AN ABSTRACT OF THE DISSERTATION OF

Eric A. Sproles for the degree of Doctor of Philosophy in Water Resources Science
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Title: Climate Change Impacts on Mountain Snowpack Presented in a Knowledge to Action
Framework

Abstract approved:

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Anne W. Nolin

Throughout many of the world's mountain ranges snowpack accumulates during the
winter and into the spring, providing a natural reservoir for water. As this reservoir
melts, it fills streams and recharges groundwater for over 1 billion people globally.
Despite its importance to water resources, our understanding of the storage capacity of
mountain snowpack is incomplete. This partial knowledge limits our abilities to assess
the impact that projected climate conditions will have on mountain snowpack and
water resources.

While understanding the effect of projected climate on mountain snowpack is a global
question, it can be best understood at the basin scale. It is at this level that decision
makers and water resource managers base their decisions and require a clarified
understanding of basin's mountain snowpack. The McKenzie River Basin located in the
central-western Cascades of Oregon exhibits characteristics typical of many mountain
river systems globally and in the Pacific Northwestern United States. Here snowmelt
provides critical water supply for hydropower, agriculture, ecosystems, recreation, and

municipalities. While there is a surplus of water in winter, the summer months see flows reach a minimum and the same groups have to compete for a limited supply.

Throughout the Pacific Northwestern United States, current analyses and those of projected future climate change impacts show rising temperatures, diminished snowpacks, and declining summertime streamflow. The impacts of climate change on water resources presents new challenges and requires fresh approaches to understanding problems that are only beginning to be recognized. Climate change also presents challenges to decision makers who need new kinds of climate and water information, and will need the scientific research community to help provide improved means of knowledge transfer.

This dissertation quantified the basin-wide distribution of snowpack across multiple decades in present and in projected climate conditions, describing a 56% decrease in mountain snowpack with regional projected temperature increases. These results were used to develop a probabilistic understanding of snowpack in projected climates. This section described a significant shift in statistical relations of snowpack. One that would be statistically likely to accumulate every 3 out of 4 years would accumulate in 1 out of 20 years. Finally this research identifies methods to improved knowledge transfer from the research community to water resource professionals. Implementation of these recommendations would enable a more effective means of dissemination to stakeholders and policy makers.

While this research focused only on the McKenzie River Basin, it has regional applications. Processes affecting snowpack in the McKenzie River Basin are similar to those in many other maritime, forested Pacific Northwest watersheds. The framework of this research could also be applied to regions outside of the Pacific Northwestern United States to gain a similar level of understanding of climate impacts on mountain snowpack.

Climate Change Impacts on Mountain Snowpack Presented
in a Knowledge to Action Framework

by
Eric A. Sproles

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APPROVED:

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Dean of the Graduate School

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

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Eric A. Sproles, Author

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CONTRIBUTION OF AUTHORS

Chapter 2: Dr. Glen Liston was the primary developer of SnowModel. Glen also helped identify sources of model error and how to improve model accuracy.

Karl Rittger provided Fractional Snow Cover imagery for the Landsat instrument that was used in model calibration.

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DEDICATION

I dedicate this work to my two daughters and their generation.

Understanding and managing water in the future will present many challenges for you.

Hopefully this work makes it a wee bit easier.

1   Climate Change Impacts on Mountain Snowpack Presented in a Knowledge to Action Framework

This research develops a knowledge-to-action framework for understanding the projected climate impacts on mountain snowpack at the watershed scale. The water storage of snowpack is quantified in present and projected climates, new probabilistic tools to assess change in snowpack and melt are developed, and a decision support tool to disseminate these results is created and assessed. This research can be incorporated into near and long-term planning and adaption strategies for projected climate change.

> *"There is a growing need for information and for more*
> *effective ways to support climate-related decisions in both the*
> *public and private sectors as a result of how rapid changes in*
> *the Earth's climate (National Research Council, 2009)."*

1.1   Introduction

Mountain snowpack is a natural and efficient storage system for water, accumulating snow throughout the winter and releasing water through melt during the spring and summer. Melt from snowpack recharges aquifers and provides a cold, clean source of water for streams. Snow accumulation is influenced by precipitation and temperature, with precipitation primarily affecting the maximum accumulation and volume of runoff. Temperature primarily influences the timing of melt (Barnett et al., 2005).

Snowpack and snowmelt provide a tremendous human, economic and ecologic resource. Globally, over one billion people rely on melt from snow and glaciers as their primary water supply (Barnett et al., 2005; Dozier, 2011). The geographic scope is not limited to regions near mountain snowpack, as melt can fill streams for distant

population centers (e.g. the Colorado, Danube, and Indus Rivers). Melt also provides water for hydropower that creates electricity for populations far away from the mountain snowpack. Industry and agriculture rely on snow and glacial meltwater to provide water at a range of economic scales. Plot-scale farmers rely on snowmelt for irrigation and food processing. Industrial manufacturing relies on snowmelt for hydropower, processing of materials and as an ingredient. And, in-between these two ends of the economic spectrum, there are a wide variety of agricultural, industrial and municipal uses for water originating from melt.

Ecologically, changes in the timing and evolution of snowpack affect the entire ecosystem (Rosenzweig et al., 2008). Species have evolved in snowy mountain environments and have become highly adapted to it (Nogués-Bravo et al., 2007). Snow provides habitat and serves as an ecological timer. The phenology (seasonal timing) of plants in snowy areas is tied to the disappearance of snow (Inouye et al., 2000). The migration patterns of ungulates (e.g. deer and elk) and the hibernation of bear species are closely associated with the appearance and disappearance of snow on the landscape (Royce and Barbour, 2001). Salmonids rely on snowmelt to provide cold, clean water for migration, hatching, and rearing. The behaviors of these species have developed over millennia and are an innate component of their species.Shifts in the accumulation and timing of snowpack would, therefore, affect the social, economic, and ecologic resources that rely on snowmelt. Projected climate change is expected to increase mean temperatures in most areas of the world (Randall et al., 2007). Barnett et al. (2005) predict globally that in snowmelt-dominated basins, peak runoff will occur earlier and will be of greater magnitude. Gaining a better understanding of the impacts of projected climate change on snow and water resources is critical as adaptation strategies are being developed to plan for potential shifts in the hydrologic cycle. This is particularly true in the maritime climate of the Pacific Northwestern (PNW) United States. The PNW has wet, but relatively mild, winters and dry summers with minimal precipitation. In this region, the demand for

water for agriculture, hydropower, endangered species, recreation, and municipalities peaks during the summer months when streamflow is at its lowest. Snow commonly accumulates close to freezing, making snowpack accumulation very sensitive to increases in temperature (Nolin and Daly, 2006). Temperatures in the PNW are expected to increase by approximately 2°C by mid-century (Mote and Salathé, 2010), and are predicted to impact the snowpack in the region.

The McKenzie River basin (MRB – 3041 km^2) in the western Cascades of Oregon is a major tributary of the greater Willamette River basin (30300 km^2). Because of its snowpack and geologic characteristics, the MRB provides 25% of low flows during the late summer and early fall, but occupies only 12% of the greater watershed (Jefferson et al., 2008). This makes the MRB an important resource for ecological, economic, urban, and agricultural interests. It also underscores the need to develop adaptation plans and strategies that include projected climate change impacts on snow in the basin.While location specific measurements of snowpack have been conducted in the MRB for decades, accurate basin-wide measurements do not exist. While the existing snow monitoring network has provided a representative index of past snow conditions, Nolin et al. (2012) found that the monitoring network may not be able to accomplish the same success in projected warmer climates were snowpack shifts up in elevation and the past is less representative of the future (Milly et al., 2008). To address the need for a spatial understanding of snowpack in present and projected climates remote sensing and models can be applied (Dozier, 2011). Additionally, a model-based approach allows projected climate scenarios to be applied to a validated model. The results provide a prognostic understanding of future snow conditions. These results can be applied to analyze how projected impacts on snowpack will affect the timing and magnitude of streamflow.

1.2   Objectives of this research

This research is organized around three primary research goals that address the affects of projected climate on snowpack and water resources in the McKenzie River basin. This research uses multiple methods that range from field data collection, physically-based modeling of snowpack, statistical methods, and qualitative surveys. The dissertation offers knowledge to action framework that provides an improved scientific understanding of snowpack in projected climates and identifying means to improve dissemination of this research and similar work. Specifically, the research objectives are:

Objective 1- Develop a better understanding of the distribution of snowpack in the MRB, and its sensitivity to warmer temperatures.

> Objective 1A - Quantify the present-day distribution of snow water equivalent.
>
> Objective 1B - Quantify the watershed-scale response of snow water equivalent to increases in temperature and variability in precipitation.
>
> Objective 1C - Quantify the watershed-scale response of snow water equivalent for projected climate scenarios.

Objective 2 - Develop a probabilistic approach to understanding snowpack in the MRB, and evaluate the effect of increased temperature on the seasonal fractional discharge of runoff in the basin.

> Objective 2A – Develop a probabilistic approach to understanding the spatial distribution of snow water equivalent and its relationship to precipitation at the basin scale
>
> Objective 2B – Calculate probabilistic thresholds of water available for runoff at the sub-basin scale

Objective 2C – examine the impacts of a 2°C temperature increase on objectives 2A and 2B.

Objective 3 – Translate the information developed in Objective 1 into a decision support tool that can readily be accessed by end users, and assess the effectiveness of this tool.

1. Objective 3A – Develop a web-based DST (SnowDash) that includes features, functionality, and information requirements based upon the feedback from practitioners.
2. Objective 3B – Assess the features and functionality of SnowDash, its overall effectiveness, and understand how users interact with the DST.
Objective 3C – Obtain feedback from users to identify supplemental features, functionality and information that will improve the DST.

1.3   Organization of Dissertation

This dissertation is organized into three chapters that address the stated objectives followed by a concluding chapter. Each chapter builds on the previous section, and improves our understanding of snowpack in the MRB, the impacts of projected climate on snowpack and runoff, and how to more effectively share this knowledge with practitioners. The end goal of this research is to provide a knowledge-to-action framework that disseminates this research, but also provides insight on how to improve on this approach in subsequent projects.

Chapter 2: Climate change impacts on mountain snowpack in the McKenzie River basin. This chapter addresses the need to develop a detailed spatial model of snowpack in the MRB. We use a physically-based distributed model to simulate the distribution of snowpack at the watershed scale. A sensitivity analysis that assesses how increased

temperatures and precipitation variability affect snowpack is applied. The results highlight the areas of the basin that are most sensitive to increases in temperature. The model also applies climate projections from the IPCC-AR4 (Randall et al., 2007) for two emissions scenarios and is run for projections through 2089. The model simulations from this chapter provide data inputs for the remaining chapters.

Chapter 3: A probabilistic approach to understanding the rain-snow transition in future climates and its affect on streamflow. This chapter develops and applies an approach that calculates the spatial exceedance probability for snowpack. The spatial model characterizes the probability that a data value (i.e. SWE, fraction of total winter precipitation that falls as snow) of a given magnitude or greater will occur in any given year. The same statistical analysis is performed on simulations that reflect an increase in temperature. The exceedance probability outputs are then applied to simplistic model that estimates runoff from rain and snowmelt.

Chapter 4: Identifying means and methods for the water resources research community to become more effectively engaged with practitioners. This research uses qualitative methods to identify ways to improve the transfer of scientific knowledge from the water resources research community to practitioners.

Chapter 5: Conclusions. The final chapter provides a synthesis of the dissertation. It summarizes the key findings and suggests subsequent research that builds on chapters 2 through 4.

The research presented in the dissertation provides a diagnostic tool to better understand the spatial distribution of snowpack in the MRB in present climatic conditions. Future climate projections provide a prognostic tool to quantify the changes in the timing and volume of snowpack in the MRB, and identify the areas of

the basin where the snowpack is most sensitive. The dissertation provides an approach that directly incorporates practitioners into this research. This approach helps identify opportunities for this dissertation, and subsequent research by the water resources community, to be applied in adaptation strategies for climate change impacts on water resources.

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2 Watershed-scale Modeling of Snow Water Equivalent Under Present Day and Future Climate Scenarios

2.1   Abstract

This study investigates the effect of projected climate change on the mountain snowpack in the McKenzie River Basin in the Cascades Mountains of Oregon, USA. Mountain snowpack is important in the Cascade Mountains as it serves as a natural reservoir for water storage during the winter months that is released during the spring and summer. The melt from this reservoir provides critical water supply for agriculture, ecosystems, and municipalities throughout the region. Current analyses and those of projected climate change impacts show rising temperatures in the region. This trend is responsible for a greater proportion of snowfall transitioning to rain, decreased storage of water in the snowpack, and a shorter snow cover season. Specifically we model the spatial distribution of Snow Water Equivalent (SWE) in the McKenzie River Basin for the period of 1989-2009. The model is evaluated using point-based measurements of SWE, precipitation, and temperature and spatially using snow cover extent from the Landsat Thematic Mapper. The validated model was then run for nine climate perturbation scenarios to examine how projected climate change would be expressed in the spatial and temporal distribution of snow water equivalent. Results show that a 2°C increase in temperatures would shift peak snowpack 12 days earlier and decrease volumetric storage of water by 56%. Snowpack between the elevations of 1000 and 1800 m are the most sensitive to increases in temperature. Upper elevations were also affected, but to a lesser degree. High elevation areas of the basin show increased snowpack in climate scenarios that include an increase in precipitation along with an increase in temperature. However in all nine of the climate projections there was an overall net loss of snow water equivalent for the watershed as a whole.

2.2 Introduction

2.2.1 Significance and Motivation

Mountain snowpack in the Pacific Northwestern United States is an important component of the hydrologic cycle. This natural reservoir stores water during the wet, winter months (December – March) and provides melt water that recharges aquifers and helps sustain streams during the drier months of the year (June – September). The McKenzie River Basin (MRB), located in the Central Western Cascades of Oregon, exhibits characteristics typical of many watersheds in this region, where ecosystems, agriculture, hydropower, municipalities, and recreation compete for a limited supply — especially in summer when stream flows reach a minimum (United States Army Corps of Engineers, 2001; Oregon Water Supply & Conservation Initiative, 2008). While up to 50% of annual precipitation falls as snow in the upper elevations of the Oregon Cascades (Serreze et al., 1999) this mountain snowpack is especially susceptible to rising temperatures (Nolin and Daly, 2006). Much of this snow falls at temperatures close to freezing, especially at elevations ranging from 800-1500 m (Nolin and Daly, 2006; Nolin et al., 2012). Throughout the region, current analyses and those of projected future climate change impacts show rising temperatures (Mote and Salathé, 2010), diminished snowpacks, and declining summertime streamflow (Service, 2004; Stewart et al., 2004; Barnett et al., 2005; Mote et al., 2005; Stewart et al., 2005; Stewart, 2009; Mote and Salathé, 2010). Despite the importance of snowpack, a watershed-scale understanding of the amount of water stored in the mountain reservoir of the MRB does not exist, limiting the ability to assess the effects of future climate which show a 2°C increase in temperatures by mid-century. A watershed-scale understanding of snow water equivalent (SWE, the amount of water stored in the snowpack) and water storage in the MRB would be a valuable benefit to those managing this vital resource.

This problem is not unique to the Oregon Cascades. Globally measurements of mountain snowpack are limited due to complex terrain and an observational network based upon sparse point-based measurements (Dozier, 2011). This is of significance as mountain snowpack provides a sustained source of water for over one billion people (Barnett et al., 2005; Dozier, 2011). Location-specific measurements limit the ability to accurately predict snowpack and runoff at the basin scale, especially in a changing climate (Bales et al., 2006). Improvements in quantifying the water storage of mountain snowpack in present and projected climates advance the ability to assess climate impacts on hydrologic processes. While climate impacts on mountain snowpack is a global concern, addressing them at the basin-level provides a scale that is appropriate to be developed into natural resource management strategies (Dozier, 2011).

The MRB is especially important as this watershed occupies 12% of the Willamette River basin but supplies nearly 25% of the late summer discharge at Portland (Hulse et al., 2002). The snow reservoir's importance has increased as Oregon's population increase 21% since 1990 has been found primarily in the Willamette River basin (Perry and Makun, 2001; United States Census Bureau, 2010). Most of Oregon's population (70%) resides in the Willamette River basin and the economy and ecosystems in the region depend heavily on the Willamette River, especially in summer months when rainfall is sparse. This makes the MRB a key resource for ecological, urban, and agricultural interests and of great interest to water resource managers in the MRB and greater Willamette River system (30,300 km^2). While measurements of snow have been conducted at the local scale for decades in the Oregon Cascades, accurate measurements of basin-wide snowpack do not exist for the MRB or other Oregon Cascades basins (Nolin, 2012). These point-based measurements are useful, but the absence of spatial clarity limits the ability to assess basin-wide impacts of projected warmer climates on snowpack.

This research examines and quantifies the sensitivity of snowpack in the MRB to projected climate change. Specifically the research objectives are to: 1) quantify the present-day and future watershed-scale distribution of snow water equivalent; 2) quantify the watershed-scale response of snow water equivalent to increases in temperature and variability in precipitation; and 3) quantify the watershed-scale response of snow water equivalent for projected climate scenarios.

2.2.2   Study Area

The McKenzie River Basin has an area of 3,041 km^2 and ranges in elevation from 150 m at the confluence with the Willamette River near the city of Eugene to over 3,100 m at the crest of the Cascades. The spatial patterns of precipitation in the MRB are controlled primarily by elevation. Average annual precipitation ranges from approximately 1000 mm in the lower elevations to over 3500 mm in the Cascade Mountains (Jefferson et al., 2008). Winter (December – February) air temperatures are commonly close to 0°C. As a result, winter precipitation is highly sensitive to temperature and can fall as rain, snow, or a rain-snow mix. In the MRB, the rain-snow transition zone is roughly 800 to 1500 m. The seasonal snow zone is situated above 1500 m and in this zone, the fraction of total annual precipitation from snow is approximately 50%. Here, deep snows accumulate throughout the winter increasing their water storage until the onset of melt, about April 1 (Serreze et al., 1999). Stream discharge for the McKenzie River follows the seasonal precipitation pattern with a maximum in February (283 m^{3}s^{-1}, near Eugene) and a minimum of 57 m^3 s^{-1} in September (Nolin et al., 2012). This disproportionate percentage of late season flow is due primarily the influence of groundwater via springs, providing both a muted and delayed stream response to snow melt (Jefferson et al., 2006). The influence of groundwater is explained by the geology of the basin. The MRB has two distinct geologic provinces, the Western Cascades and the High Cascades (Figure 2.1). The Western Cascades are a highly dissected Oligocene- to Pliocene-age volcanic landscape characterized by closed canopy forests and steep slopes. The High

Cascades provide significant groundwater recharge that explains the MRB's significant contribution to the late season discharge of the Willamette River. The High Cascades are characterized by Pleistocene-age basalt flows, vegetated forested landscape, and a poorly defined stream network (Jefferson et al., 2008).

Snowpack trends in the MRB

SWE reaches its basin-wide maximum in the mountain west on approximately April 1st (Serreze et al., 1999; Stewart et al., 2004). In the PNW, there have been significant declines in April 1 SWE and accompanying shifts streamflow have been observed (Service, 2004; Barnett et al., 2005; Mote et al., 2005; Stewart, 2009; Luce and Holden, 2009; Fritze et al., 2011). This reduction in SWE has been attributed to higher winter temperatures (Knowles et al., 2006; Mote, 2006; Fritze et al., 2011).

The MRB also exhibits declining snowpack. The snow measurement site located at Santiam Junction (44.33° N, 121.95° W) represents the longest snow measurement record in the MRB and Oregon (1941–present) (Nolin, 2012). The 10% loss of SWE per decade over the 70-year record demonstrates is statistically significant (p=0.002; Figure 2.2). This relatively low elevation snow-monitoring site exhibits a small increase in precipitation (0.3% from 1979–2010). The site exhibits a larger percentage increase in degree-day, the sum of daily mean temperatures for December through March (11% from 1985-2010). This trend in winter temperature is not statistically significant because of the relatively short data record and high interannual variability. Mote and Salathé (2010) suggest that for projected future climate, the region will experience warmer but slightly wetter winters and longer, drier summers so such changes in lower elevation snowpack may signal potential future climate change impacts for snow at higher elevations and will shift the rain-snow transition zone to higher elevations (Nolin and Daly, 2006).

Limitations of Site-based Snowpack Monitoring in the MRB

Present-day monitoring of mountain snowpack uses point-based information from the Natural Resources Conservation Service (NRCS) Snowpack Telemetry (SNOTEL) network and provides information snow water equivalent, snowpack depth, air temperature, and cumulative precipitation. The network provides valuable local information, but sites are situated within a relatively narrow range of elevations that do not necessarily capture the range of variability that exists across the topographic landscape (Nolin et al., 2012). In the MRB, the four SNOTEL sites are limited to an elevation band of 245 m (1267–1512 m) in a basin where snow typically falls at elevations between 750 and 3100 m. Over half of the snow-covered area in the MRB is located above the elevation of the highest SNOTEL site (Nolin et al. (2012). In the past, this limited configuration of SNOTEL sites has functioned successfully in helping predict streamflow (Pagano et al., 2004), however the network was not designed to monitor climate change at the watershed scale (Molotch and Bales, 2006; Brown, 2009; Nolin et al., 2012).

A point-based monitoring network limits water managers' need to quantify and evaluate the impacts of projected future climate change at the watershed scale. Previous coarse-scale snow and hydrologic modeling studies provide insights into the impacts of climate change on snowpack at the regional scale (Hamlet and Lettenmaier, 2005; Hamlet and Lettenmaier, 2007; Hamlet, 2011). However at 1/8th degree spatial resolution, these studies cannot not incorporate the finer scale effects of topography and vegetation (Hamlet and Lettenmaier, 2005). Results from Nolin et al. (2012) show that elevation and vegetation are the primary physiographic variable in determining SWE distributions in the MRB.

Both spatially distributed models and remote sensing data can provide key information on spatially varying processes at the watershed scale. In the past decade,

spatially distributed, deterministic snowpack modeling has made significant advances (Lehning et al., 2006; Marks et al., 1999; Bavay et al., 2009; Liston and Elder, 2006b). These advances provide diagnostic information on relationships between physiographic characteristics of watersheds and snowpack dynamics. Such mechanistic snowpack models also allow us to make projections for future climate scenarios. Remote sensing is an effective means of mapping the spatio-temporal character of seasonal snow (Nolin, 2011). Fractional Snow Cover Area (fSCA) mapping is the fraction of coverage of snow coverage in a pixel (Rosenthal and Dozier, 1996; Painter et al., 2009; Nolin, 2011). fSCA mapping provides an aerial estimate of snowpack, but does not quantify SWE. Based on the work of Rosenthal and Dozier (1996) and Painter et al. (2009), Rittger (personal communication) developed a computationally efficient method to compute fractional SCA from Landsat Thematic Mapper (TM). Landsat TM has a spatial resolution of 30 m. It has 6 spectral bands over the visible and near-infrared spectral range and a repeat acquisition frequency of 16 days (United States Geological Survey, 2011). Such data are at a spatial scale comparable to topographic and vegetation variations in the MRB and are appropriate for capturing the heterogeneous melt patterns in this the watershed.

2.3   Methods

The overall approach to addressing the research questions can be described in three general steps: 1) apply a physically based, spatially distributed model that uses meteorological data as model forcings; 2) calibrate and validate the model output using independent station data and maps of snow covered area from remote sensing; 3) conduct a sensitivity analysis of snowpack with regard to temperature, precipitation, and climate projections. Each of these steps is described in greater detail below.

2.3.1   Model

Model Description

SnowModel (Liston and Elder, 2006b) was used to simulate meteorological and snow conditions throughout the McKenzie River Basin. The model was run at daily time steps and at a spatial resolution of 100 m. These spatial and temporal resolutions are at a scale that captures the variability in topography and snowpack across the landscape while still retaining computational efficiency. SnowModel was selected because of its ability to simulate fine-scale meteorological conditions in complex terrain at the watershed scale with a high degree of accuracy. This provides snowpack simulations driven by accurate meteorological forcings, not by model calibrations that match measured snowpack. SnowModel has been validated across a range of snow environments including Colorado, Antarctica, Idaho, Wyoming, Alaska, Greenland, Svalbard/Norway, and the European Alps (Liston and Elder, 2006b).

