AN ABSTRACT OF THE THESIS OF

Aimee L. Brown for the degree of Master of Science in Geography presented on June 12, 2009.

Title: Understanding the Impact of Climate Change on Snowpack Extent and Measurement in the Columbia River Basin and Nested Sub Basins

Abstract approved: ________________________________

Anne W. Nolin

Shifting climate patterns in the Columbia River basin are affecting snow pack, and, as a result, stream flow throughout the region. In the Oregon Cascades, ever growing populations, and their associated activities, place increasing stress on an already over allocated hydrologic system. Political pressures, including the possibility of renegotiation or termination of the Columbia River Treaty between the United States and Canada; societal pressures, including a desire for ecosystem services and fish habitat; and economic pressures, including a need for adequate streamflow for hydropower generation and irrigation, all necessitate a better understanding of current and future snow pack. This work focuses on analyzing the ability of the current snowpack measurement system to represent and capture snowpack in the Columbia River basin and its sub basins under both today's climate and future climates. In addition, this work develops a more comprehensive knowledge of the impact climate warming will have on snow-covered areas across the region.

To determine the efficacy of current snow water equivalence (SWE) measurement sites, the locations and characteristics of sites in the McKenzie River Basin, a sub basin of the Columbia River basin, were considered. SWE was distributed through the basin using the physically based model, SnowModel. SWE values at the four SNOTEL sites in the basin ranged from 0.18-0.37 m at peak SWE. Three of the sites had SWE values greater than 180% of average SWE of the snow covered area. Using elevation, aspect and slope, a 16-node binary regression tree explained controlling variables on SWE at the basin scale. As expected, elevation is the primary determinant in SWE distribution, however, the influence of different parameters shifted throughout the accumulation and ablation seasons.

Updated high resolution PRISM precipitation and temperature data are used to map areas within the Columbia River basin and two nested sub basins that are at risk of turning from winter snow dominated precipitation regimes to winter rain dominated under warming scenarios ranging from 1-3°C. Within the Columbia River basin, the Oregon Cascades exhibit the greatest degree of sensitivity to changes in precipitation. Under a 2°C warming scenario, an increase that the International Panel on Climate Change finds highly likely to occur within the next 30 years, 30% of current-day snow covered area in Oregon's Willamette River Basin will be at risk of turning from snow to rain. The water storage that will be lost if such a change does occur (0.73 km^3) is equivalent to more than 8 months worth of water at the current rate of water use in the basin. Data from nine regional stations in the National Oceanic and Atmospheric Administration (NOAA) National Weather Service (NWS) Cooperative Observer Program were used to validate placement of snow by the model.

The conclusions of this work suggest that the placement of snow measurement sites requires refinement and improvement if the measurements are to accurately represent basin wide snowpack today and in the future. Water and natural resource managers will find the results presented here useful for siting future measurement locations that capture and represent SWE during times of interest. While political, societal and economic pressures will only increase, these findings provide early steps for the creation of a more robust system that has the potential to help stakeholders make informed decisions about their water resources, their communities and their needs.

Understanding the Impact of Climate Change on Snowpack Extent and Measurement in the Columbia River Basin and Nested Sub Basins

by

Aimee L. Brown

A THESIS

submitted to

Oregon State University

in partial fulfillment of

the requirements for the

degree of

Master of Science

Presented June 12, 2009

Commencement June 2010

Master of Science thesis of Aimee L. Brown presented on June 12, 2009.

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I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Aimee L. Brown, Author

ACKNOWLEDGEMENTS

I would like to first thank my primary advisor, Anne Nolin, for her trust, patience and support of not just my thesis but of all my research, career and life pursuits. I am thankful for my committee members, Aaron Wolf and Julia Jones, for their involvement and advice during my graduate experience. Additionally I would like to thank the faculty and staff of the OSU Geosciences department — in this case it did take a department to raise a masters. Mark S. Meyers provided his time, as well as the lab and server space that was fundamental to the creation of the numerous posters and figures that went into this work. I am thankful to the employees of the weather and streamflow forecasting group at the Bonneville Power Administration, especially Ann McMannamon, for taking me in then letting me go. Also, my sincere appreciation to Margaret Herring and Dave King at Oregon State University's Department of Extension and Experiment Station Communications.

I have been fortunate to have an amazing support network during my graduate experience. Particularly, I would like to Jay Alder for his programming mentorship, coding advice and patience. This work would not have been possible without the involvement of Eric Sproles, and would not have been nearly as much fun without the other members of our research group including Lauren Parker, Beth Copeland and Quin Ourada.

In the end, it has been my family and friends who have held me up and gotten me through. While I could never list them all, or thank them enough, I would like to acknowledge Ben Brown, Lindsay Miller, Marco Clark and Anna Pakenham.

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Chapter 1 – Introduction

In the first week of May 2009, United States President Barack Obama stood in front of the world and admitted climate change was real. To a global audience he said human activity was at its heart, and as a community we must take responsibility for a warming earth. This admission came at the end of more than a decade of wavering, neglect and a general head in the sand approach to the topic by some of the world's most powerful individuals and corporations. This refusal to admit to a problem of our own making has set us back in our ability to find a timely solution that will allow for the preservation of the way of life to which we have grown accustomed. Global warming is real, now we must face it.

The first major study of global climate change occurred 30 years ago. In 1979, the National Academy of Sciences created the Ad Hoc Study Group on Carbon Dioxide. The group looked at a series of models designed to determine the impact of adding carbon dioxide to the atmosphere and found that if atmospheric levels of CO2 continued to increase there was "no reason to doubt that climate changes will result and no reason to believe that these changes will be negligible" (Kolbert 2006). Analysis of satellite data shows that almost 15 years prior to this study, snow cover in the Northern Hemisphere was already on the decline. At the end of the 20th century the loss of historic average snowpack had already crept above 10%, and in the western United States, where as much as 60% of annual stream flow originates as snow, some areas had already seen a decrease of more than half of annual spring snow pack (IPCC 2001; Mote et al., 2003; Serreze et al., 1999).

For the last fifty years the impact of climate change on water resources in the western portion of the Columbia River basin has sat quietly under the radar. There has been some acknowledgement by hydrologists and natural resource managers that snowpack is decreasing. However, planning for, and adaptation to, these changes has remained slow even while annual snowpack's have fallen to 50% of historic averages (Mote et al., 2003; Serreze et al., 1999). Today the region faces innumerable demands on water resources that range from a need for adequate in-stream flow for endangered salmonids and steelhead, to adequate and appropriately timed flow for hydropower. Recreation, irrigation, industry, navigation, and ecosystem services all require attention as well, and all are beginning to experience trickle down effects of changing precipitation regimes in the basin. The response to these effects will require wide spread collaboration, discussion and planning at the local, regional, national and international scale.

The decline of western snow packs over the last 50 years presents perhaps the greatest current concern for water managers in large part because the activity that occurs at, and above, snowline controls downstream processes including a range of ecosystem services and groundwater recharge (Jefferson et al., 2008; Bales et al., 2006; Barnett et al., 2005; Service, 2004; Beniston 2003; Serreze et al., 1999).

The two articles contained here focus on how snow pack in the Columbia River Basin is changing in the face of climate warming, and how we as scientists, policy makers and water managers go about quantifying those changes in order to accurately manage water resources and meet societal, economic and political goals and needs. The first article, *Determining the representativeness of the NRCS SNOTEL network at the basin scale*, asks how well our current snow water equivalence measurement locations capture what is truly happening across a landscape. Snow water equivalence, or SWE, is a measure of the amount of water that would be released from the snowpack if it underwent instantaneous melt. It is the bellwether for summertime stream flow in the west, and is used in stream flow forecasting, water allocation planning and management. Accurate measurements of SWE are fundamental to the health and well being of regional ecosystems and economies. Yet, questions regarding the accuracy and trustworthiness of these point measurements in comparison to what occurs across the greater basin had not been answered with certainty leaving a gap in our understanding of the system.

The second article, *Measuring at-risk snow in the Columbia River basin and two nested sub basins*, builds on the techniques of Sturm et al., (1995) and Nolin and Daly (2006) to answer the questions: What areas are most susceptible of changing from snow dominated precipitation regimes to rain dominated systems under different warming scenarios? And, at what scale will that change occur? The areas of change are then converted to volumetric water content and placed next to our daily water usage in the basins of interest for comparison, so that we can better understand the storage capacity that will be lost under future warming scenarios. Quantifying this loss is a step toward determining if future storage facilities will be needed, and if so, at what scale. In addition, this article further examines where snow measurement sites are located today, and how these locations may be impacted by a warming climate.

The findings of this work suggest that within the next half century the hydrologic picture in the Columbia River basin will undergo a radical transformation. Changes in winter precipitation regimes will result in less snowpack overall. The resulting lack of storage from this change will likely be seen in less available water in the summer and lower late summer base flows (Jefferson et al., 2008; Service, 2004; Nash et al., 1991). Current measurements sites will likely fall outside of the snow zone, and areas where there are significant amounts of stable snow will go unmeasured forcing necessary guess work by water managers and forecasters. In addition to the issues uncovered here, declines in snowpack will also affect a range of ecosystem services and behaviors, including but not limited to increased wild fire risk, loss of habitat, decreased availability of irrigation for agriculture, warmer in channel stream temperatures and changes to plant phenology (Westerling et al., 2006; Mote et al., 2005). In many ways we as a community are completely unprepared for the disarray that such shifts will bring. New snow pack-measurement sites, water-management plans and approaches to water use and storage will be necessary if the basin is to thrive. It is not a brand new world we are entering into, but it is a different world with brand new challenges.

Chapter 2 – First Manuscript

Determining the representativeness of the NRCS SNOTEL network at the basin scale

2.1 Abstract

Across the western United States winter snows provide 70-80 percent of total annual runoff and are a primary contributor to spring and summer stream flow. Measurements of snow water equivalence (SWE) acquired by the Natural Resource Conservation Service (NRCS) snowpack telemetry system (SNOTEL) are widely used by water managers and hydrologists to forecast for stream flow in sensitive and heavily used catchments throughout the region. However, point measurements, like those made at SNOTEL sites, may not accurately represent the distribution of SWE at the basin scale. A wide range of physical and climatic variables can affect snow distribution across western catchments at a variety of spatial and temporal scales. In this study, the physical and climatic conditions represented by SNOTEL sites in the McKenzie River Basin, Oregon, are analyzed in order to answer the question: how well do point measurement locations represent conditions across the basin?

SWE was distributed through the basin using the physically based model, SnowModel. SWE values at the four SNOTEL sites in the basin ranged from 0.18-0.37 m at peak SWE. Three of the sites had SWE values greater than 180% of average SWE of the snow covered area. Using elevation, aspect and slope, a 16-node binary regression tree explained controlling variables on SWE at the basin scale. As expected, elevation is the primary determinant in SWE distribution. However, there are no SNOTEL site locations in the upper 32% of the basin where 75% of the total basin SWE is distributed. Water and natural resource managers will find the results presented here useful for siting future measurement locations that accurately capture and represent SWE throughout the accumulation and ablation seasons.

2.2 Introduction

The complexity of mountainous terrain creates incredible spatial variability in the distribution of snowpack (Elder et al., 1991; Sturm et al., 1995). Steep and varied terrain, dense vegetation, wind turbulence and variable distribution of solar radiation and precipitation combine to create large discrepancies in snow depth and cover (Sturm et al., 1995). This lack of homogeneity complicates measurement techniques of which the results are often used to: model snow melt runoff, forecast future water availability, and plan for necessary adjustments in reservoir storage and in channel flow. An inability to accurately measure snowpack in regions where hydrology is dominated by snowmelt has serious economic and ecologic consequences.

Throughout the western United States winter snow packs provide the primary source of runoff for spring and summer stream flow (Bales et al., 2006). Snowmelt contribution to total annual runoff in the Columbia River basin (CRB) is estimated at 70-80 percent (Doesken et al., 1996; Serreze et al., 1999). Future climate projections for the CRB and surrounding area suggest warmer, wetter winters and longer drier summers. The impact of these shifts is unknown, and this uncertainty is exacerbated by a lack of distributed base line measurements for snow water equivalence (SWE) at the basin scale. The distribution of SWE at the basin scale is a controlling factor in the timing and release of runoff making it also important to basin ecology and surface water chemistry (Balk et al., 2000).

To better understand and forecast for stream flow in sensitive and heavily used catchments throughout the CRB, water managers and hydrologists regularly use measurements of snow water equivalence (SWE) taken by the Natural Resource Conservation Service (NRCS) snowpack telemetry system (SNOTEL) (Serreze et al., 1999). In these watersheds where a range of interests often compete for limited water having accurate measurements of SWE is essential to good management and conflict avoidance (Elder et al., 1991).

Today's NRCS SNOTEL system evolved from a 1930s congressional mandate calling for a means to measure western snowpack so as to aid in stream flow forecasting. The original system relied on manual snow course measurements and snow surveys. Beginning in 1980 the system began to add an automated network capable of collecting snowpack and meteorological data in near real time (Serreze et al., 1999). Today there are 730 SNOTEL stations in 11 western states; 191 sites ate located in the CRB (NRCS 2009). Standard sites have a pressure sensing snow pillow, a precipitation gage and an air temperature sensor.

The temporal complexity of the SNOTEL system allows for the storage and acquisition of data across a range of time scales, and sites are designed to operate without human intervention or maintenance for up to a year. Each site is electronically monitored for problems and glitches, however access under winter conditions can be limited (NRCS, www.wcc.nrcs.usda.gov 2009). Many sites remain unvisited during winter months and it is unknown how well the point measurements made at the site capture the physical and climatic conditions of the surrounding landscape (Tom Pagano, NRCS, personal communication 2008).

Point measurements of SWE, like those made at SNOTEL sites, may not provide accurate representation of the snow at the basin scale (Elder et al., 1991), making the inference and interpolation of point measurements problematic. SNOTEL site locations likely only capture a small subset of the physical and climatic variables within a basin, and therefore the measurements taken at these sites will also only reflect a small set of actual conditions (Molotch et al., 2006).

In normal precipitation years SNOTEL point measurements have proven satisfactory for water management and forecasting (Balk et al., 2000). However errors in forecasting based on SNOTEL measurements "dramatically increase" for years with snowpack outside normal ranges (Balk et al., 2000). Work done by Daly et al., (2000) suggested that measurements of SWE taken at SNOTEL sites were biased toward overestimates of mean basin-wide SWE, however limits on current methods and technology have prevented this from being tested.

Remotely sensed data are not yet available in a fine enough resolution to be useful in mapping the distribution of SWE at the basin scale (Moltoch et al., 2006; Chang et al., 1991). Several physically based models have been developed and can successfully model snow distribution over predominantly flat or rolling terrain, however their success in mountain landscapes remains in question (Erickson et al., 2005; Winstral et al., 2002; Pomeroy et al., 1993; Liston and Sturm et al., 1998). The use of binary regression trees to model the spatial distribution of SWE in topographically complex terrain has been used in mountainous regions including the Sierra Nevada and the Rockies (Molotch et al., 2005; Winstral et al., 2002; Elder et al., 1998,). In using the regression tree methods independent variables within the basin must be selected. The relationship between these variables and snow accumulation has been shown at both the hillslope and regional scale (Molotch et al., 2006; Elder et al., 2008; Fassnacht et al., 2004).

Determining which conditions and parameters in the basin most directly impact SWE is crucial to determining where measurement should occur. However, identifying the physiographic variables that control SWE distribution is difficult, and this difficulty increases as basin size increases. The most commonly used independent variables selected are: net solar radiation, slope, elevation, and vegetation type (Molotch et al., 2005). Other variables often selected are wind direction and maximum upslope wind and aspect (Molotch et al.; 2006, Molotch et al., 2005; Winstral et al., 2002). While there is a degree of spatial autocorrelation present within these variables and SWE, the highly variable nature of snow at the plot scale yet almost ordered nature at the basin scale, makes if counterproductive to attempt to remove all spatial autocorrelation from selected datasets (Winstral et al., 2002).

The use of a spatially distributed snow model for SWE in conjunction with binary classification tree methods allows for the characterization of montane basins by enabling the identification of areas that are representative of basin wide SWE. An analysis of the relationship between a range of physical and climatic variables and SWE, similar to the work done by Molotch and Bales with snow cover extent (2006) will allow for a better understanding of how the location of the current SNOTEL measurement sites relate to basin-wide characteristics.

The primary objective of the work presented here is to determine the characteristics currently represented by SNOTEL sites locations relative to the greater basin snow covered area. The secondary objective is to determine the relationship between a range of physical and climatic variables and SWE using a binary classification-tree model (Molotch et al., 2006), and compare these to the conditions represented at SNOTEL sites. Lastly this work seeks to develop a method that could be used by water resource and land managers to locate future measurement sites.

2.3 Study Area

The McKenzie River Basin, a fourth field hydrologic unit, covers an area of about 3400 km^2 and represents about 12% of the land area in the greater Willamette River Basin within western Oregon (Fig. 2.1). Discharge from the McKenzie River accounts for nearly 34% of the flow in the main stem of the Willamette during late summer when the system is operating at base flow. The McKenzie River Basin extends from a maximum elevation of 3157 m at the summit of South Sister to 114 m at its confluence with the Willamette River. Precipitation occurs primarily in winter months with rain falling at lower elevations and snow at elevations above 800 m on average (McKenzie Watershed Atlas, 2000). The basin has two unique geologic areas: the older more worn Western Cascades and the younger more active High Cascades. Hydrology in the basin is strongly affected by this geology (Tague and Grant, 2004) with the Western Cascades having a much higher number of first and second order streams, and a much shorter residence time for groundwater. The mid to upper elevations in the basin are densely forested with Douglas fir, Western Hemlock and Western Red Cedar (Fig. 2.2). Logging was common in the basin from the 1950s-1980s and remnants of clear cuts still exist. About 68% of the basin receives persistent December-May snow cover, most of which occurs above 800 m.

This work examines the four SNOTEL site locations in the McKenzie basin's snow covered area (SCA) (Fig. 2.3). The Hogg Pass (Fig. 2.4) and Santiam Junction (Fig. 2.5) sites are located in the northwest corner of the basin, the McKenzie (Fig. 2.6) site is centrally located on the western most edge of the basin and the Roaring River site is located in the southwest corner of the basin (Table 2.1).

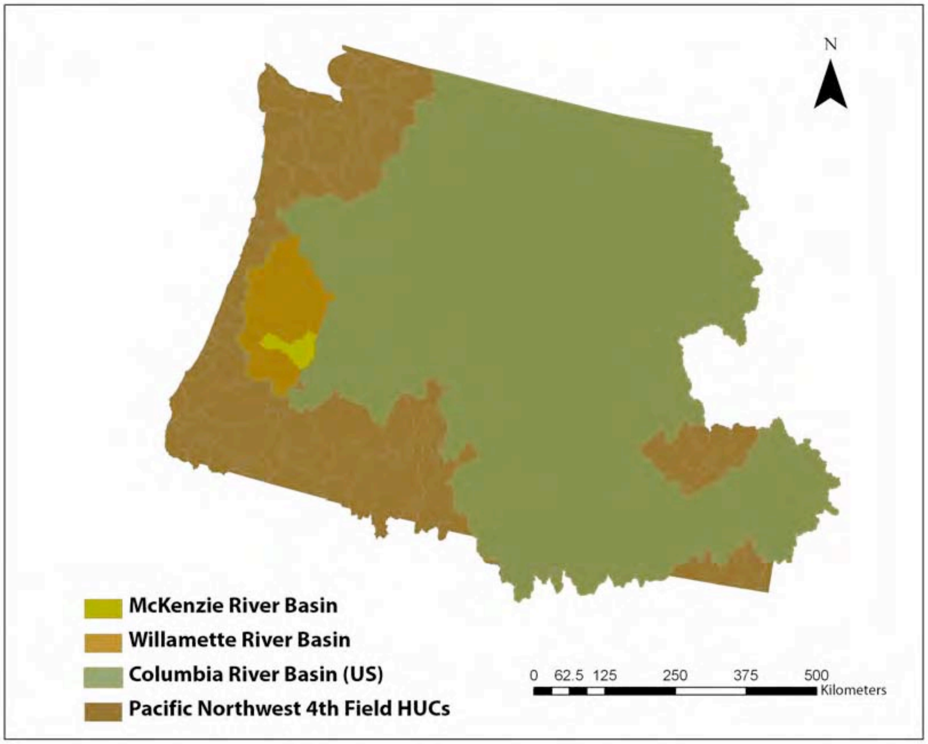

Figure 2.1: The McKenzie River Basin, a 4th field hydrologic unit, is located on the eastern edge of the Willamette River Basin in the western Cascades.

