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# Climate change impacts on runoff generation for the design of sustainable stormwater infrastructure

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ABSTRACT Climate change over the Pacific Northwest is expected to alter the hydrological cycle, such as an increase in winter flooding potential due to more precipitation falling as snow and more frequent rain on snow events. Existing infrastructure for stormwater management may be inadequate to handle the expected increase in winter flood events. Therefore, there is a need to make recommendations for the design of alternate stormwater infrastructure, such as Low Impact Development (LID), in Region X to handle stormwater in the long term. This is an important problem because stormwater issues will intensify as new roads are built and climate change increases flooding potential, and because there is a push for transportation infrastructure in Region X to become â€œgreenâ€ and LID is a deep green alternative. The long-term goal in conjunction with other projects is to identify the hydrological impacts of projected climate change for Region X and to use this information to evaluate existing Region X infrastructure and practices and to make recommendations for the design of new infrastructure to sustainably handle stormwater. The objective of this specific application is to compare the hydrological conditions for historical climate to those of a future climate over the Palouse River basin as information necessary to design sustainable transportation infrastructure. The central hypothesis is that a 2-year storm for the future climate will produce a larger amount of highway runoff than the 2-year storm for the historical climate. The objective will be achieved through the offline coupling of a hydrology model with global climate models (GCMs). Climate change scenarios will be obtained from multiple GCMs and multiple emissions scenarios to produce a range of uncertainty in future simulated runoff. The expected outcome from this project is the development of a method (that can be applied elsewhere) to generate the hydrology data needed to design sustainable infrastructure.

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## DISCLAIMER



## 1. Introduction and Background

Recently a great deal of concern has been expressed regarding the potential impacts of climate change. International bodies such as the Intergovernmental Panel on Climate Change (IPCC) or local bodies like the University of Washington Climate Impacts Group (CIG) have attempted to assess the impacts of climate change at various levels. A recent volume of Climatic Change was dedicated to climate change impacts in Washington State (Climatic Change, Vol. 102, No. 1-2, September 2010). Changes in temperature over the next 100 years are projected to occur with high levels of certainty in the Pacific Northwest (Mote and Salathé 2010). These temperature changes are expected to be on average +1.8°C by the 2040s and +3.0°C by the 2080s, compared to the 1970-1999 average (Mote and Salathé 2010). Temperature changes can have a profound effect on the amount, type and timing of precipitation (Mote and Salathé 2010). Annual average precipitation volumes can increase or decrease, the ratio of rainfall to snowfall can increase, and the seasonality of precipitation can shift toward wetter winters and dryer summers (Mote and Salathé 2010). Hydrology in particular is affected by a changing climate, as the primary driver of the hydrologic cycle is precipitation (Chow et al. 1988, Mote and Salathé 2010). This means that current assumptions about water-related engineering designs based on historical climate data may not be adequate in the future (Rosenberg et al. 2010).

General circulation model (GCM) projections for precipitation vary widely spatially and by model. In the Pacific Northwest, there are variations in both sign and magnitude of the projected annual change in precipitation (Hamlet and Lettenmaier 1999, Mote and Salathé 2010). The most consistently forecasted change for precipitation is a decrease in summer volumes when warming is projected to be largest, with a reduction of as much as 20-40% projected by a large majority (>68%) of models (Mote and Salathé 2010). For winter volumes, the majority of GCMs (>50%) project an increase, with values as high as 42% (Mote and Salathé 2010). However, on average for all models there is a slight increase in annual precipitation, with an average projected change of +1% to +2% (Mote and Salathé 2010). This change can be enhanced by a hypothesized intensification of the hydrologic cycle.

Frei et al. (1998) hypothesized that future climate scenarios will result in intensified rain events, such that the return intervals for strong storms will decrease; that is, strong storms will occur more frequently. In other words, the intensity of traditional design storms such as the 2-year, 25-year, 50-year and 100-year 24-hour storms will increase in intensity. Rosenberg et al. (2010) and Salathé et al. (2010) agree with this hypothesis on a regional basis for the Pacific Northwest.

As there is uncertainty in the eventual effects of climate change on precipitation (Mote and Salathé 2010), understanding the range of projected scenarios is important. Intensification of extreme events would result in the need for modification of current design practices as well as the enhancement of existing infrastructure meant for handling runoff (Rosenberg et al. 2010).

Standard design practices for hydraulic structures are based on the prediction of events and the allowable risk associated with them (Chow et al. 1988). Depending on the sensitivity of the structure and the desired performance in response to some event, a structure is designed based on the probability that an event, such as a rainfall or runoff volume, will not be exceeded. This is achieved by assessing the probability that an event will or will not occur by the use of statistics. The events of the past are used to determine the potential for one to occur in the future. This of course assumes independence of the variables, the same underlying distribution for the data, and stationarity of the data (Milly et al. 2008, Chow et al. 1988).

Human disturbances in river basins, such as land use change, have long compromised the assumption of stationarity within probability density functions governing uncertainties, affecting the predictive ability of planners and engineers (Milly et al. 2008). A loss of stationarity is caused by a change in variance or mean in time for the system being statistically modeled (Chow et al. 1988). Currently, substantial anthropogenic change of Earth's atmosphere, and therefore climate, is altering many hydrologic parameters, including the mean and extremes of precipitation (Milly et al. 2008). Because any ability to predict future risks associated with precipitation events rests on the ability to utilize historic data with the assumption that it still applies, it is clear that climate change is affecting the ability to assume that this is still valid.

Hydraulic structures that are designed to withstand more extreme events, in other words structures that failure is not easy to risk, may be designed to control a precipitation or streamflow event with a return interval of 50-100 or more years (Chow et al. 1988). When there is a risk of loss of life or significant economic or social damage, the use of longer return intervals is often justified. The difficulty in estimating the magnitude of these events often lies in the inadequate period for data of record and poor choices in methodology for estimating design events (Wohl 2000, Linsley 1986). Thus, the intensity of the 100-year storm or flood may be estimated based on merely 50 years of rainfall or streamflow data. While this is difficult to consider statistically defensible, it is often the only means available to estimate the risk. If one takes into account that these 50 years are affected by a loss of stationarity, the *effective* length of the precipitation record decreases (Tasker 1983). This results in higher error in the estimation probability density functions and therefore a lower confidence in the ability to design a structure that will not fail within its lifetime of service.

The use of GCMs to project the future climate based on emissions scenarios is one way to improve the ability to predict these future events. By running these GCMs, probability density functions can be constructed to represent the probability of future events occurring. While the result of running these GCMs is sensitive to a number of factors, including time period modeled, choice of GCM, downscaling method, emissions scenario and more, these results are better than assuming stationarity of non-stationary data. With an appropriate choice of GCM, downscaling technique and other hydrologic model parameters, a range of uncertainty can be assessed for future projections for precipitation events.

## 2. Problem Statement and Research Objectives

This research aims to investigate the effects of climate change, in terms of the change in the intensity of commonly-used design storms, on runoff in the Pacific Northwest. The Variable Infiltration Capacity (VIC) large-scale hydrology model (Gao et al. 2010, Liang et al. 1994) is applied to the Pacific Northwest to model the runoff due to storms of an intensity corresponding to 2, 25, 50 and 100-year average return intervals (ARI). The intensity of these storms will be estimated for the historical 1915-2006 climate and compared to projections by a suite of GCMs forced with two different greenhouse gas emissions scenarios. This study seeks to answer two questions regarding climate change and runoff:

1. How will the change in atmospheric conditions, such as intensification of extreme precipitation and a warmer climate, affect the amount of runoff generated by design storms of common return intervals?

2. What uncertain parts of projecting the climate, as it changes in time, represent the most uncertainty in forecasting runoff in the future?

## 3. Methods and Results

### 3.1. Identify the 2-year, 25-year, 50-year, and 100-year 24-hour storms for the historical and future climates.

The intensities of the 2, 25, 50 and 100-year 24-hour storms have been identified for the historical climate for the entire Pacific Northwest as well as two emissions scenarios modeled each using two GCMs for the State of Washington. The precipitation intensities were modeled using the GEV distribution, fit to the gridded annual maximum 24-hour precipitation data at 1/2 degree resolution using the method of L-moments (Hosking and Wallis 1997). Figure 1 illustrates the spatial distribution of the 50-year 24-hour storm intensities in the Pacific Northwest at 1/2-degree resolution. Figure 2 shows the projected intensities of the 50-year 24-hour storm based on the data downscaled from the CNRM CM3 model running the B1 emissions scenario. For the Monte Carlo simulation defined in objective #2, this model was given the highest probability of selection of the 10 GCMs being used.

The analysis of future climate scenarios showed that GCM-projected precipitation over the Pacific Northwest was more intense than historically-modeled storms. Figure 3 is a change plot that compares (in percent) the difference between the CNRM CM3 (B1) result and the historical baseline. Note that areas that had the highest storm intensities in the historical analysis, such as the Olympic Peninsula, often had the largest projected increase in storm intensity. However, there was no widely recognizable regional signature for the changes, possibly due to the application of statistical downscaling and a coarse simulation resolution.

A program that can be used for gridded data at any resolution and over any spatial area has been written using the C language, and will be applied further toward more emissions scenarios, downscaling methodologies and climate models. From these gridded data, hydrologic models can be used over the Pacific Northwest to simulate the runoff impact (as in Objective #2) for a variety of storm return intervals based on a number of emissions scenarios and climate models.

