IMPLEMENTING THE SOIL AND WATER ASSESSMENT TOOL FOR THE PUYALLUP RIVER WATERSHED OF WASHINGTON STATE: A FEASIBILITY ASSESSMENT

by

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ABSTRACT

Implementing the Soil and Water Assessment Tool
For the Puyallup River Watershed of Washington State: A feasibility assessment

Sarah Nicole Bell

The release of the Intergovernmental Panel on Climate Change (IPCC) 5th Assessment Report reiterates the future risks of climate change on our hydrologic systems and threat to our water supply. Hydrologic modeling can couple with carbon emission scenarios to assess risks to water resources. Regions reliant on snowpack to sustain water reserves, such as watersheds in western Washington; hydrologic models can aid resource managers and environmental planners for the challenges ahead. The Soil and Water Assessment Tool (SWAT) was used to simulate streamflow of the Puyallup River basin, located in the Puyallup River Watershed of Washington State. SWAT model ecological inputs were obtained from the GeoSpatial Data Gateway website provided by the US Department of Agriculture. Historic climate data (precipitation and temperature) was obtained through the National Oceanic and Atmospheric Administration. Streamflow data for the Puyallup River was obtained from the US Geological Survey. The model was calibrated over the time period 1960 to 1979 and validated over the time period 1980 to 2007 using the regression correlation coefficient (R^2) and the Nash-Sutcliffe Efficiency (NSE) coefficient. Simulated performance was measured at an $R^2 = 0.45$, NSE = -0.01 for calibration and $R^2 = 0.57$, NSE = -0.39 for validation. It was determined that SWAT cannot be effectively used to simulate streamflow in Puyallup River Watershed. Barriers that contributed to poor streamflow simulations included insufficient soil data of headwater streams, extreme winter precipitation events, and orographic effects of the Cascade Mountain range. Other considerations included the sensitive analysis type, implementation of snow parameter data, output statistics, and model output timeline. Barriers found during this research should be considered in future hydrologic modeling of western Washington and other snowpack dominated watersheds. The distributed hydrology soil vegetation model (DHSVM) and the variable infiltration capacity (VIC) macroscale hydrology model are listed in the literature as additional hydrologic models that have been successfully implemented in snowpack dominated watersheds.

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List Acronyms Alphabetically

95PPU	95 percent prediction uncertainty
ACM	Antecedent moisture condition
AGRR	Agricultural land-row crop
ALPHA_BF	Base flow alpha factor
AR4	4th Assessment Report
AR5	5th Assessment Report
BASINS	Better Assessment Science Integrating Point and Nonpoint Sources
CH_KI	Effective hydraulic conductivity of tributary channel alluvium
CIG	Climate Impacts Group
CN2	Initial SCS runoff curve number II
CNMAX	Maximum canopy storage
CO2	Carbon dioxide
CREAMS	Chemicals, Runoff, and Erosion from Agricultural Management Systems
DEM	Digital Elevation Model
DHSVM	Distributed hydrology soil vegetation model
DOE	Washington State Department of Ecology
ENSO	El Niño southern oscillation
EPA	Environmental Protection Agency
EPCO	Plant uptake compensation factor
ERIC	Environmental Policy Integrated Climate
ESCO	Soil evaporation compensation factor
FRSD	Forest-deciduous
FRSE	Forest-Evergreen
FRST	Forest-Mixed

GCM	Global climate model
GHG	Greenhouse gas
GIS	Geographical Information System
GLEAMS	Groundwater Loading Effects of Agricultural Management Systems
GLUE	Generalized Likelihood Uncertainty estimation
GW_DELAY	Groundwater delay time
GW_REVAP	Groundwater “revap” coefficient
GWQMN	Threshold depth of water in shallow aquifer for return flow
HAY	Hay
HRU	Hydrologic response unit
IPCC	Intergovernmental Panel on Climate Change
LH_OAT	Latin Hypercube One-factor-At-a-Time
MCMC	Markov chain Monte Carlo
MUKEY	Map unit key
NCLD	National Land Cover Data
NCSS	National Cooperative Soil Survey
NED	National Elevation Dataset
NOAA	National Oceanic and Atmospheric Administration
NPI	North Pacific Index
NSE	Nash-Sutcliffe model efficiency coefficient
ParaSol	Parameter Solution
PDO	Pacific decadal oscillation
PET	Potential evapotranspiration
PNW	Pacific Northwest
PRWC	Puyallup River Watershed Council

PSO	Particle Swarm Optimization
PSRC	Puget Sound Regional Council
QUAL2E	Enhanced Stream Water Quality Model
R2	Coefficient of determination
RCEW	Reynolds Creek Experimental Watershed
RCHRG_DP	Deep aquifer percolation fraction
RCM	Regional climate model
REVAPMN	Threshold depth of water in shallow aquifer for percolation to deep aquifer
RMSE	Root mean square error
RNGB	Range-Brush
ROTO	Routing Outputs to Outlet
SCS	Soil Conservation Service
SFTMP	Snowfall temperature
SLSOIL	Slope length for lateral subsurface flow
SMFMN	Melt factor for snow on December 21st
SMFMX	Melt factor for snow on June 21st
SMTMP	Snow melt base temperature
SNO50COV	Minimum snow water content that corresponds to 50% snow cover
SNOCOVMX	Minimum snow water content that corresponds to 100% snow cover
SNOTEL	Snowpack telemetry station
SOL_AWC	Available water capacity of the soil layer
SOL_K	Saturated hydraulic conductivity
SUFI2	Sequential Uncertainty Fitting algorithm
SURLAG	Surface runoff lag coefficient
SURRGO	Soil Survey Geographic Database

SWAT	Soil and Water Assessment Tool
SWRN	Arid rangeland
SWRRB	Simulator for Water Resources in Rural Basins
TIMP	Snow pack temperature lag factor
U.S.	United States
UIDU	Industrial
URHD	Residential-high density
URLD	Residential-low density
URM	Residential-medium density
USDA	United States Department of Agriculture
USDA-ARS	United States Department of Agriculture-Agricultural Research Service
USGS	United States Geological Survey
UTM	Universal transverse mercator
VIC	Variable infiltration capacity
WATR	Water
WETF	Wetlands-forested
WETN	Wetlands-non-forest
WSDOT	Washington State Department of Transportation

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Chapter 1. Introduction

The Intergovernmental Panel on Climate Change (IPCC) has recently released the fifth assessment report including new carbon emission scenarios for the years of 2010 through 2100. Continuous anthropogenic carbon emissions from the Industrial Revolution post-1850s to the present have influenced climate (IPCC, 2014). In the Northern Hemisphere, the last three decades (1983 to 2012) have been the warmest to date since the 1400s (IPCC, 2014). Warming trends and precipitation regime change are projected to continue. Projected temperature and precipitation shifts from the carbon emission scenarios will impact hydrology at global, national, and regional levels. Hydrology, the interaction, movement, quality, and distribution of water over land, is studied to inform policy, resource planning, and engineering. Hydrological systems will change from the melting of snow and ice, reduction in snowpack accumulation, changes in precipitation events, and warming temperatures. Quantity and quality of water resources will impact human and natural systems (IPCC, 2014).

Coastal regions will experience climate change with sea surface warming, sea level rise, and extreme weather events. Coastal regions of the western Northern Hemisphere will experience increased flooding events from changes in precipitation frequency and snowpack. Warming air temperature and rain dominated precipitation increases will decrease snowpack accumulation, and shift snowmelt timings of mountainous regions. Fluctuations in snowpack melt and accumulation will be felt with increased flooding and winter storm events (IPCC, 2014). For coastal communities changing flow times are compounded with the stressors of saltwater intrusion, increased pollution in the surface and groundwater, and a decline in water availability (Romero-Lankao et al., 2014).

Regional level exploration of climate change impact on hydrology can aid water resource planners, policy makers, and habitat managers on best management practices to sustain quantity and quality of local water supply. As human population growth continues and habitat conditions decline, water management decision will become more contentious. Assessing climate change impacts at watershed and sub-basin level will benefit adaptive management and planning for climate change mitigations.

Risk associated with future emission scenarios are discussed in the AR5 report. Risks include hydrologic change to snowpack dominated systems. Snowpack dominated systems will be heavily impacted by change in temperature and precipitation regimes, especially in the summer months when water reserves are low, but resource demand is high. The Pacific Northwest (PNW) region will be impacted by climate change as it is heavily dominated by snowpack and experiences unique regional climate phenomena. The PNW regional climate is influenced by the warming and cooling sea surface temperature and pressure phenomena Pacific Decadal Oscillation (PDO) and El Niño southern Oscillation (ENSO) events (Hamlet et al., 2005b; Zhou et al., 2014). Combined with global climate scenarios, regional impacts on hydrology are not yet well understood.

Climate change impacts of the PNW have followed global trends. Average annual temperature has increased 1.3°F since 1895 (Mote et al., 2014) and new emission scenarios project continued average annual temperature increases, reduction of summer precipitation, and increased frequency and intensity of other seasonal precipitation

(IPCC, 2014; Tohver, Hamlet, & Lee, 2014). Overall, the long term effects of warming temperatures and precipitation shifts will transition snowpack dominate watersheds into rain dominated watersheds, glaciers will retreat, and streamflow patterns and timing will shift (Mote et al., 2014).

Reduction of snowfall accumulation is evident in the spring snowpack of the Cascade Mountain range in Washington State. Though snowpack will experience annual fluctuations, overall spring snowpack has experienced reductions from mid-1900s to present (Snover et al., 2013b). Spring snowpack has decreased on average -0.8 to -2.4 percent per decade since the 1960s. (Snover et al., 2013b). About two-thirds of the U. S. glaciers in the lower 48 states are located in Washington State, most of which are in decline (Fountain et al., 2007). Glacier declines range from 7 to 49 percent in the Cascade Mountain range (Snover et al., 2013b).With glacier recession and increased melt from rising temperatures, spring streamflow peaks are shifting earlier in the year (Snover et al., 2013b). Spring streamflows are important for municipality reserves and salmon habitat. Change in peak timing will have consequences to these systems and regional economies.

Hydrologic modeling has been used to simulate future streamflow patterns with use of ecological inputs and projected environmental variables; temperature and precipitation. Cuo et al, (2011), with the use of a hydrologic model coupled with climate change scenarios, found that Puget Sound rivers' seasonal peak timings and annual flows were sensitive to climate change impacts. Sensitivity was reflected with increased winter flows and decreased summer flows as well as timing of the seasonal winter and spring peak flows. Similar results were produced by Dickerson-Lange and Mitchell (2014) for the Nooksack River located in the upper portion of Puget Sound, with headwater origin in the Cascade Mountain range. Using hydrologic modeling and downscaled climate change scenarios, simulated streamflow for the Nooksack River showed increased winter flows, decreased summer flows, a shift in timing of seasonal flows, and overall decrease in snowpack accumulation. These sensitivities are likely to be found in other river basins of the Puget Sound region.

The Puyallup River basin located in south Puget Sound of Washington State, is a snowpack dominate watershed and will be the focus of this study. The topography of Puget Sound creates a unique regional climate regime. Encompassing growing metropolises and vast forest areas, Puget Sound is also home to endangered salmon species that rely on the stream networks for spawning and survival. The glaciers of Mt. Rainer supply this watershed with much of its surface water from glacial melt and annual accumulation of snowpack. The Puyallup River Watershed will be impacted by climate change and warrants hydrological assessment. Using a computer based hydrologic model is the first step in understanding watershed specific hydrological parameter interactions.

Few studies have been conducted to investigate projected regional climate change impacts on hydrology in the lowlands of Puget Sound. Topographic influences and the regional climate phenomena Pacific Decadal Oscillation (PDO) and El Niño southern Oscillation (ENSO) will increase the uncertainty of assessing regional climatic impact on hydrology. In this thesis, the Soil and Water Assessment Tool (SWAT) will be implemented in the Puyallup River basin to assess whether this model is appropriate for modeling changes in hydrology for this region. SWAT is a physically-based and computationally efficient model that is catered for government and conservation management use. SWAT was chosen because it is a user friendly model that does not require a programming background, has a large open-sourced community, and can be operated in a Windows-based system. However, these advantages do not overshadow the history of the SWAT model's primary use in agricultural settings. Recent expansion of SWAT into mountainous terrain and snowpack dominated systems leaves questions about the feasibility and appropriateness of the SWAT application in the Puget Sound region. Existing hydrological models, the distributed hydrology soil vegetation model (DHSVM) and the variable infiltration capacity (VIC) macroscale hydrology model, have been developed and successfully implemented in the PNW region.

Puget Sound and the focus watershed of this thesis are unique due to regional climate phenomena, mountainous region impact on climate, elevation gradient influence on hydrology, snow parameters, and baseflow contribution to total streamflow yield. Traditionally implemented as an agricultural management assessment model, SWAT applications have expanded to include climate change impacts on streamflow. This thesis will discuss model feasibility, limitations, and application in the Puyallup River Watershed in the following chapters. Though the SWAT model assessment is not conclusive for model feasibility, this thesis produces a starting point to continue future SWAT assessment by listing model limitations and future suggestions.

Chapter 2. Literature Review

2.1 The Future Threat of Climate Change

The Intergovernmental Panel on Climate Change (IPCC) recently produced their fifth assessment report (AR5) on the science, risks, and adaptive management perspectives involving climate change. Climate change is a global phenomenon that impacts natural resources, ecosystem services, and human well-being. New additions to the AR5 include climate change risks (IPCC, 2013). Risks are categorized at the global level, while the effects are felt at regional and local scales. Historic observation of temperature and precipitation are used to simulate future scenarios. Future scenarios include extreme event likelihoods such as flooding, and the social and economic outcomes of these risks. Using modeling techniques to simulate future scenarios is necessary for adaptive management to prepare for the impact of climate change.[1] Future risks of climate change include shifts in regional stream hydrology. The impact of these shifts will be experienced by the populations and habitats that rely on these water systems including municipalities, land managers, and natural resources. Change will be directly related to extreme temperature and precipitation events.

Competition and conflict over water resources is also a real future threat. Water conflict will occur with current population growth trajectories, excluding the impact of extreme climate events. Water conflict is likely to occur in areas that heavily rely on snowpack feed rivers as main water sources (Polebitski, Palmer, & Waddell, 2011).

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[1] Carbon dioxide (CO_2) and other greenhouse gas emission (GHG) scenarios are used in predictions of climate change for time periods 2010 to 2100. Outcomes of the emission scenarios can be downscaled to regional levels. Regional downscaled climate scenarios give multiple levels of governance guidance to prepare and adapt for the future of climate change (IPCC, 2013).

Snowpack dominated river systems of western Washington in the PNW of the United States will be an area of concern (Polebitski et al., 2011), which arises from shifts in peak flow times. Changing temperature and precipitation regimes will alter the river streanflow controlling peak flows.

In this literature review, some of the findings of the AR5 will be summarized to give background and context for discussing the impact of climate change scenarios on hydrology. The Soil and Water Assessment Tool (SWAT) will be introduced as a modeling tool that has assessed climate change impacts to hydrology systems through future hydrograph simulations coupled with climate change projections. Hydrologic models such as SWAT can be used as an adaptive management feature to better understand future water resource demands and conflict for both human and natural ecosystems.

Key Risks of Climate Change

The main conclusion of the IPCC AR5 is that climate change is occurring and will continue to occur in the future. Even if anthropogenic stressors such as CO_2 emissions reduced to zero today, climate change impacts will continue into the future (IPCC, 2013). Today the Earth's surface temperatures are the warmest they have been in the last 30 years, with an increasing trend of hotter days and warmer nights (IPCC, 2013). Furthermore, increases in heat waves, droughts, cyclones, and other extreme events are expected to increase in frequency and intensity (IPCC, 2013). The expected increased warming events will have negative impacts on unique and threatened systems, lead to species extinctions, cause food security risks at global and regional levels, cause negative effects on human health, increase water scarcity, and water conflict (IPCC, 2014).

The key risks for North America include increased frequency of severe hot weather events, wildfire events, heat-related mortalities, heavy precipitation days, flooding events, and a decrease in number of frost days (IPCC, 2014; Romero-Lankao et al., 2014). Increased flooding events will impact ecosystem function, human health, social and economic wellbeing (IPCC, 2014; Romero-Lankao et al., 2014). The level of warming predicted for the 21st century will lead to more water conflict and, due to the increased precipitation events, contribute to flooding of major rivers fed by snowpack and ice melt (IPCC, 2014). As previously mentioned, the PNW has heavily dominated snowpack fed river systems and may experience some of these risks. Understanding the role of the hydrologic cycle and future changes may aid in mitigating future risks. Preparing for these risks will need to rely on the understanding of how hydrology will respond to increased temperature and more extreme precipitation events. Hydrologic models have aided policy, land managers, and engineers in simulating future climate change scenarios.

2.2 Climate Change in the Pacific Northwest

The PNW is defined as the area of the United States and parts of Canada as latitudes 41.5^{o}N to 49.5^{o}N and west longitudes 124^{o}W to 111^{o}W. This encompasses the states of Washington, Oregon, Idaho, western Montana, and a southern portion of British Columbia, Canada (Mote and Salathe, 2010). Recently Mote et al. (2014) demonstrated that PNW temperatures have increased about 1.3°F from 1895 to 2011. Annual mean temperatures are projected to increase 3.3°F to 9.7°F for the years of 2070 through 2099 (Mote et al., 2014). The summer months will experience the largest shift in temperature range. The upper and lower bounds of the summer temperature range will increase, leading to drier, warmer summers (Mote et al., 2014).

Mote et al. (2014) demonstrated that precipitation has overall increased during the 20th century. Annual average precipitation will change and, for the years of 2030 to 2059, the expected precipitation rate will range between a decrease of 11 percent to an increase of 12 percent (Mote et al., 2014). Overall, precipitation ranges will become increasingly more variable with most of the precipitation decreases occurring in the summer months, prolonging warmer drier summers. Temperature and precipitation change in the PNW will alter ecosystem services that provide industry and cultural significance to its inhabitants. Climate change in the PNW will impact coastal zones, forestry, ecosystem services, hydropower, and streamflows (Mote et al., 2014). The changes will challenge the economic, social, and ecological facets of the PNW.

Coastal zones of the PNW are currently and will continue to experience the effects of climate change through sea level rise, erosion, sea water intrusion into groundwater supply, and increasing ocean acidification (Mote et al., 2014). Sea levels in coastal zones have risen 8 inches since 1880. Future projections of sea level rise for the year 2100 are a range increase of 0.3 to 1.2 meters (1 to 4 feet) (Mote et al., 2014). These coastal zones harbor PNW industry such as seafood, fisheries, and ports for economic trade. Sea level rise will impair these industries (Mote et al., 2014). Sea level rise will also impact the cultural significance of historic sites that many Native American tribes attribute to the PNW coastal landscapes.

The forestry industry will be impacted as tree die-offs and landscapes changes occur, and will also be largely be driven by water deficit. Tree die-offs accumulate as temperature increases and precipitation decreases in the summer months. Drier hotter summers will lead to increases in wildfires, insect outbreaks, and disease. These observations occur presently, but are projected to continue with increased tree stress, tree vulnerability and tree die-offs, leading to increased fuel loads for wildfire (Mote et al., 2014). Shellfish, fishery, and tree industry economies will suffer from these changes, as well as the local communities that support these industries. Understanding the water systems and water sources in the PNW is crucial in preparing for these risks.

Temperature and precipitation changes will affect the hydrology of the PNW. Observations from 1960 to 2002 revealed trends in earlier peak flows from snow-dominated rivers as well as decreased run off from spring snowpack (IPCC, 2014). Hamlet and Lettenmaier (2005) found that shifts in temperature contributed to most of the snowpack accumulation declines and the changes in runoff. Sensitivity of the snowpack to increasing air temperatures led to reduced streamflows in June, increased streamflows in March, and a reduction in low elevation snowfall (Mote, 2006). Continued temperature increases will shift future snowmelt timings to occur 3 to 4 weeks earlier than 20th century averages by 2050 (Mote et al., 2014; Elsner et al., 2010). Earlier snowmelt timings reduce the snowpack reserves that traditionally sustain summer water supply demands. Low summer streamflows will reflect this change in snowmelt patterns and summer municipality reserves.

Decrease in snow accumulation and earlier peaks in snowmelt reduce the availability of surface water to meet increased and prolonged demands. With less surface water available for use in extended summer, groundwater usage will increase to meet rising demands. Increased groundwater demands will pull from the deep aquifers and reduce the amount of lateral flow from the shallow aquifers that contribute to total streamflow (Haak, 2010). Low flows create a feedback to increased risk of wild fires, reduced hydropower in the summers, increased water scarcity for irrigation in agriculture, and a disruption of Puget Sound spawning habitats for salmon and steelhead.

2.3 Climate Change Impact in the Puget Sound

The Puget Sound is located in the upper northwestern corner in the State of Washington. It is boarded by the Cascade Mountain range on the east, and the Olympic Mountains on the west. Puget Sound has many smaller arms that extend from the boarder of Canada south to the state capital of Olympia (Figure 1). Puget Sound covers an area of approximately 31,000 km^2, with an elevation range of sea level to 4,400 meters (Elsner et al., 2010). Though snow rarely falls in the lowlands of Puget Sound, annual precipitation still ranges from 600 to over 3,000 mm, mostly in the form of rain. The majority of precipitation falls between the months of October to March (Elsner et al., 2010; Cuo et al., 2011).

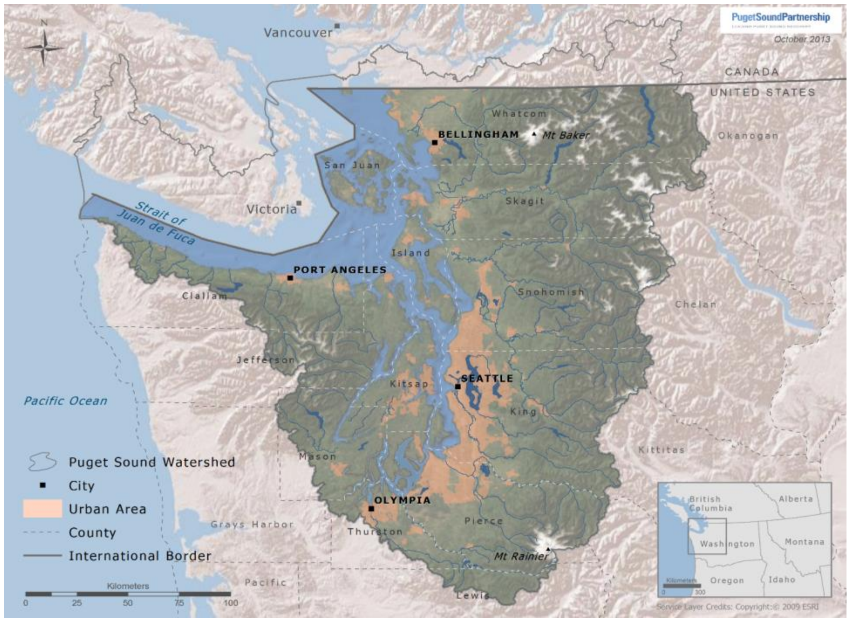

Figure 1. Aerial view of Puget Sound, Washington. Map provided by Encyclopedia of Puget Sound, published by Puget Sound Institute at the University of Washington Tacoma Center for Urban Waters. 2014. http://www.eopugetsound.org/maps

Puget Sound formed its unique structure over the last geologic ice ages and tectonic plate movements. The mountain ranges that boarder the Puget Sound began formation 5.3 million years ago during the Pliocene era by tectonic plate movement and volcanic activity (Kruckeberg, 1991). The depths of Puget Sound began formation during the Pleistocene era 2 million years ago with the advances and recessions of the alpine glaciers, leaving behind alluvium and small sediment deposits. The final formation of sinuous Puget Sound, however, is quite recent. Roughly 10,000 years ago during the Holocene era, the last glacier recession left behind the landscape we see today (Kruckeberg, 1991). This unique landscape includes the San Juan Islands, the intrusion of sea water from the Pacific Ocean into the trough of the Puget Sound, and the vast network of river systems. These river systems create large drainage basins that flow into the lowlands of Puget Sound (Kruckeberg, 1991). The inflow of freshwater from the vast network of rivers to the Pacific Ocean and Strait of Juan de Fuca makes the Puget Sound one of the largest estuary systems. It is such a unique system that Puget Sound was deemed an Estuary of National Significance by the U.S. Environmental Protection Agency (EPA) in 1988 (Kruckeber, 1991). The unique Puget Sound region has many snowpack dominated river systems that have begun to see the impacts of climate change through snowpack recession (Dickerson-Lange and Mitchell, 2014; Cuo et al., 2011).

Snowpack sensitivity in the Cascade Mountain range of western Washington was assessed by Casola et al. (2008) to find an estimated sensitivity of 20 percent snowpack loss per 1 degree Celsius rise in temperature. The sensitivity is estimated to only decrease to 16 percent with the consideration of increase in winter precipitation events (Casola et al., 2008). Increasing average temperature by one degree Celsius in the upper and lower temperature bound will decrease streamflow in Puget Sound watersheds by 0.7 to 2.4 percent (Elsner et al., 2010). Increasing the average temperature by two degrees in only the upper bounds of the range would result in streamflow decreases of 1.5 to 5.6 percent (Elsner et al., 2010). These reductions are important in planning for future water supply of the Puget Sound areas where the Washington State Census of 2000 reported 69 percent of the State's population resides. The sensitivity of Puget Sound snowpack is of concern with future climate change projections and the influence on streamflow yield. Changes in snowpack are reflected in streamflow characteristics and total yeild. Flow times and flow yeilds are important to monitor for municipal water supply, resource management, and salmon spawning habitat.

Impact on Pacific Northwest Salmon

Streamflow yield and peak flow times raise concern to the impact on salmon populations. Salmon have economic, ecological, and social importance in the PNW. The populations of PNW salmon have been in decline in the last century due to over fishing, habitat degradation, hydropower, invasive species, and now climate change (Haak, 2010). Due to these threats, many of the salmon species are listed as threatened under the Endangered Species Act (16 USC 1531 et seq).

