data source with an annual recurrence probability of 0.5, 0.1, 0.04, and 0.02 (equivalent to flows with a 2-, 10-, 25-, and 50-year return interval)[2]. These flow thresholds were then used to identify the number (frequency) of discrete flow events in each year of each station record that exceeded each flow threshold and the average duration in days that flows were above each threshold. The time series of annual frequency of exceedance and average annual duration for flow events above each threshold were then tested for trend using the MK test.

Because the trend evaluation of the frequency of occurrence and duration of high flows involved shifts in the frequency of relatively extreme (i.e., infrequent) events, a second statistical approach was used to evaluate trends in these metrics. The approach used was based on a stochastic

[2] A 100-year return interval threshold was not used, because of the very infrequent expected occurrence of flows of this magnitude over the less than 100 year long records used in the analysis.

concept of binomially distributed counts using a Generalized Linear Model or GLM[3] following the examples presented in Frei and Schär (2001).

Trends in the timing of annual maximum discharge were evaluated by identifying the Julian day that the maximum discharge occurred each year in each data source and testing for trends using the MK test.

Trend tests were conducted for the period 10/1/1961 through 9/30/2008 for 9 of the 10 stations because this was the longest period of record that included almost all of the stations. Records for the Raging River near Fall City began in July 1945, but were discontinued at the end of September 1950 and didn't resume until December 1963. Trends for the USGS Raging River gauge near Fall City were conducted for the period 10/1/1964 through 9/30/2008. Five USGS stations with substantially longer continuous records were also analyzed for trends over the available period of record for each gauge. These stations were the Skykomish River near Gold Bar (10/1/1928-9/30/2008), the Tolt River near Carnation (10/1/1937-9/30/2008), the Snoqualmie River near Carnation (10/1/1929-9/30/2008), the Cedar River near Cedar Falls (10/1/1945-9/30/2008), and the naturalized Green River flow at Howard Hanson Dam (10/1/1931-9/30/2008).

Trend tests were conducted on the DHSVM model output for these same 10 locations for the period 10/1/1961 through 9/30/2003 and for the entire length of the historic DHSVM simulations (10/1/1928-9/30/2003).

4.2 Precipitation

Precipitation data were analyzed in essentially the same way as the discharge data except that instead of annual and monthly averages, annual and monthly totals and daily maximums were evaluated for trends. Non-parametric MK trend tests were used to test for trends in the following measures of precipitation magnitude:

- Annual (Oct-Sept) total precipitation (MK test)
- Annual (Oct-Sept) maximum precipitation (MK test)
- Monthly total precipitation (MK test for each month series)
- Monthly maximum precipitation (MK test for each month series)
- Annual percentile category trends (MK test on the 5th, 10th, 20th, 30th, 40th, 50th, 60th, 70th, 80th, 90th, 95th, and the 100th-percentiles)

Trends in the frequency and duration of precipitation were evaluated using thresholds based on the percentile rank of each test dataset. Thresholds chosen for analysis were the 50th, 75th, 90th, and 95th-percentile. These precipitation thresholds were then used to identify the number (frequency) of discrete precipitation events in each year of each station record that exceeded each threshold and the average duration in days that precipitation was above each threshold. The time series of annual frequency of exceedance and average annual duration for precipitation events above each threshold were then tested for trend using the MK test. The Generalized Linear

[3] Generalized Linear Models (GLMs) are a generalization of ordinary least squares regression that allows for the incorporation of linear, logistic, and Poisson regression, via link functions, under one regression modeling framework.

Model (GLM) approach used to evaluate trends in flow frequency and duration was also used to identify trends in precipitation frequency and duration (Frei and Schär, 2001).

Trends in the timing of annual maximum precipitation were evaluated by identifying the Julian day that the maximum precipitation occurred each year in each data source and testing for trends using the MK test.

Trend tests were conducted for the period 10/1/1961 through 9/30/2008 for 7 of the 8 stations to facilitate comparisons with the discharge trend results over this same period. Records for the South Fork Tolt were not available until December 1962, so trends were conducted for this station over the period 10/1/1963 through 9/30/2008. Trend tests were also conducted for the entire length of continuous records for each of these stations (see Table 3).

4.3 Future Climate Hydrologic Model Output

Because the downscaled GCM-DHSVM model runs provided by the University of Washington and used in this study represent long term simulations of the effect of predicted future climate conditions at 25 year intervals, trend analysis of individual 75 year model runs were not conducted. The intent rather of these model runs is to capture the range of variability at each 25-year increment into the future. Therefore, changes in the distribution of discharge were determined based on a summary of monthly average flows for the historic, 2000, 2025, 2050, and 2075 simulations for each GCM-DHSVM model run for the 10 USGS gauge locations analyzed above. The cumulative frequency distributions of daily discharge for historic, 2000, 2025, 2050, and 2075 GCM-DHSVM model runs were also compared. To assess potential changes in expected flood magnitudes under the 2 GCM scenarios, the annual maximum flow return intervals (1-yr, 2-yr, 5-yr, 10-yr, 20-yr, 50-yr, and 100-yr) were calculated for each GCM-DHSVM model run. The change in the annual frequency of exceedance of the Phase 1 King County flood warning level for the Snoqualmie River (Sum of North, Middle, and South Fork flows) (see Table 1) for each GCM-DHSVM model run was also determined. These results were compared graphically.

Since the primary purpose of the DHSVM modeling was to provide reliable daily reservoir inflows for the evaluation of potential future climate change impacts on water supply (Polebitski et al., 2007a), the focus of model calibration was on matching cumulative flow and flow timing on a monthly scale. Attention was also given to calibrating the model to match daily high and low flows (Polebitski et al., 2007a). In order to evaluate the utility of using the DHSVM model output for evaluation of extreme daily flows, comparisons are made between the evaluated trends based on the historic USGS daily flow record and the calibrated DHSVM model output for these same stations.

5.0. RESULTS

The rainfall records selected for analysis represent the typical seasonal pattern of rainfall with highest monthly precipitation occurring from November through January and lowest precipitation in July and August (Figure 4). These stations also represent a continuum from low elevation stations of the Puget Lowland to stations situated on the western flanks of the Cascade Mountains (elevation range 18-609 m). As a result of the predominant flow of moist air from the Pacific Ocean to the east and the orographic effect of the Cascade Mountains, annual precipitation totals generally increase from low to high elevation (Figure 5).

With the exception of the Raging River near Fall City, the river gauges selected for analysis represent runoff from so-called *transient* basins that have high flow in winter as a result of heavier winter rainfall and another peak in flow in spring in response to snowmelt runoff as the higher elevation winter snow pack melts (Beechie et al., 2006) (Figure 6). Of particular interest in these transient basins, is the occurrence of *rain-on-snow* events that represent a combination of rain and snow melt runoff during the winter and spring. This combination of runoff typically occurs at elevations between 800 and 1,300 meters (Beechie et al, 2006) and can potentially produce more total runoff than rain or snow melt separately. Figure 7 illustrates the areas with the highest potential for rain-on-snow events in the study basins.

To illustrate the general trends in discharge, time series plots of annual streamflow percentiles including the annual minimum (based on daily averages), 25th-percentile, median, 75th-percentile, and annual maximum flow for the period of record (normalized to the long-term median flow for each record) of the 10 USGS gauges selected for analysis are shown in Figure 8. Long-term (decadal) variation is evident, particularly in the time series plots of the 25th-percentile and median flows. It also appears that the magnitude of annual maximum flows has increased, with many of the highest annual flows recorded at these stations since about 1970.

Figure 9 illustrates the same information based on the historic DHSVM output for the same stations for the period 1929 through 2003. Although the patterns were generally similar to those illustrated by the observed gauging data, the most distinct difference was the absence of a visually apparent upward shift in the magnitude of annual maximum flows after 1970.

Annual precipitation percentiles were also plotted (5th-percentile, 25th-percentile, median, 75th-percentile, and annual maximum [based on daily totals]) for the 8 study stations for the period of record normalized to the long-term median precipitation (Figure 10). The plots indicate a fair amount of between station and interannual variability in regional precipitation, although the magnitude of annual maximum precipitation appears to have increased, with many of the highest annual maximum daily total precipitation events occurring at these stations after about 1980.

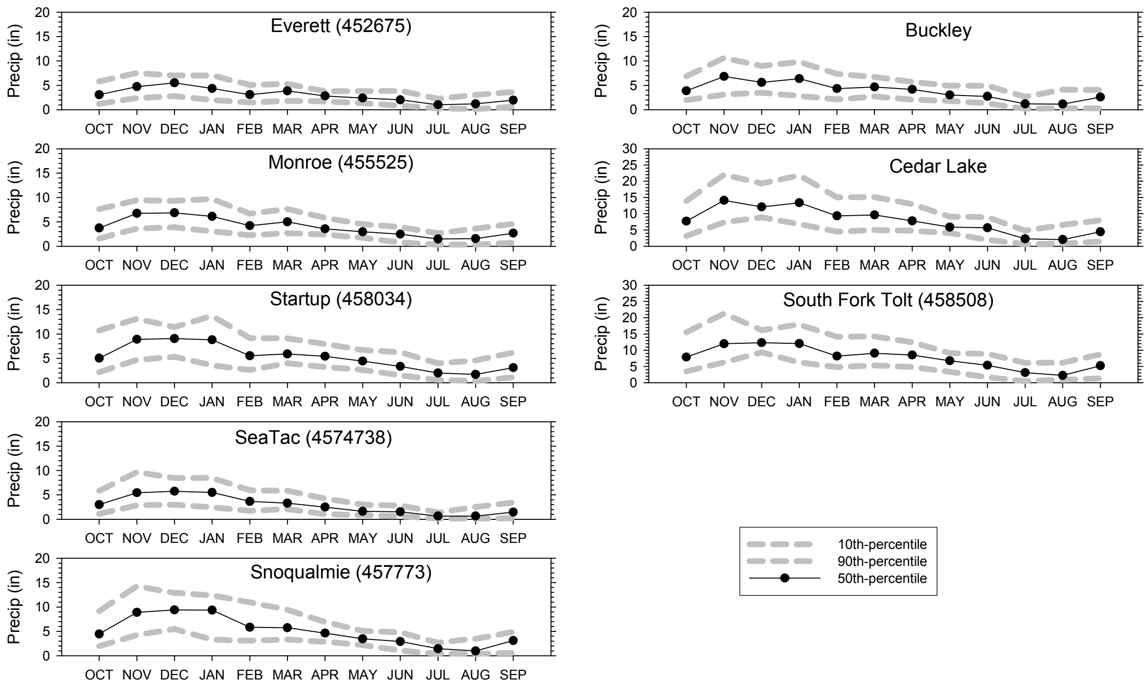

Figure 4. Monthly precipitation statistics (median, 10th-percentile, 90th-percentile) for the period 1962-2008 for the eight stations identified in Table 3.

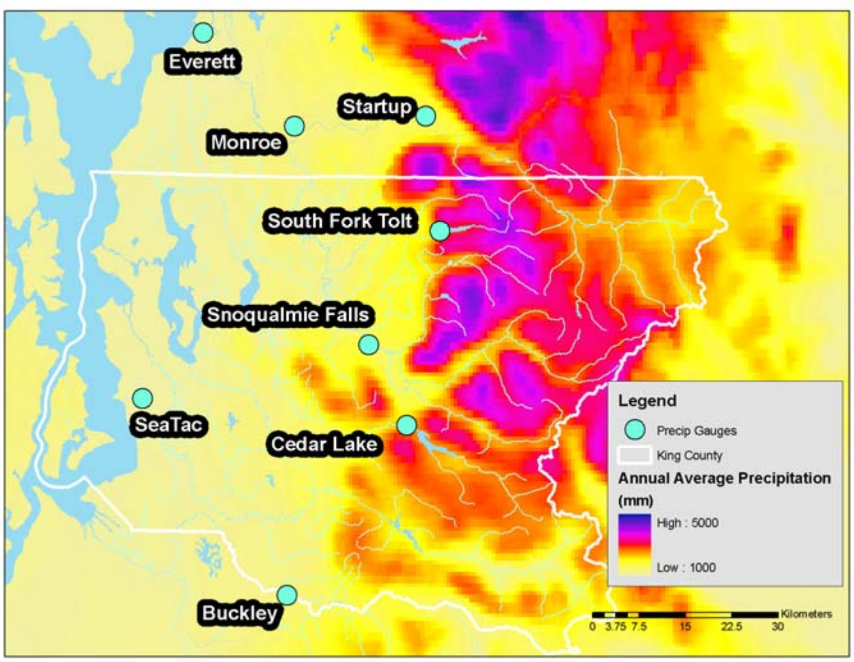

Figure 5. Long-term (1971-2000) average annual precipitation based on 30-arcsecond PRISM Group data (Oregon State University, http://www.prism.oregonstate.edu/).

Note: The location of the eight precipitation stations evaluated in this study is also shown.

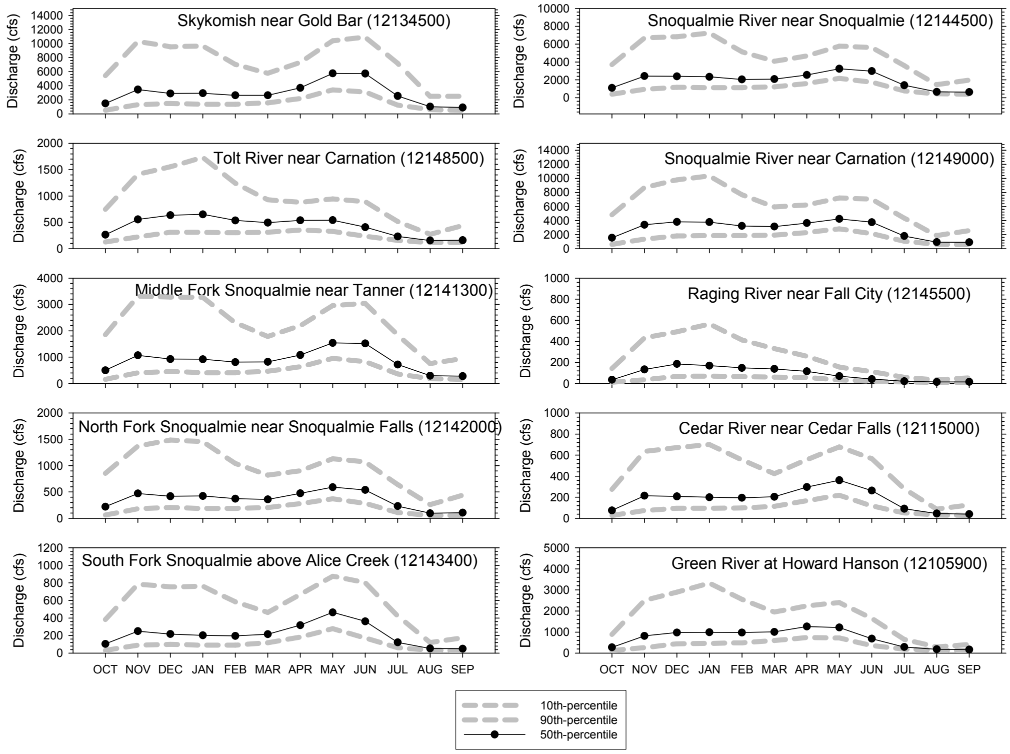

Figure 6. Monthly discharge statistics (median, 10th-percentile, 90th-percentile) for the period 1962-2008 for the 10 USGS gauging stations identified in Table 1.

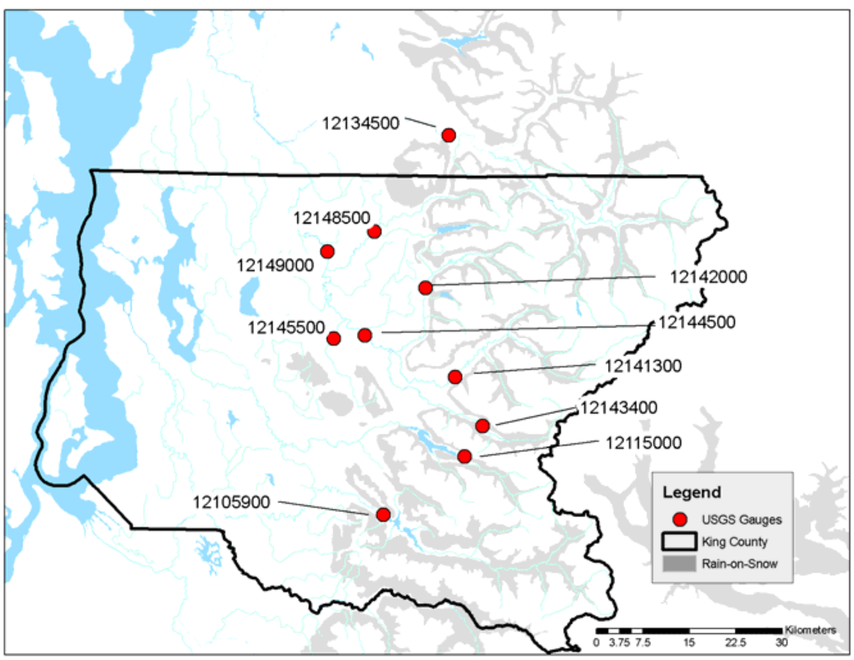

Figure 7. Map showing rain-on-snow zones as reported by Forest Practices Division, Washington State Department of Natural Resource (1991).