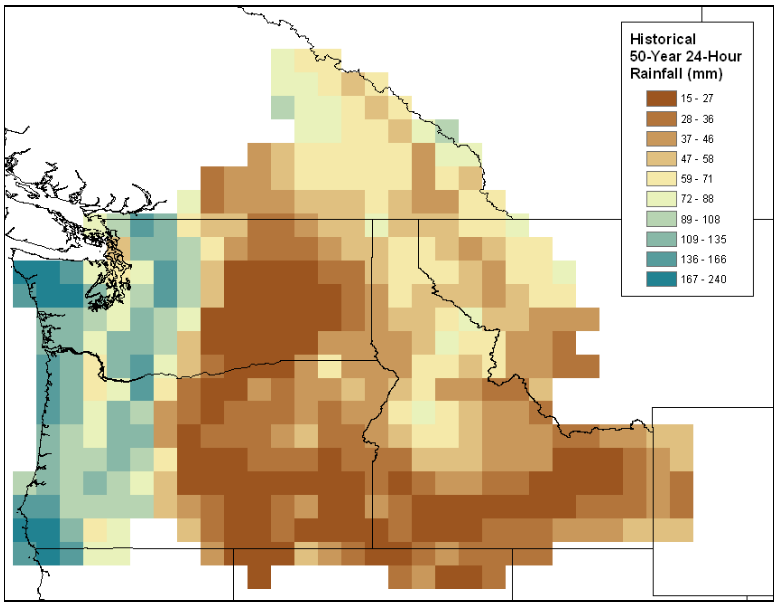


**Figure 1: Historical 24-Hour Storm Intensity, 50-Year Storm**

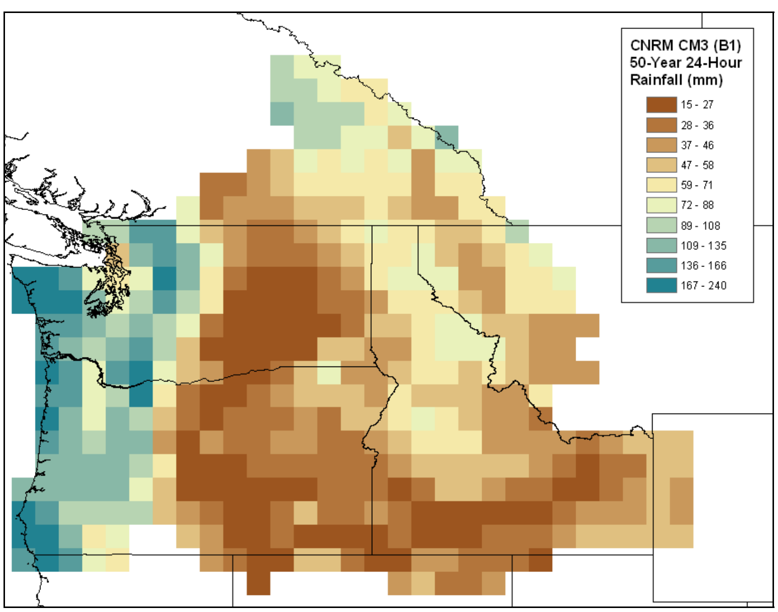


**Figure 2: CNRM CM3 (B1) 50-Year 24-Hour Storm (mm)**

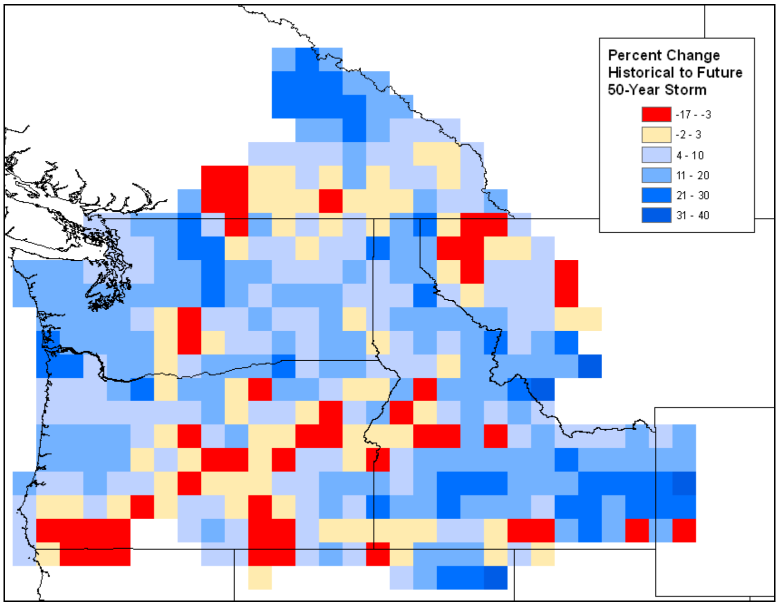

**Figure 3: Percent Change, Historical to Future 50-Year Storm**

**3.2. Simulate climate change impacts on hydrology over the entire PNW.**

We have further refined our approach as follows. To capture the uncertainty in projecting future climate, Monte Carlo simulation was employed to create a probabilistic framework for determining future runoff depths (see Wilby and Harris 2006 for an example of this methodology). Monte Carlo simulation is a method of numerically solving a system which is either deterministic or stochastic. In this case, several variables have been randomized to capture the effects of uncertainty, including emissions scenario and GCM for storm data, and antecedent snowpack and antecedent soil moisture for initializing the hydrology mode. By randomly selecting a combination of these four factors based on the skill of the estimator (in the case of GCMs) or the likelihood of occurrence (all else) a *posterior* distribution for runoff depths over the PNW can be determined. This posterior distribution is a summary of the probable runoff depths produced in a future climate. Since it is "weighted" in favor of the most likely and best metrics for quantifying climate change, the central tendency is to represent the most likely runoff depths in the future.

The Variable Infiltration Capacity (VIC; Gao et al. 2010, Liang et al. 1994) macroscale hydrology model was employed at 1/2 degree over the Pacific Northwest. The model parameters were aggregated from existing 1/16$^{th}$ degree soil and vegetation parameters, and the model run for 5000 with differing meteorological forcing data based on different SRES emissions scenarios (Nakicenovic et al. 2000) simulated with a variety of GCMs. VIC, ordinarily a continuous hydrology model, was run using synthesized events consisting of the design storm of interest, and average temperature and wind values dependent on when the annual maximum event was most likely to occur. Locations in the PNW have different precipitation regimes, so the heaviest storms are more likely to occur during different parts of the year. Figure 4 shows the season that most frequently had the annual maximum rainfall event for 1915-2006. The synthetic storm events took an average of the daily maximum and minimum temperature and the daily average wind speed for the two-week period in the year that most frequently contained the annual maximum rainfall event. These averages are taken for the historical climate and each emissions scenario-GCM pair and used in VIC with the storm intensity determined by return interval and emissions scenario-GCM pair.

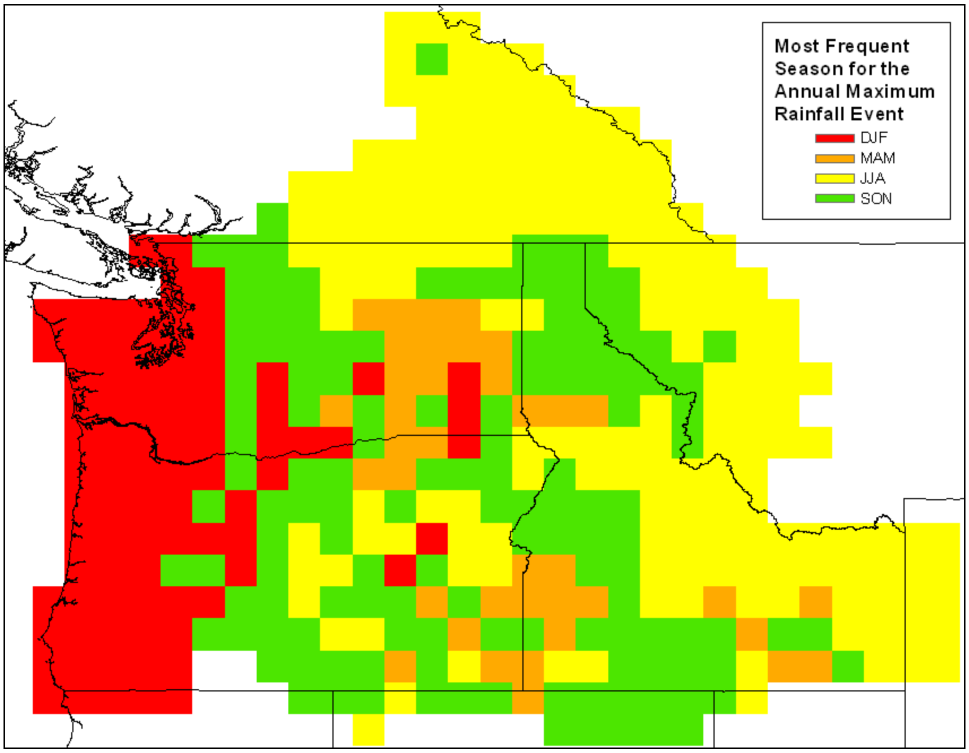

**Figure 4: Most frequent season for the annual maximum rainfall event in the Pacific Northwest**

Each realization was chosen at random based on the probability of the occurrence of each emissions scenario, and the skill of the GCM at reproducing historical temperature and precipitation. GCMs with a higher bias in re-creating 1970-1999 temperature and precipitation over the PNW were given lower selection probabilities in the Monte Carlo simulation, so that the best models (with the lowest bias) would be selected more often. Table 1 shows the ten GCMs in the study with their corresponding biases and selection probabilities. Since the assumptions governing greenhouse gas emissions in the 21st century are governed by economic, social, governmental, scientific, and more factors, the selection of any emissions scenario was given equal probability of occurrence. In this case there were two emissions scenarios, a "worst" and "best" case scenario (highest and lowest warming by the 2040s, respectively) which were each given a selection probability of 0.5. The result of the Monte Carlo simulation is a set of probability maps for runoff over the Pacific Northwest for each design storm intensity, indicating the coefficient of variation and median value for the projected future runoff depths.

**Table 1: GCM selection probabilities and biases in hindcasting 1970-1999 PNW climate**

| GCM | Average Annual T Bias (°C) | Average Monthly P Bias (cm) | A1B P | B1 P |
|---|---|---|---|---|

| | | | | |
|---|---|---|---|---|
| CCSM3 | -1.7 | 1.8 | 0.107 | 0.118 |
| CGCM3.1_t47 | -2.3 | 1.7 | 0.093 | 0.102 |
| CNRM_CM3 | -0.8 | 1.7 | 0.141 | 0.155 |
| ECHAM5 | -1.8 | 1.7 | 0.107 | 0.118 |
| ECHO_G | -2.2 | 1.7 | 0.095 | 0.105 |
| HADCM | -1.9 | 1.3 | 0.115 | 0.127 |
| HADGEM1 | -1.8 | 2.2 | 0.093 | --* |
| IPSL_CM4 | -1.6 | 2.4 | 0.092 | 0.101 |
| MIROC_3.2 | -1.5 | 3.2 | 0.075 | 0.083 |
| PCM1 | -2.8 | 1.6 | 0.082 | 0.091 |

*There were no downscaled data available for HADGEM1 running B1.

The amount of antecedent snowpack and soil moisture were simulated in VIC for all GCM-emissions scenario pairs and the historical climate, and were fit to a discretized normal distribution for selection in the Monte Carlo simulation. This benefits the analysis by assessing two uncertain quantities that can have a profound effect on runoff. The random selection of these values allows for year-to-year variability to occur as it would naturally, and also allows the effects of climate change to be represented hydrologically by more than just the change in storm intensity. Since snowpack and soil moisture can change the amount of runoff during a storm event, capturing this uncertainty was important to truly understanding the climate change-runoff relationship.

The advantage to this methodology is that it avoids reliance on a single GCM and emissions scenario. It evaluates a range of projections and produces a result that takes into account an assigned probability that the projection is correct based on the hindcasting ability of the GCM and the occurrence of that emissions scenario. It also encourages assessment of a risk-in-risk use of the runoff data.

While stormwater infrastructure may be designed to handle an amount of runoff based on a return interval of a generally small exceedance probability, the projection of those future runoff events is riddled with uncertainty. By estimating a confidence interval based on a large sample of GCMs, with varying emissions scenarios and downscaling methods, the projected runoff depth can be bracketed with a range of certainty which can be applied to design. If a highway culvert is designed to have a capacity of the runoff from the 100-year storm, it is expected that the probability in any given year of its capacity not being exceeded is 99%. However, the uncertainty of the future precipitation intensities illustrates the need for a confidence in the estimate of the 100-year event, so a structure can be designed, for example, to the 90% confidence level of the projected 100-year event. Thus a planner or an engineer can take the appropriate level of risk into account with a project. By improving the estimate of precipitation and runoff, the risk is reduced.

In general, due to a warmer climate, the Pacific Northwest is projected to experience an increase in runoff due to changes in the intensity of design storms. The magnitude of this change is highly sensitive to the choice of emissions scenario, and GCM, and the amount of snowpack and soil moisture present when the storms take place. Locations that historically experience the most rainfall and runoff are projected to see the largest increases in the future. There is good agreement among the models and scenarios that these locations will increase in runoff, but the magnitude of the change is widely variable. It is seen that a larger increase in warming (the A1B emissions scenario over the B1 scenario) is linked to a likewise larger increase in runoff. As it turns out even the worst-case SRES scenario is low in comparison to actual 21st-century emissions rates, so the top of the probability envelope in this study may not even be considered a conservative estimate for runoff in the future.

Figure 6 illustrates the historical runoff for the 50-year storm at 1/2 degree. In comparison, figure 7 shows the Monte Carlo simulation result for the future climate 50-year storm. Figure 8 shows the percent change in runoff from the historical 50-year storm to the future. The areas displaying a decrease are generally in areas outside of Washington that have complex interactions with snowmelt contribution and snowpack capture of rainfall. In the Olympic peninsula, there are two grid cells showing decreased runoff, but these cells are expected to increase more with a higher greenhouse gas emissions scenario. Figure 5 shows the coefficient of variation (CV) for all 5000 future simulations. The CV is a measure of variability in the results, defined as the standard deviation of the results divided by the mean.