Salmon need cold, pristine waters to thrive and are vulnerable to climate change. These cold river systems are changing due to warming air temperatures and decreased snowpack accumulation (Haak, 2010). Earlier snowmelt timing and decreased snowpack accumulation reduces the volume of water available when anadromous salmon return from the ocean to spawn in natural streams. Peak flows shifting into March will impact spring salmon runs that normally occur April to June. Shifted peak flow times will increase the difficulty for salmon to swim upstream and pass barriers. Flows peaking in March will also influence summer salmon runs as reduced water volumes are more susceptible to warming (Haak, 2010).

Increases in stream temperature affect fish directly through signaling run timing, metabolism, and growth rates. Stream temperatures between 22°C and 24°C can be fatal to salmon over prolonged exposure and stream temperatures over 24°C can be fatal within a few hours (Morrison, Quick, & Foreman, 2002). Indirect effects of warming streams alter in-stream ecosystems. Invertebrate and vegetation structure that fish rely on will likely change, which could affect the distribution, fitness, reproduction, and survival of these small invertebrates that fish depend on (Haak, 2010). The threat to salmon will be felt in the areas where economic and social significance is high such as the Puget Sound area of the PNW. The negative impact on salmon is not the only climate change risk for the Puget Sound. Water reservoir resources are also at risk as they will be influenced by temperature and shifting snowpack accumulation.

Puget Sound Regional Climate Variability

The topography of Washington makes for an interesting study site for climate change and hydrologic modeling. The Puget Sound acts as a giant river basin, where snowpack feeds larger watersheds that drain to the coasts of Washington and Oregon. The Cascade Mountain range divides Washington into two different climate regimes. The eastern side of the mountain range receives roughly 300 mm of precipitation annually while the western side of the mountain range, where Puget Sound resides, receives an average of 1,250 mm of precipitation annually (Elsner et al., 2010). Precipitation shifts in surrounding eastern Washington watersheds will also experience similar Puget Sound trends. The major eastern watersheds include the Columbia River and Yakima River basins (Elsner et al., 2010). The snowpack dominated Columbia River basin and transient, half snow-half rain, Yakima River basin peak flow timings and seasonal trends will mirror those projected for the Puget Sound region. Climate change impacts will be compounded by Puget Sound variability influenced by the El Niño like climate of the Pacific Decadal Oscillation (PDO) and the short termed El-Niño or La Niña phases of the El Niño Southern Oscillation (ENSO) events.

PDO and ENSO both influence sea-surface temperatures, pressure, and winds. These seasonal and annual influences are reflected in the climate seen on land through changes in air temperature, precipitation, and wind. Timescale is the major difference between the two events. ENSO events tend to last on an annual basis (6 to 18 months) while PDO effects can last for decades (20 to 30 years). PDO is the seasonal warming or cooling of sea-surface temperatures that occur over the northern Pacific Ocean. A warm phase of PDO will have climate effects similar to El Niño (cooler winter temperatures and higher winter precipitation) while a cool PDO phase will have effects similar to La Niña (warmer winter temperatures and less winter precipitation). ENSO is the long-term warming and cooling of sea surface temperatures and sea level barometric pressure known as El Niño and La Niña, respectively. When PDO and ENSO are in opposite phase of one another, such as a warm PDO with a cool or La Niña ENSO, effects of the phases are weakened. If PDO and ENSO phase are in sync, then the effects mentioned above are strengthened, such as a warm PDO and El Niño ENSO phase producing a cooler and wetter winter. The seasonal and inter-annual sea-surface temperature variability and air pressure variability, as measured by the North Pacific Index (NPI), explained 30 percent of the warming during the winters of 1920 to 2000 (Mote, 2003) using downscaled climate scenarios. This variability is important to capture as the cool phase of the PDO and ENSO increase the odds for a warmer dryer winter and spring (Climate Impacts Group [CIG], 2014) while the warm phase of the PDO and ENSO increase the odds for cooler wetter winters. The PDO and ENSO go undetected using the larger scale global climate model (GCM) scenarios (Pielke, 2011). Incorporating these regional phenomena in hydrologic modeling can reduce errors when simulating streamflow outputs for the Puget Sound.

Puget Sound Water Supply

Shifting the focus to urban development and water supply in Puget Sound, hydrologic modeling is an important tool for discerning the impacts of climate change on social wellbeing. Revealed in the 2000 census, Puget Sound houses account for 69 percent of the State's population with the majority of the water supply supported by four river basins: Cedar River, Green River, South Fork Tolt River, and Sultan River. Figure 2 references these river basins[2] (Elsner et al., 2010; Traynham et al., 2011)**.** Each of these rivers supports a multipurpose reservoir that is essential in flood control and controlling water storage (Traynham et al., 2011). These river basins are located in the northern portion of the Puget Sound with the larger metropolis cities of Seattle, Everett, Bellevue, and Tacoma and are projected to continue expansion (Polebitski et al., 2011). In an eight year period, 2000 to 2008, the Puget Sound population increased 10 percent, adding 357,000 new residents (Polebitski et al., 2011). The population rate for Puget Sound is projected to increase by 1.7 million more residents by the year 2040 based on historic populations trends of 1950 to 2000 (Puget Sound Regional Council [PSRC], 2006). If water demand stays the same while population size increases, existing water reserves will be insufficient between the years 2050 and 2075 (Traynham et al., 2011). The projected demand will not be met as climate change decreases snowpack accumulation and shifts peak flow times when water demands are highest (Traynham et al., 2011).

[2] Snohomish basin in Figure 2 encompasses the South Fork Tolt and Sultan rivers.

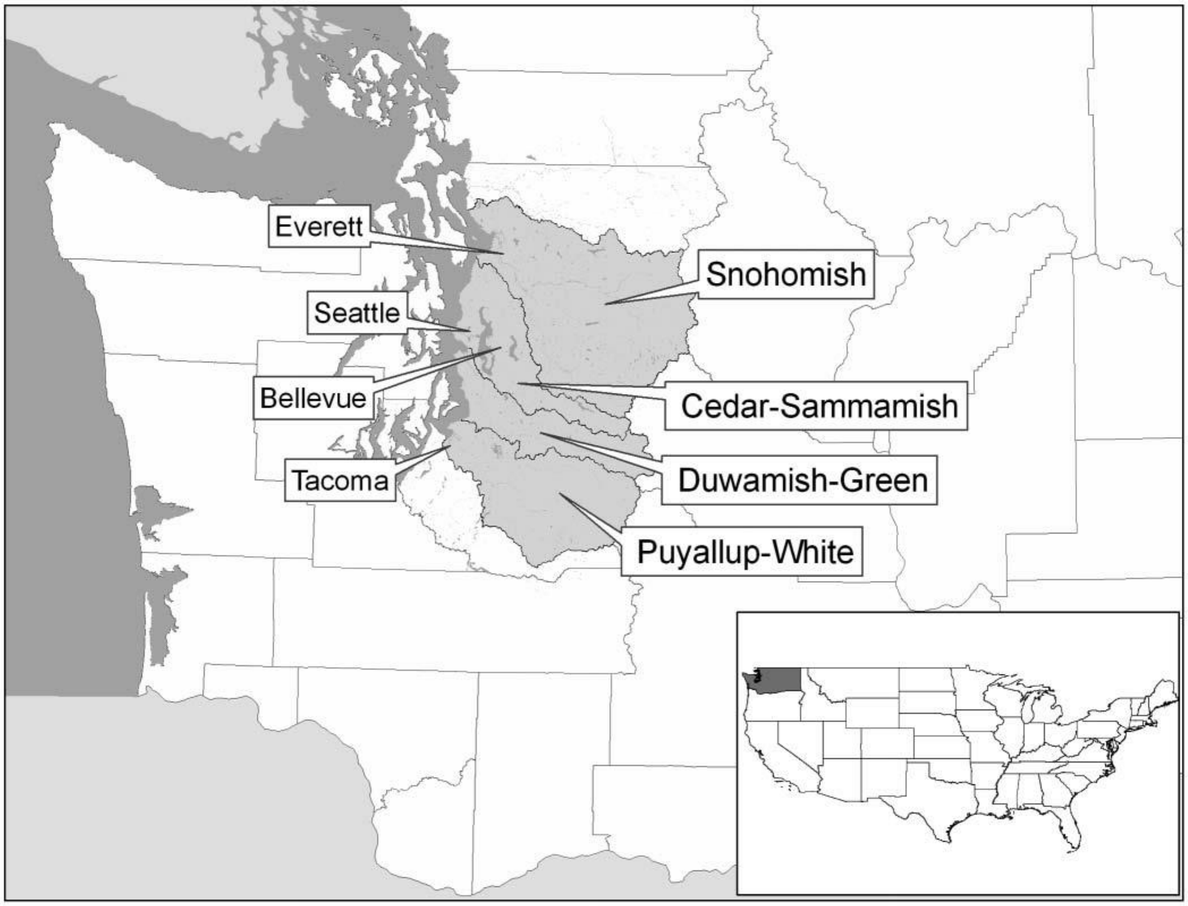

Figure 2. Washington State watersheds that supply water to Puget Sound municipalities.

Impact on Water Supply

Projected extreme precipitation events present challenges for water resource management agencies, environmental planners, and urban planners for the expanding Puget Sound region. Currently hydrographs of Puget Sound have two peak flow times. One peak occurs in the winter between November and December, and the second peak in the spring between April and May (Traynham et al., 2011). This two-peaked hydrograph is represented in Figure 3 for the Tolt River. These two-peaked hydrographs are projected to change to one-peak, as spring snowpack runoff decreases. The one-peak projection is likely to occur in snowpack dependent rivers of Washington State, by 2075 (Traynham et al., 2011), including river systems in lower Puget Sound.

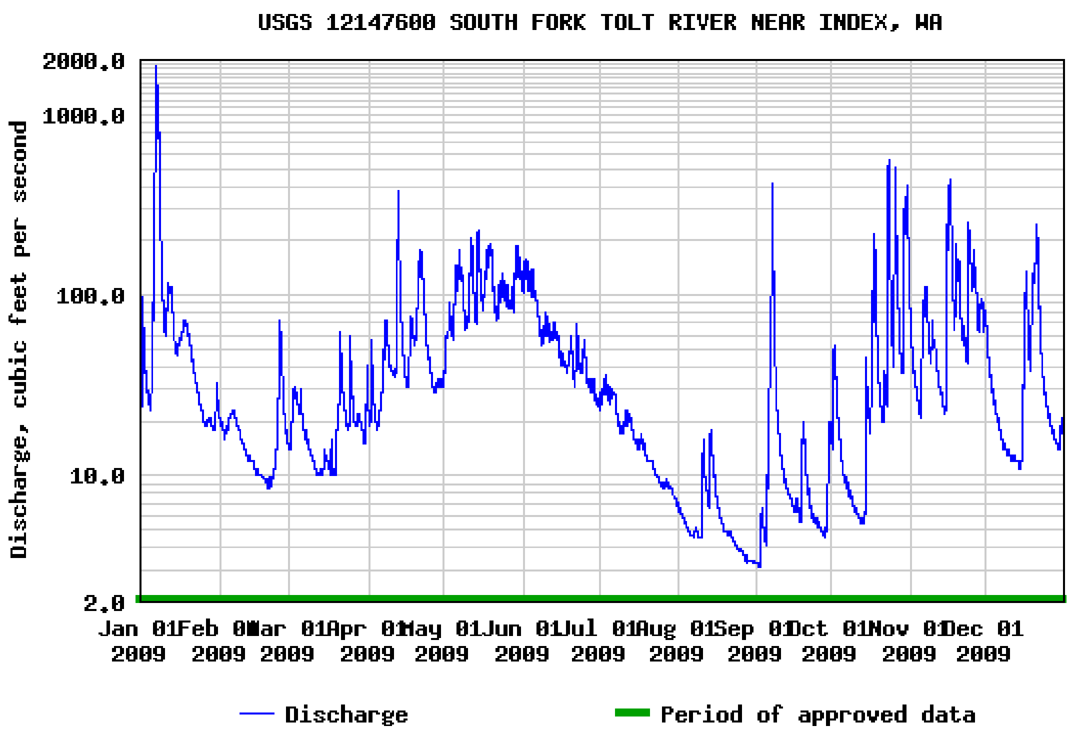

Figure 3. The South Fork Tolt River hydrograph for January 2009 to December 2009 retrieved from USGS. This graph shows two peak times streamflow. Spring snowmelt peak occurs between the months of April and May. The winter precipitation peak occurs in the fall between the months of November and December.

Historic observations show climate change impacting Seattle's municipal water systems. Wiley and Palmer (2008) attributed this trend from 1915 up to publication in 2008 to the increases in temperature (Wiley & Palmer, 2008). Evidence of change can be detected by monitoring annual streamflow in the month before and after the peak of the spring streamflow. Snowmelt flows tend to be evident in early April and peak in mid-

May before declining through the end of the summer. Monitoring flows in the months of March and June, before and after the historical peak times, will produce evidence of shifting flow times (Wiley & Palmer, 2008). This early melt will shift the mid-May peak a few weeks earlier in the year (Wiley & Palmer, 2008). The shift was observed with a 3 to 5 percent increase seen in the fraction of annual flow that occurred in the month of March for the years 1949 to 2003. The observed fraction of annual flow for June decreased 2 to 4 percent. The fraction of total annual flow shifting in the months of March and June from 1949 to 2003 implicates the shift in spring runoff (Wiley & Palmer, 2008). The Cedar River and South Fork Tolt River of the Puget Sound area demonstrate this shifting trend (Wiley & Palmer, 2008). This trend could likely occur in other snowpack dominated river systems of south Puget Sound and should be investigated using hydrologic models and future climate change scenarios.

Wiley & Palmer (2008) presented a solution of coupling downscaled global climate models (GCMs) into a hydrologic model to simulate water and energy fluxes for two Seattle reservoirs. Hydrologic modeling illustrated that climate change had already influenced the Seattle water supply system with decreasing snowpack observations from 1949 to 2003. The hydrologic model further projected an average decrease of 50 percent in snowpack for the Cedar River and Tolt River by the year 2040 (Wiley & Palmer, 2008). This trend will be seen in many of the Puget Sound metropolises as the normal doubled hydrograph peaks transition to a single peak. These estimates are a major concern for water resource managers that have historically assumed stochastic and stationary hydrologic processes for these systems (Wiley & Palmer, 2008). As in all parts of Washington, this will no longer be the assumption with climate change.

Though all of Washington will experience the changes associated with decreased snowpack, the influence of these changes on stormwater will not be felt equally. In a comparison of three major areas in Washington: Puget Sound, Spokane, and Vancouver; Rosenberg et al. (2010) found that, historically, Puget Sound has been the only area to see increases in extreme precipitation events. While the overall total annual precipitation for Puget Sound has decreased, the extreme event frequency has increased, specifically with 24-hour and two-day storms (Rosenberg et al., 2010). The most recent extreme precipitation event occurred in December 2007 with the flooding of the Chehalis River in lower Puget Sound. Washington State Department of Transportation (WSDOT) estimated the flood damage to be over $18M which accumulated from the four day closure of Interstate 5, a major north-south bound highway (Rosenberg et al., 2010). It is the extreme precipitation events, and likelihood of warmer drier summers that advocate for continued climate change impact studies on hydrology of southern Puget Sound river basins.

2.4 Puyallup River Basin of south Puget Sound

The Puyallup River basin of the Puyallup River Watershed located in south Puget Sound has been chosen as the focus watershed for this study. The basin holds historical significance, large municipalities, economic importance, and receives most of the water supply from Mt. Rainer glaciers and accumulated snow pack. Climate change will impact the glaciers and water supply of the Puyallup River basin. Assessing climate change impact on Puyallup River Watershed hydrology, can aid in preparation for addressing water rights, policies, and preparing natural resource managers for climate change adaptation. Puyallup River streamflow is currently showing a reduction during vulnerable summer months (Washington State Department of Ecology [DOE], 1995). The reduction trend is seen in other PNW and western Washington rivers (Dickerson-Lange & Mitchell, 2014; Cuo et al., 2011). Average spring snowpack measured annually on April 1st in the Cascade Mountain range had decreased 20 percent since the 1950s (Mote, 2006). Snowmelt timings now occur on average 30 days earlier than in the mid-twentieth century causing low summer flows (Fritze, Stewart, and Pebesma, 2011).

The snowmelt reductions have led to a decline in future water right applications while past senior water rights are also impacted (DOE, 1995). The majority of available water rights have been claimed for agriculture and municipality purposes as the Puyallup River Watershed is one of the most farmed and populated areas in western Washington (DOE, 2011). Without additional approved applicants, water resources need to be maintained to sustain water supply for senior water right holders (DOE, 2011) In addition to the impact from climate change, impacts from land use changes associated with population growth and the increased use of groundwater are a concern for senior water right holders as water supplies become harder to maintain (DOE, 1995). Aquatic habitats and growing municipalities depend on the quantity and quality of the basin. This dependence led the DOE to classify the Puyallup River Watershed as "high risk" (DOE, 1995). The need for a climate change impact assessment in the Puyallup River Watershed can be done with physically based hydrologic modeling.

Formation of the Puyallup River Basin

The Puyallup River basin is located in south Puget Sound (Pierce County and parts of King County). The watershed includes the cities of Tacoma, Fife, Puyallup and Sumner (Puyallup River Watershed Council [PRWC], 2014). Puyallup River Watershed began formation about 6 million years ago during the Holocene period, with the last glacier retreat occurring 16,000 years ago. This last recession was known as the Vashon stage of the Fraser Glaciation. The multiple advances and retreats during the Fraser Glaciation formed the present day Puget Sound and Puyallup River Basin (PRWC, 2014).

Puyallup River and its two main tributaries, White River and Carbon River, drain into an area of approximately 1,040 square miles or 665,000 acres (PRWC, 2014). These three rivers are the largest sources of surface water in the watershed. The watershed receives runoff from the glaciers on Mt. Rainier, from an elevation 4,392.5 meters (14,411 feet) to the low lands of Commencement Bay in Puget Sound (PRWC, 2014). Mt. Rainer influences the gradient, sediment supply, subsurface layers, and hydrology of the Puyallup River basin. The height of the mountain acts as a barrier to shifting weather, increasing precipitation accumulation on the western coastal side. These increased precipitation rates translate into increased streamflow and runoff. Mt. Rainier glaciers have retreated by 21 percent from 1913 to 1994 (Nylen, 2004) influenced by temperature increases and precipitation shifts from snow to rain-dominate. Photographs of the Nisqually Glacier on Mt. Rainier from 1930 and 2007 in Figure 4 represent the climatic impact with a major retreat of 1.3 km from 1931 to 2006 (Hekkers 2008, Nylen 2004). The Nisqually Glacier and other glaciers on the southern extent of the mountain have seen a 26 percent loss compared to a 17 percent loss of glaciers on the northern side on the mountain. This is of concern for the Puyallup River Watershed as the south-facing glaciers drain into the system. The difference of historical glacier reduction can be seen in Figure 5**.** These changes to glaciers in conjunction with extreme precipitation events will increase streamflow yield during flood seasons (PRWC, 2014). The threat of increased flood events will impact lowland developments and habitat quality.

Currently, the average precipitation in Puyallup River Watershed ranges from 762 to 1,016 mm in the lowlands near Tacoma to over 3,048 mm in the Cascade Mountains (DOE, 2011). Since the 1950s, average precipitation has steadily increased (DOE, 2011). Of the annual precipitation that falls in the Puyallup River Watershed, only a small portion is available for human and economic use. Most precipitation and high flows occur October through March, when the municipal water demands are lowest. When the water demands are highest during the summer months, streamflows are at the lowest.

As water demands increase, water conflict will follow. A majority of the water rights in the Puyallup River basin have been obtained as the watershed is one of the most farmed and populated in western Washington (DOE, 2011). As municipal and natural water demands are projected to increase, current water levels need to be maintained to sustain adequate water quality. With little water resources available to future water right requests, increased water demand from population growth, habitat maintenance, and impacts of climate change will continue to challenge water supplies in the Puyallup River basin (PRWC, 2014). Preparing and understanding these future demands can be accomplished through hydrologic modelling.

Figure 4. Image on the left captures the Nisqually Glacier on Mt. Rainier in 1930 compared to the reduction captured in the 2007 image of Nisqually Glacier. Photo Credit: Glaciers of the American West, Portland State University. Portland, Oregon.

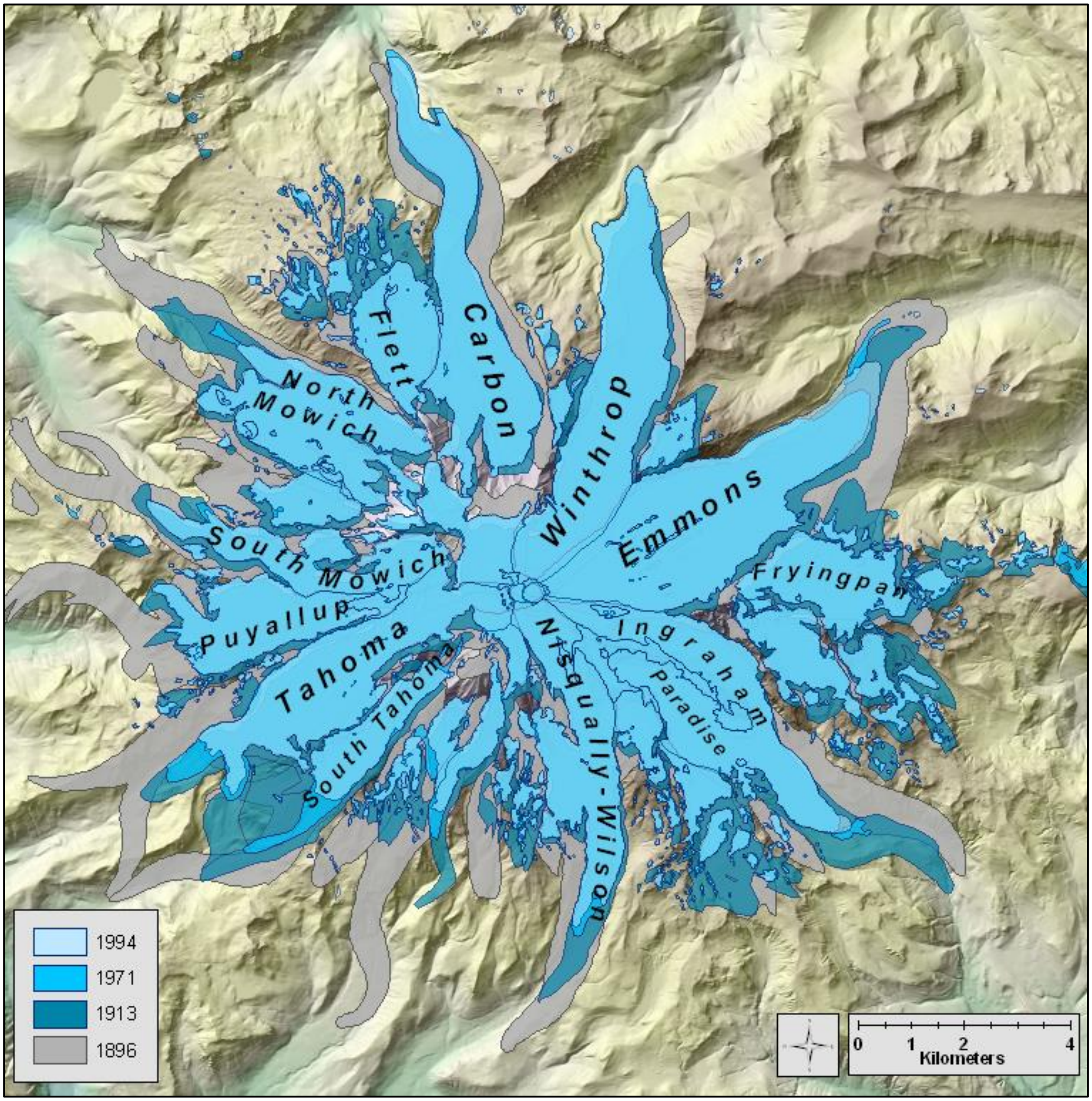

Figure 5. Map showing glacier retreat on Mt. Rainier in Washington State from 1896 to 1994. The southern glaciers have experienced more retreat than the northern glaciers. Map Credit: Glaciers of the American West, Portland State University. Portland, Oregon.

2.5 Hydrologic Modeling

Many hydrological models exist to give predictive estimates of future hydrology from climate scenarios. Hydrological modelling requires background knowledge in computer modeling and coding. Water resource managers, environmental planners, and habitat managers would benefit from a hydrological model that is user-friendly and caters to management applications. The Soil and Water Assessment Tool (SWAT) fit these criteria. SWAT has been chosen for this thesis and will be applied in the Puyallup River basin of the Puyallup River Watershed located in south Puget Sound to assess feasibility of implementation. SWAT is a continuous time model that operates at sub-basin and watershed scale to predict long-term impacts from management, agricultural practices, pollution, and environmental changes. SWAT can analyze the impacts of climate change on hydrology with streamflow simulations.

Other hydrologic models described in the literature include the distributed hydrology soil vegetation model (DHSVM) and the variable infiltration capacity (VIC) macroscale hydrology model. Both of these models have been cited as producing similar streamflow output simulations when used in Washington State (Lutz et al., 2012) including reduced summertime streamflow in the Puget Sound (Vano et al., 2010, Cuo et al., 2011). These models allow for more input manipulation than the SWAT model, as well as output manipulation and coupling with other models (Lutz et al., 2012). The DHSVM and VIC model have successfully simulated climate change impacts on multiple Washington rivers (Cuo et al., 2010; Mantua et al., 2010; Dickerson-Lange & Mitchell, 2014). SWAT has been implemented successfully in watersheds of the PNW for climate change impacts on hydrology (Jin & Sridhar, 2012; Sridhar & Nayak, 2010; Stratton et al., 2009) but has not yet been implemented or assessed in southern Puget Sound watersheds. Puget Sound streamflow outputs produced by SWAT should be similar to those produce by the DHSVM and VIC models though these models differ slightly as will be discussed.