SnowModel (Liston and Elder, 2006b) is a spatially-distributed process-based model, that computes temperature, precipitation, and the full winter season evolution of SWE (the potential water input to the terrestrial system) across a watershed including accumulation, redistribution, sublimation/evaporation, and melt at spatial resolutions down to 30 m and at hourly or daily time steps. SnowModel is composed of four sub-models: *MicroMet, EnBal, SnowTran 3D*, and *SnowPack*.

The *MicroMet* sub-model spatially distributes meteorological inputs to provide physically realistic distributions of air temperature, humidity, precipitation, temperature, wind speed and wind direction, surface pressure, incoming solar and longwave radiation (Liston and Elder, 2006a). MicroMet uses the Barnes Objective Analysis scheme (Koch et al., 1983) to distribute weighted inputs calculated as a function of geographic location. For example, if input data have a more consistent spatial distribution throughout the domain, input values will be weighted more

evenly. Conversely, if several stations are located in close proximity, they overweight the area at the expense of other stations.

The *EnBal* sub-model computes the internal energy balance of the snowpack using atmospheric conditions computed by MicroMet (Liston and Elder, 2006b). EnBal uses a standard energy balance calculation:

$$Q_m = (1 - \alpha)Q_{si} + Q_{li} + Q_{le} + Q_h + Q_e + Q_c \qquad (1)$$

where Q_m is the energy available for melt, α is surface albedo, Q_{si} is shortwave radiation, Q_{li} is the incoming longwave radiation, Q_{le} is the emitted longwave radiation, Q_h is the turbulent exchange of sensible heat, Q_e is the turbulent exchange from latent heat, and Q_c is conductive energy (Liston and Hall, 1995; Liston and Elder, 2006b). Albedo, the snowpack's ability to reflect incoming shortwave radiation, is computed at each time step based upon forested or non-forested snowpacks. A more detailed discussion of albedo follows later in the Model Modifications section.

SnowTran 3D is a physically based snow transport sub-model that distributes the transport and ablation of snow due to wind (Liston et al., 2007). This model is designed to work over variable terrain and inputs require vegetation, topography, snowpack conditions from SnowPack, and meteorological conditions from MicroMet. SnowTran 3D calculates both transport and ablation of snow due to wind (Liston et al., 2007). Wind transport can affect snow distributions, scouring slopes and forming snow drifts. Snow that accumulates in the lower elevation, Western Cascades tends to occur closer to the melting point, has higher densities, and is often sheltered by forest canopy. Higher density snowfall and a dense canopy minimize redistribution from wind (Pomeroy et al., 2002). However snowpack in the higher elevation colder, and more open High Cascades is more susceptible to wind redistribution (Winstral et al., 2002)

SnowPack is a single layer sub-model that calculates changes in snow depth and snow water equivalent from fluxes in precipitation and melt (Liston and Elder, 2006b). A maximum density of 550 kg m^{-3} was defined for the model. Conceptually maximum density would represent a unit volume of snow with its pore space filled with rain or melt water. Once this density threshold is reached all other precipitation is defined as melt water. Such a maximum density value is not an uncommon occurrence in the PNW where rain-on-snow events are common.

Model Input Data

SnowModel requires meteorological data as its fundamental input including temperature, precipitation, relative humidity, wind speed, and wind direction. The simulations used meteorological data from seven automated weather stations distributed throughout the MRB at elevations ranging from 174 m to 1509 m (Figure 2.1, Table 2.1). Although there are six stations in the HJ Andrews (HJA) Long Term Environmental Research (LTER) site, only one of these was used to avoid overweighting of the central portion of the basin. Clusters of stations were found to negatively impact model results in the outer regions of the model domain. A spatially balanced network of input stations was used to more evenly weight the forcing data across the watershed (Figure 2.1 – stations used as model forcing are highlighted in black). Only two stations in the HJA were used as forcings in the final model implementation PRI (430 m, a lower elevation) and UPL (1294 m, an upper elevation). The addition of the Eugene Airport improved model agreement by providing a datum in the western portion of the basin. Trout Creek was added to more evenly distribute precipitation in the lower portions of the basin. The upper elevation SNOTEL sites were added to more evenly distribute meteorological conditions in the upper elevations. Stations were also required to have a near-complete data record. Discussion on how this configuration was finalized is discussed in greater detail in the model calibration sub-section.

The period of for this study, WY 1989 – 2009, was constrained by the availability of meteorological data to drive model. While all seven sites had temperature and precipitation data, only PRI had relative humidity, wind speed and wind direction back to 1989 (Table 2.1). This 21-year period of record includes seasons with above average, normal, and below average snowpack, and years influenced by El Niño/La Niña-Southern Oscillation (ENSO) for the reference period (Figure 2.2a). This time period represents a warm phase of the Pacific Decadal Oscillation and compared with records dating back 70 years, SWE measurements are below the long-term mean. The model was run with a daily time step. A limited data set of hourly data (10 years) was available but because one of our goals was to model a relatively long time period, we selected the longer daily time series. Daily mean values of temperature have a long data record, however the mean underestimated the amount of snow throughout all of the calibration years. SNOTEL data are recorded at 0:00 (midnight), 6:00, 12:00, and 18:00. Through several model iterations it was found that the 0:00 provided the best simulations of SWE when compared with the other available times. This makes sense for several reasons. 0:00 represents colder temperatures that allowing precipitation to fall as snow and rain, but also represent melt during ablation phases. The pre-dawn 6:00 temperatures overestimated the accumulation of SWE and underestimated during ablation phases. Additionally daily precipitation recordings begin and end at 0:00, and using this time (0:00) allowed precipitation measurements to not be split across days.

As boundary conditions, the model requires elevation and land cover datasets for the entire model domain. The digital elevation data were obtained from the United States Geological Survey's (USGS) Seamless National Elevation Dataset (NED) (Gesch, 2007). The National Land Cover Dataset (NLCD) (Fry et al., 2009) was also obtained through USGS. Both data sets were resampled from 30 m to the model resolution of 100 m resolution in ArcGIS 9.3 and using a nearest neighbor algorithm (ESRI, 2009).

Resampling the data to a resolution of 100 m captures variability in topography and snowpack across the landscape, while reducing the computational demands by a factor of eleven. Table 2.2 shows the NLCD land cover types present in the MRD. To mesh with the vegetation types recognized in SnowModel, these NLCD land cover types were reclassified as shown in Table 2.2. The model domain was 112 km in the east–west direction and 76 km in the north-south direction. The file size of each daily model simulation for a single output (i.e. SWE, air temperature) was 9.7 MB. A single water year required approximately 200 minutes on a UNIX -operating system with 8 GB of RAM and two dual-core AMD 64-bit processors.

Model Modifications

Two primary modifications were made to SnowModel: a rain/snow precipitation partition function and an albedo decay function. The rain/snow precipitation partition function was required because in the maritime climate conditions of the Oregon Cascades wintertime temperatures commonly remain close to 0°C and mixed phase precipitation events are common. In the Pacific Northwest, empirical measurements by the United States Army Corps of Engineers (USACE) (1956) shows that the transition from rain to snow exists primarily between a temperature range of -2 to 2 °C. This relationship was implemented in the model using Eq. 2.

$$SFE = (0.25*(275.16-T_{air}))*P \qquad (2)$$

where, SFE (Snow Fall Equivalent) is the amount of amount of precipitation reaching the ground that falls as snow, T_{air} is air temperature, and P is total precipitation. Rainfall is computed as P minus SFE.

The shortwave albedo of snow (α) has significant effects on surface energy balance, internal energetics, and seasonal evolution of snowpack (Wiscombe and Warren,

1980). Shortwave albedo is a dimensionless measure that represents the snowpack's ability to reflect incoming shortwave radiation (0.3 – 3.0 μm) (Wiscombe and Warren, 1980), and is the ratio of reflected solar radiation to incident solar radiation. A value of 1.0 represents total reflection and 0.0 represents total absorption. Snow albedo evolves, tending to decay with time. New snow is highly reflective and has albedo values close to 0.8, or reflecting 80% of incoming shortwave radiation. As albedo declines, snow absorbs more incoming radiation. Snow albedo also declines faster in forested landscapes as forest litter is deposited and concentrated at the snowpack surface (Hardy et al., 2000). The differences in forested and more open areas are pertinent in the MRB where the landscape is defined by two distinct topographic regions, the Western and High Cascades. The Western Cascades are characterized by deeper soils that support dense forested landscapes, as compared to the High Cascades that have poorly developed soils and a more open and often unforested landscape (Figure 2.1). The model implements functions that represent these unforested and forested albedo decay processes. Maximum albedo values after new snowfall are set to 0.8 in unforested areas and to 0.6 in forested areas (Burles and Boon, 2011). Snow is classified as "new snow" when model precipitation results in SFE values greater than or equal to 2.5 cm. Model albedo decreases at each time step to a minimum of 0.5 using the following two equations:

for non-melting conditions

$$\alpha_t = (\alpha_{t-1} - 0.008) \qquad\qquad (3)$$

and, for melting snow

$$\alpha_t = ((\alpha_{t-1} - \alpha_{min}) * 0.98) - \alpha_{min} \qquad (4)$$

where, α_{min} is the minimum snow albedo (0.5), α_{t-1} represents the snow albedo at the previous time step, and α_t is the snow albedo value used at each time step by the model in energy balance calculations. Thus, albedo decay rate is a tunable model parameter that was determined based on SWE measurements during the ablation periods of the calibration years (see below).

2.3.2   Model Calibration and Assessment

Model calibration was done in two phases. The initial phase focused on optimizing the spatially distributed gridded values of daily precipitation and air temperature. Precipitation and temperature are first order controls on snow accumulation. The second phase focused on calibrating the model to provide the best possible SWE and snow covered area (SCA) estimates. Model evaluation of SWE and SCA combined point-based measurements and remote sensing data, providing a robust means of model calibration and validation (Bates, 2001). Water years for statistically high, low, and average peak SWE were used to calibrate the model (Table 2.3). The model was then validated using independent data from other years in the 21-year data set that also represent high, low, and average peak SWE years (Table 2.3). Once model calibration was completed for targeted years, the fully validated model was run for WY 1989 – 2009 to establish a present-day reference simulation for applying the future climate projections, and hereafter is referred to as the Reference period.

During calibration, model output data were carefully examined in the accumulation and the ablation phases. In the PNW accumulation of snowpack is temperature dependent, partitioning precipitation into rainfall and snowfall. The ablation period is governed by the surface energy budget and melt rates vary by elevation. Snowpack is transitional between 800 to 1500 m, and accumulation and ablation occur throughout the season. Above 1500 m seasonal snowcover has a more distinct ablation period that typically begins around April 1st. The configuration of meteorological stations (Table 2.1) that provided the best simulations of precipitation, temperature, and snowpack was determined by adding a station at each iteration. Model outputs of temperature and precipitation were assessed until the optimal model results were obtained.

Calibration at Meteorological Stations

Nash-Sutcliffe Efficiency (NSE) and Root Mean Square Error (RMSE) were used to evaluate model output data compared to automated station measurements. NSE is a dimensionless indicator of model performance calculated by the equation:

$$NSE = 1 - \frac{\sum_{t=1}^{T}(Q_o^t - Q_m^t)^2}{\sum_{t=1}^{T}(Q_o^t - \overline{Q})^2} \qquad (5)$$

Where Q_o^t is observed value at time t, Q_m^t is modeled value at time t, $\overline{Q}$ is the mean, and T is the total number of simulations. Where NSE = 1, simulations are a perfect match. For 0 < NSE < 1, model is more accurate than the mean. If NSE is less than 0, the mean is a better predictor (Legates and McCabe, 1999; Nash and Sutcliffe, 1970). RMSE is indicates the error of between the observed and simulated values (Armstrong and Collopy, 1992).

RMSE is retains the unit of measure and is calculated by the formula:

$$RMSE = \sqrt{\frac{\sum_{t=1}^{T}\left(Q_0^t - Q_m^t\right)^2}{T}} \qquad (6)$$

Where Q_o^t is observed value at time t, Q_m^t is modeled value at time t, and T is the total number of simulations.

Metrics for precipitation, air temperature, SWE, and SWE/P were calculated using automated station measurements for calibration and validation years (Table 3). SNOTEL stations provide measurements of temperature, precipitation, and SWE. Measurements of SWE are calculated from a pressure-sensing snow pillow (a device for automated SWE measurements). Meteorological stations in the HJA measure temperature, precipitation and SWE. Snow pillows in the HJA are not fully calibrated

and the reported data have not been fully quality controlled. Therefore the snow data in the HJA are not used for calibration or validation but are provided merely for reference. The target threshold for NSE values 0.80 or greater for all stations, as this value represents model efficiency that is very close to measured values and is significantly better than using mean values (Nash and Sutcliffe, 1970; Legates and McCabe, 1999). RMSE provided a better understanding of the scale of error that occurred in simulations, and was used as a metric to improve model results.

Air temperature proved to be a challenging parameter to calibrate due to the complex terrain of the MRB. In the MRB, temperature lapse rates do not always follow a linear temperature-elevation relationship and synoptic scale atmospheric patterns can affect local lapse rates, especially when high pressure systems dominate causing cold air pooling (Daly et al., 2010). Initial monthly lapse rates from the Washington Cascades, roughly 350 km north of the MRB, were implemented in the model (Minder et al., 2010). These lapse rates were iteratively adjusted to minimize Root Mean Squared Error (RMSE) for measured versus modeled temperature. The final iteration applied monthly lapse rate values ranging from 5.5 - 7°C km^{-1} and were 1.5°C km^{-1} cooler than Minder found in the Washington Cascades (Table 2.4). By comparison Clark et al. (2009) used a fixed value of 5°C km^{-1} in a similar study in the maritime climate of New Zealand. Methods on how to potentially improve lapse rates calculations for future work are developed in the Discussion section.

Field measurements of SWE acquired during WY 2008 and 2009 were used to augment model calibration. Manual SWE measurements were recorded at five sites throughout the basin (Figure 2.1) on approximately the first day of each month (December – July) during 2009. Snow density values for the location and date were calculated using SWE measurements taken with a Federal Sampler (snow collection device). Four snow depth measurements were conducted within one meter of the

initial SWE sample. Using the density and snow depth measurements as inputs, mean SWE values were calculated for each sample site/date. While this approach did not allow for a detailed study of variability of SWE at each site, this rapid assessment approach allowed samples at all five sites to be conducted in a single day. In addition, SWE data were provided by colleagues at the University of Idaho for two locations on 16 May 2008, 17 March 2009, and 20 March 2009 (Link, 2010). These point-based values were acquired using a Federal Sampler and are the average of 3 – 5 samples per site.

Remote Sensing Based Calibration

The spatial extent of modeled snowcover was assessed using satellite-derived maps of snow covered area. The Landsat TM fractional snow covered area data were aggregated to the 100-m grid resolution of SnowModel and the co-occurrence of modeled and measured snow cover was assessed using metrics of accuracy, precision, and recall (Table 2.5 (Painter et al., 2009)). There were only a limited number of valid images each winter because of cloud cover and the 16-day repeat orbit. For example, during WY 2009, only one image between the months of November and April had a cloud cover less than 25% in the MRB. However, each calibration year did have at least one image with cloud cover less than 10% that could effectively assess the spatial accuracy of the model. The date of Landsat images varied across years, as evaluation images were chosen with respect to their absence of cloud cover. However the image dates occurred during accumulation, peak, and ablation phases of SWE. The spatial agreement between fSCA and SnowModel results was evaluated for physiographic variables including land cover class, elevation, slope and aspect. This allows us to identify domain characteristics that were potentially misrepresented by the model.

2.3.3   Climate Perturbations

The calibrated and validated model was run for nine climate scenarios for present-day conditions, model runs were performed using a total of nine climate perturbation scenarios. Tables 2.6 and 2.7 describe the perturbations and also provide the naming system associated with each scenario. To determine the response of snowpack to increased temperature and changes in precipitation, a sensitivity analysis was conducted in three phases. The first phase increased all temperature inputs for WY 1989 – 2009 by 2°C, which is considered to be the mean annual average temperature increase in the region by mid-century (Mote and Salathé, 2010). The second and third phases retained the temperature increases, but also scaled precipitation inputs by ±10% to incorporate the uncertainty in projected future precipitation (Mote and Salathé, 2010). Results from the ±10% precipitation also provide insight into how annual variability in precipitation can affect SWE. The validated model was then rerun applying the three sets of scaled meteorological data for the reference period of WY 1989 – 2009.

A second approach to understanding climate change impacts on SWE used climate scenarios in which monthly temperature and precipitation changes were derived from regionally downscaled ensemble values of nineteen Global Circulation Models (GCM) from the Intergovernmental Panel on Climate Change (IPCC)-AR4 (Randall et al., 2007; Salathe et al., 2007; Salathé et al., 2010). Temperature and precipitation perturbations were applied using the delta method (Hay et al., 2000), an approach that applies regional or global climate model offsets to data at the local scale (Hay et al., 2000; Blöschl et al., 2007). Mote and Salathé (2010) calculated delta values for temperature and precipitation for the Pacific Northwest of the United States using the 30-year average from 1970-1999 as the base climate period (Table 2.7). These perturbations represent monthly climate projections for the Pacific Northwest. The delta values included A1B and B1 emissions scenarios for the 2020s, 2040s, and

2080s (Table 2.6). A1B scenarios represent a global approach to energy that balances fossil-based fuels and renewable energy sources and is a conservative estimation of greenhouse gas emissions. B1 represents a more significant emphasis on renewable energy sources and lower greenhouse gas emissions (Randall et al., 2007). This approach is a simplified method to incorporate sub-annual variability, but does not account for sub-monthly variability.

In total, nine sets of perturbed meteorological data were used to rerun the model. The 2°C increase with ±10% precipitation, and scenarios A1B and B1 for the projected 2020s, 2040s, and 2080s delta change to precipitation and temperature inputs. The 2020s are the GCM average over 2010-2039; the 2040s are 2030-2059, and 2080s are 2070-2099 (Table 2.6). The validated model was then rerun applying the nine climate scenarios described in Table 2.6. Each scenario was run for the reference period of WY 1989 – 2009 with the perturbed data meteorological data.

2.4   Results

The first portion of this section describes SnowModel's performance in simulating meteorological conditions and snowpack evolution. Model performance was tested using point-based measurements for accuracy of individual model outputs and remote sensing imagery assessed the spatial accuracy of model outputs. The second portion of this section addresses how projected future climate is anticipated to affect snowpack in the MRB.

2.4.1   Model Assessment

Assessment Using Data from Meteorological Stations

Model results were evaluated at fixed locations using data from automated field stations and from field measurements (Table 2.9, Figures 2.3a and b). Model simulations of precipitation (P) and air temperature (T) performed well at both input (stations used as model forcings) and reference (stations used only for validation) (Figures 2.3a and 3b). For years other than calibration and validation years, the mean NSE of P and T at all stations was 0.97 and 0.80 respectively (Table 2.9). WY 1997 and 2005 were excluded from these metrics and in subsequent calculations discussed in this section. WY 1997 experienced two large precipitation events during the winter months. Evaluation of the input data showed that in a few cases there were significant discrepancies (>1 m of annual cumulative precipitation) at several of the stations that were used as forcing data. Additionally, a few large precipitation inputs were offset by one day. As a result a storm with a significant amount of total precipitation (> 100 mm) would, in effect, be processed on two consecutive days by the model. The shifts were not systematic and appeared to be random in nature, most likely due to equipment mistiming at several stations. While the errors were present in less than 10% of the data sets they occurred on days of heavy precipitation, which magnified the error. While simulated distributed precipitation values for 1997 closely match the point-based precipitation data used as input, there was a more than two-fold over estimation of SWE at all sites. Problems were also observed in WY 2005. Simulations of spatially distributed gridded temperature and SWE did not match values from station data used for validation. This was due to extended periods of high pressure, which resulted in cold air pooling and negative temperature lapse rates (Daly et al., 2010). Extensive snowmelt and near complete loss of upper elevation snowpack occurred in mid-to-late February (National Resource Conservation Service, 2009) as warm temperatures at higher elevations and cold temperatures at low elevations persisted

for several weeks. The model deficiencies caused by such extensive temperature inversions are addressed in the Discussion section.

Simulations of precipitation performed well in all years, for all stations and across the full range of elevations used in the validation (Figure 2.3a). The mean RMSE error was 0.01 m and the mean NSE value was 0.96 for the full reference period. It is important to note that the addition of the low elevation Eugene Airport meteorological station greatly improved model performance. This station provided meteorological input data at a low elevation and at the western edge of the model domain, which improved the spatial interpolation of precipitation.

There was a modest error for temperature that was consistent with regard to elevation. The mean RMSE error was 2.5°C and the mean NSE value was 0.80 (Table 2.9 and Figure 2.3b). The SNOTEL station at Santiam Junction consistently performed below all other locations. This station is situated between an Oregon Department of Transportation facility and an airstrip. Thus, it lies at the western edge of an exposed, flat plain that is physiographically dissimilar to its surroundings and the other stations. This disturbed environment is the most likely cause of model underperformance at this location. Simulations slightly underestimated temperature at middle elevation stations (800 - 1300 m). Steep slopes dominate the topography in this portion of the basin. The upper elevation stations (1300 – 1550 m) commonly overestimated temperature. This modest bias reflects the topographic character of the MRB. The upper elevation sites are situated in the High Cascades geological province, where the topography has a more gradual slope averaging approximately 10°. In the Western Cascades geological province, slopes are steeper averaging approximately 20°, but are also frequently characterized by slopes up to 50°. In the Western Cascades during periods of high pressure, it is common to have cold air drainage, where cooler, more dense air moves down a slope and pools in valleys

creating cooler temperatures at lower elevations (Daly et al., 2010). Efforts in calibrating and evaluating temperature suggest that the standard approach of applying monthly lapse rates to temperatures would contribute to the underperformance found in this study. Perspectives on how to deal with this bias are discussed in greater detail in the Discussion section.

The data record for SWE is more limited than the records of P and T . Only the four SNOTEL sites (elev. 1267 to 1512 m) have measurements of SWE that span the full data record. These sites provide the primary reference points for model validation (Figure 2.3c). These elevations and the areas above accumulate the majority of SWE for the basin. Results closely agreed with measurements from the four SNOTEL sites during the calibration and validation years (Table 2.9 and Figures 2.3c and 2.4) as well as during the study period (mean NSE of 0.83). It is worth noting the highest SNOTEL site is situated at an elevation of 1512 m but 75% of the model-estimated SWE lies above that elevation (Figure 2.5). The absence of measurements in areas where most of the snow is located highlights the need to augment the existing monitoring network. Since this modeling work was completed, NRCS has installed the Bear Grass SNOTEL site at an elevation of 1439 m and is in the process of calibrating the site (Webb, 2011).

Hogg Pass SNOTEL, one of the four SNOTEL sites in the MRB experienced a wildfire in September 2003, just outside of the site perimeter. This wildfire burned with moderate to high severity to the east and south of the site, significantly modifying forest canopy structure. A preliminary analysis indicates that the post-fire SWE measurements are lower than the pre-fire SWE measurements. For example, prior to WY 2004, model simulations at Hogg Pass show a high level of agreement with measured SWE values (NSE = 0.91). For the period of WY 2004 – 2009, the model overestimates SWE at Hogg Pass (NSE = 0.57). The model estimates are supported by

field measurements from WY 2008 and 2009 that closely match the model and show higher SWE values than those measured at the SNOTEL site (Figure 2.6). Understanding the impacts of fire on snow in the MRB lies outside of the scope of this research.

The length and consistency of the SWE data record at lower elevation sites is more limited. With the exception of Upper Lookout Creek, snow pillows in the HJA are not calibrated and the reported data have not been fully quality assured. The result is an inconsistent dataset with values that often do not represent expected snowpack evolution in the region. Due to the questionable accuracy of the measured SWE values in the HJA, these data were not used as a metric for model validation. This issue also highlights the need for a careful calibration and regular maintenance of SWE measurement sites.