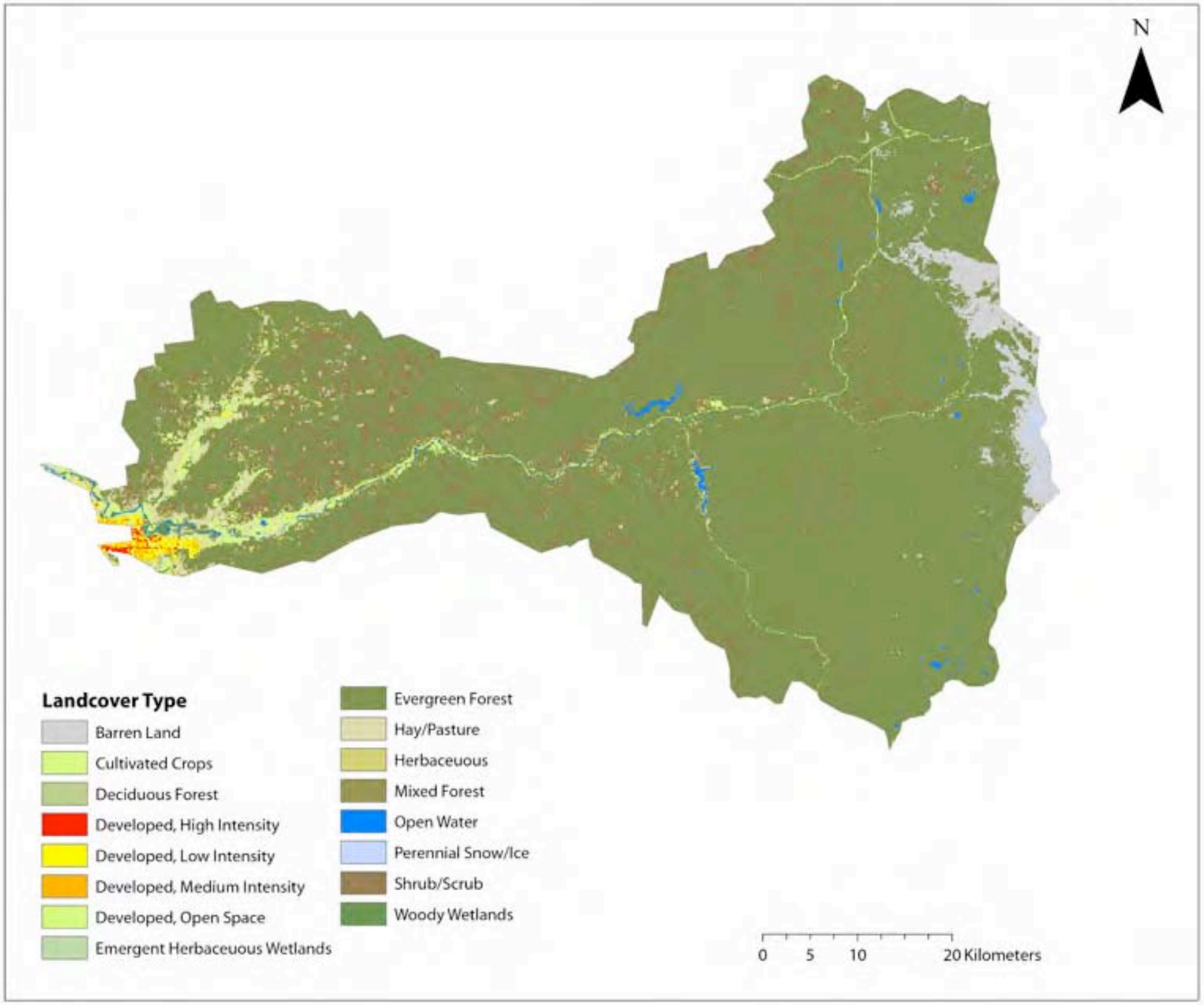

Figure 2.2: Mixed-age coniferous forests are prevalent in the basin. Source: National Land Cover Dataset, 30m.

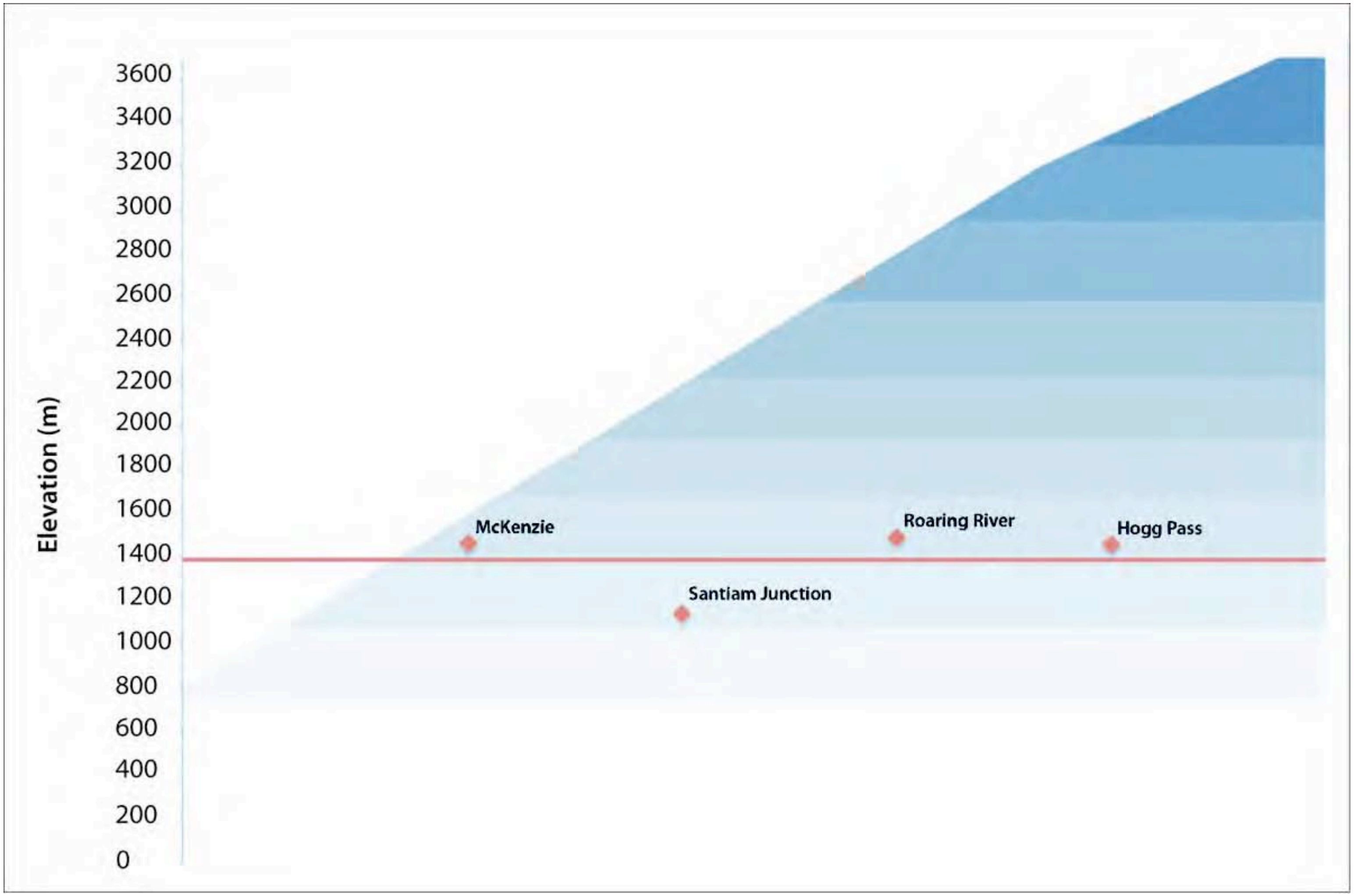

Figure 2.3: SCA covers elevations from 800-3500 m, the top of the watershed. SNOTEL sites are located between 1100-1500 m.

Table 2.1: McKenzie River Basin SNOTEL site locations and descriptions.

Site Name	Site ID	Elevation (m)	County	Land Ownership	Latitude	Longitude	Year Installed	Instrumentation
McKenzie	21E075	1463	Lane	Willamette NF	44.2	121.87	1982	Snow Water Equivalence, Precipitation, Air Temperature (4), Snow Depth
Santiam Junction	21E055	1143	Lane	Willamette NF	44.43	121.93	1979	Snow Water Equivalence, Precipitation, Air Temperature (4), Snow Depth
Roaring River	22F435	1493	Lane	Willamette NF	43.9	122.03	1981	Snow Water Equivalence, Precipitation, Air Temperature (4), Snow Depth
Hogg Pass	21E065	1460	Lane	Willamette NF	44.42	121.86	1980	Snow Water Equivalence, Precipitation, Air Temperature (4), Snow Depth (2)

Figure 2.4: Hogg Pass SNOTEL site. The open, flat area surrounded by trees acts as a wind buffer and collects snowfall during winter. Increased solar radiation in the open area tends to accelerate snowmelt in the spring.

Figure 2.5: The Santiam Junction SNOTEL site is located off a main highway, adjacent to a large cinder pit used by the Oregon Department of Transportation.

Figure 2.6: The McKenzie SNOTEL site is relatively flat with minimal vegetation, with little to no canopy cover.

2.3 Methodology

2.3.1 SnowModel

A physically based snow model driven by real data observations was selected to model snow water equivalence across the McKenzie basin, in order to enable comparisons between different areas in the basin and the SNOTEL sites. SnowModel was developed by Liston and Elder (2006). This physically based model distributes SWE spatially and temporally. Seasonal accumulation, redistribution by wind, sublimation, evaporation and melt can be accounted for and quantified. SnowModel is comprised of four sub-models: MicroMet, EnBal, SnowPack and SnowTran-3D. MicroMet distributes meteorological information; SnowTran-3D accounts for wind redistribution and canopy; EnBal calculates the energy balance of the snowpack; and SnowPack accounts for changes in snow depth and snow water equivalence (Liston et al., 2006; Nolin et al., 2009).

Using SnowModel, SWE from water year 2005 was modeled across the basin at a 100-m resolution to capture the physical and climatic variability of the area. Water year 2005 was a low snow year and was the first of three years that will be modeled. 2002 was a high snow year, and 2008 was an average year. Analysis of these years is still underway. SnowModel was run hourly on the 2005 data to capture the diurnal fluxes into and out of the snowpack (Sproles, 2009). Elevation data were from a 10-m resolution USGS Elevation Dataset and resampled to 100 m. Gridded vegetation data were derived from the 30-m National Land Cover Dataset resampled to 100 m.

The model was calibrated using point based SWE measurements from local SNOTEL sites and from three climate stations in the H.J. Andrews Experimental Forest. Remote sensing data were used to assess the spatial distribution of the modeled snow cover (Sproles 2009, Nolin et al., 2009).

2.3.2 Physiographic Parameters

Raster files of the modeled SWE were output for the first of each month, November-May, and incorporated into a Geographic Information System (GIS) characterization of the basin. Six physiographic parameters were identified as relevant to snow distribution: elevation, slope, aspect, vegetation, maximum upwind slope and solar radiation (expressed as daily duration of daylight). Elevation, slope, aspect and solar duration were calculated using a 30-m DEM then aggregated and reprojected to the 100-meter resolution of the SWE raster files. These parameters have been identified throughout the literature as relevant to snow distribution (e.g. Molotch et al. 2006; Molotch et al. 2005).

Maximum upwind slope was calculated using the approach of Winstral et al. (2002) (Fig 2.7). Maximum upwind slope is a measurement designed to quantify snow deposition as affected by wind redistribution (Molotch et al., 2006. (Winstral et al., 2002). A 270° vector was chosen for the calculation, as winter winds in the Pacific Northwest are predominantly from the west (Daly 2009, personal communication). Solar radiation was calculated assuming clear sky conditions. Daily solar radiation was calculated for each pixel in the basin on a biweekly basis for January-May.

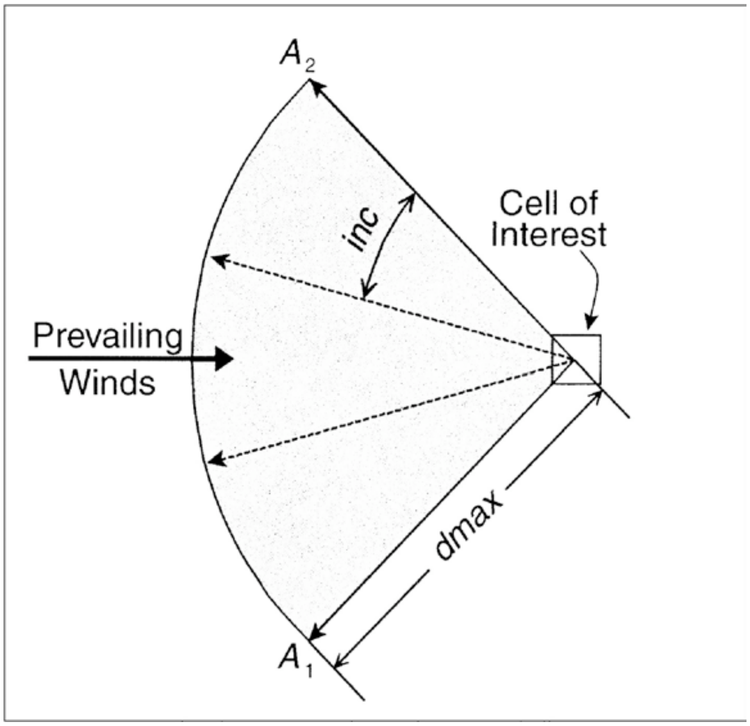

Figure 2.7: A 60° angle was used to sample grid cells situated in the path of a 270° wind vector aimed at the cell of interest (Adapted from Winstral et al. 2002).

Information for all six parameters and SWE gathered at each grid cell was compiled into a general parameter file where each grid cell in the basin had corresponding information for all parameters. A date for peak SWE was then identified and the average SWE value in the snow-covered area within the basin was calculated. The grid cells representing the average peak SWE (±10 percent) were identified for the McKenzie River Basin and these grid cells were subsequently used to subset a training data set for the binary regression classification.

2.3.3 Binary Regression Classification

Binary regression classifications (also termed "binary regression trees") can be used to analyze the non-linear relationships between a dependent variable and a range of independent variables in a nonlinear hierarchical manner (Musselman et al., 2008; Molotch et al., 2005). They are appropriate for use when the dependent variable, in this case SWE, can have any value at any point in space, and when differences between these vales are quantitative and regular. Different combinations of independent variables were included in separate tree models. The determination of which independent variables to couple with SWE was based on the import of the variables at the 100-m resolution. Elevation and aspect were included in all models.

Binary regression classifications and their resulting binary regression trees have been proven to provide accurate estimates of distributed SWE when field observations are available (Molotch et al., 2005), however they have not been applied to modeled SWE data. The classifications work by dividing the dependent variable into increasingly homogenous subsets to minimize model deviance (Molotch et al., 2006). Combinations of independent variables are built into unique tree models to assure proper fit. Using a statistical program, one hundred iterations of 10-fold cross validations were averaged to establish a relationship between model deviance and number of terminal nodes. Relationships that minimized model deviance were further explored. A binary regression classification script was provided by Molotch (2009, personal communication) and modified for use in this application.

The model introduced here uses six parameters to predict SWE distribution. The tree model that minimized deviance and maximized model fit (R^2) was selected and used to characterize the training area into classes representative of SWE.

2.4 Results

2.4.1 Physiographic Variables

There was little variation between physical and climatic variables at the SNOTEL sites and the greater McKenzie Basin SCA. (Figures 2.8-2.12). All site variables fell within one standard deviation of the mean values found for SCA. The SNOTEL sites captured the average SCA elevation well, however the upper and lower elevations were not well represented (Figure 3.14). Stations were located on flatter slopes than the average and had predominantly south facing aspects (Table 2.2). Field visits found the sites were often less vegetated than surrounding areas.

Pixel by pixel comparisions of the independent and dependednt variables tended to exhibit a higher degree of variance. However, this variation became somewhat muted at sub basin and basin scale. To measure the level of spatial autocorrelation present Moran's I (Winstral et al. 2002) was calculated for a subset of the SWE values representing ±10% of average peak SWE (7433 points). The Moran's I ranges from zero to one, with zero indicating no spatial autocorrelation and one signifying compete autocorrelation (Winstral et al., 2002). A value of 0.50 was found (p=0), indicating a strong tendency toward clustering and significant spatial autocorrelation.

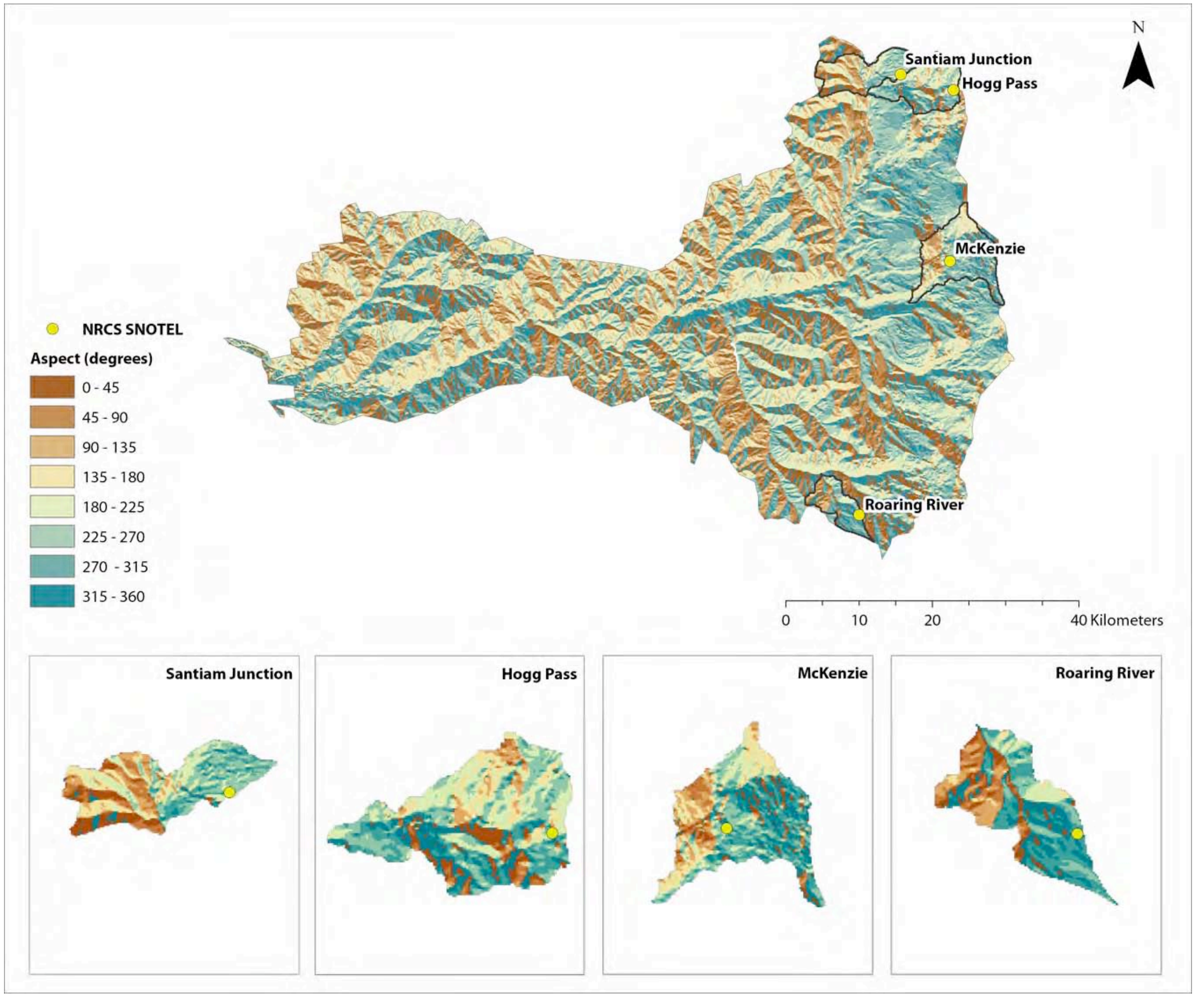

Figure 2.8: Aspect calculations for McKenzie River Basin and the four SNOTEL containing sub basins. Note that SNOTEL sites are predominantly oriented toward the south.

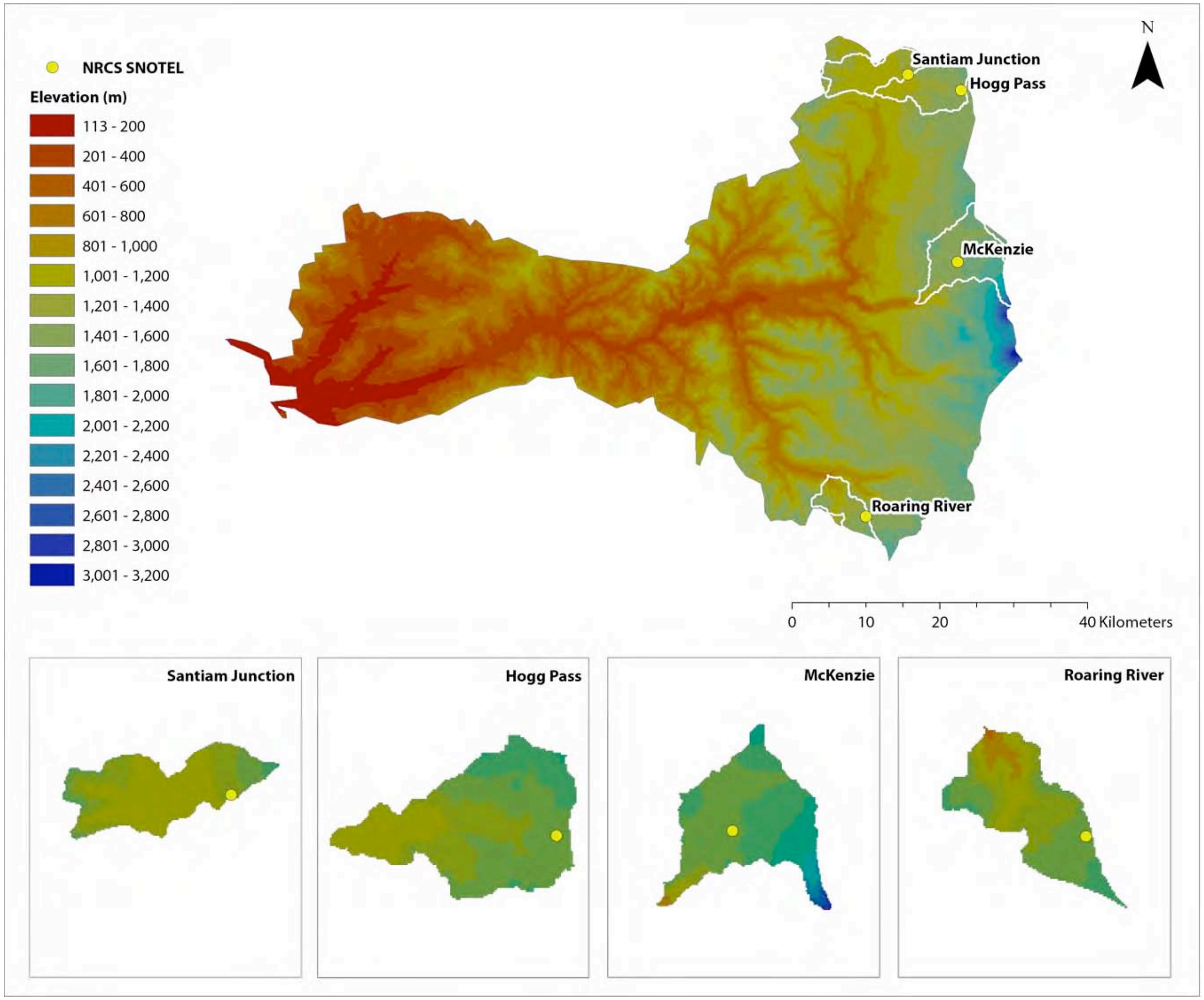

Figure 2.9: Site elevations are similar to each other, but miss both the highs and lows within the basin.