The DHSVM model is a distributed model that takes into account the influence of topography and vegetation on the water fluxes of a system in a GIS based interface and LINUX platform. DHSVM assesses the influence of topography and vegetation on the water flux of a system, similar to SWAT. Originally developed in the early 1990s, DHSVM has been improved at the Pacific Northwest National Laboratory, University of Washington, and Princeton University (Wiley & Palmer, 2008). A focus of the DHSVM model is the interaction of vegetation, liquid capture, and the ablation effect of snow accumulation under forest canopies (Elsner et al., 2010). Ablations refer to the removal of snow and ice through melting or evaporation. Using similar input parameters as SWAT (temperature, precipitation, land cover, and elevation) DHSVM can generate streamflows at a fine local scale of 30 to 150 meters (Traynham et al., 2011). Successful implementation of this model has occurred on two Puget Sound river systems, the Cedar River and South Fork Tolt River, of the PNW to look at climate changes on hydrology in order to assess impact to municipality water supply (Wiley & Palmer, 2008).

The VIC macroscale model was developed in the 1990s at the University of Washington and Princeton University; it runs on LINUX and UNIX platforms (Hamlet & Lettenmaier, 1999). VIC is a grid based land surface model that was designed to incorporate GCMs and simulate land-atmosphere fluxes, water, and energy budgets with land interaction (Elsner et al., 2010). Input parameters of VIC are also similar to those of

SWAT. This difference between the two above mentioned models and SWAT is that the SWAT model can be more accessible by users that are not familiar with computer code or LINUX based system.

For the purposes of this research, the SWAT model will be implemented to assess feasibility of an "easy to operate" hydrologic model to address climate change in a mountainous snowpack dominated watershed of the PNW. Though DHSVM and VIC models could also address climate change impact in the Puyallup River Watershed, the level of difficulty of these models will not attract the attention of resource managers that would benefit from their use. However, the SWAT model is catered to this audience where accessible training is available and limited modeling knowledge is needed to begin immediate implementation of SWAT. SWAT has historically been accessed for agricultural management but has also begun to expand in terrain similar to the Puget Sound. From this development, SWAT was chosen for assessment because success and ease of its implementation could lead to broad scale use by water resource managers.

2.6 Soil and Water Assessment Tool (SWAT)

The SWAT model is a river basin and watershed model that was developed in the early 1990s by the US Department of Agriculture-Agricultural Research Service (USDA-ARS) and Texas A&M University AgriLife Blackland Research Center. The model was developed to investigate and simulate hydrology of water in complex river basins where water resources are impacted by land use, land management, and climate change over long periods of time (Kankam-Yeboah et al., 2013). SWAT is open-sourced and is a physically-based model which requires specific information for soil, land-use, weather, and management of a watershed. Benefits of this approach allow for simulations of missing data such as stream or temperature gauging, and the quantification of input changes such as climate. SWAT uses daily and sub-daily time steps, that are time continuous and manipulated in a GIS interface (Kankam-Yeboah et al., 2013; Xu et al., 2013; Jha, 2011; Setegn et al., 2010; Jha et al., 2004). The continuous model allows for long term watershed monitoring and does not limit the timescale of future simulations. These daily and sub-daily time steps consist of average mean precipitation measurements, minimum and maximum temperature, and mean streamflow measurements.

SWAT uses a high level of spatial detail. This detail includes the use of upland processes to capture the heterogeneity of the watershed. Interconnected processes incorporated by SWAT are weather, hydrology, sedimentation, plant growth, nutrient cycling, pesticide dynamics, and management. Spatial details of hydrology include canopy storage, infiltration, redistribution, evapotranspiration, lateral subsurface flow, surface runoff, ponds and wetlands, and transmission losses. SWAT is computationally efficient, it can process an unlimited number of watershed subdivisions, and can simulate future scenarios based on environmental inputs (Jha, 2011).

SWAT is a widely used model and was chosen by the Environmental Protection Agency (EPA) as one of the models to include in the Better Assessment Science Integrating Point and Nonpoint Sources (BASINS) model packages (Jha, 2011). The SWAT model has been successfully applied to investigate the impact of climate change on watershed hydrology in the Boise and Spokane River basins of the PNW (Jin & Sridhar, 2012), the Upper Mississippi River Basin (Jha et al., 2044), the Missouri River

Basin (Stone et al., 2001), as well as internationally in West Africa (Kankam-Yeboah et al., 2013) and East China (Xu et al., 2013).

The current SWAT model has been part of the ongoing model services provided by the USDA-ARS throughout the last 30 years and there are many components of SWAT that originated in other models. Some of these models are the Groundwater Loading Effects of Agricultural Management Systems (GLEAMS) model, the Chemicals, Runoff, and Erosion from Agricultural Management Systems (CREAMS) model, and the Environmental Policy Integrated Climate (ERIC) model. These three models represent the early trials of hydrologic modeling by the USDA. Components from each model were combined to form the Simulator for Water Resources in Rural Basins (SWRRB) model. Early versions of SWAT were renditions of the SWRRB model that included components from the Routing Outputs to Outlet (ROTO) model and the Enhanced Stream Water Quality Model (QUAL2E). Later modifications in the early 2000s included carbon cycling inputs from the C-FARM model as well as including the ArcGIS platform to create ArcSWAT that can be downloaded into GIS.

As an opened sourced model, SWAT development has benefited from a community of users and developers to create calibration and validation tools for SWAT modeling. SWAT-CUP is one of these tools available for SWAT users. SWAT-CUP allows users to choose from a variety of algorithms to enable sensitivity analysis, calibration, validation, and uncertainty analysis of the model. SWAT-CUP4 links together GLUE, ParaSol, SUFI2, MCMC, and PSO algorithms and procedures for these applications.[3] The most current edition of SWAT is ArcSWAT 2012.10.16 updated in September of 2014 to be run with ArcGIS 10.2, and will be used for all analysis purpose of this research.

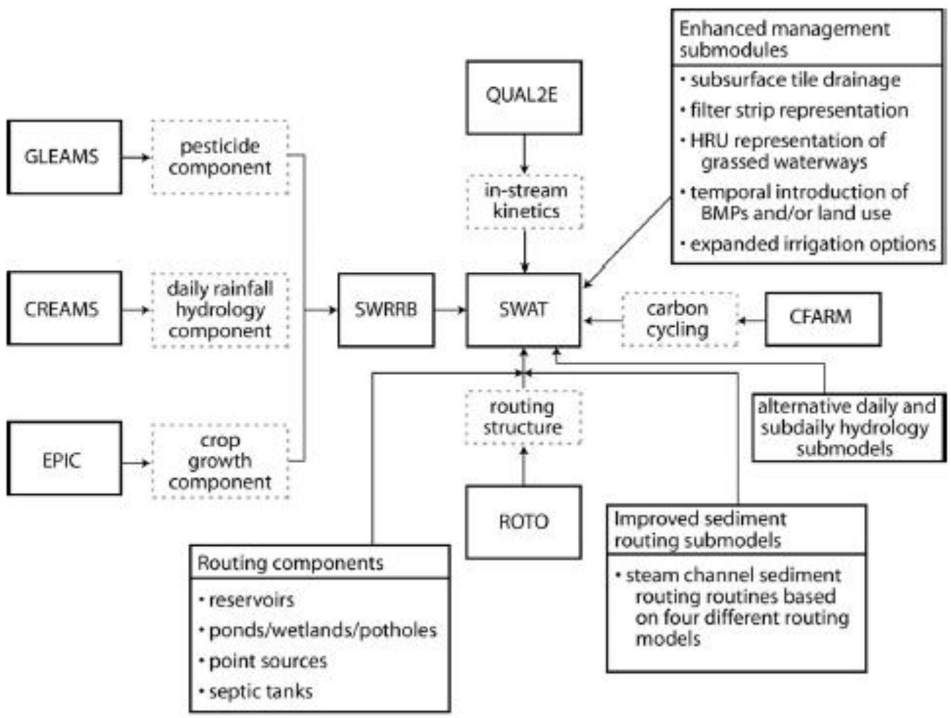

Figure 6. The history and development of the SWAT model from Arnold et al., (2012) originally adapted from Gassman et al., (2002).

SWAT was developed to incorporate readily available data that are physically based to capture spatial heterogeneity, and to reduce the need for field work. Simulations

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[3] A full description of the SWAT tools can be found on the SWAT website hosted by Texas A&M University at (http://swat.tamu.edu). For SWAT-CUP details, refer to SWAT Calibration and Uncertainty Programs User Manual available from Department of Systems Analysis, Integrated Assessment and Modelling (SIAM), Eawag, Swiss Federal Institute of Aquatic Science and Technology, Duebendorf Switzerland (www.eawag.ch/organisation/abteilungen/siam/software/swat/index_EN).

produced by SWAT are broad scale and comprehensive to recognize that hydrological processes are interactive. SWAT can incorporate GCMs and regionally downscaled climate models (RCMs) for climate change impact assessments.

There are a number of disadvantages of SWAT. First, the model assumes groundwater to be eliminated from the system once reaching the deep aquifer layer. Eliminated groundwater interactions from hydrologic modeling can be problematic for water storage, water quality, and aquatic environment assessments as interactions between groundwater and surface water are significant (Winter et al., 1998). Also, the model does not track fine sediment loads or bacterial loads. Groundwater assumptions are due to the large variability of water movement once at deep aquifer level; however, other models that account for these factors can be coupled with SWAT. Ultimately, the decision to use one hydrologic model over another is based on the research question at hand. For these purposes, the SWAT model will be implemented to assess feasibility of the model to address climate change influence on the hydrology of the Puyallup River basin located in the lower Puget Sound region. From previous literature, the DHSVM and the VIC models have been used in similar studies but require a background knowledge in computer programing, do not offer the same training support as the SWAT model community, nor do they have as long of a development history as the SWAT model. DHSVM and VIC have been used extensively in the PNW for hydrology investigations and could also be used in the Puyallup River basin as they are state of the art hydrologic models. However, SWAT was chosen for the Puyallup River basin because it takes a more holistic approach to management decisions. As a heavily agricultural model, SWAT is used for management purposes with a system based approach and will be assessed in the PNW with the Puyallup River basin.

Parameterization of Water Balance in SWAT

Hydrologic models, such as SWAT, are based on the water balance equation

(Equation 1):

$$SW_t = SW_o + \sum_{i=1}^{t}(R_i - Q_i - ET_i - P_i - QR_i)$$

Where total soil water content (SW_t) is equated from the initial soil water content (SW_o) on selected day (i) for a set number of days (t). On the selected timescale, soil water content consists of the amount of precipitation added to the system (R_i) minus the amount of surface runoff that leaves the system (Q_i), minus the amount of evapotranspiration(ET_i) that escapes, minus the amount of water that enters the vadose zone, or deep aquifer (P_i), and minus the amount of water that leaves the soil as return flow (QR_i). Return flow is not the same as lateral flow. Return flow here refers to the water that returns to river from the shallow aquifer layer (Arnold et al., 1998). Figure 7 visually represents all of the variables in the water balance equation used by SWAT for simulations.

The water cycle is climate driven and requires certain environmental inputs: precipitation, temperature, solar radiation, wind speed, and relative humidity. Data of these inputs can be acquired from observed daily data or can be simulated in hydrologic models with monthly statistics. ArcSWAT offers governmental geo-databases for environmental inputs and statistically based simulations for missing data.

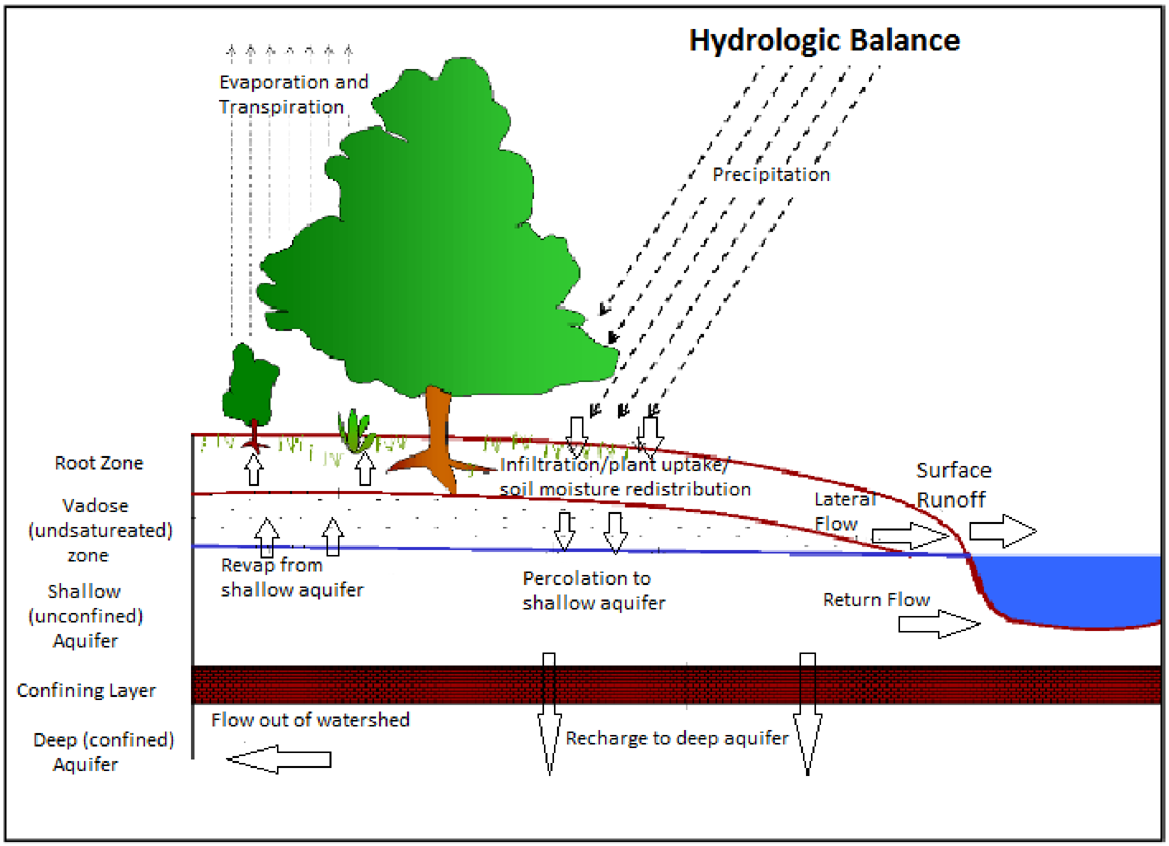

Figure 7. A visual representation of the hydrologic balance equation used in SWAT for simulations. "Revap" from the shallow aquifer to the vadose zone refers to water that evaporates or diffuses upward when overlying material is dry. Figure was reproduced from Soil and Water Assessment Tool Theoretical Documentation version 2009

SWAT Model Applications

SWAT applications can range from evaluating the effect agricultural management decisions, impact of land use transitions, natural and cultural landscape vulnerabilities, and environmental impacts on hydrology. Impacts on hydrology range from forest management, point and non-point source pollution, urbanization, and climate change. The literature that will be discussed in the following section focuses on climate change impacts on hydrology. The studies take place in river basins of the United States, including the PNW, multiple river basins in Africa, and river basins in China. The varying landscapes of the SWAT model application demonstrates the flexibility of SWAT to be calibrated to basin specific parameters in varying terrain.

Hydrologic parameters used to simulate model output vary from study to study. Studies that assessed climate change impacts on hydrology included hydrologic parameters for surface flow, baseflow, and evapotranspiration (Jha et al., 2004; Stratton et al., 2009; Sridhar & Nayak, 2010; Wu et al., 2012; Mango et al., 2011; Kanka-Yeboah et al., 2013; Jin & Sridhar, 2012). Case studies assessing the impact of climate change on streamflow were able to couple global climate models (GCMs) or regional climate models (RCMs) with SWAT. Using downscaled climate models in SWAT analysis allowed for the following investigations; future climate change scenarios impact on annual streamflow, the relationship of projected precipitation extremes on streamflow, future water scarcity and management adaptations, landscape adaptations for climate change mitigation, and assessment of culturally significant areas at risk to extreme precipitation (Jha et al., 2004; Wu et al., 2012; Mango et al., 2011; Kanka-Yeboah et al., 2013; Jin & Sridhar, 2012). Based on the methods of these case studies, assessing climate change impacts on streamflow in the Puyallup River basin should be applicable. The topography and interactions of a glacier fed system could be of concern, but two case studies in the neighboring state of Idaho were able to successfully implement SWAT in similar landscapes (Stratton et al., 2009; Sridhar & Nayak, 2010).

Each case study used projected climate change scenarios and produced a level of uncertainty for each application. Uncertainty accumulates from input data, the downscaling of global to regional climate scenarios, and the model itself. To reduce error and uncertainty, SWAT simulations were run with multiple climate change projections, include more than one climate scenario, and were replicated for multiple future timescales. The climate change impact on streamflow in two river basins of Ghana used two climate change projections with a rapid future economic growth scenario.[4] Streamflow simulations using these parameters were produced for future time periods 2020s (2006 to 2035) and 2050s (2036 to 2075) (Kanka-Yeboah et al., 2013). The two Ghana river basin simulated streamflow reductions of 22 to 50 percent for these time periods with future climate change scenarios. This approach implemented with SWAT reduced uncertainty and can be reproduced in the Puyallup River basin assessment.

More influential are the Idaho case studies that were successful in implementing SWAT in mountainous and snowpack influenced watersheds of the PNW. Sridhar and Nayak (2010) were able to implement SWAT to assess climate variability influence on hydrology with a 40 year data set (1967-2006). This study found that site specific monitoring stations were key to identify natural variability of climate and climate change impacts. Calibration of streamflow simulations at the Reynolds Mountain East weir produced an NSE=0.90 and an R^2=0.90, while validation produced an NSE=0.89 and an R^2=0.90. Streamflow peak timings showed a shifting trend of streamflow peaks occurring 8 to 10 days earlier as influence by climate warming (Sridhar & Nayak, 2010). From the

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[4] GCM projections were ECHAM4 (European Centre HAMburg, 4th Generation) and CSIRO (Commonwealth Scientific and Industrial Research Organization). These projections were based off the future emission scenario A1F1 from the IPCC AR4. The A1F1 scenario reflects a rapid future economic growth that minimizes the economic gap between countries.

streamflow output statistics, model performance of the Idaho Reynolds Mountain East weir was very good. This is significant as the PNW region experiences regional climate variability with PDO and ENSO events which was accounted for in this Idaho case study.

The additional Idaho case study produced by Stratton et al. (2009) found similar results with calibration statistics of NSE=0.79 and R^2=0.90. In addition, Stratton et al. (2009) recognized the importance of the sensitivity analysis to suggest significant and sensitive parameters as well as the elevation gradient influence on model inputs. Soil moisture output was underestimated during SWAT simulations. The underestimation indicates the need for further detail and field observations regarding soil parameters (available water content and saturated hydraulic conductivity), subsurface flow parameters, and snow parameters (lapse rate and melting factors). This is important as snowmelt and snowfall parameters are included in studies conducted in mountainous regions with snowpack influences but are not well represented in the SWAT literature. Though snowmelt and snowfall parameter interactions are not well discussed in the SWAT literature, they are important and need to be included in this terrain. Combined with downscaling and uncertainty reduction techniques in other regional studies, the Idaho case studies suggest that SWAT can be implemented in the Puyallup River Watershed.

Data Acquisition and Model Preparation

Use of SWAT requires data inputs of a digital elevation model (DEM), soil type maps, land-use maps, and climatic data (Kankam-Yehoah et al., 2013; Jha, 2011; Jha et al., 2004). The DEM, land use, and soil maps are used to divide river sub-basins into smaller subdivisions, hydrologic response units (HRUs). Each subdivision consists of similar land use types, soils, and management type. Creation of HRUs allows SWAT to simulate hydrology variable outputs for each sub-basin before accumulation of watershed impact (Kankam-Yeboah et al., 2013). The creation of HRUs in SWAT is critical as most calculations are done at this spatial level.

Water storage volumes in the soil are calculated at HRU level. These water storage profiles are snow, the soil profile (0 to 2 meters), shallow aquifer (2 to 20 meters), and deep aquifer (>20 meters) (Arnold et al., 2000; Jha et al., 2004; Jha, 2011). The SWAT model only simulates water components in the soil profile level as the aquifer levels are too variable for most management needs. These layers support the water storage volumes in the form of infiltration, evaporation, plant uptake, lateral flow, and percolation (Jha et al., 2004). Layer distinction is needed to understand the soil moisture content and calculate evapotranspiration and ground water recharge. SWAT allows up to 10 soil layers that typically occur in the 1 to 2 meter depth range for most of the United States (Srinivasan, 2015). These variables are important as they aid in determining total basin yield using the water budget equation and to compute streamflow output.

Downscaling for the Pacific Northwest

The PNW is one North American region that has downscaled GCM projections. The GCMs use annual mean temperatures as an assessment of climate change, but the regional scale of measured temperature and precipitation can give more insight into the effects on biological systems, including hydrology, linked to climate change (Abatzoglou, Rupp, & Mote, 2013). Regional projections are a more accurate assessment of localized impacts that local governments can use to better prepare for future risks. For hydrology planning, policy makers do not always have the basin and sub-basin scale information regarding climate change scenarios to adequately plan or adapt (Hamlet et al., 2013). Having long-term assessments of climate change impacts on water resources are essential for management strategies (Serrat-Capdevila et al., 2007). The lack of reference information is why downscaling is significant, as the need to incorporate climate change information into water resource planning and decision making has been acknowledged (Hamlet and Lettenmaier, 1999; Hamlet et al., 2013).

Downscaling Climate Change Scenarios

Downscaling is used to increase the precision of modeled climate projections, but will not necessarily increase the accuracy of the data generated. Uncertainty will accumulate due to changing climate variables, greenhouse gas concentrations, and model error because downscaling models increases error due to regional variability (Snover et al., 2013). Downscaled climate scenarios will be applied in the following SWAT analysis, as GCMs are not appropriate for PNW modeling because they do not capture regional variability (Hamlet et al., 2013). The coarse scaled models are not designed to take into consideration regional phenomena such as the east-west temperature and precipitation gradients that occur in coastal mountain ranges such as the Cascade Mountain range (Hamlet et al., 2013). Nor do the GCMs reflect seasonal variability influenced by PDO and ENSO.

2.7 Conclusion

As reported by the IPCC AR5 report, new climate change scenarios indicate warming temperature and shifting precipitation regimes for the PNW. Observations show these shifting trends in the Puget Sound snowpack watersheds. Using hydrologic models to incorporate future CO_2 concentrations, temperature, and precipitation changes, and assessment of climate change impacts can be simulated. These simulations can better inform local and state agencies about future water scenarios. Having a generalized assessment of future changes is important as the Puget Sound area supports social and economic benefits.

The SWAT model has been successful in producing climate change impact assessments in other river basins of the United States. The assessment of SWAT feasibility in the Puyallup River basin will be grounded in the ability of SWAT to successfully reproduce current and historical streamflow measurements with data inputs. This will be addressed in the model calibration and model validation steps. The mountainous terrain and snowpack parameters will challenge SWAT implementation in the Puget Sound lowlands. The Puyallup River basin is glacier fed and will be impacted by climate change as glaciers retreat and declining snowpack accumulation shifts peak flow times. Shifting these peak flows will increase the demand for and conflict over water resources between growing municipalities, natural resource industry demands, and local habitats. Conducting a sub-basin and watershed scale assessment will be useful for natural resource managers to apply adaptive management strategies to reduce future water conflict. This research will address the feasibility of implementing the SWAT model in the lower Puget Sound river basins.

Chapter 3. Methods

3.1 Study Area

The snowpack dominated Puyallup River Watershed, located in south Puget Sound low lands of western Washington (Figure 8), and was chosen as the study site for this thesis. The focus of the SWAT assessment was conducted in the Puyallup River basin of the watershed, shown in Figure 9, to assess SWAT model feasibility and parameter calibration. The Puyallup River basin drains a watershed approximately 1,040 square miles or 665,000 acres (PRWC, 2014). The watershed is fed from the glaciers on Mt. Rainier and is drained by the Puyallup River and two main tributaries, the White River and the Carbon River. Water supplied from the watershed is used for irrigation, municipal, and domestic supplies. The surface water from this watershed supplies fish habitat, recreation, and navigation while groundwater supplies public and single wells (Washington State Department of Ecology [DOE], 1995). These rivers are home to many endangered salmon species, supply water resources to multiple metropolises including Tacoma, and are of cultural significance to many of the native Indian tribes including the Puyallup Tribe of Indians.

Mean annual flows for the Puyallup River are approximately 3,000 cubic feet per second (cfs) with peak runoff times and flooding occurring October through March (DOE, 1995). High flows occur when the municipality supply demand is low and conversely, low flows occur in the summer when demands rise again. USGS station 12093500 on the Puyallup River reported low flows in the summer month of August that averaged 566 cfs for the years 1940 to 2000. Annual high flows for the month of December averaged 945 cfs for the same years.