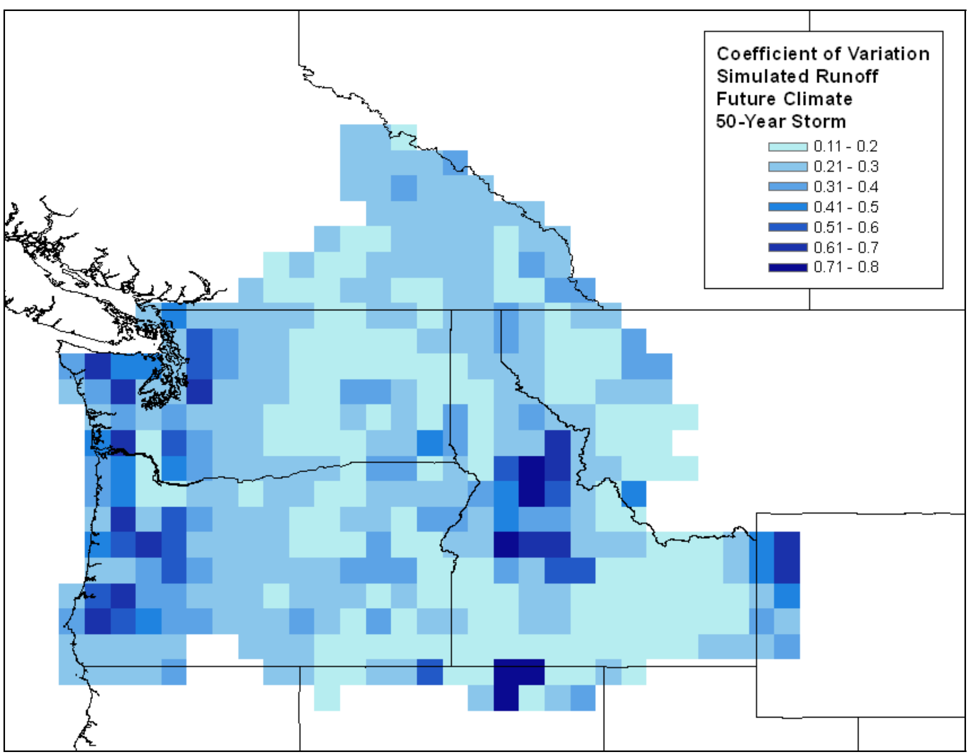


**Figure 5: Coefficient of Variation for Future Runoff**

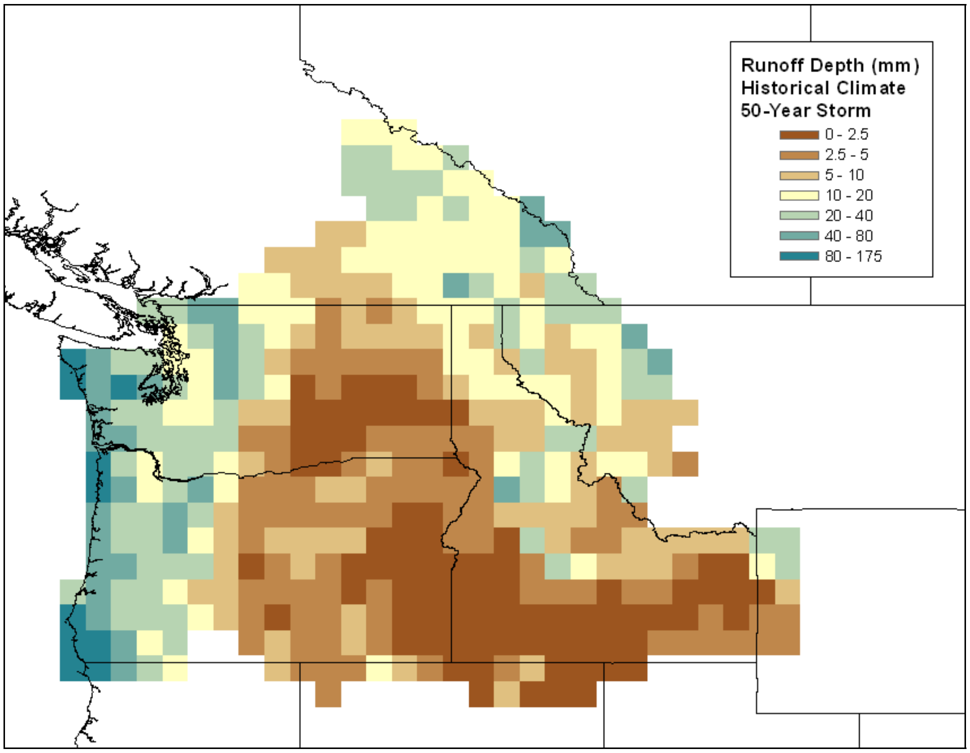


**Figure 6: Historical Runoff Depth (mm) Due to the 50-Year Storm**

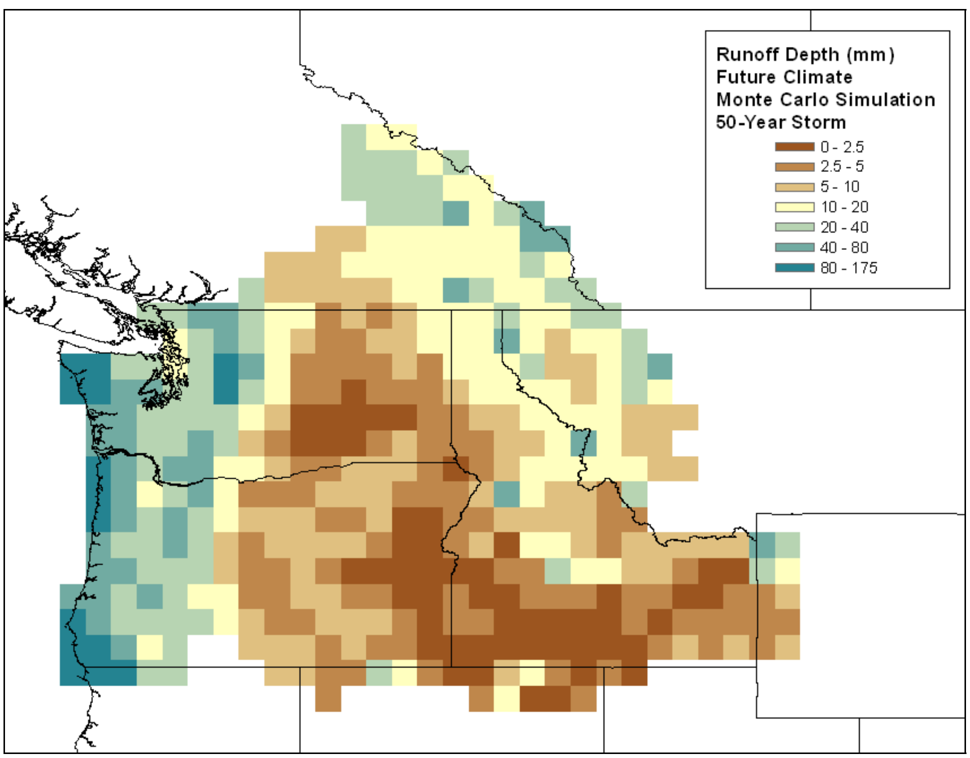


**Figure 7: Monte Carlo Simulated Future Runoff Depth (mm) Due to the 50-Year Storm**

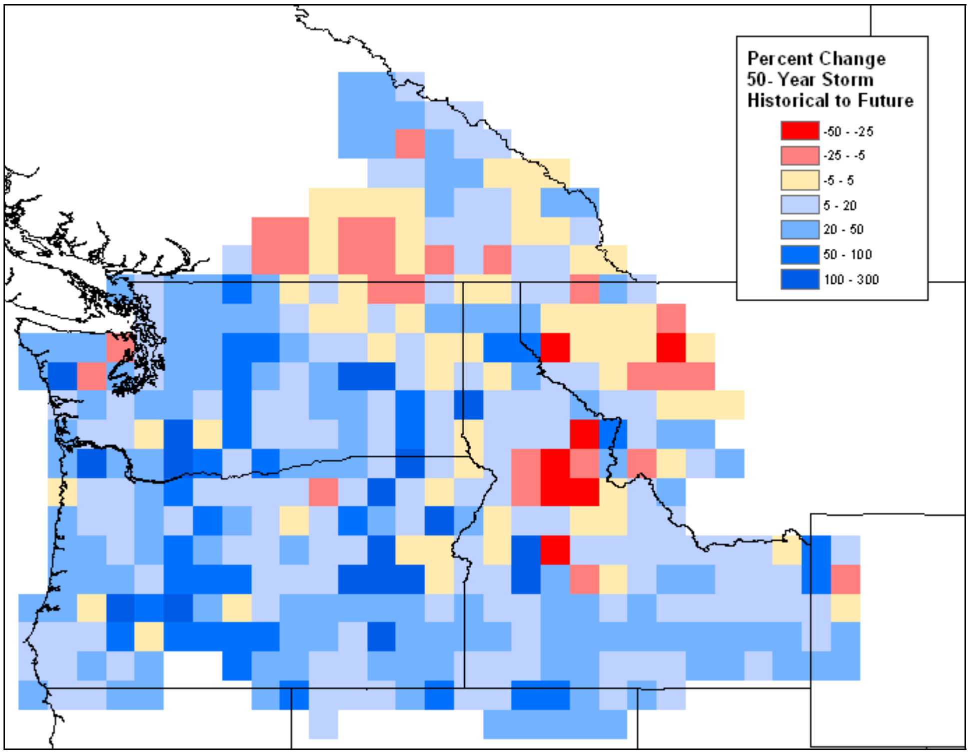

**Figure 8: Percent Change in Runoff, Historical to Future Climate**

**3.3. Simulate climate change impacts on hydrology over three small rural basins.**

We have implemented the Distributed Hydrology Soil Vegetation Model (DHSVM; Wigmosta et. al. 1994) hydrologic model over three rural basins in the state, the Queets River on the Olympic Peninsula in Northwest Washington State, the South Fork of the Palouse River in Eastern Washington, and the Potlatch River in Northern Idaho. As the objective of this study relates to understanding the impacts of climate change on stormwater for rural basins, these three study basins are appropriate for this study. The basins represent areas of predominant agriculture (Palouse, section 3.3.1), forests (Queets, section 3.3.2), and mixed agriculture/forests (Potlatch, section 3.3.3).