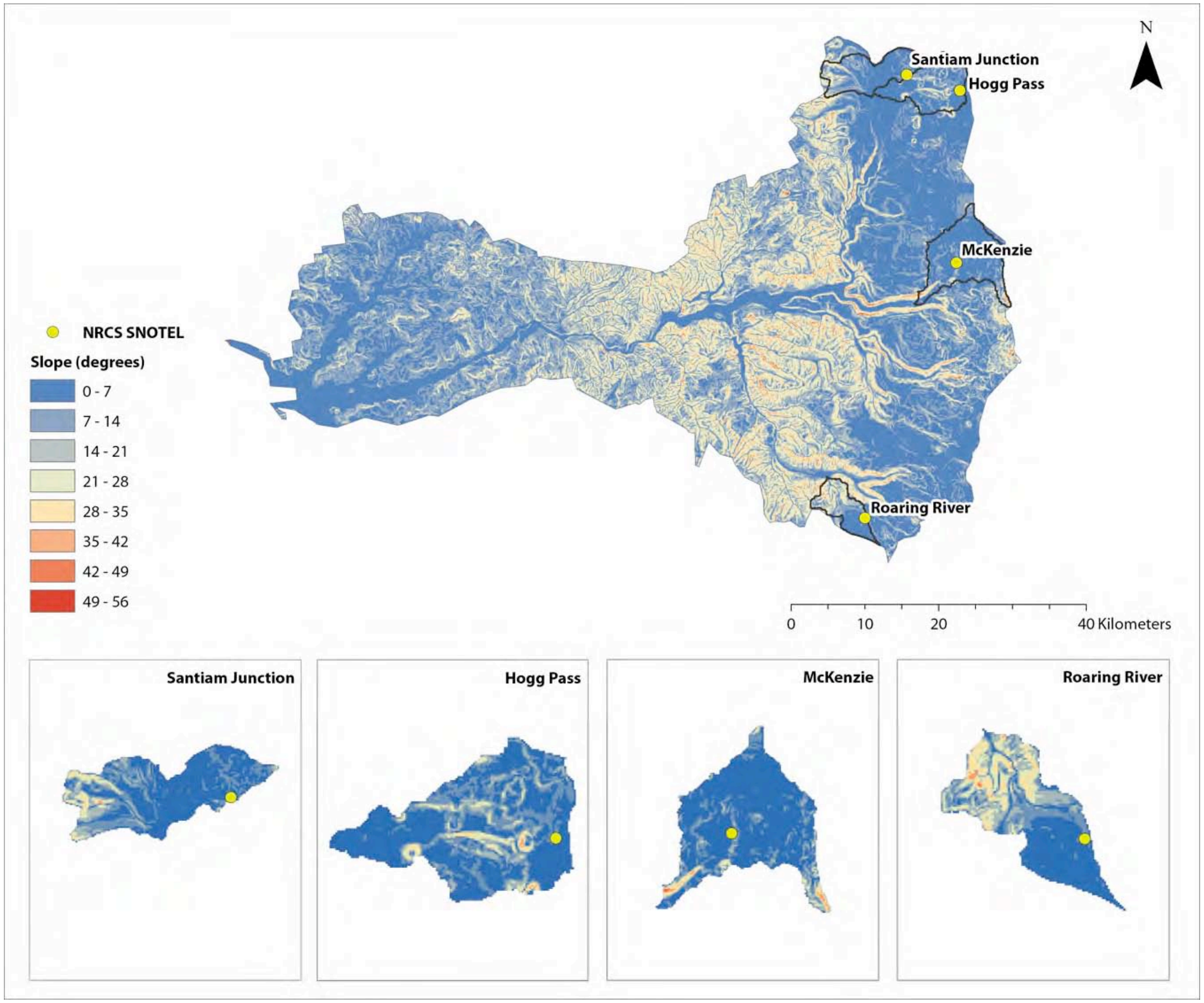

Figure 2.10: Sites are located on relatively flat slopes characteristic of the basin's mid level elevations.

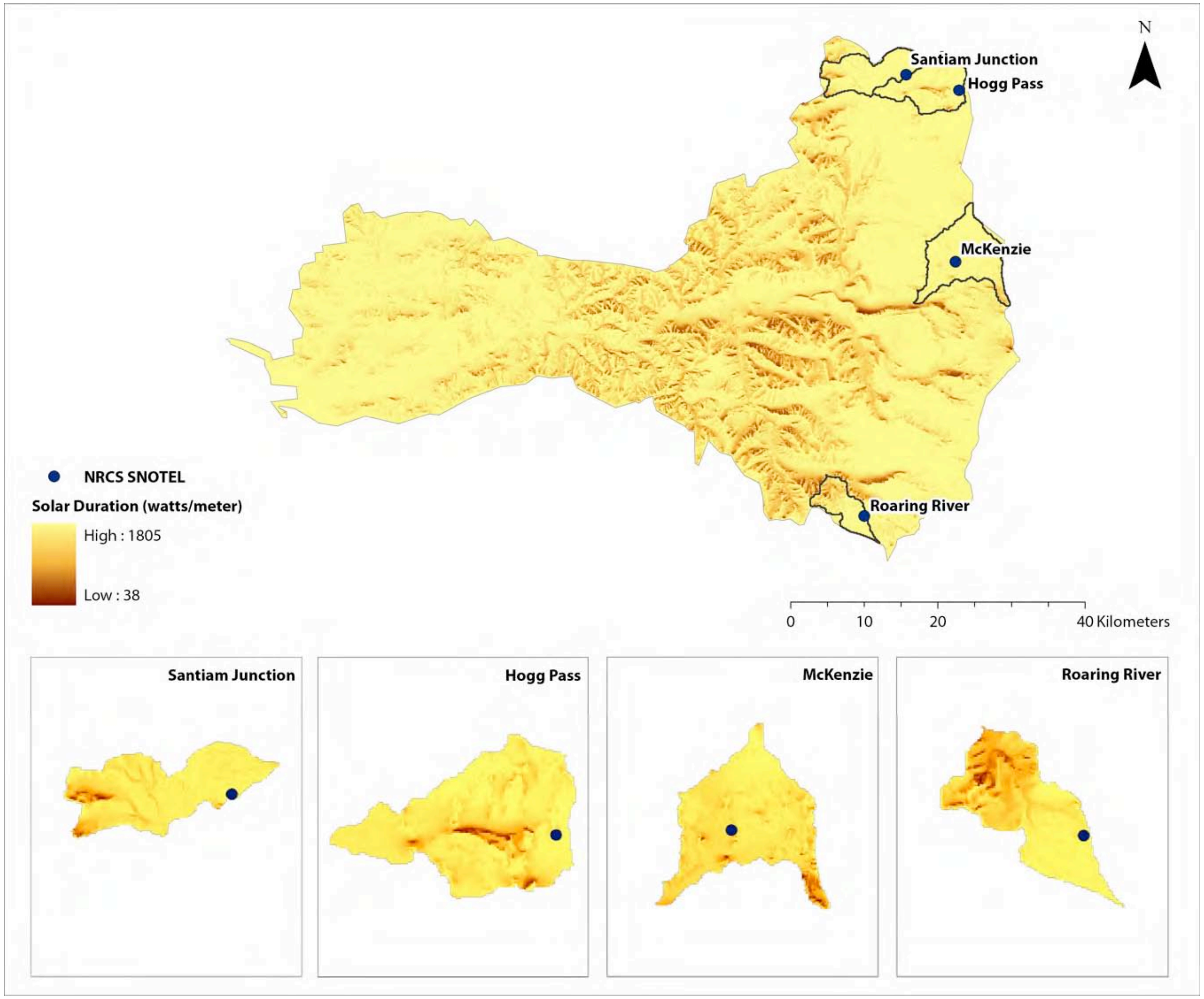

Figure 2.11: There is little variation in solar radiation across the snow-covered area of the basin.

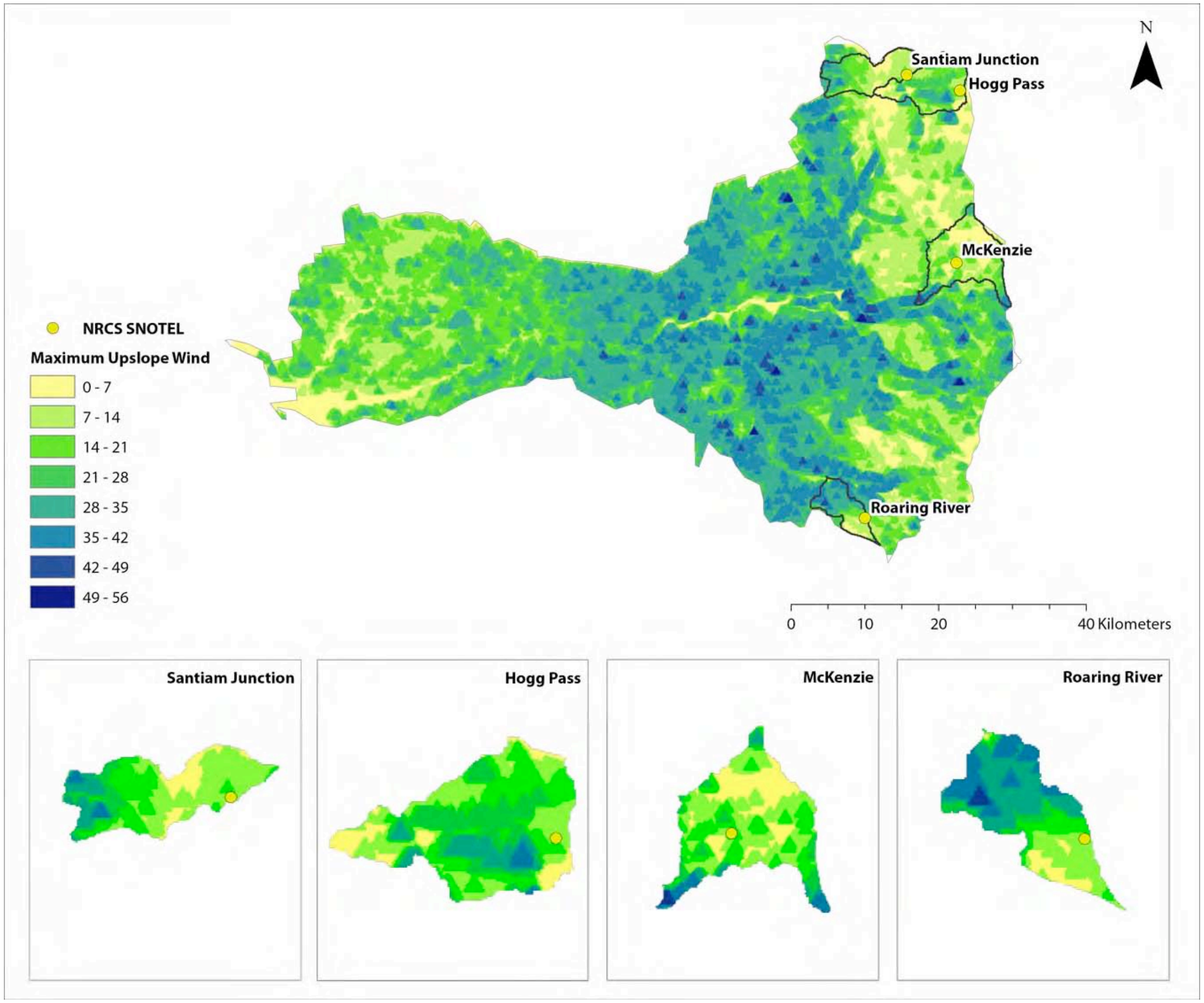

Figure 2.12: There does not appear to be a pattern in variation of maximum upwind slope at the mid and upper elevations.

Table 2.2: Averaged values of modeled physiographic parameters and modeled SWE for 2005 are shown for SCA and SNOTEL containing sub basins. Note the difference in SWE between the SCA and the SNOTEL sites.

Site Name	SWE (m)	Solar (w/m^2)	Elevation (m)	Max Upwind Slope (deg)	Vegetation	Slope (deg)	Aspect (deg)
SCA	.19	1480	1290	23	Coniferous	13	193
Hogg Pass	.35	1668	1460	16	Coniferous	8	149
Santiam Junction	.18	1670	1143	12	Coniferous	7	259
McKenzie	.37	1652	1463	17	Coniferous	1	275
Roaring River	.37	1675	1493	13	Coniferous	5	311

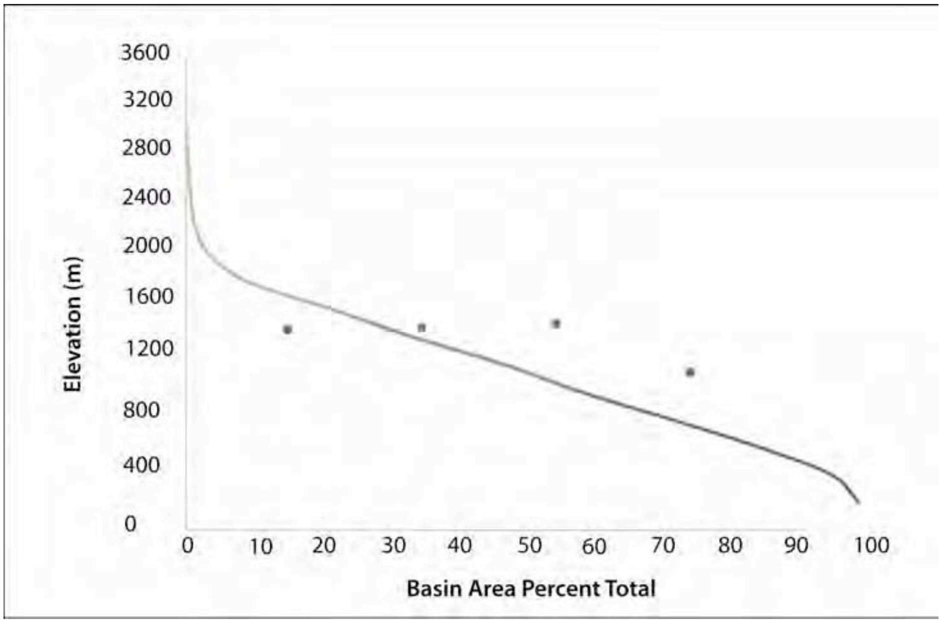

Figure 2.13: McKenzie River Basin hypsometric curve with the elevations of SNOTEL sites indicated. The sites are separated for clarity; their position relative to the x-axis is not to scale.

2.4.2 Snow Water Equivalence

SnowModel distributions of SWE are strongly correlated to elevation, with substantially greater amounts of snow at elevations above 1400 m (Fig. 2.14). However, even within similar elevation bands the distribution and amount of SWE varies throughout the accumulation and ablation season (Figures 2.15-2.19).

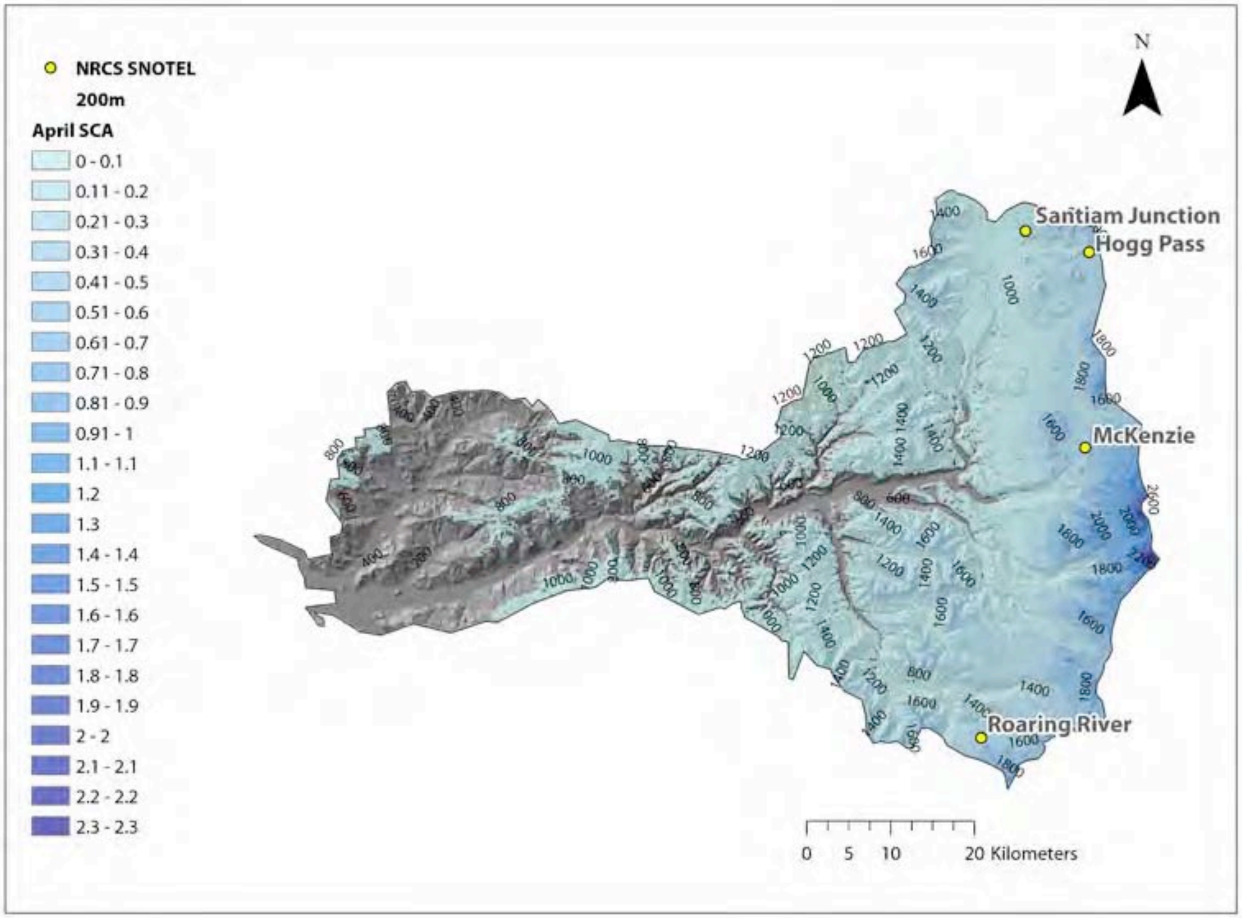

Figure 2.14: At peak SWE, the basin is largely snow covered, however, most of the basin has less than 10 cm of snow.

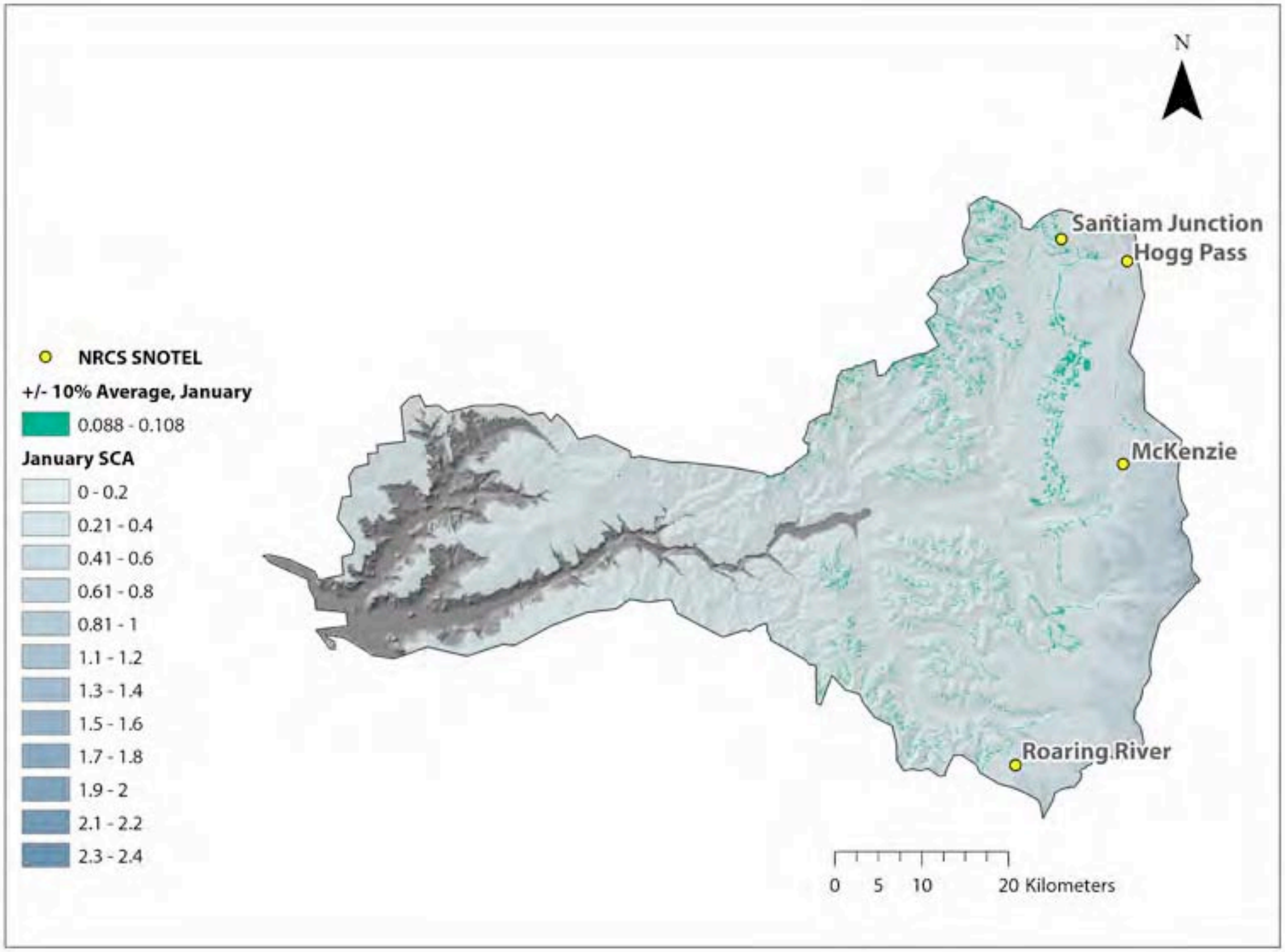

Figure 2.15: Jan. 1 SCA. Extent is greatest in January, but overall SWE is low.