Note: The 10 USGS gauging stations identified in Table 1 are also shown.

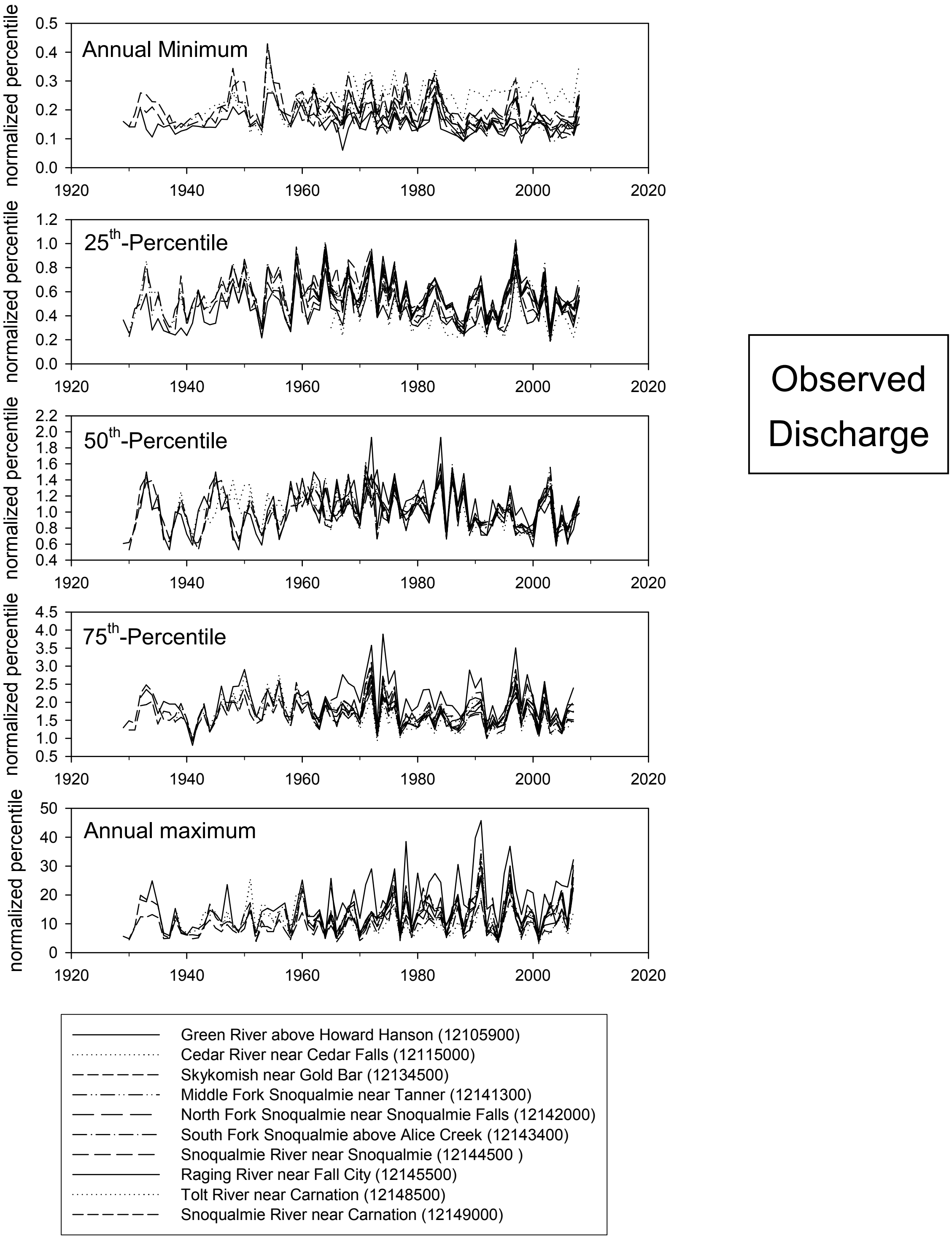

Figure 8. Time series plots of annual minimum, 25th-percentile, 50th-percentile, 75th-percentile, and annual maximum discharge (normalized to the long-term median discharge) for the period of continuous records for the 10 USGS gauging stations identified in Table 1.

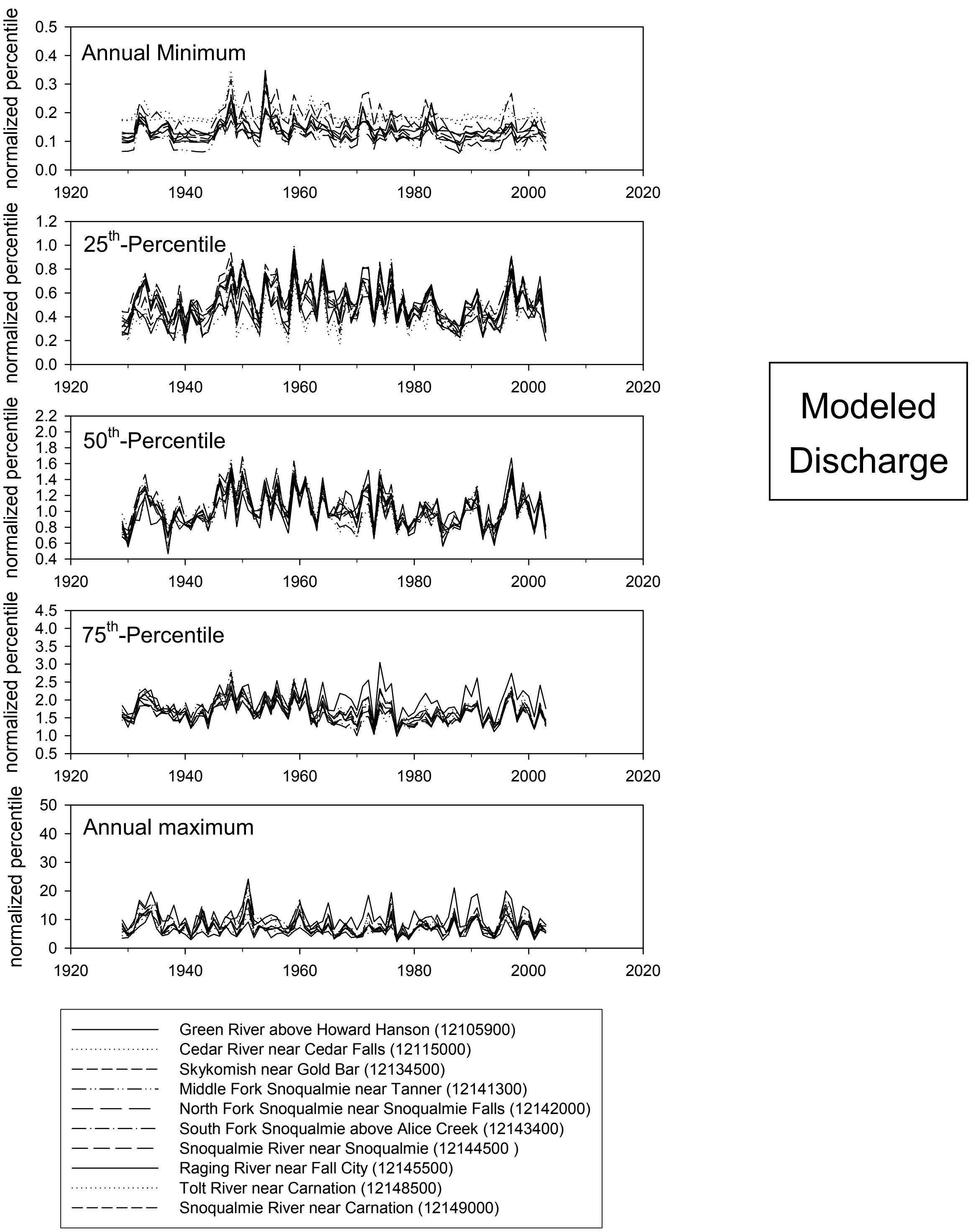

Figure 9. Time series plots of annual minimum, 25th-percentile, 50th-percentile, 75th-percentile, and annual maximum discharge (normalized to the long-term median discharge) for the period of continuous records based on DHSVM output for the 10 USGS gauging stations identified in Table 1.

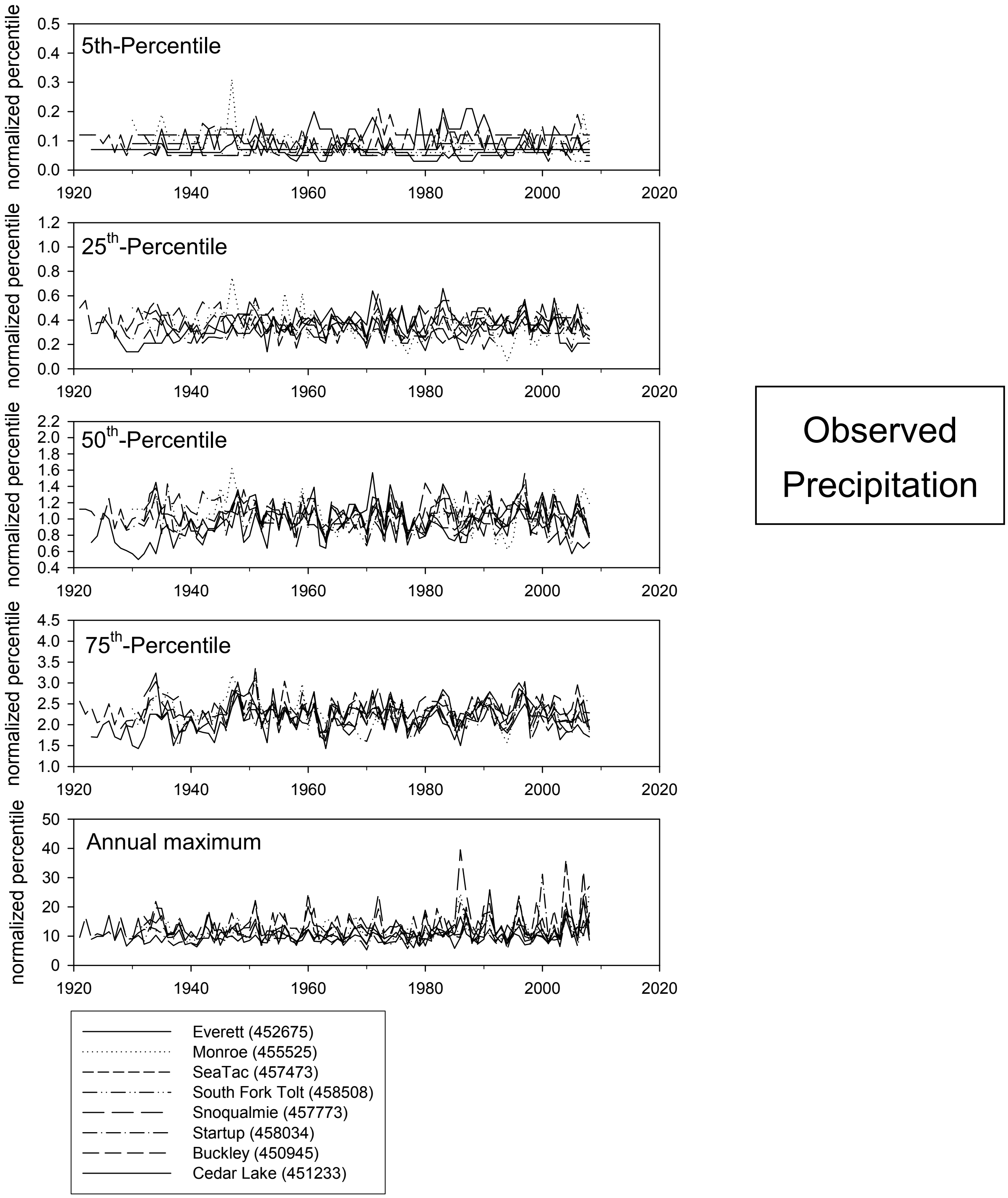

Figure 10. Time series plots of annual 5th-percentile, 25th-percentile, 50th-percentile, 75th-percentile, and annual maximum precipitation (normalized to the long-term median precipitation) for the period of continuous records for the 8 stations identified in Table 3.

5.1 Trends 1962-2008

The presentation of trend results is organized by first presenting trend analyses of flow magnitude, then presenting the results for the analysis of USGS discharge records followed by the results for evaluation of the DHSVM data for the same stations. Analysis of the precipitation data is then presented. This approach was selected to facilitate comparison of results for USGS and DHSVM data and facilitate making connections between flow trends and precipitation trends. Following presentation of trends in magnitude, trend analysis results for frequency, duration, and timing are presented using the same approach used for presentation of trends in magnitude. The presentation of trend results for annual discharge and precipitation percentiles is presented at the end of Section 5.1.

5.1.1 Discharge and Precipitation Magnitude

5.1.1.1 Annual Average and Maximum Discharge

The trend test on annual average observed discharge indicated negative or near zero trend in annual average flow over the period 1962-2008 (Appendix A1). However, no reliable statistical evidence for trends was found for any station. The trend test on annual maximum observed discharge indicated upward trends for all stations (Appendix A2). However, the statistical evidence for trends was not reliable, with the exception of strong evidence for the trend at the Skykomish River near Gold Bar (tau=0.215; p=0.034).

The trend test on annual average DHSVM modeled discharge indicated 4 negative and 6 positive trends in annual average flow over the period 1962-2003 (Appendix B1). However, no reliable statistical evidence for trends was found for any station. The trend test on annual maximum modeled discharge indicated upward trends for all stations (Appendix B2). However, the statistical evidence for trends was not reliable.

5.1.1.2 Monthly Average Discharge

The results of the trend test on observed monthly average discharge in each month over time can be found in Appendix A3. Consistently negative trends with mostly strong or very strong evidence were found for average July, August, and September flows (Figure 11). Consistently upward trends were found for November and consistent downward trends in February and December, but statistical evidence was not reliable for these trends.

The results of the trend test on monthly average DHSVM modeled discharge in each month over time can be found in Appendix B3. Consistently negative trends, including weak to very strong evidence for trends, were found for average August, September, and October flows (Figure 12). Consistently upward trends were found for February, March, and November and consistent downward trends in February and December, but statistical evidence was generally not reliable for these trends, with the exception of weak evidence for upward trends in March at two stations (Skykomish River near Gold Bar and Tolt River near Carnation).

5.1.1.3 Monthly Maximum Discharge

The results of the trend test on monthly maximum observed discharge in each month for the period 1962-2008 can be found in Appendix A4. Consistent negative trends were found for maximum observed flow in January, July, August, September, and December with evidence ranging from unreliable to strong among the 10 stations (Figure 13). Consistent upward trends in monthly maximum observed flow were found for November. However, evidence for these trends was generally unreliable with the exception of one station with weak evidence of an upward trend in November (North Fork Snoqualmie River near Snoqualmie Falls).

The results of the trend test on monthly maximum DHSVM modeled discharge in each month for the period 1962-2003 can be found in Appendix B4. Consistent negative trends were found for maximum modeled flow in January, July, August, and September, with evidence ranging from unreliable to strong among the ten stations (Figure 14). Consistent upward trends in monthly maximum flow were found for February, March, and November. Evidence for these trends ranged from unreliable to strong, with the most evidence for upward trends in March and November for the Skykomish River near Gold Bar, Tolt River near Carnation, and North Fork Snoqualmie River near Snoqualmie Falls.

5.1.1.4 Total and Maximum Precipitation

The trend test on annual total precipitation indicated 4 negative and 4 positive trends over the period 1962-2008 (Appendix C1). However, no reliable statistical evidence for trends was found, with the exception of very strong evidence for an upward trend in annual total precipitation for the South Fork Tolt (tau=0.277; p=0.008). The trend test on annual maximum precipitation indicated upward trends for all but one station (Appendix C2). However, the statistical evidence for trends was not reliable, with the exception of the trend for the South Fork Tolt station which was upward with very strong evidence (tau=0.323; p=0.002).

The results of the trend test on monthly total precipitation in each month over time can be found in Appendix C3. Consistently negative trends were found for July and August total precipitation, although the evidence for these trends was considered unreliable (Figure 15). More reliable downward trends were found in September for two stations (strong evidence). Consistently upward trends were found for October and November, but statistical evidence was generally not reliable for these trends, with the exception of weak evidence for an upward trend in November at South Fork Tolt (tau=0.186; p=0.073).

The results of the trend test on monthly maximum precipitation in each month for the period 1962-2008 can be found in Appendix C4. No completely consistent upward or downward trends were found among the eight stations (Figure 16). However, there was strong evidence for upward trends in November at two stations (Everett and South Fork Tolt).