Field measurements collected during WY 2009 at five locations in the MRB also show a high level of agreement between measured and modeled SWE values (Figure 2.7). The two upper elevation sites, S5 and S4, showed strong agreement between field measurements and simulations throughout the season, especially when estimating peak SWE in early April. Simulations at the three lower elevation field measurement sites (S3, S2, and S1) perform well during the early season. However, during the later season, the model predicts earlier melt than is typically found at these sites. This is not unexpected and demonstrates the challenges of prediction at an elevation where there is great variability within each 100 m grid cell. For example, the field measurements in April and May indicate the presence of a shallow snowpack, but the snow cover was patchy with areas nearby the measurements having no snow. Differences between field measurements and simulations at S2 (964 m) and S1 (950 m) demonstrate snowpack variability that exists at this elevation (Figure 2.7). These sites are only 260 m apart and offset 14 m in elevation. S1 has a southern exposure,

where S2 has a northern exposure. The model correctly captured these differences in SWE as a function of aspect.

Another metric, the ratio of snow water equivalent to precipitation (SWE/P) was used in model validation of SWE. NSE values for SWE/P were quite similar to the values SWE (Table 2.9). This strong correlation was expected because of the accuracy of the P simulations. In simulations that do not have high efficiency in distributing precipitation, SWE/P may be applied to improve model results by ensuring that modeled values of SWE are results of modeled values of P—a first order control on snowpack.

2.4.2 Assessment Using Remote Sensing Data

The overall accuracy of the SnowModel simulations compared to Landsat TM fSCA images was 82% for 14 years (Table 2.10 and Figure 2.8). Disagreement between the fSCA images and simulations primarily occurred where the model estimated snow cover and the fSCA did not have snow cover (13%). This degree of False Positive (FP) is expected as remotely sensed data typically omits snow cover in the steep and heavily forested landscapes that dominate the Western Cascades and the MRB (Nolin, 2011). Additionally, the fSCA product classifies any cell with a fractional snow cover value less than 15% as no snow. Thus many fSCA cells at the transitional snow line will be classified as no snow. WY 2006, 2008, and 2009 were the exceptions, showing more False Negative (FN) classifications, but with a similarly high level of agreement.

Spatial agreement was assessed using land cover, slope, aspect, and elevation to determine how these independent topographic model inputs influenced model disagreement (Table 2.11). Land cover was an important control in determining spatial agreement. The accuracy in coniferous and harvested forests was 82%, which

is the same accuracy metric for overall model performance. This relationship makes sense as these two land classes comprise 93% of the landcover in the MRB and will strongly influence model results. It is important to reiterate that for the entire study period, land cover classes used by SnowModel were based upon a static 2001 NLCD database. By contrast, the fSCA imagery is not constrained by a static land cover classification and reflects the dynamic nature of land cover – especially in the heavily forested MRB where industrial forestry and harvesting has a significant presence. As a result, the fSCA snow/no snow classifications reflect timber harvest on the ground, where the model does not. This is important as timber harvests have a significant impact on snow interception, snowpack evolution and melt rates (Harr, 1986; Storck et al., 2002). Harvested areas typically accumulate more snow (less interception from forest canopy), but also have faster melt rates as they are exposed to more incoming radiation during the ablation period. In mature conifer forests, snow does not accumulate as quickly due to interception. However, the canopy also buffers snowpack from incoming radiation during the ablation period, slowing down melt processes. Further complicating the classification process, dense canopy masks snow from Landsat imagery, which leads to FN fSCA classification. Accuracy in subalpine meadows (73%) is similarly explained. These areas were commonly harvested forests that were misclassified as grasslands in the NLCD.

Another significant source of error is for water bodies. The model does not accumulate snow over water, but the fSCA imagery captures the snow on top of frozen reservoirs and lakes. For similar reasons wetland and riparian areas have lower accuracy metrics (0.76). These areas lie at the interface of land and water and have a spectral signal that could include ice, but that would be snow free. Croplands in the lowland portions of the MRB are misclassified in the Landsat fSCA imagery. The low-elevation agricultural lands experience infrequent snow cover that last for only a few days each year. Because of the orientation of the Landsat scene, these

areas are at the edge of the scene and are most likely misclassified. This leads to a high rate of false positive values for snow cover and a value of 0.00 for recall as the model did not predict any snow in cropland pixels at the time of image acquisition. This misclassification of cropland in the lower elevations also explains the lower accuracy for the < 250 m elevation zone (Table 2.12).

At higher elevations, elevation does play a contributing role in describing model agreement. Model accuracy between 1000-2000 m is the lowest (approximately 72%) compared to other elevations. Proportionately, this elevation range represents over 60% of the spatial disagreement and can be explained by several factors. First, the rain-snow transition zone lies within the 1000-2000 m elevation band so snowcover can be patchy and sometimes transient, especially during the later part of the ablation season. The Landsat TM images were acquired during the ablation phase of the WY. Second, this elevation range is dominated by coniferous forests (both intact and harvested), which have changed since the creation of the NLCD product. As mentioned previously, changes in the forested landscape are reflected in the fSCA imagery, but not in the vegetation layer used in the model. Third, dense forest canopy masks snow cover from Landsat TM imagery, thus omitting some snow cover from classification. Slope also appears to have an influence on model agreement for slope values from 0°- 30° (93% of the MRB). Over this range of slopes, the model had 82% agreement with the Landsat fSCA (Table 2.13). Aspect did not appear to affect the agreement between the model and the Landsat fSCA as agreement and disagreement were consistent across all aspects (Table 2.15).

2.4.3 Impacts of Warmer Climate and Changing Precipitation on Snow

Sensitivity of Snowpack to Changes in Temperature and Precipitation

In the MRB, snowpack is highly sensitive to a 2°C increase in winter temperatures. Mean peak SWE (the ±5-day mean from peak SWE) decreased by an average of 56% for the reference period (Table 2.15, Figure 2.9, Appendix A). When integrated over the area of the MRB, this equals an annual average loss of 0.7 km^3 of water stored as snow. This is roughly 2.6 times larger than the volume of Cougar Reservoir, the largest impoundment in the MRB (storage capacity 0.27 km^3). While temperature is the controlling factor for changes in SWE, changing precipitation also has an impact. The T2P10 (Appendix B) and T2N10 (Appendix C) scenarios show losses of mean area-integrated peak SWE of 0.62 to 0.78 km^3, respectively, and reflect the role that precipitation variability plays on peak snowpack in the MRB. The 0.21 km^3 difference of area-integrated peak SWE predicted by the T2P10 and T2N10 scenarios is substantial. However 2°C temperature increases alone result in a 0.70 km^3 loss (Table 2.15, Figures 2.9 & 2.10). Increased precipitation in the T2P10 scenario results in additional SWE at elevations primarily over 1800 m, mitigating losses at those elevations (Appendix B). In these highest elevation portions of the basin a 2°C increase in temperature is not sufficient convert snowfall to rainfall or to significantly accelerate it snowmelt. This increase in SWE at the high elevations partially offsets some of the volumetric losses at lower elevations.

With warmer conditions, the date of peak SWE is projected to occur earlier in the winter. The average date for simulated peak SWE in the MRB during the reference period is March 31. However, in T2 the average date for peak SWE shifts 12 days earlier in the WY. Similarly, the peak SWE arrives 6 days and 22 days earlier in the T2P10 and T2N10 scenarios. It is important to reiterate that these shifts do not represent the same volume of water content, but the date that peak SWE occurs.

The sensitivity of snowpack was also analyzed at the basin (MRB) and sub-basin scale, and by elevation. The sub-basins Watershed 7 (WS 7), Mack Creek (MC) and South Fork of the McKenzie River (SFM) represent a range of sizes and elevations (Table 2.15). The high elevation regions of the MRB (greater than 1800 m) provide a stable environment for snowpack accumulation even in warmer temperatures, and dampen the effects of peak SWE loss. Results from SFM and Mack lack the high elevations, and show greater variability in peak SWE across the reference period, and a greater sensitivity to increased temperatures (Table 2.15, Figures 2.9 & 2.10). Figure 2.10 illustrates this point. Although the mean elevation of MC (1206 m) and SFM (1276 m) are almost 200 m higher than the mean elevation of the MRB (1027 m), the MRB loses 56% of peak SWE as compared to MC (69% loss) and SFM (67% loss). The SFM is the major tributary for Cougar Reservoir and extends from below the rain-snow transition at 550 m up to 1849 m. Here, the average change in area-integrated peak SWE was a reduction of roughly 0.14 km^3, which is one half of the storage capacity of Cougar Reservoir. The date of peak SWE occurs nearly one month earlier in the WY (Table 2.15).

MC is two orders of magnitude smaller than SFM, but has a similar elevation range. MC shows losses of mean peak SWE that are proportionally similar to the SFM in the T2 scenario, but with less variability between years (Table 2.15, Figure 2.10). Similar to SFM, peak SWE occurs approximately one month earlier in the WY (Table 2.15). WS7 is highly sensitive to temperature increases and projects more than an 80% reduction in mean peak SWE in all three scenarios. This small sub-basin straddles the rain-snow transition zone and does not have the higher elevations that can retain a seasonal snowpack. Volumetrically, WS7 contributes minimally to basin-wide peak SWE. However, these small basins comprise this rain-snow transition zone, and WS7 is characteristic of their shift to a more rain-dominated regime.

The sensitivity of the snowpack to temperatures by elevation was assessed for the 10-day mean of peak SWE and frequency of snow cover for WY 2007. WY 2007 was a statistically average year for SWE at the four SNOTEL sites. Peak SWE was -0.07 m of the reference mean and had a standard deviation of 0.02 m from the mean value (0.83 m). In WY 2007 the greatest net losses of peak SWE were found between 1001 and 1500 m (Figure 2.11). This elevation zone generated 53% of the basin-wide losses of SWE in the T2 scenario, and comprises 45% of the basin area. Proportionately, the areas between 1501 and 2000 m generate a more significant component of peak SWE loss. This elevation zone generated 45% of the basin-wide peak SWE losses in the T2 scenario, but only comprises 17% of the basin area. The mean loss of peak SWE lost per grid cell was 0.61 m in this elevation zone, as compared to 0.26 in areas between 1001 and 1500 m. The same general trend was found in the T2P10 and T2N10 scenarios with one exception. The magnitude of SWE loss in T2P10 is substantially less than in T2 (Figure 2.11). This represents the additional 10% of precipitation falling as snow rather than rain. Figure 2.9A shows the downward shift in peak SWE in T2P10 to be much less severe. Figure 2.9B shows increases in peak SWE. It is of note that most of these gains are above 2000 m.

The frequency of snow cover by grid cell was assessed for WY 2007 during the accumulation and melt period between Jan 1 to Sept 30, 2007. As expected, the T2 scenario was lower across the basin. But, like SWE depth, the areas between 1001 and 1500 m were significantly affected. This range of elevations saw an average of 36 fewer days of snow cover than in the reference year (Figure 2.12). Areas above 2500 m experienced similar losses in snow cover frequency. Initially, these losses at the higher elevations might not seem intuitive. However, these elevations are fully covered by snow during the winter months, so this shift represents a change in melt processes. In the MRB, these areas are above tree line, have steeper slopes, and a

west-facing aspect. This combination of factors increases incoming solar radiation that accelerates melt processes (Marks and Dozier, 1992).

Snowpack Responses Using Two IPCC Future Climate Scenarios

The response of snowpack in the MRB to IPCC-AR4 climate projections further highlights the sensitivity to temperature (Table 2.15, Figures 2.13 and 2.14). The temperature increases and precipitation changes for each decadal climate projection resulted in decreases in SWE and peak SWE shifting earlier in the WY (Table 2.15, Appendices D – I). The different impacts of the A1B and B1 emissions scenarios on SWE become pronounced with each decadal cycle moving from the 2020s to the 2080s. A1B projections reflect the higher emissions projections, higher associated temperatures, and a greater impact on snowpack. In the 2020 projections there are modest differences between the A1B and B1 values. The mild temperature increase (1°C) coupled with a 2.5% mean increase in winter precipitation actually predicts more snow n the high elevations of the basin (Appendix D and E). These areas sit above the rain/snow transition with a 1°C, and convert the extra precipitation into SWE. It should be noted that these areas still experience and overall net loss of peak SWE. However, by 2040s and 2080s the differences become pronounced in both peak SWE and date of peak SWE (Figure 2.14, Appendices G – I). The difference in the loss of mean area-integrated peak SWE in the 2020 A1B and B1 scenarios was only 0.03 km^3. This difference between the A1B and B1 scenarios grows to 0.13 km^3 in both 2040 and 2080. This volume is equal to roughly half of Cougar Reservoir. The mean date of peak SWE was 10 days earlier in the 2080B1 than the 2080A1B scenario (Table 2.15).

Projected impacts of the A1B and B1 climate change scenarios vary depending on location.. Figures 2.13 A & B show simulated SWE for WY 1999 - 2009 at Roaring River (RR), Upper Lookout Creek (UPL), and High 15 Meteorological Station (H15)

using both the A1B and B1 emissions scenarios. The elevation range of these sites extends from the rain-snow transition zone into the seasonal snow zone. RR, UPL, and H15 are projected to lose significant amounts of SWE and have earlier onset of snowmelt regardless of high, normal, or low annual snowpack. When the 2040 climate projections are applied to WY 1999 and 2008, the two largest snowpacks of the reference period, peak SWE resembles average years such as WY 2004 and 2007. This shift continues with WY 2004 and 2007 resembling below average years (e.g. WY 2001), and below average years shifting to a rain-dominated regime. These results map the spatio-temporal transition from snow-dominated to rain-dominated winter precipitation that is projected to occur in the Pacific Northwest with a $2^{o}C$ warming (Nolin and Daly, 2006)

These losses in SWE and shifts in timing of peak SWE are clearer when examining an individual year, such as WY 2007 (Figure 2.15). In WY 2007 the differences between the 2020A1B and 2020B1 do not show a distinct difference in snowpack evolution at all three sites. The differences between the A1B and B1 scenarios in 2040 and 2080 are more pronounced, particularly in the 2080 projections. H15 is adjacent to WS7 and is situated in the rain-snow transitional area. This site sees a dramatic reduction in SWE and also in the date when melt occurs. The differences between the 2040B1, 2080A1B and 2080B1 scenarios at H15 are significant with the 2080B1 closely resembling 2040A1B, and 2080A1B shifting to almost entirely rain. The differences between the 2040B1, 2080A1B and 2080B1 scenarios at UPL and RR reflect a similar pattern, while the loss of SWE in 2080A1B is significantly less than in the 2080B1 scenario. RR and UPL also suggest that during the accumulation phase there are minimal differences between the six climate projections other than 2080B1. The main differences are expressed in the timing of melt onset and the date of snow disappearance. The snow disappears about 22 days earlier at all three sites in the 2020 projections. Snow disappearance in the 2040s comes increasing earlier at

lower elevations. 2080A1B shows the most dramatic shift in the date of snow
disappearance at RR and UPL, coming about 50 days earlier in the season.

2.5   Discussion

2.5.1   Model Calibration and Assessment

Model results clearly demonstrate that precipitation and temperature are first order
controls on snowpack accumulation and determination of the timing of peak SWE.
Thus, it was critical to achieve optimal accuracy of the spatially distributed values of
P and T prior to calibrating the model based on SWE. Accurately modeled P and T
values allow snowpack to be based on these key parameters, rather than calibrating
the model just to values of SWE. This order of operations allows simulations of
snowpack to improve for the right reasons – getting their underlying controls correct
before calibrating snowpack parameters (Kirchner, 2006). This point is especially
salient when modeling snowpack for projected future climates, where high
confidence in the accuracy of P and T provides more plausible results in terms of
future snowpack projections. Not surprisingly, as the accuracy of P and T
distributions improved, the accuracy of snowpack simulations (SWE and spatial
extent) also improved. P had a high level of agreement between observations and
simulations (NSE of 0.97). There were distinct similarities between the NSE of T
(0.80) and SWE (0.83), and the accuracy of the spatial distribution of snowpack
(82%). These similarities lead to the logical conclusion that improvements in
accuracy of snowpack simulations can be made through improvements in
temperature simulations. Ideas of how to reach this goal will be discussed later in
this section.

The high level of agreement for P was attained when an evenly distributed network
of input stations was established. The Barnes Objective Analysis technique, used in

the MicroMet sub-model to distribute P and T, uses a weighted interpolation scheme that is based on the data spacing from a datum (station) to the grid cell (Koch, 1983). In initial model runs, incorporating multiple clustered stations in the HJA decreased overall model accuracy by skewing the data spacing in the weighting scheme. To create a balanced simulation surface of T and P requires stations that are widely spaced and that span the range of elevation values. Iterative testing of the model with various station combinations revealed that it was best to use just two stations in the HJA in the final model implementation: PRI (elev. 430 m) and UPL (elev. 1294 m). The addition of the Eugene station (elev. 174 m) also improved model agreement by providing a datum in the western portion of the basin. Incorporating the meteorological data from Hogg Pass, McKenzie, and Roaring River created anchor points in the eastern portion of the basin. These locations were especially pertinent in addressing the challenges associated with distributing temperature across the basin. The two distinct topographic provinces of the MRB, the steep Western Cascades and the more gentle High Cascades, contributed to these challenges and highlight a shortcoming of using a standard temperature lapse rate in a model. Daly et al. (2010) used empirical data to establish that the expected rates that exist between elevation and temperature are often decoupled from one another and are largely controlled by topography and elevation. Steeper slopes can produce cold air drainage and different lapse rates than lapse rates for more gentle slopes (Daly et al., 2010). Additionally, moisture content of a storm (as determined by its temperature, source area, and history) affects the wet adiabatic lapse rate. Daly et al. (2010) suggest that seasonal variability in lapse rates may increase with projected future climate. Though outside of the scope of this research, an improvement to the monthly static lapse rates used in SnowModel would be dynamically computed lapse rates using temperature relationships between stations at each time step. This dynamic lapse rate would then be applied across the watershed to distribute temperatures more accurately for each time step. This approach would more

accurately reflect storm-related changes in lapse rate and would also implicitly include topographic effects on lapse rate.

2.5.2 Impacts of Climate Perturbations on Snowpack

The estimations of SWE represent the reference period of 1989 – 2009, extending back to the best available data record. The reference period has a range of ENSO events that influence snowpack, but is also dominated by a warm phase of the PDO cycle. It is important to remember that these predictions are based off of this reference period, and are intended to be diagnostic in nature. These predictions are not intended to be definitive statements about snowpack, but rather as an illustrative tool to understand the trajectory of snowpack based upon projected temperatures.

Because of uncertainties around projected future climate change, the sensitivity analysis provides a perspective on snowpack response for three scenarios. Model results show that snowpack in the MRB is highly sensitive to a 2°C increase in temperature, with model results showing a 56% decrease in peak SWE for the reference period. This diminished peak also occurs on an average of 12 days earlier for the reference period. Elevations between 1000 and 2000 m are most affected in the T2 scenario as snow transitions to rain, and snow on the ground has an enhanced melt cycle. The elevation zone from 1000 – 1500 m has the greatest volumetric loss of stored water (Figure 2.11), and represents the largest areal proportion of the basin. Proportionately, the elevation zone from 1500 - 2000 m loses the most SWE. This higher elevation zone has more SWE per unit area but is not high enough to significantly buffer against SWE losses in a warmer climate.

The ±10% change in precipitation inputs explores how variability in precipitation affects snowpack. A 10% decrease in precipitation exacerbates the impacts of temperature on snowpack, especially for the elevation zone from 1000-2000 m. A

10% increase in precipitation only slightly buffers the loss of peak SWE. A notable result of the 10% increase in precipitation is identifying the shift in the rain-snow transition zone. Presently, the rain-snow transition zone is from 800-2000 m. Figure 2.9A, shows that peak SWE increases at roughly 2000 m. This 2000 m elevation threshold shows the elevation at which the extra 10% of precipitation falls as snow rather than rain.

Model results show that changes in snow accumulation and ablation at the sub-basin scale are strongly dependent on elevation and not on the size of the sub-basin (Figures 2.10A and B). SWE loss at elevations above 2000 m were not impacted as much by a 2°C increase as basins below this threshold. Snowpack at elevations above 2000 m help buffer the impacts of increased temperature. WS7, MC, and SFM do not have areas above 2000 m and saw greater percentage losses of peak SWE.

Not surprisingly, the response of snow cover frequency to a 2°C increase is very similar to the pattern of the change in SWE. Snow cover frequency in the elevation zone from 1000 - 1500 m were most affected, with some locations losing more than 80 days of snow cover in an average snow year.

The difference in the loss SWE when applying the A1B and B1 scenarios was minimal through the 2020 decadal projections (Table 2.15). The delta temperature and precipitation values show on average an increase of 1°C and a 2.5% more precipitation. This provides more snow in the upper elevations of the MRB, but the basin still projects an overall net loss of peak SWE. However, the impacts on snow from these different emissions scenarios became more distinct for the projections in the 2040s and 2080s. The differences in area-integrated peak SWE in the A1B and B1 climate scenarios are considerable ($\sim$0.125 km^3), and have water resource, socio-economic, and environmental implications.

2.5.3   Impacts Associated With a Loss of Snowpack

Potential Impacts on Streamflow

The loss of snowpack associated with warmer temperatures will have considerable affects on water resources in the MRB, especially in the sub-basins of the Western Cascades. Results show that warmer temperatures will significantly impact snowpack at elevations between 1000 and 2000 m. Especially notable is the volumetric loss of SWE between 1500 and 2000 m. It is important to remember that this loss is not solely a loss of snowpack. It represents a shift from snow to rain. This shift will be expressed in streamflow. For instance, Mack Creek experiences a significant loss of area-integrated peak SWE (69%) that occurs 32 days earlier in the WY. Jefferson (2011) found a direct relationship between the percentage of a basin in the rain-snow transition and the timing of runoff in the Northwestern United States. Basins that have more areas of seasonal (rain-snow mix) were statistically more likely to experience an earlier and higher annual peak streamflow and a lower summer streamflow.

While research has shown that the geology of the McKenzie controls baseflow in sub-basins of the MRB, (Tague and Grant, 2004; Jefferson et al., 2008; Tague et al., 2008), shifts in the form of precipitation will affect the timing and magnitude of peak runoff. Such a shift could potentially influence water resource managers' decision-making process. Sub-basins that have their headwaters in the elevation zone from 1500 - 2000 m will see dramatic losses in SWE per unit area, losing that reservoir in the middle elevations. For instance, dam operators now release flow in anticipation of runoff generated by snowmelt. As the contribution from snowmelt decreases and more runoff shifts to earlier in the year, dam operations will need to reflect these changes.

Potential Socio-economic Impacts

Snow and snowmelt serve as a resource for winter and summer recreation, agriculture, industry, municipalities, and hydropower. The differences in peak SWE for the A1B or B1 scenarios in the 2040s is considerable, roughly half the capacity of the largest reservoir in the basin. While this estimated loss only pertains to the MRB it would scale up to be major factor at the regional level. Potential management concerns pertaining to the supply of water could be compounded by shifts in the demand of water as well. Oregon's population is expected to grow by 400,000 people by 2020 (Office of Economic Analysis, 2011). The increase in population would most likely increase demand especially in the summer and fall when stakeholders compete for an already limited supply (United States Army Corps of Engineers, 2001; Oregon Water Supply & Conservation Initiative, 2008). Because mountain snowpack serves as an efficient and cost-effective reservoir any research that examines socio-economic topics should contain a mountain snowpack component. For example an examination of socio-economic impacts of the adaption costs associated with an A1B or B1-based emissions economy would need to include the costs associated with a diminished mountain snowpack.

Potential Ecosystem Impacts

Changes in the timing and evolution of snowpack affect the entire ecosystem (Rosenzweig et al., 2008), and the loss of snowpack impacts wildlife in snowy environments (McKelvey et al., 2008). The loss of snow also creates new habitat for species that are not adapted to snow. The shift in snow cover effectively shifts the biogeographic boundaries of species. As a result snow-adapted species will have to compete for less terrain at higher elevations, and species less adapted to snow will be able to expand their geographic range up in elevation. Snow cover also serves as a signal for migration and hibernation, and earlier snowmelt will impact species behavior (Inouye et al., 2000).