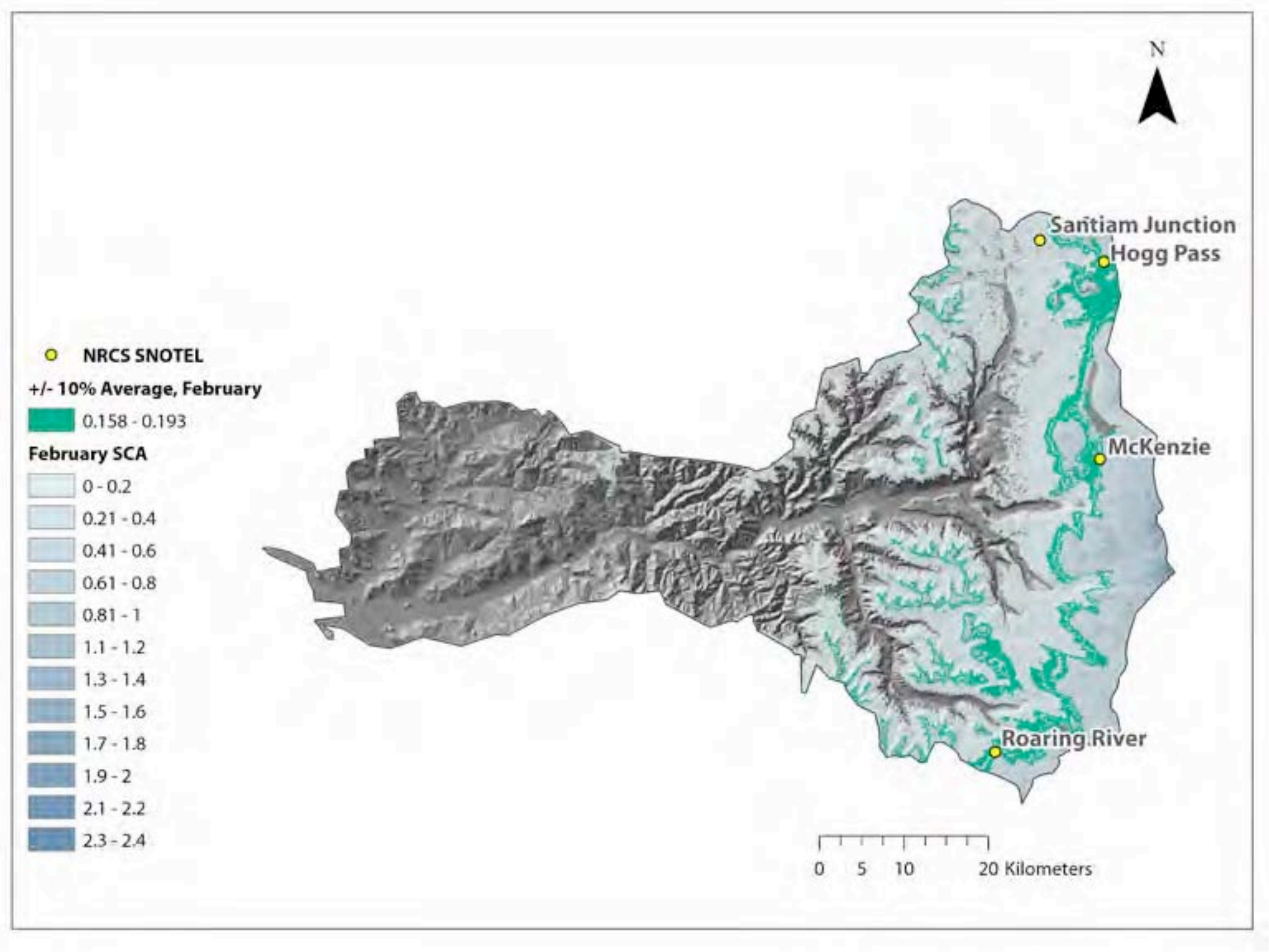

Figure 2.16: February saw a significant change in SCA extent, with melt occurring through much of the basin.

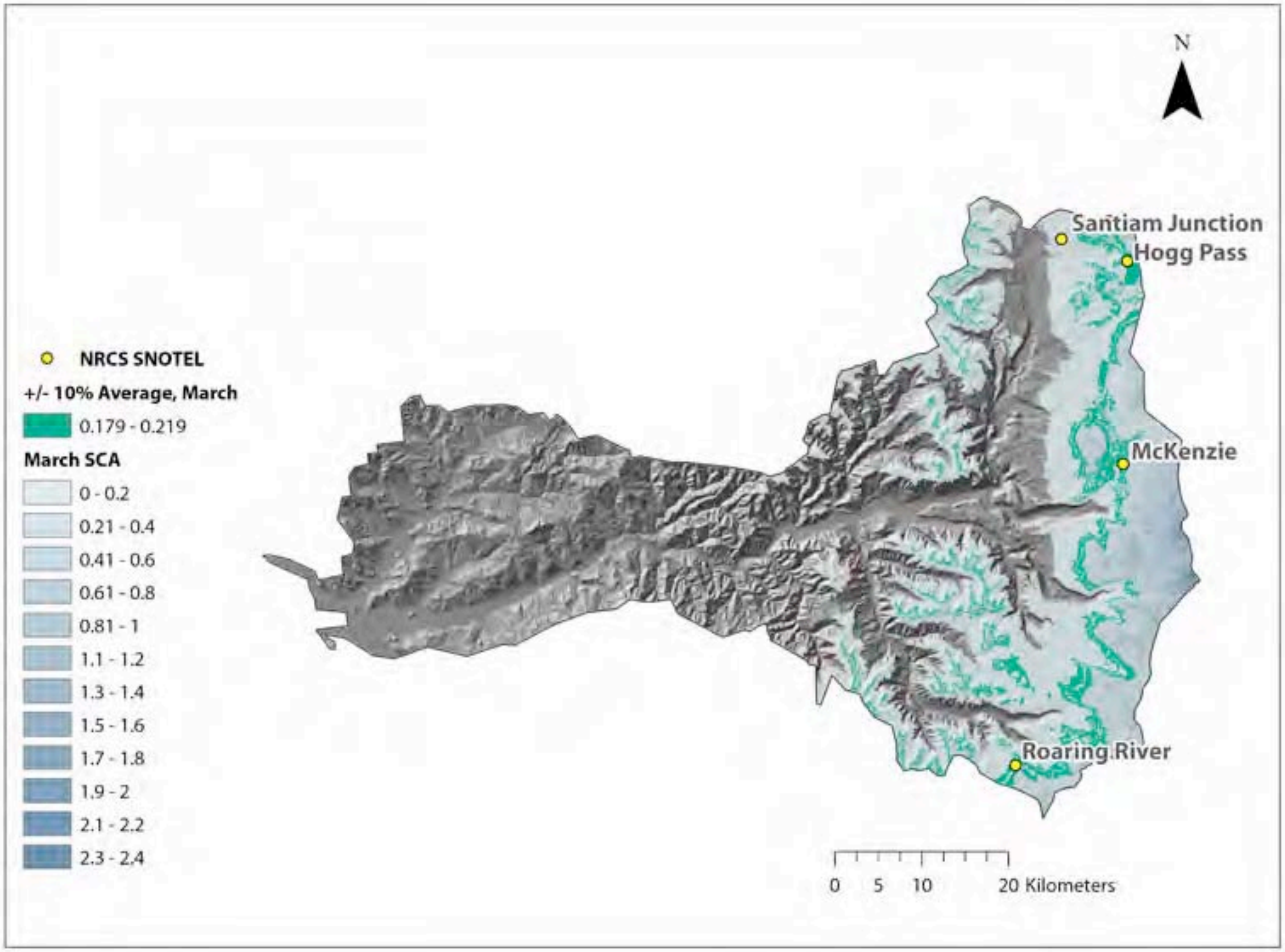

Figure 2.17: March 1 SCA. Most of the basin SWE values are near the average value for the month.

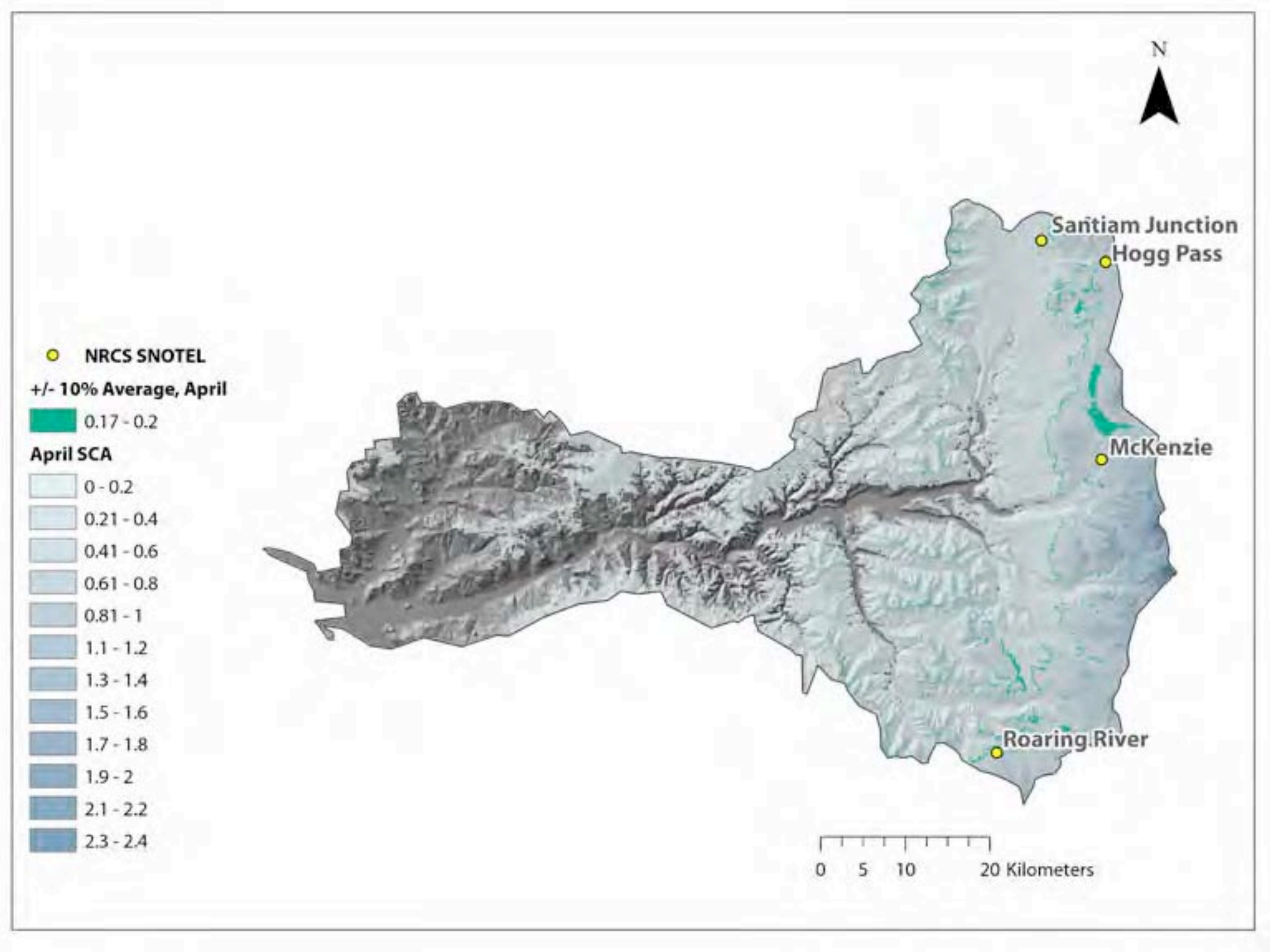

Figure 2.18: April 14, peak SWE. A storm, or series of small storms, deposited small amounts of snow at lower elevations.

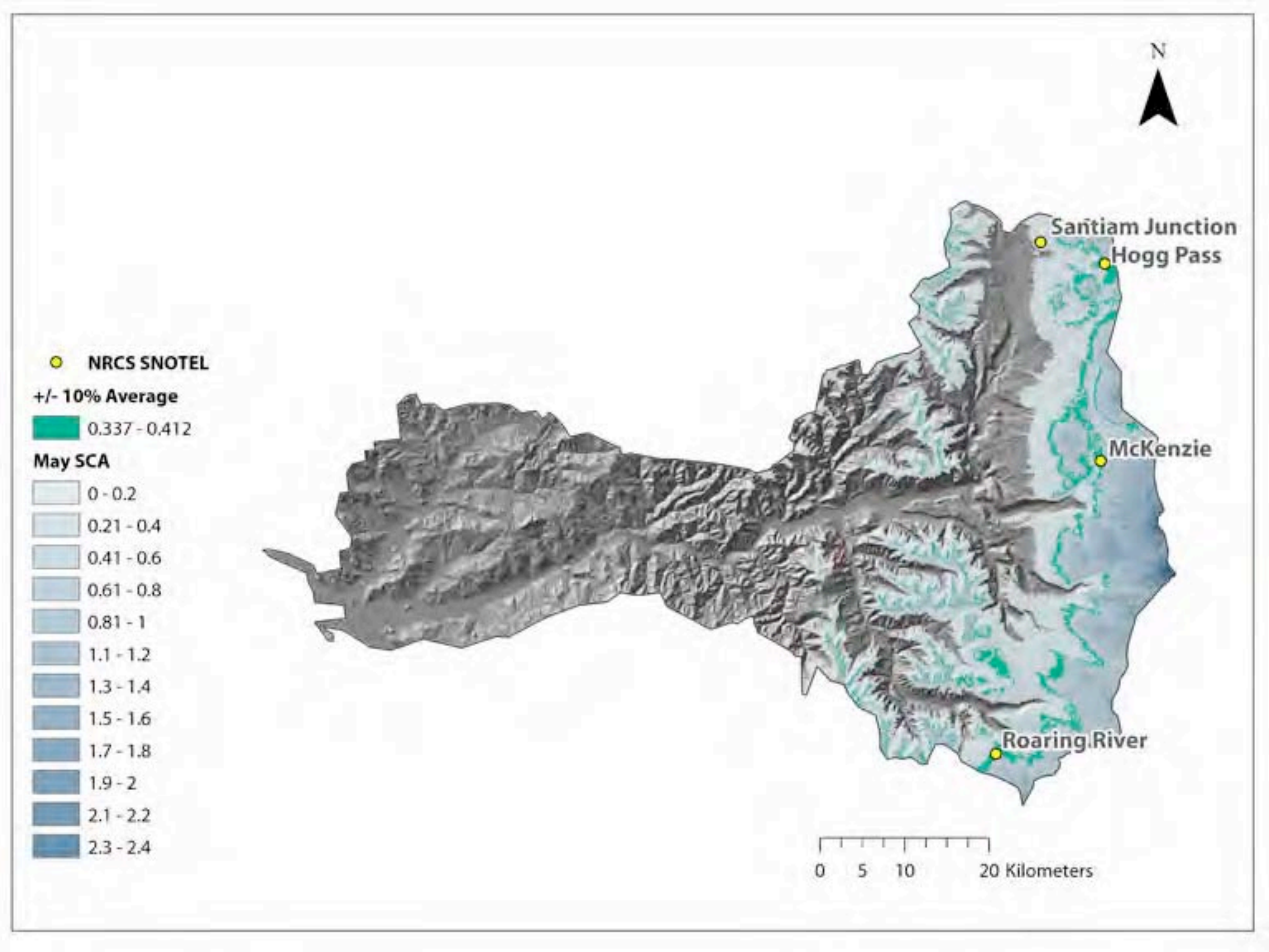

Figure 2.19: May 1 SCA. Melt is occurring, and higher elevations are retaining more snow than lower and mid elevations. Resulting in the average SWE value being higher than in previous months.

SNOTEL sites are located in areas with persistent January-May SCA. For most of the season, with the exception of January, the sites are also in areas representing ±10 % of average SWE in the basin. At peak SWE (April 14), average SWE values at the sites ranged from 0.18 m to 0.37 m. SCA peak SWE average was 0.19 (Table 2.2). With the exception of the Santiam Junction site, the sites over estimated SWE when compared to the mean SCA (Table 2.2). SWE values at Hogg Pass were 184% of mean SCA; at McKenzie and Roaring River SWE values averaged 190% greater than the mean; but at Santiam SWE values were 95% of the SCA mean.

2.4.3 Binary Regression Classification

Binary regression tree models were developed for each the first of each month January-May. Model deviance was minimized between 12 and 18 terminal nodes using elevation, slope and aspect. The inclusion of maximum upwind slope, solar radiation hours and vegetation increased deviance slightly. Model fit increased between 2 and 16 terminal nodes. The 16 terminal node regression tree is shown here (Figure 2.20). The value at the end of each branch represents all mean values of all points representative of the splitting criteria for that node. For each of the five months considered, elevation was the most important control variable of SWE. The April model was further analyzed due to its capture of peak SWE. In addition, maps depciting the percentage of SWE distributed throughout the basin at different elevations for peak SWE were created (Figure 2.21). The values for SWE at broken down by percentile are shown in Table 2. 3. At 2005 peak SWE (April 14), SWE values in the McKenzie River basin ranged from a low of less than1 mm to 1940 mm. Increases to SWE were directly linked to increasing elevation within the basin.

In April, elevation controls SWE distribution as indicated by its position in the first split of the tree (R^2=.843). Aspect was the second most imporant variable (R^2=.479) controlling the model for one split in the second level, before elevation again took preferential placement. Slope began to control structure in the third level of the tree (R^2=.373). SWE was greatest at higher elevations with relatively flat slopes and north south aspects. At the 100-m resolution vegetation did not appear to affect distribution.

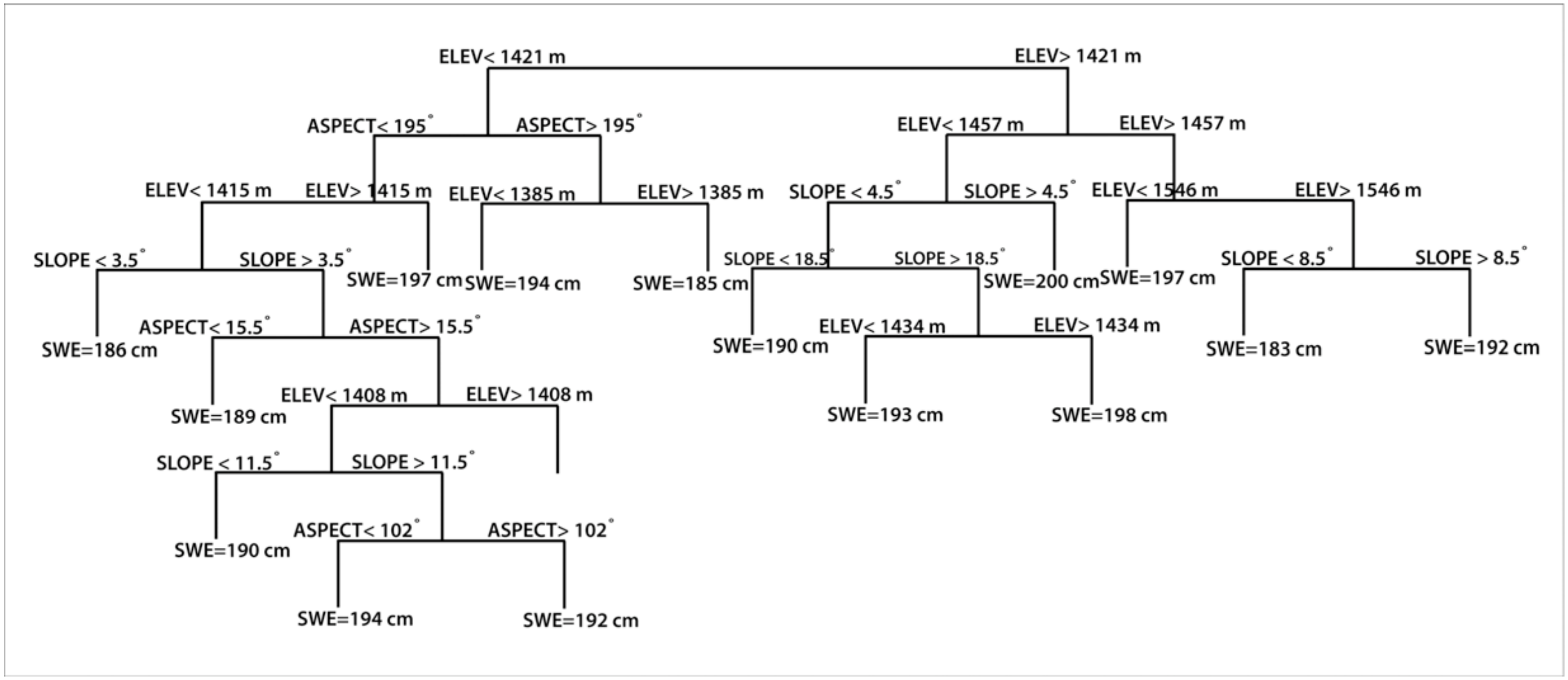

Figure 2.20: 16-node binary regression tree. The dependent variable is peak SWE (April 14, 2005). This tree is based on data from the ±10% of the average peak SWE value.