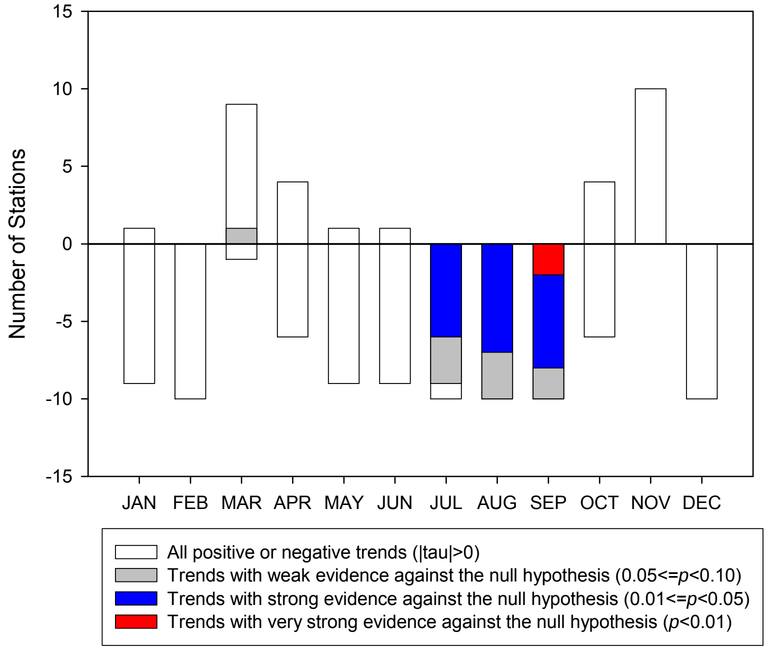

Figure 11. Frequency of trend direction and relative evidence of trends in monthly average discharge over the period 1962-2008 at the 10 gauging stations identified in Table 1.

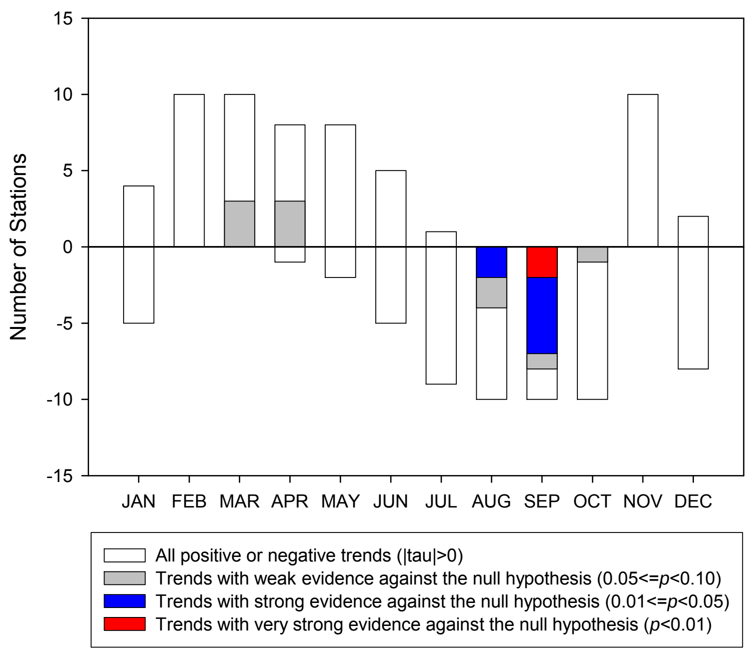

Figure 12. Frequency of trend direction and relative evidence of trends in monthly average discharge over the period 1962-2008 based on DHSVM output at the 10 USGS gauging stations identified in Table 1.

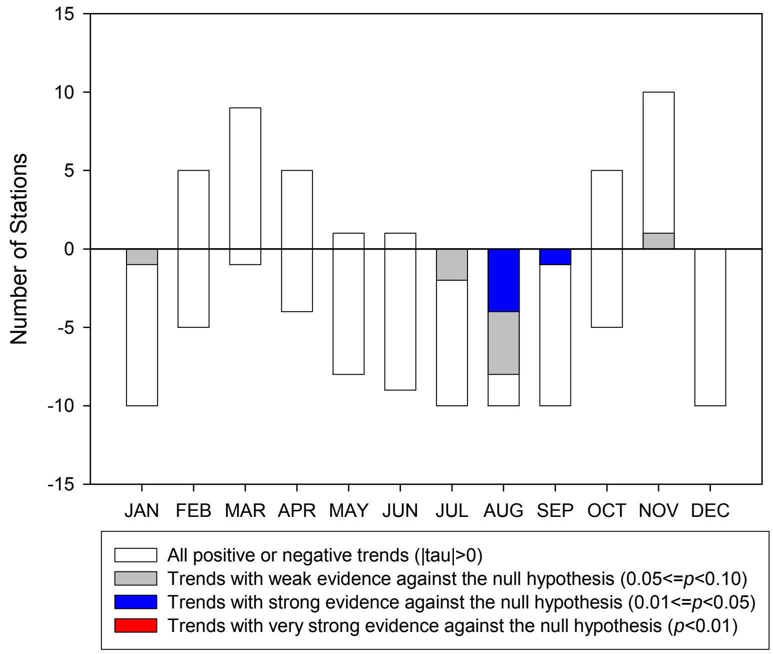

Figure 13. Frequency of trend direction and relative evidence of trends in monthly maximum discharge over the period 1962-2008 at the 10 USGS gauging stations identified in Table 1.

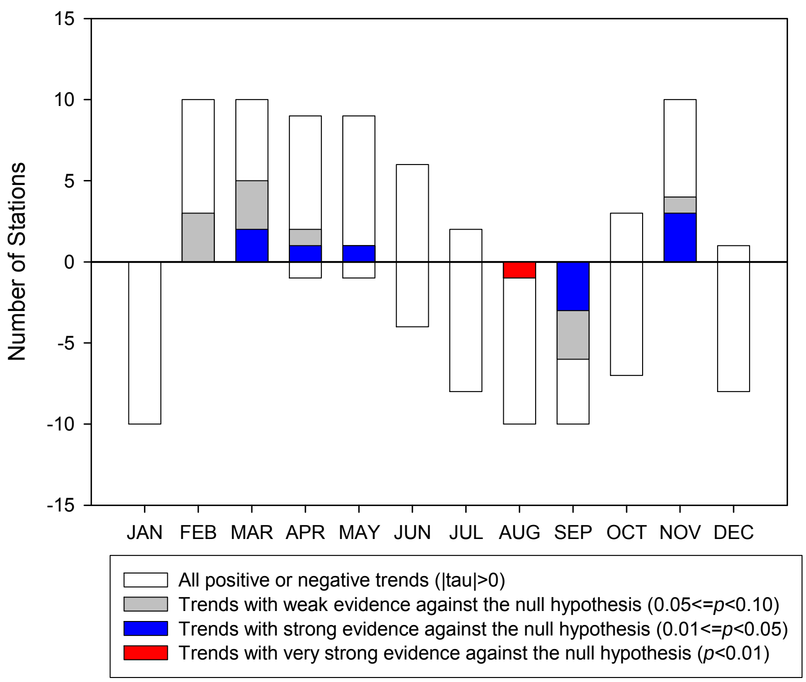

Figure 14. Frequency of trend direction and relative evidence of trends in monthly maximum discharge based on DHSVM output over the period 1962-2003 at the 10 USGS gauging stations identified in Table 1.

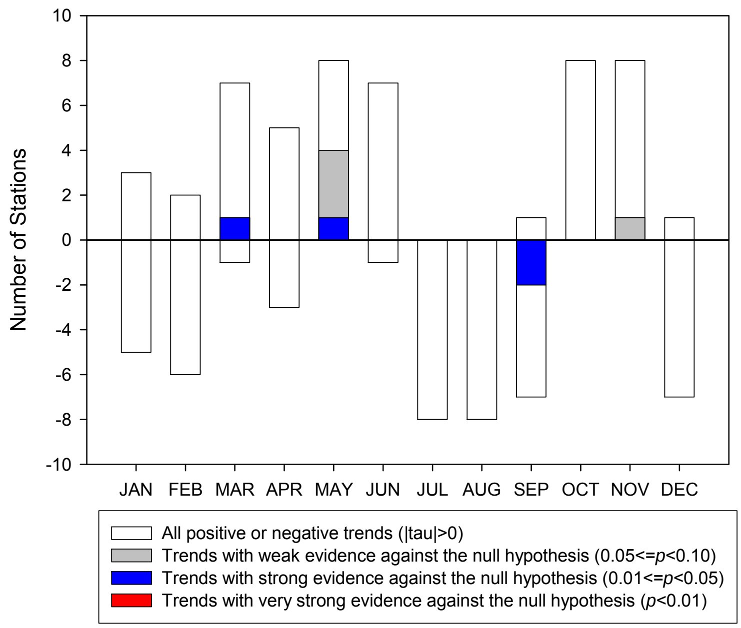

Figure 15. Frequency of trend direction and relative evidence of trends in monthly total precipitation over the period 1962-2008 based on data from the 8 stations identified in Table 3.

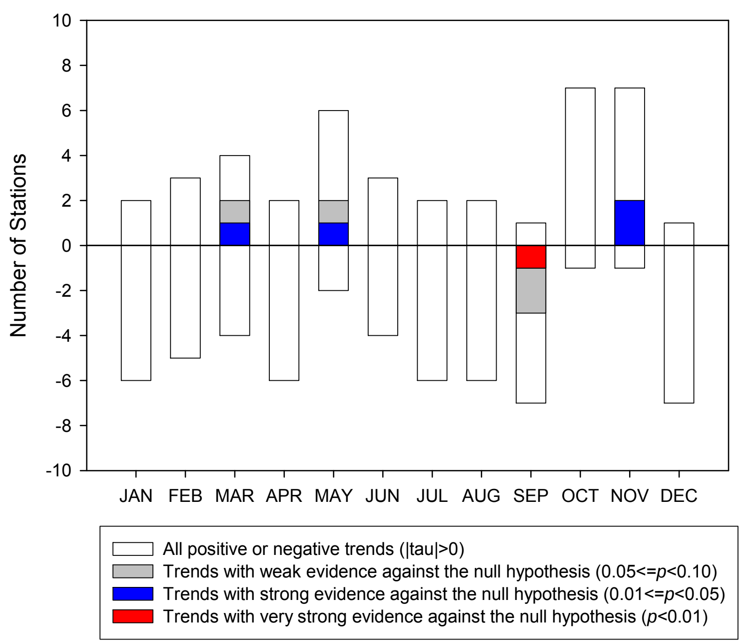

Figure 16. Frequency of trend direction and relative evidence of trends in monthly maximum precipitation over the period 1962-2008 based on data from the 8 stations identified in Table 3.

5.1.2 Discharge and Precipitation Frequency

Tests for trends in frequency used two types of tests – Mann-Kendall and Generalized Linear Modeling (GLM). The results using these two methods were not identical, but were very similar. Only the results of the GLM test are presented here. Results of the Mann-Kendall frequency trend tests can be found in Appendix A5 (USGS), Appendix B5 (DHSVM), and Appendix C5 (Precipitation).

The GLM test on USGS daily discharge frequency of exceedance of 2-yr, 10-yr, 25-yr, and 50-yr return intervals revealed mostly positive trends, although reliable trends were only detected for a few stations and return intervals (Appendix A8). Weak to strong evidence for upward trends in the frequency of exceedance of the 2-yr return interval flow was found at two stations – Skykomish River near Gold Bar (strong) and North Fork Snoqualmie (weak). Strong evidence of an upward trend was found for exceedance of the 10-yr return interval flow at North Fork Snoqualmie and weak evidence was found for an upward trend for the 25-yr return flow a the Snoqualmie River near Carnation. Figure 17 summarizes the number of positive and negative trends by return interval for the 10 stations that were evaluated for the period 1962-2008.

The GLM test on DHSVM modeled daily discharge frequency of exceedance of 2-yr, 10-yr, 25-yr, and 50-yr return intervals indicated mostly positive trends in the frequency of exceedance of 2-yr and 10-yr return intervals, a mix of upward and downward trends in the exceedance of the 25-yr return interval, and neutral to downward trends in the 50-yr return interval, although evidence for these trends ranged from unreliable to strong (Appendix B8). Strong evidence for upward trends in the frequency of exceedance of the 2-yr return interval was found for the Skykomish River near Gold Bar and the North Fork Snoqualmie River (Figure 18). Weak evidence for upward trends in the exceedance frequency in the same return interval was found for the Tolt River near Carnation and the Snoqualmie River near Carnation.

The GLM test on the frequency of exceedance of precipitation percentiles indicated mostly negative trends in the median or 50th percentile, a mix of upward and downward trend at the 75th-percentile, and predominantly upward trends in the 90th- and 95th-percentiles, with increasing evidence of upward trends as the percentile threshold increased (Appendix C8). Very strong evidence for upward trends was found for the South Fork Tolt (75th-, 90th-, and 95th-percentile) and strong evidence for SeaTac (95th-percentile) (Figure 19). Weak evidence for upward trends was found for SeaTac and Everett (90th-percentile) and Buckley (95th-percentile).

5.1.3 Discharge and Precipitation Duration

Tests for trends in duration of exceedances used two types of tests – Mann-Kendall and GLM. The results using these two methods were not identical, but were very similar. Only the results of the GLM test are presented here. Results of the Mann-Kendall frequency trend tests can be found in Appendix A6 (USGS), Appendix B6 (DHSVM), and Appendix C6 (Precipitation).

The GLM test on USGS daily discharge duration of exceedance of 2-yr, 10-yr, 25-yr, and 50-yr return intervals indicated a mix of upward and downward trends in duration of exceedance of the 2-yr return interval and mostly positive trends in the higher return intervals (Appendix A9). Figure 20 summarizes the number of positive and negative trends by return interval for the 10-stations that were evaluated for the period 1962-2008. The most substantial evidence of upward trends was found for the 10-yr return interval – 1 station with strong evidence (North Fork

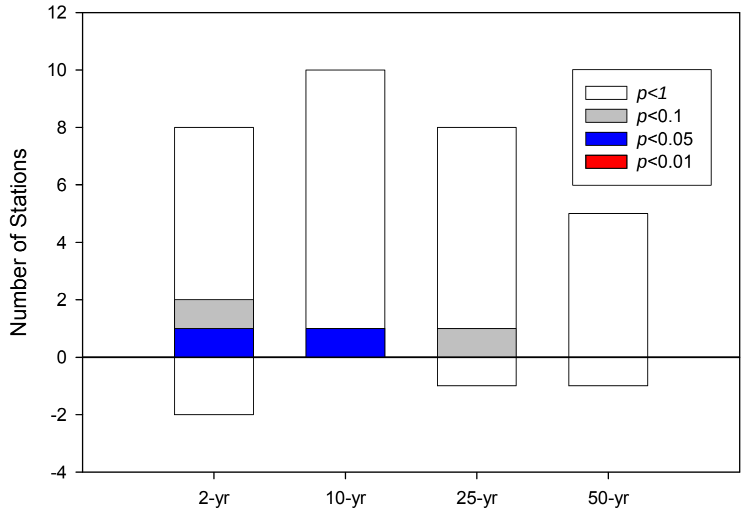

Figure 17. Frequency of trend direction and relative evidence of trends in the frequency of exceedance of 2-yr, 10-yr, 25-yr, and 50-yr flow return frequencies over the period 1962-2008 at the 10 USGS gauging stations identified in Table 1.

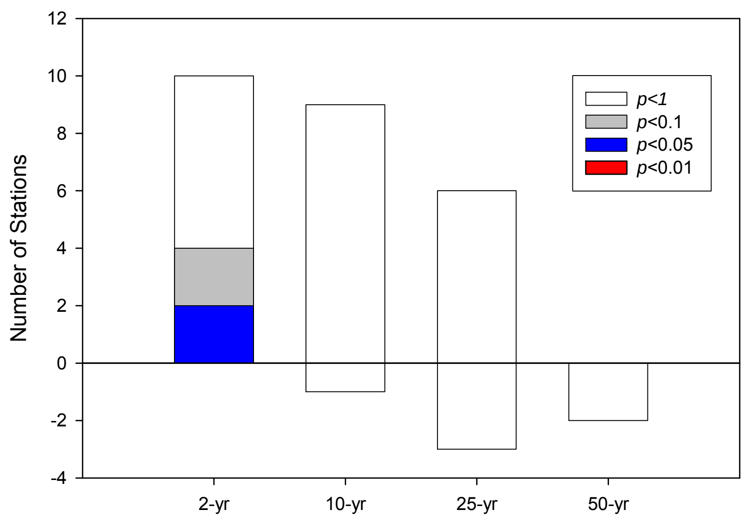

Figure 18. Frequency of trend direction and relative evidence of trends in the frequency of exceedance of 2-yr, 10-yr, 25-yr, and 50-yr flow return frequencies over the period 1962-2003 based on DHSVM output at the 10 USGS gauging stations identified in Table 1.