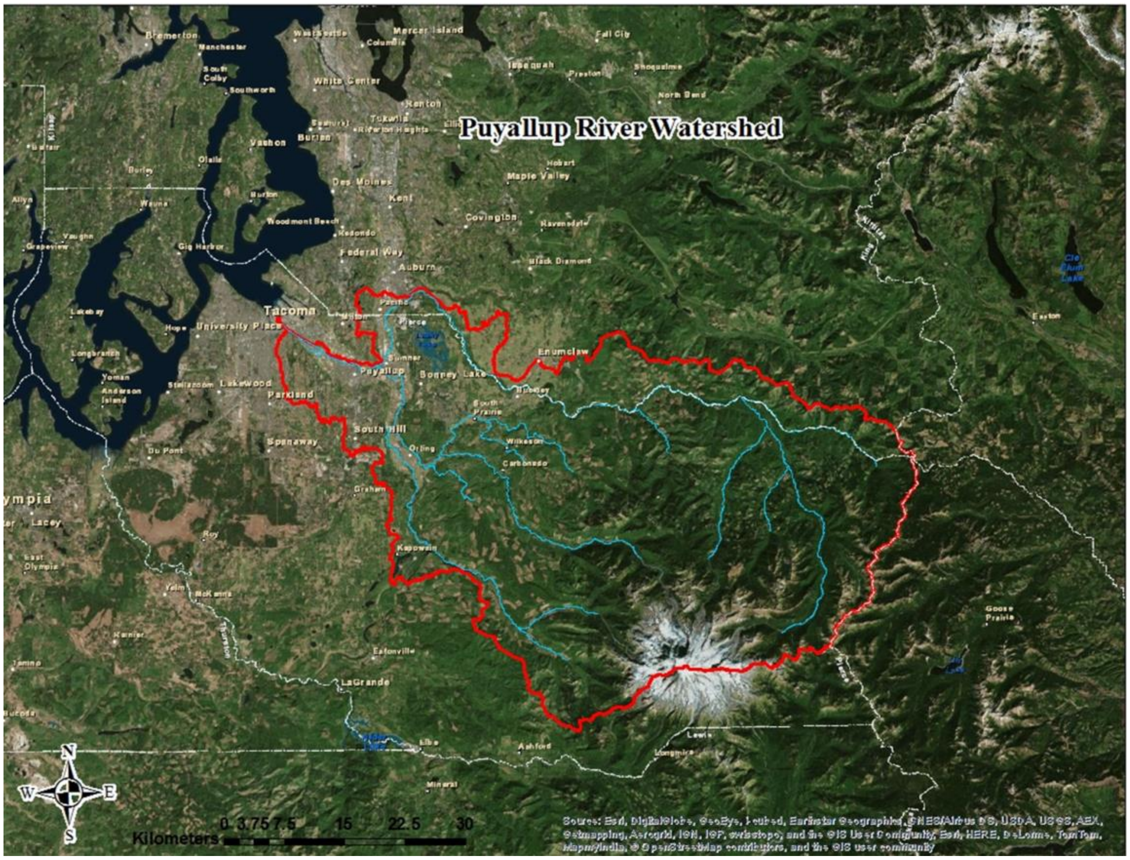

Figure 8. The Puyallup River Watershed outlined in red house portions of Mt. Rainer and extends into the lowlands of Puget Sound located in Washington State. Upper watershed is vastly forested and lower watershed is more urbanized.

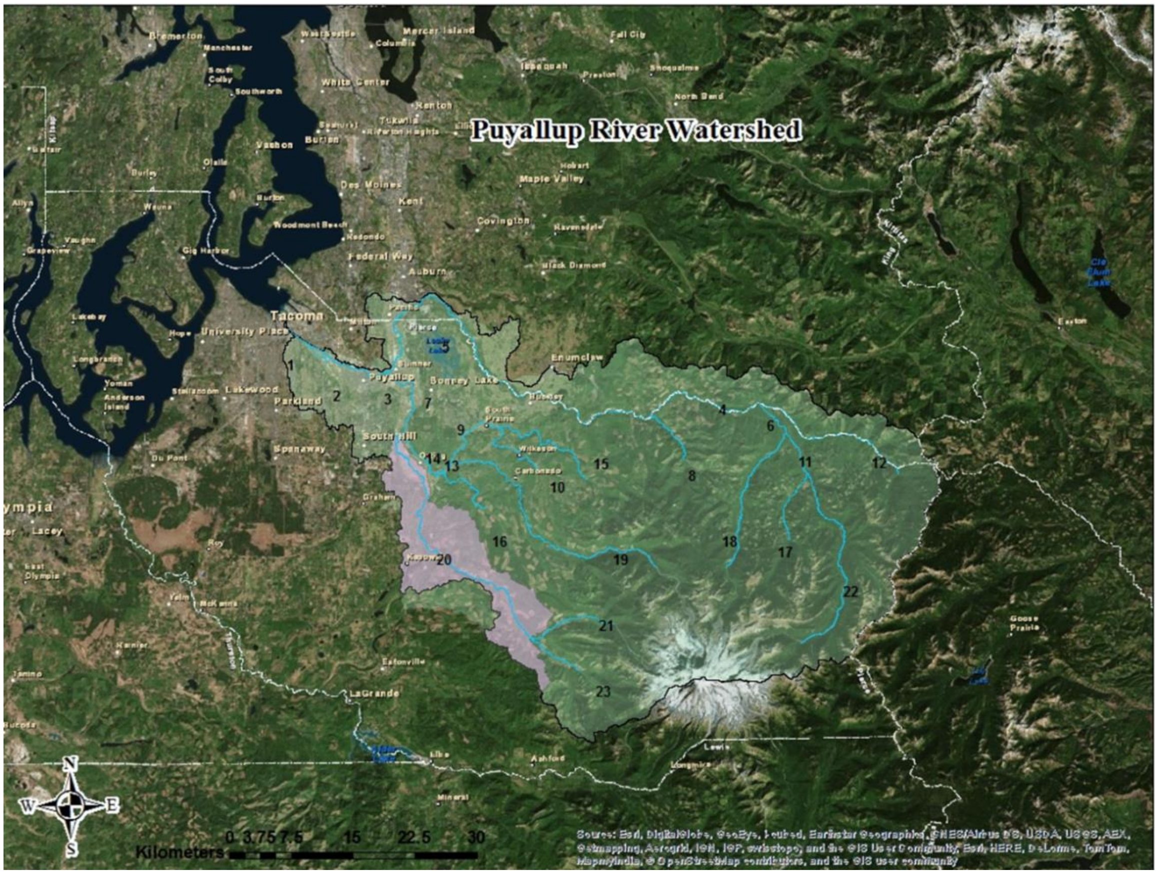

Figure 9. The Puyallup River basin highlighted in pink (sub-basin 20) is the focus basin for the SWAT model feasibility assessment.

3.2 Model Input Data

Spatially explicit datasets are needed for topography, soil parameters for hydrology characteristics, and climate data at daily time steps. Input data for SWAT include the DEM, land-use data, soil properties, temperature, and precipitation data.

Digital Elevation Model (DEM)

The 30-meter resolution DEM was downloaded from the GeoSpatial Data Gateway provided by the US Department of Agriculture Natural Resources Conservation Services. The DEM is part of the National Elevation Dataset (NED) that originated with the U.S. Geological Survey (USGS). NED datasets use the Nearest Neighbor resampling method to interpolate continuous elevation data in a Universal Transverse Mercator (UTM) projection to make seamless maps. DEM quality is of high importance as the DEM layer sets the foundation for stream network delineation. Multiple DEM raster files were downloaded, combined, and projected to UTM ZONE 10 N for western Washington with datum NAD 1983. DEMs were chosen for Pierce and King Counties of Washington State at a 30-meter resolution. Three meter and 10-meter resolutions were available but 30-meter resolution maps were chosen as seen in the SWAT literature for DEM selection. Sub-basin delineation, shown in Figure 10, was created from the DEM layer based on land surface and drainage patterns. Drainage patterns were used to determine flow direction and movement.

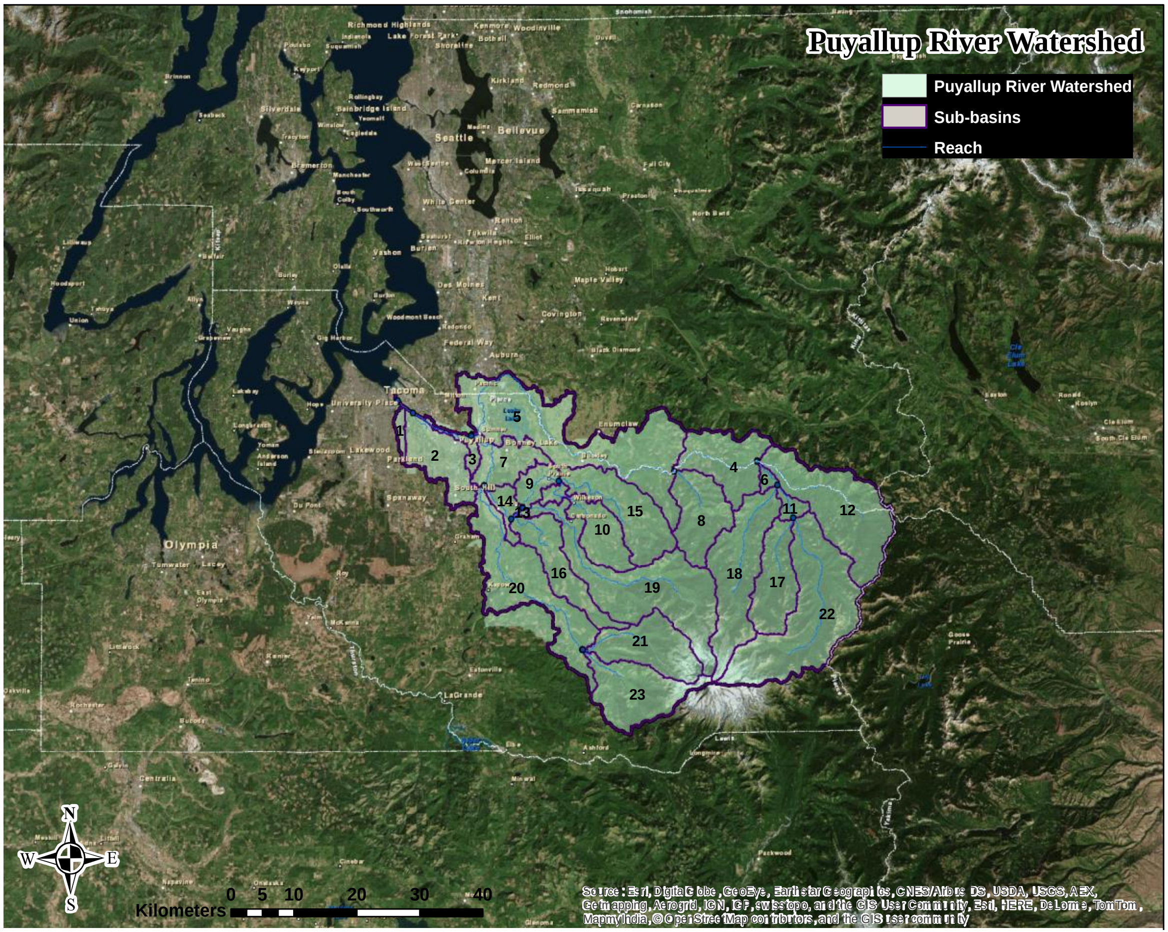

Figure10. Map of the Puyallup River Watershed located in the south Puget Sound lowlands of Western Washington. The watershed was divided into 23 sub-basins. Each sub-basin was further divided into hydrologic response units (HRUs) from unique combinations of slope, soil, and land-use classes.

Land-use Data

Land-use data was accessed through the USDA GeoSpatial Data Gateway. The 2011 National Land Cover Data Set (NLCD) was used for land-use input. NLCD used a 16-class land cover classification scheme at a 30-meter spatial resolution in a UTM projection. Generated land classes were broken down into two categories: urban land use and vegetation type. Urban land use classes included 1) residential-low density, 2) residential-medium density, 3) residential-high density, and 4) industrial. Vegetation classes included 1) water, 2) arid rangeland, 3) forest-deciduous, 4) forest-evergreen, 5) forest-mixed, 6) range-brush, 7) range-grasses, 8) hay, 9) agricultural land-row crops, 10) wetlands-forested, and 11) wetlands-non-forested. The Puyallup River Watershed had a total of 15 land-use classes for simulations.

Soil Data

Soil data were obtained from the USDA GeoSpatial Data Gateway. Soil Survey Geographic Database (SURRGO), originated with the U.S. Department of Agriculture, Natural Resources Conservation Service and further developed by the National Cooperative Soil Survey (NCSS). The gridded soil layer linked soil attributes to a unique map unit key (MUKEY) that allowed for additional county level soil surveys to be added to the SURRGO database. Soil properties are necessary for the SWAT model as rainfall events and destination of flow depend on the composition and conditions of the soil. Soil properties such as texture, chemical composition, physical properties, moisture content, hydraulic conductivity, bulk density, and organic carbon content are needed. These properties are needed for each soil type and each soil layer as they influence the movement of water. These properties were provided by the SURRGO database and county level soil surveys. Deficiencies in soil survey information around Mt. Rainier in the SURRGO database lead to areas being identified as No Digital Data in the county level soil survey. Otherwise, soil classes for the Puyallup River Watershed can be found in Table 2 in the Appendix. Soil grids were downloaded in NAD 1983 Albers Equal Area Conic spatial reference and projected into UTM.

Climate Data

Daily observed data for precipitation (mm), minimum temperature (C°), and maximum temperature (C°) were downloaded for Pierce County and King County of Washington State from National Oceanic and Atmospheric Administration (NOAA) National Climatic Data Center. Seven weather stations were chosen based on availability of 50-year datasets, 1960 to 2010. Weather station location and averages are available in Table 3 and Table 4. Missing data occurred for stations at various months or days and was statistically simulated in SWAT. Other climate data simulated in SWAT included wind speed, humidity, solar radiation, and evapotranspiration. These simulations were based on national weather gage datasets within the SWAT model.

Streamflow Data

Daily streamflow data was obtained on the USGS website for 19 surface flow stations throughout the Puyallup River basin. SWAT model calibration and validation used observed streamflow data to measure simulation accuracy. The station of focus, USGS station 12093500, was located along the Puyallup River at Orting Washington. This station was chosen for sensitivity, calibration, and validation procedures because of its location by the watershed outlet and complete record of historical measurements. Streamflow measurements from 1960 to 1979 were used for calibration and streamflow measurement from 1980 to 2007 were used for validation. Streamflow data was normalized to the area of the drainage basin to yield units of mm/day. This was done by converting flow from units of cubic feet per second (cfs) to millimeters per day (mm/day) for both calibration and validation following Equation 2. Conversion to millimeters occurred so that streamflow was more relatable to precipitation input that is also measured in millimeters, but results are reported as m^3/s. Figure 11 represents average daily flow for USGS station 12093500.

(Equation 2):

Convert drainage area to square feet:

$$172\ miles^2 * \frac{27{,}878{,}400\ ft^2}{1\ mile^2} = 4{,}795{,}084{,}800\ ft^2$$

Convert cubic feet per second to cubic feet per day

$$\frac{1\ ft^3}{1\ second} * \frac{60\ seconds}{1\ minute} * \frac{60\ minutes}{1\ hour} * \frac{24\ hours}{1\ day} = \frac{86{,}400 ft^3}{day}$$

Combine conversions

$$\frac{86{,}400 ft^3 / day}{4{,}795{,}084{,}800\ ft^2} = \frac{0.000189899\ ft}{day}$$

Convert to millimeters for model input

$$\frac{0.000189899\ ft}{day} * \frac{12\ in}{1\ ft} * \frac{25.4\ mm}{1\ in} = \frac{0.005492\ mm}{day}$$

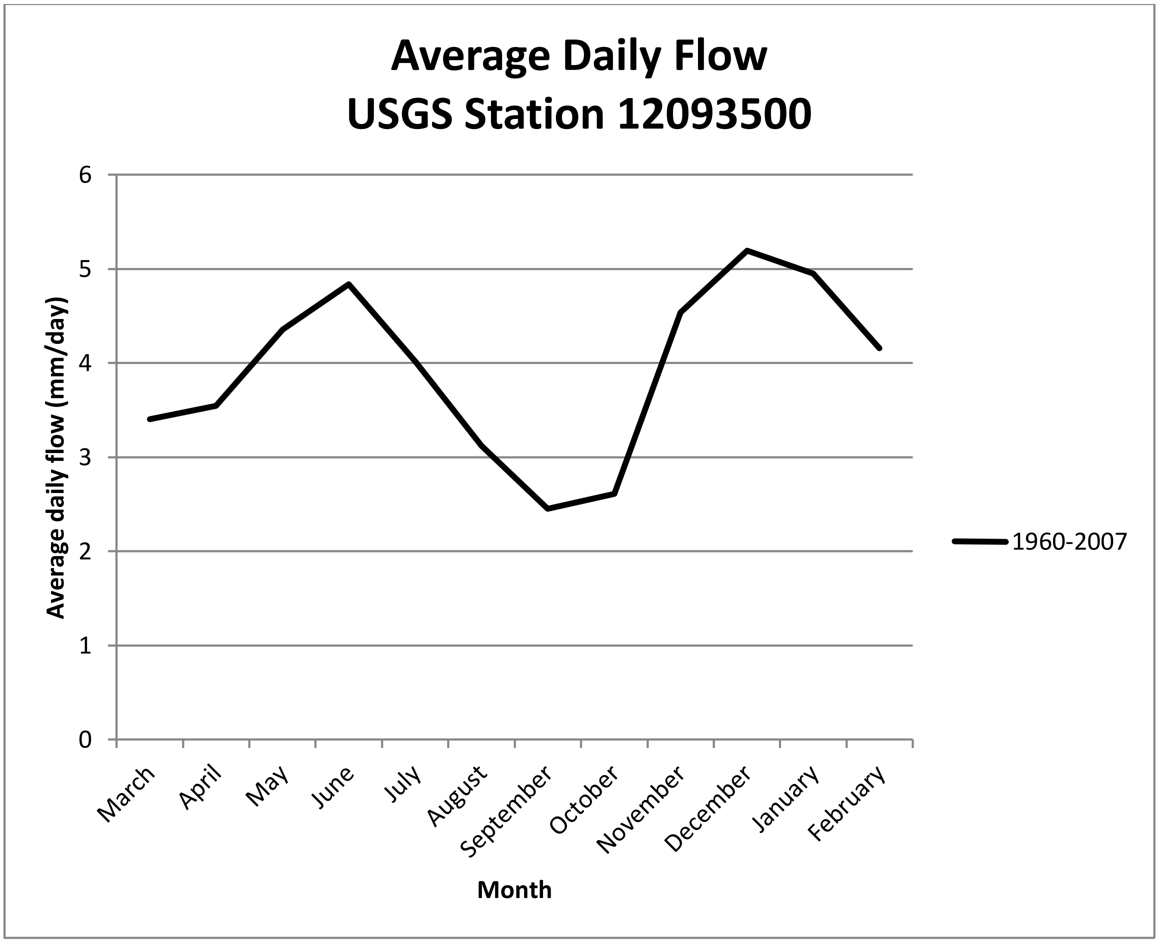

Figure 11. USGS surface water station 12093500, Puyallup River at Orting Washington. Average daily flow (mm/day) were aggregated by month for 1960 to 2007. Observations show two peaks, in the winter from precipitation and in the late spring from snowmelt. Data source: USGS

3.3 SWAT Setup and Sensitivity Analysis

SWAT model setup began with delineation of the watershed based on the obtained data. Watershed delineation included DEM setup, stream definition, outlet and inlet definition, watershed outlet selection, and watershed outlet definition. The stream definition was created using the DEM layer instead of burning in a stream network or National Hydrology Dataset. This decision to use the DEM layer over predefined stream network was to limit sub-basin and HRU definitions. Since each reach is assigned to one sub-basin, including all tributaries would increase the computation power needed and error in final simulations. Using the DEM to define stream network simplified sub-basin definition. Sub-basin outlets were defined so that each reach of a channel was assigned to one sub-basin. With the selection of one watershed outlet, the watershed was delineated to form 23 sub-basins (Figure 10), with the focus of assessment in sub-basin 20, the Puyallup River basin (Figure 9).

Hydrologic response units (HRUs) were defined using land-use, soil, and slope data grids. Rainfall and temperature input files were added to SWAT. Elevation bands were added to SWAT input tables to account for snow accumulation of Mt. Rainier. Elevation band ranges (meters) were adapted from Cuo et al. (2011), as follows: band 1: 0-500 m, band 2: 500-1000 m, band 3: 1000-1500 m, band 4: >1500 m.

SWAT DEM setup produced nine elevation ranges in 500 meter increments, from sea level to 4,500 meters (Figure 12). Land-use classification resulted in fifteen classes (Figure 13). The SURRGO database used for soil classification in SWAT resulted in 233 soil classes, 104 were listed in sub-basin 20 (Figure 14). After the three layer classifications, 5 HRUs were derived for sub-basin 20 from unique combinations of slope, land-use, and soil type.

After an initial SWAT simulation was conducted, sensitivity analysis was performed to highlight basin specific parameters that drive model simulations and create sensitivities to model outputs (Arnold et al., 2012). Highlighting sensitive parameters was necessary for calibration to assess over and under estimation of output variables.[5] Sensitivity analysis was conducted using SWAT-CUP and a chosen algorithm, which, for the Puyallup River basin analysis, the Sequential Uncertainty Fitting-2 (SUFI2) algorithm was used. SUFI2 was chosen to produce practical results as simulations are not dependent on previous iterations (Srinivasan, 2015) and based on its use in PNW-based Idaho watersheds (Jin & Sirdhar, 2012). Regression correlation coefficient (R^2) and the Nash-Sutcliffe model efficiency (NSE) coefficient measured how well simulated data compared to observed data. Current literature has a range of acceptable R^2 and NSE values as reflected in Table 1 of the Appendix.

Streamflow simulations for sensitivity analysis followed Kankam-Yeboah et al. (2013) and Jha (2011). This included a short time period of 1960 to 1965 for sensitivity analysis and the Curve Number method (Jin & Sridhar, 2012) for surface runoff estimation based on precipitation. Streamflow simulations were compared to observed flow data from USGS stream gage 12093500. Simulations were opened and viewed using SWAT-CUP for sensitivity analysis of parameters, calibration, and validation. SWAT-CUP was designed as an interface for SWAT to link the inputs and outputs of a calibration program to the model through text file formats.

Twenty-one parameters were observed for sensitivity analysis of streamflow using the automated Latin Hypercube One-factor-At-a-Time (LH-OAT) sensitivity analysis provided in SWAT-CUP snowpack dominated watershed literature from the

[5] The SWAT model provides a sensitivity analysis tool that uses the Latin Hypercube One-factor-At-a-Time (LH-OAT) method. The LH-OAT is a combination of the global sensitivity analysis method Latin Hypercube (LH) (McKay, 1979) and the local sensitivity analysis method One-factor-At-a-Time (OAT) (Morris, 1991) (Kankam-Yeboah et al., 2013; Mango et al., 2011). The global method allows for all parameter values to change together and the local method changes parameter values one at a time (Arnold et al., 2012).

PNW area (Sridhar & Nayka 2010, Jin & Sridhar 2012). Parameters chosen for calibration manipulation are listed in Table 5. Using the LH-OAT analysis, a t-test was produced to identify the significance and sensitivity of each parameter. Without expert knowledge, a trial and error method of parameter range adjustment was used for calibration using SWAT-CUP (Srinivasan, 2015). Expert knowledge would lead to manual calibration of parameter ranges in the SWAT input tables (Srinivasan, 2015).

Parameter	Parameter Name
CN2*	Initial SCS runoff curve number II
CNMAX*^	Maximum canopy storage
ALPHA_BF^	Base flow alpha factor
GW_DELAY^	Groundwater delay time
GWQMN^	Threshold depth of water in shallow aquifer for return flow
EPCO^	Plant uptake compensation factor
ESCO*^	Soil evaporation compensation factor
SOL_AWC*^	Available water capacity of the soil layer
SOL_K*^	Saturated hydraulic conductivity
RCHRG_DP*^	Deep aquifer percolation fraction
REVAPMN*^	Threshold depth of water in shallow aquifer for percolation to deep aquifer
GW_REVAP^	Groundwater "revap" coefficient
SLSOIL*^	Slope length for lateral subsurface flow
SURLAG^	Surface runoff lag coefficient
TIMP*^	Snow pack temperature lag factor
SMFMX	Melt factor for snow on June 21
SMFMN	Melt factor for snow on December 21
SFTMP	Snowfall temperature
SMTMP	Snow melt base temperature
SNOCOVMX	Minimum snow water content that corresponds to 100% snow cover
SNO50COV	Minimum snow water content that corresponds to 50% snow cover

Table 5. Parameter and parameter description for the calibration of Puyallup River sub-basin (sub-basin 20). (*) represents parameters that produced a positive t-Stat, indicating sensitivity. (^) represents parameters that produced a p-value greater than 0.02, indicating significance. Snow parameters were added to calibration as suggested by the literature.

3.4 Parameters

Surface Runoff

CANMX

CANMX is the maximum canopy storage (mm H_2O) in the amount of water intercepted by plant canopy. The influence of the canopy storage depends on the density of coverage and the type of plant species. Species with greater foliage will intercept more water and varies daily based on leaf area index. CANMX influences surface runoff, evapotranspiration, and precipitation infiltration all of which influence total streamflow yield. The amount of water interception at canopy level from precipitation and evapotranspiration are considered a loss from the drainage basin. Calibration of CANMX occurred in the default range of 0 to 100 as initial estimates began at 0, without prior knowledge of CANMX in the Puyallup River basin, calibration adjustments started with default range.

CN2

The initial SCS runoff curve number for moisture condition II is a function of soil permeability, land use, and soil water condition. CN2 was developed by USDA Natural Resources Conservation Services, also known as the Soil Conservation Service (SCS). CN2 was chosen because it represents soil moisture conditions for average moisture conditions (versus dry (wilting point) or wet (field capacity) conditions) and is chosen for most modeling approaches. CN is calculated to predict runoff directly from precipitation and is the potential of runoff from precipitation after evaporation, absorption, transpiration, and percolation are removed. CN depends upon soil hydrologic group (A, B, C, or D), condition (poor, fair, good), and land-use type. Ranging from 30 to 100 with runoff potential increasing as the CN gets higher. Lower runoff potential is usually found where more permeable soils exist while high runoff potential is common where soils are more impervious. When CN is increased, surface runoff is increased in simulation.

The Puyallup River basin has three land-use types (FRSE, FRST, and RNGB)[6], two soil types (Barneston and Kapowsin)[7], and were found in hydrographic groups B and D. Group B has moderate infiltration rates and group D has slow infiltration rate, so CN ranges may not overlap (Table 6). Identifying CN is a prime example of the importance of defining sub-basin HRUs. CN can be calculated at the HRU level for each unique combination of soil, land-use type, and soil characteristic. HRU 1 in Puyallup River basin is forested, has Barneston soil in hydrographic group B, and has a gravelly texture while composed mainly of sand. Based on cover type, woods, it was assumed that the CN could range from 55 to 66 for this HRU. Taking into consideration the soil moisture condition or antecedent moisture condition (AMC), CN2 was used to represent average soil moisture condition before a precipitation event, allowing the range to shift slightly due to residual soil moisture of previous precipitation. Based on the land cover types and hydrologic groups for the Puyallup River basin, the range for CN2 calibration was 55 to 83.

