SNOWMELT HYDROLOGY OF MT. RAINIER, WASHINGTON, RIVERS: IMPLICATIONS FOR FUTURE WATER RESOURCES MANAGEMENT

by

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ABSTRACT

Snowmelt Hydrology of Mt. Rainier Rivers: Implications for Future Water Resources Management

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High elevation snowsheds on Mt. Rainier are critical sources of snowmelt flows that provide reliable water and power supplies for the rapidly growing communities of the South Sound. Recent regional scale analyses indicate that snowmelt flow quantities are declining and runoff timing dates have been occurring earlier across the western US since the middle of the 20th century. Observed trends are spatially coherent over large domains, yet finer grained basin scale analyses are needed to detect the magnitude of regional trend signals in Mt. Rainier watersheds. The purpose of this study is to establish quantitative estimates of snowpack volumes, snowmelt flow quantities and peak runoff timing dates to investigate temporal trends in Mt. Rainier snow hydrology. Results indicate that snowmelt flows account for 38.8% to 48.8% of annual flow in Mt. Rainier Rivers illustrating that snowmelt flows largely dictate flow regimes. Trend analyses reveal significant declines in spring snowpack volumes and subsequent snowmelt proportions since the middle of the 20th century and streamflow timing trends indicate that spring runoff peaks are shifting to earlier in the year. These findings confirm that observed regional hydroclimatic trend signals are present at Mt. Rainier and suggest that large scale climatic drivers are influencing declines in snowmelt parameters. Furthermore, these results present profound implications to water managers as the stresses placed on water resources resultant of declines in Mt. Rainier snowmelt will be compounded by population growth and climate change effects. Therefore, this study provides valuable insights for future water planning applications and basin scale hydrologic research in the Pacific Northwest.

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1. Introduction and Background

Montane snowpack serves as a critical natural storage mechanism for the water resources of the Pacific Northwest. The regional benefits of natural storage are exemplified during the arid summer and fall seasons when precipitation inputs to surface water are limited, and the majority of streamflow is contributed by the gradual melting of annual snowpack. Spring snowmelt runoff accounts for substantial portions of annual flow in several major rivers flowing from the Cascade Range into the Puget Sound Basin with peak runoff periods occurring from March through June.

The timing and magnitude of snowmelt flows form the basis of regional reservoir operations in which spring inflows are retained to provide a reliable water supply for the duration of the summer and fall months. In addition to ensuring dry season water supply, storage facilities are operated to optimize flood control, hydropower production, recreation, and instream flow goals. The abilities of each resource sector to meet reliability goals hinge upon the timely occurrence of snowmelt influxes; resource productivity is a function of hydrologic variability. Therefore, snowmelt runoff flows are essential in providing the communities of the Puget Sound region with the security of reliable water supplies and low cost hydropower.

Continued population growth and possible climate change effects threaten to jeopardize the abilities of current water resource regimes to maintain efficient operations and attainable reliability goals. In order to accurately prepare for the associated strains on regional water resources accurate studies detailing the dynamics of basin scale snow hydrology are required to develop successful adaptive management strategies to aid in meeting future demands.

High elevation snowsheds on Mt. Rainier are the primary sources of snowmelt runoff for water resource sectors supporting the communities of the South Sound region, including the rapidly growing cities of Tacoma and Olympia. The Nisqually, Cowlitz, Puyallup, White, and Carbon Rivers originate on Mt. Rainier and all support regional demands for municipal water supplies, irrigation water, and hydroelectric generation. Similar to other Puget Sound regions, the communities of the South Sound face challenges arising from population growth and climate change implications. Thus reliable and accessible data pertaining to the hydrologic characteristics and temporal variations in the snowmelt flows of Mt. Rainier Rivers is necessary for future water resource planning efforts in the South Sound. Therefore, the hydrologic characteristics of each Mt. Rainier river form the basis of this report.

Increasing concerns surrounding the implications of climate change and population growth to water resources of the American West initiated the growth of a distinct hydroclimatic discourse to investigate the interface between snowmelt flows and hydroclimatic variation. Numerous studies have analyzed the dynamics of snowmelt hydrology in the Pacific Northwest (Fountain and Tangborn, 1985; Pelto, 1993; Hamlet et al., 1995; Miles et al., 2000; Mote, 2003, 2005, 2008; Bach, 2002) and the greater western United States (Mote et al., 2005; Mote, 2006; Regonda et al., 2005; Stewart et al., 2004, 2005; Cayan et al. 2001; Dettinger and Cayan, 1995) in which quantifications and temporal trend analyses of snowpack, snowmelt runoff, and spring streamflow timing parameters are central foci.

The majority of research detailing snowmelt runoff hydrology assesses hydroclimatic variability as a function of historical climate to identify temporal trends in seasonal snowmelt flows (Hamlet et al., 1995; Miles et al., 2000; Mote, 2003, 2005, 2008; Mote et al., 2005; Mote, 2006; Regonda et al., 2005; Stewart et al., 2005). The results of these studies are regionally coherent and indicate that spring snowpack and snowmelt flows have been steadily declining across western North America since the mid 20th century. Mote et al. (2005, 2003) found that spring snow water equivalencies (SWE) have declined from 10-60% in snowmelt dominated basins across the West, with the highest observed declines occurring in Pacific Northwest watersheds (Mote et al. 2003, 2005; Stewart et al. 2004, 2005; Regonda et al. 2005). Recent analyses assessing temporal SWE variations in the Washington Cascades indicate pronounced negative trends corresponding to losses of annual snowpack ranging from 15-35% of mid 20th century means (Mote et al. 2008). High trend coherence between large and regional scales suggest that declines in snowpack are not spatially isolated; spring snowpack volumes are decreasing across large domains and suggest that snowpack volumes in Mt. Rainier watersheds are also diminishing.

Subsequent declines in snowmelt runoff (Wahl, 1992; Aguado et al. 1992; Pupacko, 1993; Dettinger and Cayan, 1995; Stewart et al. 2004, 2005; Regonda et al. 2005) coupled with earlier occurrences of annual snowmelt runoff periods (Stewart et al. 2004, 2005; Regonda et al. 2005; Cayan et al. 2001) have been observed in hundreds of basins across western North America. Stewart et al. (2005) found that snowmelt flows occurring from April to July are decreasing in 81% of 241 rivers sampled in western North America. Again, the largest decreases were observed in low elevation basins across the Pacific Northwest.

Regonda et al (2005) and Stewart et al. (2005) have established statistically significant negative trends for spring snowmelt timing where the annual snowmelt pulse is occurring earlier in the water year and observed trends correspond to shifts on monthly scales. Stewart et al. (2005) sampled the same 241 rivers discussed above and found negative timing trends for 71% of the rivers where nearly half (49%) are statistically significant (α=.10) indicating that linkages between flow timing and snowmelt flow variability are inherent.

Decreasing snowmelt flows and earlier timing pulses are becoming commonplace across the American West and threaten to decrease water resource productivity in several snow-dominant systems. Similar to trends in SWE, snowmelt flow and timing trends exhibit high degrees of spatial coherence indicating that negative runoff and timing trends are inherently related to variations in observed seasonal snowpack volumes. Widespread declines in snowmelt runoff timing and flow quantities across large spatial domains, and the Pacific Northwest in particular, suggest that the regionally declining trends in snowmelt parameters are likely occurring at Mt. Rainier and warrants further localized study.

Increasing temperature trends have been established as the primary climatic driver influencing declines in snowmelt parameters across the American West (Miles et al., 2000; Mote, 2003, 2005, 2008; Mote et al., 2005; Regonda et al., 2005; Stewart et al., 2005), yet uncertainties remain as to the cause of increasing temperatures, especially in the Pacific Northwest (Hamlet and Lettenmaier, 1999; Miles et al., 2000; Mote, 2003, 2005, 2008; Mote et al., 2005; Mote, 2006; Regonda et al., 2005; Stewart et al., 2005). Long-term historical variation in Pacific Northwest hydroclimatic conditions corroborate well with the fluctuations of the Pacific Decadal Oscillation (PDO) (Mantua et al. 1997; Hamlet and Lettenmaier, 1999; Miles et al. 2000; Payne et al. 2004; Mote, 2003, 2005, 2008). The PDO affects regional weather as a result of shifts in sea surface temperature in the North Pacific Ocean, and alternates between warm (positive) and cool (negative) phases on a cycle of 20-30 years. Positive PDO regimes are characterized by warm and dry conditions whereas negative regimes display cold and moist weather patterns (Mantua et al. 1997). Subsequently, the effects of PDO greatly influence snowmelt hydrology at Mt. Rainier on decadal timescales and may partially mask the effects of climate change. To assess the relationships between local hydrology and global scale climate further studies detailing trends associated with the PDO are necessary to assess the sensitivity of Mt. Rainier snowpack and streamflow to phase state oscillation and large scale climate variability.

The results of the aforementioned studies clearly indicate that snowmelt runoff parameters are declining over vast spatial domains and that profound impacts to regional water resources are imminent if current trends continue. Providing accurate information to water managers operating in the Puget Sound region will require fine-grained analyses to isolate the local effects of regionally significant trends. Therefore, the purpose of this study is to apply the techniques of previous regional analyses to the watersheds of Mt. Rainier to quantify the magnitudes of snowmelt influence for each river and to detect and assess the effects of observed regional trends on local watershed scales.

In order to produce meaningful results for water management purposes the analyses included in this study are driven by the following central questions: (1) How do snowpack, snowmelt, and streamflow timing parameters interact to shape the annual hydrologic variability for each Mt. Rainier river? (2) Are regional hydroclimatic trend signals of the past century present in the hydrologic records of Mt. Rainier rivers? (3) How does the PDO influence snowmelt hydrology at Mt. Rainier? (4) What are the implications of hydrologic shifts to water resource sectors that rely upon Mt. Rainier snowmelt to fulfill resource demands in the South Sound?

The results of this study will provide water managers and communities in the South Sound region with accurate information detailing the importance of snowmelt flow, timing, snowpack, and large scale climatic drivers to local water resource sectors. Findings will aid in critical adaptation strategy development to combat the implications of population growth and climate change to water scarcity and demand. Additionally, this study will provide a firm baseline for further fine-grained studies pertaining to snowmelt hydrology and water resources of the Pacific Northwest.

Furthermore, this study is an important contribution to the field of environmental studies as a whole by integrating the implications of social and environmental change. Linking variations in hydrologic conditions to critical resource sectors employs central methods of interdisciplinary research to arrive at conclusions that are useful to both the natural and social sciences. Thus, the results of this study will aid in the development of both environmental and social adaptations to the increasingly challenging hardships of a changing world.

2. Geography, Climate, and Water Resources

An understanding of watershed characteristics is fundamental to exploring the importance of snowmelt contributions and runoff timing as each basin possesses unique physiographic settings and water resource regimes that respond differently to variations in snowmelt flows. The purpose of this section is to illustrate the pertinent characteristics of each watershed in the study area to better understand the susceptibility of both natural and social systems to snowmelt variability. Each basin is characterized by Water Resource Inventory Area (WA Dept. of Ecology) to more efficiently outline water resources activities and provide a helpful format for future watershed planning applications. A map of the entire study area with WRIA divisions is provided on page 8.

2.1 *Regional Hydroclimate*

Pacific Northwest climate is characterized in the Koppen climate classification system as a Marine West Coast climate with wet and mild winters and warm and dry summers. However, average annual temperature and precipitation values within the study area vary considerably with differences in elevation. All of the watersheds analyzed in this study have a minimum elevation of sea level and a maximum elevation of 14,411 ft. at the top of Mt. Rainier. Annual precipitation values range from 35 inches in the lowlands to more than 150 inches in the higher mountainous terrain. Temperature also varies as a function of elevation with warmer temperatures in the lowland valleys and cooler temperatures in the mountains. Thus, elevation dictates the type of precipitation (snow vs. rain) and subsequent hydrologic response to precipitation inputs. Significant snowfall occurs on the slopes of Mt. Rainier each winter; snowfall records range from 330 inches to 1,122 inches recorded at Paradise. As a result, much of the winter precipitation in the study area is stored in the snowpack until the spring thaw when snowmelt is gradually released to rivers and aquifers.