From a vegetation perspective, snow insulates the ground, providing a sustained source of soil moisture, and serves as a trigger that signals plant growth (Loik et al., 2004; Royce and Barbour, 2001). An ecosystem that experiences a shift to earlier snow melt and less snow cover will affect soil-plant water relationships and photosynthesis. This shift triggers plant growth to start and end earlier in the season due to moisture stress later in the summer (Royce and Barbour, 2001; Loik et al., 2004; Thomas et al., 2009). Such ecosystem shifts have already been documented. Work by Rosenzweig et al. (2008) used existing data records to identify the correlations between increased temperatures and changes in biological and physical systems across North America and Europe. Similar research found that the bloom of plant species and peak runoff in the western United States have both shifted to earlier in the season (Cayan et al., 2001). A secondary component of reduced snowpack and soil moisture are drier conditions that increase the likelihood of broad-scale disturbance such as forest fires (Palmer, 1917; Westerling et al., 2006).

2.6   Conclusions

These validated model simulations of snowpack represent a significant advance in understanding the distribution of snowpack in the MRB and also other climatologic and topographically similar basins. A detailed spatial and temporal understanding of snowpack was developed for present conditions and serves as a prognostic tool for understanding snowpack in projected future climates.

The results of this research are not intended to serve as a precise indicator of what snowpack in the MRB will look like in the future. Rather they are intended to serve as a way to understand basin-wide trends of snowpack in present conditions and how these trends may shift in the future. Although this study focused on a single watershed, it has regional applications. Processes affecting snowpack in the

McKenzie River Basin are similar to those in many other maritime, forested Pacific Northwest watersheds. This research provides insights into the mechanisms controlling snowpacks in such environments and serves as an example of the magnitude and types of changes that may affect similar watersheds in a warmer climate. Moreover, with the modifications made to the model (rain-snow partitioning, albedo decay function), this model can readily be transitioned north and south to other basins on the western slope of the Cascades (same maritime climate) with minimal reconfiguration.

The MRB will increasingly experience more precipitation falling as rain rather than snow in warmer conditions. The exception to this statement is in the high elevations of the watershed in the 2020 scenarios where increased temperatures are still below the melting point and a slight increase in precipitation will result in greater SWE. However even with gains at high elevations, there is still a considerable net loss of snowpack (-33%) compared with an average snow year under present-day conditions. These model results highlight the temperature sensitivity of snow in the MRB. In these conditions, precipitation will increasingly fall as rain instead of snow. Areas presently in the rain/snow transition zone will become dominated almost entirely by rain. Higher elevation zones will also experience diminished snowpack, however snow will continue to play a significant role in their hydrologic character. Losses in SWE and declining snow frequency will impact years with high, low and average snowpack and will change the statistical representation and human perceptions of what a high, low and average snowpack represents. The changes in snowpack in the MRB will affect the timing and magnitude of runoff during the winter, spring, and summer months as more precipitation shifts from snow to rain (Tague and Grant, 2004; Stewart et al., 2005; Jefferson et al., 2008; Tague et al., 2008).

Understanding how these shifts will affect discharge remains a goal for future research, and has direct implications on hydropower and flood control operations. These results have already helped water resource professionals choose a site for a new SNOTEL station (Webb, 2011) and develop water management strategies for municipal water use (Morgenstern, 2010). Because these model simulations are run at moderately high spatial and temporal resolutions, the sensitivity of sub-basins to diminished snowpack can also be evaluated. This scale appropriate approach provides water resource managers the ability to implement adaptive measures at the sub-basin scale Dozier (Morgenstern, 2010). This research will continue to help in understanding what snowpack will look like in the future and how to better plan for adapting to the challenges that will come with the expected shifts in the delivery of precipitation and the accumulation of snow.

Future research could include developing a model component that computes lapse rates on a time step basis, which would improve model results. Additionally, the land cover classification scheme used in the model portrayed a static landscape. Incorporating a land cover classification that would change through time including changes in forest harvest and fire would improve the model by providing a more accurate depiction of conditions on the ground. Applications of the model have merit in helping understand ecosystem impacts associated with diminished snowpack. Similarly the research highlights the differences in snowpack between A1B and B1 emissions scenarios. Assessing the impacts to physical and ecological systems associated with each scenario would help develop a more realistic estimate of the true costs of projected climate impacts and potential adaptation strategies.

Mountain snowpack is a key common-pool resource, providing a natural reservoir that supplies water for drinking, worship, hydropower, agriculture, ecosystems, industry, and recreation for over 1 billion people globally. The spatial distribution of

snowpack and its sensitivity to climate change at basin scale does not provide global answers, but it does provide clarity at a scale appropriate for developing management strategies for the future.