**3.3.1. Palouse**. We have refined the implementation of DHSVM over the Palouse River in eastern Washington State (Figure 9), including adapting the model (which was developed primarily for forested mountainous hillslopes) for the agricultural region of the Palouse for our stormwater runoff study. It is important to make these modifications to improve our simulations of runoff in both the historical and future climate scenarios. Improvements include the following:

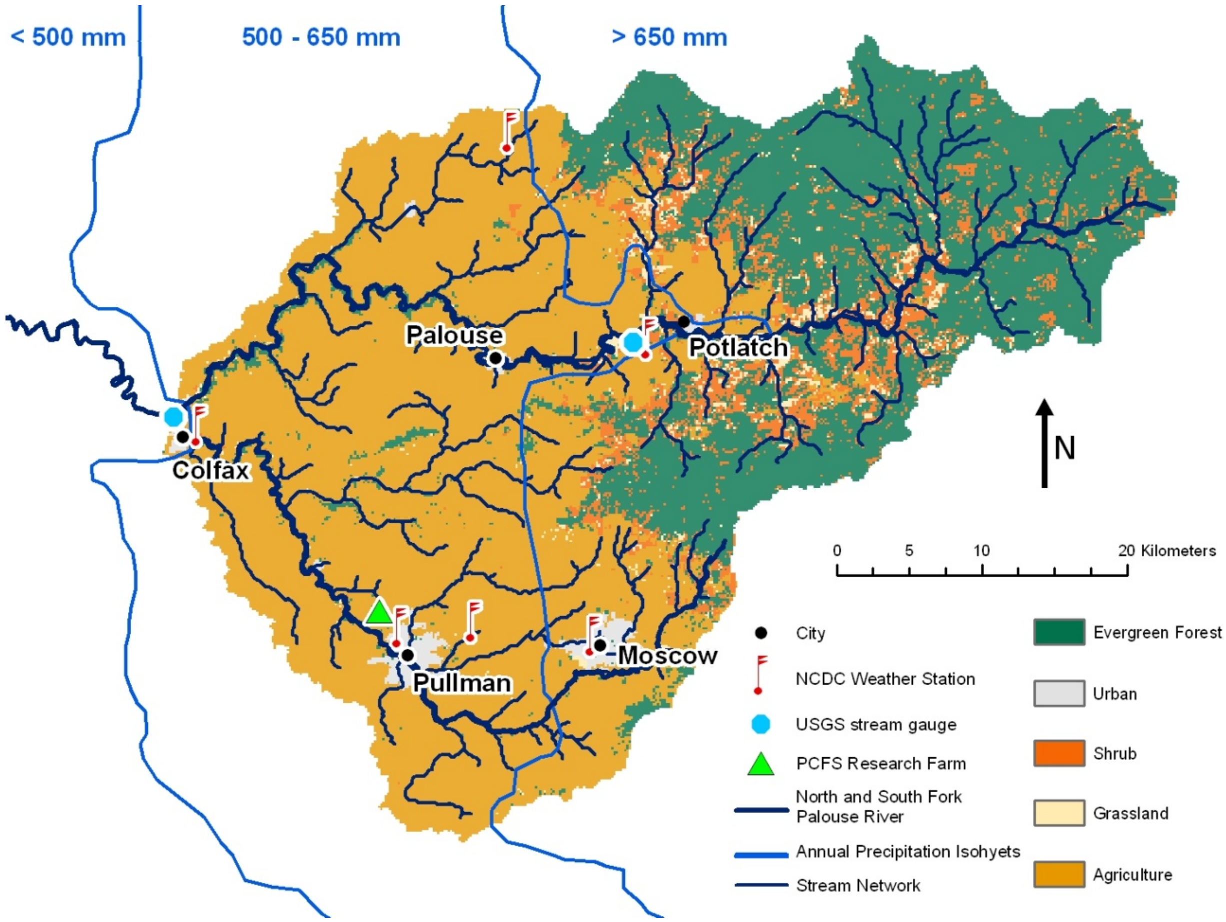


**Figure 9: Upper Palouse River basin containing the North and South forks of the Palouse River.**

1) Modification of infiltration for frozen soils: The maximum infiltration rate is modified during soil freezing so that infiltration is decreased through the infiltration excess mechanism. An equation similar to that employed by Wigmosta et al. (2009) is used in which maximum infiltration rate is adjusted by

$$I_f = c_f I_u \qquad \text{(eqn 1)}$$

in which $I_f$ is the maximum infiltration rate for frozen soil, $I_u$ is the maximum infiltration rate for unfrozen soil, and $c_f$ is a factor of 0.005 when the soil is frozen.

2) Modification of soil radiation parameters for reduced tillage scenarios: Factors that affect the calculation of surface temperature in DHSVM include soil and vegetation albedo and transmittance of radiation through the overstory and understory (Wigmosta et al., 1994). The amount of radiation reflected from the surface will vary by the surface albedo and will differ between a light-colored crop residue and a darker bare soil. Novak et al. (2000) developed a model for simulating the distribution of radiation through surface residue that considers the effects of residue on shortwave and longwave radiation. In their work, multiple layers of stacked flat residue are considered; radiation through the

residue is partially inhibited based on the percentage of ground covered and the number of residue layers. A transmissivity factor is applied to shortwave radiation, and longwave radiation is multiplied by a 'view factor' representing the percentage of soil visible from above residue. Novak et al. (2000) reported transmissivity values ranging from 0.03 to 0.76 based on the number of residue layers covering the surface. View factors for their model were calculated from transmissivity values; for a single residue layer, as would be the case in NT management, the view factor would be equal to the transmissivity. A similar transmissivity factor was added to the DHSVM calculations for radiation through the understory. Incoming shortwave radiation, $R_s$, is calculated in DHSVM using the equation

$$R_n = R_s T_u (1 - A_s) \qquad \text{(eqn 2)}$$

where $R_n$ is the net solar radiation reaching the surface, $R_s$ is incoming solar radiation, $T_u$ is the understory transmittance, and $A_s$ is albedo. $T_u$ was set to 0.76, which is the transmittance specified by Novak et al. (2000) for a single residue layer, and $A_s$ was set to 0.25 for crop residue and 0.1 for bare soil, as given by Breuer et al. (2003). A view factor representing the percent of soil visible through crop residue was added to the longwave radiation energy balance so that longwave radiation was calculated by

$$R_L = F_v \sigma T^4 \qquad \text{(eqn 3)}$$

in which $R_L$ is longwave radiation, $F_v$ is the view factor, σ is the Stefan-Boltzmann constant, and $T$ is the temperature of the substance emitting radiation. $F_v$ was set to 0.76 for crop residue, following Novak et al. (2000). This equation was applied as radiation passed through the residue layer, either being emitted upward from the soil surface or downward from the air or overstory vegetation.

Sensitivity simulations were performed to understand the response of the model to the above changes. For example, Figure 10 shows the simulated soil moisture content under two tillage scenarios (NT = no till; CT = conventional till) and with the frozen soil algorithm both on and off. This figure demonstrates that the differences between tillage scenarios are much larger than the effects of the frozen soil algorithm.

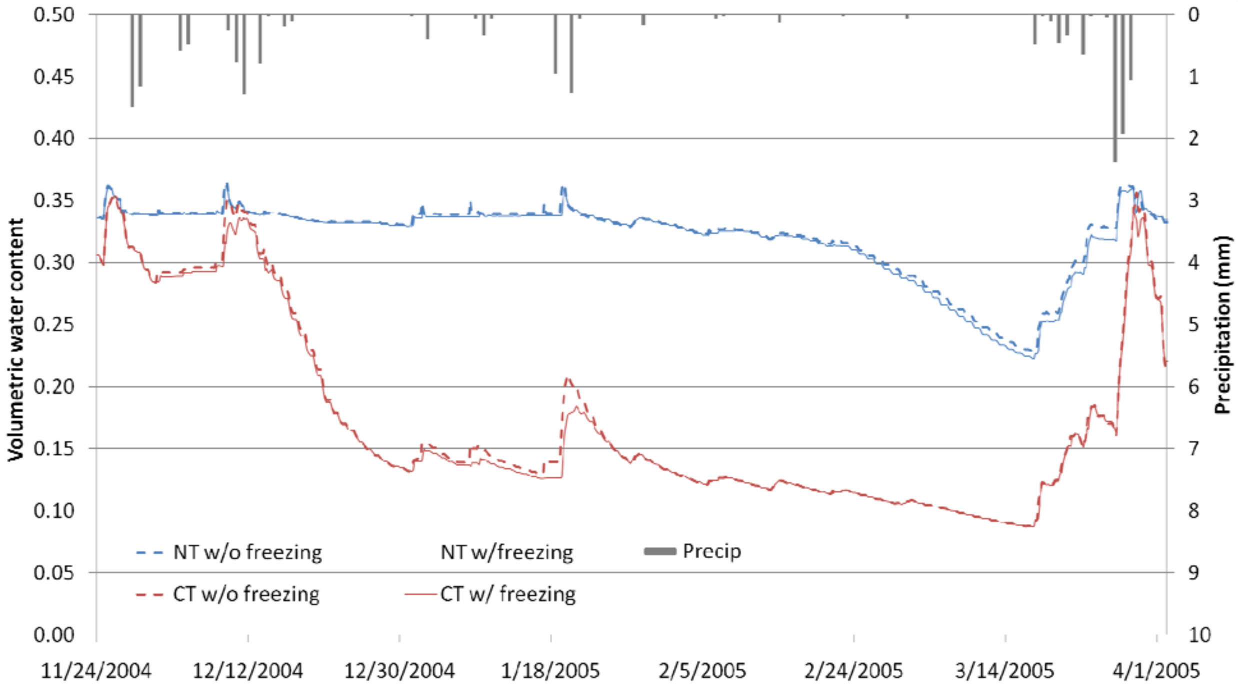


**Figure 10. Average daily volumetric water content for NT and CT scenarios with and without reduced infiltration during days with frozen ground.**

**3.3.2. Queets**. We have also implemented DHSVM over the Queets basin, which is a watershed that is in the Olympic Experimental State Forest (OESF) of northwestern Washington, which is one of the wettest locations in the continental United States (Daly et al., 2002), with the precipitation ranging annually from 2500-6000 mm (NOAA, 1978). The OESF, with a total area of 1080 km$^2$, is located on the western side of the Olympic Peninsula, and ranges in elevation from 0-2398 m. This area is susceptible to higher runoff rates because of its history of logging. The Hoh, Bogachiel, Calawah, Hoko, Sol-e-Duc, and Queets are some of the river basins in this area. For this study the Queets Basin located in Jefferson county (figure 11) was selected because it has a wide range of geographical properties (e.g. steep slopes and high elevation) with a long period of recorded historical streamflow data (1948-present). The upper basin lies in the Olympic National Park and the National Forest while the lower basin is managed by the DNR where wide spread logging has occurred.

In understanding the runoff regime of the Queets basin, we needed to be able to correctly identify logged areas. We applied Landsat 5-TM (NASA, 1984) images to identify historical deforestation activities. Multiple studies across the globe have confirmed that Landsat images can detect timber harvesting with high confidence using a variety of methods (Sader and Winne, 1992; Skole and Tucker, 1993; Cohen et al., 1998; Wilson and Sader, 2002; Sohn and Rebello, 2002). For this study we used the supervised classification method as applied by Sohn and Rebello (2002).