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[6] FRSE=evergreen forest, FRST=mixed forest, and RNGB=range-bush.

[7] Barneston and Kapowsin soil series are formed by volcanic ash and glacier deposits found in outwash and glacial drift plains. www.soilseries.sc.egov.usda.gov

Soil Hydrologic Group	Characteristics
A	High infiltration rates. Mostly sands or gravels, deep and well drained. High rate of water transmission. Low runoff potential.
B	Moderate infiltration rates. Moderately fine to coarse textures. Deep and moderately well to well drained. Moderate rate of transmission.
C	Slow infiltration rates. Moderately fine to fine texture. Slow rate of water transmission. High runoff potential.
D	Very slow infiltration rate. Moderately fine to fine texture. High permanent water table. Clay pan or clay layer near the surface. Shallow soils over nearly impervious material. Very slow rate of water transmission

Table 6. Hydrologic soil groups with defining characteristics.

SOL_AWC

The available water capacity of the soil layer (mm H_2O/ mm soil), is the water present at field capacity minus the water present at vegetation permanent wilting point, leaving the water available for plant growth. Available water content is an indication of soil quality and is important for vegetation growth, nutrient transport, and biological activities. Available water capacity in this area is influenced by agricultural practices and possible soil salt concentration if salt water intrusion occurs in the Puget Sound lowlands. Soil texture and composition also influences available water content. Sandy soils usually range from 25 to 100 (mm/mm), loam (silt) soil ranges from 100 to 175 (mm/mm), and clay ranges from 175 to 250 (mm/mm) (Brouwer et al., 1985). The soil type of the Puyallup River basin is mostly composed of sand and silt as shown in Table 7. The range used for SOL_AWC calibration was 80 to110 (mm/mm) to account for the sandy like soil type of the Puyallup River basin.

HRU	**Landuse Type**	**Soil Type**	**% Clay**	**% Silt**	**% Sand**	**Hydrologic Group**
1	FRSE	Barneston	3	30.2	66.8	B
2	FRST	Kapowsin	18	38.8	43.2	D
3	FRST	Kapowsin	18	38.8	43.2	D
4	RNGB	Barneston	3	30.2	66.8	B
5	RNGB	Barneston	3	30.2	66.8	B

Table 7. Puyallup River sub-basin (sub-basin 20) HRU description of land-use type, soil name, and composition. FRSE=Forest-Evergreen, FRST=Forest-Mixed, RNGB=Range-Brush.

SURLAG

The surface runoff lag coefficient accounts for surface runoff in larger basins that does not meet the mainstem of a river on the day of generation. SURLAG controls the fraction of runoff that is available in the main channel on any given day in relation to time of concentration greater than a day. Time of concentration is the time required for runoff to travel from the most distant point of an area to the outlet. As SURLAG decreases the more water is stored in soil before it reaches the main channel. SURLAG can be influenced by slope, land use, soil, size, and shape of the basin. SURLAG range determination for calibration was guided by SWAT literature from other sites in the PNW but was mostly calibrated through trial and error. Initial SURLAG estimates for the Puyallup River basin were 2, with the full SURLAG range of 0.05 to 24 used during calibration. Full range was used during calibration to account for the lack of known SURLAG estimates in the basin.

SOL_K

The saturated hydraulic conductivity (Ksat) (mm/hr) of the soil layer is a measurement of the ease of water to move through saturated soil. Soil property textures influence water movement with sandy soils generally having a more rapid movement, silts having a medium movement, and clays having a slow movement. The soil types for the Puyallup River basin are mostly composed of sand and silt. Using saturated hydraulic conductivity class table provided by USDA Natural Resources Conservation Service, sandy soil Ksat Rate (μm/sec) range from 42.34 to 141.14, and silt soils Ksat Rate (μm/sec) range from 4.23 to 14.11. After conversion, the Puyallup River basin had a SOL_K range of 152 to 508 (mm/hr) for sandy soil and 15 to 51 (mm/hr) for silt soil during calibration. These ranges housed initial SOL_K estimates of 32 (mm/hr) for the silty soil type and 100 (mm/hr) for the sandy soil.

SLSOIL

SLSOIL is the slope length for lateral subsurface flow (m). Increasing slope length can increase lateral flow in shallow subsurface layers. Lateral flow is the movement of water from the vadose zone that enters the stream instead of percolating to groundwater. The lateral subsurface flow is generally 5 to 20 percent of total groundwater contribution and is dependent upon soil layer conductivity, slope, and the slope length. Based on SWAT Check outputs before the calibration step, a number of warnings were produced, including lateral flow being greater than the groundwater flow, and that surface runoff may be too low. Slope lengths were found to be very small, at 0.5 meters; slope length should generally be between 15 to 150 m (White et al., 2014). Short slope lengths reduce the time and distance for water to move downslope through the soil layers before contributing to streamflow as lateral flow. Low slope length also decreases water in the soil layer, creating a drier soil reducing the surface runoff. SLSOIL for all HRUs in the basin were changed to 15 meters before calibration to correct initial warnings in SWAT Check. The range for calibration, 15 to 150 meters was chosen based on SWAT documentation guidelines.

Base flow

ALPHA_BF

Base flow is the flow below the groundwater table that discharges to a stream and responds to the water table and stream gradients. There must be a downhill gradient for base flow to contribute to streamflow. If the water table is below stream level, then the groundwater will not contribute to runoff and there will not be baseflow contribution. The base flow alpha factor (1/days), measured as a constant, is the response of groundwater flow to changes in streamflow recharge. The constant ranges from 0.1 to 0.3 for slow response and 0.9 to 1.0 for quick response to recharge. Base flow alpha factor, also known as base flow recession, depends on the topography, geology, slope, vegetation, and drainage density of the watershed. Each of these factors will differ for each watershed and sub-basin. Small basins with steep hillslopes, shallow soils, high drainage density, and shallow aquifers can be expected to have small base flow recession constants. In the Puyallup River basin, there are mixed slopes, shallow and steep, and default values for soil depth, drainage density, and aquifer depth. From these values, ALPHA_BF was underestimated and needed to be increased in calibration. The full ALPHA_BF range, 0 to 1 was used, again due to a lacking of known observations in the basin.

GW_DELAY

Groundwater delay time is the time it takes in days for water to percolate from the vadose zone of the soil profile to the shallow aquifer. Properties that influence time of water transfer are the depth of the water table and hydraulic properties of soil layers. Within the saturated soil layers, layers with larger particle size will allow the percolation of water more quickly leading to high conductivity. Regions of low conductivity are layers with smaller particle size such as sand or clay, where water takes longer to move through layers. The Puyallup River basin soil composition is mostly sand, fine particulate size. Without knowing water table depth, low soil conductivity and basin location in the lowlands of the watershed indicated that the groundwater delay would be large, so upper bounds of the range were increased. Increasing GW_DELAY increases the time water takes to enter the shallow aquifer from the soil profile, decreasing the time for the water to contribute to streamflow.

GWQMN

The groundwater minimum depth in the shallow aquifer is the threshold (mm H_2O) that is required for base flow to return back to the reach. Base flow is the groundwater contribution to streamflow based on water table depth. As the groundwater minimum is increased, baseflow is decreased. The SURRGO database provided 1,000 mm H_2O groundwater depth for the Puyallup River basin; however, based on the differing soil types, the upper and lower bounds of the GWQMN were adjusted to find a more accurate measurement. Based on information provided by USGS for Thurston County groundwater station 465033122570202, groundwater depth from the 1980s to current has ranged between 10 to 40 feet below surface (roughly 3,000 to 12,000 mm). Thurston County is south of the study site and in the Puget Sound lowlands. No groundwater stations were available for Pierce County or the Puyallup River Watershed. The groundwater measurement ranges for this area, up to the 5,000 mm maximum, were used as a starting point for range adjustments during calibration.

RCHRG_DP

Recharge depth is the deep aquifer percolation fraction. The coefficient is the fraction of water from the root zone and shallow aquifer that percolates to the deep aquifer. The parameter ranges from 0.0 to 1.0. Water that reaches the deep aquifer layer is considered lost from the system; it was still calibrated for the Puyallup River basin as water can be pulled from the deep aquifer for irrigation purposes and return to the system later. SURRGO database defaults RCHRG_DP at 0.05, and range 0 to 1 was adjusted based of graphical representation from simulations. Without known or observed values, range adjustments based on simulations outputs were used.

REVAPMN

REVAPMN is the threshold depth of water in the shallow aquifer needed for percolation (mm H_2O) to occur into the deep aquifer. REVAPMN is the threshold depth where movement from shallow aquifer to the unsaturated zone cannot occur if the volume of the shallow aquifer is not greater or equal to REVAPMN. Increasing

REVAPMN changes the ease of flow of the groundwater system between layers and increases availability of groundwater to contribute to streamflow. The range used in calibration was the default range of 0 to 500 mm. Defaults range was used and later adjusted based out simulation output due to lack of known or observed measurement for the basin.

GW_REVAP

Groundwater “revap” coefficient refers to the movement of water from the shallow aquifer to the unsaturated zone that lies above. As evaporation and root uptake diminish water in the unsaturated zone, water is replaced by diffusion from the underlying aquifer. The type of vegetation influences the “revap” process and are significant in watersheds with deep-rooted vegetation. GW_REVAP ranges from 0 to 1. As GW_REVAP approaches 0, water transmission between layers is restricted and as GW_REVAP approaches 1, the rate of water transmission approaches the rate of potential evapotranspiration (PET). GW_REVAP for the Puyallup River basin was initially simulated at 0.02. A range of 0.02 to 0.2 was used for calibration as forested vegetation in the Puyallup River basin is deep rooted and may restrict transmission.

Snow Cover/ Snow Melt

Snow fall is stored as snow pack in SWAT. Precipitation is classified as snow fall when the average daily temperature falls below the set temperature range. When air temperature falls below this range, any precipitation is added to snow pack and referred to as snow water equivalent. SMFMX and SMFMN parameters impact the snow water equivalent by the temperatures at which snow can fall and melt for a sub-basin. The mass balance equation for snow pack is:

(Equation 3): $SNO = SNO + R_{day} - E_{sub} - SNO_{mlt}$

Snow pack is the amount/depth of snow that occurs over an area. SNO is the water content of the snow pack (mm H_2O) on a given day, R_{day} is the amount of precipitation (mm H_2O), E_{sub} is the amount of sublimation (mm H_2O), and SNO_{mlt} is the amount of snow melt (mm H_2O).

SFTMP

SFTMP is snowfall temperature (°C) where the mean air temperature will allow precipitation to fall as rain or snow/freezing rain. This temperature range should be between -5°C and 5°C. The default for SFTMP is 1.0. If the average daily air temperature is less than the range temperature, then precipitation for the HRU will be classified as snow and snow precipitation is added to snow pack.

SMTMP

SMTMP is snow melt base temperature (°C) where snow pack will not melt until snowpack threshold is met. This temperature should be between -5°C and 5°C. The default SMTMP is 0.50; however the full range of SFTMP was used in calibration to account for lowland temperature of snow melt, where the range is likely to be warmer for the Puyallup River basin due to low elevation. When calibrating sub-basins at higher elevations, such as around Mt. Rainier, this range may need further adjustment.

SNOCOVMX

SNOCOVMX is the minimum snow water content corresponding to 100 percent snow cover, $SNO_{100,}$ (mm H_2O). Snow cover will rarely be evenly distributed over an area, often leaving exposed bare ground. Ground exposure can influence snow melt through albedo effect. Snow water content below SNOCOVMX results in bare ground exposure. To compute snow melt, the fraction of this bare ground to snow cover has to be quantified. Snow cover is expressed as an aerial depletion curve where seasonal variability of snow pack is a function of current snow pack and snow melt factor. The depletion curve requires a snow depth threshold where there will always be 100 percent snow cover at SNO_{100}. Threshold depth is influenced by vegetation distribution, wind loading, wind scouring, slope, and aspect. Ranging from 0.0 to 1.0, the smaller SNO_{100}, or the less water content corresponding to snow coverage, the less of an impact on snow melt. If the water content exceeds SNO_{100} then the depth of the snow is considered uniform over the area, SNO_{100}=1.0. As SNO_{100} increases to 1.0, the more importance is put on snow melt processes and the more snow cover. Depending of the percent of SNO_{100}, or minimum water content needed for 100 percent coverage, the volume of snow required for full coverage varies. Usually the lower the SNO_{100}, the smaller the volume of snow needed for coverage. The lower the water content and volume of snow, the less important snow melt becomes. Snow coverage will have more importance at higher elevations and less importance at lower elevations as is the case of the Puyallup River basin. Ranges for snow water content were chosen from literature in similar study areas of the Pacific Northwest. Inclusion of this parameter for the Puyallup River basin could be questionable, as snow melt influence surface flows, but snow cover is minimal at these elevations.

SNO50COV

SNO50COV is the fraction of snow volume from SNOCOVMX that will be 50 percent snow cover. This fraction is assumed to be a nonlinear relationship between snow water content and snow cover. SNO50COV is also represented by an aerial depletion curve. Here the water content can be adjusted to find 50 percent of coverage from SNO_{100}. SNO50COV range varies from 0.01 to 0.99. Again, increasing snow water content increases the volume of snow necessary to increase the fraction of aerial coverage.

Snow melt is a linear function in SWAT calculated as the difference between average snow pack-maximum air temperature and the threshold temperature for snow melt. The snow melt equation:

(Equation 4): $$SNO_{mlt} = b_{mlt} \times sno_{cov} \times \left[\frac{T_{snow}+T_{mx}}{2} - T_{mlt}\right]$$

where SNO_{mlt} is the amount of snow melt (mm H_2O) on any given day, b_{mlt} is the melt factor (mm H_2O/°C-day), sno_{cov} is the fraction of area covered by snow, T_{snow} is the snow pack temperature (°C), T_{mx} is the maximum air temperature (°C), and T_{mlt} is the temperature above when snow melt occurs (°C). The b_{mlt} is seasonally determined and measured by the SMFMX and SMFMN parameters.

SMFMX

SMFMX is the snow melt factor on June 21st (mm H_2O/°C-day). June 21st is a standard indicator in watershed literature for the beginning of the summer season when snow melt begins. SMFMX and SMFMN vary the amount of snow melt to occur throughout the year and account for the impact of snow pack density on snow melt. As an example, in rural areas, the range of snow melt factor varies from 1.4 to 6.9 mm H_2O/°C-day while the range for urban areas varies from 3.0 to 8.0 mm H_2O/°C-day. The range increases in high density areas due to snow compaction from vehicles, pedestrians, and compaction on top of impervious surfaces such as asphalt. This parameter is not required in the SWAT model but was included for this watershed because of the significance of snowpack to river systems. The default of SMFMX is 4.5, but as the study site resides in the Northern Hemisphere, where heavier snowfall occurs and so the range of SMFMX was increased.

SMFMN

SMFMN is the snow melt factor on December 21st (mm H_2O/°C-day). December 21st is a standard indicator in watershed literature for the end of summer and the beginning of winter where snow fall starts to accumulate. Just as SMFMX above, SMFMN accounts for the impact of snow pack density on snow melt. Together with SMFMX, these parameters allow the rate of snow melt to vary seasonally throughout the year as described by the snow melt equation. For rural areas, SMFMN has a range that varies between 1.4 to 6.9 mm H_2O/°C-day and a range that vary between 3.0 to 8.0 mm H_2O/°C-day for urban areas. The default of SMFMN is 4.5, but as the study site resides in the Northern Hemisphere were snow fall is heavier and the range of SMFMN was increased.

TIMP

TIMP is the snow pack temperature lag factor. This accounts for the effect of previous day's snow pack temperature on the present day snow pack temperature. The lag factor accounts for snow pack density, depth, and temperature. The lag factor ranges from 0.01 to 1.0. As the factor approaches 1.0, the temperature from the previous days have less of an impact while the present day mean air temperature has a greater effect on snow pack temperature. The default setting for TIMP is 1.0, where previous day snow pack temperature had less impact. The full range was used for calibration of the Puyallup River basin to account for lack of known measurements.

Evapotranspiration

Evapotranspiration is the processes by which water on the Earth's surface in converted to water vapor and is the primary method that water is removed from a watershed. It is estimated that 62 percent of all precipitation goes through evapotranspiration and is greater than runoff in most watersheds (Dingman, 1994). Evapotranspiration estimates are critical in understanding how climate changes, such as increased temperature, will impact water resources. Evapotranspiration was represented in calibration with the use of the plant compensation factor (EPCO) and the soil evaporation compensation factor (ESCO).

EPCO

EPCO is the plant compensation factor. This factor is the amount of water that vegetation will uptake that is required by the plant for evapotranspiration, which varies daily and depends on water availability in the soil. The compensation factor ranges from 0.01 to 1.00. Depending on water availability in the layers, the closer to 1.0 the factor reaches the more the water demand must be met by lower layers in the soil. SWAT defaults to 1.0 for EPCO, calibration using SWAT-CUP began with range 0.01 to 1.00 and was adjusted based on simulation graphical outputs.

ESCO

ESCO is the soil evaporation compensation factor used to modify the depth of soil layers used to meet evaporation demand. ESCO ranges from 0.01 to 1.0, as the coefficient decreases, evaporative demand in the model can extract from lower soil layers. ESCO was set to 0.95 from the SURGGO database, leaving only an upper range increase of 0.05. During calibration the ESCO range was set to 0.01 to 1.0 and adjusted based on simulation graphical output.

3.5 Calibration and Validation

Calibration and validation were done using the Sequential Uncertainty Fitting 2 (SUFI-2) algorithm as part of SWAT-CUP. Developed by Abbaspour et al. (2004, 2007), SUFI-2 is a calibration algorithm that accounts for all sources of uncertainty in a model. These sources include uncertainties with parameters, driving variables such as precipitation, SWAT model execution, and observed data such as streamflow.

After the sensitive parameters were identified, calibration of the model aggregated daily observations to monthly averages for the time period of 1960 to 1979 with observed stream gage data near Orting, Washington. The 20-year time scale was chosen to account for wet and dry years that occur as part of the PNW regional variability, which is due to the inter-annual El Niño Southern Oscillation (ENSO) and inter-decadal Pacific Decadal Oscillation (PDO). The data range includes part of the cool phase that began in 1947 and ended in 1976 when a warm phase began in 1977. Monthly time steps for the years 1980 through 2007 were used for the validation of the model.

The NSE indicated how well the simulated and observed plot fit a 1:1 regression line. Fitting a 1:1 regression line describes the power of a hydrologic model to predict outcomes. Though there are no standardized acceptable ranges for these statistics, the closer the values approach 1, the better the model will perform at simulating predictions that closely match observed data.

The other measurement of simulation accuracy is the 95PPU in the graphical representation of the simulated flows versus observed. The 95PPU stands for the 95 percent prediction uncertainty or P-factor. The 95PPU measured how well the observed data fit into a 95 percent confidence range of uncertainty from the simulated output. R-factor measures the range of output uncertainty represented by the visual band. A well-calibrated model will have a small R-factor, represented as a thin 95PPU band that houses the observed measurements.

During the calibration process, the sensitive parameters were adjusted by trial and error to match the simulated streamflow to observed streamflow. For climate change scenario assessments, both low and high flows need to be captured by model simulations.

Having a baseline of hydrology characteristics is important as future climate shifts are expected to have drastic impacts on hydrograph peaks, future snow accumulation, and snow melt. For validation of the model, SWAT model was run with the calibrated input parameters. All input parameter ranges remained constant for validation of the 1980 to 2007 time series.

Table and Figures

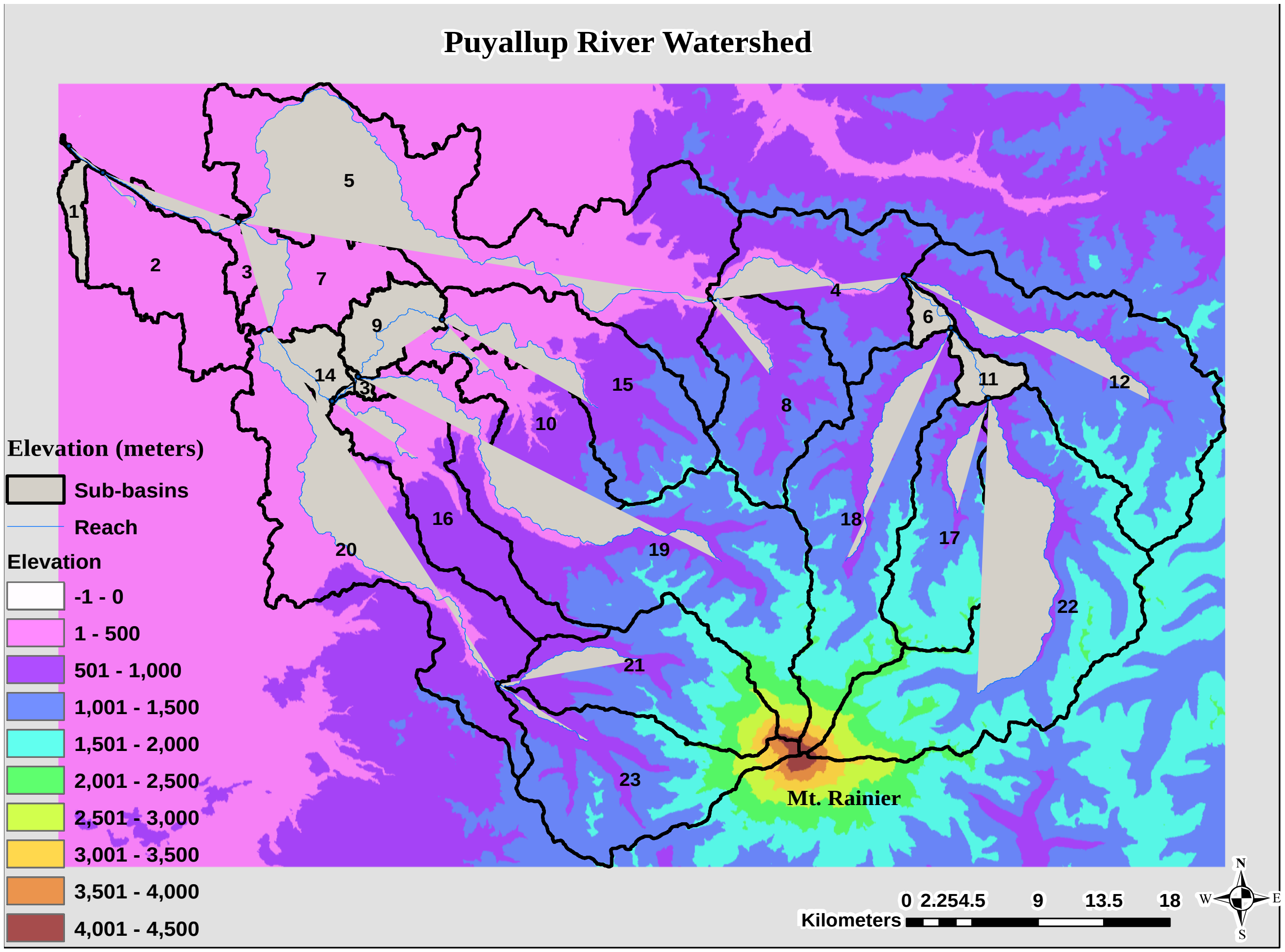

Figure 12. Puyallup River Watershed elevation map (meters) generated in SWAT using digital elevation maps (DEM) retrieved from USGS. Elevation ranges from sea level in the lower sub-basins to the top of Mt. Rainer approximately 4,800 meters (14,400 ft).

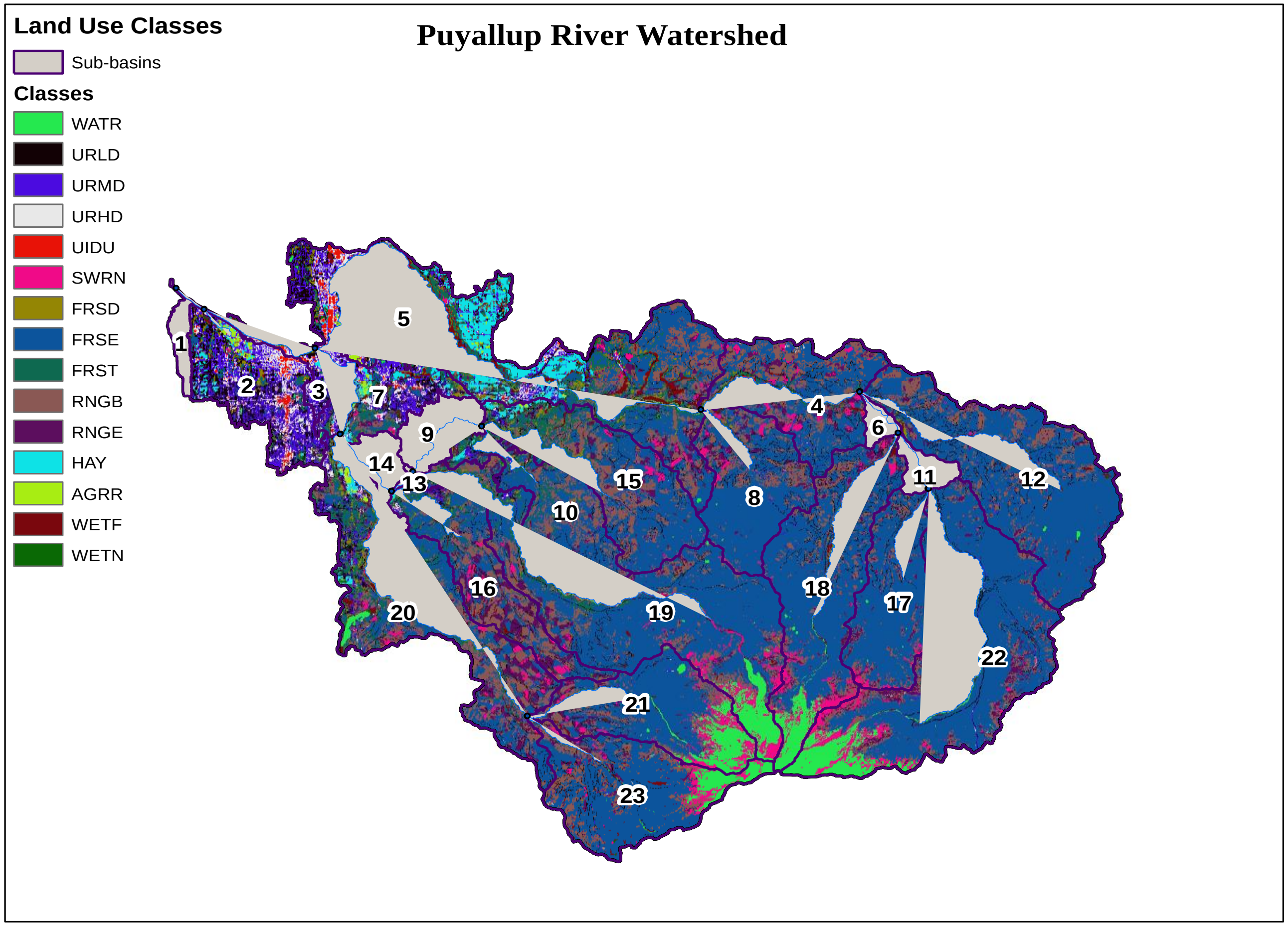

Figure 13. Land-use classes created in SWAT using National Land-use Cover Data (NLCD) 2011 retrieved from USGS. Classes: WATR=water, URLD= residential-low density, URMD- urban residential-medium density, URHD= residential-high density, UIDU=industrial, SWRN= arid rangeland, FRSD= forest-deciduous, FRSE= forest-evergreen, FRST= forest-mixed, RNGB= range-bush, RNGE= range-grasses, HAY= hay, AGRR= agricultural land-row crops, WETF= wetlands-forested, and WETN= wetlands-non-forested.