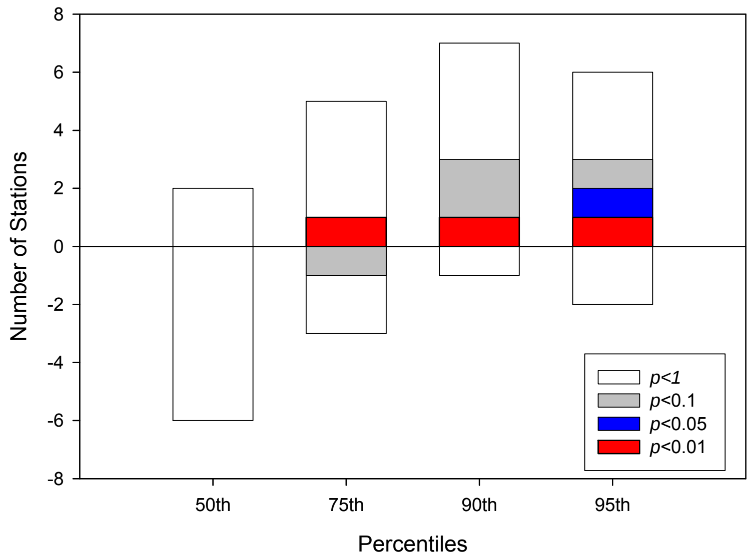

Figure 19. Frequency of trend direction and relative evidence of trends in the frequency of exceedance of 50th-, 75th-, 90th-, and 95th-percentile daily precipitation totals over the period 1962-2008 at the 8 precipitation stations identified in Table 3.

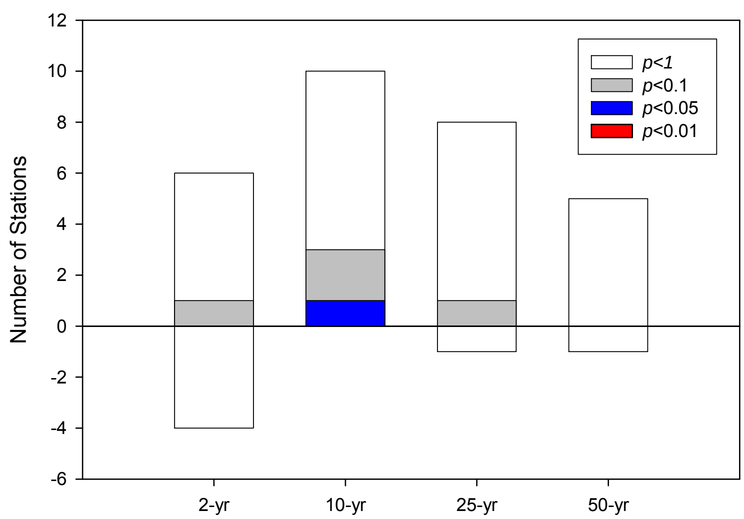

Figure 20. Frequency of trend direction and relative evidence of trends in the duration of exceedances of 2-yr, 10-yr, 25-yr, and 50-yr flow return frequencies over the period 1962-2008 at the 10 USGS gauging stations identified in Table 1.

Snoqualmie) and 2 stations with weak evidence (Snoqualmie River near Carnation and Cedar River near Cedar Falls).

The GLM test on DHSVM daily discharge duration of exceedance of 2-yr, 10-yr, 25-yr, and 50-yr return intervals indicated positive trends in the frequency of exceedance of the 2-yr return interval, a mix of upward and downward trends in the duration of exceedance of the 10-yr and 25-yr return interval, and neutral to downward trends in the 50-yr return interval, although evidence for these trends ranged from unreliable to strong (Appendix B9). Strong evidence for upward trends in the duration of exceedance of the 2-yr return interval was found for the Skykomish River near Gold Bar and the North Fork Snoqualmie River (Figure 21). Weak evidence for an upward trend in the duration of exceedance of the same return interval was found for the Snoqualmie River near Carnation.

The GLM test on the duration of exceedance of precipitation percentiles indicated mostly upward trends, with weak to strong evidence for trends in the duration of precipitation above the 90^{th}- and 95^{th}-percentiles (Appendix C9). Strong evidence for an upward trend was found for SeaTac (95^{th}-percentile) (Figure 22). Weak evidence for upward trends was found for Everett (90^{th}-percentile) and Buckley (95^{th}-percentile).

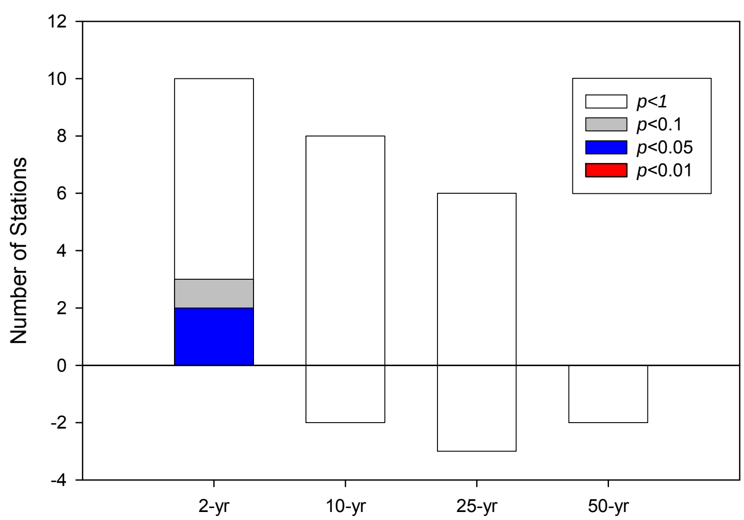

Figure 21. Frequency of trend direction and relative evidence of trends in the duration of exceedance of 2-yr, 10-yr, 25-yr, and 50-yr flow return frequencies over the period 1962-2003 based on DHSVM output at the 10 USGS gauging stations identified in Table 1.

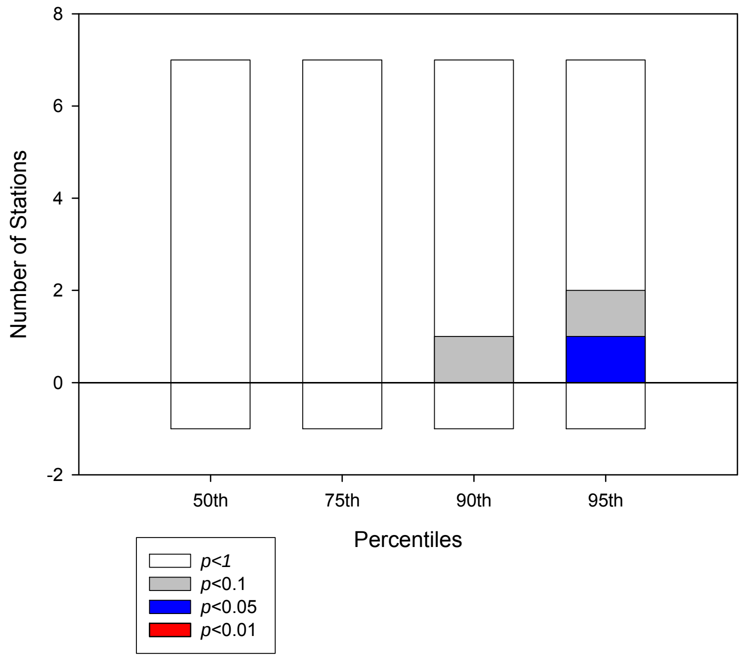

Figure 22. Frequency of trend direction and relative evidence of trends in the duration of exceedance of 50th-, 75th-, 90th-, and 95th-percentile daily precipitation totals over the period 1962-2003 at the 8 precipitation stations identified in Table 3.

5.1.4 Discharge and Precipitation Timing

The Mann-Kendall trend test on the timing of annual maximum discharge for the period 1962-2008 indicated 8 downward and 2 upward trends, but no reliable evidence was found (Appendix A7). Figure 23 shows the time series of the timing of the annual maximum discharge at each of the 10 stations over the period 1962-2008. Visual inspection of these records suggests a step change in the timing and the interannual variation in the timing of annual maximum discharge at several stations beginning after 1980. Of particular note are the increase in variability and earlier occurrence of high flows in some years after 1980 in the Skykomish River, the Tolt River near Carnation, the North Fork Snoqualmie, the Middle Fork Snoqualmie, the Snoqualmie River near Snoqualmie, the Snoqualmie River near Carnation, and the Cedar River near Cedar Falls (see Figure 23).

The trend test on the timing of annual maximum discharge predicted by DHSVM for the period 1962-2003 indicated 5 upward and 5 downward trends, but no reliable evidence for these trends was found (Appendix B7). Visual inspection of the time series of the timing of maximum discharge from 1962-2003 indicates patterns similar to those that can be seen in the USGS gauge observations (Figure 24). Variability appears to increase after 1980 at the same stations. Since land cover is fixed in the DHSVM model over the entire simulation, these patterns are most likely due to shifts in climate, although attribution of these shifts to global climate change or decadal variability can not be determined at this time.

The trend test on the timing of annual maximum precipitation indicated 7 downward (i.e., earlier timing) trends and 1 upward trend, with no reliable evidence for a trend except for one station (Appendix C7). There was strong evidence for a trend toward earlier timing of annual maximum precipitation at Everett (tau=-0.204; *p*=0.045). Figure 25 shows the time series of the timing of annual maximum precipitation at each of the 8 stations over the period 1962-2008. Visual inspection of these records suggests a step change in the timing and the interannual variation in the timing of annual maximum precipitation at several stations beginning after 1980.

Scatter plots that show the relationship between the timing and magnitude of annual maximum discharge (USGS and DHSVM) and precipitation (1962-2008) are shown in Figure 26, Figure 27, and Figure 28. Although these plots show that the DHSVM model results do not match the absolute magnitudes of observed flows, the predicted distribution of timing of annual maximum flows is similar with annual peak flows occurring between October and June of the following year with the highest peaks occurring around November (see Figure 26 and Figure 27). The distribution of annual precipitation maximums occurs over a broader time period than flows – between November and September of the following year (Figure 28). Consistent with the timing of discharge, highest maximum precipitation tends to occur around November.

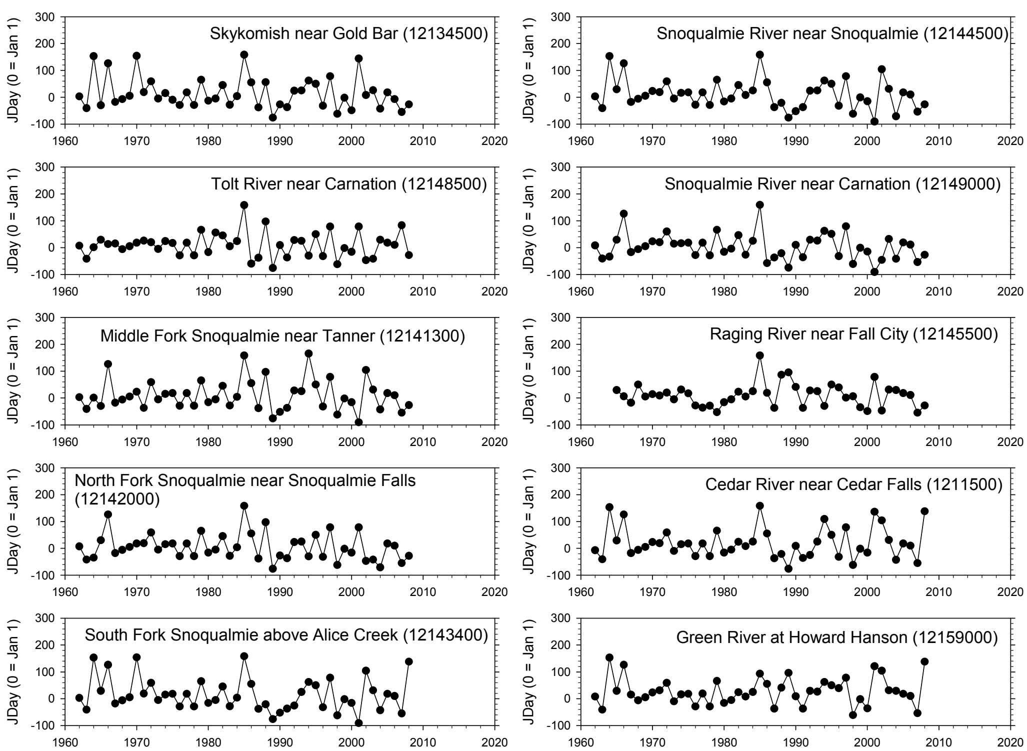

Figure 23. Time series plots of the timing of annual (water year) maximum discharge for the period 1962-2008 for the 10 USGS gauging stations identified in Table 1.

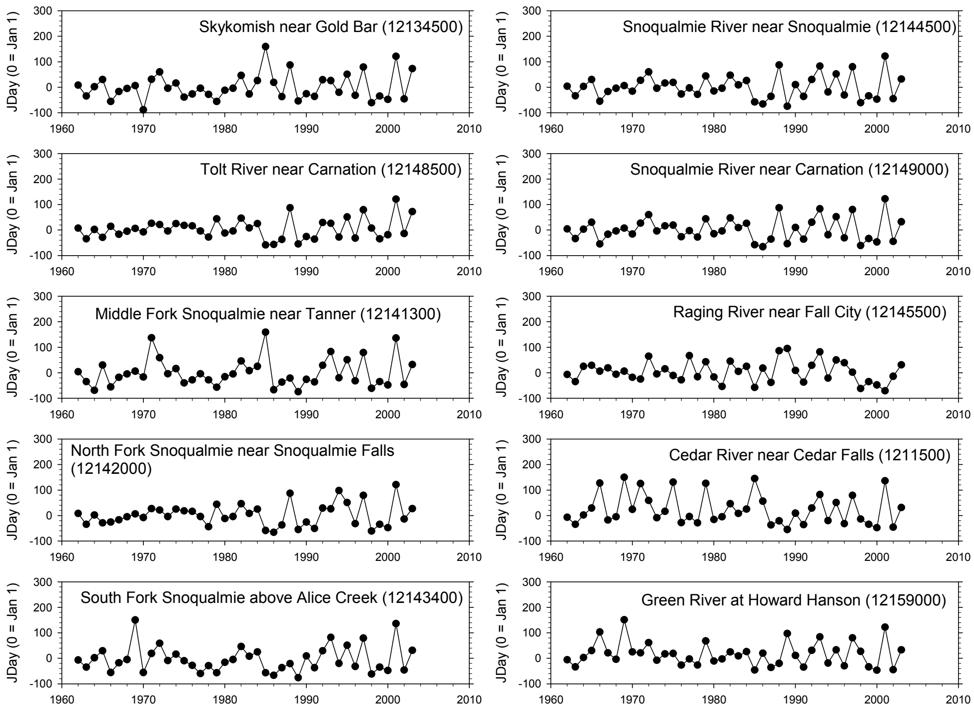

Figure 24. Time series plots of the timing of annual (water year) maximum discharge for the period 1962-2003 based on DHSVM output for the 10 USGS gauging stations identified in Table 1.

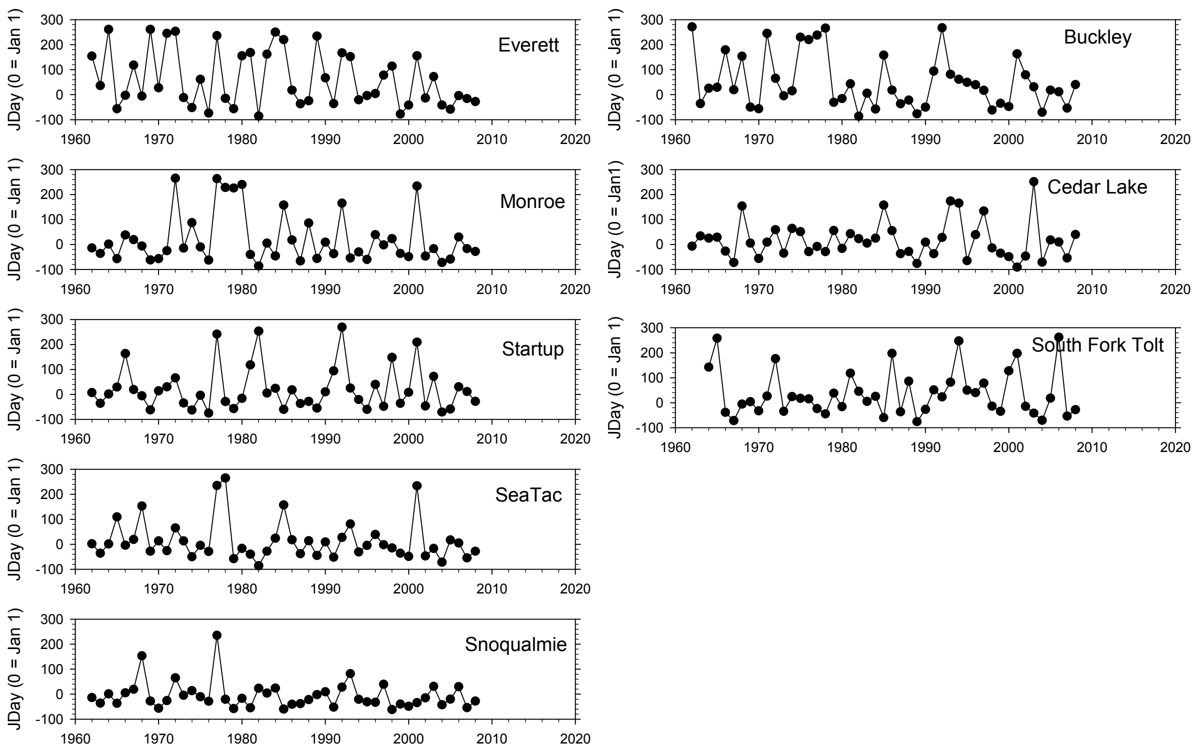

Figure 25. Time series plots of the timing of annual (water year) maximum precipitation for the period 1962-2008 based on the 8 stations identified in Table 3.