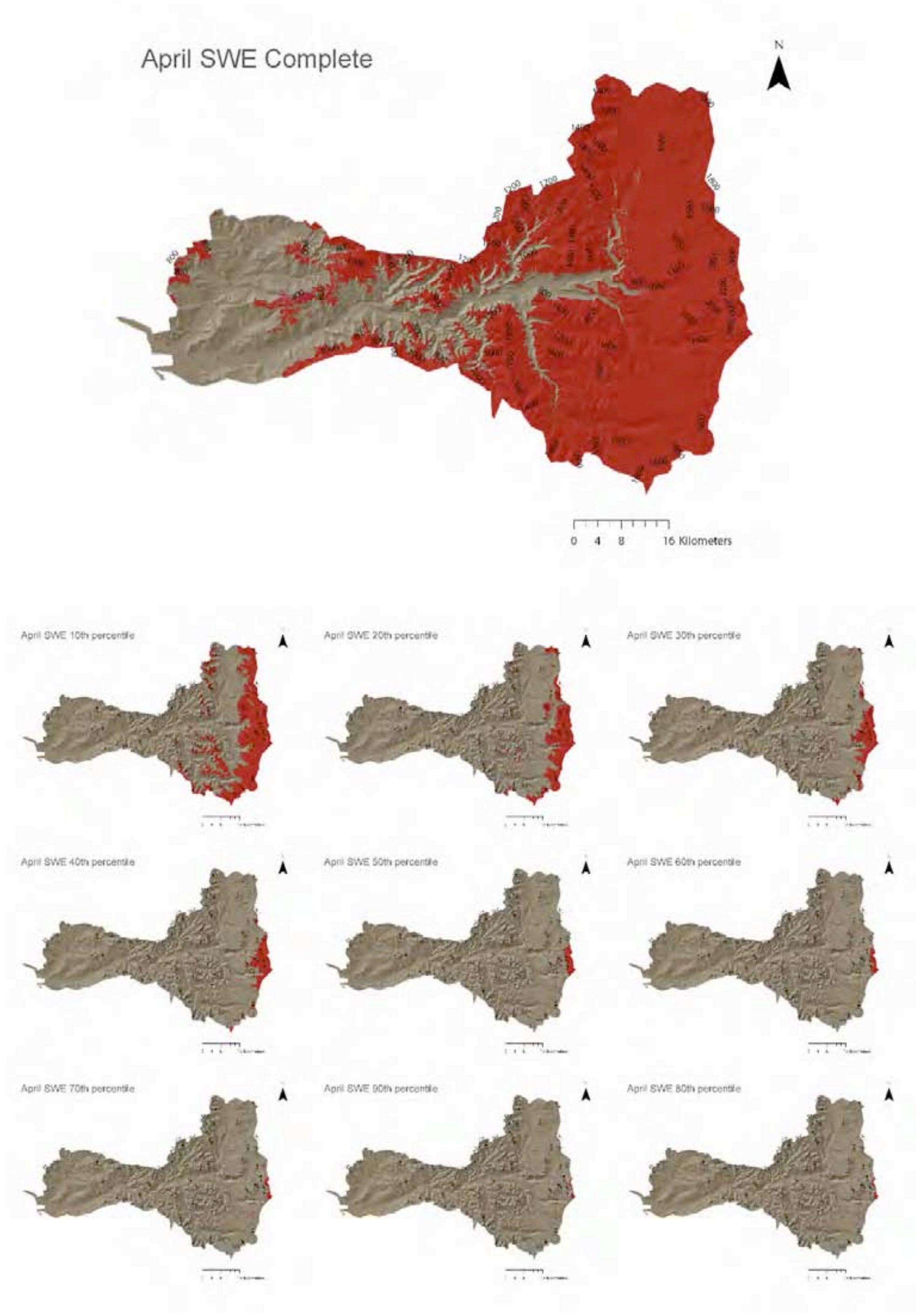

Figure 2.21: Each map shows a percentage of SWE values as they are distributed across the basin. 100% is associated with the largest value that SWE has (1940 mm). For example, the 10th percentile map shows the extent of area covered by SWE values from190mm to 1940 mm. April SWE complete is a representation of all the SWE in the basin in terms of covered area.

Table 2.3: Peak SWE values broken down by percentile.

Percent	SWE (mm)
90-100	1750-1940
80-90	1550-1749
70-80	1350-1549
60-70	1160-1349
50-60	970-1159
40-50	770-969
30-40	580-769
20-30	380-579
10-20	190-379
0-10	0-189

To determine the influences on SWE at elevations above 1400 m throughout the accumulation and ablation seasons, binary regression tree models were also created for the first of every month using a subsample of the data that took into account only the area within the basin located above this elevation threshold (Figure 2.22).

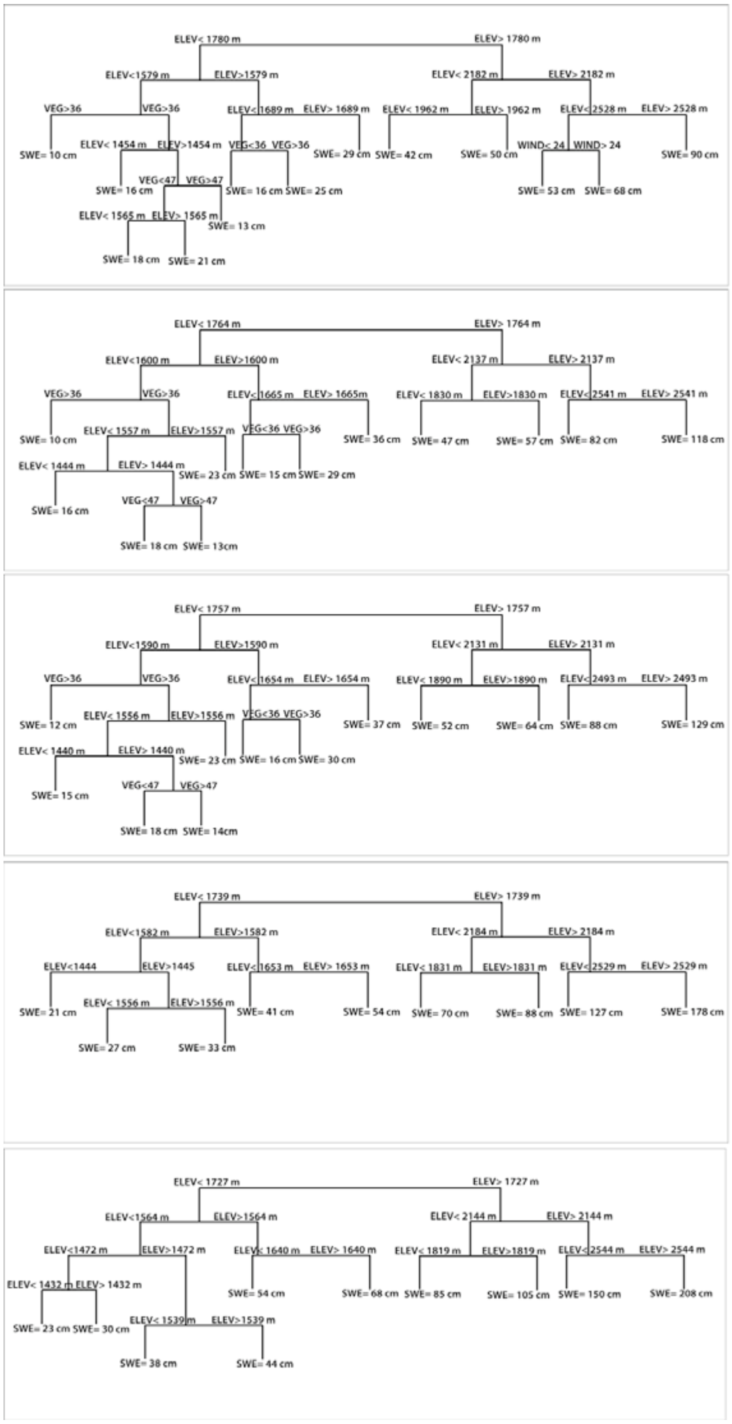

Figure 2.22: Monthly binary regression trees for the McKenzie River basin elevations at 1400 meters and above. From top to bottom: Jan-May. Elevation is always the controlling variable in the relationship between SWE and six other physiographic variables during this study year; however, in the accumulation months, vegetation and wind redistribuition also affect SWE distribution. During the abalation season, it is only elevation that impacts SWE distribution.

2.5 Discussion

The use of SnowModel to distribute SWE across the watershed provided novel information regarding the relationships between different physical and climatic parameters. At the 100-meter resolution, the physical and climatic parameters studied did not appear to vary much between SNOTEL sites and the larger snow covered area. With regard to which parameters influenced SWE, the relationship between elevation and SWE was the most significant, especially during ablation when temperature controls melt. The incorporation of a finer resolution vegetation index into the model may provide more information about the strength of the relationship between SWE distribution and vegetation. Variation in the influence of different parameters throughout the accumulation and ablation season may be tied to the weather systems that were occurring at the time of measurement. Future work will focus on linking data from SNOTEL and meteorological stations with weather patterns and snow accumulation as created by the model. Continuing work should also focus on determining if a threshold exists where variations in point measurements at the small scale balance out to represent the mean of the larger basin.

An analysis of the basin shows that current SNOTEL locations capture the average characteristics of the basin reasonably well. However, there remain questions concerning both the importance and relevance of average values and of the importance of variablity across different spatial scales.

SnowModel places minimal SWE across a large portion of the basin. As shown in the basin hypsometric (Fig. 2.14) more than 70% of the basin is below 1400 m. This disproportionate amount of area and the corresponding number of grid cells with SWE values less than 0.1 m could muddy the importance of the higher elevation SWE. The SCA of the basin totalled 2297 km^2 and of that 739 km^2 was above 1400 m. This high elevation area contained 43,599 m of SWE and represented about 75% of the total SWE in the SCA. A means to weight the importance of different elevation bands for SWE values would be helpful in determining whether the use of an average SWE value calculated from the entire SCA is appropriate. This is important to consider when looking at physiographic variables because if specific areas are more important to SWE it would follow that it is the characteristics of those areas that should be considered in determining representativenesss not necessarily the SCA average.

Use of Moran's I suggested a high incidence of spatial autocorrelation in the data set. This violates the rule of assumed independence and introduces a degree of uncertainty related to the independent samples used in the statistical tests. Winstral (2002) discussed the inherent spatial autocorrleation of the alpine snow environment, and suggested that because of snow's propensity to be highly variable at the point scale, yet relatively ordered at the basin scale it is "exceedingly difficult, if not impossible, to collect a representative sample set that does not include some degree of spatial autocorrelation." Given this, the data set was left intact to allow for analysis of both small-scale variablity and basin-wide patterns.

At three of the four SNOTEL sites in the basin, SWE measurements were more than 180% higher than the average value of SWE. A closer analysis of the conditions represented by the Santiam Junction SNOTEL site may be beneficial in determining the reasons it so closely captured average SCA SWE. The overestimation of SWE may have important implications on water forecasting and management.

All of the SNOTEL sites are located in areas that maintained snow cover from January-May. The May 1 map (Fig. 2.19) suggests high volumes of SWE remain in higher elevations even while the majority of the basin is melting out. These areas will continue to have snow even after the SNOTEL sites are completely snow free. This suggests a need to develop a method to weight areas of the basin to aid in the understanding of the areas that most contribute to basin SWE.

Binary classification trees were based on monthly values of ± 10% average SWE and the associated physiographic variables, and also on areas above 1400 m to aid in understanding what is occuring at high elevations. The results from the models suggest that elevation is always the controlling variable in SWE distribution followed by aspect and slope during the ablation season in the areas ± 10% average SWE. In the accumulation season (January-March), maximum upwind slope and vegetation play secondary roles to elevation in areas above 1400 m. Higher resloution data may change this relationship. Work by Musselman et al. (2008) found that canopy interception and vegetation played a large role in controlling snow distribution and depth in all seasons.

The fit of the model (R^2=.27) was comparable to previous work in densely forested, compex terrain (Erxleben et al. 2002, R^2 =.25). However, the model fit was significantly lower than Molotch et als. work in the headwaters of the Rio Grande where R^2=.75. This large discrepancy may be related to a significant difference in the size of the area sampled. Future work should look at appropriate techniques and adaptations of classifciation trees from the hillslope to the basin scale.

2.6 Conclusions

SNOTEL stations in the McKenzie River Basin are preferentially located in the elevations between 1100-1500 meters. While these locations are largely representative of the average SWE of the basin SCA, there is no measurement available of the lower and higher elevations where snowpack is often much deeper and exists much longer into the spring and summer. Using a 16-node binary classification tree, elevation, aspect and slope were shown to control the distribution of SWE in the areas identified as ±10% of the average in the SCA.

With the exception of the Santiam Junction SNOTEL site, average SCA SWE is grossly overestimated by SNOTEL stations in the basin when comparing modeled data. This is likely related to small-scale variability at the sites. Siting for future SNOTEL locations may benefit from this analysis and should be coupled with SWE data modeled under a climate-warming scenario. Applying an appropriate climate-warming scenario to SnowModel's distribution of SWE provides an opportunity to better understand future measurement needs. By incorporating SWE data modeled under warmer winter conditions with the classification and characterization methods identified here we can create a better understanding of areas that will represent basin SWE in the future.

Water and natural resource managers may be best served by diversifying their measurement locations, especially into higher elevations and areas not artificially cleared of vegetation. Locating sites above 1400 m could provide more robust measurements of SWE, and better information during the ablation season, as snow tends to remain at higher elevations longer. The implications of these findings include inaccuracies in streamflow forecasting and water allocation planning. The overestimation of SWE at SNOTEL sites may result in water managers assuming there is more snow, and therefore more water, available in the basin than is actually present. This introduces inaccuracies and problems to models based on these measurements, and further complicates planning for reservoir storage, fish and wildlife management and available flow for ecosystem services and hydropower generation.

Chapter 3 – Second Manuscript

Measuring at-risk snow in the Columbia River basin and two nested sub basins

3.1 Abstract

Updated high resolution PRISM precipitation and temperature data are used to map areas within the Columbia River basin and two nested sub basins that are at risk of turning from winter snow dominated precipitation regimes to winter rain dominated under warming scenarios ranging from 1-3°C. Within the Columbia basin the Oregon Cascades exhibit the greatest degree of sensitivity to changes in precipitation. This region is also one of the most heavily populated areas in the basin where a range of demands regularly compete for increasingly limited water resources. Under a 2°C warming scenario, an increase that the International Panel on Climate Change finds highly likely to occur within the next 30 years, 30% of the current day snow covered area in Oregon's Willamette River Basin will be at risk of turning from snow to rain. The water storage that will be lost if such a change does occur (.73 km^3) is equivalent to more than 8 months worth of the total current water usage in the basin. The primary implication of these findings is an increased need for water storage systems within the region. These systems will require the ability to retain winter precipitation for summer use. Data from nine regional stations in the National Oceanic and Atmospheric Administration (NOAA) National Weather Service (NWS) Cooperative Observer Program are used to validate the model.

3.2 Introduction

Winter snows power the Pacific Northwest. Hydropower, irrigation, industry, flood control and recreation are dependent on adequate stream flow, and it is from the mountain ranges of the Columbia River basin (CRB) that this flow originates. The Cascade and Rocky Mountains, and their high elevation catchments, provide natural storage systems for seasonal snowfall that upon melting in spring provides 40-80% of the Columbia's flow (Hamlet et al., 2005; Serreze et al., 1999). Yet this is not a static system, and a changing climate is rapidly altering how, when, and where snow accumulates and ablates across the region.

Current research in the PNW and CRB shows a decline of winter snow pack during the last half century. However, not all areas have been affected equally (Knowles et al. 2006). The largest declines to snow pack occurred in the Pacific Northwest, specifically in the Oregon Cascades (Mote et al., 2005; Mote et al., 2003; Serreze et al., 1999). The susceptibility of this area is linked to the regional geography and climatology resulting in elevated sensitivity to warming temperatures. In addition, watersheds in the mid to lower elevations of Oregon's western Cascades already receive winter precipitation that is a mix of rain and snow. Snow in the region accumulates at temperatures close to 0°C, and requires less energy to either change precipitation phase or melt (Jefferson et al., 2008). As winter temperatures continue to climb over the next 100 years the declining trend in snow pack will only increase, according to the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) (Fig. 3.1). By 2050, it is expected that the Cascade snowpack will be 50-70 % less than what the region accumulates today (Leung et al., 2004; Leung et al., 1999).

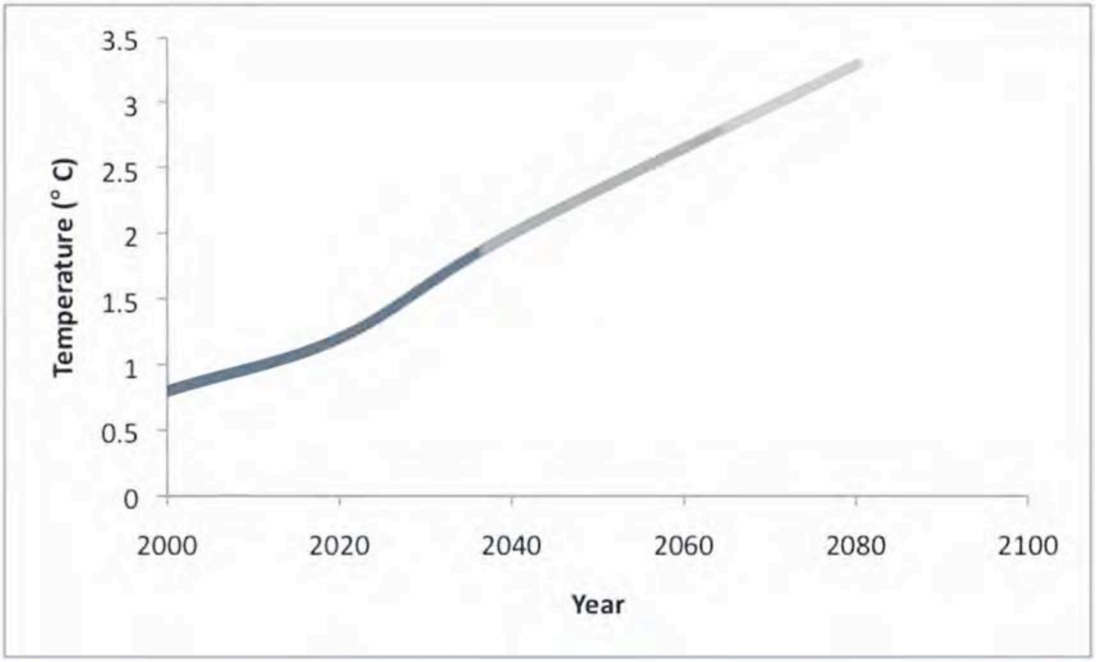

Figure 3.1: IPPC 4th Assessment warming trend for the PNW. Temperature will increase 1.2°C by 2020, 2.0°C by 2040 and 3.0°C by 2080.

In areas where the hydrologic cycle is largely driven by snowmelt, this decrease has widespread implications for future water availability and use. The ability to accurately measure snow covered area and extent in light of climate change is crucial to successful management and planning. Managers, however, require an understanding of the hydrologic processes occurring in mountainous regions in order to make informed decisions at the national, regional and watershed scale (Bales et al., 2006; Nolin and Daly, 2006).

The use of snow cover mapping to determine snow covered area (SCA) across a range of scales can provide valuable information regarding the extent of snow cover, and in addition can be used to identify areas with higher or lower accumulation and ablation rates. However, mapping has its failures including an inability to determine the amount of snow within an area. There is current research underway to develop remote sensing tools capable of determine extent and amount, but they remain relatively coarse and unsuited to the mountainous regions of the PNW and CRB (Klein et al., 1998; Fassnacht et al., 2003). By incorporating new higher resolution climate data with a digital elevation model it is possible to at least determine where snow is falling, accumulating and melting.

A climatologically based snow cover classification system incorporates temperature, precipitation and wind speed data to determine snow classes across a landscape (Nolin and Daly, 2006; Sturm et al., 1995). Here snow cover is defined as the layer of snow that covers an area and incorporates both depth and extent (Sturm et al., 1995). Because accurate measurements of wind speed are difficult to attain, vegetation is used as a proxy for wind speed. The presence or absence of trees has been shown to correlate strongly with low or high wind speeds respectively (Sturm 2001). The relationship between these three climatic parameters and snow cover can be depicted using a binary classification system. The binary system based on these parameters incorporates three questions that when answered divide snow cover into eight classes and a snow free zone. The questions are: 1) Does the snow cover exist in an area of high or low wind, 2) Does the snow cover exist in an area of high or low temperature, and 3) Does the snow cover exist in an area with high temperatures (near 0°C) or in an area of low temperatures? By looking at how and where these classes are located geographically it becomes possible to determine snow cover at a macro scale. Further by increasing the temperature range of the data used in the classification system by 1-3°C, a warming that falls within the range determined by the IPCC to be highly probable, it is possible to forecast the geographic areas most at risk of turning from a snow dominated winter precipitation regime to a rain dominated system given projected climate warming scenarios.