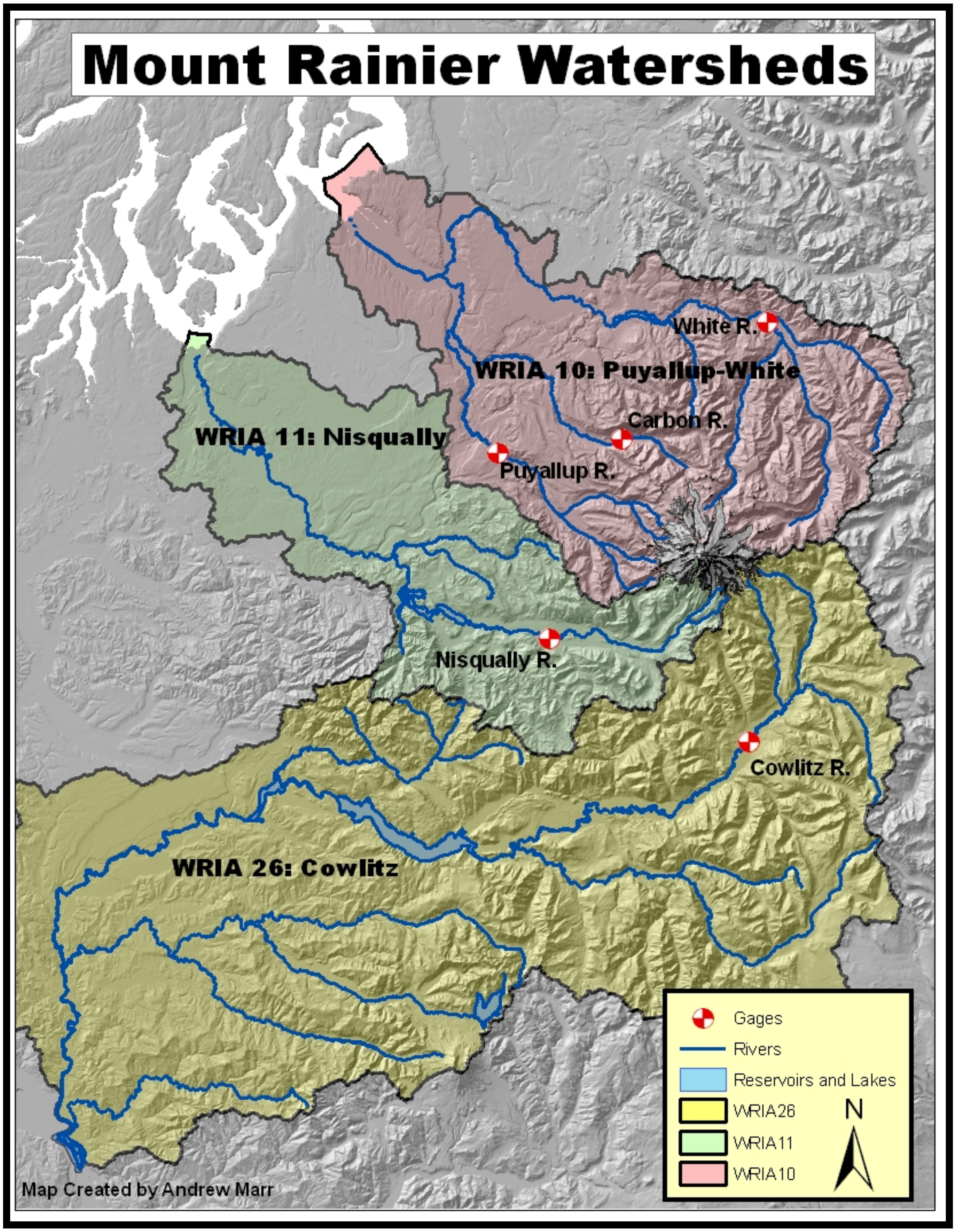

Figure 1.1: Mt. Rainier watersheds, rivers, reservoirs and gauging stations.

2.2 *Regional Physiography*

All five rivers originate on the flanks of Mt. Rainier and flow westward to Puget Sound with the exception of the Cowlitz which is a tributary to the Columbia River. Each basin is split by two physiographic regions: the Cascade province in the east and Puget Lowlands in the west (WDNR, 2009). The Cascade province is mountainous with steep topographic gradients that confine the rivers to narrow forested valleys or canyons. Hydraulic gradients are high in the upper reaches, especially in tributary basins. The impacts of human development are scarce as basin areas in the Cascade province lie in forest lands and Mt. Rainier National Park. The Puget Lowland is a low elevation basin characterized by gentle topographic gradients and broad floodplains dominated by agriculture and urban development. Thus, the majority of socially important implications of snowmelt variation are encountered in the lower portions of each basin where water use is abundant.

2.3 *Nisqually River Basin: WRIA 11*

2.3.1 Geographic Features

The Nisqually River originates on the southern flank of Mt. Rainier at the terminus of the Nisqually Glacier and flows 78 miles to southern Puget Sound draining an area of 711 square miles. Headwater tributaries contribute flow from high altitude snowsheds and glaciers including the Kautz, Van Trump, and South Tahoma Glaciers. The river flows freely through the Cascade province in steep walled mountainous valleys until the hydraulic gradient begins to ease once the river leaves the national park. The first gauging station downstream of headwaters exists at river mile (RM) 57.8 near the town of National (USGS 12082500) and serves as the best gauge for analyzing snowmelt derived flows.

The river becomes impounded by Alder Dam, which forms Alder Reservoir at RM 44.2. Alder Reservoir serves as a storage facility for hydroelectric production at Alder Dam and has a storage capacity of 231,900 acre feet. La Grande Dam impounds the river at RM 42.5 and forms a second storage reservoir, La Grande Reservoir, which is has a storage capacity of 2,700 acre feet. Storage releases from La Grande Dam are utilized for power generation through the use of a diversionary canal. The Nisqually flows freely through the lowlands until RM 26.2 where the Centralia Canal diverts flows from the river to a power generation facility 14 miles downstream. For the remaining 12.6 miles, the river flows through lowland terrain until reaching the Nisqually Estuary, a biologically rich tide flat area, which is now designated as Nisqually National Wildlife Refuge.

2.3.2 Water Resources

Hydropower production is the predominant water resource sector operating within the basin and largely dictates current water management structures. Cumulatively, the three hydroelectric projects within the Nisqually Basin produce 573.012 gigawatt hours of electricity annually. The City of Tacoma owns and operates both Alder and La Grande Dams which collectively produce 573 gigawatt hours annually to power 40,500 homes (Tacoma Public Utilities, 2010). The third project is a run-of-river dam owned and operated by the City of Centralia which produces 12 megawatt hours annually. Large scale diversions such as the Alder Dam have greatly altered the natural flow regimes of the river below the storage reservoirs, thus flows below the dams more accurately reflect hydropower production schedules than that of hydroclimatic variation.

Increasing population and urban development within the basin have resulted in widespread allocations of water for municipal, domestic, and irrigation uses. As of 2002, there were 938 active water right permits, applications, and certificates for the lower Nisqually Basin, and 2,677 claims for new allocations (Watershed Professionals Network (WPN), 2002). Of the 2,677 claims 351 are surface water claims with the remainder requesting groundwater rights. 2,452 claims are for domestic and municipal consumptive use, 64 for irrigation, and 109 for stock watering (WPN, 2002). The total allocated amount for the lower basin in 2002 was 63,078 acre feet/year, excluding an additional 58,000 acre feet/year strictly for hydropower production (WPN, 2002). Major municipal right holders include the Cities of Olympia, Lacey, Yelm, DuPont, and Centralia; Tacoma Public Utilities holds nearly all of the hydropower rights.

Consequences of hydropower operations have been dire for Nisqually salmon, as dams have limited the upstream extent of rearing habitat and altered sedimentation rates downstream of all hydroelectric projects. In an effort to curtail the degradation of salmon habitat and to enhance water availability instream flow regulations are mandated by the Washington Department of Ecology (WA DOE) and are supplemented by storage releases required by the Federal Energy Regulatory Commission (FERC) for hydropower projects. WRIA 11 was one of the first watersheds to implement instream flow regulations and support the adoption of instream flow rules through watershed planning efforts; flow regulations were enacted into law for the Nisqually River and associated tributaries in 1981 and continue to the present, although watershed planning in the basin is continuously evolving amongst utilities, water right holders, the Nisqually Tribe and regulatory bodies (WA DOE, 2008).

2.4 Cowlitz River Basin: WRIA 26

2.4.1 Geographic Features

The Cowlitz River originates at the confluence of Clear Fork and the Ohanepecosh River in northeastern Lewis County and flows southwest for 133 miles to the Columbia River draining a total area of 2,840 square miles. The Clear Fork drains high mountain terrain and provides significant snowmelt to the upper Cowlitz, whereas the Ohanepecosh River originates amongst several tributary glaciers on the southeastern flank of Mt. Rainier. Major tributary glaciers include the Cowlitz, Ingraham, Whitman, and Ohanepecosh Glaciers. The first gauging station on the Cowlitz is near the town of Packwood at RM 126.5 (USGS 14226500) and provides the most accurate flow data for snowmelt quantification purposes.

The upper Cowlitz flows freely for the first 44.5 miles until the first impoundment structure, Cowlitz Falls Dam, at RM 88.5. The resultant Cowlitz Falls Reservoir (Scanewa Lake) is the smallest storage facility in the basin with a capacity of 11,000 acre feet covering a geographic area of 610 acres. The second impoundment structure is Mossyrock Dam which supports Riffe Lake, the basin's largest storage reservoir. Riffe Lake extends upstream to RM 65.6 and has a storage capacity of 1,298,002 acre feet and occupies a geographic area of 11,335 acres. The third, and last, major storage reservoir is Mayfield Lake which is directly downstream of Mossyrock Dam. Mayfield Lake has a storage capacity of 133,720 acre feet and a surface area of 2,200 acres. Beyond the major storage reservoirs the Cowlitz continues southeast towards the Columbia and accepts the mainstem's primary downstream tributary, the Toutle River, 20 miles before reaching the Columbia River at the community of Longview.

2.4.2 Water Resources

The Cowlitz River supports the largest hydropower generation sector in the study area with three major production facilities. The City of Tacoma owns and operates Mossyrock and Mayfield Dams which collectively produce 1,904 gigawatt hours annually to supply 136,000 homes in the Tacoma area with low cost electricity (Tacoma Public Utilities, 2010). Cowlitz Falls Dam is owned and operated by Lewis Public Utility District (LPUD) and generates 260 gigawatt hours annually to supply 1/3 of the total electricity demand for the service area of the LPUD. Both Mossyrock and Mayfield Dams impound large reservoirs which are controlled to provide flood mitigation and numerous recreation opportunities such as fishing, camping, and boating. Subsequently, large scale impoundments on the Cowlitz have resulted in drastic alterations to natural flow regimes resulting in increased scarcity for downstream uses. In response, water resource management in the Cowlitz is currently evolving to accommodate the various needs of multiple sectors including environmental objectives.

Watershed planning efforts in WRIA 26 have not produced state regulated instream flow rules despite the fact that quantitative flow requirements have been proposed by a diverse group of interests in the current watershed plan (WDOE, 2010). During the writing period of this study, draft rules existed for WRIA 26 that would set instream flows, reserves, and basin closures for the watershed. Importantly, the watershed planning process has yielded a recommendation for closing much of the basin to further appropriations. Ecology expects to adopt the final rules for WRIA 26 in September, 2010 (WDOE, 2010). FERC flow requirements apply to each of the hydroelectric facilities operating in the basin and provide a source of flow for environmental applications (Tacoma

Public Utilities, 2010; WDOE, 2008). Further state regulated flows will occur in conjunction with federally mandated FERC flows providing much needed flow augmentation for ecosystem restoration.

Several consumptive users hold water rights in the Cowlitz Basin. As of 2010, there were 900 permits and certificates to appropriate surface water in WRIA 26. Predominant water right classifications include irrigation, stock water, and domestic uses. Major municipal rights are held by the cities of Kelso and Longview in which the Cowlitz provides the majority of the domestic water supplies for each respective city (WDOE, 2010). Increases in population will ultimately lead to an increase in water demands throughout WRIA 26 and add further tension between hydropower entities, water right holders, and environmental interests.

2.5 Puyallup, White, and Carbon River Basins: WRIA 10

2.5.1 Geographic Features

WRIA 10 (Puyallup-White) includes the watersheds of the Puyallup, White and Carbon Rivers in a single planning unit. All three rivers converge in the Puget Lowland near Tacoma before entering Puget Sound through a common mouth. WRIA 10 encompasses an area of 948 square miles that drains the entire northern half of Mt. Rainier. The White River originates at the termini of the Emmons and Inter Glaciers and flows northwest for 68 miles draining 464 square miles. The Puyallup River flows northeast from the Puyallup Glacier for 45 miles until draining into Puget Sound at Tacoma. The Puyallup River basin covers 405.1 square miles of WRIA 10. The Carbon River is the shortest river in WRIA 10 running 30 miles from the terminus of the Carbon Glacier where it meets the Puyallup near Orting. The Carbon drains 78.9 square miles, most of which is forest land including one of the only remaining temperate rainforest stands in the Southern Cascades.

Impoundments have been constructed in each basin with the largest structures in place on the White and Puyallup Rivers. Mud Mountain Dam on the White River provides flood control for the communities in the lower reaches of WRIA 10 and is owned and operated by the US Army Corps of Engineers. The White River flows for approximately 10 miles past Mud Mountain Dam where up to 2,000 cubic feet/second of White River flows are diverted to form Lake Tapps reservoir with a storage capacity of 46,700 acre feet (Cascade Water Alliance, 2010). The Electron Dam in the upper reaches of the Puyallup Basin diverts river flows for hydroelectric production although the project does not impound flows. The largest anthropogenic alteration in WRIA 10 is the straightening of the Lower Puyallup near Tacoma where the river is contained between concrete walls to prohibit meander and flood damage and to improve the navigability of the mouth.