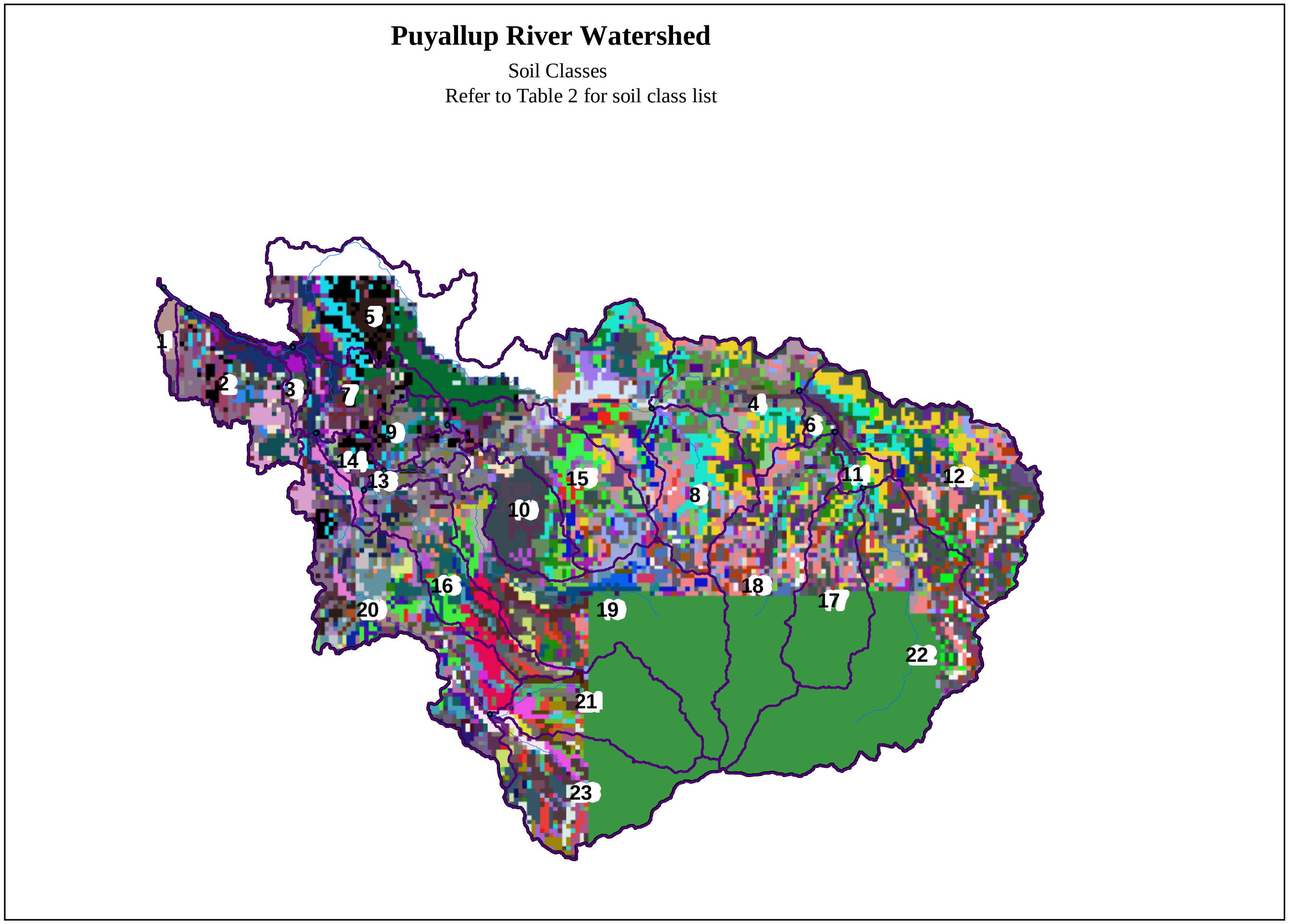

Figure 14. Soil classification created in SWAT using soil data from the Soil survey Geographic Database (SURRGO). 233 soil classes exist and are listed in Table 2 of the Appendix. 104 soil classes are found in the Puyallup River basin. The large green soil classification represents the portion of soil on and around Mt. Rainier that had no available digital data.

								Average Precipitation (mm)									
Station ID	**USGS ID**	**Latitude**	**Longitude**	**Elevation (m)**	**Annual**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
1	450945	47.17	-122.000	210	1234.6	156.7	125.1	116.2	103.3	83.9	75.3	32	42.5	64.8	109.1	176.4	153.7
2	455224	47.13	-122.267	177.1	1078.8	149.3	116	104.2	84.6	61.7	55.6	23.7	32.5	49.5	93.5	163.6	148.8
3	456803	47.20	-122.333	15.20	1043	152.4	117.3	102.7	78.1	52.5	45.9	20	29.8	45.6	91.1	160.7	151.1
4	453357	47.13	-121.633	47.45	1672.1	232.4	170.7	156.3	132.8	101.5	88.6	38.1	49.8	84.2	147.6	246.6	229.1
5	456385	46.92	-121.533	1068	1820.9	282.2	209	186.2	122.2	85	70.6	28.8	38.8	75	154.9	290.5	286.2
6	458278	47.25	-122.417	280.4	989.9	148.5	111.2	96.6	72.2	46.2	38.4	18.2	27.1	42.8	88.3	157.6	146.7
7	459171	46.90	-121.550	47.2	1888.9	291.5	215.7	192.3	127.1	90	71.8	29.6	40.8	78.3	159.9	301.3	298

Table 3. USGS weather stations. Daily precipitation (mm) observations were used as SWAT model inputs.

									Average Temperature (^{0}C)									
Station ID	**USGS ID**	**Latitude**	**Longitude**	**Elevation (m)**		**Annual**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
1	450945	47.167	-122.000	210	**Tmax**	15.6	7.4	9.7	11.6	14.7	18.3	21.1	24.6	24.6	21.5	15.6	10.4	7.5
					Tmin	5.1	0.5	1.3	1.9	3.6	6.3	9	10.5	10.5	8.5	5.4	2.7	0.8
2	455224	47.133	-122.267	177.1	**Tmax**	15.2	7	9.2	11.2	14.1	17.8	20.5	23.9	24	21	15.4	10.1	7.2
					Tmin	4.9	-0	0.6	1.7	3.4	6.2	8.9	10.5	10.7	8.4	5.1	2.2	0.4
3	456803	47.2	-122.333	15.2	**Tmax**	16.4	8	10	12.5	15.7	19.5	22.3	25.5	25.3	22.1	16.4	11	8.1
					Tmin	5.4	0.6	1.4	2.2	3.9	6.7	9.5	11	10.9	8.7	5.7	2.8	1
4	453357	47.133	-121.633	47.45	**Tmax**	13.1	4.1	6.5	8.6	11.9	15.9	18.9	22.6	22.5	19.7	13.8	7.5	4.3
					Tmin	3.1	-2	-1	-0.3	1.5	4.4	7.3	9.1	9	6.7	3.5	0.5	-1.5
5	456385	46.917	-121.533	1068	**Tmax**	11.5	2.7	4.7	6.3	9.7	13.9	17.6	22	21.9	18.6	12.3	5.7	2.9
					Tmin	1.5	-4	-3	-2.4	-0.4	2.5	5.6	8	8	5.6	2.1	-1.2	-3.2
6	458278	47.25	-122.417	280.4	**Tmax**	16.1	8.2	10	12.2	15.3	19	21.7	24.7	24.5	21.5	16.2	11.1	8.3
					Tmin	6.8	1.8	2.6	3.5	5.3	8	10.7	12.4	12.5	10.5	7.3	4.2	2.2
7	459171	46.9	-121.550	47.2	**Tmax**	11.2	2.3	4.3	5.9	9.4	13.6	17.3	21.8	21.7	18.3	12	5.3	2.4
					Tmin	1.3	-4	-3	-2.6	-0.6	2.3	5.4	7.9	7.9	5.5	2	-1.5	-3.6

Table 4. USGS weather stations. Daily temperature maximum and minimum (℃) were used as SWAT model inputs.

Chapter 4. Results

4.1 Watershed Delineation

Figures 12, 13, and 14 were produced from SWAT model setup. Figures represent digital elevation, land-use classification, and soil classification for the watershed and Puyallup River basin (sub-basin 20). DEM setup produced nine elevation ranges in 500 meter increments, from sea level to 4,500 meters (Figure 12). Land-use classification resulted in fifteen classes (Figure 13). The SURRGO database used for soil classification in SWAT resulted in 233 soil classes, 104 of which were listed in the Puyallup River basin (Figure 14). After the three-layer classifications, 5 HRUs were derived for the Puyallup River basin from unique combinations of slope, land-use, and soil type.

4.2 Sensitivity Analysis

The LH-OAT analysis highlighted the following variables as sensitive parameters for the watershed: initial SCS curve number for moisture condition II (CN2), maximum canopy storage (CANMX), threshold water depth in the shallow aquifer (REVAPMN), snowpack temperature lag factor (TIMP), slope length (SLSOIL), soil evaporation compensation factor (ESCO), saturated hydraulic conductivity (SOL_K), available water capacity (SOL_AWC), and deep aquifer percolation fraction (RCHRG_DP). P-values for all parameters, except CN2, were > 0.2. Parameters with a P-value greater than 0.2 should be considered for calibration (R. Srinivasan, personal communication, January 2015). CN2 was included in calibration, even with a p-value less than 0.2. This decision was made because CN2 had the highest t-stat rating of all parameters, t > 2.0. Though CN2 was not highlighted as significant for this particular sub-basin, the high sensitivity suggests the importance of CN2 in parameter interactions. P-value and t-Stat are represented in Figure 16 for each parameter. From the sensitivity analysis fifteen parameters were highlighted for suggested use in calibration.

The literature suggests that snowfall and snow melt parameters should also be considered for a snowpack dominated watershed. As such, a total of 21 model input parameters were chosen for calibration based on sensitivity analysis and literature review of SWAT model applications in snowpack dominated watersheds of the Pacific Northwest (PNW). These parameters were broken into surface flow, baseflow, snow cover/snow melt, and evapotranspiration categories in Table 8.

Table 9 describes the sensitive parameters and function with initial simulated SWAT estimates, acceptable ranges for calibration, and ending calibration ranges. Initial SWAT estimates were a result of initial simulations following data input. Acceptable ranges for calibration were compiled from the literature and SWAT theoretical documentation. Calibration ranges were the ranges that produced the best calibration results for this thesis based on statistical outputs. The calibration ranges listed in the final column of Table 9 should be used with caution as the calibration step needed to be revisited, as discussed later. The acceptable ranges for parameters can also be relative or absolute. Relative ranges are listed as 0-1 and represent a percentage range or adjustment, 1 to 100 percent. Absolute parameter ranges can only be adjusted or replaced within the bounds of the range listed in Table 9.

Most initial simulation ranges fell into acceptable parameter ranges. REVAPMN was initially simulated at 750 mm; the acceptable range was 0-500 mm. REVAPMN addresses the availability of groundwater to contribute to streamflow by setting the threshold depth in the shallow aquifer. In the instance of initial simulation, the shallow aquifer would have to meet a minimum depth of 750 mm to contribute to streamflow. This parameter was overestimated in initial simulation and was adjusted to occur below 100 mm for threshold depth.

Parameter Category	Parameter	Parameter Description
Surface Flow	CANMX	Maximum Canopy Storage
	CN2	Curve Number for Moisture Condition II
	SOL_AWC	Soil Water Capacity
	SOL_K	Saturated Hydraulic Conductivity
	SURLAG	Surface Runoff Lag Coefficient
	SLSOIL	Slope Length
Baseflow	ALPHA_BF	Baseflow Alpha Factor
	GW_DELAY	Groundwater Delay
	GWQMN	Threshold Water Depth in the Shallow Aquifer
	RCHRG_DP	Deep Aquifer percolation fraction
	REVAPMN	Threshold Water Depth in Shallow Aquifer for "revap"
	GW_REVAP	Groundwater "revap" Coefficient
Snow cover/Snow melt	SFTMP	Snowfall Mean Air Temperature
	SMTMP	Snow Melt Mean Air Temperature
	SNOCOVMX	Snow Water Equivalent for 100% Snow Cover
	SNO50COV	Snow Water Equivalent for 50% Snow Coverage
	SMFMX	Snow Melt Factor on June 21st
	SMFMN	Snow Melt Factor on December 21st
	TIMP	Snow Pack Temperature Lag Factor
Evapotranspiration	EPCO	Plant Compensation Factor
	ESCO	Soil Evaporation Compensation Factor

Table 8. Twenty-one parameter and parameter descriptions used during calibration. Parameters were divided into four categories: surface flow, baseflow, snow cover/snow melt, and evapotranspiration.

Parameter	Description	Initial Range	Acceptable Range	Calibration Range
CN2	Initial SCS CN II value	55-61	35-98	54.1-79.3
SOL_AWC	Available water capacity (mm H_2O/mm soil)	25-250	0-1	80-110
SURLAG	Surface runoff lag time (days)	2	0.05-24	10-15
SLSOIL	Slope length (m)	100	0-150	50-60
CNMAX	Maximum canopy storage (mm)	0	0-100	0-100
ALPHA_BF	Base-flow alpha factor (days)	0.0275	0-1	0-0.5
GW_DELAY	Groundwater delay (days)	31	0-500	300-350
GWQMN	Threshold water depth In the shallow aquifer for flow (mm)	1000	0-5000	400-500
RCHRG_DP	Deep aquifer percolation fraction	0.05	0-1	0-0.2
REVAPMN	Threshold water depth in the shallow aquifer for "revap" (mm)	750	0-500	20-30
GW_REVAP	Groundwater "revap" coefficient	0.02	0-1	0.02-0.20
EPCO	Plant uptake compensation factor	1	0-1	0-0.3
ESCO	Soil evaporation compensation factor	0.95	0-1	0-0.2
SMFMX	Snow melt factor on June 21 (mm H^2O/°C-day)	4.5	0-20	3-7
SMFMN	Snow melt factor on December 21 (mm H^2O/°C-day)	4.5	0-20	2-5
SNOCOVMX	Minimum snow water content for 100% snow cover (mm H^2O)	N/A	0-500	450-500
SNO50COV	Minimum snow water content for 50% snow cover (mm H^2O)	N/A	0-1	0-1
SFTMP	Snow fall base temperature (°C)	1	-20 to + 20	0-5
SMTMP	Snowmelt base temperature (°C)	0.5	-20 to + 20	-5 to +5
TIMP	Snowpack temperature lag factor	1	0-1	0.5-1
SOL_K	Saturated hydraulic conductivity (mm/hr)	32, 100	0-2000	30-150

Table 9. Calibration parameters for the Puyallup River basin (sub-basin 20) of the Puyallup River Watershed. Parameter, parameter description, initial estimates, acceptable parameter range, and ranges used in calibration are listed. Initial range estimates are a result of SWAT model simulation from provided input data. Some initial ranges were not listed as noted by "N/A" and were added during calibration. Ranges can be relative or absolute. Relative ranges, represented as 0-1, result in multiplying initial values by a percent. Absolute ranges represent value replacement between the upper and lower bounds during calibration. Most initial simulation ranges, excluding REVAPMN, occurred in the acceptable parameter ranges.

4.3 Calibration/Validation

Calibration included observed streamflow measurements from the Puyallup River for the years of 1960 to 1979, whereas validation used years 1980 to 2007. Final simulated streamflow statistics for the Puyallup River were NSE=-0.01, R^2=0.45 and NSE=0.39, R^2=0.57 for calibration and validation respectfully. The final simulation improved from the initial values of R^2=0.35 and NSE=-3.79. Both calibration and validation included all 21 parameter inputs. Visual representation of simulated outputs for calibration and validation are represented in Figure 17 and Figure 18. Simulations used observed streamflow measurements from the Puyallup River at Orting, Washington.

The calibration/validation figures showed that the model did not reproduce historical data well. Overall, streamflow was underestimated in the calibration step. Calibration especially underestimated peak flows in the winter of 1960/61, spring of 1964, winter of 1964/65, spring peak of 1974, and spring peak of 1975. CN2, GWQMN, ESCO, RCHRG_DP, GW_REVAP, GW_DELAY, and SLSOIL parameter adjustments were able to produce the best calibration results. Increasing parameter values for CN2, RCHRG_DP, GW_DELAY, and ESCO influences simulation outputs by increasing surface runoff, increasing deep aquifer recharge, increasing the time water resides in the soil layers before entering the shallow aquifer, and decreasing evaporation. Decreasing GWQMN, and GW_REVAP parameter ranges influenced simulations through increased baseflow, and increased water transfer from shallow aquifer to soil layers allowing for an increase in baseflow. These parameter adjustments increased baseflow and total streamflow yeild estimates. The progression of calibration trials can be seen in Figure 15. As each set of parameters was adjusted, simulations became more accurate as described by simulation statistics. Baseflow was not underestimated uniformly during calibration. From years

1960 to 1969, baseflow was more underestimated when compared to the later decade of 1970 to 1979.

Simulations using calibrated parameter ranges for validation produced more accurate simulations. Validation simulations more closely resembled observed streamflow producing a larger R^2. Accuracy differences in simulations are likely due to more complete streamflow readings from gaging stations in later years that were used in the validation stages and timescale influence. The validation time series is closer to input data time series such as the land-use change input maps. The observed streamflow values in the calibration time series had more "extreme" peaks, many ranging between 30 to 40 m^3/s. Many validation time series peaks were below 30 m^3/s and could account for the better R^2 value during validation. Underestimation still occurred in validation but simulated streamflow was closer to observed streamflow peaks. Underestimated peaks occurred in the fall of 1980, spring of 1981, the summer melt of 1983, spring of 1985, winter of 1990/91, winter of 1996, spring of 2001, and fall of 2004. However, peak streamflows were simulated more accurately in the winter of 1982, winter 1984, winter of 1998, and winter of 2002.

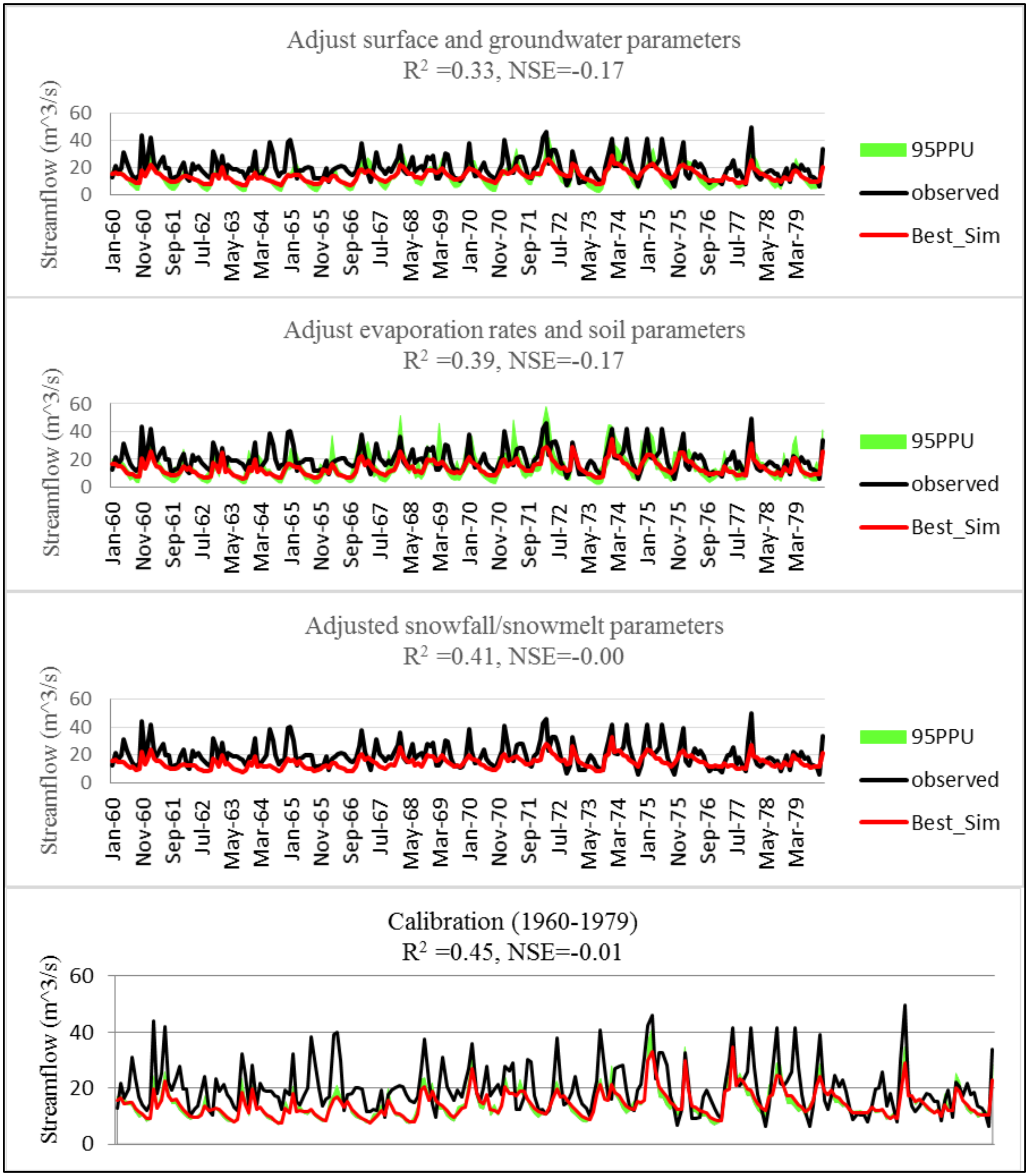

Figure 15. Progression of parameter adjustments for calibration. Parameter adjustments change simulation output, represented in red, to better represent observed streamflow, represented in black, within the bounds of the 95PPU represented in green.

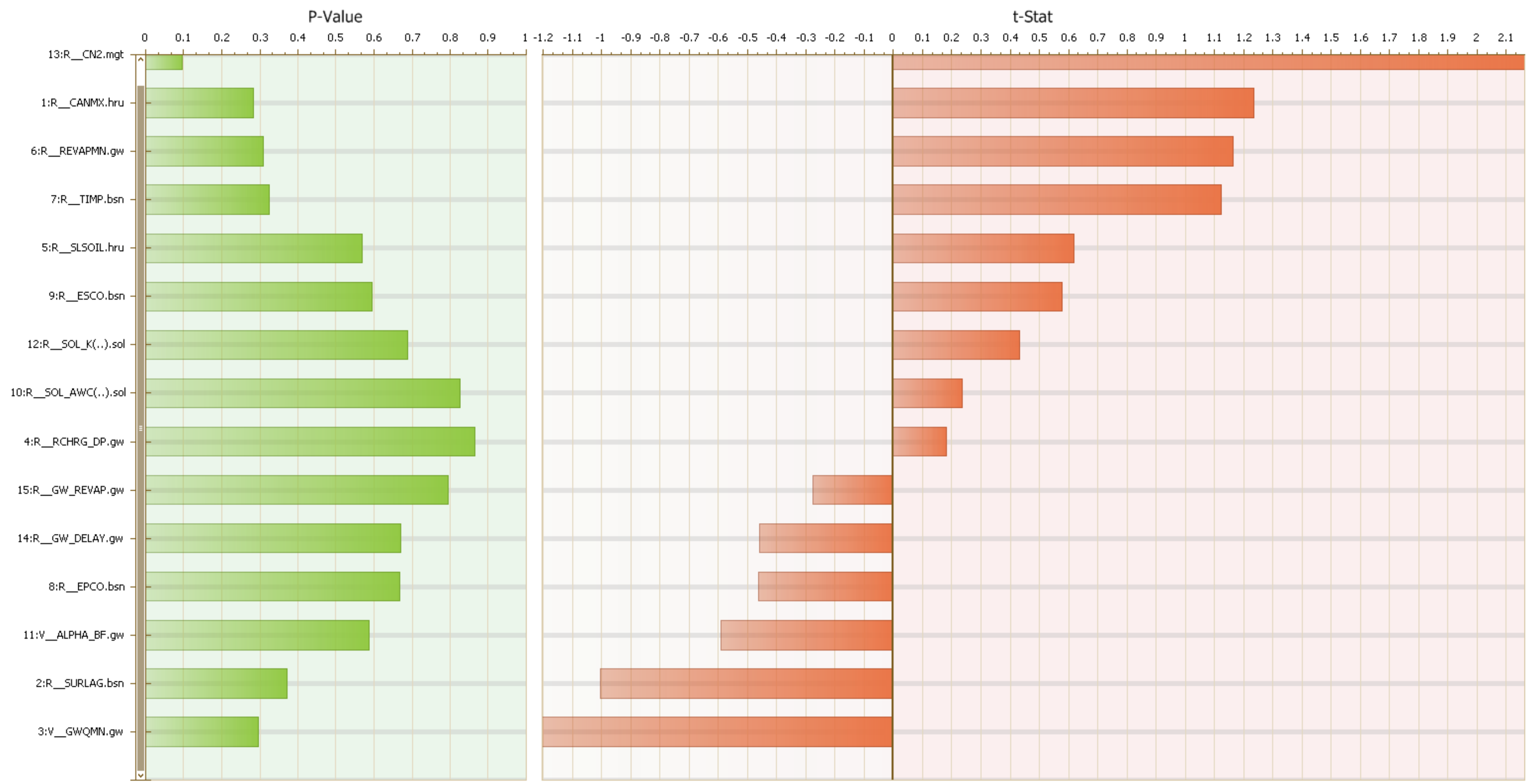

Figure 16. Graphical output of the global sensitivity analysis using LH-OAT provided by SWAT-CUP. Parameters are listed on the y-axis with corresponding P-value and t-Stat on the x-axis. Larger t-Stats indicate more sensitivity. Larger P-values indicate significance of the parameter to the system. The most sensitive parameters are CN2 (t=2.16), CANMX (t=1.24), REVAPMN (t=1.16), TIMP (t=1.12), SLSOIL (t=0.62), ESCO (t=0.58), SOL_K (t=0.43), SOL_AWC (t=0.24), and RCHRG_DP (t=0.18). All the parameters except CN2 had a p>0.2, a threshold for inclusion as suggested by the literature.