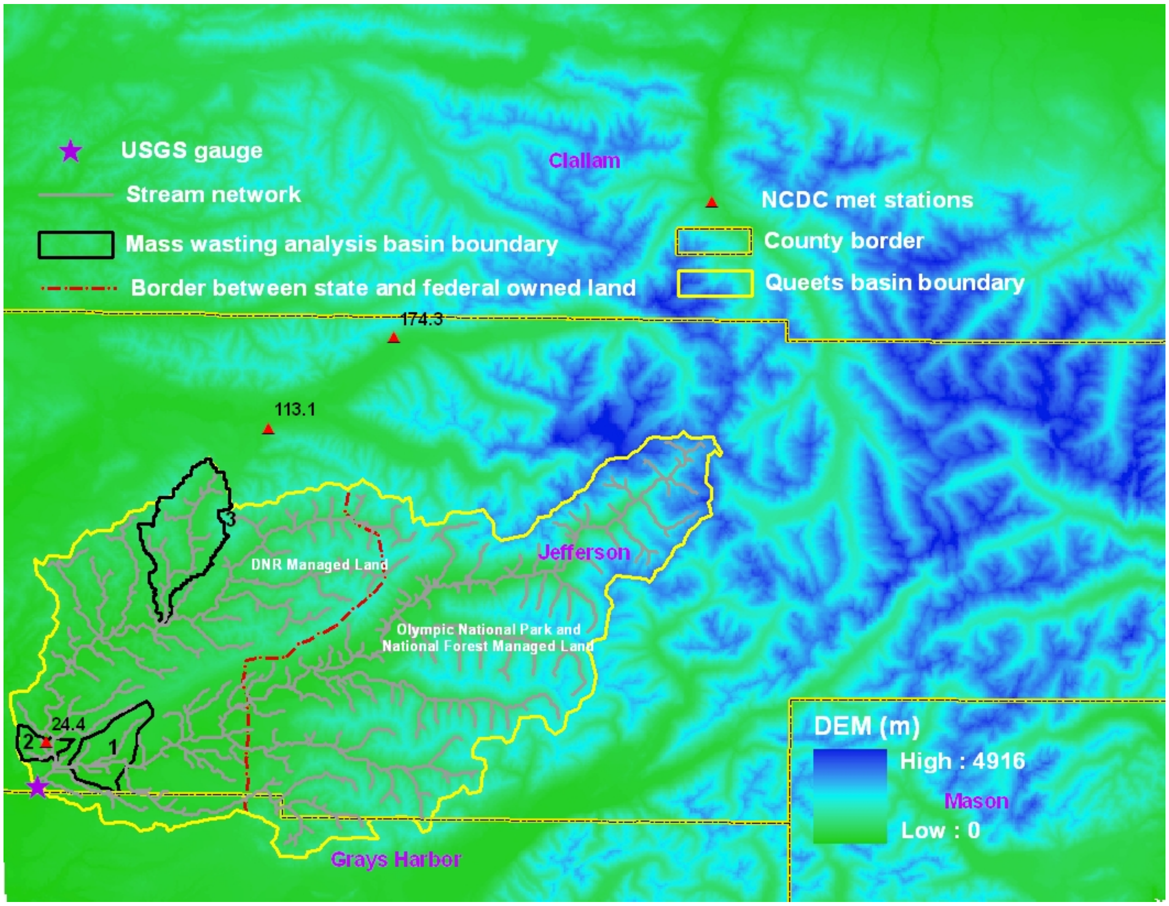


**Figure 11: The Queets Basin, located on the Olympic Peninsula of Washington State.**

Landsat-5 TM images used for this study were collected from the USGS Global Visualization Viewer (GLOVIS, 2006). Images with the least amount of cloud cover (August 1986, September 1990 and August 1996) were selected and processed using ENVI©. We applied the Chander and Markham (2003) radiometric calibration procedures for converting the digital numbers (DN's) from image data to top-of-atmospheric reflectance. Following the method outlined by Sohn and Rebello (2002), the area was classified into five types of landcover: clear-cut, old growth trees, newly planted trees or grassland, developed areas, and water. Three control points of known vegetation for each land cover type were used to train the classification. We selected these control points from a 1990 USGS National Aerial Photography Program (NAPP) image (U.S. Geological Survey, 1991). We applied a sequential image differencing approach (Cohen et al., 1998) to reduce the error in miss-classifying naturally bare or non-forested lands as clear-cut. For this, we also processed Landsat images (figure 12a) for 1986 and 1996 (before and after our 1990 image). Any areas classified as clear-cut in all three images were re-labeled as permanent bare land (because the areas would have been replanted in the meantime if they had experienced clear-cutting). In figure 12b, yellow areas show the clearcut areas derived using supervised classification method over a portion of the study area.

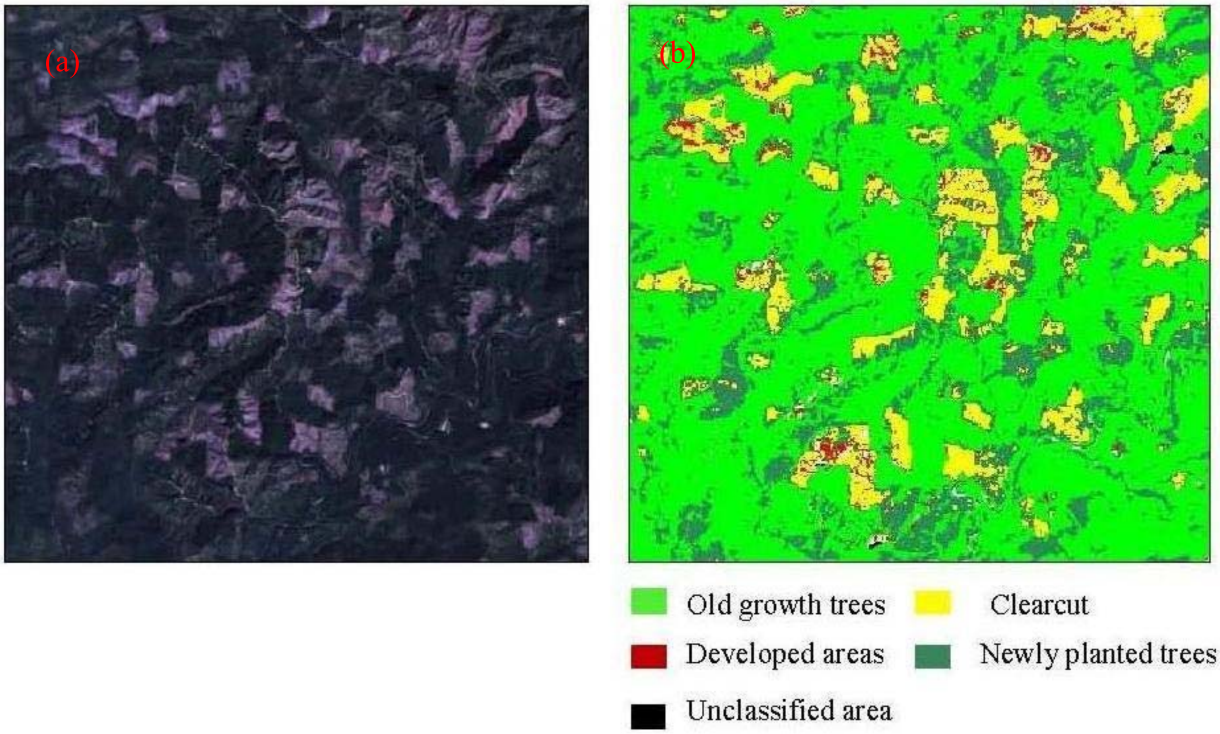


**Figure 12: (a) Land cover classification results using the supervised classification method of Sohn and Rebello (2002). (b) The raw landsat-5 TM image of September 1990.**

The DHSVM implementation over the Queets Basin was calibrated and evaluated with historical USGS streamflow measurements at the outlet of the Queets Basin. DHSVM-simulated streamflow is sensitive to several soil parameters, including lateral hydraulic conductivity, vertical hydraulic conductivity, maximum infiltration rate, and porosity. These parameters were therefore targeted for calibration and values were chosen to reduce the error in simulated streamflow. The streamflow record was divided into the calibration and evaluation periods of 1991-1995 and 1985-1990, respectively. The Nash Sutcliffe efficiency (Nash and Sutcliffe, 1970) for streamflow was 0.74 and 0.71 over the calibration and evaluation periods, respectively; while the relative bias for annually-averaged streamflow was -13% and -8% for the calibration and evaluation periods, respectively. The relative bias is simulated minus observed flows as percentage of observed flow. Comparison of monthly simulated and observed streamflow demonstrates that, while the timing of the peaks is good, we are underestimating the magnitude of the peaks (Figure 13), which we believe to be caused by an underestimation of precipitation. Although the precipitation data used to drive the model have been adjusted to account for orographic influences using the Parameter-elevation Regressions on Independent Slopes Model (PRISM; Daly et al., 2002), we suspect that the data do not capture the strong gradients of precipitation with elevation that are known to occur on the western slope of the Olympic Peninsula (Minder et al., 2008). As the precipitation gauges are located in the lower elevations (Fig. 11), it is probable that the under-prediction of streamflow is due to underestimated precipitation over the higher elevations. Because we are investigating the effects of climate change on stormwater, we are primarily interested in the lower half of the Queets Basin. Therefore, to the extent that is suggested by Fig. 13, we may not be underestimating precipitation in the lower basin where we focus our study.

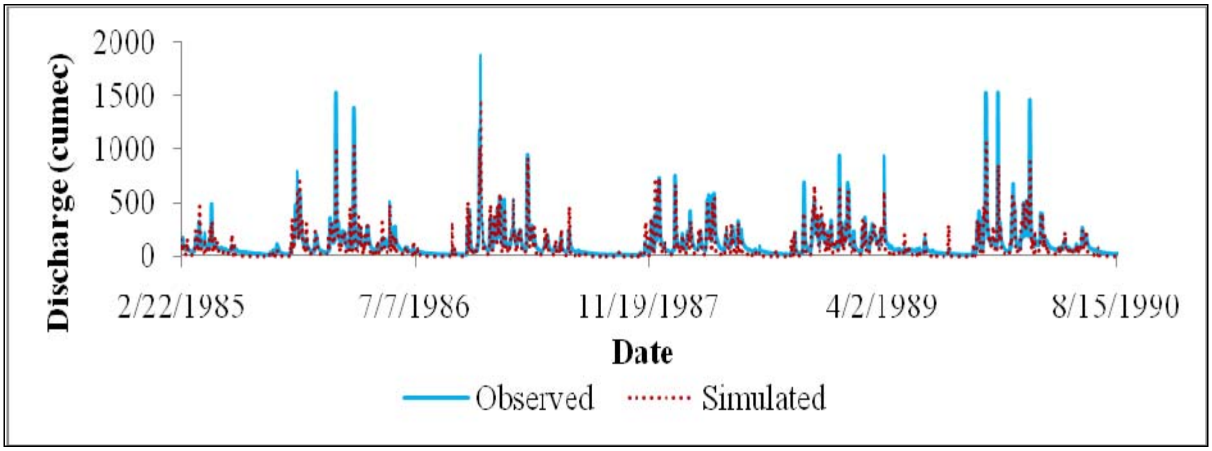


**Figure 13: Observed and modeled Queets streamflow over the evaluation period of 1985-1990.**

**3.3.3. Potlatch**. We have also implemented DHSVM over a mixed agriculture/forest basin in northern Idaho, the Potlatch Basin (Figure 14). Here are incorporating the effects of both tillage practices (in the lower agricultural regions) and climate change on runoff generation over the Potlatch basin. The Potlatch River basin near Julietta, ID was examined using DHSVM, including calibration and evaluation over the historical period of streamflow observations between 08/15/2003 and 12/31/2006 using Geological Survey streamflow records (figure 15). The Maintaince of Variance type 2 (MOVE.2) method (Hirsch et al. 1982) was used to extend the observed streamflow record at the Potlatch gauge statistically by comparing to long-term streamflow observations at the bottom of the Palouse basin (see section 3.3.1). The results of this extension are shown in figure 16. This allowed us to examine the long-term simulations.

To examine the effects of climate change on runoff generation over the Potlatch basin, nine GCMs and 2 emissions scenarios were chosen to be run for the year 2045 using the data of Elsner et al. (2010). This resulted in 18 future climate simulations. These runoff simulations were averaged and compared to historical runoff (Figure 17).