2.5.2 Water Resources

WRIA 10 has been a regionally important watershed for decades due to its close proximity to major population centers. High demands for hydropower, consumptive uses and irrigation have resulted in severe over-allocations which necessitated a basin closure in 1980. Legally (WAC 173-510), no further water appropriations are to be made to new users in WRIA 10 unless obtained through the procedures of transfers and leases (WDOE, 2008) Therefore, further development in the basin is hindered by the relative unavailability of water resources and further growing water scarcity.

Predominant water resource sectors operating within the basin are domestic and municipal water suppliers, irrigation, and hydropower. There are currently 1211 total water rights issued in WRIA 10 with 687 rights to surface water bodies (WDOE, 2010). Municipalities hold the rights to the largest volumes of water and include Auburn, Orting, Puyallup, Bonney Lake, and Tacoma making WRIA 10 one of the largest sources of drinking water in the South Sound. In comparison to the other WRIAs in the study area, the White-Puyallup basin is not a significant source of hydropower with only one major project. The Electron Dam owned by Puget Sound Energy is capable of meeting peak electricity demand for 17,000 regional homes (PSE, 2009).

Despite the basin closure, progress is being made to increase the municipal water supplies in WRIA 10. In 2004, Puget Sound Energy (PSE) ceased power production at Lake Tapps and subsequently sold the storage facility and associated water rights to Cascade Water Alliance (CWA), a non-profit water supplier. CWA plans on utilizing stored White River flows in Lake Tapps to secure a water supply for the next 60 years for 8 communities serving 370,000 people (CWA, 2010; WDOE, 2006). Therefore, the implications of snowmelt variability to WRIA 10 water resources are stark, especially in regards to further water supply development.

2.6 Aggregated Resource Impacts

Snowmelt flows from Mt. Rainier dictate the productivity of water resource operations for a large geographic area stretching from Tacoma to the Columbia River. Cumulatively, hydroelectric projects in the study area provide 193,500 regional homes with power supplies, and Mt. Rainier runoff supports 176 municipal water supply rights. Additionally, each river fulfills numerous domestic, irrigation, and environmental demands throughout each WRIA. Basin closures in WRIA 10 and near certain closures in WRIA 26 provide visible evidence that population growth is already beginning to strain current water resource availability in the Puget Sound region, and with an expected population of nearly 7.7 million people by 2010 (WOFM, 2007) it is imperative that resource management adaptation begin to address the challenges of future demands. Furthermore, population effects are compounded by uncertainties introduced from climate change effects. Therefore, impacts to snowmelt hydrology need to be understood in order to accurately prepare water managers for the implementation of adaptive measures.

3. Methods

The following analytical methods were chosen due to their high degree of applicability to the central research questions of this study. Importantly, the techniques used here have been accepted in the greater discourse and provide a means to detect regional hydrologic trend signals at Mt. Rainier. Secondly, the methodologies employed herein allow for reliable estimates of snowmelt flows and timing to be calculated and easily transferred to water managers for planning applications.

3.1 Data

Flow data for each river was obtained from the United States Geological Survey (USGS) surface water data network. Discharge data from USGS is reported and analyzed as monthly mean discharge values measured in cubic feet per second (cfs). Gauging stations were selected to achieve maximum accuracy for snowmelt flow estimates and therefore were required to be upstream of all obstructions and diversions and be proximal to snowmelt sources. Each gauging station for all five basins is the first station downstream of headwaters, and exist above all major diversions or impediments to natural flow. A comprehensive list of gauging station attributes is given in table 3.1. After gauge selection and data importing was complete, each dataset was re-organized in terms of water year (October-September). For example, water year 2007 began in October of 2006 and concluded in September of 2007.

River	USGS Station	USGS Station ID	Drainage Area (mi.^{2})	Period of Record
Nisqually	National	12082500	133	1944-2006
White	Greenwater	12097000	216	1930-1975
Puyallup	Electron	1209200	92.8	1957-2008
Cowlitz	Packwood	14226500	287	1948-2008
Carbon	Fairfax	1209400	78.9	1930-1977

Table 3.1: Data parameters for each watershed

April 1st snow water equivalency (SWE) data was obtained from the Natural Resource Conservation Service for the SNOTEL station located at Paradise. The Paradise station was selected as it is the only accurate and regularly maintained snowpack station in the study area. SWE is reported in inches of liquid water equivalent and all analyses herein remain in units of inches. Monthly mean temperature and precipitation data for each gauging station location was gathered to enhance understanding of basin hydrography and compare climatic variation in the study area. Additionally, data was obtained for Tacoma, the study area's low point, and for Paradise (National Park Service, 2007) to illustrate the magnitude of spatial variation on a large scale. Precipitation is reported in inches and temperature is recorded in degrees Fahrenheit.

Prior to any analysis, all datasets were screened for outliers and normality. No severely anomalous river flow, SWE, or climatic data points were observed and flow density curves well approximate a normal distribution. Assumptions of normality were confirmed with histograms, quantile plots skewness tests and kurtosis tests.

3.2 Hydrography

The first step in identifying the magnitude of snowmelt influence for a watershed is to understand the major hydrographic characteristics of the basin. Hydrographs for each river were created using mean monthly flow data in order to assess annual patterns of flow. Precipitation data for each gauging station area was plotted along with the hydrograph to gain insights into the average hydrologic response of each river in regards to average precipitation. Once hydrographs were completed, dominant hydrologic regimes were delineated for each basin as either transient or snow-dominant systems. Rivers displaying two prominent runoff peaks (bi-modal) were delineated as transient and rivers displaying only one runoff peak in the spring (right skewed) were delineated as snowmelt dominated.

3.3 Quantification of Snowmelt Flows

In order to accurately estimate snowmelt contributions to annual flow, all discharge recorded during the months of April, May, June, and July (AMJJ) is considered to be of snowmelt origin. Although the use of AMJJ flows as proxies for snowmelt flow is quite general and inherently noisy with non-snowmelt inputs (rainfall and baseflow) its use here is highly appropriate. Firstly, studies that are highly relevant to this paper utilize AMJJ fractional flows to delineate snowmelt contributions (Stewart et al. 2004, 2005). Secondly, the hydroclimate of the study area lends itself well to the use of AMJJ as substantial spring snowpack, perennial snowfields, and glacier ice likely prolong the snowmelt runoff season at Mt. Rainier. Additionally, low summer precipitation strictly limits non-snowmelt sources from entering surface water systems.

To alleviate some of the uncertainties associated with the use of AMJJ fractions, dynamics between snowpack and AMJJ flow were addressed. Relationships between April 1st SWE and AMJJ flows were assessed through linear regression analyses for each river using the following equation:

$$y_{AMJJ} = b_1 X_{SWE} + \varepsilon_{1SWE}$$

Here y_{AMJJ} is the mean annual AMJJ flow for each river, b_1 is the linear coefficient corresponding to April 1st SWE , and ε_{1SWE} represents noise introduced by non-snowmelt derived inputs. Regression results are utilized to determine how well spring snowpack volumes correlate with AMJJ flow and therefore provided a basis for validating the use of AMJJ flows as an effective proxy for estimating snowmelt contributions. Furthermore, SWE and AMJJ regressions provided insights into major sources of flow variation for each basin.

Two metrics are applied to snowmelt flow estimates: proportions of annual flow, and AMJJ discharge volumes. Proportions represent the fraction of mean annual flow that was observed during the AMJJ period, and results are given in terms of percentage of mean annual flow. AMJJ flow volumes were calculated by converting mean monthly discharge values to acre feet using the following algorithm:

cfs → cfd (cfs x 86,400) → cf/period → af/period ((cf/period)/43,560) → af_{AMJJ}

$$af_{AMJJ} = \Sigma af / AMJJ$$

where:

cfs= *cubic feet per second*
cfd= *cubic feet per day*
86,400 = *seconds per day*
cf/period = *cubic feet per month*
43,560 = *ft^3 per acre feet*
af/period = *acre feet per month*
af_{AMJJ} = *the sum of af/period for AMJJ*

Quantifying river flows in terms of proportions and volumes provides for a more in depth analysis of temporal trends. AMJJ proportions and volumes are distinctly different measures in which inconsistencies in their coherence can be effectively used to identify shifts in hydroclimate (Bach, 2002). Secondly, AMJJ fractional flows were converted to acre feet to increase the applicability of the findings of this study to water resource management applications.

Snowmelt contributions are estimated for individual basins and for the study area as a whole (aggregate). Aggregated flows were calculated to establish a baseline estimate of total mean annual snowmelt proportions and volumes originating from Mt. Rainier snow sources. Data gaps in flow records for each river necessitated the analysis of three differing datasets in order to obtain accurate estimates of aggregated snowmelt volumes. The three datasets detail the following time periods: 1958-1975, 1958-2006, and 1992-2006. The 1958-1975 period is the only period when all five rivers have consistent records and was selected for the purpose. The 1958-1975 period serves to provide a basic baseline estimate for the entire aggregate. The 1958-2006 time period was selected as it is the longest period of record with the most rivers consistently represented (Nisqually, Puyallup, and Cowlitz). The latter period (1992-2006) provides the best estimate of current mean snowmelt flows; all rivers besides the White are represented. Additionally, the same methodology for quantification of snowmelt flows discussed above is applied to each river individually in order to illustrate the importance of snowmelt to each basin. All results are reported with a 95% confidence interval (α =.05) with the exception of the Carbon and White Rivers in which means are reported with a 90% confidence interval (α=.10).

3.4 Snowmelt Runoff Timing

Snowmelt runoff timing is quantified for both the aggregate and individual basins in order to establish mean snowmelt timing dates and to provide a basis for temporal trend analyses pertaining to the seasonality of AMJJ fractional flows. A majority of studies analyzing trends in streamflow timing throughout the western United States (Stewart et al. 2004, 2005; Regonda et al. 2005; Cayan et al. 2001; Dettinger and Cayan, 1995; Wahl, 1992) employ calculations of snowmelt pulse onset date (Cayan et al. 2001) or center of mass flow timing date (CT) (Stewart et al. 2005, 2004) to assess snowmelt timing. The calculation of CT date was selected for use in this analysis to be consistent with similar studies of western United States runoff timing (Stewart et al. 2005, 2004) and for it's compatibility with the AMJJ proxy.

CT is defined as the date marking the center of mass of annual flow for each water year (Stewart et al. 2005), or the date when half of the flow for each water year has occurred. Therefore, CT dates do not directly pinpoint snowmelt runoff timing dates with the accuracy of the Cayan et al. (2001) onset pulse algorithm, although high correlations (r = 0.5 – 0.8) have been established between the two measures (Stewart et al. 2005). Stewart et al. (2005) also find that the CT date provides a "time integrated perspective of the timing of this pulse and the overall distribution of flow for each year, and is less noisy than the spring pulse onset date" (p.1139). Given the empirical success of the CT date and applicability to monthly datasets, it is clear that the use of CT methodology will yield the most accurate results for Mt. Rainier rivers. The CT date is calculated from the following equation:

$$\mathbf{CT} = \sum(t_i\, q_i) \,/\, \sum q_i$$

Here t_i is the time in days since the beginning of the water year (wyd), and q_i is the corresponding streamflow for month i. The CT equation was adopted from Stewart et al. (2004, 2005).

Streamflow timing for the aggregate was calculated using the time periods in section 3.3 to correct for inconsistencies in flow data. The aggregated mean CT date for the entire period of record (1930-2008) was calculated by compiling every CT date for each river during their respective periods of records. Once all CT dates were compiled, the average date was calculated to give the long-term mean aggregate CT date. Snowmelt timing for each individual basin was calculated by applying the CT equation to each river's flow records. Mean annual CT dates were then calculated from the results of the CT equation and reported in units of water year day (wyd).

In an effort to better understand the relationship between snowmelt timing (CT) and snowpack, linear regressions were performed on corresponding CT and SWE time series to assess CT trend significance as a function of SWE variation. The following regression was performed for each river's historical record:

$$y_{CT} = b_1 X_{SWE} + \varepsilon_{1SWE}$$

Here y_{CT} is the mean annual CT date for each river, b_1 is the linear coefficient corresponding to April 1st SWE , and ε_{1SWE} represents noise introduced by non-snow variables.

3.5 Temporal Trend Analysis

Hydrologic trends are of great interest to water resource managers and as of late are receiving increasing attention by climate researchers. In response to this increase, temporal trend analyses were employed to assess changes over time in snowmelt contribution, overall water year discharge, snowmelt timing (CT), and SWE. Trends in snowmelt contribution, annual discharge, CT, and SWE well approximate linear functions, thus simple regression analyses were utilized to gain insights into the significance of temporal variations. Trend significance is assessed through the use of *t* and *F* tests at the 95% confidence level (α = .05).