The original snow classification system designed by Sturm et al. (1995) was run globally at a 0.5°*0.5° resolution. Work by Nolin and Daly (2006) used the 4-kilometer resolution Parameter–elevation Regression on Independent Slopes Model (PRISM) dataset to classify snow cover in the Pacific Northwest region of North America. This study extends the work of Sturm et al. and Nolin and Daly by using the 800-meter PRISM data made available in July 2008 to map snow cover in the U.S. portion of the Columbia River Basin, and two nested sub basins: the Willamette River Basin and the McKenzie River Basin. The 800-meter dataset is the most recent and highest resolution dataset available and represents a five times finer spatial resolution than that used by Nolin and Daly in 2006.

PRISM uses point-based measurements of precipitation and temperature, as well as a range of other climatic and statistical parameters and concepts, to produce gridded representations of climate over a variety of spatial and temporal scales (Daly et al., 1994). The incorporation of a digital elevation model, a knowledge-based system and human expertise makes PRISM data highly suited to incorporation in GIS and furthers understanding of how climate changes spatially (Daly et al., 2002).

The incorporation of a higher resolution dataset into the protocol developed by Nolin and Daly (2006) allows for a detailed application of a climatologically based snow classification system to the CRB and two nested sub basins. The primary objective of the work presented here is to map snow in the CRB using the 800-meter PRISM data and warming scenarios ranging from 1-3°C to determine which geographic areas are most susceptible to conversion from a snow dominated precipitation regime to a rain dominated regime. Data from nine regional cooperative sites in the National Oceanic and Atmospheric Administration (NOAA) National Weather Service (NWS) Cooperative Observer Program are used to validate the use of PRISM data in this capacity. The secondary objective is to calculate the percentage of snow-covered area (SCA) per basin that is at risk of disappearing under the different warming scenarios and to determine the impact of that change on the hydrologic system. Lastly, this work seeks to determine if a threshold exists where an increase in temperature results in a significant change in total area of at-risk snow.

3.3 Study Areas and Site Description

This research focuses on the United States portion of the Columbia River Basin (CRB), and two nested sub basins: the Willamette River Watershed and the McKenzie River Watershed (Figures 3.2 and 3.3).

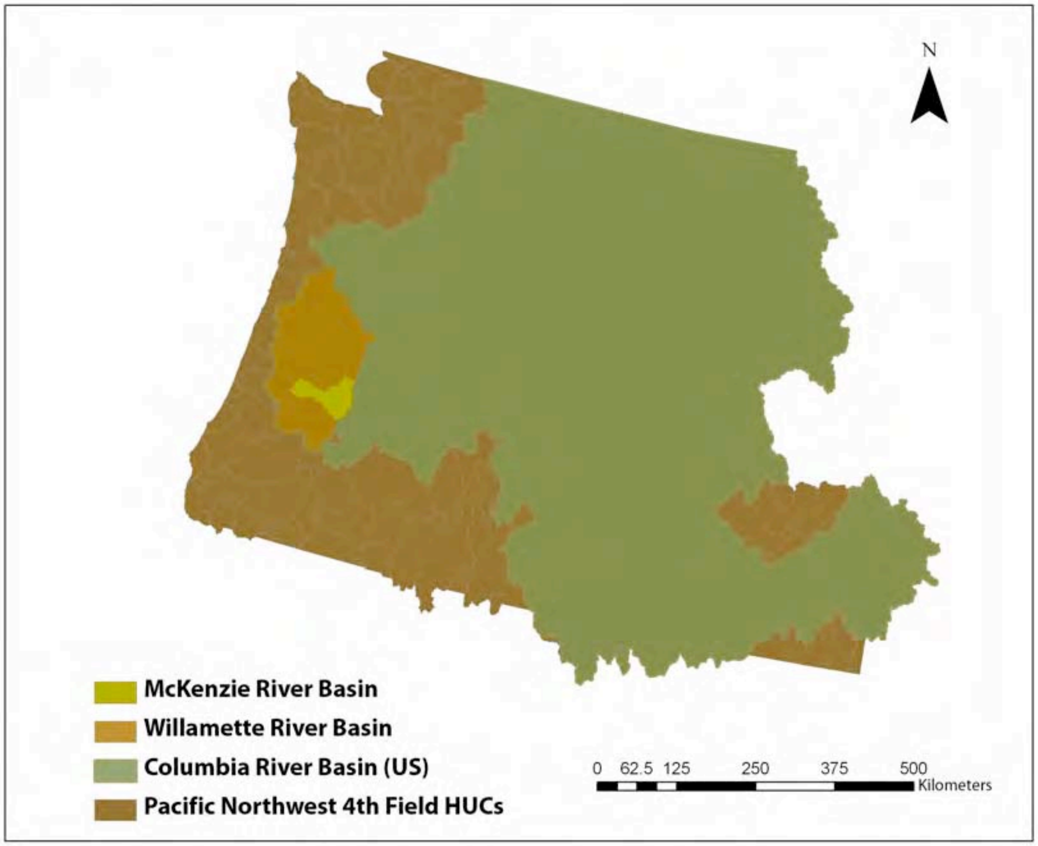

Figure 3.2: The Columbia River Basin and two nested sub basins: The Willamette River Basin and the McKenzie River Basin.

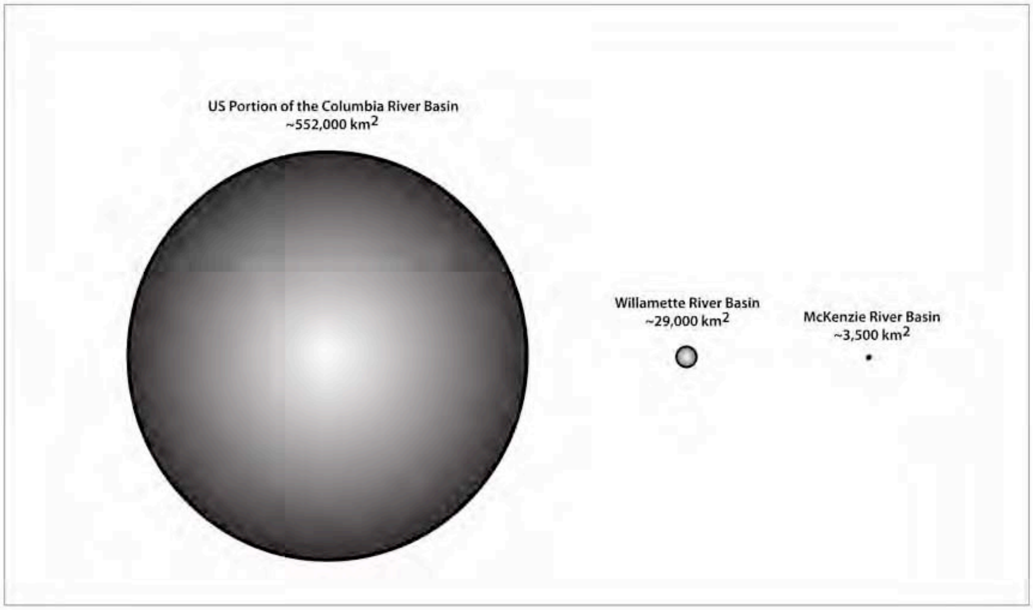

Figure 3.3: The area represented by the Columbia, Willamette and McKenzie River Basins. The spatial variability of the study basins impacts geographic and climatic variability.

3.3.1 The Columbia River Basin

The CRB contains portions of seven states: Oregon, Washington, Idaho, Montana, Wyoming, Nevada and California and one Canadian province, British Columbia. The US portion of the basin is roughly 552,000 km^2, and another 119,000 km^2 is in Canada. The Columbia River has the fourth highest annual discharge in the United States at $167.7*10^9$ m^3 (Serreze et al., 1999). About half of the river's yearly flow volume is stored behind a series of large dams for flood control, hydropower, navigation and irrigation. There are ten major tributaries to the river: the Kootenay and Okanagan in Canada, and the Wenatchee, Spokane, Yakima, Snake, Deschutes, Willamette, Cowlitz and Lewis in the U.S. The main stem flows more than 1900 km from its headwaters in between the Selkirk Mountains and the Continental Divide to its outlet to the Pacific Ocean at Astoria, Oregon. The CRB has a diverse and varied ecology ranging from extremely cold and wet to hot and dry. Eco regions range from semi-arid plateaus and high desert, to temperate rain forests and deep gorges. Precipitation ranges from almost 3 meters to less than 15 cm and falls primarily from November to March. Two distinct large mountain ranges run through the basin. The Cascade Ranges runs north south through the western portion of the basin, and the Rockies run north south through the eastern portion of the basin. The majority of the basin lies east of the Cascades in the colder, drier Rocky Mountain Landform Region (Muckleston 2003). Winter snow occurs throughout the basin however accumulation tends to occur primarily in the mountain ranges and at elevations above 800 m (Fig. 3.4). About 38% of the basin is snow covered from December-February. Within this study only the U.S. portion of the basin was considered due to a lack of available data for the Canadian portion of the basin.

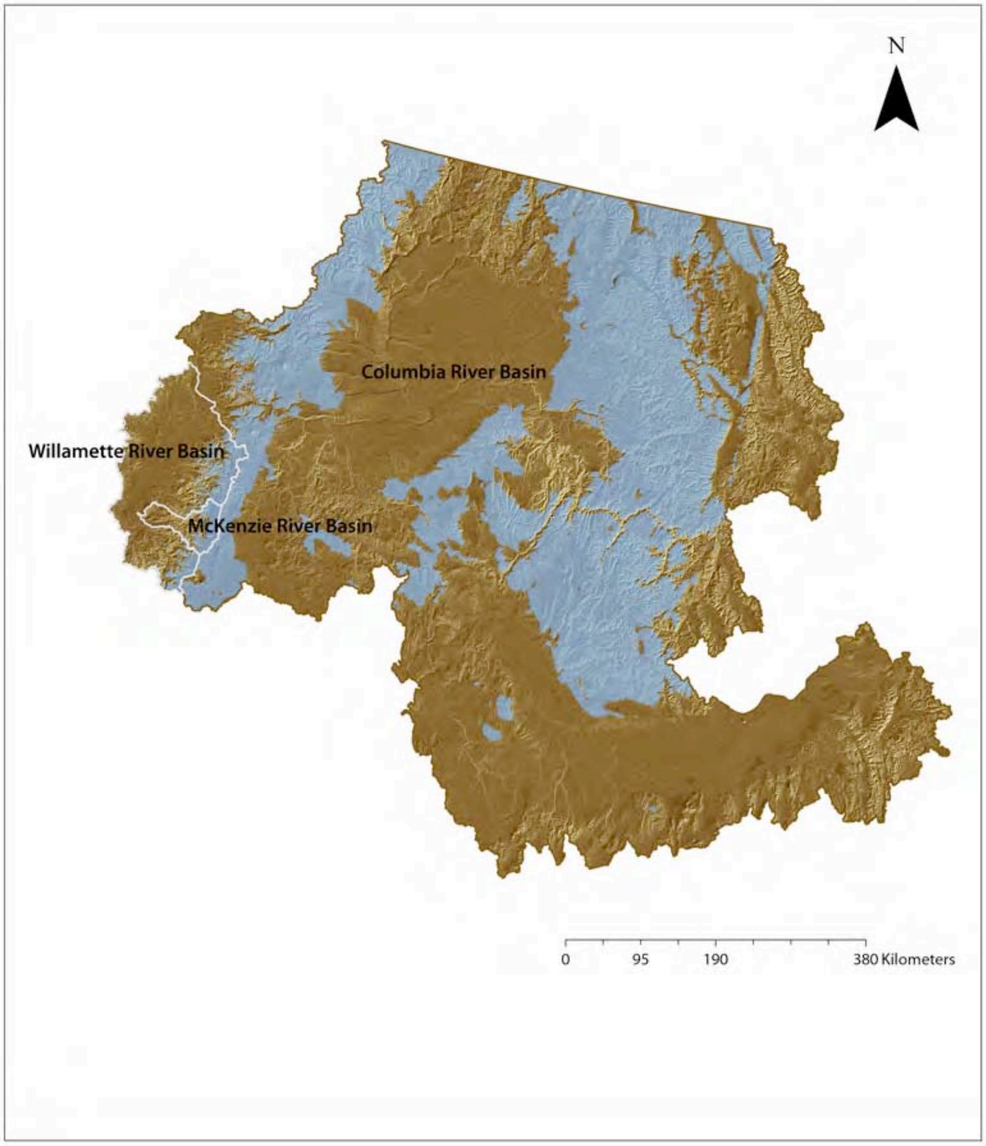

Figure 3.4: Snow Covered Area extent for Dec.-Feb. based on 1971-2000 800-m resolution PRISM data.

3.3.2 The Willamette River Basin

The Willamette River Basin drains the area south of the Columbia and west of the Cascades. It is Oregon's largest watershed and has an area greater than 29,000 km^2. It is also the largest population hub with about 70 percent of the state's population. About 22% of the basin is farmed and about 70% is forested. The remaining 8% of the basin is urbanized. About 70% of the water used in the basin is surface water. During the winter months of December, January, February about 4000 km^2, or 14% of the basin, is snow covered. The Willamette River is the 12 largest river in the US, and it is fed by 13 major tributaries in the basin. In total, there are more than 16,000 miles of streams within the reach, most of which are predominantly fed by snowmelt from the Cascades. The waterways support a variety of human and non-human life, including several species of endangered salmonids. The basin ranges in elevation from just above sea level to about 3500 m (Fig. 3.5). Snow can occur throughout the basin, however seasonal snow cover tends to accumulate at elevations above 800 m in the Western Cascades on the eastern edge of the basin.

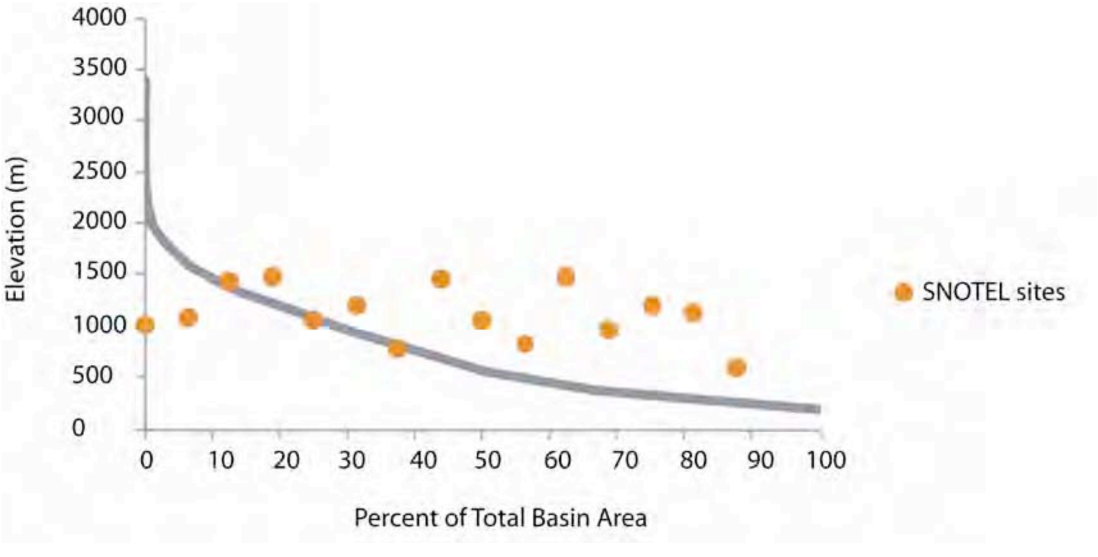

Figure 3.5: Hypsometric curve of the Willamette River Basin with the elevation of current snow measurement sites shown. This curve shows that most (~85%) of the basin is below 1500 m. However, snow accumulates from about 800 m to 3500 m, and there are no SNOTEL sites at elevations above 1500 m.

3.3.3 The McKenzie River Basin

The McKenzie River Basin, which is nested inside the eastern limits of the Willamette River Basin, covers an area of about 3400 km^2 representing about 12% of the Willamette's total area. Discharge from the McKenzie accounts for nearly 34% of the Willamette River's late summer flow, however. The McKenzie River Basin extends from a maximum elevation of 3157 m at the summit of South Sister to 114 m at its confluence with the Willamette River. Precipitation occurs primarily in winter months with rain falling at lower elevations and snow at elevations about 800 m on average. The basin has two unique geologic areas: the older more worn Western Cascades and the younger more active High Cascades. The mid to upper elevations in the basin are densely forested with Douglas Fir, Western Hemlock and Western Red Cedar (Fig. 3.6). Logging was common in the basin from the 1950s-1980s.

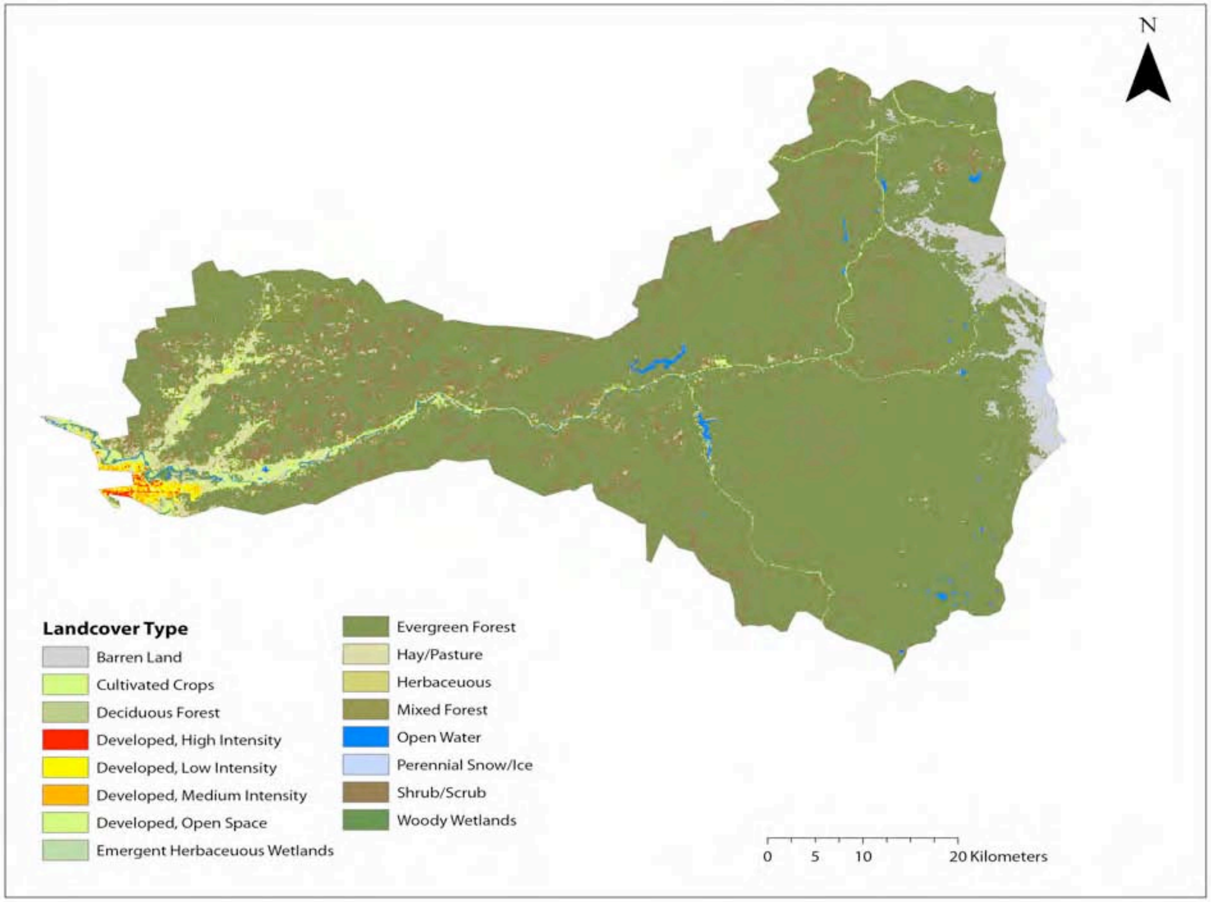

Figure 3.6: Coniferous forests dominate McKenzie River Basin land cover. Source: National Landcover Dataset, 30-m.

3.4 Methods

The data preparation and study methodology for this project was based on the Nolin and Daly (2006, here after referred to as ND), work in the Pacific Northwest, then refined for use with the higher resolution data, a longer period of record, a larger spatial distribution that included the U.S. portion of the CRB, and a series of warming scenarios. Historical monthly averages of mean temperature and precipitation from December, January and February 1971-2008 were used to create gridded GeoTiff files of the entire United States. The monthly mean temperature (T_{mean}) was computed using the PRISM values for mean monthly maximum temperature (T_{max}) and mean monthly minimum temperature (T_{min}), where $T_{mean}=(T_{max}+T_{min})/2$ (ND). Using the approach of Sturm et al., (1995) and Nolin and Daly (2006), we used vegetation cover fraction as a proxy for wind speed. The vegetation cover fraction maps are produced using satellite data from the Moderate Resolution Imaging Spectroradiometer (MODIS) (Global Land Cover Facility 2009). Values of percent forest cover were aggregated and reprojected to the 800-m PRISM resolution. Grid cells with an aggregated value of forest cover less than 35% were designated as having high wind speed whereas those with greater than 35% forest cover were designated as having low wind speed.

The temperature, precipitation and wind speed data layers were then combined into a single data set and analyzed using a binary decision tree classification (ND). This classification approach allows each grid cell in the CRB domain to be classified as snow vs. non-snow, warm snow vs. cold snow, high precipitation vs. low precipitation, and high wind vs. low wind (Fig. 3.7).