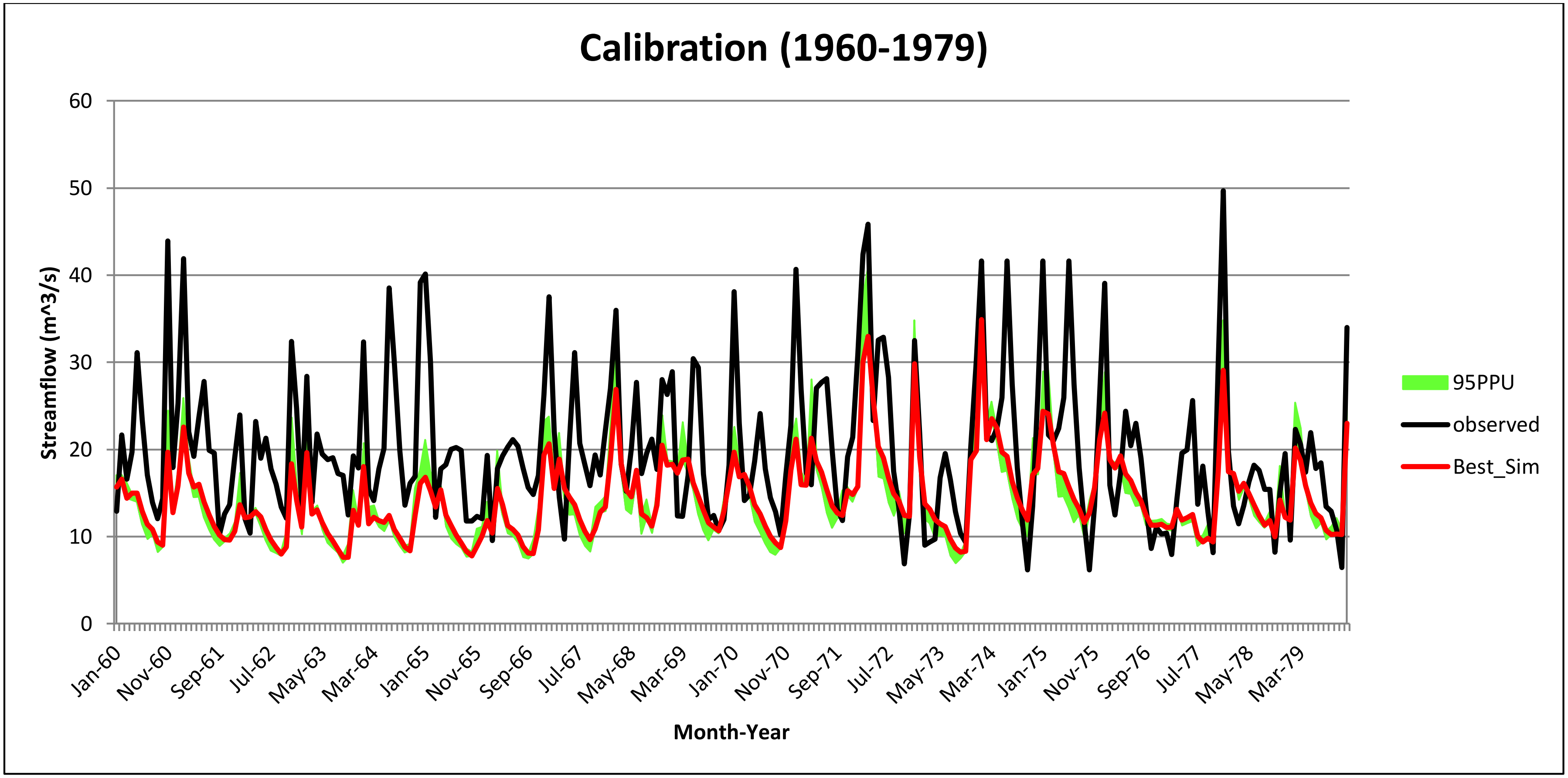

Figure 17. Parameter calibration for the Puyallup River basin of the Puyallup River Watershed, time period 1960-1979, as expanded from Figure 15. The solid black line represents observed streamflow of the Puyallup River, red represents the simulated streamflow after parameter adjustments, and 95PPU represents the 95% prediction uncertainty. R^2= 0.45 and NSE= -0.01. Simulated streamflow was underestimated for peak streamflows.

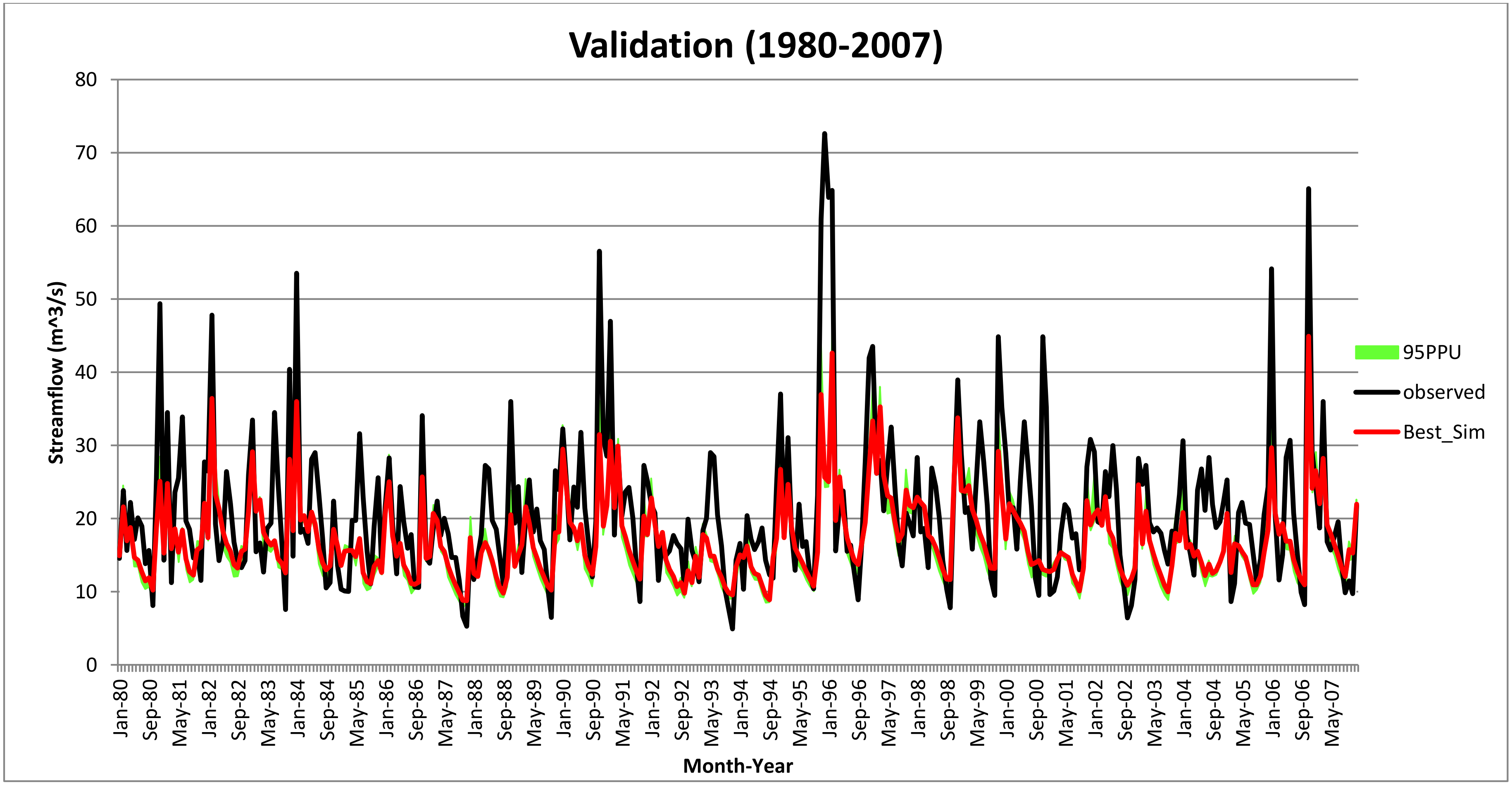

Figure 18. Parameter validation for the Puyallup River basin of the Puyallup River Watershed, time period 1980-2007. Validation used parameter ranges from calibration. The solid black line represents observed streamflow of the Puyallup River, red represents the simulated streamflow after parameter calibration, and 95PPU represents the 95% prediction uncertainty. R^2*=0.57 and NSE=0.39.*

Chapter 5. Discussion

Calibration/Validation

Overall, the SWAT simulations for the Puyallup River Basin did not produce accurate streamflow output during the calibration or validation steps of the SWAT model. Streamflow was underestimated during model calibration likely due to model assumptions, lack of complete soil survey data, and the use of a mountainous snowpack watershed. Historically SWAT model application has occurred in agricultural type watersheds for management assessments. Literature was limited for SWAT applications in snowpack dominated watersheds of the Pacific Northwest and Puget Sound region, but SWAT was successfully implemented for two watersheds in the neighboring state of Idaho. The Puyallup River basin results were less than satisfactory, producing R^2 and NSE statistics <0.70, in comparison to the Idaho watersheds and SWAT literature. The unsatisfactory calibration results can be attributed to model assumptions regarding groundwater interactions, scarce soil data, and orographic effects of a mountainous region, particularly the windward verse leeward influence of the Cascade Mountain range.

Idaho Watershed Comparisons

In Reynolds Creek Experimental Watershed (RCEW) Idaho, calibration and validation of three sub-basins performed well, producing simulation statistics greater than 0.07 (Sridhar and Nayak, 2010). Table 10 displays calibration and validation statistics for the RCEW, the Spokane River basin, and the Boise River basin of Idaho (Jin and Sridhar, 2012). The secondary Idaho study was included to support successful SWAT implementation in Washington State, as the Spokane River basin extended into the eastern portion of Washington State. Simulations of the Spokane River basin in Washington were able to produce acceptable calibration results, R^2 and NSE values greater than 0.07. The Spokane River basin was similar to the Puyallup River basin in that streamflow originated from an elevation greater than 1,000 meters and settled in lowlands less than 600 meters. The Idaho studies are important for this thesis in that the Idaho streamflow assessments using SWAT supports the success of calibration and validation in a snowpack dominated watersheds of the Pacific Northwest. However, it is important to note that the Idaho watersheds occurred on the eastern side of the Cascade Mountain range.

Orographic Effect

The Cascade Mountain range creates regional barriers between the maritime climate along the western coast line and the drier climate on eastern leeward side of the Cascade Mountain range. The orographic effects of the Cascades are depicted in Figure 19 and Figure 20, highlighting the contrast of precipitation rates on the western and eastern side of the mountain range. Idaho watersheds received considerably less annual precipitation on the eastern side of the mountain range in comparison to the Puget Sound region on the western side of the mountain range. The dramatic contrast in monthly and annual precipitation could have been a barrier for calibration of the SWAT model on the western maritime side of the mountain range as the extreme seasonal precipitation events were not well represented in simulations.

Though this barrier is not explicitly stated in the literature, simulations during calibration could be impacted by influences of orographic effects on soil moisture and baseflow contribution driven by precipitation and evaporation rates. Streamflow has been found to be less impacted by soil moisture and baseflow contribution on the eastern side of the Cascade Mountains due to the reduced rate of precipitation and drier climate (Stratton et al., 2009; Jin and Sridhar, 2012). The drier climate and increased temperature range east of the Cascades drive the evaporation rate to be more water limited than energy limited. The water limitation factor allows for soil moisture and baseflow being less sensitive to temperature fluctuations driven by climatic change (Tohver, Hamlet, & Lee, 2014). The western side of the mountain range has a higher precipitation rate with an evaporation rate that is energy limited (Tohver, Hamlet, & Lee, 2014). Therefore soil moisture and baseflow contribution will have a larger effect on streamflow yield and more likely to be influenced by climatic change. From these observations, the sensitive soil moisture and baseflow components could have increased difficulty of calibration in the Puyallup River basin because of higher precipitation events seen in a maritime climate.

5.1 Underestimated Flow

Model Assumptions

Streamflow was underestimated in multiple trials of the Puyallup River basin calibration process. The uneven distribution of baseflow to total streamflow yield could be influenced by land-use change that occurred during the 1970s. Other studies have found that underlying model assumptions attributed to underestimated flow outputs (Xu et al., 2013). The SWAT water budget equation excludes water obtained in the deep aquifer layer through percolation. For modeling purposes, exclusion of deep aquifer water is due to the complexities of groundwater interactions. SWAT assumes water entering the deep aquifer does not diffuse back into the shallow aquifer layer to which water could then contribute to total streamflow yield as return flow. This assumption has not been an issue in SWAT application literature occurring in agricultural settings, where precipitation rates resemble those found in eastern Washington.

However, the Puyallup River basin sensitivity analysis found groundwater parameters significant in baseflow interactions, including percolation from the deep aquifer layer, which does not align with SWAT model assumptions. Significant baseflow parameters include threshold water depth in the shallow aquifer for "revap" (REVAPMN), deep aquifer percolation fraction (RCHRG_DP), groundwater "revap" coefficient (GW_REVAP), groundwater delay time (GW_DELAY), and threshold water depth in the shallow aquifer for flow (GWQMN). Due to SWAT model assumptions, model simulations do not accurately represent baseflow contribution to total streamflow during storm events (Sanadhya, Gironas, & Arabi, 2014; Ahl et al., 2008) as deep aquifer percolation is not included in the SWAT water equation but was deemed significant in the sensitivity analysis. Low baseflow contribution is seen in Figure 17 simulation during winter months when storm flows are high from surface runoff. However, baseflow contribution is low in the summer months as when baseflow contribution rate should increase during times of low precipitation. For forested mountainous regions like the Puget Sound lowlands, streamflow inputs typically originate from groundwater contribution and lateral flow from the shallow aquifer (Bachmair and Weiler, 2011), but this was not represented in the calibration output. Without accurate baseflow representation, simulations are more likely to be underrepresented.

Model assumptions, sensitive groundwater parameters, and the under representation of baseflow in the calibration output led to the use of Baseflow Filter Program. Baseflow Filter Program, as described by Arnold et al. (1995) and Arnold et al. (1999), estimated baseflow contribution and groundwater recharge using streamflow records. Implementing daily streamflow data from the Puyallup River during the calibration timescale (1960 to 1979), baseflow contribution to total streamflow for the Puyallup River was estimated to be 66 to 76 percent for total streamflow yeild during the calibration time period. The high contribution of baseflow and the underlying SWAT assumptions could contribute to underestimated streamflow during calibration. Use of the Baseflow Filter Program or an alternative like it, were not typical in the SWAT literature and therefore not implemented in this thesis. Baseflow and groundwater contribution to a system is based upon geographic components and climatic influences (Winter et al., 1998). Contributions to a stream can be based on depth of aquifer layers, slope of streambanks and underlying groundwater flow systems (Winter et al., 1998). Contributions are also climatically driven as certain parts of a stream may only receive groundwater contributions during low or high precipitation periods (Winter et al., 1998). Understanding the groundwater interaction and baseflow contributions in the Puyallup River basin would have help in estimating seasonal streamflow yields. Upon reflection, future research should include a Baseflow Filter Program to understand the baseflow contribution and verify the significance of groundwater parameter importance.

Surface flow was also underestimated during calibration as evident in the peak flow times occurring in winter and spring months. Winter peak flows included heavy precipitation events while spring peak flows are a combination of precipitation and spring snowpack melt. These peaks are underestimated in SWAT simulations most likely from a combination of factors that will be touched on here and discussed in further detail below. These factors include low baseflow contribution assumption in the model, heavy precipitation events that occur annually in the PNW, and the addition of spring snowmelt. The extreme winter precipitation rates of western Washington are reflected in the observed measurements but are not reproduced in simulation outputs. To remedy observed and simulated streamflow yeild discrepancy, baseflow and surface flow should be calibrated separately for snowpack dominated watersheds and areas with orographic influences. The majority of the existing SWAT literature does not address this concept and therefore it was not applied in this thesis but should be implemented for future research.

Soil

Underestimated streamflow simulations also stem from the poor soil survey data around Mt. Rainier. County level soil surveys were combined with SURGGO database to increase coverage of the Puyallup River Watershed. Detailed soil data was missing from a large portion of the watershed including the surrounding area of Mt. Rainier as evident in Figure 14 where the large green soil classification around Mt. Rainier represents no available digital data. Glacial melt and subsurface headwater interactions take place in the data scale region and were therefore not accurately represented in the soil database as discovered post-simulation. Capturing headwater interactions are important in the

Puyallup River Watershed as Puget Sound lowland headwater channels are sensitivity to the changes in hydrology (Buffington et al., 2003) and are influenced by glacial melt and sediment interactions. Further, the SURGGO database did not include detailed sediment or subsurface soil properties including glacial alluvial deposits in the lowlands of Puget Sound. Alluvial glacier deposits were not addressed as an important interaction in the sensitivity analysis due to a lack of detailed soil data. Parameter CH_KI accounts for the effective hydraulic conductivity of tributary channel alluvium, or the speed to which water can move through soil layers in smaller channels of alluvial deposits. From work produced by USGS (1998), it is known that the geologic characteristics of glacier processes in the Puget Sound influence aquifer interactions, including alluvial deposits. The absence of CH_KI in the sensitivity analysis suggests that the lack of detailed soil data down plays the interaction of subsurface properties and groundwater contribution to total streamflow.

Effects of poor detailed soil data was documented by Sanadhya, Gironas, & Arabi (2014) in a snowpack dominated watershed of Colorado, where the lack of soil data affected success of model calibration. The Colorado study found SOL_K, hydraulic conductivity of soil, and ALPHA_BF, base flow recession constant, to be the most important parameters influencing streamflow (Sanadhya, Gironas, & Arabi, 2014). The same parameters where highlighted in the Puyallup River basin sensitivity analysis and indicate the movement of water through the soil layers and groundwater contribution to be significant in total streamflow for snowpack dominated systems (Sanadhya, Gironas, & Arabi, 2014). Without detailed soil data, or with missing soil data, SOL_K initial parameter ranges will not be accurately represented as soil layer properties and characteristic determine the parameter range. Field verification may be necessary for snowpack dominated sites as government databases are more likely to input default values for data scarce regions, such as the area around Mt. Rainier.

Snowfall

The relationship between elevation, snow fall, snow accumulation, temperature gradients, and snow melt in a mountainous landscape may also play a role in underestimated streamflow during calibration. Since initial development, SWAT snowfall and snowmelt algorithms have evolved to more accurately portray the contribution of snow parameters to total streamflow (Fontain et al., 2002). Puyallup River basin peak streamflow events are greatly influenced by subsurface parameters, snow parameters, and the interaction between snow processes and groundwater. Sensitivity analysis indicated snowmelt, groundwater recharge, and groundwater interactions as significant and relevant processes for this snowpack dominated watershed. Other snowpack dominated watersheds are consistent in highlighting these parameters as influential in these systems (Sanadhya, Gironas, & Arabi, 2014; Sridhar and Nayak, 2010).

Model setup lacked detailed time series data beyond temperature and precipitation inputs to depict snow parameters. Snow melt and snow fall was calculated in SWAT through air temperature adjustments, but these variables are also influenced by dew point temperature, wind movement, and solar radiation. SWAT simulated these additional parameters, but would have benefited from observed data inputs. Snow melt factor on June 21st, SMFMX, and snowmelt factor on December 21st, SMFMN, are two parameters dependent on more than air temperature. Snow density and snow water content also influence snow melt, but were not included as model inputs or highlighted in the initial sensitivity analysis. Observed snowmelt and snowfall inputs are obtainable through national snowpack telemetry stations (SNOTEL) provided by the Natural Resources Conservation Service through the U.S. Department of Agriculture. However, these stations were not implemented prior to 1980 and were not used during calibration or validation. SNOTEL site 679 would be beneficial for the Puyallup River basin and is located on Mt. Rainier at 1,564 meters (5,130 feet) elevation. SNOTEL site 679 collects precipitation, snow depth, snow water equivalent, and temperature observations. Using observed data from a SNOTEL site would have narrowed input ranges for snow melt and snow cover parameters needed for SWAT simulation. Snow parameters were not included in the initial sensitivity analysis of the Puyallup River basin because the sub-basin outlet resided at a low elevation range. Snow parameters were included in calibration due to headwater origins at higher elevations and as suggested by SWAT literature. Calibration should have begun at headwater origin and progressed toward the watershed outlet one sub-basin at a time but did not occur due to data scarcity of soil data. For these reasons, the Puyallup River basin was chosen as an initial calibration site to assess SWAT implementation.

Elevation bands impact snow parameters and were defined at watershed level as suggested by Cuo et al. (2011). After further investigation, for a snowpack dominated watershed such as the Puyallup, elevation bands should be defined at sub-basin level and include a lapse rate calculation (Sanadhya, Gironas, & Arabi, 2014). Lapse rates represent the temperature and precipitation gradients of increasing elevations in mountainous regions and define the rate at which temperature decreases with increasing elevation. Snowmelt and snow accumulation processes are sensitive to slight temperature changes at higher elevations (Sanadhya, Gironas, & Arabi, 2014). The sensitivity of snow parameters to temperature gradients warrant lapse rate at each elevation band, per sub-basin, and should be simulated at a daily time step instead of an aggregated monthly time step to capture climate sensitivity. Lapse rates can be determined by fitting a linear regression model to annual precipitation and mean annual temperature against observation station elevation. The rate of increase can then been manually incorporated into SWAT model set up for each elevation band in each sub-basin. This was not done for this thesis as only one study in the literature review suggested the use of an externally generated lapse rate for elevation bands. Detailed snow parameter inputs from SNOTEL stations and externally generated lapse rate should be included in future research for the calibration of snow parameters.

Sensitivity Analysis Type

The parameter sensitivities found in snowpack dominated watershed heavily rely on baseflow, subsurface, and snow processes interactions. As mentioned previously, certain parameters were not highlighted in the Puyallup River basin sensitivity analysis. Parameter sensitivities could have been overlooked due to lack of soil data, poor elevation band definitions, or lack of snow processes inputs. These parameters could have also been overlooked due to the chosen method for sensitivity analysis, the Latin-Hypercube-One-Factor-at-a-Time (LH-OAT) analysis provided by SWAT-CUP, which assesses the response of total streamflow to changes in various parameters.

The use of a variance-based global sensitivity analysis method could better represent the parameter interactions of a snowpack dominate watershed (Sanadya, Gionas, & Arabi, 2014) than the sensitivity analysis employed here. Sanadya, Gionas, & Arabi (2014) found that the monthly pattern and timing of peak flows in the hydrograph were more informative when investigating a snowpack dominated watershed than total annual streamflow yeilds. Streamflow pattern and timing better represents snow melt and subsurface parameter interactions due to sensitive in slight temperature and elevation gradients. Monitoring change in timing of peak flows are better indicators of parameter interactions than monitoring total streamflow yeild. From this observation, use of the LH-OAT in SWAT-CUP, may have missed key parameter interactions by focusing on total flow outputs. For a watershed with high seasonal and annual flows, when compared to annual flows of neighboring Idaho watersheds, the extreme winter precipitation combined with the high baseflow contribution could be viewed as outlier events in an LH-OAT analysis. Shifting focus during the sensitivity analysis to include only months with peak seasonal flows, such as winter and spring, could reduce the appearance of outlier events and reveal snow parameter processes on streamflow.

Through the investigation of analysis methods, Sanadhya et al. (2014) also found that the model output and type of statistical measurement influences the importance put on parameter interactions. Subsurface parameter interactions had greater influence on simulated month streamflow output when the Nash-Sutcliffe efficiency (NSE) coefficient was used (Sanadhya et al., 2014). Snow, groundwater, and subsurface parameter interactions had more influence on simulated monthly sreamflow outputs when coefficient of determination (R^2) and the root mean square error (RMSE) were used

(Sanadhya et al., 2014). Excluding NSE and incorporating RMSE as a method for streamflow measurement would shift the focus to pattern and timing of peak flow in the hydrograph instead of total flow output. Sanadhya et al. (2014) found this method more effective for streamflow simulations in a snowpack dominated watershed. As a relatively new finding, R^2 and NSE were the standard in the SWAT literature and were followed in this research; however, RMSE could be included, but should not replace NSE in future work.