3.6 PDO Phase State, Snowmelt Flow and Snowpack

Numerous studies have identified PDO phase state as a significant driver of snowmelt flow and SWE variation (Hamlet et al., 1995; Miles et al., 2000; Mote, 2003, 2005, 2008; Stewart et al., 2004, 2005, Regonda et al., 2005).To investigate the influence of the PDO on Mt. Rainier hydroclimate, two-sample t-tests are employed to investigate the hypotheses that there are significant differences (α=.05) in snowmelt runoff and SWE volumes respective of PDO phase state. The null hypothesis states that there is no difference in flow or SWE volumes due to phase state alterations. Oscillations of the PDO are categorized as either positive or negative; the last negative phase occurred from 1947-1976 and the latest positive phase occurred from 1976-1998 (Mantua et al. 1997). The Nisqually and Cowlitz datasets were the only records that contained enough data points to span both phases and were the only two rivers analyzed for PDO related differences. Flow data and SWE records for each watershed were categorized by phase state prior to analysis.

3.7 Synthesis

Although each technique described in this section provides important information on particular hydrologic parameters, the combination of techniques acts to synthesize sources of variation resulting in a concise and convenient analysis of Mt. Rainier snow hydrology. Therefore, the results of this report will provide water managers with a versatile tool for planning purposes in which data for individual basins and parameters may be isolated or integrated to suit further research needs.

4. Results

4.1 *Hydrography*

Regional rivers are classified as rain dominant, transient, or snow dominant systems. Rain dominant systems occur in low elevation basins where the primary input to surface water is rain and hydrologic response is initiated almost immediately following a precipitation event. Hydrographs of rain dominated systems display a characteristic peak flow period during the winter months when regional precipitation is at a maximum and exhibit a left skewed flow distribution. Transient (rain and snow dominated) systems occur at moderate elevations where precipitation type may alternate between snow and rain several times a year. Typically, accumulated snow does not linger for the duration of the winter as snowpack and is input to the river system several times as temperatures fluctuate. Transient hydrographs are typified as having two peaks: one in the winter (rain) and another in the spring (snowmelt) resulting in a bi-modal flow distribution. Snow dominant systems occur at high elevations where winter temperatures remain below freezing and snowfall acts as the primary precipitation type. Subsequently, runoff is delayed as the majority of winter precipitation is stored in the snowpack until the snowmelt begins. Snow dominant hydrographs display peak flows occurring during the spring and summer months and follow a right skewed flow distribution.

4.1.1 Nisqually River

The Upper Nisqually River exhibits a distinct bi-modal flow distribution typical of a transient watershed. The transient nature of streamflow is best illustrated when plotted with mean monthly precipitation at Ashford, Washington, the closest precipitation station to the National gauge (Fig. 4.1). Discharge closely reflects winter precipitation inputs until the snowmelt pulse from higher elevation snowpack begins in April. In the spring, precipitation ceases to be a major hydrologic input to the Nisqually. The input shift from rain to snowmelt sources serves to illustrate the importance of high elevation snowshed contributions to the Nisqually River during the dry summer months.

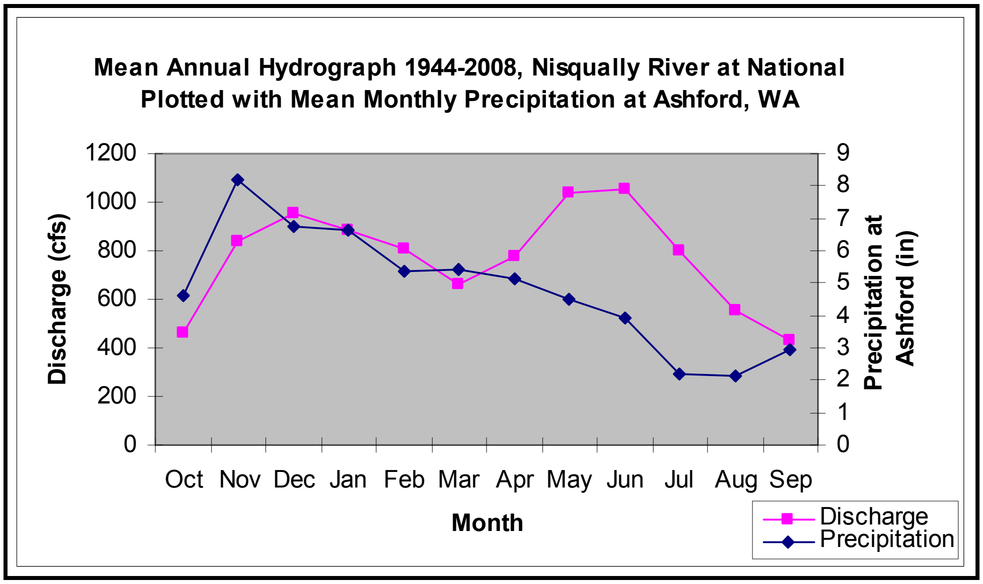

Figure 4.1: Mean annual hydrograph: Upper Nisqually River

4.1.2 Cowlitz River

The upper Cowlitz River is a snowmelt dominated system in which pronounced annual discharge peaks occur during the melt season and account for considerable proportions of annual flow. Snowshed contributions are apparent in the upper Cowlitz River hydrograph during the springtime months, which is observed in the right skewed flow distribution (Fig.4.2). When plotted with mean monthly precipitation at Packwood, Washington (same location as gauging station) discharge and precipitation relationships are not as coherent as those displayed by transient or rain dominated systems. The lack of winter coherence is indicative of earlier high elevation snowpack formation over large spatial domains.

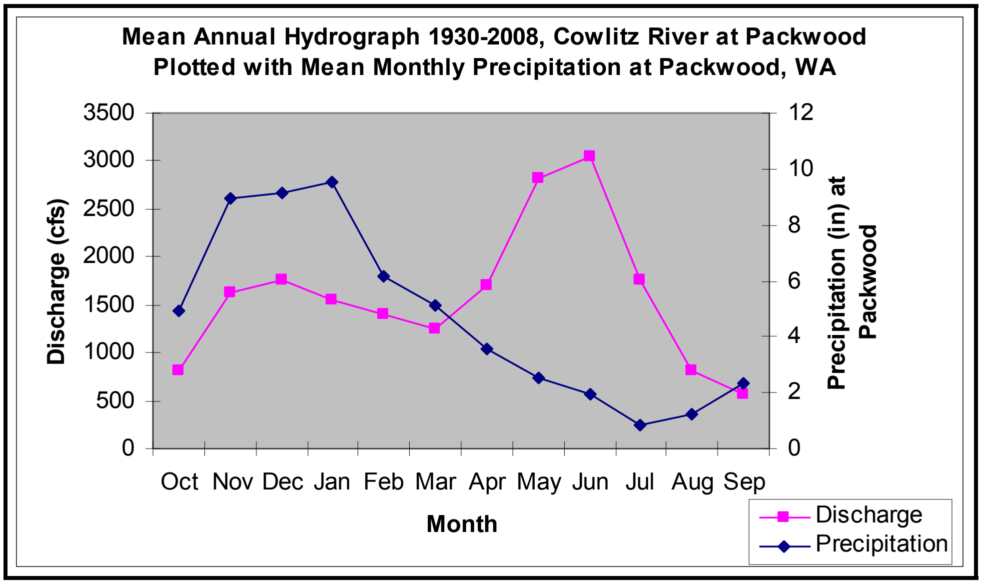

Figure 4.2: Mean annual hydrograph: Upper Cowlitz River

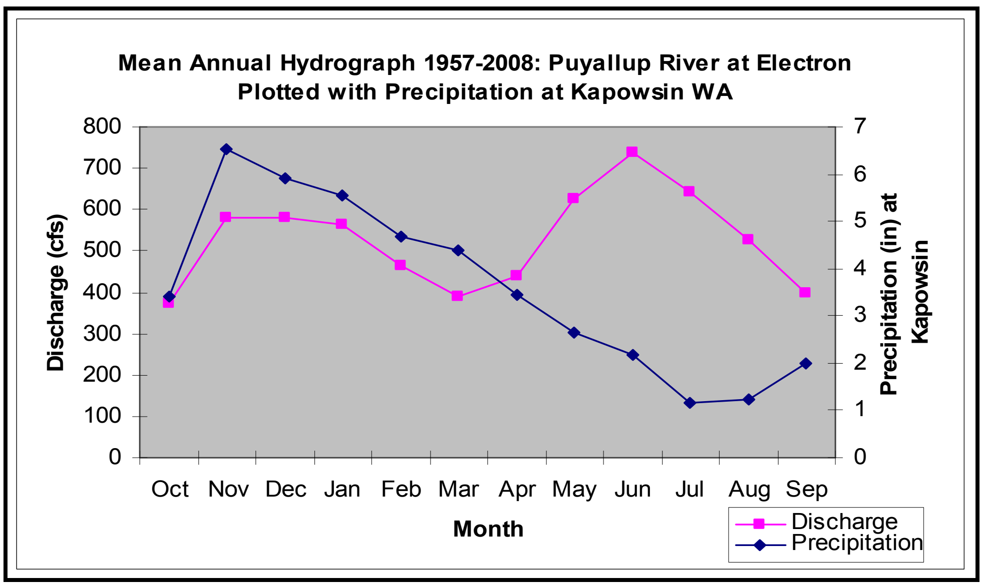

Figure 4.3: Mean annual hydrograph: Upper Puyallup River

4.1.3 Puyallup River

The upper Puyallup River is a transient system displaying a bi-modal flow distribution with both rain and snowmelt derived discharge peaks (Figure 4.3). The upper Puyallup hydrograph is plotted with mean monthly precipitation at Kapowsin, Washington (the closest precipitation station to the Electron gauging station). Precipitation and flow coherence are well defined during the winter months and the characteristic shift to snowmelt dominance is clearly observed in April. Similar to the other transient systems within the study, it is apparent that seasonal snowmelt is a critical source of runoff during the dry summer months.

4.1.4 White River

Hydrographic analyses for the White River do not reflect current conditions as flow data for the upper reaches of the basin ended in 1975. However, it is relevant to this study to identify the basin type for the White River as predominant hydrologic conditions likely remain similar. The annual hydrograph for the White River displays a right skewed flow distribution indicating snowmelt dominance (Fig. 4.4). There is a general lack of coherence between winter precipitation and discharge indicating substantial snowpack formation early in the winter. The typical snowmelt pulse occurs in April when snowshed contributions begin to dominate flow.

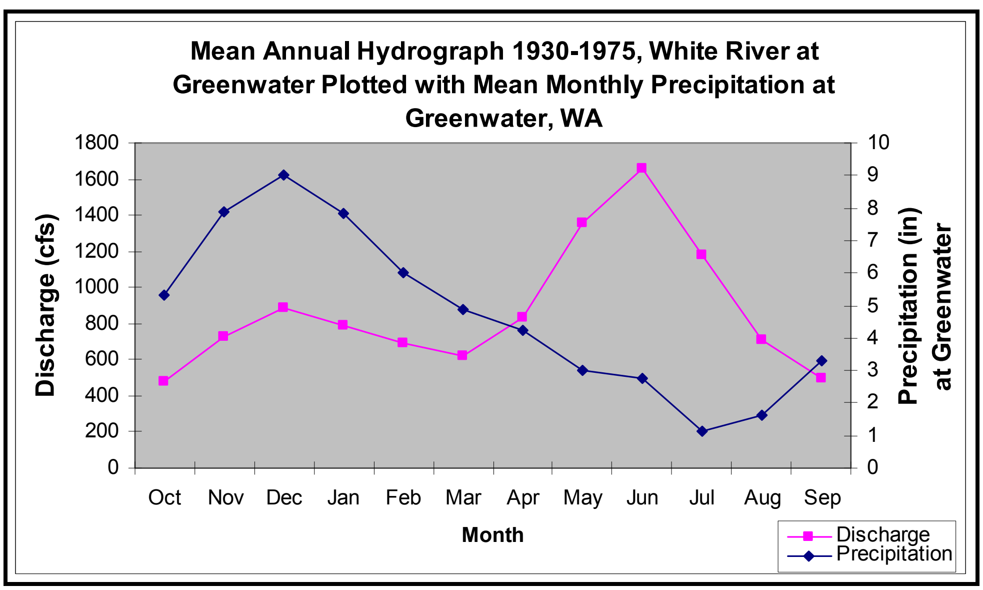

Figure 4.4: Mean annual hydrograph: Upper White River

4.1.5 Carbon River

Hydrographic analyses for the Carbon River do not reflect current conditions as flow data for the upper reaches of the basin ended in 1977. Although data limitations exist, quantification of snowmelt flows is still plausible and useful for management purposes. The annual hydrograph for the Carbon River follows a bi-modal distribution indicating a transient system (Fig 4.5). The hydrograph is plotted with mean monthly precipitation at the Carbon River Entrance to Mt. Rainier National Park, which is the closest precipitation station to the gauge at Fairfax. Winter precipitation is coherent with discharge and is indicative of rain dominant fall and winter flow regimes. It is not until April that high elevation snowmelt acts as the primary input for river flows.