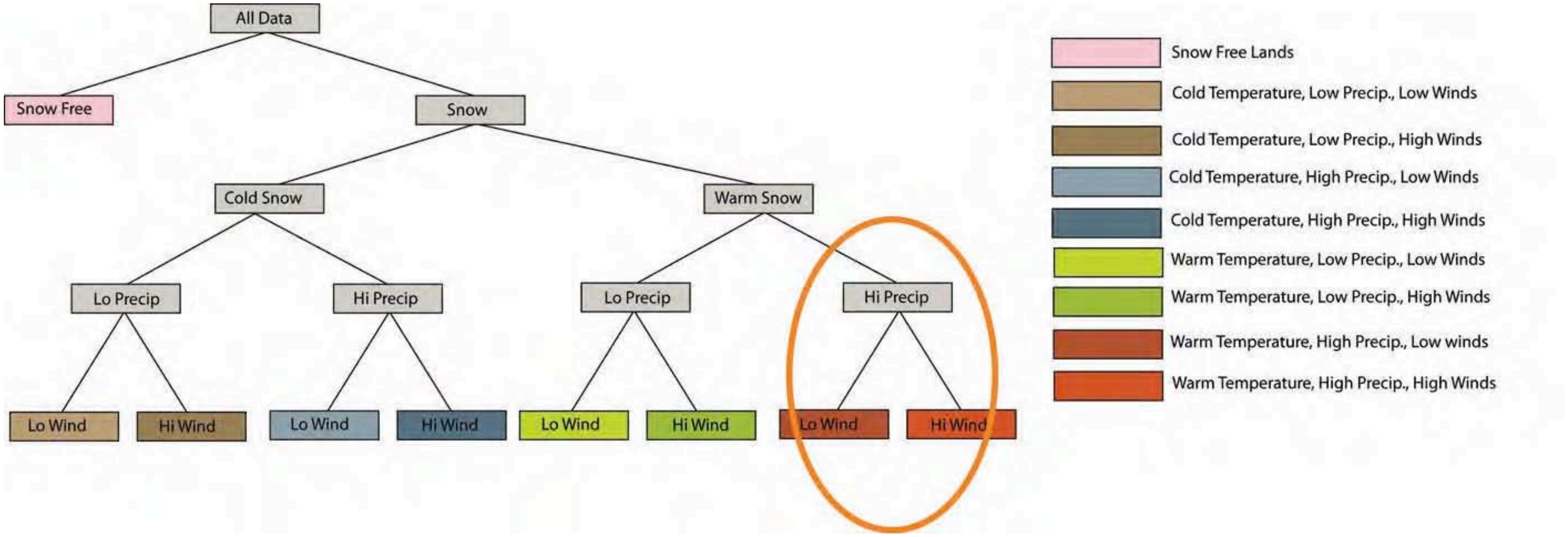

Figure 3.7: A binary decision tree is used to create nine descriptive classes of snow cover based on temperature, precipitation and wind speed. Warm snow, high precipitation, and low and high wind classes (circled here in orange) are considered at-risk within this study.

Grid cells that are classified as warm snow with high precipitation are of particular interest because these are the locations where even a small increase in winter temperature would likely result in a significant shift from snowfall to rainfall. Thus, we explored the sensitivity of potential future snow cover using incremental increases in temperature and applying these to the temperature data used in the binary decision tree. A series of subsets of the U.S. temperature, precipitation and wind speed files were then taken for the Columbia River Basin with projected climate warming of 1.0, 1.5, 2.0, 2.5 and 3.0°C.

The accuracy of the snow cover extent created with the 800-meter PRISM data was validated using data from the NOAA/NWS Cooperative program. Nine cooperative stations located in the western region of the CRB were identified and their historical records of snow depth for December, January and February were analyzed (Fig. 3.8).

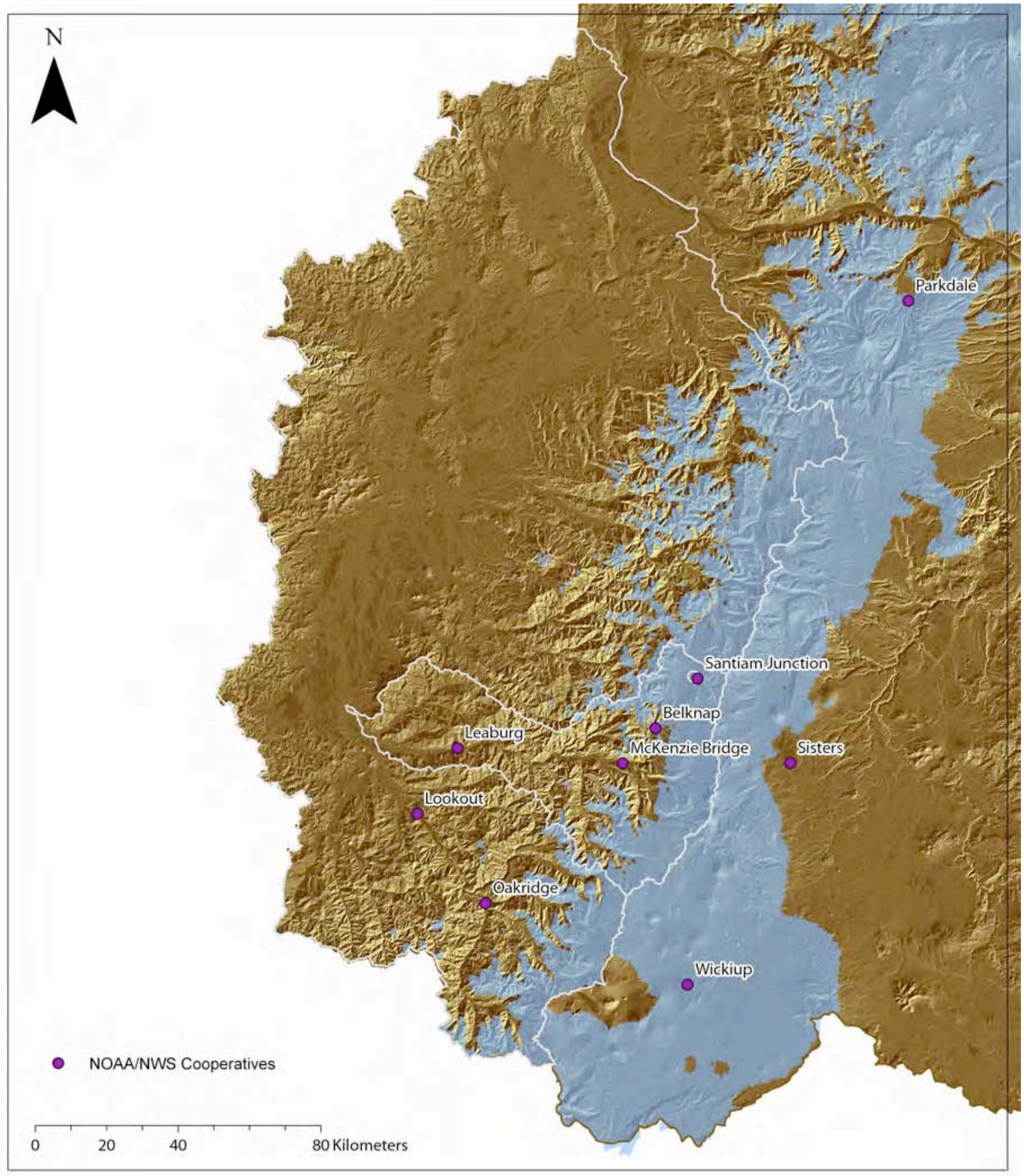

Figure 3.8: Nine sites from the NOAA\NWS Cooperative Program were selected for validation purposes.

Snow cover at each site was binned into two classes, snow, represented as 1, and no-snow, represented as 0. The percent of months with snow was calculated for the period of record. Using a one-sample t-test, with the null hypothesis that the mean of all months should equal 50 the probability of snow occurring at any one site in any given year was calculated (Table 3.1).

Table 3.1: NOAA\NWS Cooperative sites are used to validate placement of snow along the snowline in the Oregon Cascades. Probability is expressed as a p-value.

Site Name	Period of Record	Years Used	Latitude	Longitude	Elevation (m)	% Dec.-Feb. Snow	Probability of Dec. Snow	Probability of Jan. Snow	Probability of Feb. Snow
Belknap Springs	1960-2008	1970-2008	44.28	-122.03	656	74	0.0007	0.0002	0.0025
Leaburg	1933-2008	1970-2008	44.10	-122.68	207	33	0.9929	0.8661	0.9975
Lookout Point	1955-2008	1970-2008	43.91	-122.75	216	16	0.9999	0.9999	0.9999
McKenzie Bridge R.S.	1954-1970	1954-1970	44.17	-122.11	450	90	0.0001	0.0003	0.0003
Oakridge	1914-2008	1970-2008	43.74	-122.44	389	38	0.5	0.9425	0.9996
Parkdale R.S.	1980-2008	1980-2008	45.5	-121.58	527	90	0.0001	0.0001	0.0001
Santiam Junction	1949-2008	1987-2008	44.43	-121.94	1143	97	0.0001	0.0001	0.0001
Sisters R.S.	1958-2008	1972-2008	44.29	-121.54	970	74	0.0009	0.0002	0.027
Wickiup Dam	1941-2008	1970-2008	43.68	-121.68	1328	96	0.0001	0.0001	0.0001

Elevation bands of the basin were created every 200 meters using a 30-meter DEM from the 2005 National Hydrography Dataset Plus produced by the United States Environmental Protection Agency and the United State Geological Survey. The snow cover classification for every threshold value was then analyzed for each elevation band and for the basin as a whole using a decision tree based on a binary classification system. This process was then repeated for the Willamette basin and the McKenzie basin.

The total area of the CRB was calculated using the 30-m DEM. The total SCAwas then calculated for each temperature-increase scenario for the CRB and the two nested basins of interest. The area of at-risk-snow in each warming scenario, and for each basin, was calculated as a percentage of the respective total SCA. To determine the amount of water represented by the areas of at-risk-snow, data from the United States Department of Agriculture (USDA) Natural Resource Conservation Service (NRCS) Snow Telemetry (SNOTEL) network were analyzed. Mean snow water equivalence values from SNOTEL stations within the areas classified as at-risk were averaged over the period of record. This value was used to represent SWE across the greater area and a volume of water represented by the current snow cover was calculated in terms of cubic kilometers.

3.5 Results

PRISM data for the present day climate regime show total SCA for December-February of 38% in the CRB. Under a 2°C warming scenario only 1-2% of snow is at risk of turning to rain. However, the Willamette and McKenzie basins show a much higher potential loss of snowpack. In the same warming scenario, 28-30% of the snow in the Willamette basin and 25-27% of snow in the McKenzie Basin is at risk of turning to rain (Table 3.2). Under all warming scenarios, the Willamette and McKenzie basins show significantly higher losses than the average loss of the greater CRB. Spatial results of the warming scenarios are shown in Figures 3.9-3.11.

Table 3.2: Warming scenarios considered likely by the IPCC were applied to each basin; then SCA and area of at-risk snow were calculated.

Basin	Warming Scenario (°C)	Area (km²)	Total SCA (km²)	At-Risk Area (km²)	% SCA At-Risk
McKenzie	1	3467	1319	8	1
-	1.5	-	-	139	11
-	2	-	-	342	26
-	2.5	-	-	571	43
-	3	-	-	734	56
Willamette	1	29777	4873	28	1
-	1.5	-	-	547	11
-	2	-	-	1429	29
-	2.5	-	-	2346	48
-	3	-	-	2978	61
Columbia	1	551981	210138	32	<1
-	1.5	-	-	692	<1
-	2	-	-	2356	1
-	2.5	-	-	5072	2
-	3	-	-	8785	4

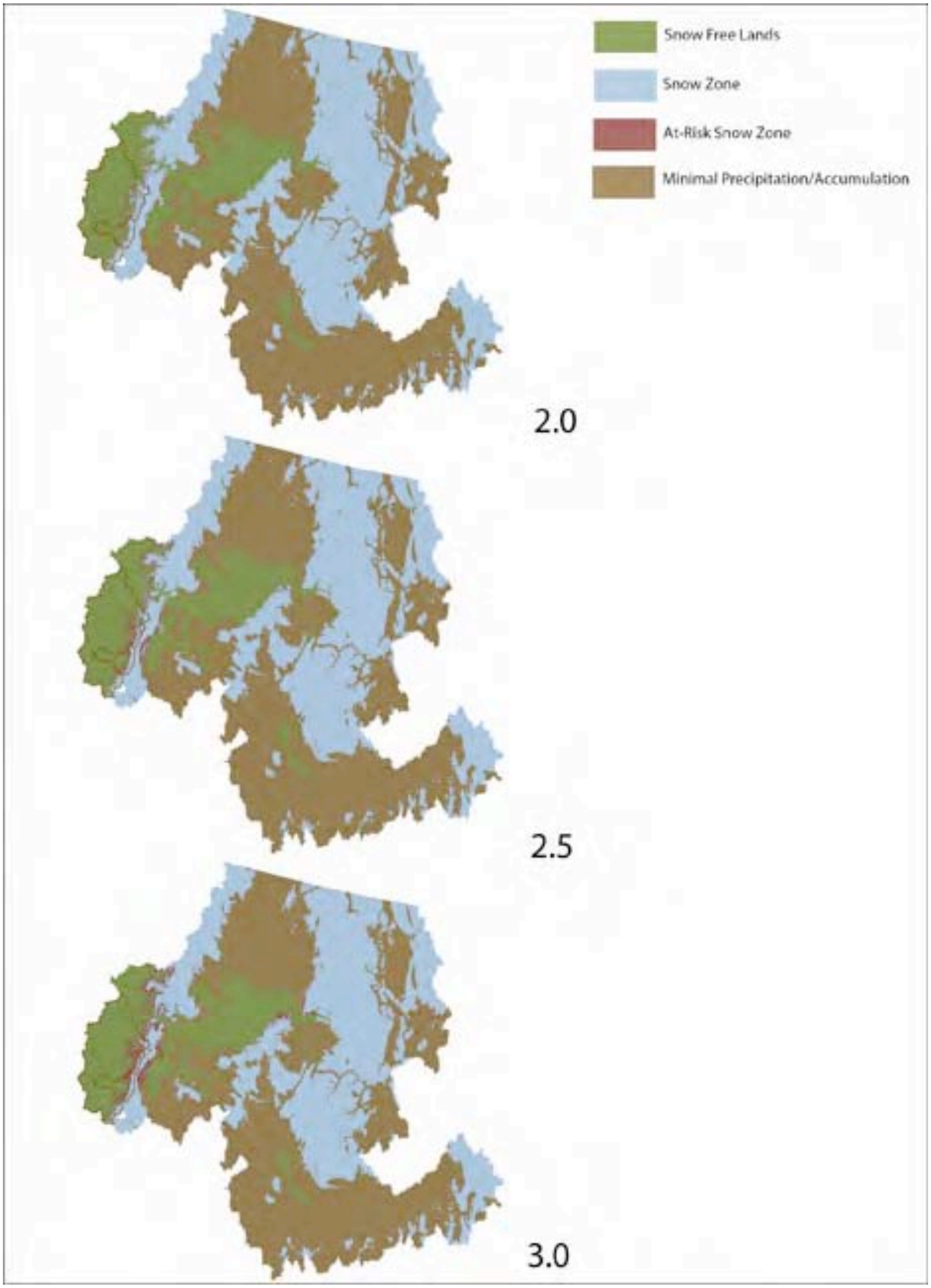

Figure 3.9: Warming scenarios in the CRB are most prominent after a 2.0° C increase occurs. Here, at-risk snow appears most prominently on the western slopes of the Oregon Cascades.

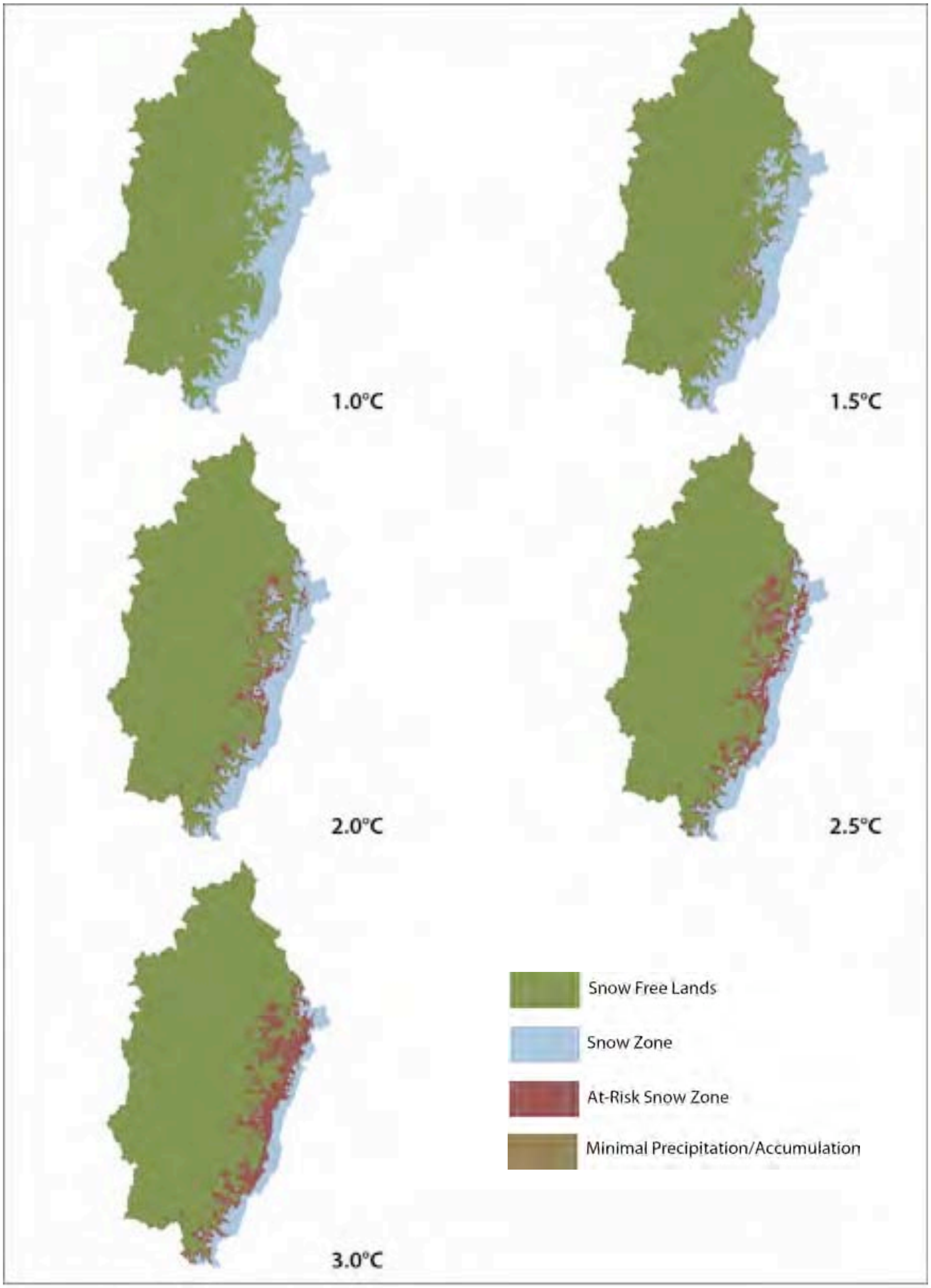

Figure 3.10: Willamette River Basin warming scenarios. Change in snow class is most prominent at scenarios greater than 1.5°C.

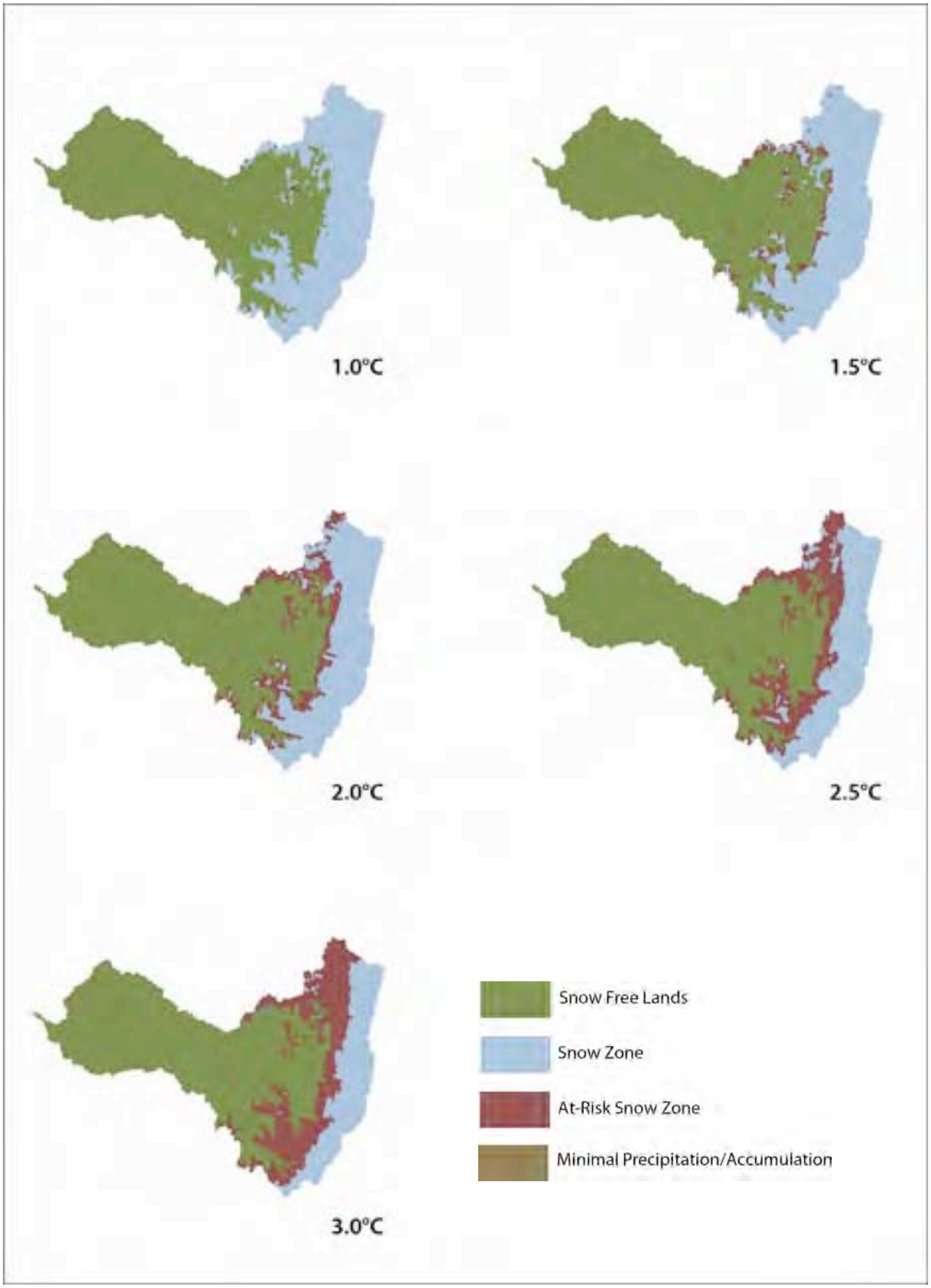

Figure 3.11: Warming scenarios applied to the McKenzie River Basin. Again, changes are seen most prominently at temperatures above 1.5° C.