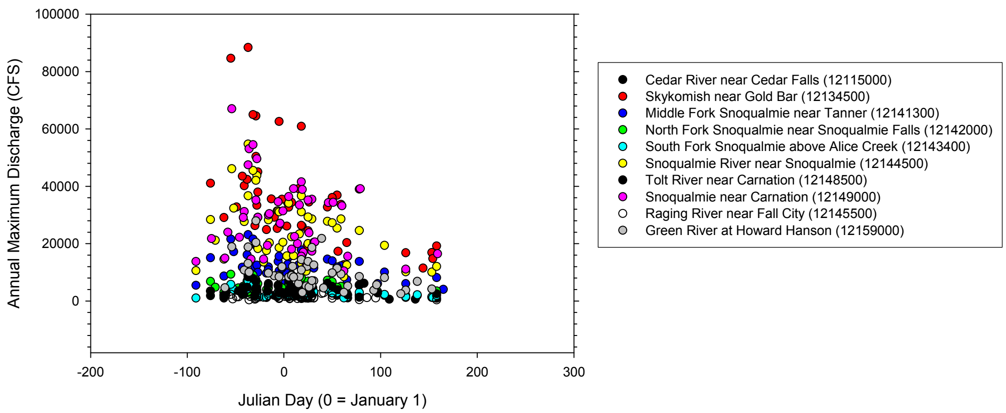

Figure 26. Scatter plot of the timing of annual (water year) maximum discharge vs. annual maximum discharge for the period 1962-2008 for the 10 USGS gauging stations identified in Table.

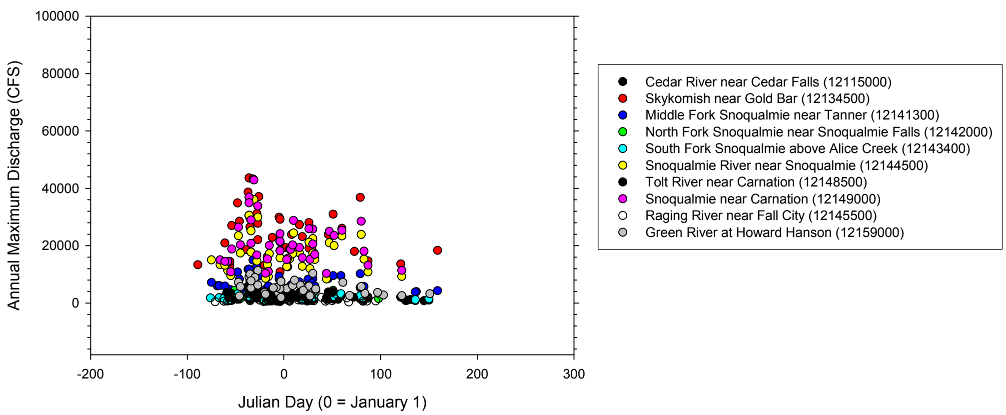

Figure 27. Scatter plot of the timing of annual (water year) maximum discharge vs. annual maximum discharge for the period 1962-2003 based on DHSVM output for the 10 USGS gauging stations identified in Table 1.

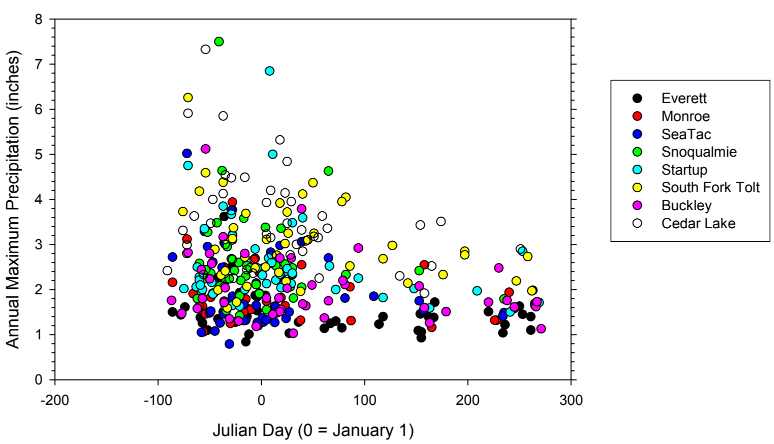

Figure 28. Scatter plot of the timing of annual (water year) maximum precipitation vs. annual maximum precipitation for the period 1962-2008 for the 8 stations identified in Table 3.

5.1.5 Discharge and Precipitation Percentiles

The results of the Mann-Kendall tests on trends in the annual flow percentiles from 0 (minimum) to 100 (maximum) in 10-percentile increments are provided in Appendix A10. Figure 29 shows the direction, magnitude (cfs per year), and relative strength of the evidence for trends for each station. Generally, strong to very strong evidence for downward trends was found for flow in the lower percentiles (0, 10, 20, and 30th-percentiles). Trends above the 30th-percentile and up to the 90th-percentile were consistently downward, but there was no reliable evidence for these trends. Trends in the 100th-percentile (i.e., annual maximum discharge) were consistently upward and of much greater magnitude than any of the other trends. However, evidence for these trends was not reliable, with the exception of strong evidence for an upward trend in the annual maximum flow in the Skykomish River near Gold Bar.

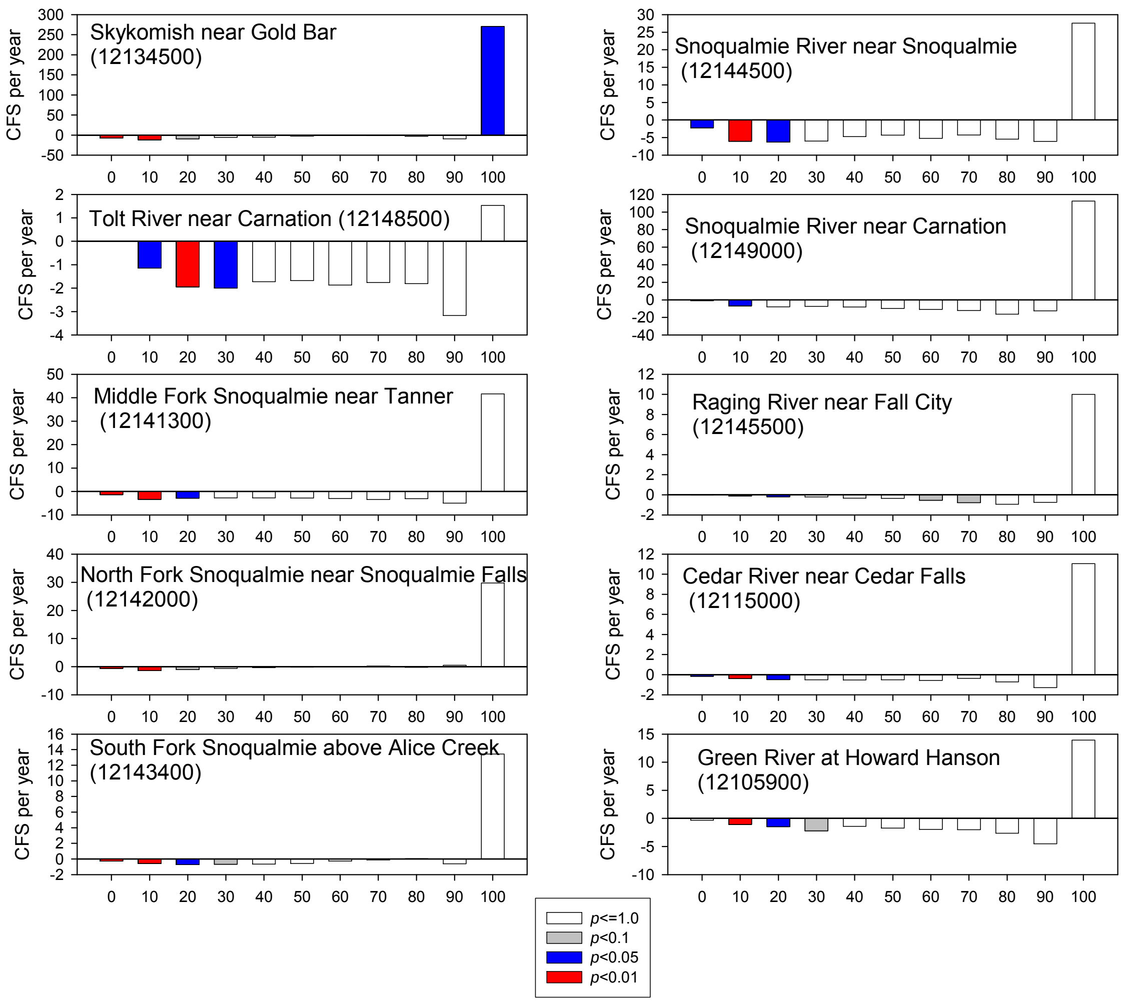

Figure 29. Direction, magnitude (cfs per year), and relative evidence of trends in annual percentiles of daily discharge over the period 1962-2008 at the 10 USGS gauging stations identified in Table 1.

The results of the trend tests on time series of annual flow percentiles predicted by DHSVM for the period 1962-2003 for the same USGS stations are provided in Appendix B10. The trend patterns were similar to those observed in the USGS observations – downward trends in the lowest percentiles (some with strong to very strong evidence) with an upward trend (with the greatest magnitude) in the 100th-percentile (Figure 30). However, upward trends were also observed in other high percentiles – 60, 70, 80, and 90th-percentiles.

The results of the trend tests on trends in the annual precipitation percentiles are provided in Appendix C10. Figure 31 shows the direction, magnitude (inches per 100 years), and relative strength of the evidence for trends for each station. Generally, relatively strong trends were upwards and in only the higher percentiles. Strong evidence for an upward trend was found for the 90th-percentile and very strong evidence was found for the 95th and 100th-percentile for the South Fork Tolt station.

5.2 Trends in Period of Record through 2008

The trend analysis results for records that extend back before 1962 can be found in Appendix D (USGS), Appendix E (DHSVM), and Appendix F (Precipitation). Figures similar to those presented above for trends over the period 1962 through 2008 are provided for trends over the period of record for discharge and precipitation gauges with longer records in Appendix G. In general, evidence for distinct trends is generally weak, although the pattern of increasing trends in river discharge and precipitation in November and February and overall declines in lower annual percentiles of daily discharge and an increase in the highest percentile equivalent to the annual maximum discharge reflect the trends noted above for the period 1962 through 2003.

5.3 Future Climate Scenario Discharge

The plots of monthly average flow for historic, 2000, 2025, 2050, and 2075 GCM-DHSVM model runs under the ECHAM5 A2 and IPSL CM4 A2 climate model scenarios predict a distinct shift in the magnitude and timing of spring runoff in river basins where winter rain and spring snowmelt runoff generate high flows (see Appendix H). Recall that the ECHAM5 A2 model predicted a moderate increase in temperature and precipitation by 2040 and the IPSL CM4 A2 model predicted an even larger increase in temperature and precipitation. To illustrate this shift, monthly average discharge predicted by DHSVM for the two climate model scenario combinations for current (2000) and future conditions (2025, 2050, and 2075) for the Snoqualmie River near Snoqualmie is presented in Figure 32. DHSVM output for the Snoqualmie River for the ECHAM5 A2 and IPSL CM4 A2 climate model runs indicate the potential for a shift from the current transient flow of winter and spring high flow events shifting to higher flow in winter (especially in January) as more precipitation over the basin falls as rain during winter rather than accumulating as snow and melting off in spring. Lower flows are also predicted for the spring and summer months in these model runs, particularly May through July.

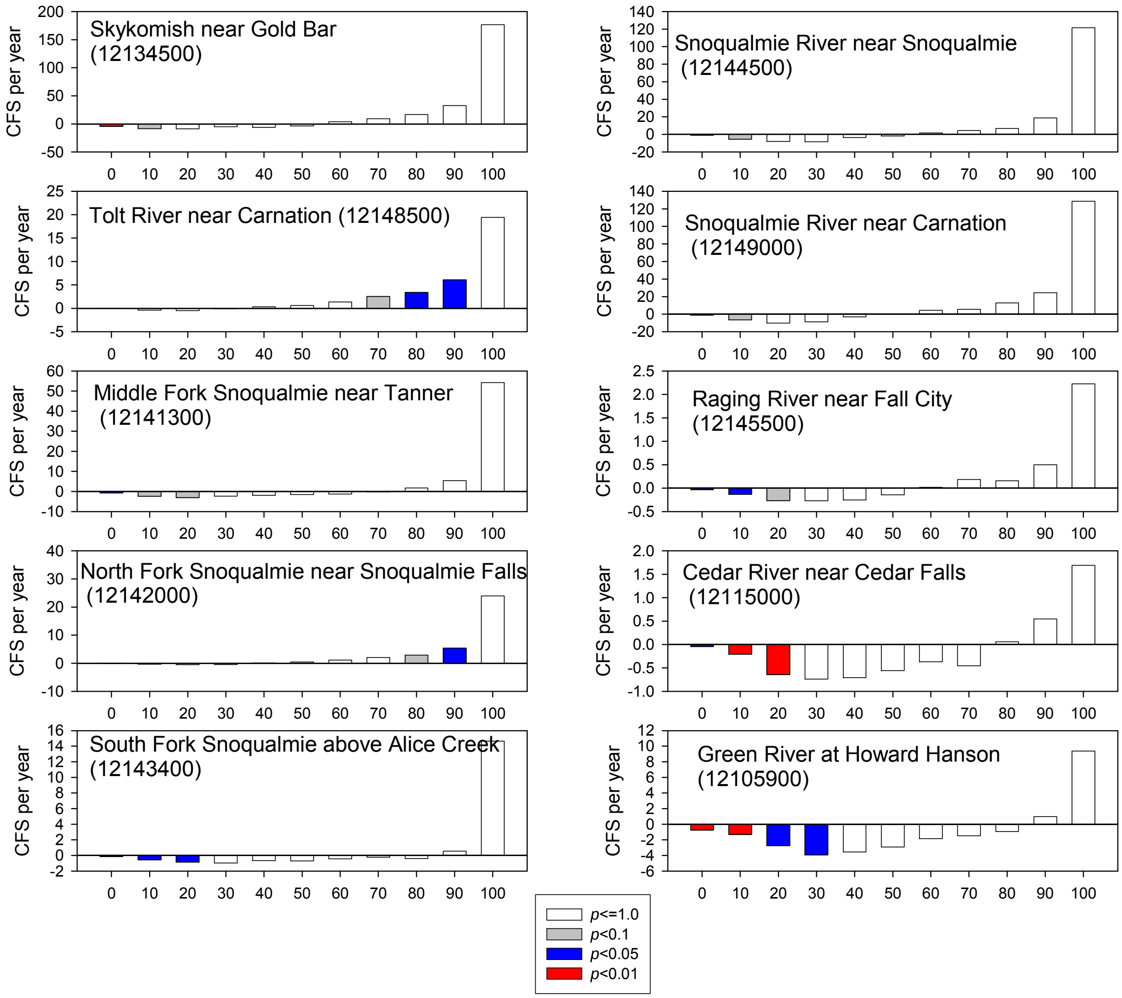

Figure 30. Direction, magnitude (cfs per year), and relative evidence of trends in annual percentiles of daily discharge over the period 1962-2003 based on DHSVM output at the 10 USGS gauging locations identified in Table 1.