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2.8   Figures
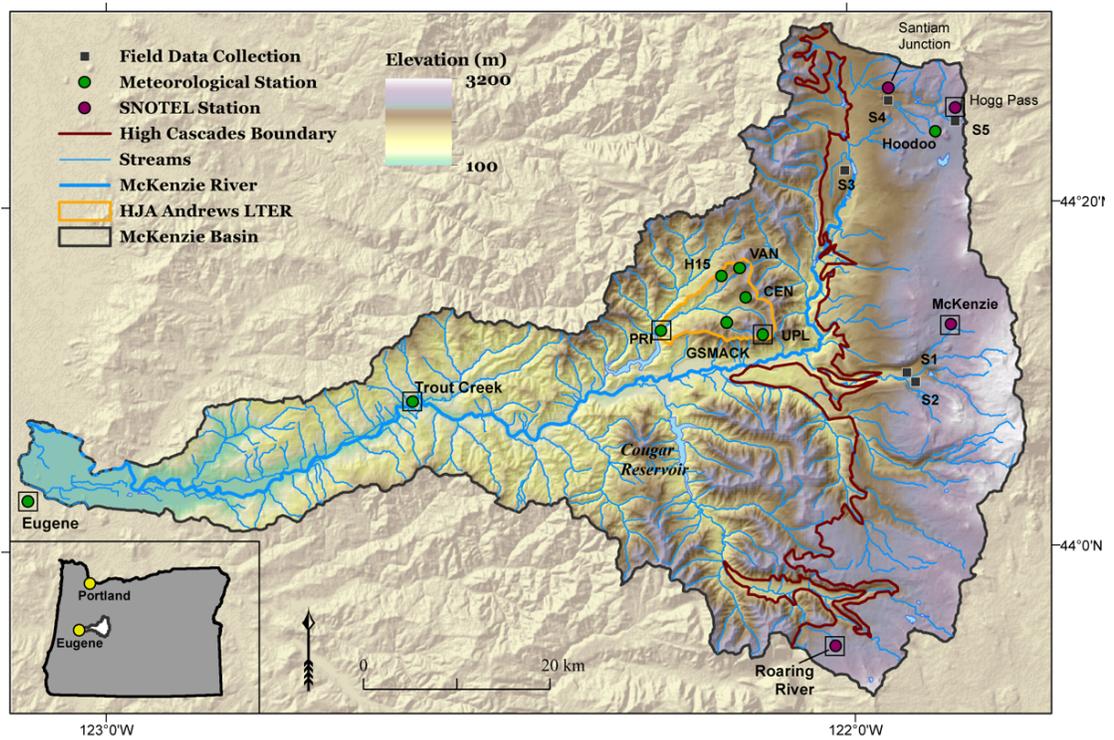
Figure 2.1: Context map for the McKenzie River Basin, Oregon.
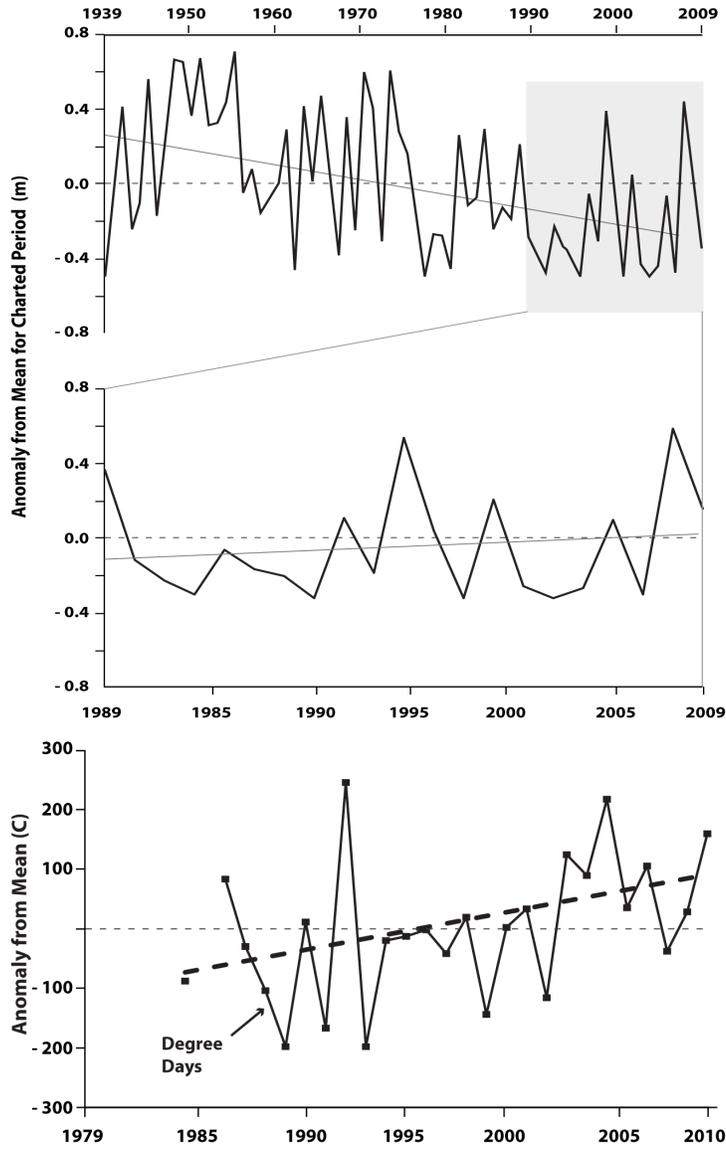
Figure 2.2: Trends of SWE and temperature at Santiam Junction
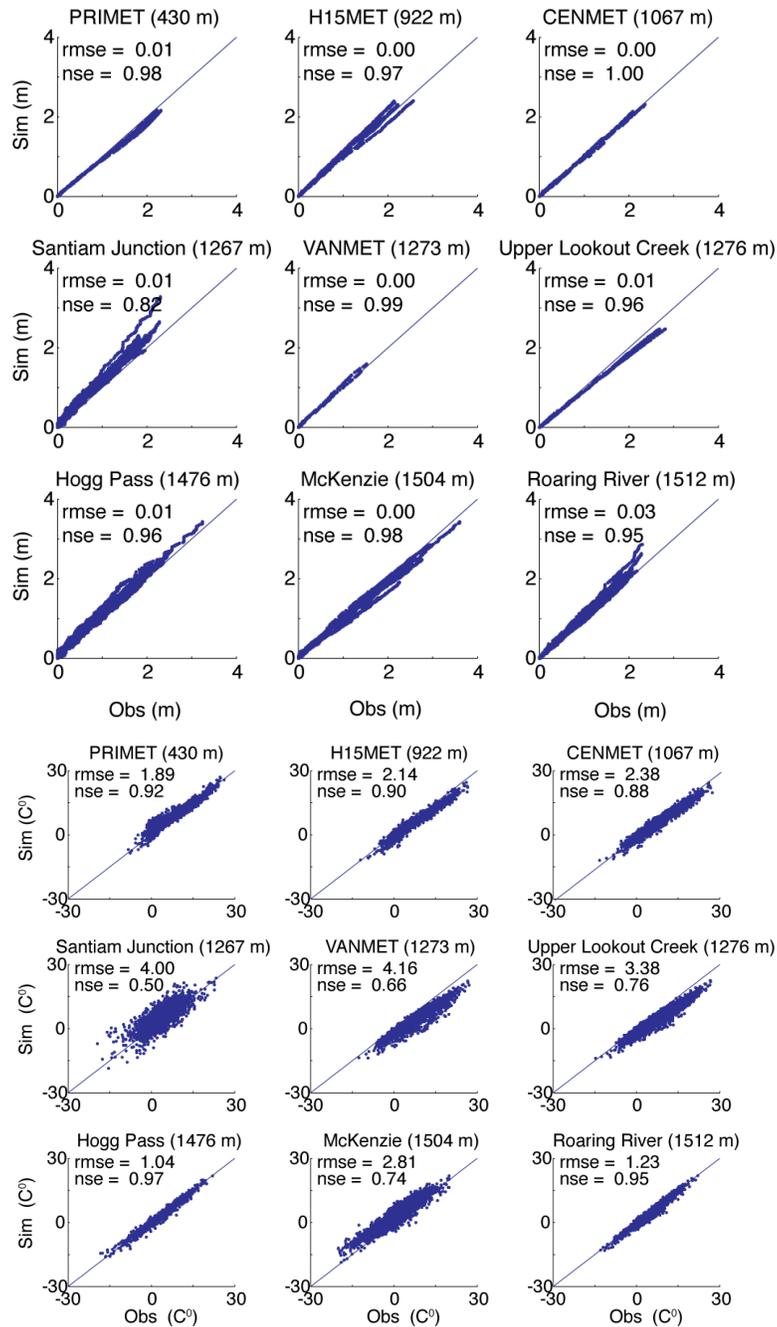
Figure 2.3: Model performance (precipitation - top, temperature - bottom)
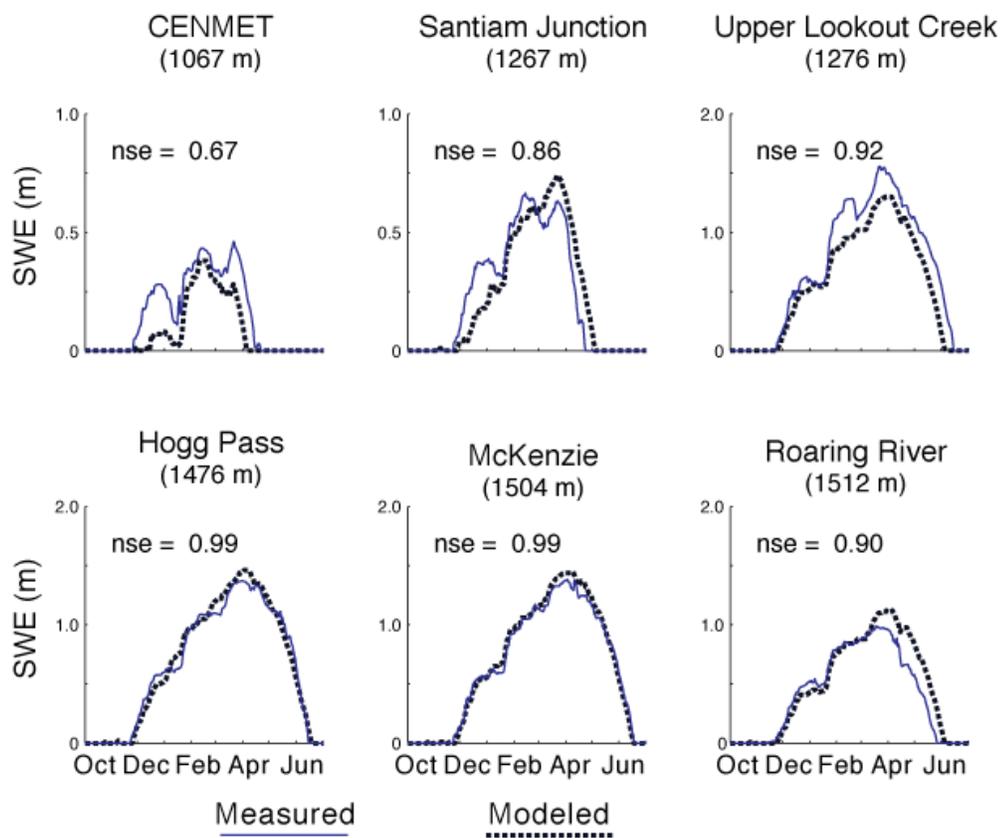
Figure 2.3 (continued) – Model Performance (SWE - WY 2002).
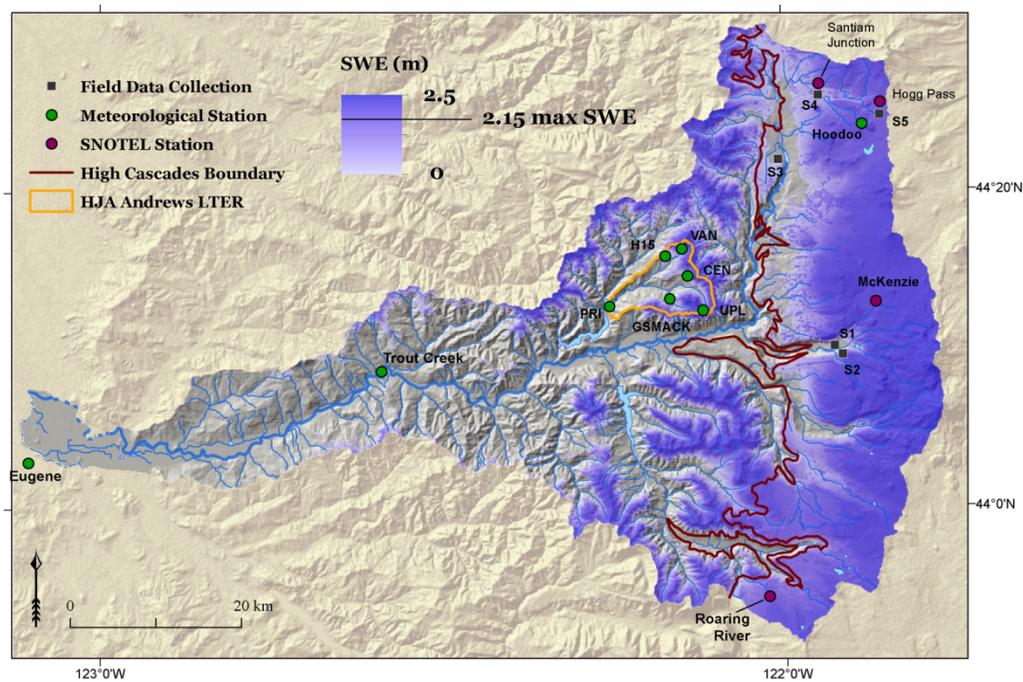
Figure 2.4: Map of simulated SWE on April 1st, 2009 for Reference conditions.
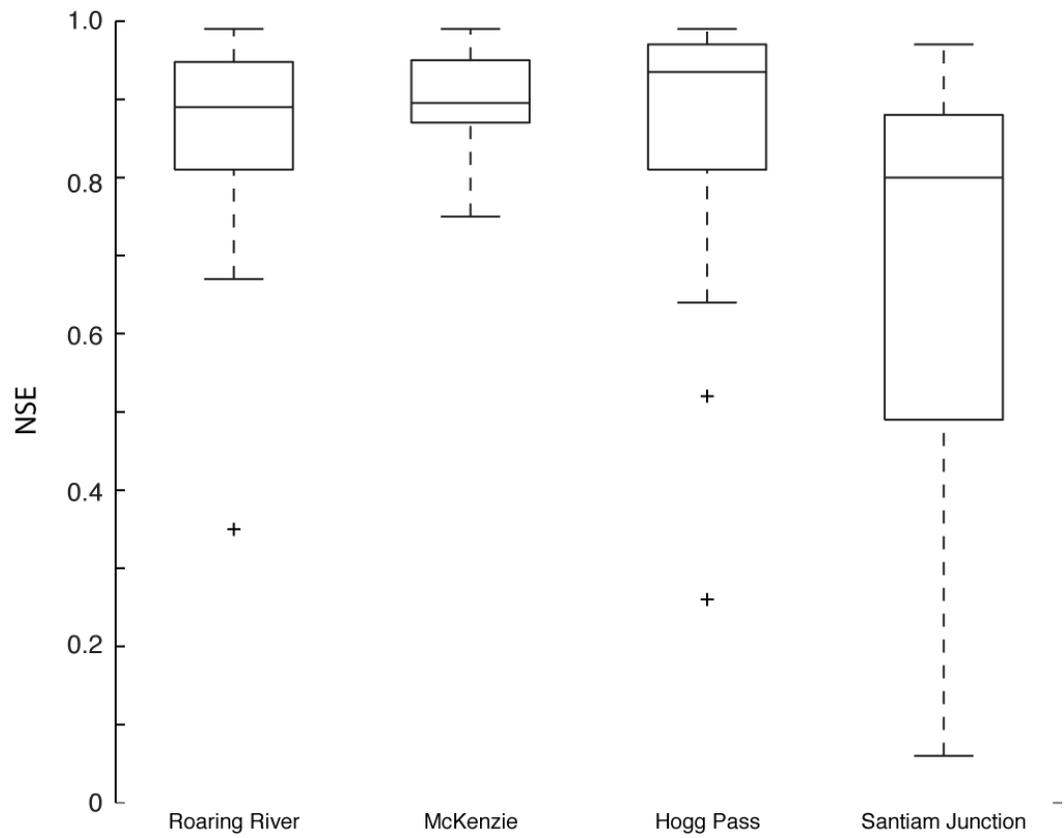
Figure 2.5: The range of NSE measures for SWE at the four SNOTEL stations.
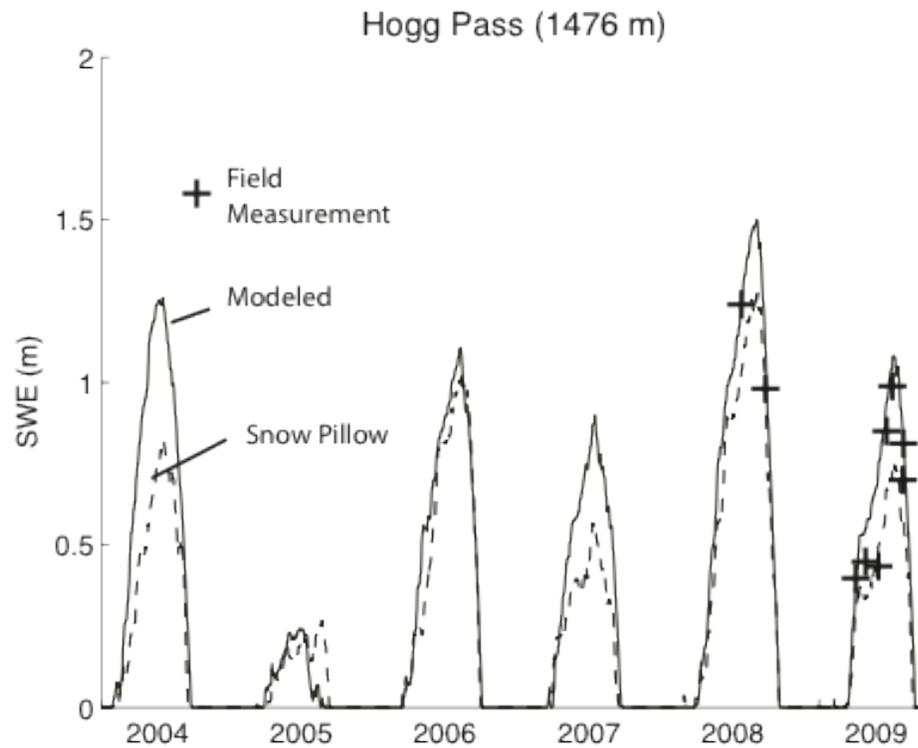
Figure 2.6: Impact of fire on SWE measurements at Hogg Pass. Differences between station measurements (SNOTEL), field measurements, and model simulations are shown.
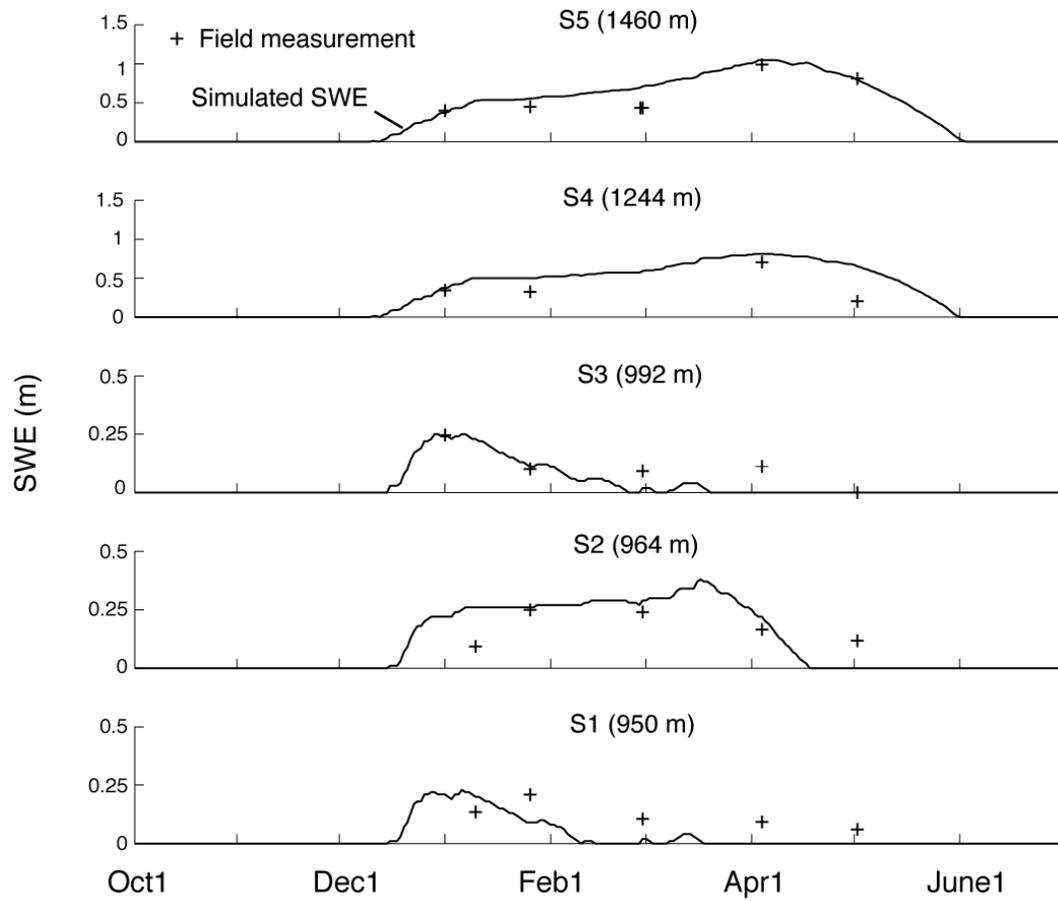
Figure 2.7: Field measurements for WY 2009
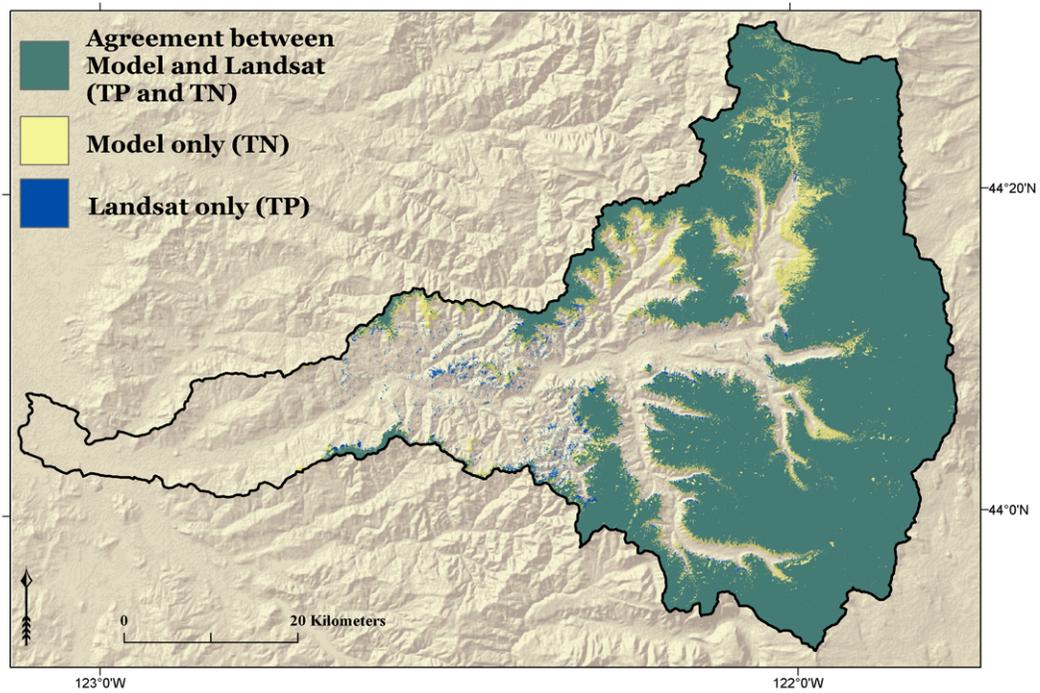
Figure 2.8: Agreement between Landsat fSCA and model simulations on March 29th, 1998.
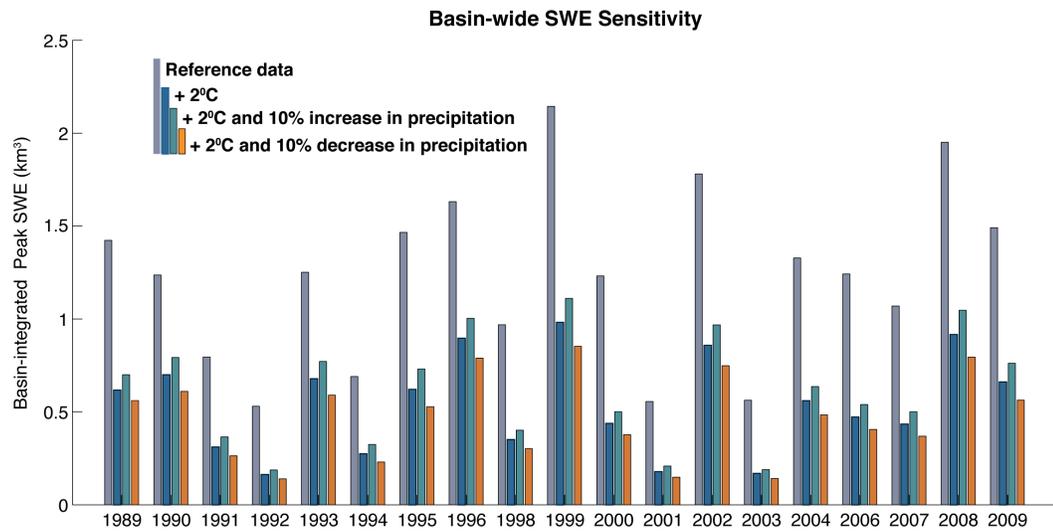
Figure 2.9: Peak SWE integrated over the area of the MRB and its sensitivity to a 2°C increase in temperature.
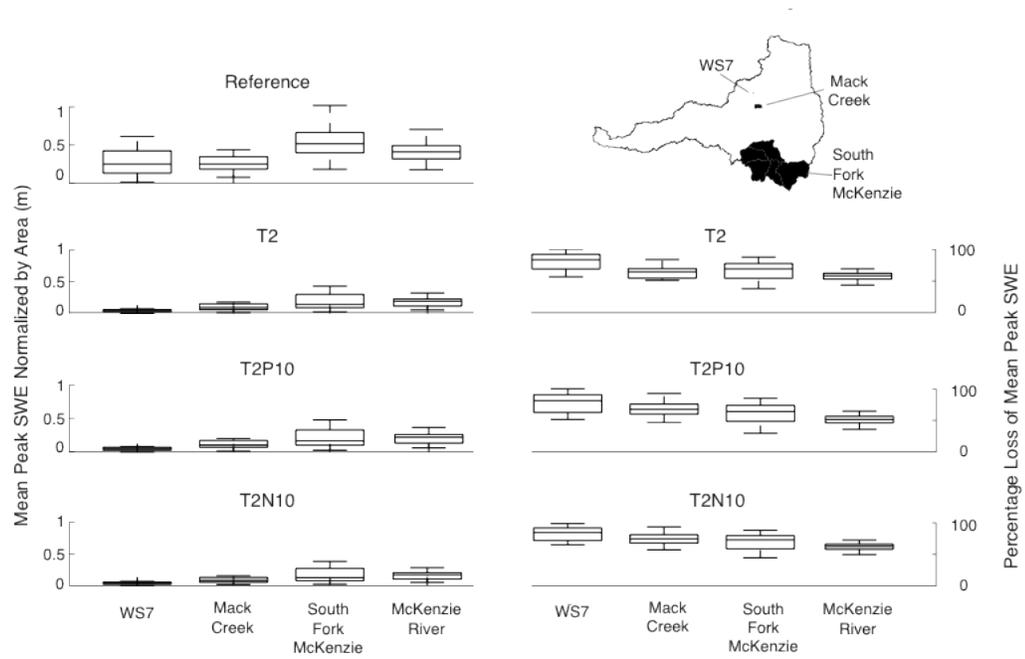
Figure 2.10: The range of integrated peak SWE by basin and sub-basin, and also the affects of a 2°C increase in temperature.
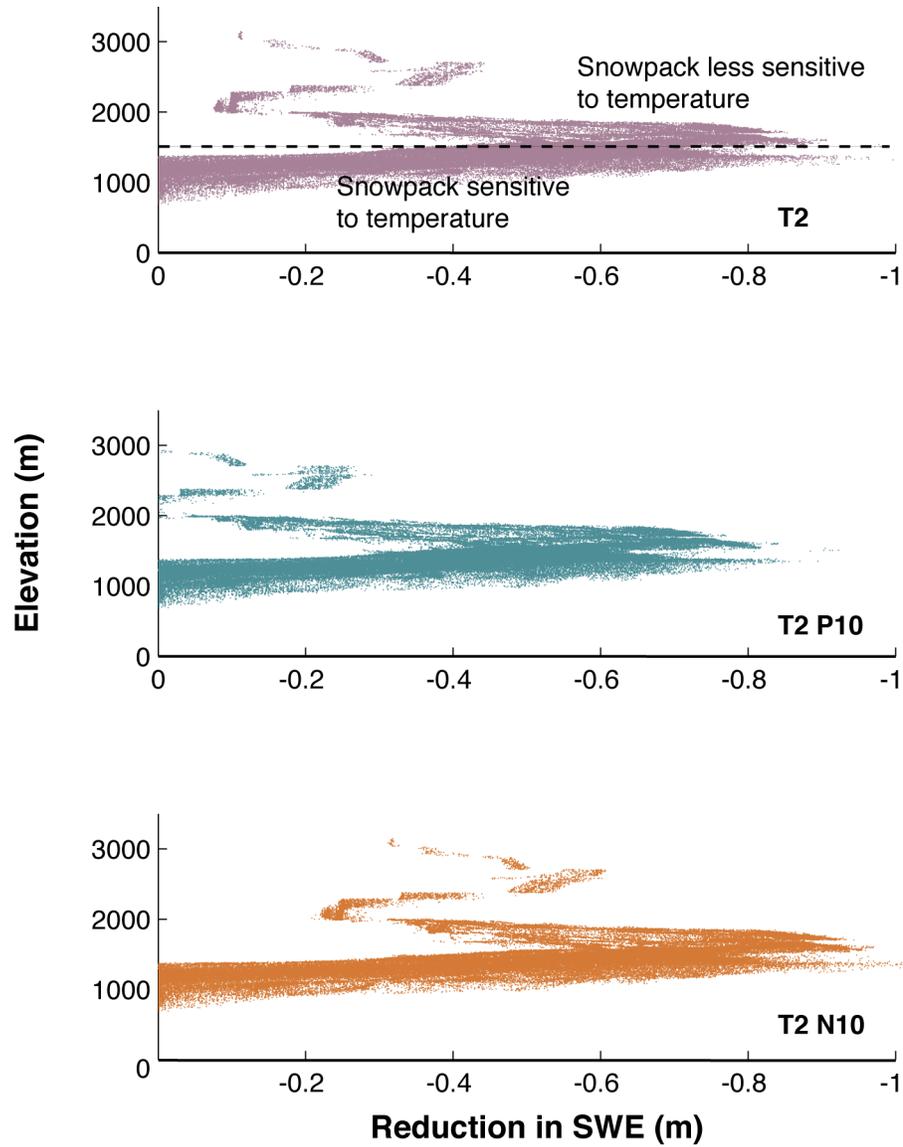
Figure 2.11:Loss of SWE by elevation. Greatest SWE losses are between 1000 and 1800m. The scenarios are T2 (upper), T2P10 (middle), and T2N10 (lower). Each dot on the plot represents a grid cell in the MRB.
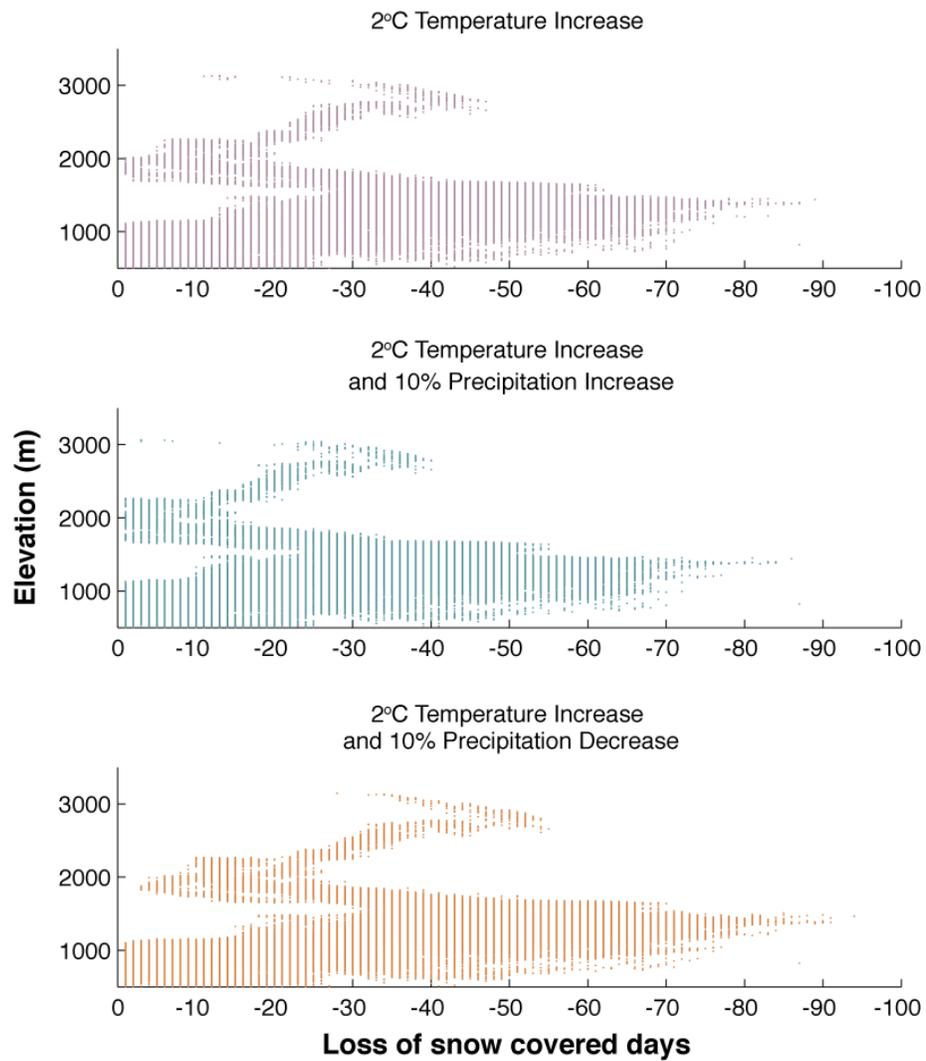
Figure 2.12: Loss of snow cover by elevation. Reduction of snow cover frequency is greatest between 1000 and 1800 m. Each dot on the plot represents a grid cell in the MRB.
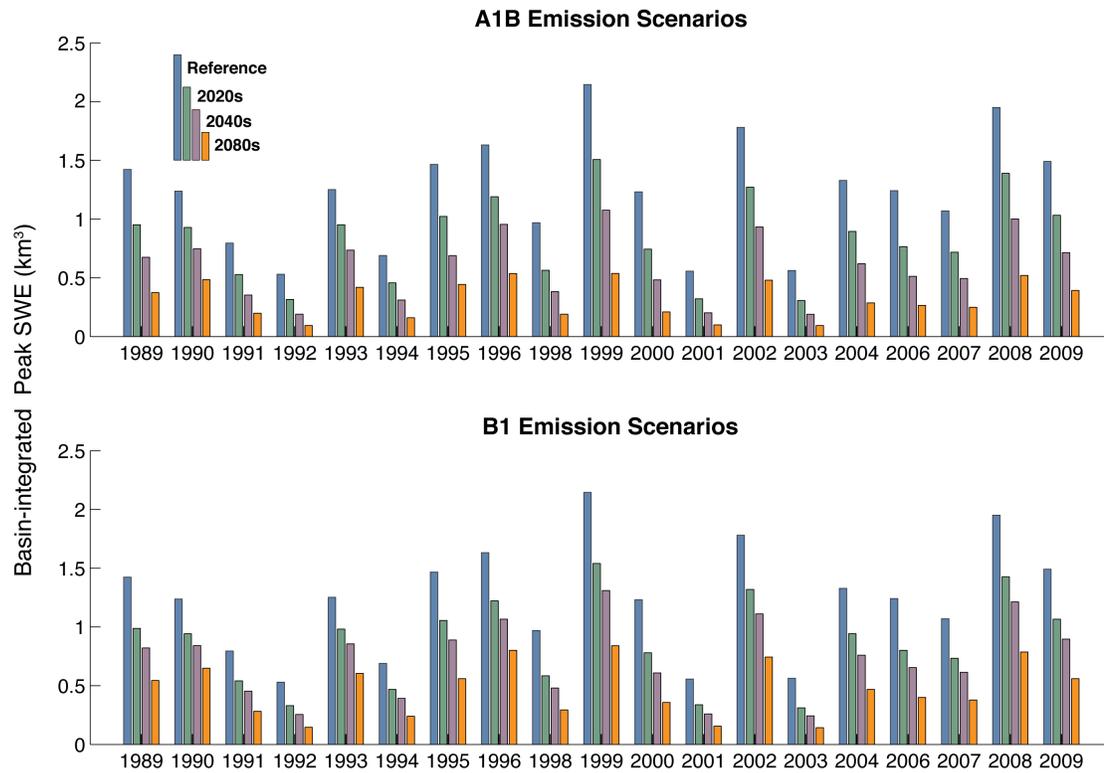
Figure 2.13: Peak SWE integrated over the area of the MRB for each of the two climate scenarios, for the 2020s, 2040s, and 2080s.
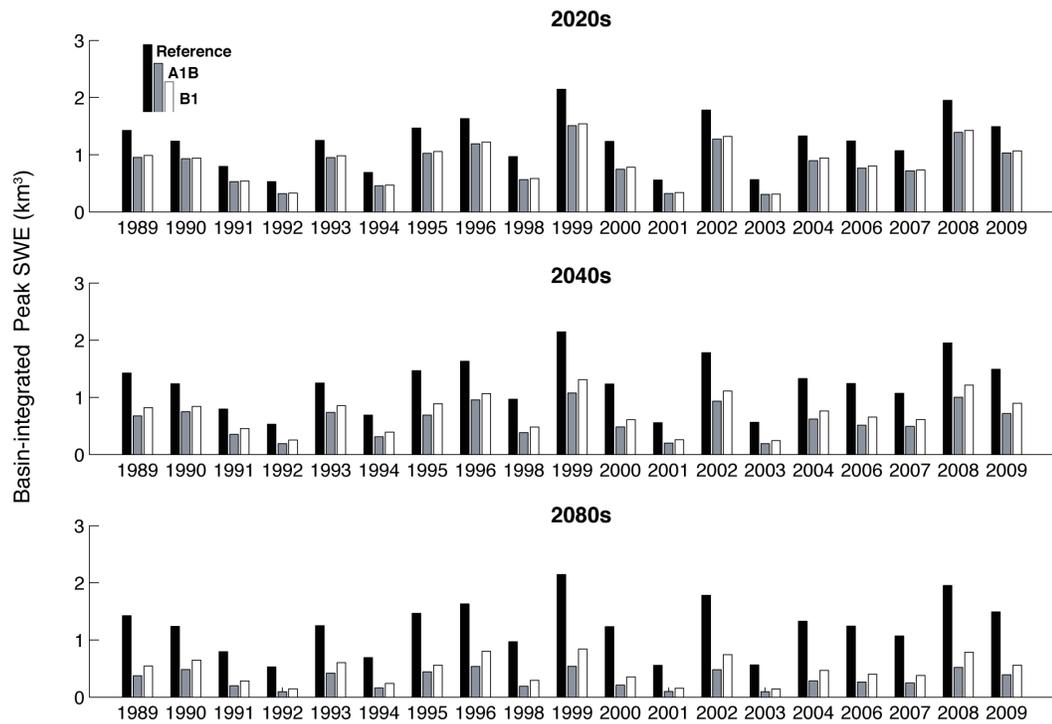
Figure 2.14: Peak SWE integrated over the area of the MRB for the A1B and B1 emissions scenarios for the 2020s, 2040s, and 2080s.
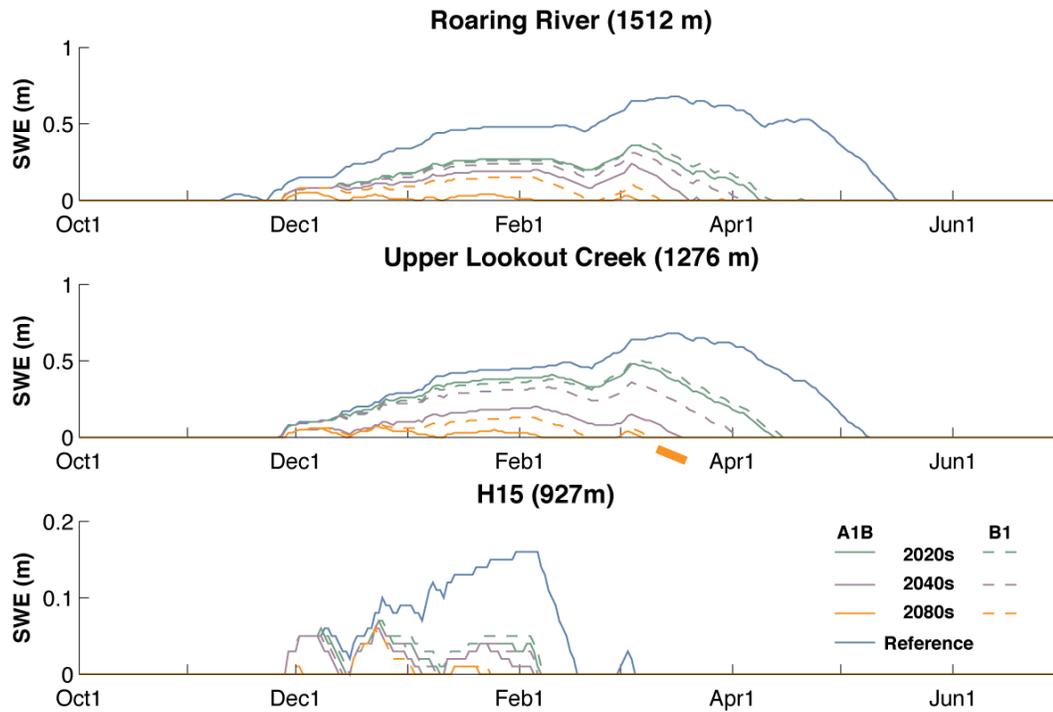
Figure 2.15: Differences of A1B and B1 emissions scenarios at three locations for WY 2007 (Statistically average).

2.9 Tables

Table 2.1: Meteorological and snow monitoring stations that were applied as model forcings and/or in evaluation of simulation results.
Air Temperature, P - Precipitation, RH – Relative humidity, Wind – Wind speed and direction, SWE – Snow water equivalent; NWS – National Weather Service, HJA LTER – HJ Andrews Long Term Ecological Research site, NRCS – National Resource Conservation Service.