As expected the greatest increase in at-risk snow area is associated with the largest warming trend. Basin size does not appear to directly affect declines in snow cover, indicating that is likely more basin topography and climatology then area that controls areas of susceptibility (Fig. 3.12).

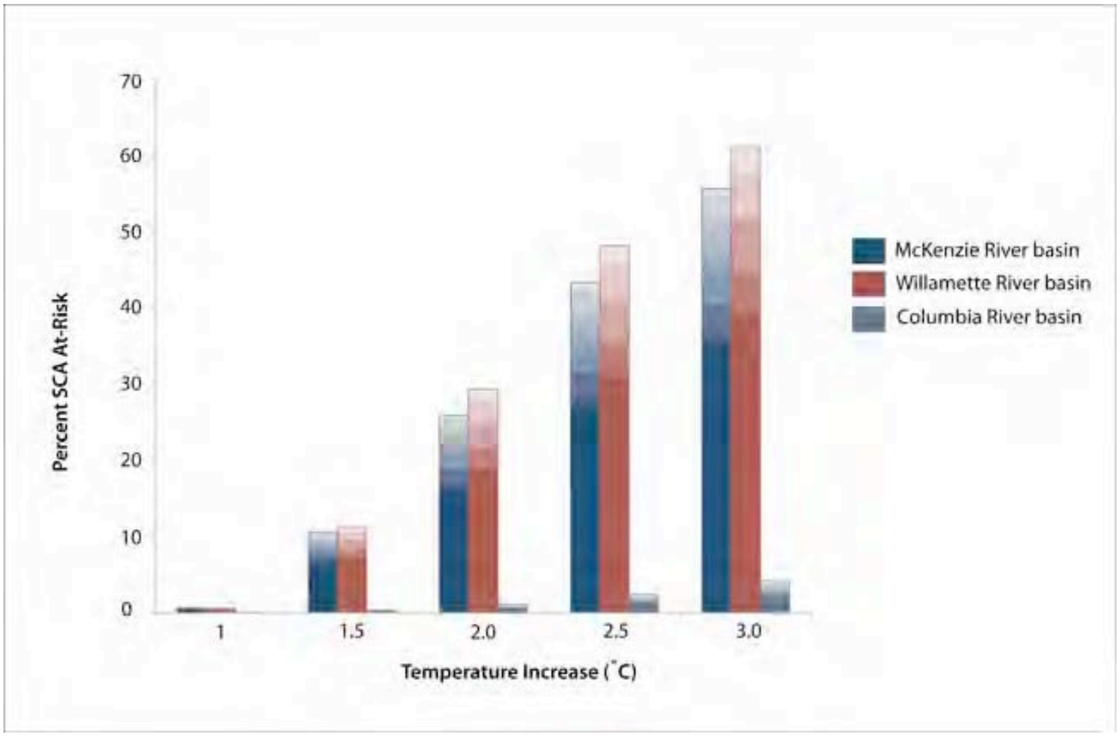

Figure 3.12: Potential loss of snow cover increases in a linear relationship with temperature increase.

The use of cooperative sites to validate placement of snow showed some discrepancies in the PRISM model, though this may have been due in part to problems with the period of record and with accurate coordinates for the geographic placement of the sites. Of the six sites that showed a high degree of significance for snow cover Jan.-Dec., (Table 3.1) two, McKenzie and Sisters, were located outside of the SCA that was created using PRISM data (Fig. 3.8). It is likely that the results for the McKenzie site were affected by inaccuracies in placement and a truncated period of record that does not overlap with the period of record used in the PRISM data.

Within the CRB, the western slopes of Oregon's Cascade mountain range are most susceptible to changes in climate and as a result to potential changes in snowpack. Located along the edge of the eastern Willamette Basin, the western Cascades are a largely low elevation range that will likely experience large changes to winter precipitation. In this area, a 2°C warming creates an area of 1429 km^2 at-risk of turning from a winter snow dominated to a winter rain dominated climate regime. The average SWE estimate within this area, based on the historic record was approximately 51 cm.. This is an average value derived from 29 years of April 1, peak SWE data collected at eight of the 16 United States Department of Agriculture Natural Resources Conservation Service (NRCS) Snow Telemetry (SNOTEL) sites within the basin. These eight sites are located within the area that would be considered "at risk" given a 2°C warming (Fig. 3.13). The loss of the snow in this area would represent a volumetric loss of 0.7 km^3 of water that would otherwise be stored in the snowpack and released during the ablation season to support spring and summer stream flows (Table 3.3).

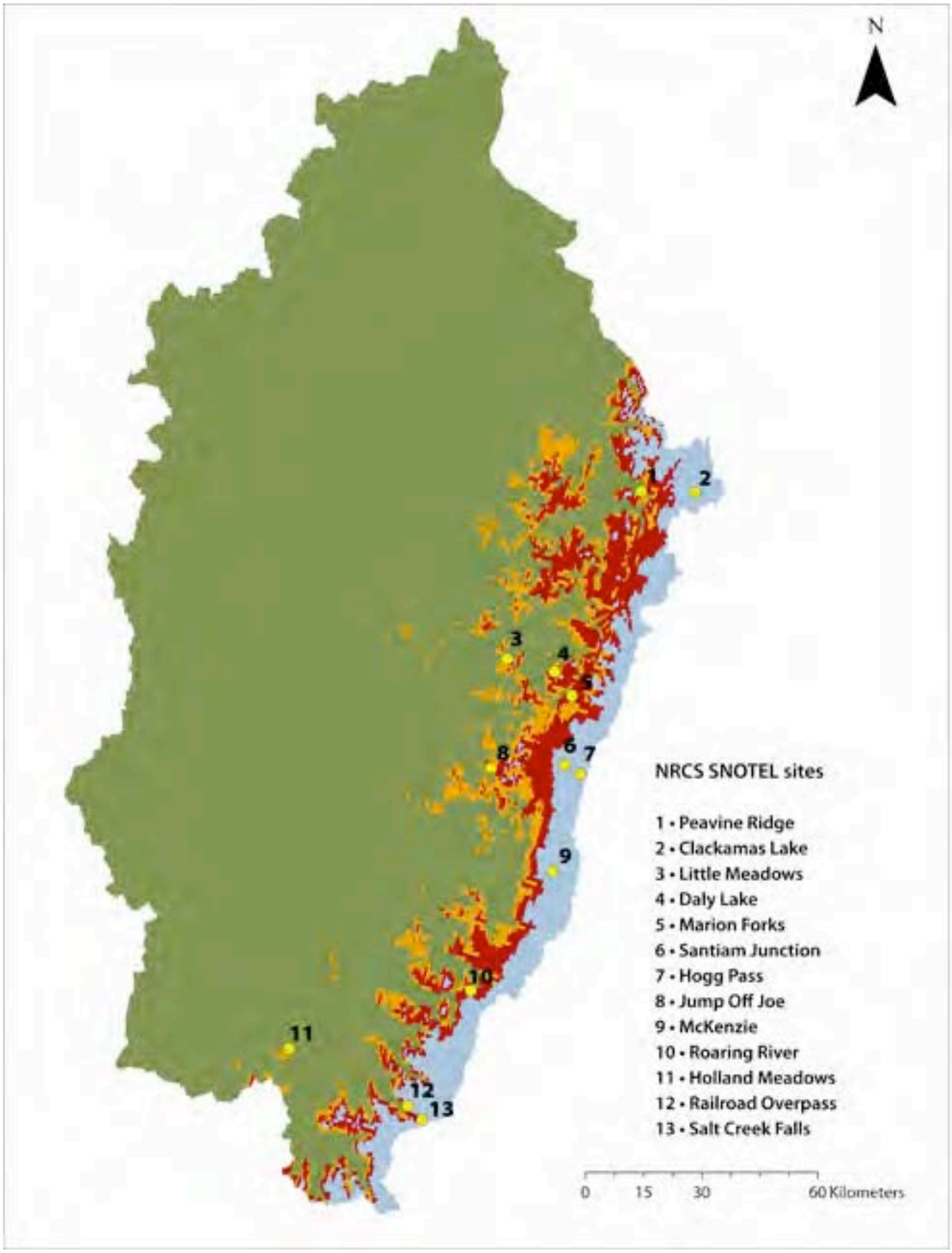

Figure 3.13: Willamette River Basin with SNOTEL sites. At-risk snow cover is represented under a 2° C warming (red) and a 3° C warming (orange). Eight of the 13 SNOTEL sites are located in the "at-risk" snow zone.

Table 3.3: Average SWE for the Willamette River Basin is derived from data collected at SNOTEL stations in the at-risk areas. There was insufficient data available to calculate the 1°C and 1.5° C scenarios.

Warming Scenario (C°)	Area At-Risk Snow (km^3)	Equivalent Volume of Water (km^3)	Equivalent Volume of Water (US Gallons)
2.0	1429	0.7	$1.92*10^{11}$
2.5	2346	1.2	$3.17*10^{11}$
3.0	2978	1.5	$3.96*10^{11}$

3.5 Discussion

Warming winter temperatures have immediate and relevant impact on the extent of SCA in the Oregon Cascades. This region's sensitivity to climate change can be seen under all warming scenarios. If the regional trend of temperature increase suggested by the IPCC to be highly likely continues, the Willamette River Basin will experience a more than a 10% loss of December, January, February SCA in the next decade. Within the next 70 years there will be a 60% decline in snowpack. Expected changes to SCA in the McKenzie River Basin are similar to those of the Willamette. A 10% loss will likely occur in the next ten years, and by 2080, SCA will have decreased by 55%. The CRB is much less susceptible to loss of Dec.-Feb. SCA (Table 3.1).

Potential future declines in mid-winter snow covered area in the Willamette and McKenzie basins appear to correlate with elevation, however a range of other physical and climatic variables may impact where and when snow is accumulating and ablating. The model used here can only show where snow extent is declining; it provides minimal information about why some areas are more sensitive to change. This information has direct import for the measurement of snow pack especially in the smaller, more vulnerable watersheds located in the western Cascades.

Changes in SCA may have drastic impacts on the Willamette River Basin, because of its level of development and large population. The IPCC AR4 (2007) has projected a 2.0°C warming in the basin by midcentury. Under such a warming, SCA in the basin would be reduced by almost 30%. The amount of water released, about 0.7 km^3, would be enough to provide the basin with 243 days of water at the current usage of 800 million gallons per day (Table 3.2) (Wentz, 1995). Increasing the warming by 0.5°C increases that number to 1.3 years.

Declines in winter storage within the snowpack would also have ramifications for water management and fish. Changes in the shape of the annual hydrograph would result in changes in streamflow, and could impact the amount of available water in the for fish, hydropower and irrigation. New strategies would need to be developed to store, release and allocate water throughout the year.

These numbers should be approached with skepticism, however. The volumetric equivalent of the snow in the at-risk areas is based on point measurements of average peak SWE values from SNOTEL sites that may not be representative of the basin. In addition, though the PRISM dataset used is of a much higher resolution than data used in previous snow cover mapping, it remains relatively coarse, and could be over or under estimating snow cover, especially in topographically complex terrain. Future work should involve a more in-depth analysis of snow cover at the cooperative sites. A greater number of sites should be selected and a more rigorous statistical analysis should be undertaken.

3.6 Conclusion

Modeling the impact of different climate warming scenarios on SCA during the core winter months in the Columbia River basin begins to illustrate what the landscape will look like should current warming trends continue. However, this work does little to explain where water for the West will come from if the free storage currently provided by snow pack is no longer available. The shift from a snow dominated winter precipitation regime to a rain-dominated pattern will result in higher winter flows, earlier peak flows and lower summer flows. Simply put there will be excess water available in the winter when it is not needed, and a shortage of water in the summer when it is often desperately needed. The areas that are most vulnerable to this shift in precipitation are also the areas that are most dependent on adequate and regular water supply for their large human populations and industry.

Estimates of future climate warming in the west indicate that snow cover loss will continue and may accelerate as temperature thresholds are reached and then exceeded (Hamlet et al., 1999). There is no doubt that water resources in the west will be affected by this change. The findings presented here provide a broad look at how changes in winter precipitation regimes will affect snow pack and available water. Water managers may wish to consider these findings as they create long term plans for water use and allocation. Without a way to store and later release winter precipitation, in-stream flows may experience increased changes throughout the year.

Additional and future work in this area may focus on ensuring the accuracy of SWE measurements to better and more accurately determine the amount of water storage that will be lost as precipitation regimes changes. In addition, work could be done to better determine the relationship between snow cover loss at different locations in the basins and stream flow. Policy makers and natural resource managers may wish to explore viable storage options to replace the “free” storage that will be lost as snowpack disappears. Reservoirs, holding tanks and ground water pumping may all be investigated further. In addition, conservation, changes in water use and management and new technologies could all be explored as options to combat a decrease in storage availability resulting from this type of loss.

Chapter 4 – Discussion and Conclusions

The global hydrologic system is undergoing rapid transformation. Climate change is forcing shifts in the timing, phase and amount of precipitation received around the world. In the western United States these shifts directly impact winter snowpack; in most cases are causing a reduction in annual accumulation of snow. This decline transfers immediately to changes to stream flow especially in timing of peak flow and late summer volumes. The implications of these shifts for water managers are many, and include a need for increased storage capacity, changes in streamflow management for fish, flood control, and hydropower, and changes in how water is allocated and shared between users and across political, economic and social realms.

The Treaty Between the United States of America and Canada Relating to the Cooperative Development of the Water Resources of the Columbia River Basin, or the Columbia River Treaty, the binding international document between the U.S. and Canada that dictates how water in the Columbia River basin should be managed will likely expire in 2024, and may enter into a renegotiation phase beginning in 2014. In April 2009, the first international symposium was held to discuss the challenges facing the treaty and its renegotiation. While many critical issues have arisen since the drafting of the original treaty document, including the development of the Endangered Species Act, widespread regional population growth and the acknowledgement that the rights of several Native American groups may have been ignored, it is arguable that changes to the climate system and therefore changes to water availability and storage, pose some of the greatest uncertainty to the basin and to successful renegotiation and management.

The findings of this thesis are of immediate use to water managers and natural resource planners preparing for renegotiation and for successful water governance at regional and small basin scale. The results of the first article show that should temperature increases continue to occur as determined highly likely by the IPPC, the amount of storage lost due to melting snowpack in the Willamette River Basin over the course of one season will be equivalent to the amount of water used by the entire basin over the course of one year. The snowline will move upward in elevation and more than half of the snow covered area we are accustomed to seeing today will be at risk of disappearing as more precipitation turns from snow to rain. This places greater pressure on higher elevations where colder temperatures may buffer the snowpack allowing for continued accumulation of stable snowpack. However, the findings of the second article show that these areas that will likely only grow in the hydrologic significance are largely unaccounted for by the current measurement system. In addition the areas where point measurements are currently taken fail to accurately capture basin wide snow measurements. In most cases these sites showed measurements greater than 180% of the basin wide average value for snow water equivalence.

This all speaks to increasing levels of variability and possible instability across the Columbia River basin in terms of water availability and conflict free water management. Wolf et al. (2003) put forward the idea that the "likelihood of conflict rises as the rate of change within the basin exceeds the institutional capacity to absorb that change." Preliminary research to quantify historic variability in the Columbia River basin suggests many of the areas found by this thesis to be most susceptible to radical changes in snowpack and precipitation regimes due to shifting climate patterns are areas that have previously had minimal precipitation variability (Fig. 4.1).

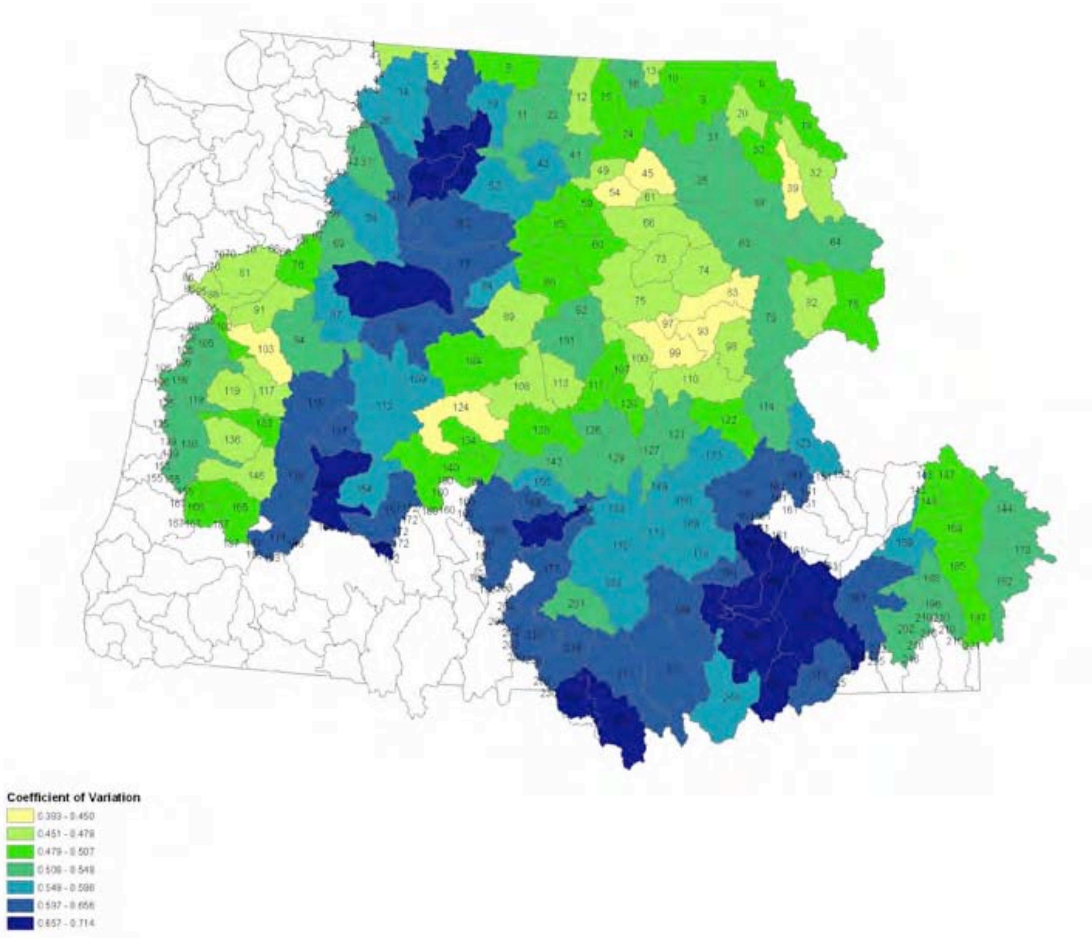

Figure 4.1: Coefficient of Variation data for Columbia River basin 4th field hydrologic units. Areas, like Oregon's western Cascades, which this work found highly susceptible to climate-induced changes, have historically experienced minimal amounts of precipitation variation. Data Source: PRISM.

While the ability of these small basins to absorb changes in precipitation is currently unknown, it can be hypothesized that basins that have had high levels of historic variability may be better positioned to manage for future precipitation variability. Conversely, areas like the McKenzie River Basin and the greater Willamette basin, that have had minimal variability may not have the infrastructure in place to appropriately cope with, manage for and adapt to changes in water availability and timing.

The management of the scenarios outlined in this thesis and elsewhere at the small watershed scale has implications for the greater Columbia River basin. The Willamette River and the tributaries west of the Cascades provide almost one quarter of the total annual flow volume in the Columbia (Table 4.1).

Table 4.1: Columbia River basin contributing systems (Muckleston, 2003).

Contributing System	Catchment Area (km^2)	Volume (km^3)	Percent of Total Flow
Mainstem above Pend Oreille excluding the Kootenay	37600	40.7	18.8
Kootenay River basin	49700	25.9	11.7
Clark Fork	67300	23.4	10.6
Mainstem Tributaries from International Border to Snake River Confluence	282300	23.4	10.6
Snake River Basin	72500	45.6	20.5
Mainstem Tributaries between Snake River and Cascade Range	49200	11.1	5
Mainstem Tributaries West of Cascade Range	670800	51.8	23.3

Decision makers in the region must work together to provide the infrastructure necessary to insure future water stability at the sub basin and basin scale. The loss of snowpack and corresponding loss of free water storage places increased stress on the region. Developing new tools, relationships and water management strategies will be imperative for economic and environmental health.

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