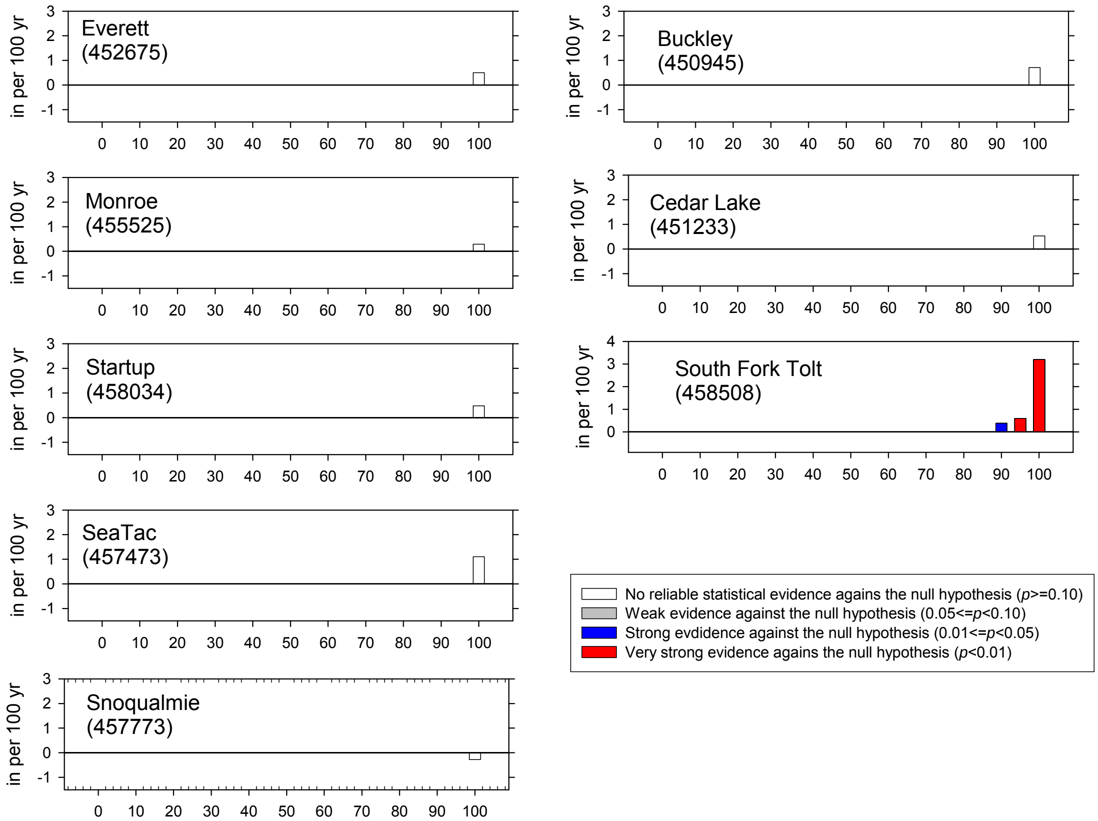

Figure 31. Direction, magnitude (inches per 100 years), and relative evidence of trends in annual percentiles of daily precipitation totals over the period 1962-2008 at the 8 stations identified in Table 3.

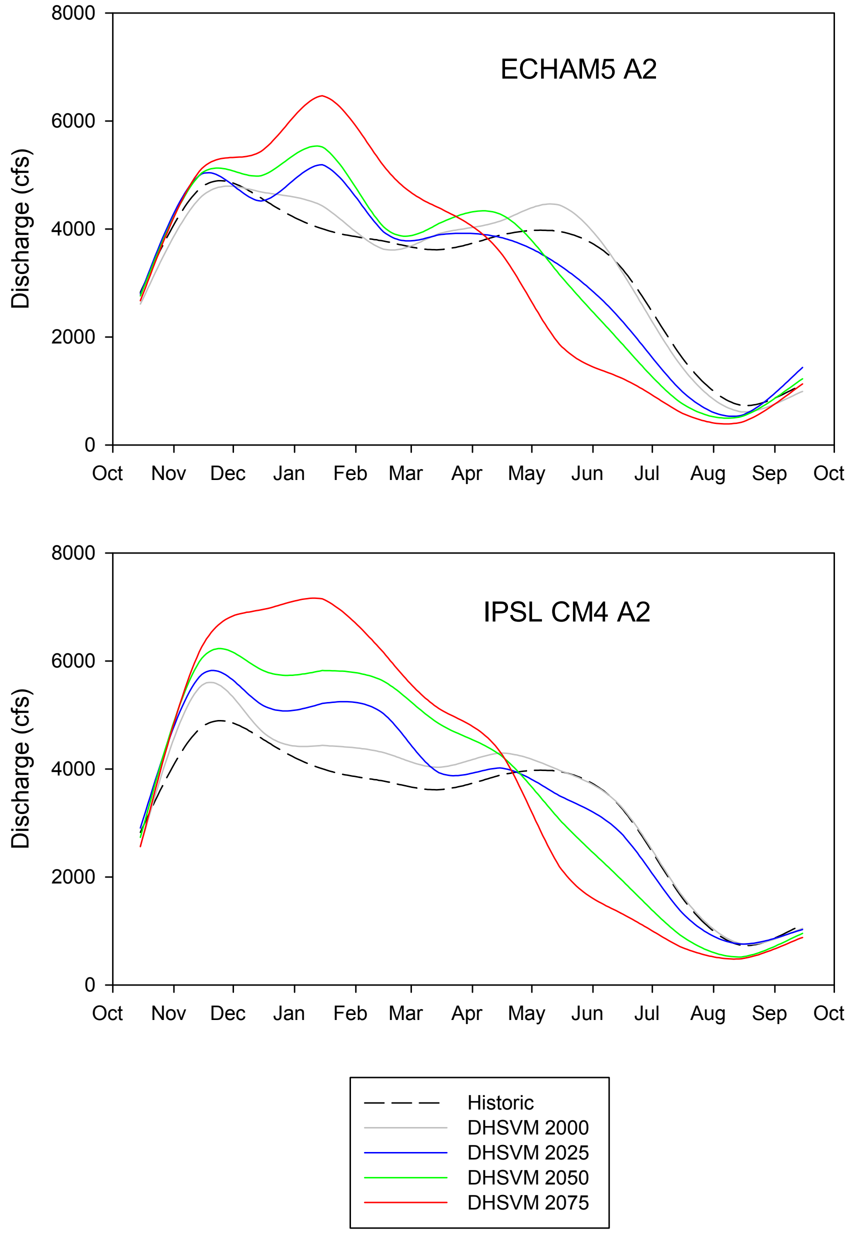

Figure 32. Projected monthly average flows for the Snoqualmie River near Snoqualmie (USGS 12144500) based on DHSVM output using downscaled climate predictions from the ECHAM5 and IPSL CM4 A2 Scenarios representing current and future periods centered on years 2000, 2025, 2050, 2075.

Note: Model-predicted historic monthly average for the same time period is also shown. Data provided by provided by Austin Polebitski and Richard Palmer as part of the work conducted for Regional Water Supply Planning Climate Change Technical Subcommittee (www.govlink.org/regional-water-planning/).

Another way of visually evaluating the shift in the magnitude of flows predicted by the GCM-DHSVM model runs is to plot the cumulative probability distribution of the flow predicted by a particular GCM-DHSVM model for current (2000) and predicted future (2025, 2050, and 2075) conditions (see Appendix I). Figure 33 shows the cumulative probability distribution of predicted flows for each GCM-DHSVM model run combination for the Snoqualmie River near Snoqualmie. Review of Figure 33 indicates that the ECHAM5 A2 and IPSL CM4 A2 predict increases in higher flows (and a dramatic decrease in lower flows).

Another way to evaluate potential shifts in future flow magnitudes is to plot the shift in projected magnitudes of various annual maximum daily flow return intervals. Generally, the ECHAM5 A2 and IPSL CM4 A2 DHSVM model runs indicate an increase in the magnitude of 1-yr, 2-yr, 5-yr, 10-yr, 20-yr, 50-yr, and 100-yr return flows (see Appendix J). Figure 34 illustrates the projected changes for the Snoqualmie River near Snoqualmie.

A potentially more relevant analysis is the illustration of projected changes in the frequency of exceedance of various King County flood warning levels. As an example, Figure 35 shows the change in the monthly frequency of exceedance of the Phase 1 flood warning level for the Snoqualmie River (6000 cfs), which is based on the sum of flows from the North, Middle, and South Forks of the Snoqualmie River. This figure illustrates the overall shift upward in the frequency of exceedance of the Phase 1 flood warning level and shift towards more frequent threshold exceedances in November through March for the ECHAM5 A2 and IPSL CM4 A2 model runs.

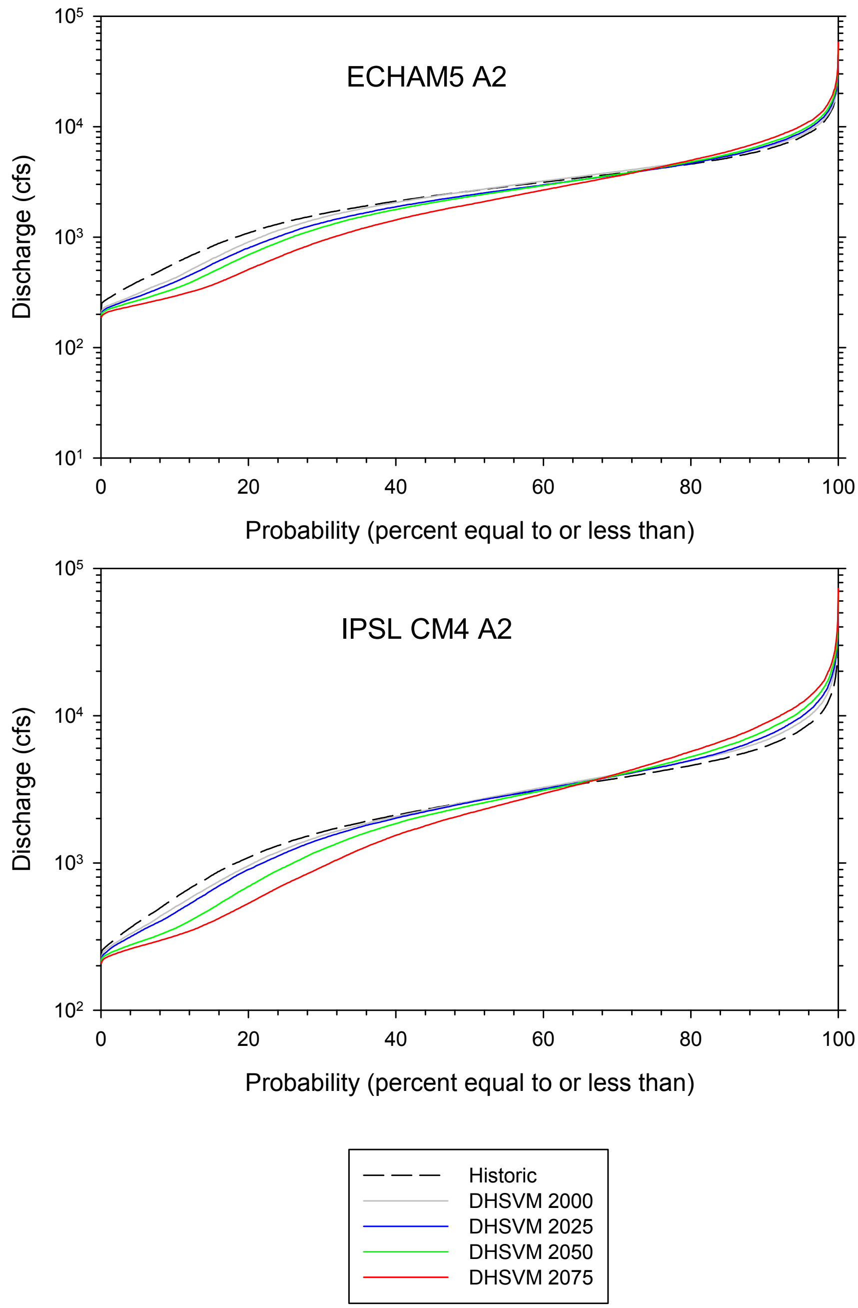

Figure 33. Projected daily cumulative distribution frequencies of flow at Snoqualmie River near Snoqualmie (USGS 12144500) based on DHSVM output using downscaled climate predictions from the ECHAM5 and IPSL CM4 A2 Scenarios representing current and future periods centered on years 2000, 2025, 2050, 2075.

Note: Model-predicted historic cumulative distribution frequency for the same time period is also shown. Data provided by provided by Austin Polebitski and Richard Palmer as part of the work conducted for Regional Water Supply Planning Climate Change Technical Subcommittee (www.govlink.org/regional-water-planning/).

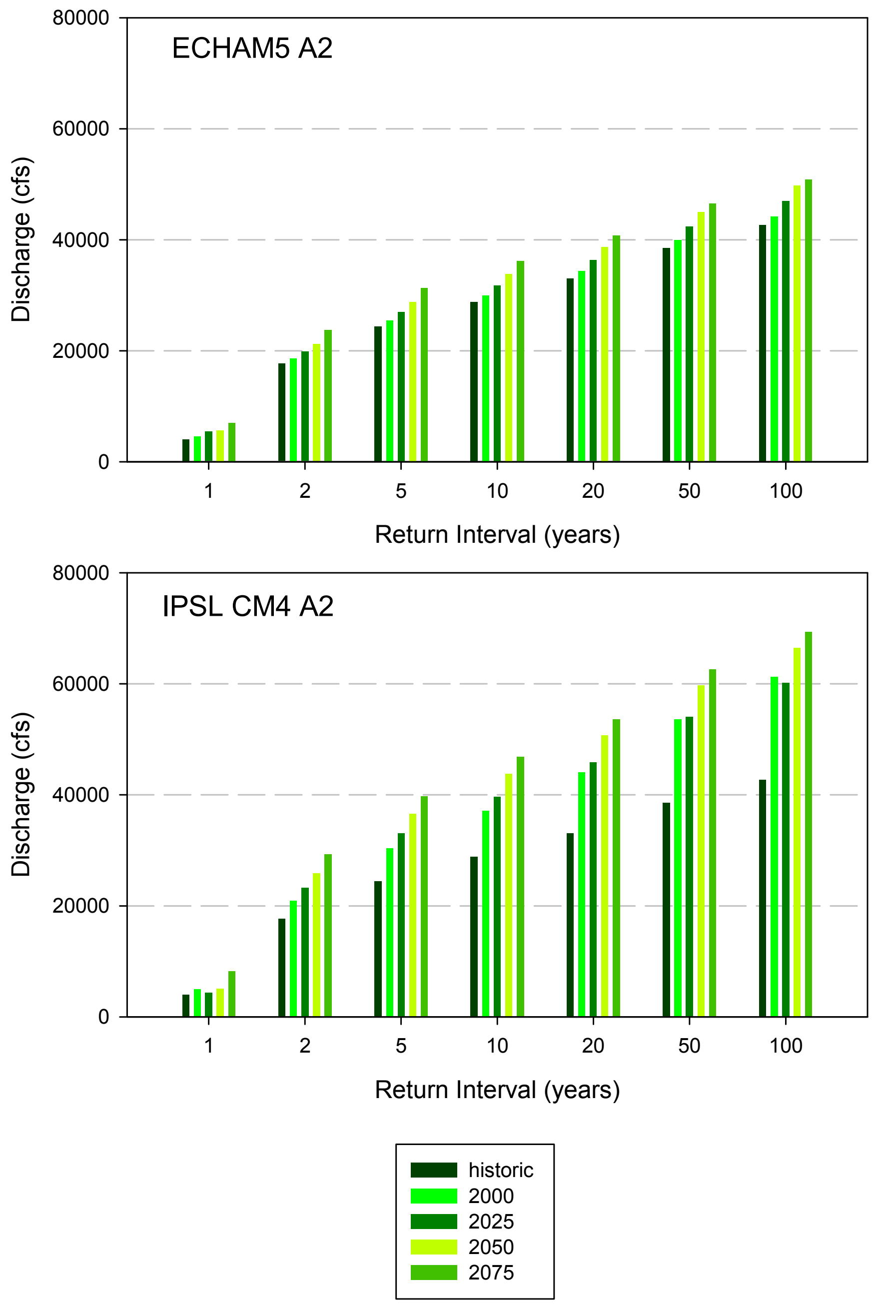

Figure 34. Projected return interval flows for Snoqualmie River near Snoqualmie (USGS 12144500) based on DHSVM output using downscaled climate predictions from the ECHAM5 and IPSL CM4 A2 Scenarios representing current and future periods centered on years 2000, 2025, 2050, 2075.

Note: Model-predicted historic return interval flows for the same time period are also shown. Data provided by provided by Austin Polebitski and Richard Palmer as part of the work conducted for Regional Water Supply Planning Climate Change Technical Subcommittee (www.govlink.org/regional-water-planning/).