Station name	Measure-ments used	Used as model forcing	Used in Evaluation	Elevation (m)	Run by
Eugene Airport	T, P	Yes	No	174	NWS
Trout Creek	P	No	Yes	230	NWS
PRIMET	T, P, RH, Wind, SWE	Yes	Yes	430	HJA LTER
H15MET	T, P, RH, Wind	No	Yes	922	HJA LTER
CENMET	T, P, RH, Wind, SWE	No	Yes	1018	HJA LTER
VANMET	T, P, RH, Wind, SWE	No	Yes	1273	HJA LTER
UPLMET	T, P, RH, Wind, SWE	Yes	Yes	1294	HJA LTER
Santiam Junction	T, P, SWE	No	Yes	1267	NRCS
Hogg Pass	T, P, SWE	Yes	Yes	1451	NRCS
McKenzie	T, P, SWE	Yes	Yes	1454	NRCS
Roaring River	T, P, SWE	Yes	Yes	1512	NRCS

Table 2.2: Land cover classifications used by SnowModel, and the equivalent classifications originating from the NLCD dataset. Snow holding depth must be exceeded be for it is available for wind transport. Vegetation types in **bold** are values that were used in the model domain.

	SnowModel Vegetation Type	Snow Holding Depth (m)	% of Model Domain	NLCD Equivalent	NLCD Code(s)
1	**Coniferous forest**	**15**	**67.8**	**Evergreen forest**	**42**
2	**Deciduous forest**	**12**	**0.4**	**Deciduous forest**	**41**
3	**Mixed forest**	**14**	**1.2**	**Mixed forest**	**43**
4	Scattered short-conifer	8			
5	**Clearcut conifer**	**4**	**11.2**	**Transitional**	**33**
6	Mesic upland shrub	0.5			
7	Xeric upland shrub	0.25			
8	Playa shrubland	1			
9	**Shrub wetland/riparian**	**1.75**	**0.5**	**Wetlands**	**91 - 92**
10	Erect shrub tundra	0.65			
11	Low shrub tundra	0.3			
12	Grassland rangeland	0.15			
13	**Subalpine meadow**	**0.25**	**0.1**	**Grasslands**	**71**
14	Tundra (non-tussock)	0.15			
15	Tundra (tussock)	0.2			
16	**Prostrate shrub**	**0.1**	**2.7**	**Shrubland**	**51**
17	Arctic wetland	0.2			
18	**Bare**	**0.01**	**2.3**	**Bare rock**	**31**
19	**Water/possibly frozen**	**0.01**	**1.0**	**Open water**	**11**
			0.1	**Perennial ice/snow**	**12**
20	**Permanent snow/glacier**	**0.01**			
21	**Residential/urban**	**0.01**	**2.8**	**Developed**	**21 - 23**
22	Tall crops	0.4			
23	**Short crops**	**0.25**	**9.9**	**Cultivated**	**81 - 85**

Table 2.3:Water years used in the calibration and validation of the model. Selected Values in parentheses represent the deviation from the mean (in meters) of peak SWE measurements at Santiam Junction, Hogg Pass, Roaring River, and McKenzie. Years noted by an * represent years with field measurements of SWE.

Type of Snowpack	Calibration	Validation
Low	2001 (-0.35)	1992 (-0.46)
	2004 (0.00),	
Medium	2007 (0.17),	1990 (-0.09)
	2009* (0.31)	
High	2008* (0.57)	1999 (0.71)

Table 2.4: Lapse rate values (°C km^{-1}) used in SnowModel and those published by Minder et al. The values posted by Minder are for the Washington Cascades, which are approximately 350 km north of the MRB.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
SnowModel	7	7.3	7.7	7.7	8.3	7	5.5	5.5	5.3	6	6.9	7
Minder et al	5.5	5.8	6.2	6.2	5.8	5.5	4	4	3.8	4.5	5.4	5.5

Table 2.5: Performance metrics used in assessing model simulations with Landsat fSCA imagery. Evaluation was conducted at 100 m resolution.

Performance measure	Definition	Description
Accuracy	$\dfrac{TP + TN}{TP + TN + FP + FN}$	The ratio of correctly identified grid cells to total grid cells.
Precision	$\dfrac{TP}{TP + FP}$	The degree to how the classification performs across classifications and can identify a systematic bias.
Recall	$\dfrac{TP}{TP + FN}$	The proportion of actual positives that are identified as positives.

TP: true positive (snow in the Landsat fSCA image and snow in the model simulation)
TN: true negative (no snow in the Landsat fSCA image and no snow in the model simulation)
FP: true positive (no snow in the Landsat fSCA image and snow in the model simulation)
FN: false negative (snow in the Landsat fSCA image and no snow in the model simulation)

Table 2.6: Descriptions and symbols for the nine iterations used in this research.

Name	Description
Reference Period	Climate data based upon observed conditions for WY 1989 - 2009
T2	Reference Period perturbed with: - 2°C increase in daily temperature forcings
T2P10	Reference Period perturbed with: - 2°C increase in daily temperature forcings - a 10% increase in daily precipitation forcings
T2N10	Reference Period perturbed with: - 2°C increase in daily temperature forcings - a 10% increase in daily precipitation forcings
2020A1B	Reference Period perturbed to reflect projected monthly delta changes to P and T: - for the 2010-2039 - in an A1B emissions scenario
2020B1	Reference Period perturbed to reflect projected monthly delta changes to P and T: - for the 2010-2039 - in an B1 emissions scenario
2040A1B	Reference Period perturbed to reflect projected monthly delta changes to P and T: - for the 2030-2059 - in an A1B emissions scenario
2040B1	Reference Period perturbed to reflect projected monthly delta changes to P and T: - for the 2030-2059 - in an B1 emissions scenario
2080A1B	Reference Period perturbed to reflect projected monthly delta changes to P and T: - for the 2070-2099 - in an A1B emissions scenario
2080B1	Reference Period perturbed to reflect projected monthly delta changes to P and T: - for the 2070-2099 - in an B1 emissions scenario

Table 2.7: Meteorological perturbations for projected climate scenarios that were applied to reference meteorological inputs.

SRES B1 Temperature (°C)

	Jan	Feb	Mar	Apr	May	Jun
2020s	1.10	1.08	1.11	1.03	1.01	1.06
2040s	1.49	1.41	1.46	1.45	1.37	1.44
2080s	2.53	2.39	2.27	2.23	2.04	2.49
	Jul	Aug	Sep	Oct	Nov	Dec
2020s	1.34	1.30	1.21	0.99	0.79	1.01
2040s	2.05	2.05	1.90	1.37	1.17	1.65
2080s	3.07	3.22	2.91	2.14	2.12	2.53

SRES B1 Precipitation (%)

	Jan	Feb	Mar	Apr	May	Jun
2020s	0.89	-0.61	3.40	3.35	0.08	-1.36
2040s	-1.21	0.34	5.58	3.39	1.98	-1.14
2080s	5.19	3.22	3.06	6.11	2.91	-6.69
	Jul	Aug	Sep	Oct	Nov	Dec
2020s	-0.94	-3.48	-6.32	6.66	6.07	3.81
2040s	-4.91	-8.69	-6.49	5.19	7.04	6.61
2080s	-10.52	-15.58	-4.72	6.90	8.81	9.35

SRES A1B Temperature (°C)

	Jan	Feb	Mar	Apr	May	Jun
2020s	1.22	0.99	1.11	0.99	1.01	1.28
2040s	1.99	1.75	1.90	1.74	1.68	2.13
2080s	3.59	3.25	3.22	2.87	2.69	3.66
	Jul	Aug	Sep	Oct	Nov	Dec
2020s	1.59	1.60	1.37	1.00	0.83	1.17
2040s	2.79	2.72	2.50	1.86	1.56	1.94
2080s	4.59	4.73	4.20	3.15	2.85	3.40

SRES A1B Precipitation (%)

	Jan	Feb	Mar	Apr	May	Jun
2020s	0.01	0.16	2.04	1.30	-1.24	-5.87
2040s	4.38	0.77	6.28	5.75	-0.56	-9.97
2080s	6.23	6.95	10.50	8.83	-0.09	-11.06
	Jul	Aug	Sep	Oct	Nov	Dec
2020s	-9.89	-9.78	-8.53	2.41	5.66	2.93
2040s	-15.45	-12.17	-12.51	6.94	8.11	5.53
2080s	-18.08	-22.04	-8.23	12.71	11.21	10.91

Table 2.8: Global Circulation Models that were used in calculating the composite delta climate values for the Pacific Northwest.

Model Name	Country/Institution
bccr	Norway/Bjerknes Centre for Climate Research
ccsm3	United States/National Center for Atmospheric Research
cgcm3.1_t47	Canada/Environment Canada
cgcm3.1_t63	Canada/Environment Canada
cnrm_cm3	France/Meteo France
csiro_3_5	Australia/Commonwealth Scientific and Industrial Research Organisation
echam5	Germany/ Max Plank Institute of Meteorology
echo_g	Germany/ Meteorological Institute of the University of Bonn
fgoals1_0_g	China/Institute for Atmospheric Physics
gfdl_cm2_1	United States/National Oceanic and Atmospheric Organization
giss_aom	United States/Goddard Institute for Space Studies
giss_er	United States/Goddard Institute for Space Studies
Hadcm	United Kingdom/Hadley Centre
hadgem1 (a1b only)	United Kingdom/Hadley Centre
inmcm3_0	Russia/Institute for Numerical Mathematics
ipsl_cm4	France/ Institut Pierre Simon Laplace
miroc_3.2	Japan/National Institute for Environmental Studies
miroc3_2_hi	Japan/National Institute for Environmental Studies
pcm1	United States/National Center for Atmospheric Research

Table 2.9: Mean Nash Sutcliffe Efficiency (NSE) Rating and Root Mean Squared Error for Daily SWE, SWE/P, and T and Annual P.
These stations all have 10 or years of record, Stations noted by an asterisk * are SWE measurements that have been reviewed and calibrated.

Station	Mean NSE of SWE	Mean NSE of SWE/P	# of years of SWE	Mean RMSE of annual cumulative P (m)	Mean RMSE of T (°C)
PRIMET*	-	-	-	0.01	1.89
H15MET	-	-	-	0.00	2.14
CENMET	0.33	0.50	11	0.04	2.38
Santiam Junction*	0.74	0.73	21	0.01	4.00
VANMET	0.18	0.26	16	0.00	4.16
UPLMET*	0.88	0.82	10	0.01	3.38
Hogg Pass*	0.90	0.86	21	0.01	1.04
McKenzie*	0.87	0.82	21	0.00	2.81
Roaring River*	0.86	0.92	21	0.03	1.29

Table 2.10:The accuracy, precision, and recall
metrics for agreement between simulations of
snow and Landsat images.

Date	Accuracy	Precision	Recall
Accumulation Period			
2/27/93	73	22	6
3/21/01	83	64	99
2/7/03	86	71	93
3/11/09	91	89	98
Near Peak Snowpack			
3/28/92	90	9	1
3/29/98	91	89	98
3/29/04	80	64	99
Ablation Period			
4/17/99	81	71	93
5/11/02	82	89	98
4/22/95	79	20	1
4/11/97	78	64	99
4/20/06	76	89	98
5/9/07	81	71	93
4/25/08	79	64	99
All Years	82	71	93

Table 2.11: The accuracy, precision, and recall metrics for agreement for simulations of snow and Landsat images by land class.

Land Cover Classification	% of Basin	Accuracy	Precision	Recall
Coniferous forest	82	0.81	0.71	0.87
Deciduous forest	< 1	0.94	1.00	0.14
Mixed forest	1	0.94	1.00	0.14
Harvested forest	11	0.82	0.71	0.92
Subalpine meadow	< 1	0.73	0.83	0.79
Shrub wetland/ riparian	< 1	0.76	0.77	0.93
Shrub	1	0.86	0.73	0.67
Bare / rock	4	0.94	0.94	1.00
Water	< 1	0.86	0.92	0.82
Permanent snow/glacier	< 1	0.98	0.98	1.00
Developed	1	0.85	0.62	0.76
Crops	< 1	0.77	1.00	0.00

Table 2.12: The accuracy, precision, and recall metrics for agreement for simulations of snow and Landsat images by elevation.

Elevation (m)	% of Basin	Accuracy	Precision	Recall
Up to 250	1	0.81	No snow predicted	No snow predicted
251 to 500	8	0.92	No snow predicted	No snow predicted
501 to 750	16	0.90	0.30	0.50
751 to 1000	17	0.87	0.65	0.61
1001 to 1250	21	0.74	0.83	0.63
1251 to 1500	21	0.71	0.98	0.67
1501 to 1750	12	0.86	1.00	0.86
1751 to 2000	4	0.96	1.00	0.96
2001 to 2250	1	0.99	1.00	0.99
2251 to 2500	< 1	0.99	1.00	0.99
2501 to 2750	< 1	0.97	1.00	0.97
2751 to 3000	< 1	0.96	1.00	0.96
3001 to 3250	< 1	0.97	1.00	0.97

Table 2.13: The accuracy, precision, and recall metrics for agreement for simulations of snow and Landsat images by slope.

Slope	% of Basin	Accuracy	Precision	Recall
0 - 10	43	0.83	0.91	0.80
11 to 20	29	0.82	0.86	0.70
21 to 30	21	0.81	0.86	0.62
31 to 40	6	0.78	0.88	0.55
41 to 50	< 1	0.74	0.88	0.56
> 50	< 1	0.93	1.00	0.93

Table 2.14: The accuracy, precision, and recall metrics for agreement for simulations of snow and Landsat images by aspect.

Aspect	% of Basin	% of Basin	Accuracy	Precision
0 to 30	8	0.83	0.88	0.75
31 to 60	7	0.84	0.87	0.76
61 to 90	7	0.85	0.86	0.76
91 to 120	6	0.84	0.86	0.74
121 to 150	6	0.84	0.86	0.73
151 to 180	7	0.84	0.88	0.71
181 to 210	9	0.83	0.89	0.72
211 to 240	10	0.83	0.90	0.75
241 to 270	11	0.83	0.91	0.77
271 to 300	11	0.83	0.92	0.78
301 to 330	9	0.83	0.89	0.78
331 to 359	9	0.83	0.88	0.76

Table 2.15: Changes in peak SWE, % of peak SWE lost, and the shift in the number of days earlier

	Scenario	Watershed 7	Mack Creek	SF McKenzie	McKenzie
Area (km^2)		0.15	6	410	3041
Elevation Range (m)		931 – 1102	765 – 1626	550 – 1849	114 - 3147
Mean Elevation (m)		1021	1206	1276	1027
Mean Peak SWE (km^3)		4.60E-05	3.10E-02	0.21	1.26
Mean Date of Peak SWE		14-Mar	19-Mar	22-Mar	31-Mar
Mean Peak SWE	T2	8.00E-06	9.6E-3	0.07	0.56
	T2P10	9.10E-06	1.1E-2	0.09	0.64
	T2N10	6.90E-05	8.3E-3	0.07	0.48
% of Mean Peak SWE Lost	T2	83	69	67	56
	T2P10	80	65	57	49
	T2N10	85	73	67	62
Shift of Mean Date of Peak SWE	T2	27	32	30	12
	T2P10	27	26	31	6
	T2N10	27	33	34	22
Mean Peak SWE	2020A1B	1.90E-05	1.7E-2	0.13	0.86
	2040A1B	9.40E-06	1.1E-2	0.09	0.62
	2080A1B	6.20E-06	3.8E-3	0.02	0.25
% of Mean Peak SWE Lost	2020A1B	59	46	42	33
	2040A1B	80	65	57	51
	2080A1B	87	88	84	80
Shift of Mean Date of Peak SWE	2020A1B	20	8	18	5
	2040A1B	27	16	30	10
	2080A1B	33	24	48	26
Mean Peak SWE	2020B1	2.10E-05	1.8E-2	0.14	0.89
	2040B1	1.30E-05	1.4E-2	0.11	0.75
	2080B1	1.00E-05	7.5E-3	0.03	0.38
% of Mean Peak SWE Lost	2020B1	54	42	33	29
	2040B1	72	55	48	40
	2080B1	78	76	86	70
Shift of Mean Date of Peak SWE	2020B1	20	16	19	5
	2040B1	26	22	21	5
	2080B1	31	36	43	16