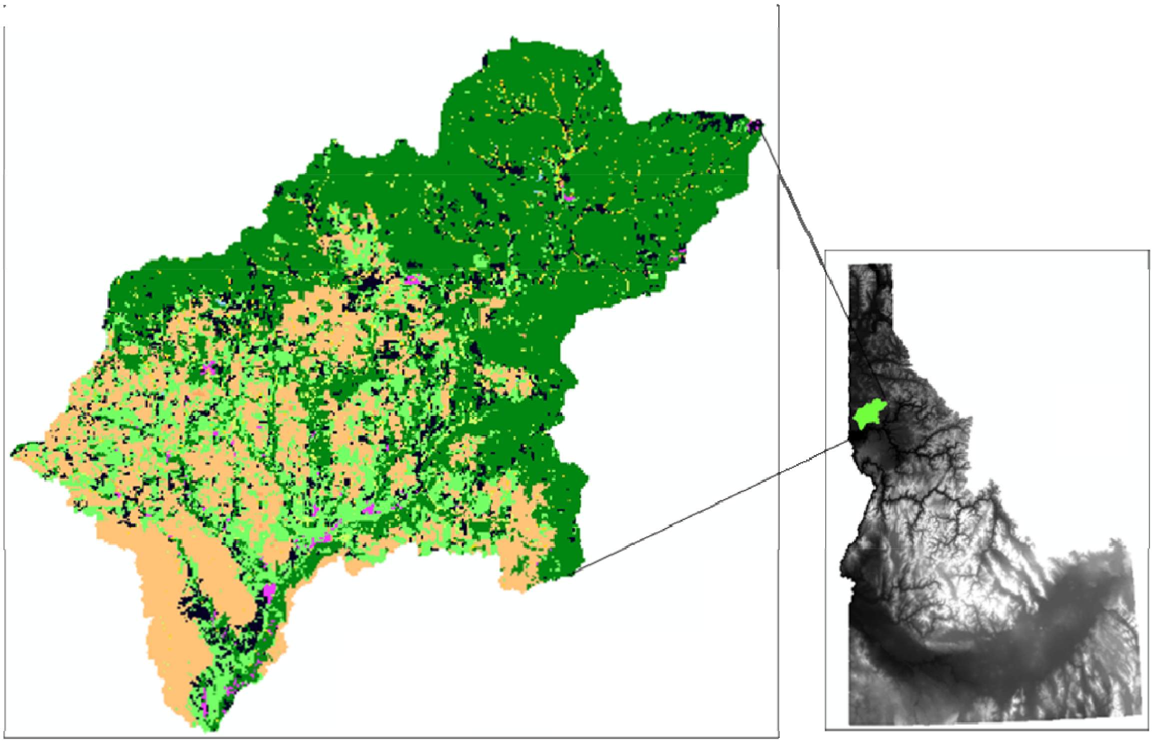

**Figure 14: Potlatch Watershed in northern Idaho.**

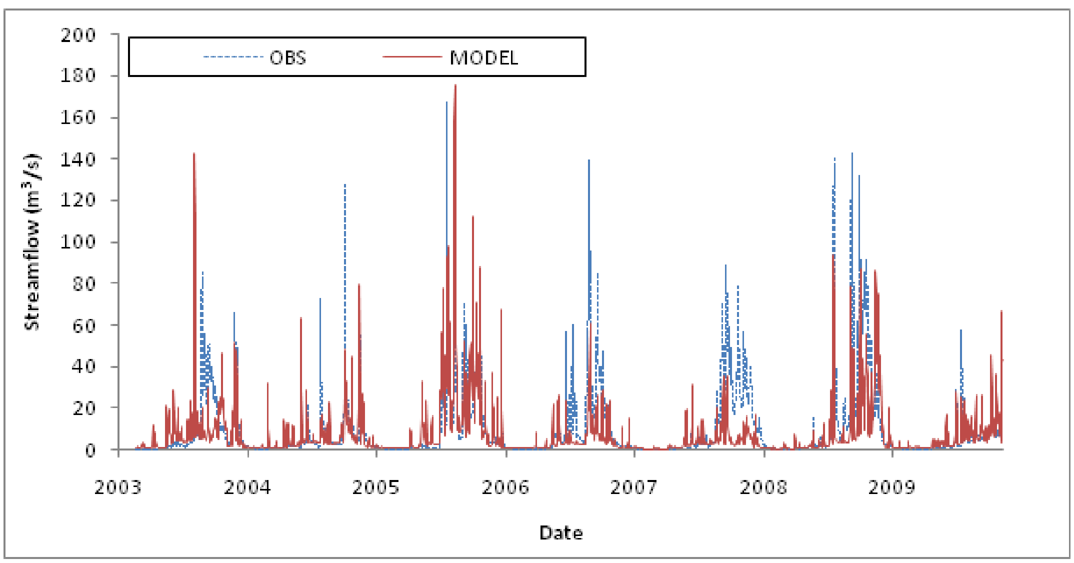


**Figure 15: Comparison between observed and DHSM-simulated streamflow from the Potlatch basin.**

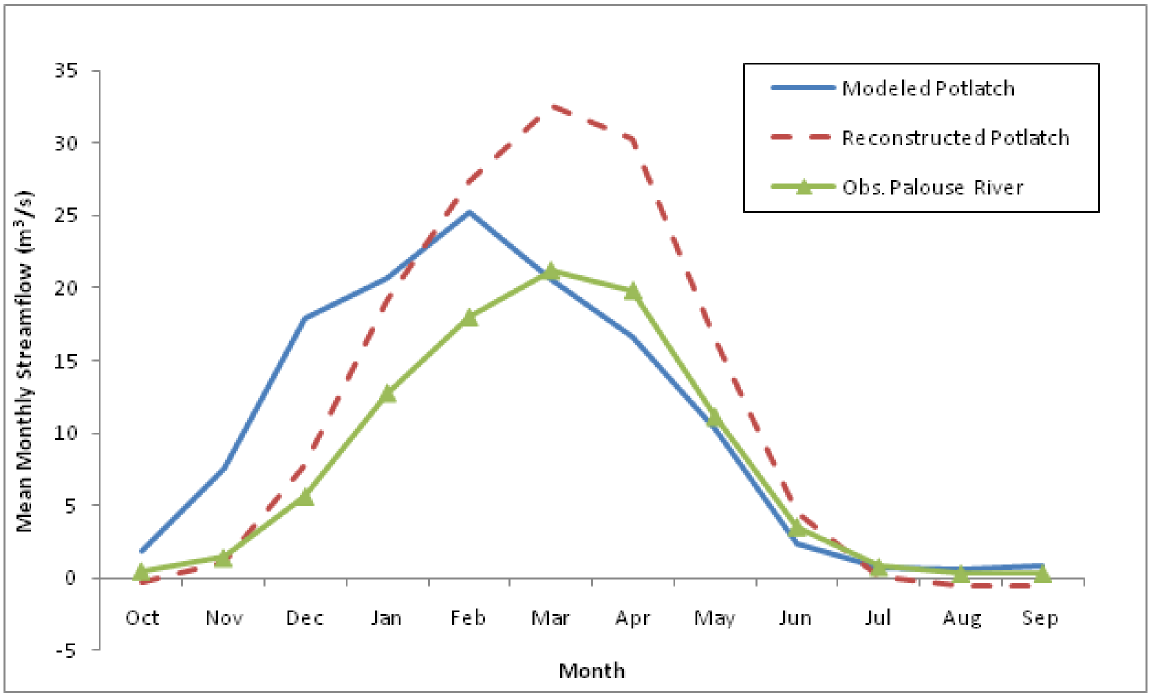


**Figure 16. Comparison between observed and reconstructed streamflow at the Potlatch gauge.**

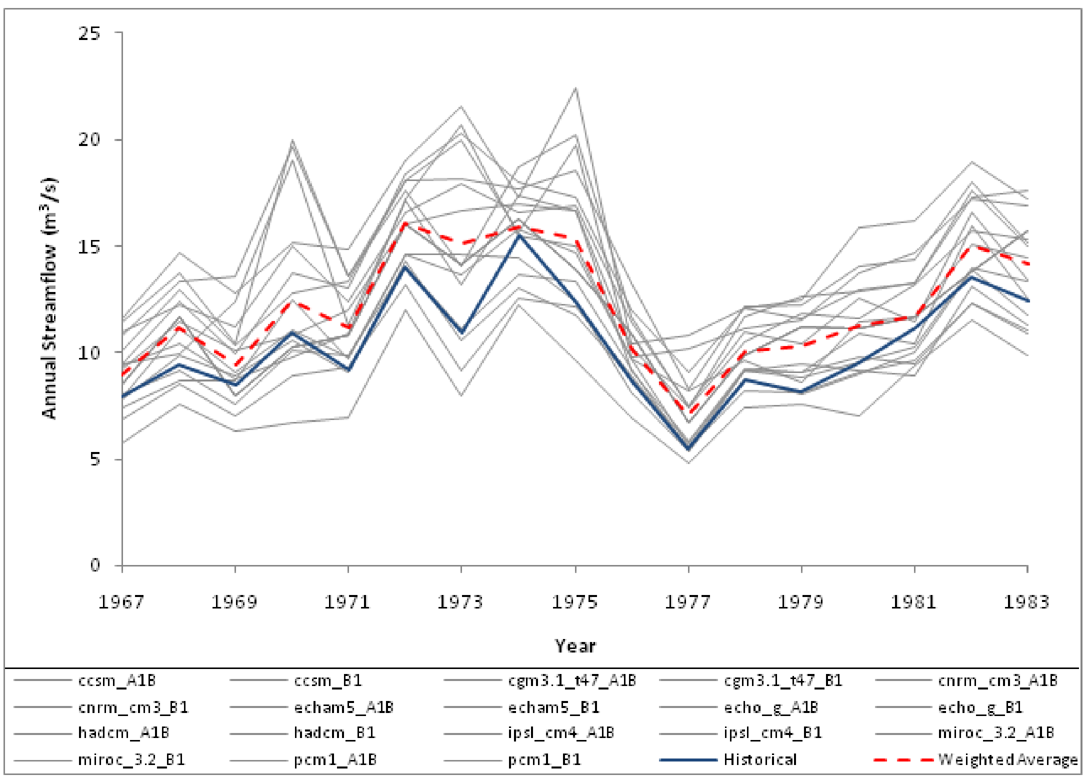


**Figure 17. Year 2045 streamflow response to various GCMs and emissions scenarios (gray lines), mean of 2045 streamflow predictions (red line), and historical streamflow simulations (blue line).**

### 3.4. Cumulative Distribution Functions (CDFs) as Risk-Assessment Tools

Using results from the hydrologic simulations coupled with the Monte Carlo analysis, we created cumulative distribution functions (CDFs) of the likelihood of response in runoff volumes by the year 2045 for each of our rural basins. The CDFs shown below are distributions of the simulated runoff depths due to the 50-year storm that can be used at a more local scale (such as scales more relevant for the Palouse, Queets, and Potlatch basins) for probable average runoff depths. They are illustrated with two distribution fits; the solid line indicating the better fit of the two. The non-exceedance probabilities can be used in conjunction with the storm return interval non-exceedance to scale down the half-degree results to a local scale for use in assessing the reliability of existing water control structure design values. Figure 18 shows the CDF over the Potlatch basin (see section 3.3.3); figure 19 shows the CDF for the Palouse basin (see section 3.3.1), and figure 20 shows the CDF for the Queets basin (see section 3.3.2). The distributions (normal and lognormal) can be used to find runoff depths for a range of non-exceedance probabilities, and to find the median future runoff depth corresponding to a specified storm return interval.

For a culvert meant to handle the 50-year storm runoff, it would be expected to be exceeded in only 2% of years. However, the culvert was likely designed with historical precipitation data. If the culvert were meant to handle 9 mm of runoff from a catchment in a historical climate, from the CDF the probability of non-exceedance of a 9 mm runoff event is 0.80. This suggests a reduced reliability for the culvert and increased risk of failure in its lifetime of service. Each of these CDFs can be used as a risk assessment tool to compare historical design runoff depths with their future non-exceedance probability for a comparable return interval event.