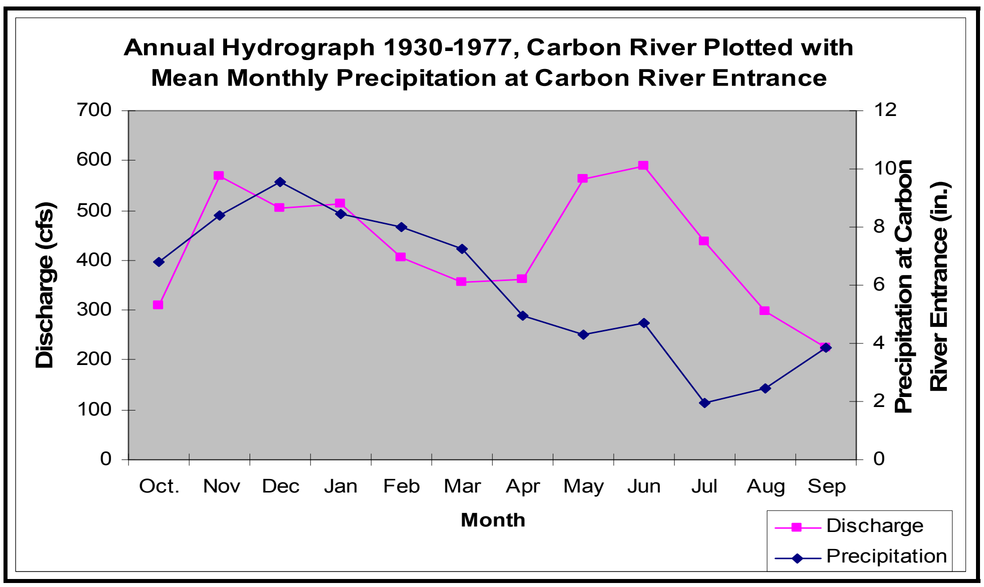

Figure 4.5: Mean annual hydrograph: Upper Carbon River

4.2 *Snowmelt Contributions to Aggregated Annual Flow*

4.2.1 Spring Snowpack and Runoff Dynamics

Regression analyses were utilized to investigate the relationships between spring runoff and annual snowpack for all five rivers. Relatively large distances between gauges and snowmelt sources exist for each river in the study area which inherently introduces noise to each snowmelt dataset from non-snowmelt inputs. Therefore, regression analyses provided insights into how much variability in each streamflow record can be explained by variations in annual snowpack quantities. Additionally, regression results serve to further clarify the effectiveness of using AMJJ fractional flows as proxies for estimating overall snowmelt contributions.

Aggregated AMJJ discharge was regressed on April 1st snow water equivalency (SWE) data recorded at Paradise. Regression results indicate very strong relationships between April 1st SWE and AMJJ discharge for each river. SWE coefficients for each regression are statistically significant (α=.05) with R^2 values ranging from .42 to .79, indicating that substantial portions of variation in AMJJ flows for each river can be explained by snowpack variability (Table 4.1).

River	t	p(t)	f	p(f)	Adj.R^2
Nisqually	10.017	<.001	233.2	<.001	0.64
Cowlitz	15.3	<.001	233.2	<.001	0.79
Puyallup	6.79	<.001	46.1	<.001	0.49
Carbon	4.96	<.001	24.6	<.001	0.42
White	8.29	<.001	68.75	<.001	0.69

Table 4.1: AMJJ and SWE regression results.

Paradise April 1st SWE best describes flow variation for the Nisqually, Cowlitz, and White Rivers during the snowmelt runoff period. Paradise is located proximal to the watershed divide for the Nisqually and Cowlitz hence the strong explanatory power for each respective river. The high correlations affirm that there is minor variability in snowpack formation in the study area allowing Paradise SWE data to serve as accurate proxies for estimating annual snowpack influences for all 5 watersheds.

4.2.2 Aggregated Snowmelt Flow Proportions

Estimates of total snowmelt runoff proportions from Mt. Rainier were calculated using three datasets. The first dataset includes records from all five rivers from 1958-1975 which is the only time period when concurrent records exist for all five watersheds. The second dataset includes records from 1958-2006 and utilizes flow records from the Nisqually, Cowlitz, and Puyallup Rivers. This time period was selected for analysis as it provides the longest time period of consistent records for the greatest number of rivers. The third dataset takes advantage of renewed data collection for the Carbon River and includes records for each river with the exception of the White, from 1992-2006. Estimates derived from the 1992-2006 dataset provide the best insights into modern snowmelt quantities. Mean aggregated snowmelt quantities during the 1958-1975 period are 44.78% ±2.8% (α=.05) and range from 33.3% to 55.47% of annual flow. Aggregated snowmelt contributions from 1958-2006 are nearly identical to that of the complete aggregate estimate with mean annual snowmelt flows of 44.80% ±2.82% (α=.05). However, snowmelt flows during the 1958-2006 period are more variable ranging from 25.46% to 67.69% of annual flow. Mean annual snowmelt contributions during the 1992-2006 period are slightly lower at 41.58%±3.61% (α=.05) and range from 25.02% to 51% of annual flow.

4.2.3 Aggregated Snowmelt Flow Quantities

Aggregated snowmelt volumes were quantified to better extend these findings to water resources applications. Therefore, all snowmelt flow quantities were converted from cubic feet per second (cfs) to acre feet (AF). The mean snowmelt volume in Mt. Rainier rivers from 1958-1975 is 1.42 million acre feet ± 135.89 acre feet (α=.05) and ranges from 867,621 to 1,990,147.2 acre feet. Meltwater quantities for the 1958-2006 period range from 531, 260 to 1,420,317 acre feet with a mean volume of

895,551.63 acre feet ± 55,128 acre feet (α=.05). Mean snowmelt volume for the recent period (1992-2006) is 969,292 acre feet ± 111,087.5 acre feet (α=.05). Mean annual snowmelt proportions and quantities for each time period are summarized in Table 4.2.

Period	Rivers	Annual Snowmelt Proportion	Quantity (af)
1958-1975	N,C,P,Ca. W	44.78%	1,419,738
1958-2006	N, C, P	44.80%	895,551
1992-2006	N,C,P,Ca.	41.58%	969,296

Table 4.2: Summary of aggregated snowmelt flow data. N= Nisqually; C= Cowlitz; P= Puyallup; Ca. = Carbon; W= White.

4.2.4 Aggregate Trend Analysis

Temporal trend analyses were conducted for the 1958-2006 period in order to identify significant changes in snowmelt flow quantities, proportions and overall annual (12 month water year) discharge. Trend analyses were also conducted for April 1st snow water equivalencies (SWE) at Paradise in an effort to corroborate trends in snowmelt runoff with SWE variability. 1958-2006 aggregated snowmelt flows are highly correlated with Paradise SWE (R^2 = .789, t= 13.35, p=<.001). Subsequently, temporal trends in SWE and snowmelt flows are highly coherent (Fig. 4.6).

Snowmelt quantities and 1958-2006 Paradise SWE were found to be declining over time at similar rates, which is shown graphically in Figure 4.6. Although clear negative trends are observed for both SWE and runoff, neither trend is statistically significant at the 95% confidence level: SWE (t= -1.35, F= 1.83, p = .18), aggregated snowmelt flow (t= -1.45, F= 2.1, p = .154). However, aggregated mean annual snowmelt proportions were found to be significantly decreasing (t= -2.194, F= 4.815, p=.0332) suggesting increases in non-snow precipitation inputs over time.

Importantly, overall annual discharge for the aggregate was found to be trend neutral with no significant gains or losses (p= .174). The potential causes and implications of significantly declining proportions of annual flow in relation to trivial fluctuations in overall annual discharge are addressed in Chapter 5.

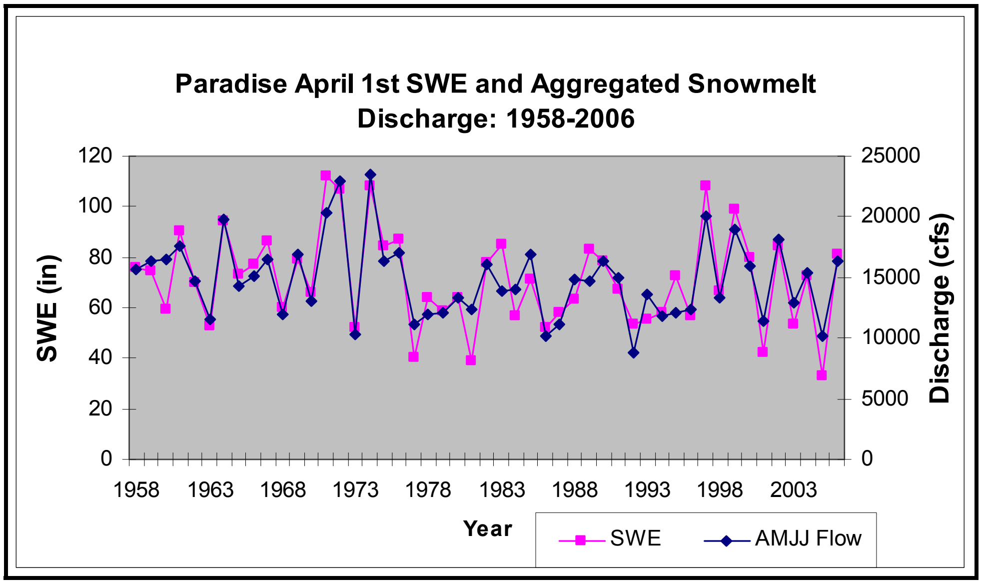

Figure 4.6: Time series of SWE and aggregated AMJJ flow.

4.2.5 Long Term Snow Water Equivalent Trends

Paradise April 1st SWE records date back to 1944 and extend to the present, therefore longer term trend analyses detailing SWE variability were possible. Results indicate that spring snowpack totals have been significantly (α=.05) decreasing for the entire duration of record (t= -2.62, F= 6.846, p= .01). These findings are consistent with decreases in both mean annual snowmelt quantities and snowmelt flow proportions outlined above.

4.3 Snowmelt Contributions to Annual Flow in Individual Basins

Snowmelt quantities in all five rivers were calculated individually to examine runoff variability on basin scales. Mean annual snowmelt flows were estimated in terms of proportions of mean annual discharge and through the calculation of AMJJ flow volumes. Temporal trend analyses were applied to quantification results in order to identify trends in runoff over time and provide insights into possible spatial variation in the study area. Table 4.3 provides snowmelt proportions and flow quantities for each river:

River	Mean Annual Snowmelt Proportion	Mean AMJJ Flow Volume (af)
Nisqually	39.8%	221,394
Cowlitz	49.1%	564,744
Puyallup	39.0%	108,492
White	48.6%	304,114
Carbon	41.6%	127,380

Table 4. 3: Mean annual snowmelt quantities for Mt. Rainier Rivers.

4.3.1 Nisqually

In general, snowmelt contributions to the Nisqually River are low compared to the other rivers in the study area. The average proportion of snowmelt flows in the upper basin is 39.8%±1.5 %(α=.05) of annual flow at National, and ranges from 24.2% to 55.1% (n=61, σ=6.3) throughout the period of record. Therefore, snowmelt flows rarely account for more than half of total annual flows, results which are consistent with the transient hydrography of the basin. Mean annual snowmelt volumes range from 131,582 acre feet to 332,406 acre feet (σ=45,532) and average 221,394 ± 11,243 acre feet.

Nisqually River trend analyses indicate that both snowmelt proportions and AMJJ volumes are steadily decreasing over time, and represent one of this study's key findings. Annual proportions of snowmelt flow were found to be significantly decreasing ($t= -2.28$, $F= 5.22$, $p= .026$) concurrently with significant decreases in AMJJ flow quantities ($t= -2.19$, $F= 4.824$, $p= .032$). Trends are shown graphically in Figure (4.7).