2.10 Appendices
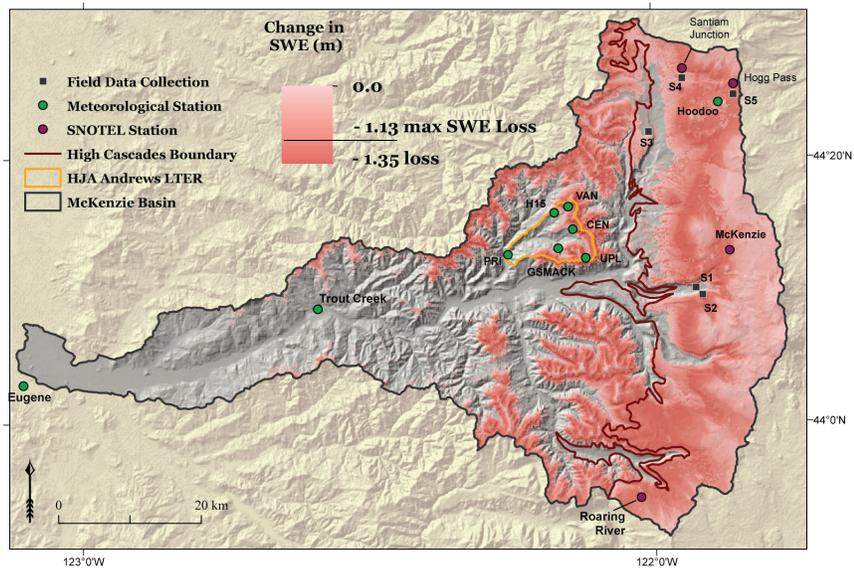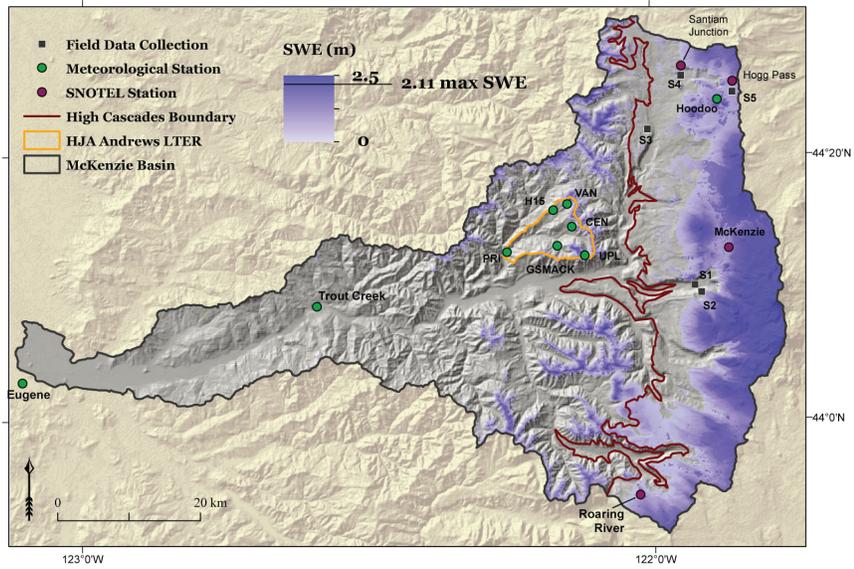
Appendix A: Simulated SWE (above) and SWE loss (below) with a 2°C increase in temperature.
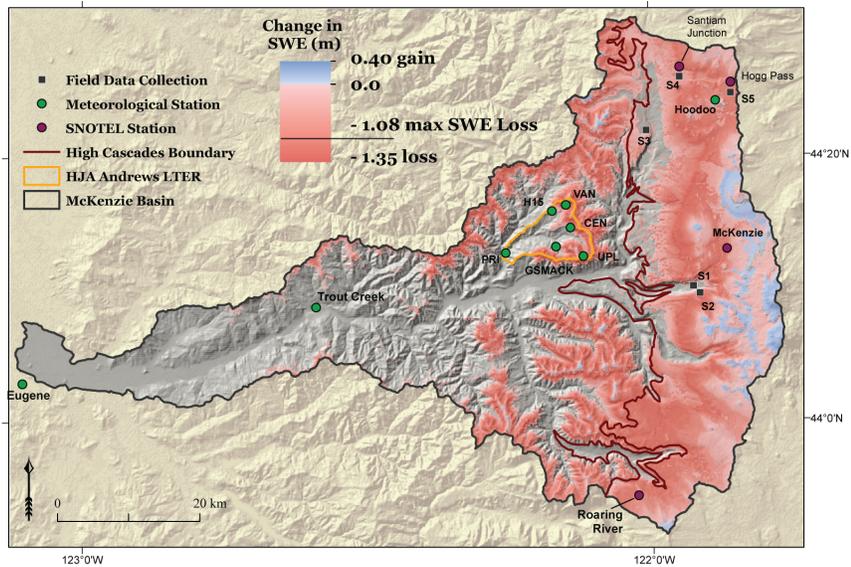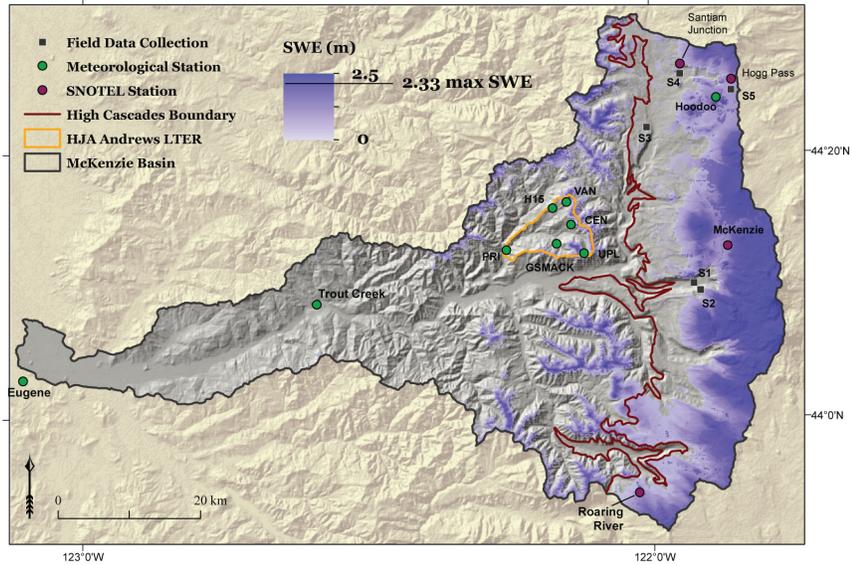
Appendix B: Simulated SWE (above) and SWE loss (below) with a 2°C increase in temperature and a 10% increase in precipitation.
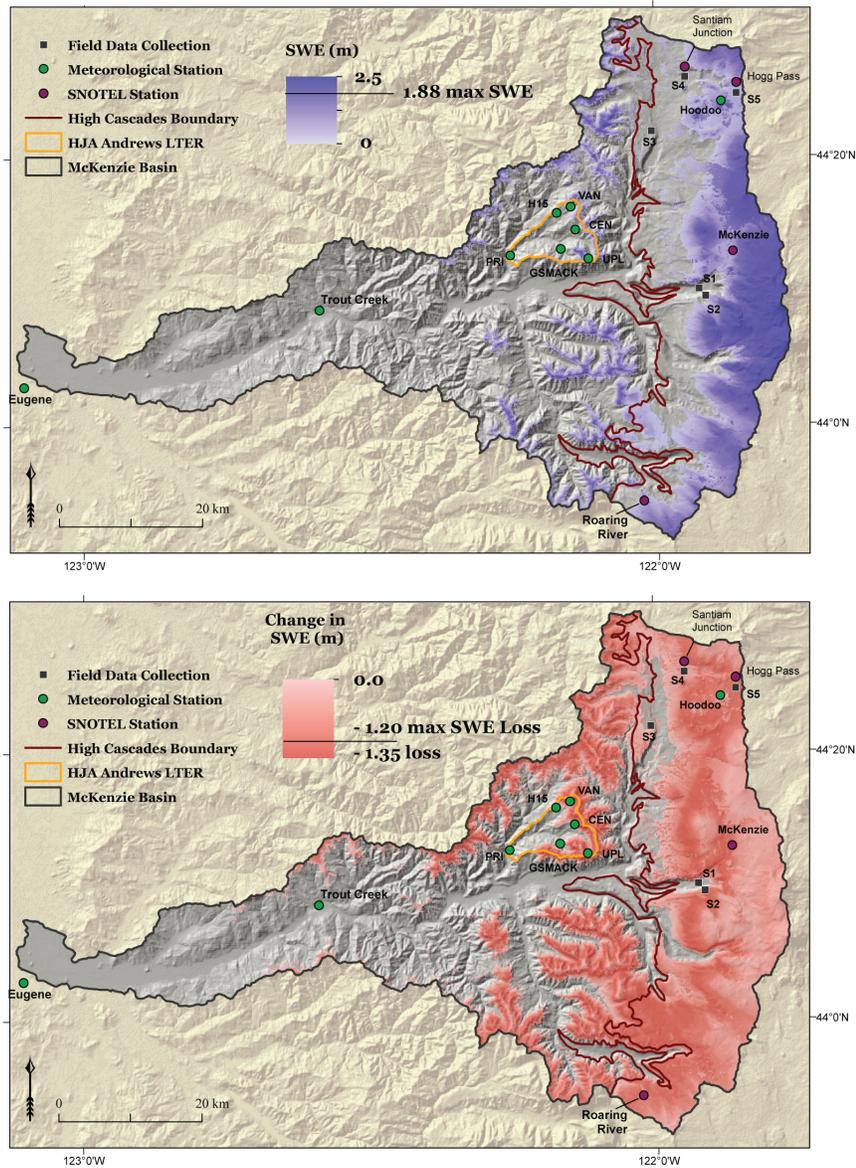
Appendix C: Simulated SWE (above) and SWE loss (below) with a 2°C increase in temperature and a 10% decrease in precipitation.
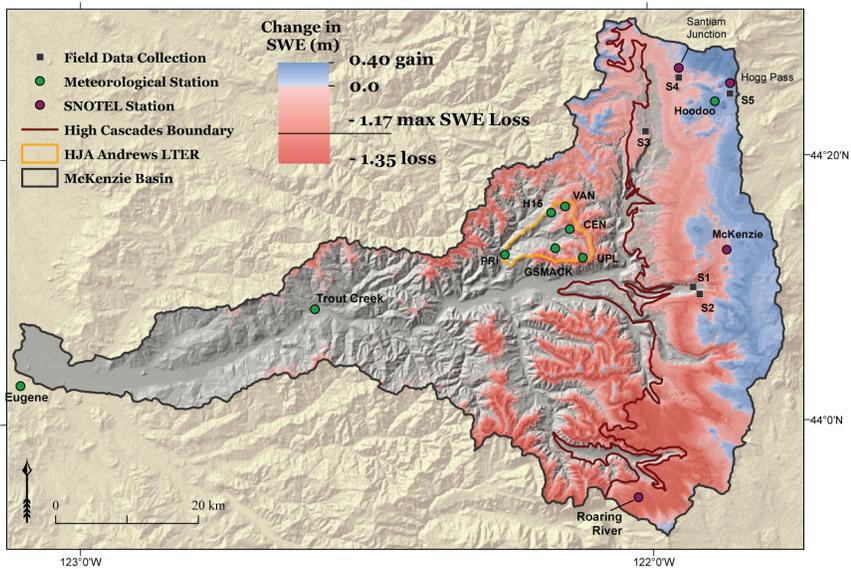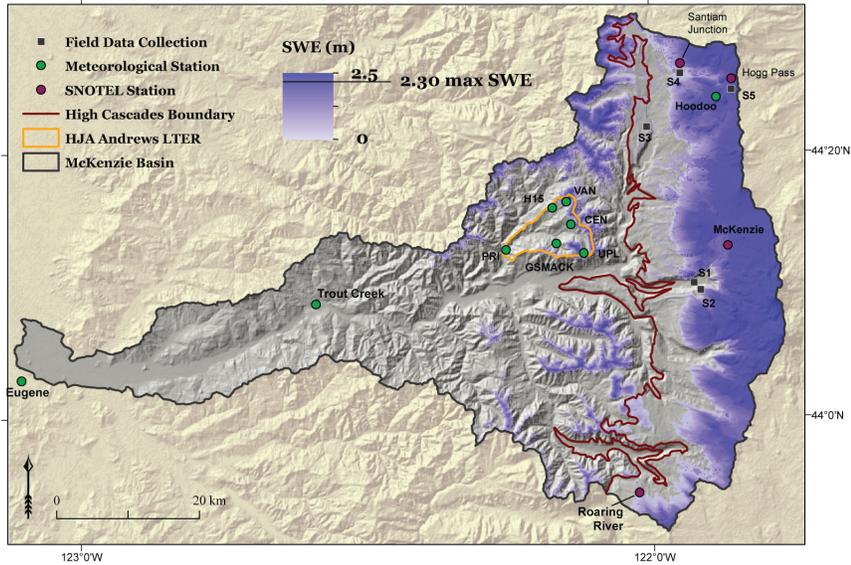
Appendix D: Simulated SWE (above) and SWE loss (below) with a 2020A1B climate projection applied.
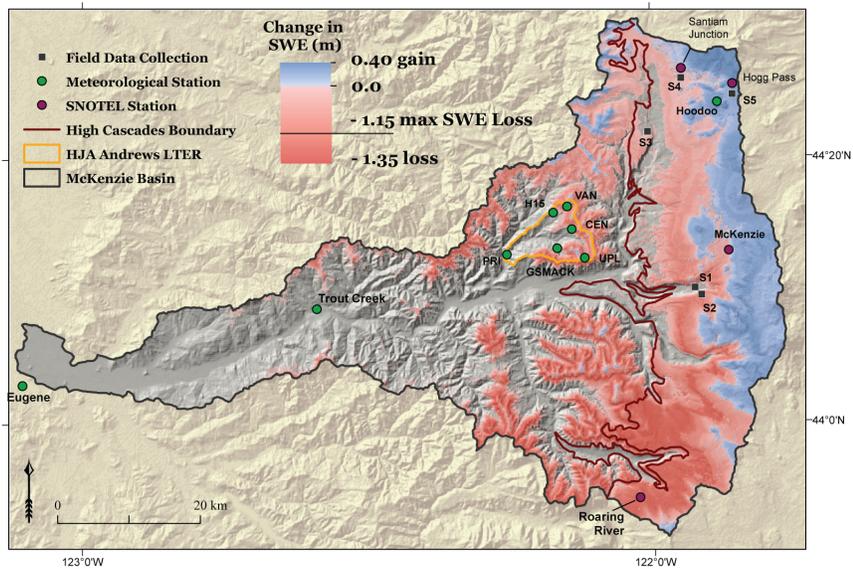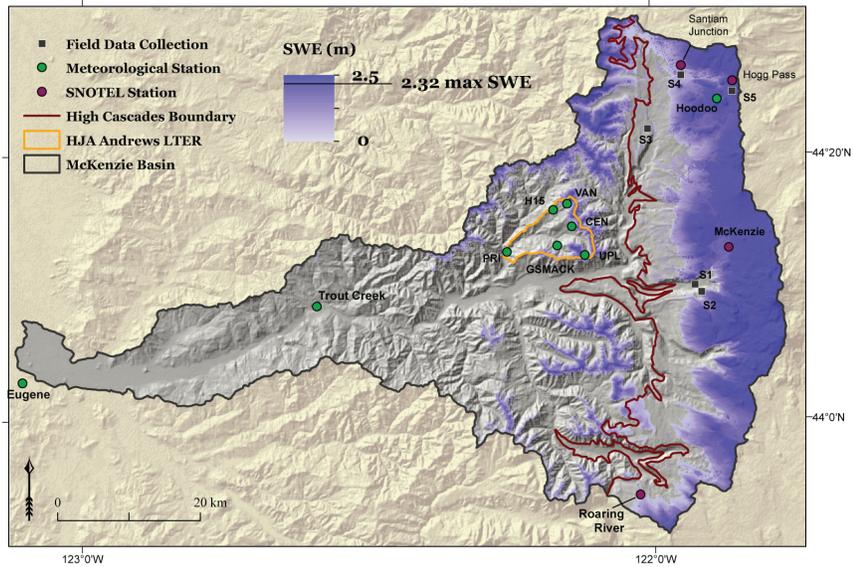
Appendix E: Simulated SWE (above) and SWE loss (below) with a 2020B1 climate projection applied.
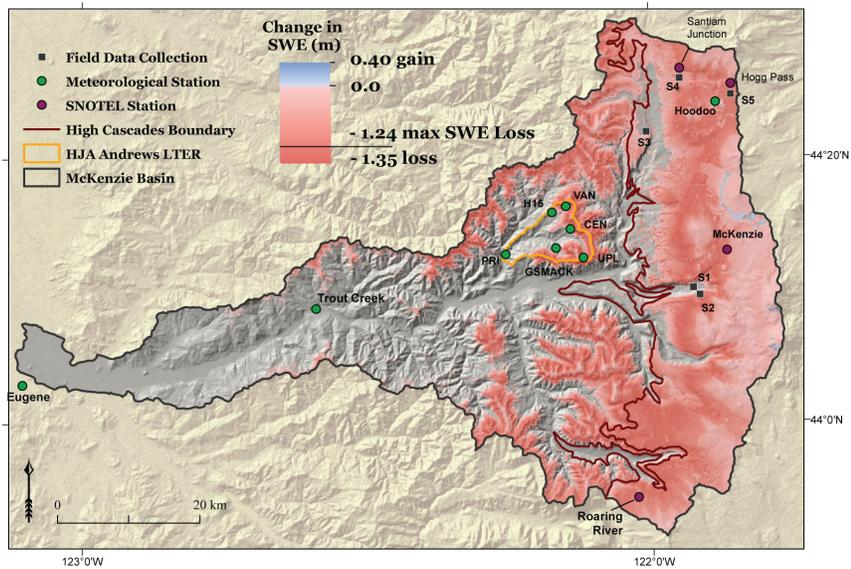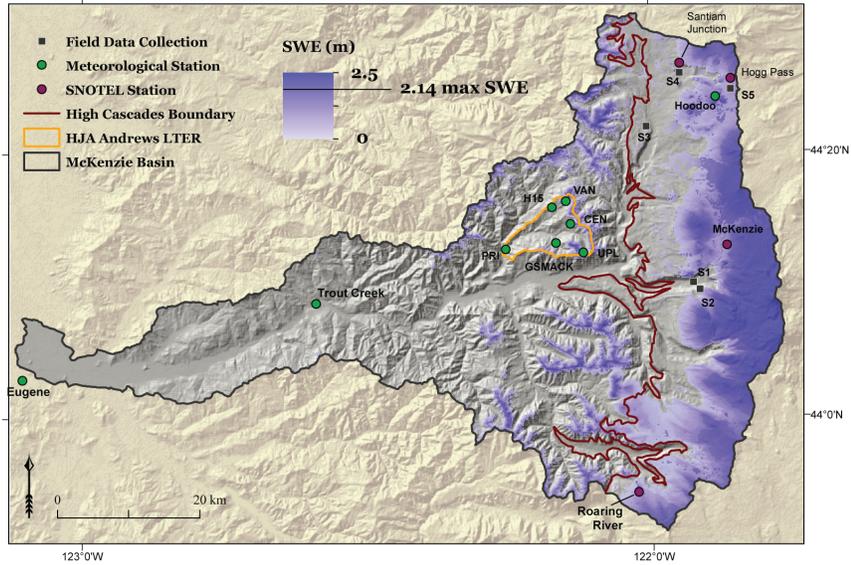
Appendix F: Simulated SWE (above) and SWE loss (below) with a 2040A1B climate projection applied.
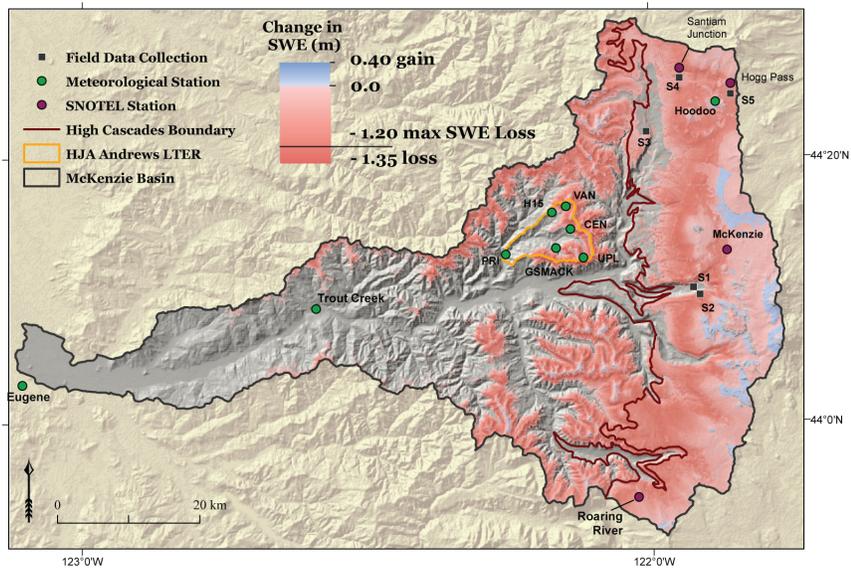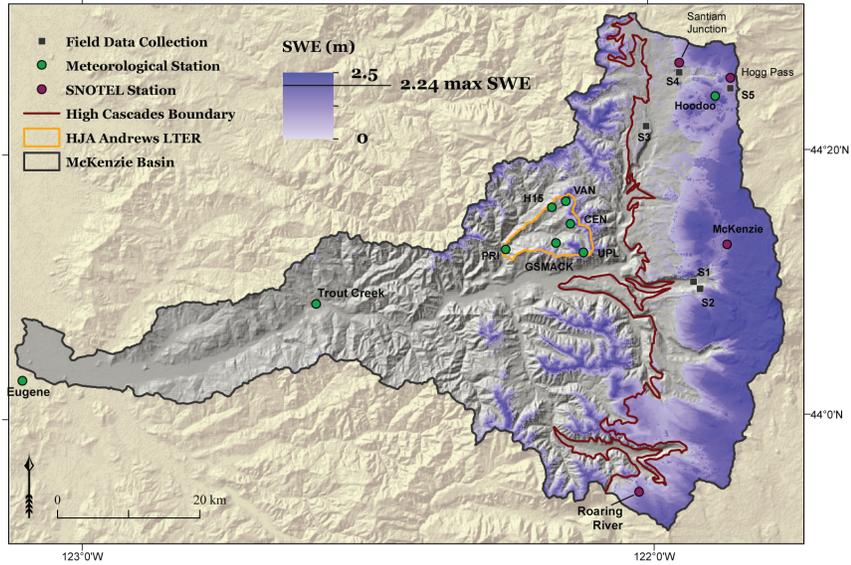
Appendix G: Simulated SWE (above) and SWE loss (below) with a 2040B1 climate projection applied.
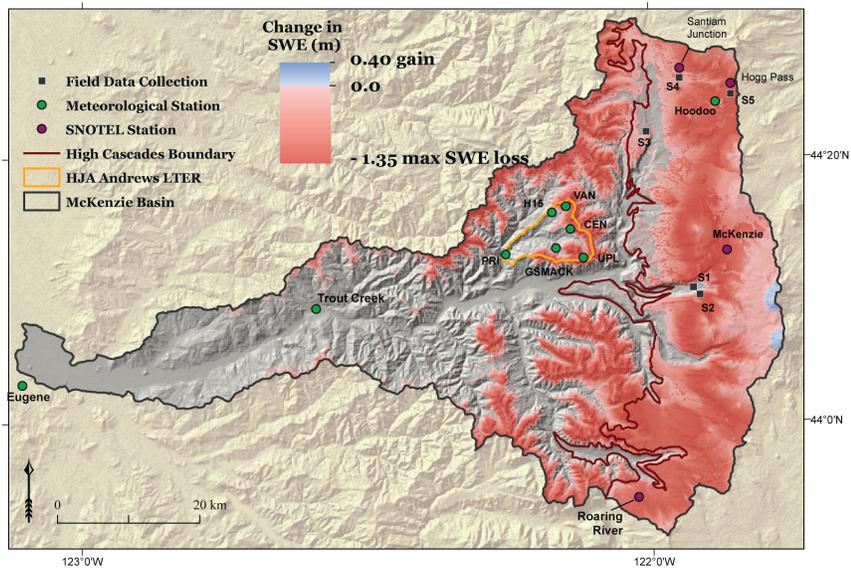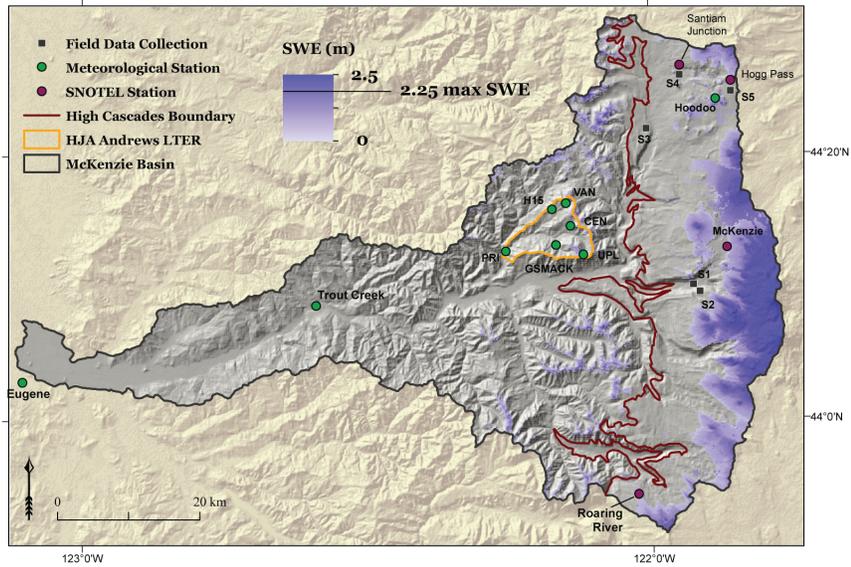
Appendix H: Simulated SWE (above) and SWE loss (below) with a 2080A1B climate projection applied.
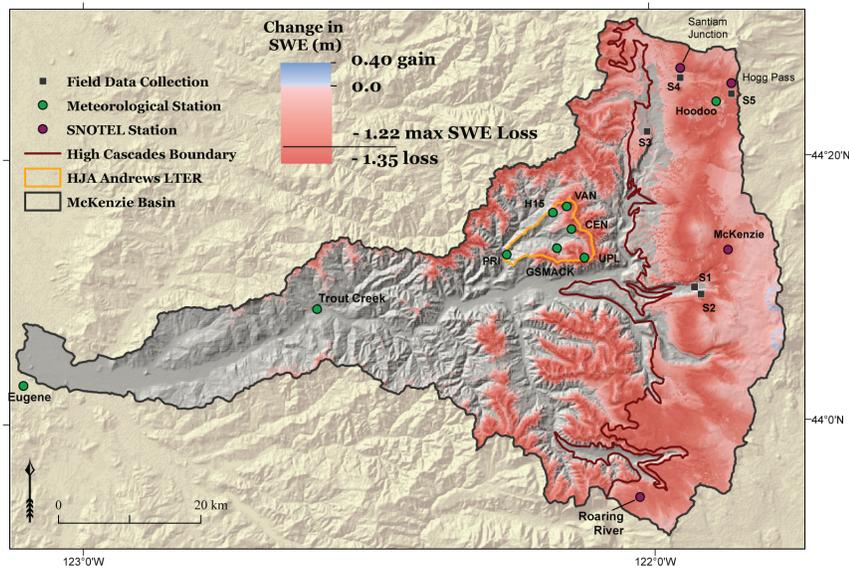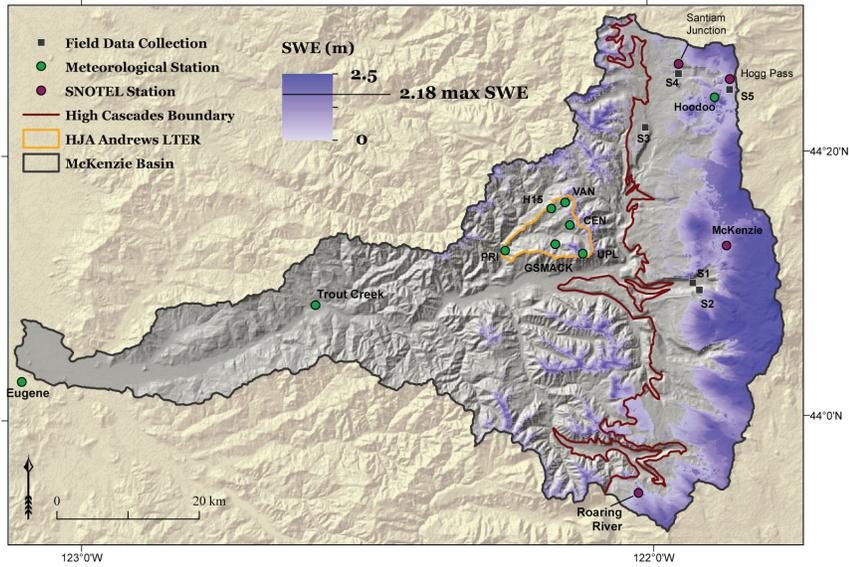
Appendix I: Simulated SWE (above) and SWE loss (below) with a 2080B1 climate projection applied.

3   A Probabilistic Approach to Understanding the Rain-snow Transition in Future Climates and its Affect on Streamflow

3.1   Abstract

Snowpack in the maritime climate of the western Oregon Cascades is highly sensitive
to temperature. Projected future warming in the region would shift the present rain-
snow transition zone up in elevation, resulting in a diminished snowpack for this
snow-dominated system. This research examines the effect of increased
temperatures on the probabilistic spatial distribution of snow water equivalent
(SWE), the ratio of snow water equivalent to precipitation (SWE/P) and the timing of
water available for runoff (WAR) in the McKenzie River Basin in the western Oregon
Cascades. SWE, SWE/P, and WAR were calculated from validated, physically based
model results. These results were compiled for water years 1990 – 2009. To
determine the response of snowpack to increases in temperature a sensitivity
analysis was conducted with all temperature inputs for WY 1989 – 2009 increased
by 2°C. This is considered to be the mean annual temperature increase in the region
by mid-century. The exceedance probabilities of SWE and SWE/P were calculated
spatially for each 100 m-grid cell of the model domain in present conditions and with
a 2°C increase in temperature. The grid-based calculations provide a probabilistic
estimation of where the spatial and temporal dynamics of snowpack accumulation
and ablation will be most affected by projected warmer climates. Results show
greater than 50% loses of volumetric SWE in the basin across exceedance
probabilities. For a 2°C temperature increase, contoured values of SWE/P shift up in
elevation by 260 m. Water Available for Runoff (WAR), composed of rain and
snowmelt, was calculated for all 19 years. A 2°C temperature increase has minimal
affects in sub-basins of the McKenzie near the rain-snow transition zone. However, in
higher elevation sub-basins that accumulate significant snow throughout the winter
the temporal centroid for WAR shifts 10 days earlier.

3.2   Introduction

3.2.1   Significance and Motivation

Mountain watersheds in snow-dominated regions provide critical winter water storage and sustained melt that fills streams and recharges aquifers (Nogués-Bravo et al., 2007; Dozier, 2011). There is a clear need to quantify and prepare for climate impacts on mountain hydrology (Bales et al., 2006; National Research Council, 2009), which is underscored by the fact that globally melt from snow and glaciers provides water for over one billion people (Barnett et al., 2005). The impacts of climate change on winter water storage presents new challenges that require fresh approaches to understanding problems that are only beginning to be understood. However in addressing the need to understand climate impacts on mountain hydrology, challenges arise from the reality that there is an incomplete understanding of climate change and mountain hydrology (Bales et al., 2006; National Research Council, 2009; Dozier, 2011).