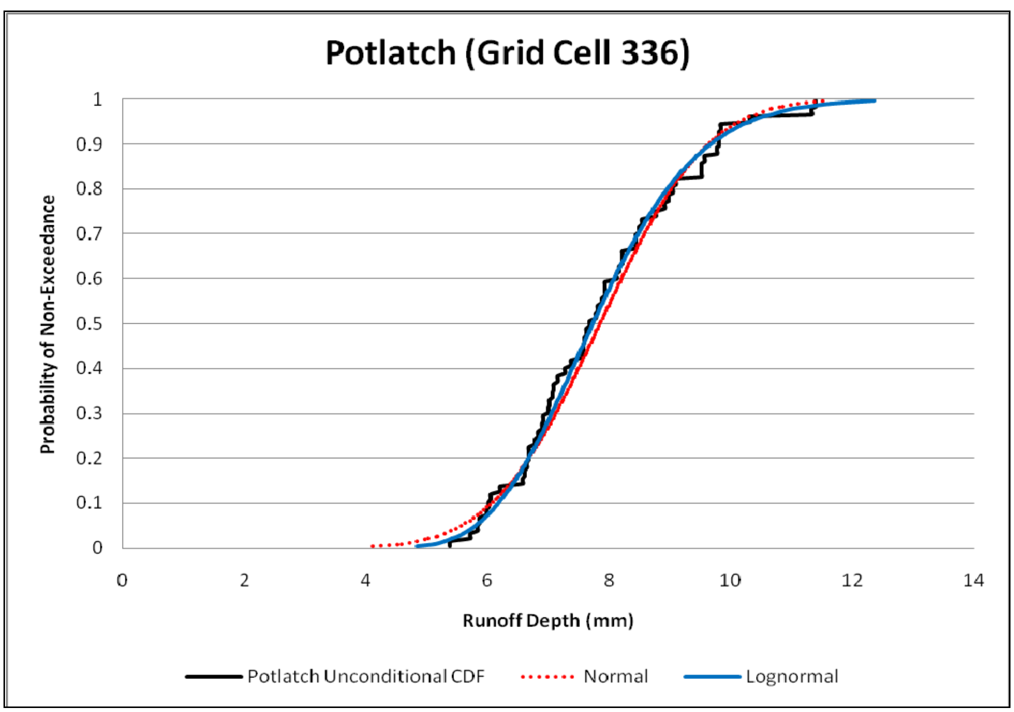


**Figure 18: Potlatch runoff CDF**

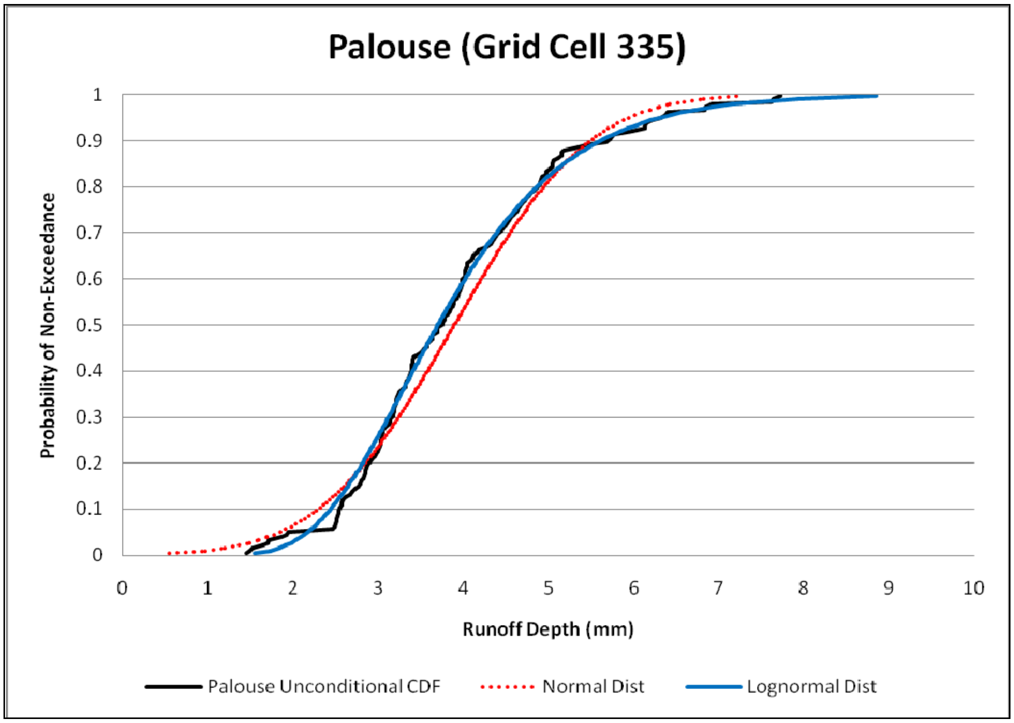


**Figure 19: Palouse runoff CDF**

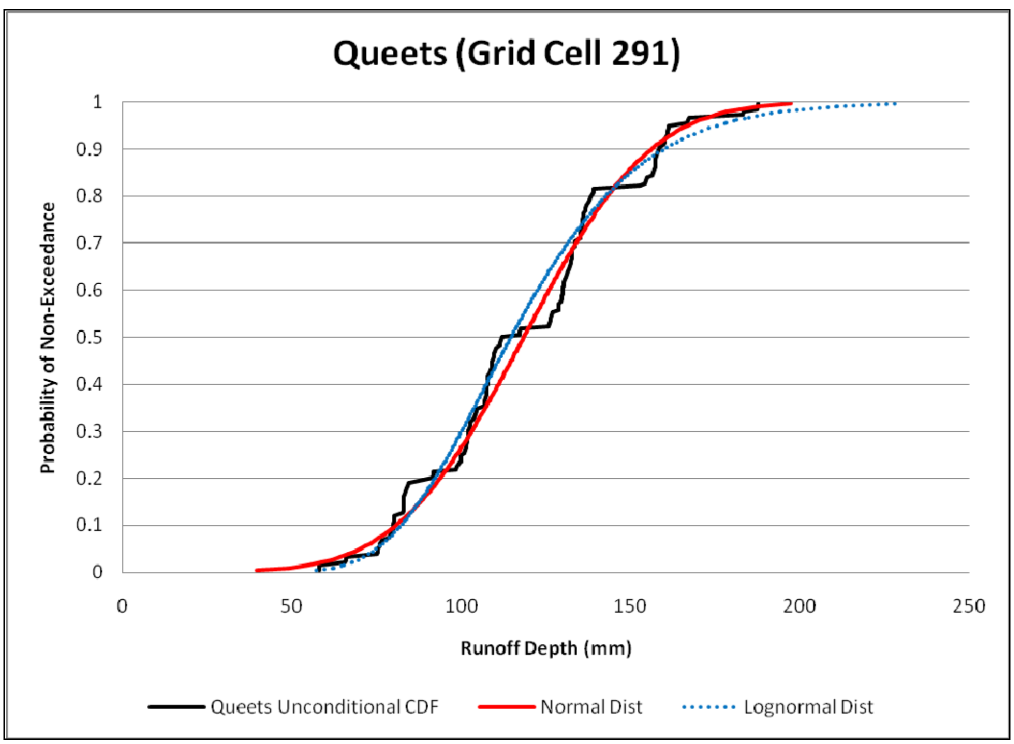


**Figure 20: Queets runoff CDF**

## 5. Discussion

The combination of several uncertain parameters in estimating future runoff when doing any hydrologic assessment makes it difficult to pin down a single answer as being "correct" when forecasting future hydrologic fluxes such as runoff. While two emissions scenarios were selected in this study, and were intended to reflect the worst and best case for emissions in the 2040s, there are infinitely more paths that humans on Earth can follow going forward (Nakicenovic and Swart 2000). $CO_2$ emissions in the early $20^{th}$ century have already exceeded even the most fossil fuel-intensive emissions scenario (A1FI) developed in the late 1990s by the IPCC (Raupach et al. 2007). This means that the uncertainty in emissions scenario reflected in this study is not all-inclusive, since the actual emissions exceed even the study's "worst case". Since these emissions scenarios drive the GCMs used for creating the future climate data used to make hydrologic predictions, the uncertainty in their estimate gets amplified as other layers of uncertainty are added.

In the case of the runoff analysis, the difference between the worst-case A1B and best-case B1 emissions scenarios was a range of -30% to +45% of the historical runoff, with a strong regional signal. The overall change in mean and variance for the Pacific Northwest was small likely due to temperature-driven increases in evapotranspiration (ET) and decreases in soil moisture counteracting intensified storm events in many places. Since a choice of emissions scenario for modeling has a long-reaching impact on other variables, such as soil moisture and snowpack in this study, the safest approach seems to be a bracketing method to choosing an emissions scenario. By selecting scenarios to model that represent the worst and best case; the risks can be reduced by understanding a basic range of possibility.

The selection of GCM in this case offered little insight into understanding changing runoff in the Pacific Northwest. While the magnitude of runoff depth changed slightly between the models, no changes in the regional signature of the runoff occurred. Also, the result data from a particular GCM is strongly correlated to the precipitation bias of the GCM when evaluating past climate conditions. Thus, evaluations such as that performed by Mote and Salathé (2010), which ranked the models in terms of their ability to re-create historical climate specifically in the Pacific Northwest, are important for selecting a model that is most "realistic" when performing studies on a particular area. Different GCMs have different strengths and weaknesses, and will perform better over different regions based on methods for solving planetary atmospheric and oceanic circulation within the model. Selecting model output that best describes the region of interest is important for performing experiments for future climate in that region.

While the hindcasting ability of a GCM does not necessarily evaluate the ability of a model to predict changes in the climate going forward, it is clear that the future scenarios that are forecasted reflect the bias that each model has when evaluating the historical climate.

Soil moisture and snowpack conditions in the future are affected significantly by a warming climate. Increased temperatures cause an increase in soil moisture loss to evapotranspiration and a reduction in water stored as snowpack. These effects can change the amount, and especially in the case of snowpack, the timing of runoff. Since snowpack storage declines in a warmer climate, due to earlier melting and a decrease in the amount of precipitation that falls as snow, the effect of spring snowmelt-caused runoff decreases.

It is shown that decreased snowpack is correlated to increasing runoff in many places in the Pacific Northwest. While this study did not specifically examine the effects of climate change on winter runoff events, many of the events were "staged" to take place in winter conditions. In the locations where snowpack had significant presence when the annual maximum events occurred most frequently, such as the Olympic peninsula, the decreased presence of snowpack was related to a large (greater than 50%) increase in runoff due to the 50-year event in the future.

Soil moisture did not have as significant an effect on the future runoff depth as would have been anticipated. While a minimum change of +11% of the median soil moisture runoff depth was observed for the difference between the highest and lowest quantiles, there was no clear trend in where the soil moisture effects would be greatest. Predicting soil moisture in a changing climate would prove difficult because of the estimate of the water balance of the soil layers. Precipitation is the greatest predictor for soil moisture, and precipitation changes in the future are highly uncertain according to emissions scenario and GCM.

The areas at highest risk due to changes in runoff are the locations that in general already handle a large amount of runoff and which are projected to experience a large average increase in runoff for common design events. One such area is the Olympic peninsula, which experiences the heaviest precipitation in the Pacific Northwest and produces the highest runoff, but is also projected by weighted average to increase runoff production, in some cases by more than 10%. However, this area is also the most uncertain in terms of the range of events simulated using this method. While the prediction is fraught with uncertainty, the consensus of the models in the suite show that runoff due to these common design storm events in the Pacific Northwest will increase.

Although this study quantified the uncertainty associated with the various inputs to a hydrologic assessment, it is not exhaustive in that effort. One component contributing to forecasting uncertainty that went unanalyzed in this study is that of the methodology used for downscaling the meteorological data. While the emissions scenarios and GCMs project different versions of a future climate, no clear pattern in change related to the topography and characteristic weather of the PNW emerges on a broad scale. The coarse 1/2 degree resolution for the hydrologic simulation is also to blame, as it averages a large number of explicit features that would characterize changes. In the case of emissions scenarios, the pattern created in the difference between the A1B and B1 runs tells us little about what different warming scenarios will do in the Pacific Northwest. Pinning down the cause of this is more difficult, but spatial issues, between downscaling large GCM grid cells and 1/2 degree hydrologic simulation, certainly play a role.