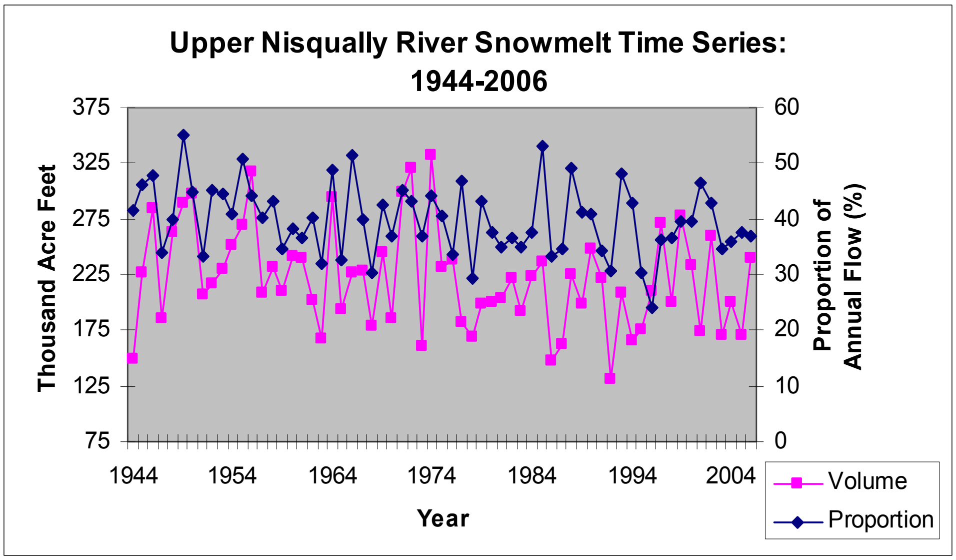

Figure 4.7: Snowmelt flow trend: Upper Nisqually River

4.3.2 Cowlitz

The Cowlitz River comprises of the largest snowmelt dominated basin originating on Mt. Rainier and contributes substantial spring and early summer flows to regional hydrology. Mean annual snowmelt contributions account for 49.1%±1.7% (α=.05) of mean annual flows at Packwood. Snowmelt proportional flows display a high degree of variability with annual proportions ranging from 26.4% to 71.4% (n=79, σ= 8.89) of annual discharge. These figures corroborate well with the observed snow dominant nature of Cowlitz hydrography by essentially accounting for half of the total annual discharge for the upper reaches of the basin. Additionally, the large range and high variance of proportional values are indicative of sensitive climatic response, especially in regards to spring snowpack; correlations between Paradise SWE and Cowlitz discharge are the highest in the study area (R^2= .79). Mean AMJJ discharge volumes range from 280,504 acre feet to 908,592 acre feet (n=79, σ= 150,443) and average 564,744 acre feet ± 33,175 acre feet (α=.05).

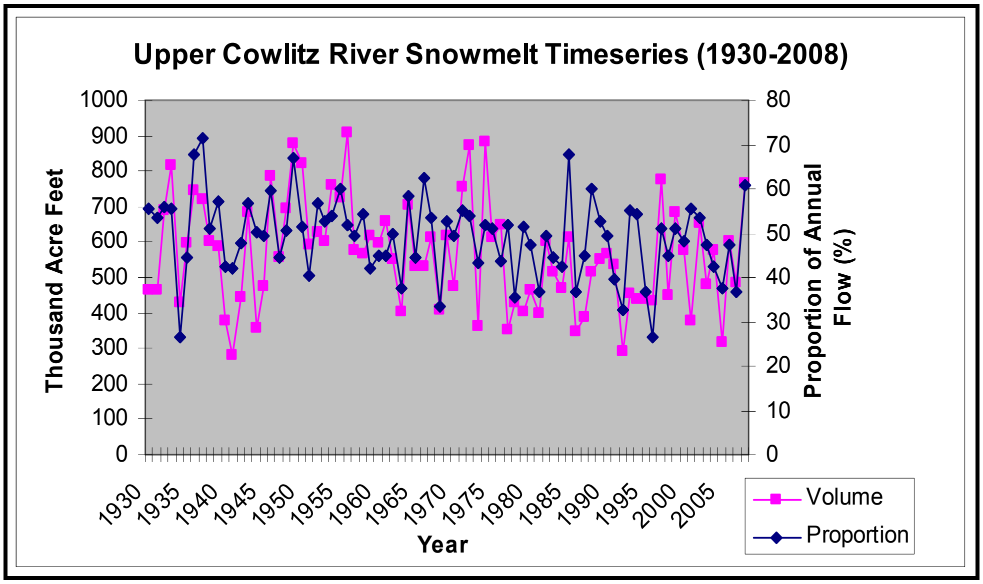

Figure 4.8: Snowmelt flow trend: Upper Cowlitz River

Temporal trend analyses for the Cowlitz River are similar to those detailing Nisqually River flow as both snowmelt fractional flows and melt season discharge quantities are steadily decreasing over time. Again, these findings are amongst the most important observations in this study.

Snowmelt proportions are significantly (α=.05) decreasing (t= -2.27, F= 5.15, p=.026) resultant from significant declines in snowmelt season discharge volumes (t= -2.03, F=4.12, p=.04), which are displayed graphically in Figure 4.8. The similarities in temporal trend behavior between the Nisqually and Cowlitz Rivers raise questions about spatial influences on long term trends primarily due to the close proximities of their respective high elevation snowsheds, and the fact that both rivers are the only systems displaying statistically significant negative trends in the study area.

4.3.3 Puyallup

The Upper Puyallup River contributes the least amount of snowmelt flows to the region in terms of both snowmelt proportion and quantity. Snowmelt flow proportions range from 24% to 53.8% of annual flow (n= 51, σ= 5.77) with an average snowmelt fraction of 38.96%±1.58 (α=.05). Mean annual snowmelt quantities range from 76,596.1 acre feet to 151,123 acre feet (n=51, σ= 15839.4). The mean annual snowmelt volume for the basin is 108,492 acre feet ± 4,347.2 acre feet. The aforementioned quantification results are consistent with a transient dominated hydrograph.

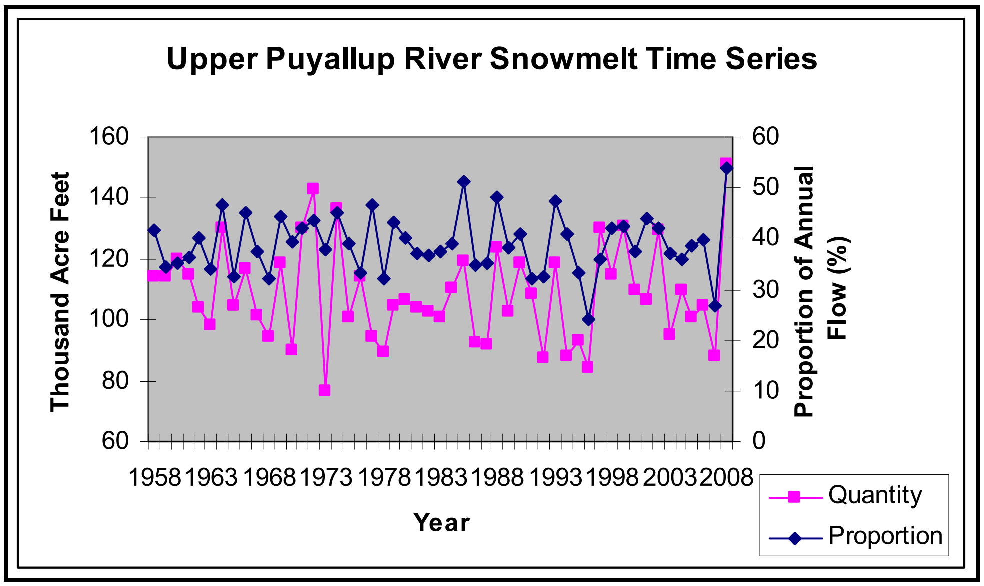

Figure 4.9: Snowmelt flow trend: Upper Puyallup River

The Puyallup River is also experiencing declines in mean snowmelt proportions and quantities over time, although, trend analyses indicate that the decline of Puyallup snowmelt flows is not as pronounced as those identified for the Nisqually and Cowlitz (Fig. 4.9). Statistically significant negative trends were not identified for snowmelt proportions (t= -.637, F= .406, p=.527) or snowmelt quantities (t= -.202, F= 1.03, p= .841).

Puyallup snowmelt quantity coefficients regressed on time are nearly zero (-30.74) indicating that snowmelt flow quantities are essentially stagnant and are not experiencing any significant deviations from observed long term means. Variability in snowmelt proportion accurately follows quantity fluctuations further elucidating the stability of temporal snowmelt trends for the Puyallup River.

4.3.4 White

Incomplete records for the upper reaches of the White River prevented analysis beyond 1975. However, observed long term trends in similar basins are not strong enough to drastically alter current means. Therefore, taking into consideration observed trends, the assumption is made that White River flows have not increased or decreased by magnitudes that render available White River data useless for snowmelt estimation purposes. In order to help mitigate for temporal uncertainties, all means for the White River are reported with a 90% confidence interval. No time series regressions were utilized due to the shortness of the available record and inapplicability to current and future water resource goals.

The White River is the second largest river originating on Mt. Rainier in terms of drainage area (216 mi.^{2}) and snowmelt contribution. Annual snowmelt quantities range from 186,653 acre feet to 452,818 acre feet (n= 45, σ= 59,106.8) with an average of 304,114 acre feet ± 23,614 acre feet. 48.6% ± 2.73% of annual flow is attributable to snowmelt inputs where Snowmelt proportions range from 28.26% to 65.31% of mean annual flow (n=45, σ= 6.84). The high degree of variability is likely due to annual variations in snowpack volumes as the White River is highly snow dominant; correlation of flow quantity to Paradise SWE is the second highest in the study area (R^2= .69). Close similarities between the White

River and the Nisqually and Cowlitz Rivers in terms of snowpack correlation suggest that White River snowmelt trends are likely decreasing.

4.3.5 Carbon

Accurate flow records for the upper reaches of the Carbon River ended in 1977 therefore trend analyses were not conducted for Carbon River snowmelt proportions or quantities. Trend strengths of neighboring rivers were again used to support the assumption that current Carbon River flows are not substantially different from that of the existing period of record even if temporal variations are occurring. As in the case with the White River, Carbon flows are reported with a 90% confidence interval. Additionally, the Carbon River's low correlation with Paradise SWE (R^2= .42) compared to the higher correlations of rivers experiencing negative trends suggests that Carbon River flows are not experiencing significant declines in snowmelt flow and are likely similar to trends observed for the Puyallup system.

The Carbon River Basin is the smallest catchment studied (78.9 mi.^{2}) and total snowmelt contributions rank as the second smallest in the study area. The mean annual snowmelt proportion is 41.55% ± 2.65% of annual flow and is consistent with the basin's transient hydrography. Carbon River snowmelt proportions range from 24.09% to 58.42% (n=48, σ=6.84), which serves to supplement the aforementioned assumption regarding snowmelt and streamflow relationships. Snowmelt flow quantities range from 183,843 acre feet to 76,011 acre feet (n= 48, σ= 23,943) with an average annual volume of 127,380 acre feet.

4.4 *Aggregated Snowmelt Runoff Timing*

The timing of snowmelt flows are critical for sustaining water resource reliability goals and are therefore equally as important as snowmelt flow proportions and quantities for resource planning purposes. For the purposes of this study, center of mass flow timing dates (CT) are calculated for use as a proxy in identifying the starting date of the snowmelt season. Snowmelt timing dates are given for the study area as a whole (aggregate) and for each individual basin. Temporal trend regressions were performed for the aggregate dataset (1958-2006) and for each basin to identify shifts in snowmelt peaks over time. CT variation was also analyzed in terms of SWE variability to indentify linkages between CT shifts and spring snowpack volumes.

4.4.1 Aggregated Snowmelt Timing

In order to accurately estimate the beginning of the snowmelt season for Mt Rainier rivers four datasets were utilized to capture CT dates. The same datasets used to calculate aggregated snowmelt proportions and quantities are used for snowmelt timing estimation in order to alleviate uncertainties due to inconsistent records (see section 4.2.2 for explanation). Aggregated CT results are given in Table 4.4.

Period	Rivers	Mean CT (d)	Date Range (α=.05)
1930-2008	All	201 ± 2.5	April 17-April 23
1958-1975	N,C,P,Ca. W	205 ± 4.2	April 20-April 28
1958-2006	N, C, P	197 ± 3	April 13th-April 19
1992-2006	N,C,P,Ca.	192 ± 5.2	April 6- April 16

Figure 4.4: Mean snowmelt timing dates for Mt. Rainier Rivers

Mean CT dates indicate that the annual snowmelt pulse begins in early to late April and has been decreasing over time. During the 1958-1975 period, in which consistent records for all five rivers exist, snowmelt flows began in late April. In contrast, during the 1992-2006 period in which all rivers except the White are included, mean CT dates occur no later than mid-April. Although the White River is a significant source of snowmelt flows, and likely would delay the 1992-2006 CT date, these findings nonetheless suggest that shifts in CT date towards earlier in the spring are occurring for Mt. Rainier Rivers. Furthermore, shifts in CT appear to be intrinsically linked to declines in Mt. Rainier SWE; regression results indicate statistically significant negative trends (p=.008) when CT is regressed on SWE.

4.4.2 1958-2006 Temporal Trend Analysis of CT Date

A regression analysis was performed on the 1958-2006 dataset in order to indentify long-term trends in aggregated snowmelt runoff timing. The 1958-2006 time period was selected as it is the longest period of time where there are consistent records and for the overall applicability of the trend analysis to current water resource goals. Snowmelt timing was found to be decreasing over time, although the trend is not significant at the 95% confidence level (t=-1.608, F= 2.82, p= .09). However, the trend is significant at the 90% confidence level suggesting that the mean CT day for the Nisqually, Cowlitz, and Puyallup Rivers is advancing and snowmelt runoff in Mt. Rainier Rivers is occurring earlier in the year. Regression results are supported by comparing the mean CT date for the 1992-2006 period (April 11th) to that of the 1958-2006 period (April, 16th) where the difference in mean CT date is 5 days earlier.