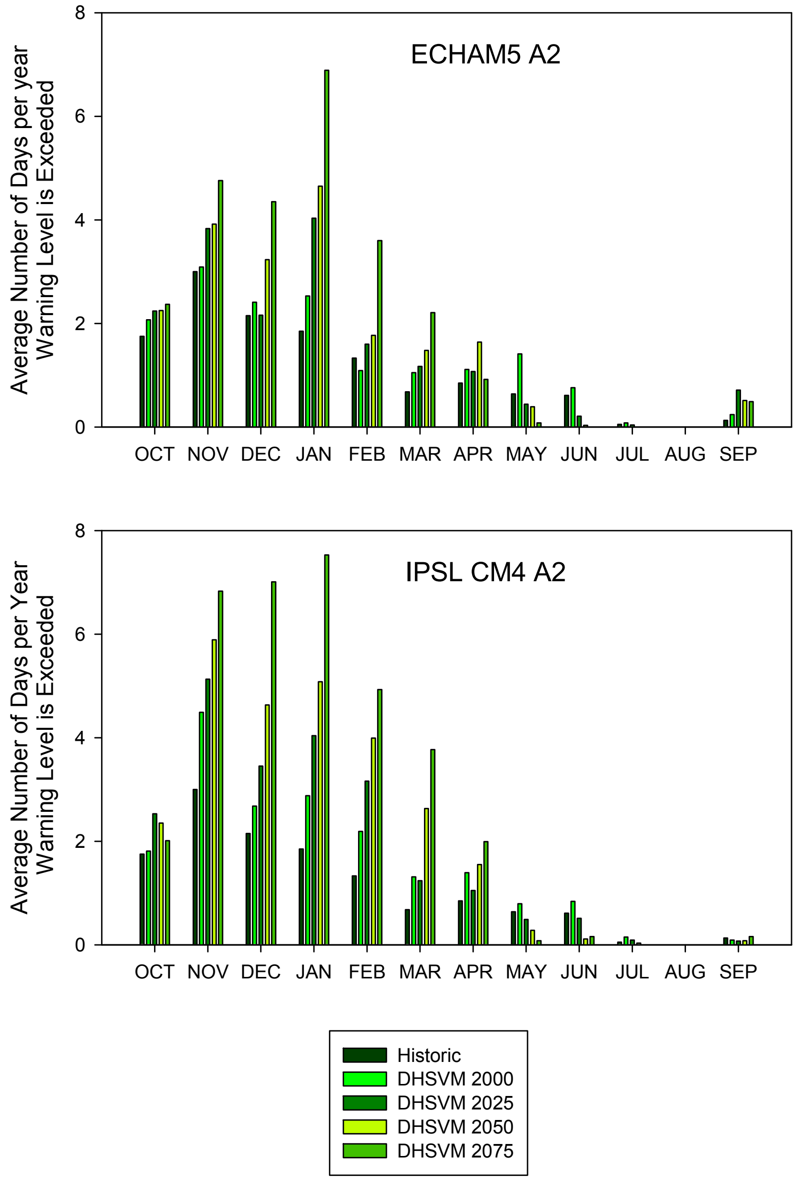

Figure 35. Monthly distribution of the annual average frequency of exceedance of the Phase 1 flood warning level (6000 cfs) based on the sum of DHSVM output for the North, Middle, and South Fork Snoqualmie River from the ECHAM5 and IPSL CM4 A2 Scenarios representing current and future periods centered on years 2000, 2025, 2050, 2075.

Note: Model-predicted historic exceedance frequency for the same time period is also shown. Data provided by provided by Austin Polebitski and Richard Palmer as part of the work conducted for Regional Water Supply Planning Climate Change Technical Subcommittee (www.govlink.org/regional-water-planning/).

6.0. DISCUSSION

6.1 Trends in Flow Magnitude

Trend analysis of long-term King County river discharge records (1962-2008) in nine unregulated rivers and the naturalized flow record for the Green River at Howard Hanson Dam provide strong evidence for declining trends in summer flow (Jul-Sep), but generally weak or unreliable evidence ($p \geq 0.1$) for upward trends in high flows. For example, upward trends in annual maximum discharge were found at all stations, but the evidence for trends was not reliable with the exception of strong evidence ($0.01 \leq p < 0.05$) of a trend for the Skykomish River near Gold Bar. There was also a seasonal pattern to the monthly flow trends, with most consistent upward trends in monthly average and maximum discharge in March and November. However, evidence for these upward trends was mostly unreliable, with the exception of weak evidence ($0.05 \leq p < 0.10$) for an upward trend at the North Fork Snoqualmie River near Snoqualmie Falls.

The results of the trend analysis of annual flow percentiles complimented the findings of the annual and monthly trends (see Figure 29). Consistent declining trends in the annual minimum through 90th percentile flows were found in all rivers, with strong and very strong ($p < 0.01$) evidence for declining trends in the minimum through 20th percentile flows. The annual maximum (100th percentile) flow trend was consistently upward, but only the Skykomish River trend was considered to have strong evidence of a trend.

6.2 Trends in High Flow Frequency and Magnitude

Trends in the frequency of exceedance of the 2-yr, 10-yr, 25-yr, and 50-yr return flows were most typically upward, with most trends unreliable, with the exception of weak to strong evidence of trend limited to upward trends in the frequency of exceedance of the 2-yr and 10-yr flows on the Skykomish near Gold Bar and the North Fork Snoqualmie River near Snoqualmie Falls. Trends in the duration of exceedances of the frequency of exceedance of 2-yr, 10-yr, 25-yr, and 50-yr return flows was also most typically upward, with weak to strong evidence for upward trends in the duration of flows greater than the 2-yr and 10-yr flow return frequencies (Cedar River near Cedar Falls, Snoqualmie River near Carnation, North Fork Snoqualmie, and the Skykomish River).

6.3 Trends in Annual Maximum Flow Timing

Trends in the timing of annual maximum discharge indicated primarily negative trends (i.e., trend toward earlier peak runoff in each water year (exceptions were naturalized Green River at Howard Hanson and Tolt River near Carnation), although the evidence for these trends was not reliable. Visual inspection of time series plots of the timing of the annual maximum discharge suggested a shift toward earlier and/or more variable timing of the annual maximum discharge after 1980 (see Figure 23).

6.4 Transient Rain-on-Snow Basins

Based on the plots of monthly discharge statistics and the rain-on-snow map (Figure 6 and Figure 7, respectively), the river basins evaluated in this report are transient (i.e., influenced by spring snowmelt and winter snow and rainfall runoff). The Raging River is an exception and is dominated by winter rainfall runoff. Although variation in the depth and cover of snow in the transient basins evaluated here combine with the timing of extreme rainfall events to generate extreme river flows, compilation and analysis of monthly snow accumulation data was beyond the scope of this initial study. Recent studies of snowpack trends (e.g. Casola et al., 2009; Stoelinga et al., 2010) have noted that long-term trends in snowpack are difficult to detect due to the large interannual and long term natural variability of the data. Using more sophisticated techniques, these studies have identified and quantified historic snowpack declines and projected future snowpack declines in response to global and regional warming in response to anthropogenic climate change. Nonetheless, it appears that the identified flow trends can be related, at least in part, to trends observed in precipitation.

For example, the trends in annual maximum precipitation over the same period (1962-2008) were generally upward (exception Snoqualmie station), although the evidence for trends was unreliable with the exception of the very strong evidence ($p<0.01$) for the South Fork Tolt station. Monthly total precipitation also generally trended downward July through September consistent with the downward trends in average discharge in these months. Upward trends in maximum precipitation in October and November, with one exception (Cedar River near Cedar Falls), with strong evidence of an upward trend in November at two stations (Everett and South Fork Tolt), are consistent with the observed upward trends in November discharge (see Figure 13 and Figure 16). Observed upward trends in river discharge in March are not as easily explained by upward trends in precipitation, as trends in March maximum precipitation were equally divided between upward and downward trends, although there was stronger evidence for the upward trends (Buckley-weak evidence; South Fork Tolt-strong evidence). These results are consistent with winter (November) rain and spring (March) snow-rain influence in these basins.

The trend towards earlier timing of annual maximum precipitation, although lacking reliable evidence, is consistent with the trend toward earlier timing in maximum discharge. Comparison of the scatter plots of the timing of annual maximum discharge and precipitation illustrate how closely annual peak discharge and precipitation are coupled, with the most extreme events (precipitation and discharge) typically occurring in November or December (see Figure 26 and Figure 28).

Although it appears that an upward shift in annual maximum discharge may have occurred sometime in the 1970s, it seems plausible that some of the observed upward trends in annual maximum discharge may be associated with another apparent shift upward in annual extreme precipitation after 1980 (see Figure 8 and Figure 10).

6.5 Evaluation of Hydrology Model for Extreme Flow Analysis

In order to project the potential effect of global climate change on local river flow, we have used hydrologic model output provided by the University of Washington. The model development and calibration was documented by Polebitski et al. (2007a) in the context of the use of the model for regional water supply planning in response to climate change. By evaluating the modeled discharge representing 1962-2008 flow conditions in the same way the observed USGS data were analyzed for trends, it is possible to make some assessment of the ability of the model to capture relevant changes in flow magnitude in response to climate change.

Comparisons of the observed and modeled percentile time series plots of discharge indicate that the model did not reproduce the relative magnitude of annual maximum events; particularly after 1970 (see Figure 8and Figure 9). Nonetheless, the trend test results for annual maximum discharge were very similar to that for the observed data – consistent upward trends with no reliable evidence. The consistent downward trend in monthly average flows with weak to strong evidence was also reflected in the modeled flows, although the consistent declining trend extended into October (see Figure 11 and Figure 12). The upward trend in monthly maximum discharge in March and November was also reproduced in the modeled flows, mostly upward trends with weak to strong evidence also occurred in February, April, and May in the modeled flows (see Figure 13 and Figure 14). Trends in annual percentile flows based on the DHSVM model were similar to those in the observed data – declining trends in the lower flow percentiles and upward trends in the annual maximum (100th percentile) flow, but the modeled discharge also indicated upward trends in upper percentile flows (40th to 90th percentiles) at some stations. Weak to strong evidence for some of these upward trends in modeled discharge was found at the Tolt River near Carnation and North Fork Snoqualmie River stations (see Figure 29 and Figure 30).

Trends in the frequency of exceedance of 2-yr, 10-yr, 25-yr, and 50-yr return flows based on modeled discharge reflected the general pattern of trends in the observed data, with consistent upward trends in the frequency of exceedance of shorter return period flows (2-yr and 10-yr) (see Figure 17 and Figure 18). The pattern of trends in the duration of exceedances of the same return flow thresholds was not reproduced well by the modeled discharge. Trends in the duration of exceedances in the modeled discharge were consistently upward with weak to strong evidence at three locations, with declining numbers of upward vs. downward trends, where trends in the observed data were mixed at the 2-yr flow threshold with more evidence for trends at the 10-yr return flow threshold (see Figure 20 and Figure 21).

With respect to trends in timing, the timing of annual maximum of modeled discharge was mixed between upward and downward trends compared to the observed flow data that indicated more consistent (8 of 10 stations) downward trends (i.e., earlier timing), although no reliable evidence was found for any of these trends (see Figure 23 and Figure 24).

In general, it appears that the flows modeled using DHSVM do not reproduce the magnitude of extreme events over the period 1962-2008 very well, but the model does reproduce much of the relative trend in extreme (high and low) flow magnitudes. The model also appears to reproduce the frequency of exceedance of various return interval flows, but does not reproduce trends in high flow duration or timing very well.

In general, all models have embedded uncertainties (theoretical, conceptual, empirical, parametrical, and spatial/temporal) that result from the multitude of assumptions, simplifications, and errors in the model and the data used in model development and calibration (Oreskes, 1998). All models are necessarily simplifications of the real world. In general, it is impossible to demonstrate the predictive reliability of a model of a complex natural system ahead of time. The real test of the predictive reliability of any model requires testing the model against new and improved monitoring data as climate changes and management decisions and actions are implemented across these study basins. However, the potential usefulness of any model is a function of its calibration, quality of the data, and the proposed application of the model.

That the model does not reproduce all of the observed trends in the flow metrics is not surprising as this was not a focus of the model calibration process (Polebitski et al., 2007a). Since the primary purpose of the DHSVM modeling was to provide reliable reservoir inflows for the evaluation of potential future climate change impacts on water supply, the focus of model calibration was on matching cumulative flow and flow timing on a monthly scale. Attention was also given to calibrating the model to match daily high and low flows, but extremely high flows were often under-predicted (Polebitski et al., 2007a). Polebitski et al. (2007a) also acknowledge the difficulty in demonstrating the reliability of the model to reproduce the daily winter accumulation and loss of snow cover since the observations of snow water equivalent are typically for a few single points that are not representative of area and depth of snow cover over these basins, which is the model output that needs to be confirmed with data. Another point made by Polebitski et al., (2007a) is that the model assumes that the land cover (primarily managed forests in these basins) is static over the simulation period, so if changes in forest cover, maturity, and/or management practices have had an appreciable affect on extreme flows in any of these basins, the model is not expected to reproduce these effects.

Despite these caveats, it is our judgment that evaluation of the hydrologic model output based on potential future climate conditions provides an initial indication of the direction and magnitude of expected changes in extreme flows.

6.6 Evaluation of Future Climate Impacts on Extreme Flow Events

The projections based on downscaled data from the ECHAM5 A2 and IPSL CM4 A2 hydrologic model runs are consistent with historical trends, albeit with weak evidence, in extreme high (and low) flows. Both GCMs under Scenario A2 predicted increasing magnitudes extreme flows from 2000 through 2075 for almost all return intervals considered (see Figure 34 and Appendix J). The downscaled GCM-DHSVM runs also predicted declines in summer flow (see Figure 32 and Appendix H) that are consistent with the mostly strong and very strong downward trends in summer flow (see Figure 11 and Figure 29). The shift toward consistently higher winter flows predicted by the models is not as closely reflected in the historical data, which showed the most consistent upward trends (with little reliable evidence) for the months of March and November (see Figure 11). The predicted shift toward earlier runoff timing is also consistent with the trends in the timing of annual maximum discharge, although the evidence for historic trends was unreliable.

In general, the same qualifications apply to the downscaled climate model simulations that have been used as input for simulations of future flow conditions using DHSVM – the global climate models (or GCMs) have embedded uncertainties and are necessary simplifications of the real world. These models are also inherently difficult to test primarily due to the large difference in scale of the GCM grids (measured in hundreds of square kilometers) and the scale of local observations of weather.

However, since the modeling work summarized in this report was conducted, an effort has been made to further evaluate the quality of the historic realizations of 20 GCMs with respect to simulating local climate conditions (Mote and Salathé, 2009; Hamlet et al., 2010). These evaluations were conducted with the intent of developing a reliability ensemble averaging approach to weight results from relatively better model in an ensemble averaging approach (Mote and Salathé, 2009) or to select a smaller subset of most reliable models for use in the assessment (Hamlet et al., 2010). The evaluations have included bias in the prediction of precipitation and temperature, ability to reproduce observed temperature trends, and the ability of each model to reproduce the spatial variability of sea level pressure. Sea level pressure is an indicator of the ability of the models to correctly simulate the location and intensity of the Aleutian Low, which plays a significant role in the delivery of winter rain to the coast of the Pacific Northwest.

Based on these evaluations, the 20 models were ranked and the GISS ER model was ranked last by Mote and Salathé (2009) due primarily to its poor ability to reproduce the distribution of sea level pressure. GISS ER also did not appear in the top 10 models selected by Hamlet et al. (2010) for use in a recent climate change assessment of the Columbia River, Puget Sound, and coastal basins. The IPSL CM4 model was ranked 19th overall by Mote and Salathé (2009), but did appear in the top 10 (but not in the top 5) models selected by Hamlet et al. (2010). ECHAM5 was ranked 4th by Mote and Salathé (2009) and appeared in the top 5 models selected by Hamlet et al. (2010).

In addition to consideration of the ability of any particular GCM to reliably simulate major features of regional climate, there are particular strengths and weaknesses of the various methods used to downscale GCM predictions, which are generally made at a fairly coarse resolution, to a finer scale for use in basin-scale hydrologic models. Elsner et al. (2009) and Hamlet et al. (2010) provide a detailed discussion of the available downscaling methods and their pros and cons. In the downscaled hydrologic model output analyzed here, Polebitski et al. (2007b) used a form of bias correction and statistical downscaling (BCSD) to convert GCM model predictions to daily hydrologic model inputs. Hamlet et al. (2010) caution the use of the BCSD approach for daily flood risk analysis because of downscaling artifacts not associated with the GCM that can be introduced by this method. Another method known as the Delta Method was employed in the Washington Climate Change Impacts Assessment (Climate Impacts Group, 2009). This method is somewhat simpler and is immune to the potential downscaling artifact described for the BCSD method, but it does not capture information about within-month changes in timing, duration, or spatial variability of extremes simulated by the GCM.

Selection of GCMs for future studies focused on the evaluation of climate change impacts on extreme river flows should use the rankings and approaches described by Mote and Salathé (2009) and Hamlet et al. (2010) as guidance. Care should also be given to the choice of downscaling methods used – perhaps considering the use of a hybrid method (Delta-BCSD) introduced by Hamlet et al. (2010).

7.0. SUMMARY AND CONCLUSIONS

Although little of the evidence for trends in the magnitude, frequency, duration, and timing of maximum precipitation and flow was strong or very strong, patterns in trend direction across the study area since 1962 suggest a shift to earlier runoff timing (spring to winter) and increases in magnitude of extreme precipitation and discharge events. These results are consistent with the results of other trend studies (e.g., Polebitski and Palmer, 2006; Madsen and Figdor, 2007) and modeling studies (e.g., Polebitski and Palmer, 2006; Elsner et al., 2009; Hamlet et al., 2010) of the effect of future climate change on regional river flows. Detection and attribution studies that use a combination of global climate models, hydrologic models, and observations to detect the influence of anthropogenic climate change effects beyond the range of natural historic variability are also consistent with the results of this study (Barnett et al., 2008; Das et al., 2009; Hidalgo et al., 2009).

Ideally, we would use results from a larger number of global climate models and scenarios to provide an indication of the range and central tendency of the potential impacts of future climate change on King County river flows, such as might be provided with an ensemble approach (Climate Impacts Group, 2009; Hamlet et al., 2010).