When downscaling GCM outputs, which often have grid cells between 1 and 5 degrees in latitude and longitude, it is important to capture the regional information contained within that grid cell, especially when estimating extreme events or locations with complicated topography. Salathé et al. (2010) showed that the use of models to resolve the coarse-resolution GCM outputs to a finer grid, while regarding the complicated topography and coastlines, does a better job of matching regional signatures of meteorology in an area. The hybrid delta downscaling method used for the data in this study is limited by historical data and scaling the temperature and precipitation based on GCM-projected changes. However, use of a numerical weather model or a regional climate model (RCM) similar to Salathé et al (2010) could produce dynamically-downscaled meteorology data for a future climate which could represent the changes in climate on a finer temporal scale, as well as resolving explicitly important regional features, such as changes in elevation, on a finer spatial scale.

## 5. Conclusions, Limitations, and Future Directions

### 5.1. Conclusions

Using Monte Carlo simulation with the VIC hydrology model, we forecasted runoff conditions in the Pacific Northwest, and this forecast allowed us to answer two questions about the effects of climate change on runoff. First, how will the change in atmospheric conditions, such as intensification of extreme precipitation and a warmer climate, affect the amount of runoff generated by design storms of commonly-used return intervals; and second, what uncertain parts of projecting climate, as it changes in time, represent the most uncertainty in forecasting runoff in the future?

The forecast shows a general increase in runoff depth for events caused by design storms of 2, 25, 50 and 100-year average return intervals; however, the uncertainty in this forecast is large. A majority of locations in the Pacific Northwest show an increase in runoff depth for all of the return intervals tested. While this very generally explains why engineers and planners whose job is to deal with water have reason to be concerned in the future about runoff, this conclusion alone does not offer any assistance in planning for climate change. While there are tools that exist to attempt to understand the state of the climate going forward, such as the IPCC emissions scenarios and GCM projections for the climate, the range of uncertainty in these tools makes it difficult to precisely quantify changes in measurable hydrologic fluxes, such as runoff. Understanding the source of uncertainty can help avoid making mistakes such as reliance on the output of a single GCM, or even a range of emissions scenarios (which we have discovered are all low). The GCMs and emissions scenarios are the driving factors behind understanding the potential future climate. The range in results for future temperature and precipitation is due to uncertainty from predicting the course of greenhouse gas emissions and the ability of GCMs to produce accurate forecasts of climate in the future in response to the greenhouse gas emissions scenarios. While there is no current way to evaluate the ability of a GCM to produce realistic climate forecasts, the current method of evaluating GCMs by their ability to re-create past climate reveals that a model's bias in this hindcasting is significantly correlated to the results that it will produce in the future. Because all models in this study display a positive, "wet" bias for precipitation in hindcasting, some of the resulting projected increases could be due to this effect.

The effect of changing snowpack and soil moisture shows a clear relationship for runoff, with increased soil moisture increasing runoff for all cells in the domain, and reduced snowpack increasing runoff for a majority of the Pacific Northwest. While trends regarding soil moisture in the face of climate change are not clear due to uncertainties in forecasting precipitation, the reduction in snowpack caused by a warming climate looks to be another mechanism for increasing risk in regard to runoff in the future. The areas in the Pacific Northwest that are most at risk are the wet regions that historically produce significant runoff and are projected to experience an increase in runoff due to climate change. Thus, parts of the Olympic peninsula and the Puget Sound region appear to be most at-risk in the future in regard to handling runoff. However, these areas also have the most uncertainty when projecting future runoff depths. The envelope of possible future conditions due to climate change is very large, and due to the uncertainties for each component of making a forecast, achieving high confidence in the probability that a water control structure will not fail in its lifetime of service is much more difficult.

**5.2. Limitations**

There were three major limitations contained within this study. The first was the use of the daily timestep. Since the meteorological data were at a 24-hour timestep by calendar day, a systematic low bias was introduced for the 24-hour events. Instead of considering the annual maximum 24-hour precipitation totals, which could span two days, the largest calendar day total was considered instead. Another limitation was the aggregation and spatial scale for the hydrologic model. Since the parameters and meteorological data were aggregated from 1/16 to 1/2 degree, the most extreme features were averaged out with each step of aggregation. This is significant when addressing grid cells that experience the most extreme precipitation, as the coarser resolution cell would not reflect the intensity of the most intense fine resolution contained within. In places with large changes in elevation and therefore precipitation, such as the Olympic peninsula or the Cascade Mountains, cells with very high precipitation and a high risk regarding runoff may be averaged with several low-intensity cells, reducing the visible risk in that area. The third major limitation arises from the VIC model itself. VIC is capable of simulating the effects of frozen soils, which could have a significant impact on runoff in areas where rainfall occurs in times when the water content of the soil is frozen. This creates a systematic low bias in the results for runoff.

**5.3. Future Directions**

In order to reduce uncertainties in projecting the effects of climate change on runoff in the Pacific Northwest, several steps can be taken toward improving the forecast. The use of dynamically-downscaled climate data would do a better job of characterizing the precipitation regimes encountered in the Pacific Northwest due to complex topography and coastlines, which are not well-characterized by coarse-scale GCM output and the delta downscaling method. The dynamic downscaling would also do a better job of capturing the intensification of precipitation events that is expected to occur due to climate change, and would affect design storms used for runoff-related design the most. The use of a finer spatial scale for the downscaled results and the hydrologic simulation would do a better job of characterizing extremes as well as local hydrologic response to those extreme events than larger, lumped average cells. Finally, using continuous distributions for the soil moisture and snowpack and a larger sample size for the Monte Carlo simulation of future results would produce a better estimate of the posterior distribution of runoff depths for the future climate scenarios.

Going forward into an uncertain future, this study serves one primary purpose. This study serves as a framework for engineers and planners who need to plan for risks associated with climate change in the future. Many current practices rely on a single emissions scenario and GCM forecast to make a forecast for future conditions. This study has shown that the individual selection of either of these parameters to achieve a result runs the risk of being completely misleading, since the variability in result that occurs from the selection of either parameter is very high. By considering a range of possibilities and evaluating the central tendency in the results for climate change projections, an appropriate amount of risk can be assumed. A single point gives no assurance of reliability whatsoever. This is also a warning to those in areas sensitive to flooding or to runoff-related problems such as erosion. While the historical 25-year event is expected to be exceeded in only 4% of years in a stationary climate, the increased intensity of these extreme events in a changing climate means the storm or flood with the intensity equal to the historical 25-year event will be exceeded more often. This holds for events of all average return intervals – the intensity of an event associated with a long ARI would increase, and the ARI for that specific intensity would decrease.

In this study we only evaluated the effects of one downscaling method. As extensively discussed previously, the comparison of a dynamic downscaling method to the delta method could produce interesting results regarding the effects of the Pacific Northwest's complicated topography. Investigating changing contributions of snowmelt and snowpack to runoff in a warming climate would offer insight into areas where runoff makes a significant contribution to runoff and streamflow, specifically west of the Cascades.

**6. Directly-Related Presentations and Publications**

Karlovits, G., and J.C. Adam, 2010, Uncertainty analysis of climate change effects on runoff for the Pacific Northwest, WSU Water Forum, Nov 4, Spokane, WA.

Karlovits, G., and J.C. Adam, 2010, Monte Carlo simulation to characterize stormwater runoff uncertainty in a changing climate, American Geophysical Union, Dec 13, San Francisco, CA (accepted). (The authors gratefully acknowledge TransNOW for student travel support.)

Karlovits, G., and J.C. Adam, 2011, Probabilistic climate change analysis for stormwater runoff in the Pacific Northwest, American Meteorological Society, Jan 25, Seattle, WA (accepted).

Karlovits, G., and J.C. Adam, 2011, Monte Carlo simulation to characterize stormwater runoff uncertainty in a changing climate, Water Resources Research (in preparation).

**References**

Breuer, L., K. Eckhardt, and H.-G. Frede (2003), Plant parameter values for models in temperate climates, Ecological Modeling, 169, 237-293.

Cherkauer, K., and D. Lettenmaier (1999), Hydrologic effects of frozen soils in the upper Mississippi River basin, *Journal of Geophysical Research-Atmospheres*, 19599-19610.

Elsner, M., L. Cuo, N. Voisin, J. Deems, A. Hamlet, J. Vano, K. Mickelson, S. Lee, and D. Lettenmaier (2010), Implications of 21st century climate change for the hydrology of Washington State, *Climatic Change*, 225-260.

Frei, C., C. Schar, D. Luthi, and H. Davies (1998), Heavy precipitation processes in a warmer climate, *Geophysical Research Letters*, 1431-1434.

Gao, H., Q. Tang, X. Shi, C. Zhu, T. J. Bohn, F. Su, J. Sheffield, M. Pan, D. P. Lettenmaier, and E. F. Wood (2010), Water Budget Record from Variable Infiltration Capacity (VIC) Model, *Algorithm Theoretical Basis Document for Terrestrial Water Cycle Data Records*, *(In Review)*.

Hamlet, A., and D. Lettenmaier (2005), Production of temporally consistent gridded

precipitation and temperature fields for the continental United States, *Journal of Hydrometeorology*, 330-336.
Hosking, J. R. M., and J. R. Wallis (1997), *Regional Frequency Analysis: An Approach Based On L-Moments*, Cambridge University Press.
Liang, X., D. Lettenmaier, E Wood, and S. Burges (1994), A simple hydrologically based model of land-surface water and energy fluxes for general-circulation models, *Journal of Geophysical Research-Atmospheres*, 14415-14428.
Maurer, E., A. Wood, J. Adam, D. Lettenmaier, and B. Nijssen (2002), A long-term hydrologically based dataset of land surface fluxes and states for the conterminous United States, *Journal of Climate*, 3237-3251.
Milly, P., J. Betancourt, M. Falkenmark, R. Hirsch, Z. Kundzewicz, D. Lettenmaier, and R. Stouffer (2008), Climate change - Stationarity is dead: Whither water management?, *Science*, 573-574.
Mitchell, T., T. Carter, P. Jones, M. Hulme, and M. New (2004), A comprehensive set of climate scenarios for Europe and the globe: the observed record (1901–2000) and 16 scenarios (2001–2100) *Rep.*, Tyndall Centre Working Paper No 55, University of East Anglia, Norwich, UK.
Mote, P., and E. Salathe (2010), Future climate in the Pacific Northwest, *Climatic Change*, 29-50.
Nakicenovic, N. (2000), Greenhouse gas emissions scenarios, *Technological Forecasting and Social Change*, 149-166.
Novak, M. D., W. Chen, and M. A. Hares (2000), Simulating the radiation distribution within a barley-straw mulch, Agricultural and Forest Meteorology, 102, 173-186.
Raupach, M., G. Marland, P. Ciais, C. Le Quere, J. Canadell, G. Klepper, and C. Field (2007), Global and regional drivers of accelerating CO2 emissions, *Proceedings of the National Academy of Sciences of the United States of America*, 10288-10293.
Rosenberg, E., P. Keys, D. Booth, D. Hartley, J. Burkey, A. Steinemann, and D. Lettenmaier (2010), Precipitation extremes and the impacts of climate change on stormwater infrastructure in Washington State, *Climatic Change*, 319-349.
Salathe, E., L. Leung, Y. Qian, and Y. Zhang (2010), Regional climate model projections for the State of Washington, *Climatic Change*, 51-75.
Tasker, G. (1983), Effective record length for the T-year event, *Journal of Hydrology*, 39-47.
Wigmosta, M.S., L. Vail, and D. P. Lettenmaier (1994). A distributed hydrology-vegetation model for complex terrain, *Wat. Resour. Res.,* 30, 1665-1679.
Wigmosta, M. S., L. J. Lane, J. D. Tagestad, and A. M. Coleman (2009), Hydrologic and erosion models to assess land use and management practices affecting soil erosion, Journal of Hydrologic Engineering, 14(1), 27-41.
Wilby, R., and I. Harris (2006), A framework for assessing uncertainties in climate change impacts: Low-flow scenarios for the River Thames, UK, *Water Resources Research*, -.