4.5 *Snowmelt Runoff Timing for Individual Basins*

4.5.1 Nisqually

CT dates for the Nisqually River are the earliest in the study area with a mean date of April 7th and CT of water year day (wyd) 188± 5.3. Considerable variability exists for the basin with CT dates ranging from 240 wyd to 140 wyd (σ= 20.14) which is equivalent to February 18th to May 29th. Linear trend analyses indicate that snowmelt runoff timing in the Upper Nisqually basin is trending towards earlier dates as evidenced by a highly negative and significant trend in CT (t= -3.2, F= 10.22, p= <.001). CT trends are consistent with negative trends in Nisqually River snowmelt proportions and quantities further validating that CT variation is influenced by spring snowpack volumes.

4.5.2 Cowlitz

The Cowlitz River displays the least variability in runoff timing throughout the study area with a mean CT date of wyd 201±3.6 and a range of 238 wyd to 151 wyd (σ= 15.9) which corresponds to a mean calendar date of April 20th which ranges from March 1st to May 27th. Temporal trend analyses indicate that snowmelt runoff in the Cowlitz River basin is occurring early in the year, and significantly advancing over time (t= -2.16, F= 4.6, p= .03). Concurrent with trends observed for the Nisqually River, snowmelt timing advances in the Cowlitz Basin are consistent with declines in snowmelt runoff proportions and quantities and further suggest that snowpack volumes are influential upon runoff timing in snow dominant river systems.

4.5.3 Puyallup

The mean CT date for the Puyallup River is the second latest in the study area at wyd 207± 5.12wyd. The calendar date of the long term Puyallup CT mean is April 26th. Additionally, the Puyallup has a large range of mean annual CT dates spanning from 154 wyd (March 4th) to 243 wyd (June 1st) (σ=18.04). Trend analysis yielded a slightly negative and non-significant trend (t= -.20, F= .04, p= .80). Puyallup CT trend intensity is reflected in Puyallup flow relationships with SWE (R^2= .49) and is consistent other SWE and CT relationships in the study area.

4.5.4 White and Carbon

No CT trend analyses for the White or Carbon Rivers were performed due to data limitations, however observed trends for other rivers in the study area are not strong enough to greatly alter historical means. Therefore, substantial deviations in CT since the late 1970's are unlikely for the White and Carbon Rivers which permits CT calculations from available records to provide reliable estimates current snowmelt timing.

The mean annual CT date for the White River is the latest in the study area at wyd 218 (May 7th) ± 6.7 wyd. CT dates for the White River have the greatest range in the study area spanning from 146wyd to 260 wyd (February 24th to June 18th respectively) (σ= 22.5). Similarities between the White River and the Cowlitz River, namely high correlations between flow and SWE, indicate that CT trends for the White River are most likely declining at rates comparable to those found for the Cowlitz.

The Carbon River has the second earliest CT date in the study area at wyd 199 (April 18th) ± 6.4 wyd, and a range of 137 wyd to 243 wyd (February 15th to June 1st respectively) (σ= 22.5). The Carbon River is a transient system like the Nisqually and Puyallup, although mixed results in trend analyses exist for the Nisqually and Puyallup rivers. Therefore it is difficult to extend trend results from other transient basins to the Carbon. However, Carbon River runoff is least correlated with SWE, suggesting that CT trends are similar to that of the Puyallup which also displays a low correlation with snowpack.

4.5.5 PDO Phase State, Snowmelt Flow and Snowpack

Results of two sample t-tests indicate that significant differences in AMJJ snowmelt proportions and SWE exist between positive and negative phases of the PDO. Due to limitations in period of record, only the Nisqually and Cowlitz Rivers had enough observations to adequately span both phases. During negative phases of the PDO, snowmelt contributions of the Nisqually ($t=3.65$, $p<.01$) and Cowlitz ($t=4.74$, $p<.01$) were significantly greater than contributions observed during positive phases. Results comparing phase state and winter snow accumulations are consistent with the observed differences in AMJJ flow where Paradise SWE values are significantly higher during negative PDO phase states ($t=3.8$, $p<.01$). Therefore, more snow accumulation and subsequent AMJJ flows occur in response to cooler and wetter conditions for the Nisqually and Cowlitz Rivers. Although it is difficult to confidently estimate PDO effects for the Puyallup, White, and Carbon Rivers, the convincing differences observed for the Nisqually and Cowlitz suggest that the PDO has profound effects over the entire study area.

5. Discussion

The results of this study indicate that the hydrologic regimes of Mt. Rainier rivers are heavily influenced by the magnitude and timing of snowmelt inputs. The role of snow in annual hydrologic variability is elucidated by the high degree of coherence observed between streamflow variations and fluctuations in spring snowpack; large April 1st SWE volumes generate high AMJJ fractional flow proportions and quantities. Snowmelt flow magnitudes also influence annual streamflow timing for Mt. Rainier Rivers, where later CT dates are associated with large spring snowpacks and early dates occur during years of low snow volume. Temporal trend analyses of AMJJ flow, annual streamflow timing, and snow water equivalencies provide the most important findings of this study as numerous negative trends for all three parameters were identified, several of which are statistically significant. Additionally, the role of the Pacific Decadal Oscillation as a substantial driver of hydrologic variation has been confirmed for the study area through the identification of significant differences in SWE and AMJJ flow in regards to PDO phase state. Therefore, the findings outlined in this study present numerous implications for future water resource planning goals and provide insights into potential hydrologic responses of Mt. Rainier Rivers to climate change effects.

5.1 Quantification of Snowmelt Flows

Snowmelt runoff accounts for substantial portions of annual flow quantities for all five rivers in the study area with proportions ranging from 39% to 49.1% of total annual discharge. Although only the Cowlitz and White Rivers are delineated as snow dominated systems, the remaining three transient stream hydrographs display pronounced AMJJ peaks in which a third of annual runoff occurs in a four month period. Stewart et al. (2005) determined that less than 30% of mean annual flow in regional transient basins occurs during the AMJJ period, suggesting that Mt.

Rainier transient streams better represent hybrid systems in which snowmelt influences may be more influential that rainfall inputs. Thus, snowmelt inputs are major components of annual flow in each watershed regardless of hydrographic classification by providing critical flow augmentation during the dry summer and fall months when other local transient systems are well into recessional states.

Estimates of Mt. Rainier snowmelt proportions and quantities are consistent with similar studies investigating snowmelt flows across western North America (Stewart et al. 2004, 2005; Regonda et al. 2005; Cayan et al. 2001; Dettinger and Cayan, 1995). However, studies pertaining to Pacific Northwest snowmelt are more useful for corroboration (Mote, 2008; Bach, 2002; Miles et al. 2000; Pelto, 1993). Bach's 2002 study of snowshed contributions to the Nooksack River utilizes similar methodologies to quantify snowmelt flows from Mt. Baker and serves as the only fine grained comparison to this study. Hydrographic characteristics of Mt. Baker and Mt. Rainier are very similar as both systems originate on large glaciated volcanoes and possess similar climates (Bach, 2002). Annual snowmelt flows in the Nooksack River range from 27.9% to 63.9% percent of annual flow (Bach, 2002) which is highly consistent with the range of annual snowmelt proportions at Mt. Rainier. The high degree of coherence in estimates serves to further validate the accuracy of AMJJ flow proportions calculated for Mt. Rainier. The combined results of this study and Bach's (2002) work on Mt. Baker provide a firm baseline for estimating snowmelt dynamics in the Pacific Northwest by establishing a working dataset for future water resource planning.

5.2 Snowmelt Runoff Timing

Snowmelt timing dates (CT) calculated for Mt. Rainier corroborate well with mean CT dates from similar snow fed systems observed across large spatial domains (Stewart et al. 2004, 2005; Regonda et al. 2005; Cayan et al. 2001; Dettinger and Cayan, 1995). Snowmelt flows originating from Mt. Rainier generally begin to dominate the hydrographs of all five rivers from early April to early May which is consistent with CT dates for other Pacific Northwest rivers (Stewart et al. 2005, 2004; Bach, 2002, Miles et al. 2000; Hamlet and Lettenmaier, 1999). Similar to other regions in the American West, Mt. Rainier CT dates vary annually on large temporal scales, sometimes changing by periods measured in months (Stewart et al. 2005; Regonda et al. 2005; Cayan et al. 2001). Highly significant positive relationships (p=.008) established between aggregated CT date and April 1st SWE volumes at Mt. Rainier illustrate fundamental linkages between winter snow accumulation and snowmelt timing. Given the importance of snowmelt timing to current reservoir operation schedules, quantifications of CT date will provide helpful foundations for water availability forecasting in the future.

5.3 Hydrologic Trend Analyses

Temporal trend analyses of AMJJ flow quantity, streamflow timing (CT), and April 1st SWE provide the most valuable results of this study as trends are of great interest to both water resource managers and climate researchers. Overall, trends for all three parameters are negative; declining trends were observed for both aggregated and individual basins indicating that hydroclimatic variables at Mt. Rainier are shifting away from observed long term conditions. Negative trends in AMJJ flow, CT, and SWE parameters present profound implications to water resource sectors and threaten to alter fundamental components of the current resource operation regime. Furthermore, the observed declines in snowmelt parameters serve to verify that regional trend signals are present in Mt. Rainier watersheds, and suggest that climate change effects are already beginning to influence local snow hydrology.

5.3.1 Spring Snowpack

The significantly negative trend in Paradise SWE indicates that spring snowpack volumes have been steadily decreasing since records began in 1940. SWE trend results for Mt. Rainier are consistent with findings from several studies detailing Pacific Northwest snowpack (Mote et al. 2008; Hamlet et al. 2005, Mote et al. 2003) and with studies analyzing SWE trends from mountainous regions throughout western North America (Mote et al. 2006; Hamlet et al. 2005; Mote et al. 2005; Stewart et al. 2005; Regonda et al. 2005). Mote et al. (2008) find that SWE declines from 1950-2006 range from 15%-35% in the Washington Cascades, where studies encompassing larger domains find basin scale decreases from 20%-80% during the latter half of the 20th century (Hamlet et al. 2005, Mote et al. 2003, Regonda et al. 2005).

High spatial trend coherence (local and regional) indicates that Mt. Rainier SWE trends are likely occurring in response to large scale climatic variation, although it is unclear whether PDO influences or climate change effects are significant drivers. Cayan et al. (2001) established that warming trends from1948-2002 throughout the western US are regional in extent and argued that a combination of PDO phase and greenhouse gas forcing is driving the warming. Mote et al. (2003) found similar trends in PNW temperature and related regional climatic variation to fluctuations in spring snow water equivalencies. Results from Mote et al. (2003) indicate that regional warming trends account for most of the declines in SWE whereas precipitation had secondary effects. Furthermore, Mote et al. (2003) conclude that temperature trends are occurring independently from PDO phase state, and in a supplementary study (Mote et al. 2008) assert that SWE declines in the Cascades are “largely unrelated to Pacific climate variability and strongly congruent with trends expected from rising greenhouse gases” (p.208). Therefore, it is likely that the observed declining trends in Mt. Rainier spring snowpack can be partially attributed to the effects of global and local climate change and will continue to decline as anthropogenic warming accelerates.

Local water resource managers rely upon historic hydroclimatic records for streamflow forecasting purposes in which April 1st SWE is the central parameter used to estimate AMJJ streamflow potentials. Continued declines in annual SWE will alter current runoff forecasting methodologies by rendering contemporary historical approaches as unreliable. Water managers will be required to implement new water supply forecasting techniques that do not heavily integrate historical variations in SWE. New methods must incorporate forecasted climate change effects with increased field data in order to accurately establish accurate water supply predictions. Failure to abandon historically integrated approaches will result in the issuance of in-accurate streamflow forecasts inflicting potentially large economic damage to agricultural and municipal water sectors.

5.3.2 AMJJ Flows

Negative temporal trends were identified for the aggregate (1958-2006) and for the Cowlitz and Nisqually Rivers and a near stagnant trend was identified for the Puyallup River. Declining trends in AMJJ flow proportions are consistent with numerous studies analyzing snowmelt systems across the western United States (Wahl, 1992; Aguado et al. 1992; Pupacko, 1993; Dettinger and Cayan, 1995; Stewart et al. 2004, 2005; Regonda et al. 2005) Of particular interest is the finding that aggregated AMJJ flow quantities are not decreasing at a significant rate ($p = .154$) whereas aggregated AMJJ flow proportions are significantly decreasing ($p = .03$). The difference in decline magnitude between aggregated AMJJ flow proportions and AMJJ flow quantity further validates the findings of Mote et al. (2003, 2008) that temperature is driving snowpack decline. Aggregated annual (12 month) flows were not found to be significantly decreasing, suggesting that declines in AMJJ flow proportions are resultant of more precipitation falling as rain in the winter limiting the amount of meltwater stored in high elevation snowsheds for release during the AMJJ period (Bach, 2002). The observed imbalance in streamflow decline provides further evidence that streamflow variations are likely being driven by climate change effects.