NSE assesses the predictive accuracy of model outputs to observed data. The best calibration results from the Puyallup River basin produced an NSE of -0.01. Though parameter ranges could have continued to be adjusted to increase NSE, an NSE less than 0 indicated that the observed mean of the calibration data (1960 to 1979) was a better predictor of streamflow than the model simulations by incorporating peak winter flows. NSE has been used in the hydrologic model literature to assess model simulated streamflow compared to observed data. However, NSE is sensitive to extreme values or outliers. The sensitivity of snowpack dominated watersheds to changes in temperature produce extreme spring and winter streamflow peaks in a snowpack dominated system, this is common in the PNW. Based on the nature of snowpack dominated peak timings and the findings from Sanahya et al. (2014), using RMSE to focus of the timing and pattern of peak flows would have better represented snowmelt processes and interactions.

Additional Influences

Upon further reflection, other challenges in the SWAT model setup could have contributed to calibration issues. The quality of the input data, specifically precipitation and measured streamflow, could influence calibration. Multiple years of precipitation data had missing observations in some months. Missing data was simulated in SWAT using regression analysis, as was suggested in the SWAT literature as a troubleshooting method. Extreme winter flows could have amplified the missing observations and accounted for some of the under representation of simulated streamflow in the early station data for months with high seasonal flows; winters of 1960/61 and 1964/65.

Land-use data could have also accounted for calibration errors. The 2011 National Land Cover Data map used in model set up may not accurately represent land-use classifications that occurred during the calibration time period. The Puyallup River has been heavily influenced by irrigation practices, man-made alterations, and municipal storage facilities post-1960s. Most notable are the Mud Mountain Dam construction in the 1940s, logging activities from the 1940s to the 1970s, and channelization projects that were completed in the 1970s (Kerwin, 1999). Though not suggested in the SWAT literature, calibration time series should have used data closer to the 2011 land-use data. Perhaps validation (1980 to 2007) and calibration (1960 to 1979) time series should have been switched to better represent land-use impact on streamflow at the HRU level. Though not explicitly stated, the Idaho case studies seemed to follow this logic as calibration occurred during years 1997 to 2006 and validation time periods included years 1960 to 1979.

5.2 Moving Forward (Recommendations)

Had the calibration of SWAT simulations been successful for the Puyallup River basin, climate change scenarios would have been implemented to simulate future streamflow. Evidence provided by Mantua, Tohver, and Hamlet (2010) show that snowpack dominated watersheds in the Puget Sound area are currently and will continue to transition from snow to rain dominate basins. Using the variable infiltration capacity (VIC) hydrologic model and climate change scenarios A1B[8] and B1[9] from the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4), streamflows for the Puget Sound area will see a decrease in spring snowmelt, increase in winter precipitation in the form of rain, and reduced summer precipitation (Mantua, Tohver, and Hamlet, 2010; Tohver, Hamlet, & Lee, 2014). The precipitation regime changes will increase peak streamflows in the winter and shift the spring peak snowmelt to a few weeks earlier. These changes will be represented in the hydrograph as a transition from a two-peaked (spring/winter) to one-peaked (winter) system. The shift in the hydrograph will lead to an increase in winter flood events and a decrease in spring snowmelt that normally sustains summer water demands for habitat and municipalities.

This evidence is consistent with a study conducted for the Nooksack River in the upper Puget Sound region of Washington. The Distributed-Hydrology-Soil-Vegetation Model (DHSVM) was implemented in this snowpack dominated system with downscaled

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[8] A1B scenario represents a future of rapid economic growth, a mid-century peak global population, a rapid introduction of new technologies, and a balanced reliance on multiple energy sources. Relative to 1980-1999, A1B scenario temperature range will increase 0.3°-0.9°C for years 2090-2099 (IPCC, 2007).

[9] The B1 scenario represents a future with steady global population with a mid-century peak, an introduction of resource-efficient technologies, and environmental sustainability initiatives. Relative to 1980-1999, B1 scenario temperature range will increase of 1.1-2.9°C for years 2090-2099 (IPCC, 2007).

global climate models A2[10] and B1[11] from the IPCC AR4. The model simulated a future forecast of increased winter flows, shifting of spring time snowmelt peak from decreased snowpack accumulation, and a decrease in summer flows.

Physically based hydrologic models, such as VIC and DHSVM, are both represented in the literature, implemented in the Pacific Northwest, and were able to simulate future hydrology responses to changing climate. SWAT has been successful in assessing climate change impacts on hydrology in many regions including Idaho in the Pacific Northwest, but was not successfully calibrated in the Puyallup River basin. DHSVM and VIC are two alternative models that could be implemented in the Puyallup River Watershed. DHSVM was developed specifically for mountainous regions (Wigmosta, Vail, & Lettemaier, 1994) while VIC incorporates more detailed snow algorithms to take into consideration canopy influence on snow and new snow accumulation as well as calibrates snow parameters separately per elevation band (Maurer, 2011).

5.3 Conclusion

Determining hydrologic model capabilities and limitations is often difficult from model documentation and literature. Only during application do site specific limitations

[10] A2 scenario represents a heterogeneous future that is self-reliant, with an increasing population growth, and economies that develop regionally at a slower pace. Relative to 1980-1999 A2 scenario temperature range will increase 2.0-5.4^{o}C for years 2090-2099 (IPCC, 2007).

[11] The B1 scenario represents a future with steady global population with a mid-century peak, an introduction of resource-efficient technologies, and environmental sustainability initiatives. Relative to 1980-1999, B1 scenario temperature range will increase of 1.1-2.9^{o}C for years 2090-2099 (IPCC, 2007).

and alternative approaches become visible. For the Puyallup River Watershed those limitations were scarce soil data, lacking snow parameter input, model assumptions, model output type, and analysis methods. These limitations prevented successful calibration of the SWAT model in the Puyallup River basin. Continued research to implement SWAT in this watershed would need to correct soil data with field verification, include lapse rates and SNOTEL data, separate baseflow and surface flow calibration, and define elevation bands at sub-basin level to accurately represent snow, subsurface, and groundwater interactions. Other considerations should be made for calibration time scale range and input data time step. Calibration time scale, or the range of years, should still include a time set that will reflect regional dry and wet years as it did in this research but the time scale should be closer in range to other input data dates such as the recent 2011 National Land Cover data.

Time step for calibration should also be carefully chosen. Daily observations were aggregated into monthly observations for calibration input, but should be left at daily time step with focus on months with peak flows versus annual flows. This will shift the focus to pattern and timing of streamflow versus total annual streamflow yield. This option is more suitable in a region that has extreme seasonal precipitation events like the Puyallup River Watershed. For immediate implementation of hydrologic modeling in the PNW, VIC or DHSVM would be preferred models, as they have been developed to specifically represent mountainous ranges and snow parameter interactions in PNW region.

Tables and Figures

Sub-basin	Time period	Simulation	R2	NSE
Puyallup River	1960-1979	Calibration	0.45	-0.01
	1980-2007	Validation	0.57	0.39
RME*	1997-2006	Calibration	0.9	0.9
	1967-1996	Validation	0.89	0.89
Tollgate*	1997-2006	Calibration	0.87	0.84
	1967-1996	Validation	0.85	0.82
Outlet*	1997-2006	Calibration	0.82	0.7
	1967-1996	Validation	0.71	0.68
Parma**	1959-1963	Calibration	0.8	0.73
	1964-2004	Validation	0.82	0.79
Arrowrock**	1959-1963	Calibration	0.75	0.75
	1964-2004	Validation	0.77	0.7
Post Falls***	1978-1980	Calibration	0.76	0.58
	1953-1977	Validation	0.72	0.65
Spokane****	1978-1980	Calibration	0.75	0.55
	1953-1977	Validation	0.71	0.62
	1981-1999	Validation	0.66	0.41

Table 10. RME=Reynolds Mountain East. (*)= sub-basin located in the Reynolds Creek Experimental Watershed in Idaho. (**)=sub-basin located in Boise River basin, Idaho. (***)=sub-basin located in Spokane River basin, Idaho. (****)=sub-basin located in Spokane River basin, Washington.

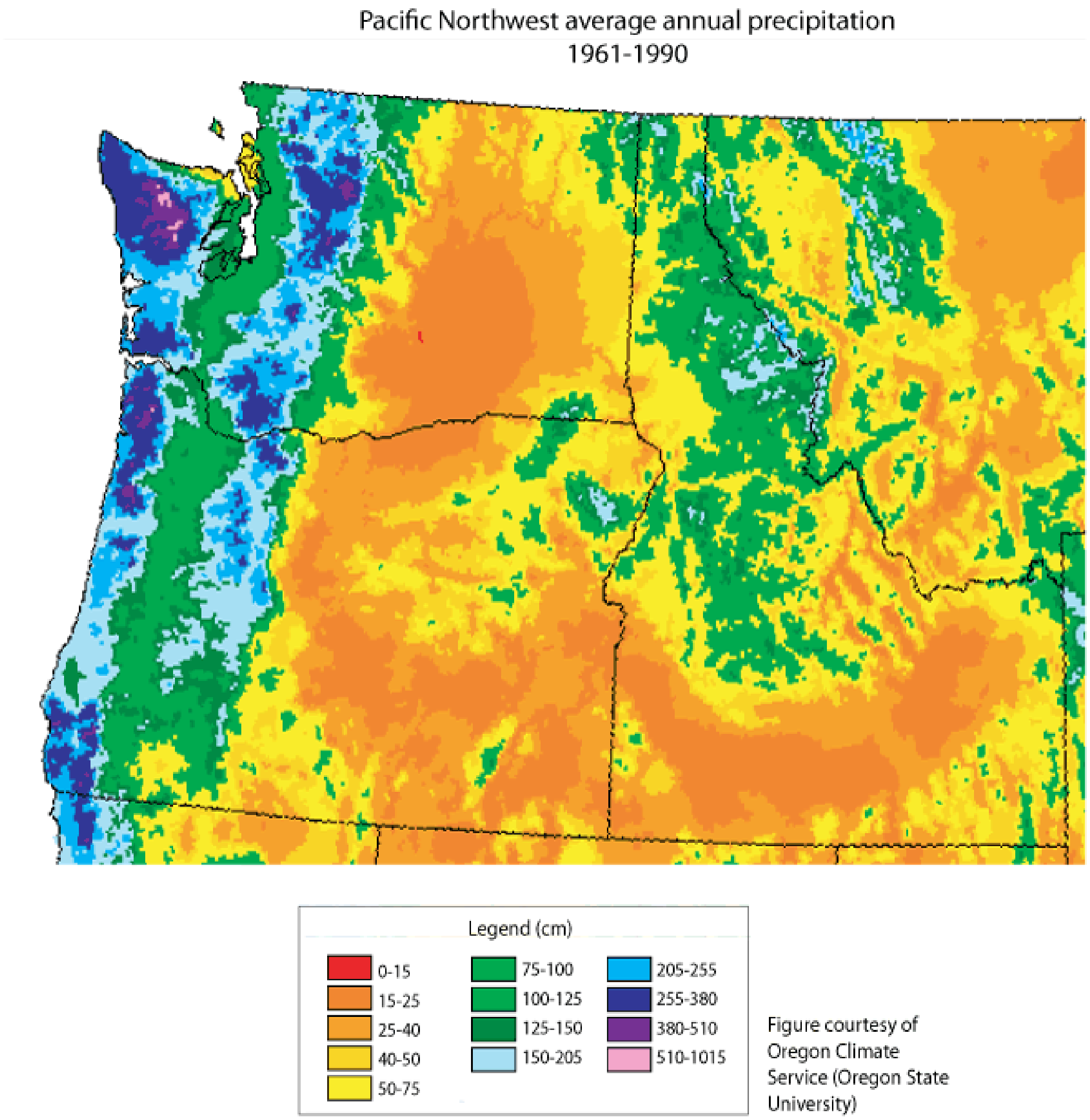

Figure 19. Average annual precipitation (cm) of 1961-1990 for the Pacific Northwest: Washington, Oregon, Idaho, and western Montana. The map showcases a wetter climate west of the Cascade Mountain range, the windward that extends the coast of Washington and Oregon. The eastern side has a drier climate. The Puget Sound lowlands west of the Cascade Mountain range receive more annual precipitation than the watersheds of Idaho. Difference of annual precipitation ranges can influence the ease of SWAT model calibration when using total streamflow yield as an output and calculating snow parameters due to mountain range effects on climate. Figure retrieved April 2015 from Climate Impacts Group, University of Washington.

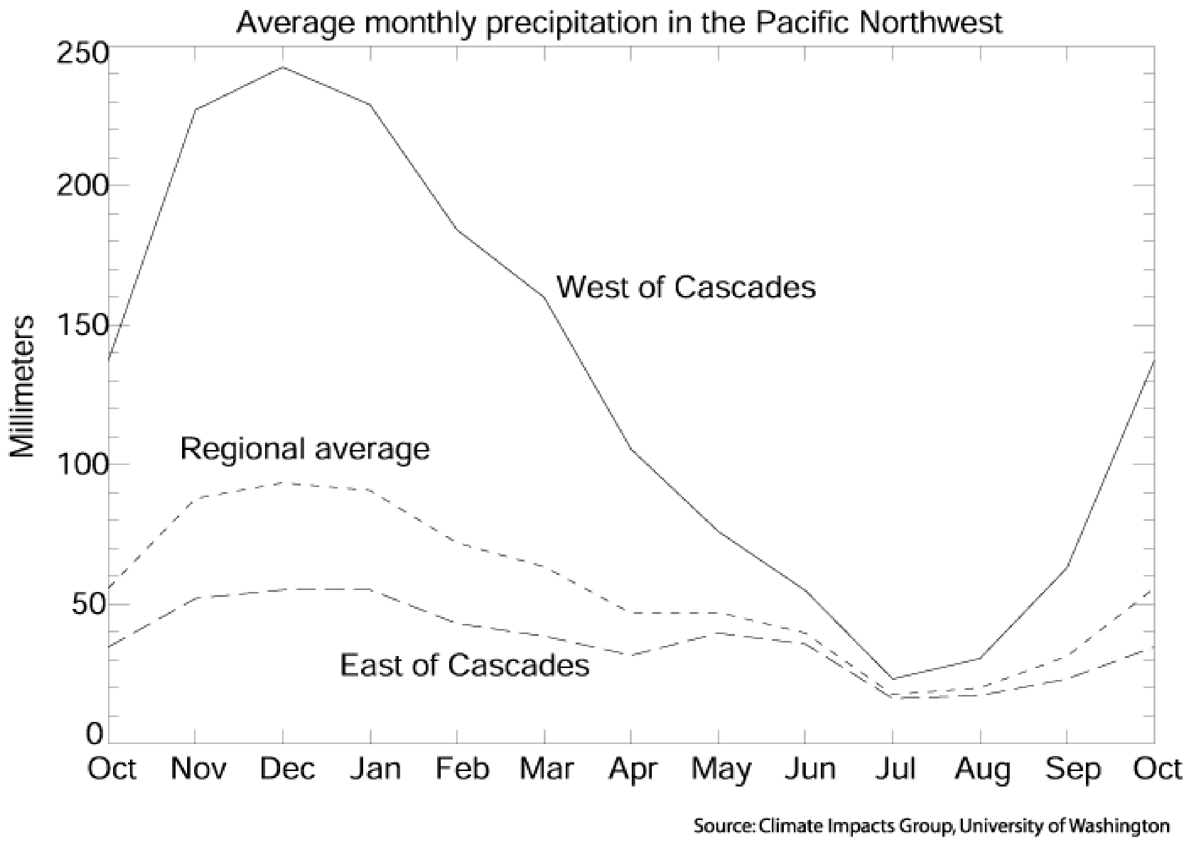

Figure 20. Average monthly precipitation (mm) for the Pacific Northwest from 1900-1998. The western side of the Cascade Mountain range receives more precipitation than eastern side of the Cascades all year round. The greatest difference of precipitation occurs in the winter months. Figure retrieved April 2015 from Climate Impacts Group, University of Washington.

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Appendices

Table 1. A consolidation of referenced literature to portray the variation of sensitivity tools, sensitive parameters, calibration/validation statistics, time scales, and error statistics. Parameter definitions are as follows: ALPHA_BF=Baseflow alpha factor, BIOMIX=biological mixing efficiency, BLAI=maximum potential leaf area index, CANMX=maximum canopy storage, CH_K2=effective hydraulic conductivity, CH_N=Manning's n value, CN=runoff curve number, CN2=initial SCS runoff curve number, EPCO=plant uptake compensation factor, ESCO=soil evaporation compensation factor, GW_DELAY=groundwater delay time, GW_REVAP= ground water "revap" coefficient, GWQMN= threshold depth of water in shallow aquifer required for return flow, RECHRG_DP=deep aquifer percolation fraction, REVAPMN=threshold depth of water in shallow aquifer for percolation, SMFMN=melt factor for snow on December 21, SMTMP=snow melt base temperature, SOL_ALB=moist soil albedo, SOL_AWC=available water capacity of soil layer, SOL_K=saturated hydraulic conductivity, SOL_Z=depth from soil surface to bottom of layer, SPCO=maximum amount of sediment that can be transported, and SURLAG=surface runoff lag coefficient. In depth definition can be found in SWAT2012 Input/Output File Documentation at (swat.tamu.edu/documentation/).

Paper	**Sensitivity Analysis**	**Sensitive Parameters**	**Calibration**	**Validation**	**Error Analysis**	**SWAT simulation ability**
Arnold et al., 2000	Referenced	CN ESCO SOL_AWC	1960-1980 R^2=0.89 (average annual flow)	1981-1985 R^2=0.65 (monthly stream flow)		In agreement with two other base flow models
Jha et al., 2004		Streamflow	1989-1997 Annual R^2= 0.91; NSE=0.91 Monthly R^2= 0.75; NSE=0.67	1980-1988 Annual R^2= 0.89; NSE=0.86 Monthly R^2= 0.70; NSE=0.59	BIAS RMSE	Was able to produce stream flows with reasonable accuracy
Jha 2011	Influence coefficient method	CN ESCO SOL_AWC	1988-1993 Monthly flows R^2= 0.86; NSE=0.85	1982-1987 Monthly flows R^2= 0.69; NSE=0.61		Strong correlation found between predicted and simulated flows
Mango et al., 2011	ParaSol SUFI-2	ESCO CN2 ALPHA_BF GWQMN SOL_Z REVAPMN SOL_AWC CH_K2	Rain gauge data 1996-2003 for calibration R^2= 0.09; NSE=-0.53 RFE data	Rain gauge data 1996-2003 for validation R^2= 0.32; NSE=-0.06		Correlation between simulations and rain gauge data were poor. Simulated data with infrared Rainfall Estimated

		BLAI CANMX	2002-2005 for calibration R^2= 0.56; NSE=0.43	RFE data 2002-2005 for validation R^2= 0.43; NSE=0.23		(RFE) were fair.
Kankam-Yeboah et al., 2013	LH-OAT	CN ESCO EPCO SOL_AWC GW_REVAP GW_DELAY RECHRG_DP GWQMN ALPHA_BF SOL_Z REVAPMN SOL_K SOL_ALB	White Volta 1983-1993 R^2= 0.76; NSE=0.76; PBIAS(%)=-1.5 Pra 1964-1978 R^2= 0.80; NSE=0.79; PBIAS(%)=8.1	White Volta 1994-2000 R^2= 0.79; NSE=0.68; PBIAS(%)=8.1 Pra 1979-1991 R^2= 0.76; NSE=0.69; PBIAS(%)=11.9		Monthly simulations for calibration and validation were deemed to have performed well
Xu et al., 2013	LH-OAT	SOL_AWC GW_REVAP CN2 SOL_K ESCO RCHRG_DP BIOMIX CANMX SOL_Z GWQMN	1980-1995 Quzhou basin NSE=0.86 RBIAS(%)=-9.34 Lanxi basin NSE=0.86 RBIAS(%)=0.61 Jinhua basin NSE=0.76 PBIAS(%)=8.95	1980-1995 Quzhou basin NSE=0.77 RBIAS(%)=-10.10 Lanxi basin NSE=0.89 RBIAS(%)=-4.88 Jinhua basin NSE=0.89 PBIAS(%)=-0.42	Relative change of future predictions compared to baseline observations of 1961-1990	Model showed reasonable performance in simulating monthly river flows
Zahabiyoun et al., 2013		CN2 SOL_AWC SMTMP ESCO SMFMN CH_K2 REVAPMN GW_REVAP ALPHA_BF	SWAT-CUP (SUFI-2) 1992-1996 R^2=0.82 NSE=0.8	1998-2000 R^2=0.77 NSE=0.73		SWAT-CUP performed well for simulated data

Table 2. Soil types found in the Puyallup River Watershed with corresponding areas and percent composition of the watershed.

Soil Type	**Area (ha)**	**Area (acres) (acres)**	**% of Watershed f**
Alderwood	8714.56	21534.11	3.52
Alkridge	1152.56	2848.04	0.47
Altapeak	1157.81	2861.00	0.46
Andic Cryumbrepts	977.14	2414.55	0.4
Aquic Xerofluvents	955.80	2361.83	0.39
Arents	885.63	2188.44	0.36
Barneston	6661.48	16460.85	2.69
Beausite	1419.42	3507.46	0.58
Bellicum	1120.81	2769.57	0.45
Bellingham	162.67	401.96	0.07
Borohemists	258.35	638.40	0.1
Briscot	1105.99	2732.97	0.45
Bromo	242.41	599.00	0.1
Buckley	4609.11	11389.35	1.86
Cattcreek	2834.52	7004.23	1.15
Cayuse	1302.33	3218.12	0.53
Chehalis	15.95	39.41	0.01
Chinkmin	1448.13	3578.39	0.59
Christoff	323.21	798.66	0.13
Chuckanut	15.95	39.41	0.01
Cinebar	161.60	399.33	0.07
Cotteral	47.84	118.22	0.02
Cryofluvents	260.48	643.66	0.11
Cryohemists	371.33	917.59	0.15
Dobbs	47.84	118.22	0.02
Dupont	246.87	610.03	0.1
Elwell	4231.68	10456.70	1.71
Ethania	3449.32	8523.44	1.4
Everett	4492.37	11100.88	1.82
Foss	634.79	1568.60	0.26
Greenwater	181.88	449.42	0.07
Grotto	2272.09	5614.46	0.92
Haywire	5467.24	13509.83	2.21
Hinker	30.27	74.79	0.01
Humaquepts	966.50	2388.28	0.39
Index	674.06	1665.63	0.27
Indianola	2660.23	6573.55	1.08
Jonas	2654.91	6560.42	1.09

Kanaskat	818.65	2022.93	0.33
Kapowsin	6721.23	16608.50	2.72
Kindy	615.58	1521.14	0.25
Kitsap	1263.77	3122.84	0.51
Klaber	48.55	119.97	0.02
Klapatche	307.26	759.25	0.13
Larrupin	2327.31	5750.89	0.94
Lemolo	1536.30	3796.27	0.62
Littlejohn	2260.54	5585.91	0.92
Lynnwood	276.43	683.07	0.11
Mashel	3105.27	7673.29	1.25
McKenna	48.91	120.85	0.02
Mowich	491.90	1215.51	0.2
Nagrom	5080.10	12553.19	2.05
Nargar	15.95	39.41	0.01
National	224.33	554.33	0.09
Neilton	268.06	662.40	0.11
Newberg	290.75	718.45	0.12
Nimue	21857.99	54012.17	8.84
Norma	210.58	520.36	0.09
Oakes	3998.56	9880.65	1.62
Ogarty	1720.23	4250.78	0.69
Ohop	1398.09	3454.74	0.57
Orthents, avalanche chutes	296.77	733.33	0.12
Orting	1432.18	3538.99	0.58
Ovall	1297.08	3205.16	0.52
Pheeney	732.96	1811.18	0.3
Pierking	1212.03	2994.98	0.49
Pilchuck	2286.62	5650.36	0.92
Pitcher	12391.76	30620.65	5.01
Pits	147.71	365.00	0.06
Playco	15354.63	37942.07	6.21
Puget	160.54	396.70	0.06
Puyallup	2992.79	7395.33	1.21
Ragnar	414.00	1023.02	0.16
Reggad	616.01	1522.19	0.25
Reichel	490.84	1212.88	0.2
Riverwash	401.95	993.25	0.16
Rober	15.95	39.41	0.01
Rubble land	740.05	1828.69	0.3

Rugles	869.05	2147.46	0.35
Scamman	565.05	1396.26	0.23
Semiahmoo	208.38	514.93	0.08
Serene	177.55	438.74	0.07
Shalcar	652.87	1613.26	0.26
Snohomish	324.27	801.29	0.13
Snoqualmie	437.04	1079.95	0.18
Spukwash	374.24	924.77	0.15
Stahl	309.88	765.74	0.12
Sulsavar	533.72	1318.84	0.22
Sultan	936.59	2314.37	0.38
Tanwax	63.79	157.63	0.03
Tisch	4.11	10.16	<0.01
Tokul	195.63	483.40	0.08
Tusip	1096.21	2708.80	0.44
Typic Haplorthods	786.76	1944.11	0.32
Udifluvents	389.13	961.55	0.16
Vailton	1732.21	4280.38	0.7
Water	3222.86	7963.86	1.3
Wilkeson	1677.21	4144.46	0.68
Winston	1845.69	4560.78	0.75
Xerochrepts	2372.74	5863.16	0.96
Xerorthents	63.79	157.63	0.03
Zynbar	4778.73	11808.47	1.93
Rock outcrop	3397.72	8395.94	1.37
Rock outcrop-Cayuse complex, 30 to 90% slopes	1002.79	2477.96	0.41
Rock outcrop-Haywire complex, 45 to 90% slopes	3628.72	8966.74	1.47
Rock outcrop-Rubbleland-Haywire complex, 45 to 90% slopes	470.56	1162.79	0.19
Rock outcrop-Rubbleland-Serene complex, 45 to 90% slopes	384.87	951.04	0.16
No Digital Data Available (around Mt. Rainier)	54742.74	135272.05	22.13
Grand Total	**247330.24**	**611165.39**	**100.07**