The results of the analyses presented in this report suggest an increase in the magnitude, duration, frequency, and a trend toward earlier timing of extreme precipitation and river flow that is the result of some combination of natural background variation in precipitation during the period of record, and climate change-related shifts in temperature (upward) and snow accumulation and melt. The detection of these trends is difficult not only because of the relative infrequent nature of extreme events and the record lengths evaluated (Type II errors), but difficult also because of changes in land cover (primarily forest harvest and regrowth) that have occurred over the period of analysis (Bowling et al., 2000; Moore and Wondzell, 2005; Grant et al., 2008). Nonetheless, it seems probable that the evidence for trends in extreme flows will become stronger if the potential climate impacts on river flows in King County described in this report are any indication of future river flow conditions.

Traditionally, flood management has been based on the use of historical data to estimate return probabilities of floods of specific magnitudes. However, trends in observed data and modeling of potential future conditions suggest that this approach (based on the assumption of stationarity) is no longer valid. Unfortunately, there is no other approach to this type of analysis that has reached the level of what might be considered a consistent standard practice that would be suitable for a nationwide flood management program like the Federal Emergency Management Agency (FEMA). The issue of stationarity and the potential of a future hydrologic regime with every greater frequency and magnitude of high flows also suggest more integrated water management approaches (Green, 2004; Meyer et al., 2009).

In general, given the preliminary evidence of changes to date, and the anticipated future changes based on computer modeling, it seems reasonable to pursue management strategies that facilitate adaptation to potential future increases in the frequency and magnitude of large floods (Whitely-Binder et al., 2009; Cromwell et al., 2009).

8.0. REFERENCES

Barnett, T.P. et al. 2008. Human-induced changes in the hydrology of the western United States. Science 319:1080-1083.

Beechie, T., E. Buhle, M. Ruckelshaus, A. Fullerton, and L. Holsinger. 2006. Hydrologic regime and the conservation of salmon life history diversity. Ecological Conservation 130:560-572.

Bonfils, C. et al. 2008. Detection and attribution of temperature changes in the mountainous western United States. Journal of Climate 21:6404-6424.

Bowling, L.C., P. Stork, and D.P. Lettenmaier. 2000. Hydrologic effects of logging in western Washington, United States. Water Resources Research 36(11):3223-3240.

Brettman, K. 20 October 2008. Personal communication (e-mail to Curtis DeGasperi, King County, DNRP). Seattle District , U.S. Army Corps of Engineers, Seattle, WA.

Casola, J.H., L. Cuo, B. Livneh, D.P. Lettenmaier, M. Stoelinga, P.W. Mote, and J.W. Wallace. 2009. Assessing the impacts of global warming on snowpack in the Washington Cascades. Journal of Climate 22:2758-2772. DOI:10.1175/2008JCLI2612.1

Climate Impacts Group. 2009. The Washington Climate Change Impacts Assessment, M. McGuire Elsner, J. Littell, and L Whitely Binder (eds). Center for Science in the Earth System, Joint Institute for the Study of the Atmosphere and Oceans, University of Washington, Seattle, Washington. Available at: http://www.cses.washington.edu/db/pdf/wacciareport681.pdf

Cromwell III, J.E., R.D. Colton, S.J. Rubin, J. Mobley, K. Reinhardt, R. Wilson, and C.N. Herrick. 2009. Implications of Climate Change for Adaptation by Wastewater and Stormwater Agencies. Water Environment Research Foundation, Denver, CO. Project No. CC2R08.

Cuo, L., D.P. Lettenmaier, M. Alberti, and J.E. Richey. 2009. Effects of a century of land cover and climate change on the hydrology of the Puget Sound basin. Hydrological Processes 23:907-933. DOI: 10.1002/hyp.7228

Das, T., H.G. Hidalgo, M.D. Dettinger, D.R. Cayan, D.W. Pierce, C. Bonfils, T.P. Barnett, G. Bala, and A. Mirin. 2009. Structure and detectability of trends in hydrological measures over the Western United States. Journal of Hydrometeorology 10:871-892. DOI: 10.1175/2009JHM1095.1

Dettinger, M. 2004. Fifty-two years of "Pineapple-Express" storms across the west coast of North America. Prepared for California Energy Commission. Scripps Institution of Oceanography, San Diego, CA.

Elsner, M.M., L. Cuo, N. Voisin, J.S. Deems, A.F. Hamlet, J.A. Vano, K.E.B. Mickelson, S.-Y. Lee, and D.P. Lettenmaier. 2009. Implications of 21st Century Climate Change for the Hydrology of Washington State. Chapter 3. In: The Washington Climate Change Impacts Assessment, M. McGuire Elsner, J. Littell, and L. Whitely Binder (eds). Center for Science in the Earth System, Joint Institute for the Study of the Atmosphere and Oceans, University of Washington, Seattle, Washington. http://cses.washington.edu/db/pdf/wacciach3hydrology644.pdf

Flynn, K.M., W.H. Kirby, and P.R. Hummel. 2006. User's manual for program PeakFQ, Annual Flood Frequency Analysis Using Bulletin 17B Guidelines: U.S. Geological Survey Techniques and Methods Book 4, Chapter B4, 42 pgs. http://water.usgs.gov/software/PeakFQ/, accessed September 5, 2008.

Frei, C. and C. Schär. 2001. Detection probability of trends in rare events: Theory and application to heavy precipitation in the Alpine Region. Journal of Climate 14:1568-1584.

Grant, G.E., S.L. Lewis, F.J. Swanson, J.H. Cissel, and J.J. McDonnell. 2008. Effects of Forest Practices on Peak Flows and Consequent Channel Response: A State-of-Science Report for Western Oregon and Washington. Pacific Northwest Research Station, U.S. Department of Agriculture. General Technical Report PNW-GR-760. http://www.fs.fed.us/pnw/pubs/pnw_gtr760.pdf

Green, C. 2004. Flood risk management in the context of Integrated Water Resource Management (IWRM). Flood Hazard Research Centre, Middlesex University, UK. http://www.fhrc.mdx.ac.uk/resources/docs_pdfs/wuhanfin.pdf

Groisman, P.Y., R.W. Knight, and T.R. Karl. 2001. Heavy precipitation and high streamflow in the contiguous United States: Trends in the twentieth century. Bulletin of the American Meteorological Society 82(2):219-246.

Groisman, P.Y., R.W. Knight, D.R. Easterling, T.R. Karl, G.C. Hegerl, and V.N. Razunaev. 2005. Trends in intense precipitation in the climate record. Journal of Climate 18:1326-1349.

Hamlet, A.F. and D. P. Lettenmaier. 2007. Effects of 20th century warming and climate variability on flood risk in the western U.S. Water Resources Research 43, W06427, doi:10.1029/2006WR005099.

Hamlet, A.F. et al. 2010. Hydrologic Climate Change Scenarios for the Pacific Northwest Columbia River Basin and Coastal Drainages. In review. http://www.hydro.washington.edu/2860/, accessed January 19, 2010.

Helsel, D.R., Mueller, D.K., and Slack, J.R., 2006, Computer program for the Kendall family of trend tests: U.S. Geological Survey Scientific Investigations Report 2005–5275, 4 p. http://pubs.usgs.gov/sir/2005/5275/pdf/sir2005-5275.pdf, accessed September 5, 2008.

Hidalgo, H.G., T. Das, M.D. Dettinger, D.R. Cayan, D.W. Pierce, T.P. Barnett, G. Bala, A. Mirin, A.W. Wood, C. Bonfils, B.D. Santer, and T. Nozawa. 2009. Detection and attribution of streamflow timing changes to climate change in the Western United States. Journal of Climate 22:3838-3855. DOI:10.1175/2009JCLI2470.1

IPCC (Intergovernmental Panel on Climate Change, World Meteorological Organization, & United Nations Environment Programme). (2007). IPCC fourth assessment climate change 2007. Geneva: WMO. http://www.ipcc.ch/

Kresch, D. and K. Dinicola. No date. What causes floods in Washington state? U.S. Geological Survey Fact Sheet 228-96. http://wa.water.usgs.gov/projects/pugethazards/PDF/FS_228-96.pdf

Kundzewicz, Z.W., D. Graczyk, T. Maurer, I. Pińskwar, M. Radziejewski, C. Svensson and M. Szwed. 2005. Trend detection in river flow series: 1. Annual maximum flow. Hydrol. Sci. J. 50(5):797–810.

Kunkel, K.E., D.R. Easterling, K. Redmond, and K. Hubbard. 2003. Temporal variations of extreme precipitation events in the United States: 1895-2000. Geophysical Research Letters 30(17), 1900, doi:10.1029/2003GL018052.

Lins, H. 2005. Streamflow trends in the United States. U.S. Geological Survey, Washington, DC. USGS Fact Sheet 2005-3017.

McCabe, G.J., M.P. Clark, and L.E. Hay. 2007. Rain-on-snow events in the western United States. American Meteorological Society doi:10.1175/BAMS-88-3-319.

Madsen, T. and E. Figdor. 2007. When it rains, it pours. Global warming and the rising frequency of extreme precipitation in the United States. http://www.environmentamerica.org/uploads/oy/ws/oywshWAwZy-EXPsabQKd4A/When-It-Rains-It-Pours----US---WEB.pdf , accessed May 13, 2009.

Meaker, B. 20 November 2008. Personal communication (e-mail to Curtis DeGasperi, King County DNRP). Snohomish County Public Utility District #1, Everett, WA.

Meyer, V., D. Haase, and S. Scheuer. 2009. Flood risk assessment in European river basins – concept, methods, and challenges exemplified at the Mulde River. Integrated Environmental Assessment and Management 5:17-26.

Michaels, P.J. et al. 2004. Trends in precipitation on the wettest days of the year across the contiguous USA. International Journal of Climatology 24:1873-1882.

Milly, P.C.D., J. Bentancourt, M. Falkenmark, R.M. Hirsch, Z.W. Kundzewicz, D.P. Lettenmaier, and R.J. Stouffer. 2008. Stationarity is dead: wither water management? Science 319:573-574.

Milly, P.C.D., R.T. Wetherald, K.A. Dunne, and T.L. Delworth. 2002. Increasing risk of great floods in a changing climate. Nature 415:514-517.

Mote, P.W., D.J. Canning, D.L. Fluharty, R.C. Francis, J.F. Franklin, A.F. Hamlet, M. Hershman, M. Holmberg, K.N. Ideker, W.S. Keeton, D.P. Lettenmaier, L.R. Leung, N.J. Mantua, E.L. Miles, B. Noble, H. Parandvash, D.W. Peterson, A.K. Snover, and S.R. Willard. 1999. Impacts of Climate Variability and Change, Pacific Northwest. National Atmospheric and Oceanic Administration, Office of Global Programs, and JISAO/SMA Climate Impacts Group, Seattle, WA. 110 pp. http://cses.washington.edu/db/pdf/moteetalgreenbook96.pdf, accessed March 16, 2010.

Mote, P.W., E.P. Salathé, and C. Peacock. 2005. Scenarios of Future Climate for the Pacific Northwest. Climate Impacts Group, Center for Science in the Earth System, Joint Institute for the Study of the Atmosphere and Ocean, University of Washington, Seattle. http://www.cses.washington.edu/db/pdf/kc05scenarios462.pdf, accessed September 5, 2008.

Moore, R.D. and S.M. Wondzell. 2005. Physical hydrology and the effects of forest harvesting in the Pacific Northwest: A review. Journal of the American Water Resources Association 41(4):763-784.

Neiman, P.J., F.M. Ralph, G.A. Wick, J.D. Lundquist, M.D. Dettinger. 2008. Meteorlogical characteristics and overland precipitation impacts of atmospheric rivers affecting the west coast of North America based on eight years of SSM/I satellite observations. Journal of Hydrometeorology 9:22-47.

Newman, M.C. 2008. "What exactly are you inferring?" A closer look at hypothesis testing. Environmental Toxicology and Chemistry 27(5):1013-1019.

NHC. 2006. Flood Insurance Mapping Study for the Snoqualmie River and Skykomish River. King and Snohomish Counties, WA. Prepared for Federal Emergency Management Agency. Northwest Hydraulic Consultants, Inc., Seattle, WA.

Mote, P.W. and E. Salathé. 2009. Future Climate in the Pacific Northwest. Chapter 1: Scenarios. In: The Washington Climate Change Impacts Assessment, M. McGuire Elsner, J. Littell, and L Whitely Binder (eds). Center for Science in the Earth System, Joint Institute for the Study of the Atmosphere and Oceans, University of Washington, Seattle, Washington. http://www.cses.washington.edu/db/pdf/wacciareport681.pdf

O'Connor, J.E. and J.E. Costa. 2003. Large floods in the United States: Where they happen and why. U.S. Geological Survey, Washington, D.C. U.S. Geological Survey Circular 1245.

Oreskes, N. 1998. Evaluation (Not validation) of quantitative models. Environmental Health Perspectives 106:1453-1460.

Palmer, R.N. 2007. Technical Memorandum #6: Framework for Incorporating Climate Change into Water Resources Planning. A report prepared by the Climate Change Technical Subcommittee of the Regional Water Supply Planning Process, Seattle, WA. http://www.climate.tag.washington.edu/techmemos/Tech%20Memo%206%20-Final%2012-13.pdf, accessed September 5, 2008.

Pielke, R.A. and M.W. Downton. 2000. Precipitation and damaging floods: Trends in the United States, 1932-97. Journal of Climate 13(20):3625-3637.

Pierce, D.W. et al. 2008. Attribution of declining western U.S. snowpack to human effects. Journal of Climate 21:6425-6444.

Polebitski, A. and R. Palmer. 2006. Projected impacts of climate change and implications for river flows in the Pacific Northwest. Presentation to King County staff, November 7, 2006. Department of Civil and Environmental Engineering, University of Washington, Seattle, WA.

Polebitski, A., L. Traynham, and R.N. Palmer. 2007a. Technical Memorandum #5: Approach for Developing Climate Impacted Streamflow Data and its Quality Assurance/Quality Control. A report prepared by the Climate Change Technical Subcommittee of the Regional Water Supply Planning Process, Seattle, WA. http://www.climate.tag.washington.edu/techmemos/Technical_Memo_5%20(12-13-07).pdf, accessed September 5, 2008.

Polebitski, A., M.W. Wiley, and R.N. Palmer. 2007b. Technical Memorandum #2: Methodology for Downscaling Meteorological Data for Evaluating Climate Change. A report prepared by the Climate Change Technical Subcommittee of the Regional Water Supply Planning Process, Seattle, WA. http://www.climate.tag.washington.edu/techmemos/Technical%20Memo%202%20(12-13-07).pdf, accessed September 5, 2008.

Polebitski, A., L. Traynham, and R.N. Palmer. 2007c. Technical Memorandum #4: Approach for Developing Climate Impacted Meteorological Data and its Quality Assurance/Quality Control. A report prepared by the Climate Change Technical Subcommittee of the Regional Water Supply Planning Process, Seattle, WA. http://www.climate.tag.washington.edu/techmemos/Technical%20Memo%204%20_12-13-07.pdf.

Ralph, R.M. et al. 2006. Flooding on California's Russian River: Role of atmospheric rivers. Geophysical Research Letters 33, L13801, doi:10.1029/2006GL026689.

Regonda, S.K., B. Rajagopalan, M. Clark, and J. Pitlick. 2005. Seasonal cycle shifts in hydroclimatology over the western United States. Journal of Climate 18:372-384.

Salathé, E. 2006. Influences of a shift in North Pacific storm tracks on western North American precipitation under global warming. Geophysical Research Letters 33: L19820, doi:10.1029/2006GL026882.

Schick, L. no date. Impacts of atmospheric rivers on flooding in western Washington. Seattle District, U.S. Army Corps of Engineers, Seattle, WA.

Small, D., S. Islam, and R.M. Vogel. 2006. Trends in precipitation and streamflow in the eastern U.S.: Paradox or perception? Geophysical Research Letters 33, L03403, doi:10.1029/2005GL024995.

Stoelinga, M.T., M.D. Albright, and C.F. Mass. 2010. A new look at snowpack trends in the Cascade Mountains. Journal of Climate. In Press.

Washington State Hazard Mitigation Plan. November 2007. http://www.emd.wa.gov/plans/washington_state_hazard_mitigation_plan.shtml, accessed May 11, 2009.

Whitely-Binder, L.C. J.K. Barcelos, D.B. Booth, M. Darzen, M.M. Elsner, R.A. Fenske, T.F. Graham, A.F. Hamlet, J. Hodges-Howell, D.D. Huppert, E.A. Rosenberg, C. Stöckle, and J. Vano. 2009. Preparing for climate change in Washington State. Chapter 11. In: *The Washington Climate Change Impacts Assessment: Evaluating Washington's Future in a Changing Climate*, Climate Impacts Group, University of Washington, Seattle, Washington. http://cses.washington.edu/db/pdf/wacciach11adapt654.pdf, accessed November 1, 2009.

Williams, C.N., Jr., R.S. Vose, D.R. Easterling, and M.J. Menne. 2006. United States Historical Climatology Network Daily Temperature, Precipitation, and Snow Data. ORNL/CDIAC-118, NDP-070. Data available on-line:

(http://cdiac.ornl.gov/epubs/ndp/ushcn/newushcn.html) from the Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, Oak Ridge, Tennessee.