The Nisqually and Cowlitz rivers are experiencing significant declines in AMJJ streamflow whereas the Puyallup time series indicates a trend neutral pattern. These findings suggest that AMJJ flows are declining only in snowmelt dominated systems and transient rivers are not experiencing significant alterations to historical variability. Data limitations for the White and Carbon Rivers forbid conclusions to be made that snowmelt dependence is exclusively controlling declines in AMJJ flows. Here, the relationships between flow and SWE are utilized to hypothesize that White River AMJJ flows are likely decreasing and Carbon River flows are likely trend neutral. Snowmelt period runoff in the Cowlitz is strongly correlated with SWE variation (R^2= .69) indicating that AMJJ flows are highly dictated by spring snowpack volumes suggesting that the overall trend in White River snowmelt is decreasing at similar rates as those identified for the Nisqually and Cowlitz systems. Alternatively, the relatively low snowpack correlation observed for Carbon River snowmelt (R^2= .42) can be used to confidently infer that AMJJ flow trends are trivially neutral in strength.

Decreases in annual AMJJ flow proportions and quantities have the potential to drastically alter water resources operating regimes. Currently, spring flows are utilized to re-fill reservoirs following winter flood control drawdowns to provide water for the arid summer and early fall seasons when inputs to reservoirs are at annual low volumes. The neutral trend in overall discharge indicates that more runoff will occur during mid-winter resulting in an increase of flood control releases. Increased flood control releases will place even more dependence on snowmelt flows to meet present reservoir demand curves therefore increasing the likelihood of severe water scarcity and potential drought during the late summer and fall.

The combination of projected climate change impacts and population growth further confounds impending water scarcity conflicts resulting from decreasing snowmelt flow. Shifts in energy demand are likely to occur as a result of regional warming that will generate higher demands for cooling energy during the summer (Hamlet et al. 2009). Subsequently, heightened demands for hydropower will require utilities to spill additional reservoir water during the summer further exacerbating current tensions between the hydropower sector and instream flow rules (Payne et al. 2004; Hamlet and Lettenmaier, 1999). Adaptation measures will require the creation of new storage facilities or the expansion of current reservoirs in an effort to capture more water during the winter months while simultaneously complying with flood control guidelines.

5.3.3 Streamflow Timing

Trends in Mt. Rainier streamflow timing closely follow the observed trends in SWE and AMJJ flow proportions for both the aggregated dataset and individual rivers. For the aggregate period of 1958-2006 negative trends in CT date were identified and are significant at the 90% confidence level ($p = .09$); results which are highly consistent with similar studies (Stewart et al. 2005, 2004; Regonda et al. 2005, Cayan et al. 2001; Dettinger and Cayan, 1995). Similar to variations in AMJJ flows, CT date displays significant positive coherence with SWE ($p = .008$), although SWE is not an accurate explanation for annual CT variation ($R^2 = .122$), largely because CT is an expression of total annual flow and does not isolate snowmelt inputs alone (Stewart et al. 2005).

CT dates are occurring significantly earlier in the year for the Nisqually ($p < .001$) and Cowlitz ($p = .03$) Rivers, whereas CT dates for the Puyallup remain trend neutral ($p = .80$). Due to similarities in correlations with SWE and overall hydrographic regime, results from the above rivers can be used to predict CT trends in the White and Carbon Rivers. Utilizing this assumption, it is likely that the CT date for the White River is occurring earlier in the year and remaining stagnant for the Carbon River. Decreasing trends for the Nisqually and Cowlitz are very consistent with findings from studies analyzing snow dominant rivers in western North America (Stewart et al. 2005, 2004; Regonda et al. 2005, Cayan et al. 2001; Dettinger and Cayan, 1995), and especially with Stewart et al (2005) where the largest CT advances were identified in the Pacific Northwest. High degrees of spatial coherence with snow dominated rivers suggest that declines in CT are likely linked to regional scale trends.

In terms of water resource management, streamflow timing is equally important as flow quantity. Numerous management structures dependant on snowmelt flows in the Pacific Northwest rely upon the timely occurrence of the snowmelt peak in April to adequately meet allocation goals (Payne et al. 2004; Hamlet and Lettenmaier, 1999). Shifts in annual CT dates towards earlier center timing ultimately shift the hydrograph to the left, where more flow occurs during the winter months, the spring snowmelt peak occurs earlier, and summer and fall flows diminish. Present water management schedules will need to be revised to accommodate for the earlier influx of snowmelt.

Reservoir operations are the most sensitive water resource sector to shifts in CT as regional refill schedules are fine tuned to snowmelt pulse timing for hydropower and flood control optimization. As a result, reservoir retention and release schedules dictate water availability beyond impoundments which greatly affects the ability of downstream sectors to meet reliability goals. Earlier CT dates have profound implications for current and future instream flow compliance in each WRIA primarily due to further reductions in summer and fall flows. If current trends continue, existing tensions between instream flow rules and reservoir optimization will be exacerbated necessitating policy reform and further litigation.

Stewart et al. (2004) applied a “business as usual” climate change model to historical streamflow timing records to assess potential shifts in CT if current greenhouse gas emissions continue to escalate. Results indicate substantial advances in CT dates from 30-40 days by 2099, with the greatest advances occurring in the Pacific Northwest. Observed CT trends at Mt. Rainier are certainly consistent with the aforementioned forecast and may represent the initial stages of climate change induced CT shifts. Thus, the implications of climate change to Mt. Rainier CT dates are drastic, especially when coupled with expected declines in SWE (Mote et al. 2003, 2008) and AMJJ fractional flows (Stewart et al. 204, 2005; Regonda et al. 2005, Bach, 2002).

Mt. Rainier Hydroclimate and the PDO

The PDO has been shown to be an accurate proxy for water forecasting in the Pacific Northwest (Mantua et al. 1997; Hamlet and Lettenmaier, 1999; Miles et al. 2000; Mote et al. 2003, Payne et al. 2004). Significant differences between positive and negative PDO phase state and hydroclimatic variables at Mt. Rainier confirm that oscillations of the PDO influence variations in SWE and AMJJ fractional flows. The stark differences observed in hydrology during differing phase periods indicate that Mt. Rainier streamflow is highly responsive to large scale climatic variation and suggest that the impacts of climate change on Mt. Rainier hydroclimate will be profound. PDO indices will continue to be a valuable tool for water forecasting although uncertainties remain as to the effects of climate change on PDO behavior (Mote et al. 2003, 2008). In the event that climate change effects intensify current PDO regimes its consideration in planning purposes will increase in value by providing a reliable baseline for water availability purposes.

6. Conclusions

The purpose of this study was to investigate the role of snowmelt parameters as a source of hydrologic variation in Mt. Rainier watersheds with the overarching goal of providing water managers with hydrologic data for use in future water resources forecasting applications. Detailed fine-grained data will be required to develop effective adaptive strategies for water resource sectors facing impending strains from population growth and climate change.

In order to provide useful results, quantifications and temporal trend analyses were carried out for three hydroclimatic parameters: AMJJ fractional flows, snowmelt pulse timing (CT), and snow water equivalencies (SWE). The combined analyses of the three parameters yielded useful results that synthesize sources of variability to illustrate the major dynamics influencing the snowmelt hydrology of Mt. Rainier Rivers. Furthermore, the influence of the Pacific Decadal Oscillation on Mt. Rainier streamflow and snowpack variation was investigated to identify linkages between local hydrography and global scale climate; a key indicator of how Mt. Rainier rivers may respond to large scale climatic change. It is apparent from the findings of this study that significant hydrologic change is occurring in Mt. Rainier watersheds, and that drastic revisions to current water resource management regimes will be necessary for adaptation if observed trends continue.

Key findings can be summarized in five ways: (1) Annual AMJJ flows account for essentially half of the annual runoff for the aggregate and snow-dominant systems where transient systems display distinct snowmelt pulses (2) AMJJ flow quantities and proportions are decreasing for the aggregate, Nisqually, and Cowlitz Rivers (3) SWE has been significantly decreasing since at least 1940 (4) Runoff timing (CT) is shifting to earlier in the year for the aggregate and snow dominated basins;

transient basins are trend neutral confirming that SWE is a main driver of CT date in snow-dominant basins (5) AMJJ runoff and SWE are sensitive to PDO phase state suggesting that Mt. Rainier hydroclimate is highly responsive to large scale climatic variability.

Increasing water scarcity is the starkest implication illustrated by the results of this study. The combination of decreasing SWE and AMJJ flows compounded with earlier snowmelt timing will ultimately lead to reductions in summer and fall water supplies and increase the frequency of droughts. Currently, water is over allocated in each basin and tensions already exist surrounding the allocation of present day late season supply. Thus, intensified declines in streamflows coupled with population growth will exacerbate current water allocation conflicts and require intensive policy reform.

Importantly, changes will have to be made to current reservoir refill schedules to alleviate growing tensions between water use interests. Revisions must include optimization changes for hydropower as likely increases in flood frequency during the winter will necessitate the release of power generation storage for flood control evacuations leading to scarcer and more expensive hydropower during the summer. Projected increases in temperature are likely to cause a shift in the regional electricity demand curve resulting from heightened summer cooling requirements (Hamlet at al. 2009). Expected increases in summer hydropower production range from 9-11% (Hamlet et al. 2009) which will place further strains on reservoir rule curves especially for the large hydropower facilities located on the Nisqually and Cowlitz Rivers. Thus, further increases in both climate change intensity and population growth will inevitably cause summer hydropower demand to increase concurrent with further decreasing AMJJ flows and earlier CT dates, and may force utilities to purchase power from the grid or explore alternate energy sources.

Additional reductions in hydropower allocations will be necessitated in order to maintain instream flow requirements for wildlife and senior water rights, irrigation, and recreation levels. The impending tradeoffs between hydropower production and downstream uses elucidate the multi-faceted nature of the implications likely to occur in response to decreases in snowmelt flows; ramifications extend to both physical and social arenas. Upholding the environmental quality of each river will come at high societal costs to power producers and consumers, irrigators, and water right holders as water rationing to fulfill each sector's goals will need to become commonplace. Consequently, disagreements are sure to arise leading to lengthy and expensive policy reform and related environmental litigation between water resource sectors, environmental groups, government regulatory bodies and tribes. Therefore, environmental restoration and instream flow rule making efforts are likely to proceed at slower rates further complicating already sensitive political issues.

PDO phase state was shown to significantly affect Mt. Rainier hydroclimate indicating that large scale climatic processes are significant drivers of hydrologic variation. These results provide ample reason to believe that SWE, CT, and AMJJ flows will be altered as a result of anthropogenic climate change. To date, PDO signals are not strong enough to completely dictate the declines in regional spring snowpack (Mote et al. 2008) suggesting that climate change effects are, at least in part, responsible for the observed declines in Mt. Rainier SWE, AMJJ flows, and earlier CT dates. Continued global warming will result in intensified negative trends for all three parameters, especially in snow dominant basins. Therefore it is likely that the Nisqually, Cowlitz, and White Rivers will experience the most drastic declines in AMJJ flows.

Climate change impacts to Mt. Rainier hydrology will require local water managers to implement revisions to fundamental forecasting and planning methodologies in order to meet the future demands of a rapidly growing population. Importantly, managers will be required to abandon historically integrated approaches to water forecasting as such techniques will no longer accurately predict AMJJ flow and CT date due to hydrologic uncertainty introduced by a warming climate. Importantly, managers must begin to incorporate climate change into resource planning processes (Whitely, 2006) to assess both the physical and social implications of warming to water availability. A key step in that process will involve the application of hydrologic data, similar to the findings presented here, to hydrologic modeling to assess effects at basin scales. Such models integrated with watershed planning efforts will greatly improve the abilities of water managers to prepare for adaptations.

Data and methodological limitations combined with the conclusions generated from this study provide opportunities for improved future research. Data limitations existed as the largest barrier to acquiring accurate AMJJ flow estimates and CT dates for the White and Carbon Rivers. Inconsistent records for the respective basins prevented high accuracy results from being attained thus further investigation into historical hydrologic conditions is required to improve upon the results presented here. Interpolation may be utilized to accurately estimate historical flows for the upper reaches of the White and Carbon Rivers providing more robust quantifications for each respective basin and the aggregate. Improved monitoring of snowpack volumes would greatly enhance the understanding of climate and streamflow relationships, however implementation would be costly. Questions still remain surrounding aggregated temporal trend discrepancies between AMJJ quantities and proportions where more detailed meteorological analyses are needed to fully understand the causes of differing trend magnitudes.

Overall, the findings of this study provide water managers in the South Sound region with an accurate hydrologic dataset to assist in future watershed planning applications. Importantly, the detection of declining streamflow and advanced runoff peaks provides confirmation that regional snowmelt resources are decreasing and actions must begin to take place to prepare for future perturbations in snowmelt flows. Additionally, this study provides a framework for future basin scale studies across the Northwest and makes important contributions to the greater discourse pertaining to climate change associated effects on snowmelt hydrology.

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