While understanding climate impacts on snow is a global concern, addressing them at the basin-level provides a scale that is appropriate to be developed into natural resource management strategies (Dozier, 2011). This research focuses on the McKenzie River Basin (MRB) on the western slope of the Oregon Cascades, USA. The MRB exhibits characteristics typical of many river systems in the western United States, where snow accumulates in the higher elevations throughout the wet winter months and provides a sustained source of melt through the spring and into summer. In this watershed farmers, fish, hydropower, and municipal users compete for a limited supply — especially in summer when stream flow reaches a minimum. Future climate projections anticipate warmer and slightly wetter winters and longer, drier summers (Mote and Salathé, 2010; Salathé et al., 2010) but watershed-scale impacts of these regional projections are not well understood .

This research provides a spatially-based, probabilistic approach to better understand the statistical thresholds of mountain snowpack, precipitation, and melt in present and projected climates in the MRB. Specifically the objectives of this research are to: 1) develop a probabilistic approach to understanding the spatial distribution of snow water equivalent and its relationship to precipitation at the basin scale; 2) calculate probabilistic thresholds of water available for runoff at the sub-basin scale; and 3) examine the impacts of a 2°C temperature increase on objectives 1 and 2.

3.2.2 Study Area

The McKenzie River Basin (Figure 3.1), located in the central-western Cascades of Oregon, has an area of 3041 km^2 and extends from a maximum elevation of 3157 m at the summit of the Cascades to 114 m at its confluence with the Willamette River. The MRB exhibits characteristics typical of many watersheds in the western Cascades in terms of climate, elevation range, and land cover type. There are distinct wet and dry seasons with wet winter months followed by warm, dry summers. Average annual precipitation ranges from 1000 mm in the lower elevations to over 3500 mm in the Cascade Mountains, with over 70% falling between November and March (Jefferson et al., 2008). Discharge for the McKenzie River follows the seasonal precipitation pattern with a maximum in February (283 m^{3}s^{-1}) and a minimum of 57 m^{3}s^{-1} in September (Nolin et al., 2012). This relatively large percentage of late season flow is due primarily to the influence of groundwater via springs, exhibiting both a muted and delayed stream response to snow melt (Jefferson et al., 2008). The demand for water is highest during summer months when streamflow is at its annual minimum. During the periods of low summer flows, water is commonly over-appropriated leading to competing demands between farmers, fish, hydropower, industry, recreation, and municipal users (United States Army Corps of Engineers, 2001; Oregon Water Supply & Conservation Initiative, 2008).

In the MRB winter air temperatures are commonly close to 0°C. As a result, winter precipitation is highly sensitive to temperature and can fall as rain, snow, or both simultaneously. There are several useful metrics for understanding snowpack in a maritime climate. Precipitation (P) is the sum of rainfall and snowfall. Snow Water Equivalent (SWE) is the amount of water stored in the snowpack (m) at a given location. When SWE is multiplied by area, this represents the volumetric water storage of mountain watersheds. The dimensionless ratio of SWE to P (SWE/P) is used to show the proportion of water storage as snow relative to total annual precipitation. When calculated at time intervals, SWE/P represents SWE at that time step in relation to the cumulative precipitation up until that time step. This ratio minimizes the effects of variable precipitation on the accumulation of SWE, while still accounting for the impacts of temperature on accumulation and melt. In the MRB, SWE increases with elevation, as does the ratio of SWE/P. The elevation of the rain-snow transition zone is roughly 800 to 1500 m. Above this elevation, SWE/P exceeds 50% and SWE increases until the onset of melt on about April 1 (Serreze et al., 1999).

The proportion of winter precipitation that falls as snow has declined across the western United States over the past century (Knowles et al., 2006; Feng and Hu, 2007). In particular, the maritime snowpacks of the Pacific Northwest have seen significant declines in SWE (Mote et al., 2005; Abatzoglou, 2011). A portion of the snowpack reduction can be explained by changes in modes of climate variability such as the Pacific Decadal Oscillation (PDO) and the Pacific-North American (PNA) pattern but a significant amount of the decline is due to a long term increase in temperatures unassociated with these patterns (Mote, 2006; Abatzoglou, 2011). In the MRB for example, a snow monitoring site at Santiam Junction (1139 m, 44.33° N, 121.95° W) shows a statistically significant loss of SWE equal of roughly 10% per decade over the period 1941-2010 (Nolin, 2012). This relatively low elevation snow-

monitoring site exhibits a small increase in precipitation (0.3% from 1979–2010), although the trend is not statistically significant. The site exhibits a larger percentage increase in degree-day, the sum of daily mean temperatures for December through March (11% from 1985-2010). This trend in winter temperature is not statistically significant because of the relatively short data record and high interannual variability. Similar changes in temperature and precipitation are described in future climate projections for the region (Mote and Salathé, 2010). In the Cascades and the MRB mean daily temperatures are expected to increase by 2°C by mid century causing the rain-snow transition zone to shift up in elevation leading to subsequent decreases in SWE (Nolin and Daly, 2006).

In the wet, maritime Pacific Northwest a scarcity of water seems counterintuitive. However concerns for water scarcity are affected by the projected declines in SWE in the Cascades, and are amplified by recent and projected population increases in the state (Office of Economic Analysis, 2011). Under current water use policies, it is likely to surmise that increased population will lead to increase water demands thereby increasing the potential for water scarcity in the drier summer months (United States Army Corps of Engineers, 2001; Oregon Water Supply & Conservation Initiative, 2008). Water resource managers make decisions based past experience, however in a non-stationary climate system past water management practices may no longer be successful in the future (Milly et al., 2008; Pederson et al., 2011). New methods of analyzing climate change impacts on snow need to be developed (Dozier, 2011) and managers will benefit from new metrics that account for the range of statistical outcomes and can be applied to mountain watersheds with minimal data records.

3.2.3   Probabilistic Metrics and Simple Models as Descriptive Tools

A spatially-based, probabilistic approach to SWE and SWE/P presents a new metric that helps better analyze the impact of climate change on snowpack with regards to time and location. This approach is novel to understanding snow and helps develop statistical thresholds, or upper or lower limits of predicted snowpack conditions. While probabilistic approaches are common to streamflow hydrology, spatial approaches to probabilistic questions are less common. A notable application of a spatially-based, probabilistic approach was developed by Graf (1984). This research applied a spatial approach for understanding and predicting river channel migration based on the history of the river's location, creating a probabilistic map of river movement. The map outlined the character of the river system that identified areas where channel migration was more likely to occur. This approach allows deterministic decisions to be placed in context of the river's probable outcomes, and provides a holistic picture of the fluvial system (Graf, 1984).

Probabilistic metrics can be incorporated into simplified hydrologic models that help describe the statistical thresholds of hydrologic processes. Simplified hydrologic models do not provide the precise deterministic outcomes characteristic of highly parameterized models. Instead they capture the main hydrologic processes and develop a better understanding of how watersheds respond to variable inputs (McDonnell et al., 2007; Tague and Grant, 2009; Tetzlaff et al., 2010) such as precipitation, snowmelt, and recharge. Tague and Grant (2009) developed a simple model that uses snowmelt as the single input and a drainage efficiency coefficient as the only parameter to understand the sensitivity of streamflow to increasing temperature in two sub-basins of the MRB, Lookout Creek (LC) and the McKenzie River above Clear Lake (MCL) (Table 3.1). Their research provided insights on the relationship between timing of peak snowmelt and streamflow and how this relationship is influenced by subsurface drainage rates (Tague and Grant, 2009).

Their results showed late summer streamflow in the MCL to be more sensitive to increased temperatures than LC. At a higher elevation, MCL receives more snow and has a lower drainage efficiency than the more rain influenced and higher drainage efficiency LC. These factors changes in the timing of melt are expressed throughout the spring and summer.

3.3   Methods

3.3.1   Data Description

This research uses validated model outputs of SWE, SWE/P, and water available for runoff (WAR, the combined input of snowmelt and rain) previously computed by Sproles (2012). These values were simulated on a daily time step at 100-m resolution for the McKenzie River basin for water years (WY) 1989 - 2009. A water year (WY) is the 12-month period beginning on October 1. WY 1997 and 2005 were excluded in subsequent calculations of input data problems. In total there were 19 years of reference data. To better understand the spatial and temporal sensitivity of SWE to increased winter temperature a 2°C increase in temperature was applied for each daily time step and SWE, SWE/P, and WAR was modeled for the 19 years. Hereafter, these data sets will be referred to as Reference and T2.

3.3.2   Spatial Exceedance Probability

Exceedance probability (p) is the probability that a data value (i.e. SWE, precipitation, SWE/P) of a given magnitude or greater will occur in any given year:

$$p = \frac{m}{n+1} \qquad\qquad (1)$$

where m is the rank from highest to lowest of the input and n is the number of inputs (Dingman, 2002). Exceedance probability is a useful statistic because it describes the

likelihood that a value with particular magnitude *or greater* will occur. It is used commonly in flood and drought predictions providing upper and lower statistical bounds along with an associated streamflow. For example, a low exceedance probability for SWE, p20, describes the statistical likelihood that a SWE value would be met or exceeded 20% of the time, and represents a high value of SWE that would have a low frequency of occurrence. A high exceedance probability, p80, describes the statistical likelihood that a SWE value would be met or exceeded 80% of the time, and represents a relatively low SWE value that would be a more common occurrence. Spatial exceedance probability is the exceedance probability for each model grid cell and can be readily represented as a map.

Values of spatial exceedance probability were calculated for SWE and SWE/P using 15-day mean values centered on February 1 and April 1. These 15-day mean values were used to minimize the effect of individual events (melt, snowfall) while still capturing the overall snowpack characteristics. Each date and data set in the Reference and T2 scenarios included 19 input variables, representing the 19 years of the data record. The model domain has grid dimensions of 759 rows × 1121 columns. Here, each of the 19 two-dimensional data sets (759 rows × 1121 columns) was decomposed into 19 one-dimensional vectors (1 × 850,839), one for each year. The location information of each grid cell was retained for subsequent mapping. For each year, values in each vector were then sorted from highest to lowest. The 19 × 850,839 data matrix was reshaped into 19 data matrices of dimension 759 × 1121. Each of the 19 matrices represents an exceedance probability (Table 3.2).

The spatial exceedence probabilities of SWE and SWE/P were then mapped and contours of SWE/P were created at 0.1 intervals. To examine the relationship between spatial exceedence probability and elevation, mean elevations for each contour were derived using a 100-m digital elevation model. The shift in mean

elevation of each contour was calculated from the Reference to the T2 scenario. This simple probabilistic spatial metric provides insight into how a 2°C increase in temperature affects the relationship between elevation and the rain-snow transition across the watershed.

3.3.3   Exceedance Probability of Water Available for Runoff

Following a methodology similar to Tague and Grant (2009) the daily exceedance probabilities of WAR were used to calculate the geologically-mediated values of WAR in LC and MC.

$$Q(t) = Q_0 e^{(-kt)} \tag{2}$$

Where Q(t) is daily WAR with the influence of geology included, at time, t (in days) Q_0 are values representing the daily exceedance probabilities of WAR. k drainage is the base flow constant of an individual watershed and is a function of drainage efficiency which tends to vary across geological classes. Values for k were 0.01 for LC and 0.028 for MCL (Tague and Grant, 2009), and implies that LC drains more quickly. k values were derived using baseflow recession analysis (Tallaksen, 1995). Table 3.1 and Figure 3.1 provide additional insight into sub-basin characteristics. Daily exceedance probabilities for WAR were calculated using a moving 15-day mean value. The 15-day mean was applied to capture overall precipitation and melt characteristics on those dates, but not allow a single event to dominate the input value. Each date in the Reference and T2 scenarios included 19 input variables, representing the 19 years of the data record. While Tague and Grant used only snowmelt as the input, both snowmelt and rainfall were included in this study because in the T2 scenario both forms of precipitation are important contributors to winter runoff. The values of Q(t) in both the reference and T2 scenarios were normalized by watershed area, providing a unit recharge for each basin. This

conceptual model evaluates the statistical range of WAR and how these trends shift with a 2°C increase.

3.3.4   Change in Water Available for Runoff

The temporal centroid (CT) has been used as a hydrologic metric to identify the day of the water year when half of the annual discharge has occurred (Regonda et al., 2005; Jefferson et al., 2008). Here, it is used to define the day of the water year when half of the water available for runoff has occurred. CT for WAR in LC and MCL were calculated in the Reference and T2 scenarios as:

$$CT = \sum (t_i q_i) \Big/ \sum q_i \qquad (3)$$

where t_i is time in days and q_i is WAR for the corresponding day (Dingman, 2002). CT of WAR reflects the precipitation and snow melt characteristics of a sub-basin, where more rain dominant systems would have an earlier CT date. Basins more heavily influenced by snow will have a later CT date.

3.4   Results

3.4.1   Spatial Exceedance Probability

The spatial distribution of the exceedance probability (p) of SWE on April 1 for the MRB is shown in Figures 3.2–3.4, which represent Reference and T2 conditions. The spatial variability throughout the watershed and across exceedance probabilities demonstrates that spatial differences in the volumetric storage of SWE are strongly affected by elevation, which is a proxy for temperature. Here, we compare magnitudes of SWE that occur frequently (p80), commonly (p50), and rarely (p20) for both the Reference and T2 scenarios. For p80 in the Reference scenario, the total

April 1 water storage is 0.69 km^3 compared with only 0.24 km^3 of water storage in the T2 scenario, a decline of 65 percent for the entire basin (Table 3.3). For p50 in the Reference conditions, the total April 1 storage of water is 1.11 km^3 compared with 0.41 km^3 in the T2 scenario. The storage capacity of Cougar Reservoir, the largest reservoir in the MRB, is 0.25 km^3.

Figure 3.5 represents the exceedance probability of peak SWE integrated over the MRB. Comparing the Reference and T2 cases, at all exceedance probabilities there is a significant downward shift in this volumetric quantity for a 2°C temperature increase. This downward shift also indicates that the difference between years of high and low peak SWE will decrease with the Reference scenario having a peak SWE range of 1.6 km^3 and the T2 scenario having a peak SWE range of 0.8 km^3. The 50% decrease in the range of values represents a basin that is increasingly dominated by rain, and less influenced by snow. It also represents a change in the statistics that describe the exceedance probability of SWE. For instance, the peak SWE in a p75 year (3 out of four years) in the Reference scenario is roughly equal to a p5 (1 out of 20 years) in the T2 scenario. Thus, the magnitude of peak SWE that has frequently occurred over the past two decades is rather unlikely to occur in a warmer climate

3.4.2   Elevational Shifts in the Ratio of SWE/P

The simple but telling metric of SWE/P contours (Table 3.4) describes the relationship between elevation, the phase of precipitation (rainfall vs. snowfall), and snowpack evolution (accumulation and ablation). The general trend across exceedance probabilities is that SWE/P increases by 0.1 for every 60 m elevation gain once seasonal snowcover begins to accumulate. For a 2°C increase in temperature the SWE/P contour shifts upward by approximately 260 m in elevation. This can be attributed to several factors. The most significant is factor is the shift from snowfall to rainfall during the accumulation period, especially on snowpack at

elevations below 1200 m. The secondary factor is the increased temperature during the ablation phase, which accelerates melt. Melt events during the ablation phase also contribute to the decline in SWE/P in a warmer climate.

The spatial distribution of the p50 of SWE/P on April 1 in the Reference and T2 scenarios is shown in Figure 3.6. Because SWE is normalized by P this metric highlights the influence of temperature on snowpack evolution. The similarity between the map of SWE/P and SWE (Figure 3.3) demonstrates that snowpack in maritime locations such as the MRB is governed primarily by temperature not precipitation. The pronounced sensitivity of SWE to increased temperatures is evident in the T2 scenario shown in Figure 3.6.

3.4.3 Exceedance Probability of Water Available for Runoff

As shown in Figure 3.7, shifts in the timing and magnitude of WAR with a 2°C increase are most profound in the snow-dominated MCL, especially for low values of exceedance probabilities, For a probability of p20 there is an increase in WAR from December to mid-February and a decrease from the beginning of March into June. p80 describes a similar temporal trend, but with lesser magnitude. This implies that the impacts of increased temperature are minimal with statistically more common (p80) thresholds of WAR, and have a greater impact on less common (p20), higher threshold values. The rain-dominated LC exhibits relatively small differences in the timing and magnitude of WAR across a range of exceedance probabilities. The only exception is a slight shift during February in the p20 time series. This suggests that the impacts of increased temperature are minimal in LC, which makes intuitive sense as LC is a rain-dominated basin. It is important to remember that these times series are the exceedance probabilities of 15-day mean values of WAR and that the signals associated with large single events that are more common in a rain dominated system have been reduced.

3.4.4 Change in the Timing of Water Available for Runoff

Shifts in the temporal centroid of WAR for sub-basins of the MRB due to increased temperature vary depending on elevation (Table 3.1, Figure 3.8). For instance in LC, a middle elevation basin that is rain-dominated, a 2°C increase sees a one day shift in the CT of WAR. This is evident in Figures 3.7 and 3.8 where minimal changes in WAR with regards to timing a described throughout the water year. However in the more snow-dominated headwaters of MCL, a 2°C increase results in CT for WAR coming on average 10 days earlier over the 19 years. The 2°C increase also reduced the inter-annual variability of the temporal centroid of MCL as the system becomes more influenced by increasing amounts of rain in the winter rather than snowmelt spread throughout the spring and early summer.

3.5 Discussion and Conclusion

This work applied a probabilistic approach to understanding the geographic distribution of SWE and SWE/P for the present-day climate and for a 2°C temperature increase. For present-day climate conditions, results show consistent snowpack in the upper elevations of the basin (2000 m and above) in all probability ranges. Between 1500 – 2000 m the probability of SWE values greater than 1.0m begins to decline at exceedance probabilities above the p60 threshold. This decline is responsible for the distinct break in slope shift near p60 (Figure 3.5). This break is a result of elevations around 1500m contributing less SWE to overall basin storage below the p60 threshold. This break does not occur in with a 2°C increase as SWE has been reduced across the basin. This results in less variation with regards to Peak SWE across exceedance probabilities, and is shown by the more gradual slope of T2 in Figure 3.5.

With a 2°C increase in temperature, the p50 threshold shows a dramatic reduction in SWE. The upper elevations still retain snow, however the basin as a whole loses 0.7 km^3 of water storage in the form of SWE. A 2°C increase in temperature shifts SWE/P contours up in elevation, effectively moving present rain-snow transition relationships up 260 m.

Shifts in the temporal centroid of WAR reflect the changes in the form of precipitation and the accumulation and ablation of SWE that result from increased winter temperatures. The probabilistic approach to time series data helps define the range of potential outcomes that are associated with climate change impacts on water resources. For basins such as LC that are presently rain-dominated, a 2°C temperature increase has minimal impact with regard to the timing of WAR (Figures 3.7and 3.8). However for basins such as the MCL that rely on snowmelt as a water source in the spring and early summer, warmer winter temperatures result in significant shift in the temporal centroid of WAR. Because MRB streamflow during the summer months is sustained by groundwater recharged from snowmelt, the shifts suggest lower summer base flows in the MRB. These findings are consistent with a study by Tague and Grant (2009) that applied a hydrologic model and found a similar decrease in summer streamflow in the upper elevations of the MRB. The shift in WAR for the MCL is also accompanied by a reduction in variability. The hydrologic system shows a moderate increase in winter discharge as WAR shifts to earlier in the WY, suggesting an increased likelihood for mild to moderate winter flooding in the upper regions of the basin as areas dominated by snow shift to rain. Similar results have been found in the adjacent Santiam River basin (Surfleet and Tullos, in review).

The approach presented here departs from a deterministic view that can produce answers that are precise, but at times imperfect (Leopold, 1964; Graf, 1984).

This is not to say that deterministic solutions do not have significant merit. However, predicting the impacts of projected climate change on water resources from solely a deterministic perspective may fail to convey the range of potential outcomes especially with regards to time and space. Climate change impact analysis is often presented in probabilistic terms that use the probability of different scenarios (Randall, 2007). Thus it is consistent to consider probability in estimating snow. This research provides a range of potential outcomes for snow in present and projected climates. The value of a probabilistic approach lies in defining the range of statistical probabilities and to ensure that management decisions and strategies work within the bounds of these possibilities. This allows ecologic and economic decisions to be made that weigh reward against the range of risks.

Using results from the spatial exceedance probability of snow, adaption strategies can be developed that are proactive instead of reactive. For instance an exceedance probability of p80 with a 2°C temperature increase indicates that the MRB would lose approximately 0.45 km^3 of water stored as snow. This loss of snowpack water storage is approximately 1.8 times more than the largest reservoir in the basin. This is a dramatic reduction in snowpack, and varies significantly from the normal and stationary conditions upon which present-day management plans are based upon (Milly et al., 2008). Understanding the probability of such significant losses of snowpack help understand potential outcomes and their consequences, and make appropriate adaption strategies. While this research focused on the McKenzie River Basin, snowpack processes in this basin can be applied in other maritime Pacific Northwest watersheds. The framework used here could be expanded to other basins on the western slope of the Cascades with minimal reconfiguration.

Future research would include developing a more detailed understanding of the relationship between the SWE/P ratio and stream discharge. Validated relationships

could be applied to other ungauged watersheds with similar geology, vegetation, and climate. This would enable the application of model-based approaches to predict streamflow in locations where stream gauge data are unavailable, allowing basins that are potentially more sensitive to variations in temperature to identify be identified. This advance would be significant as water resource managers often manage at the sub-basin scale, so it is valuable to understand how projected climate change is expressed at this management level (Morgenstern, 2010). The probabilistic techniques and approaches that were used here are not intended to replace deterministic methods in water resources research. Rather they are intended to provide a conceptual understanding of snow and water resources in present-day conditions and for warmer winters. This understanding is not focused solely on individual modeled values of SWE, but rather on a range of possible values, which can help develop more insightful future management strategies.

3.6   Bibliography

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3.7   Figures
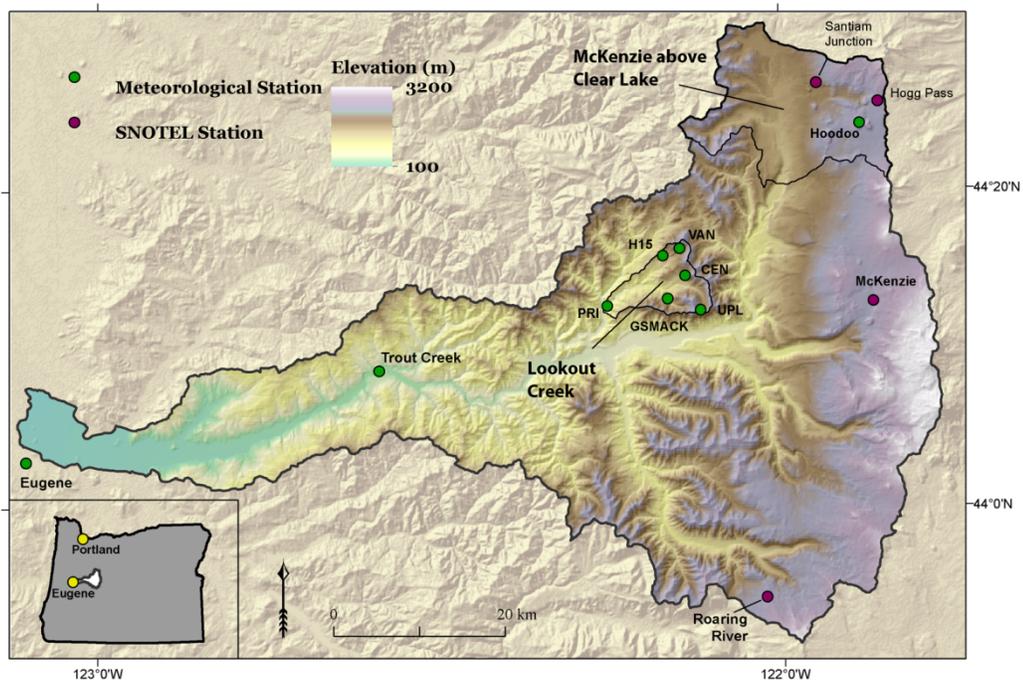
Figure 3.1: Context Map for the McKenzie River Basin, Oregon
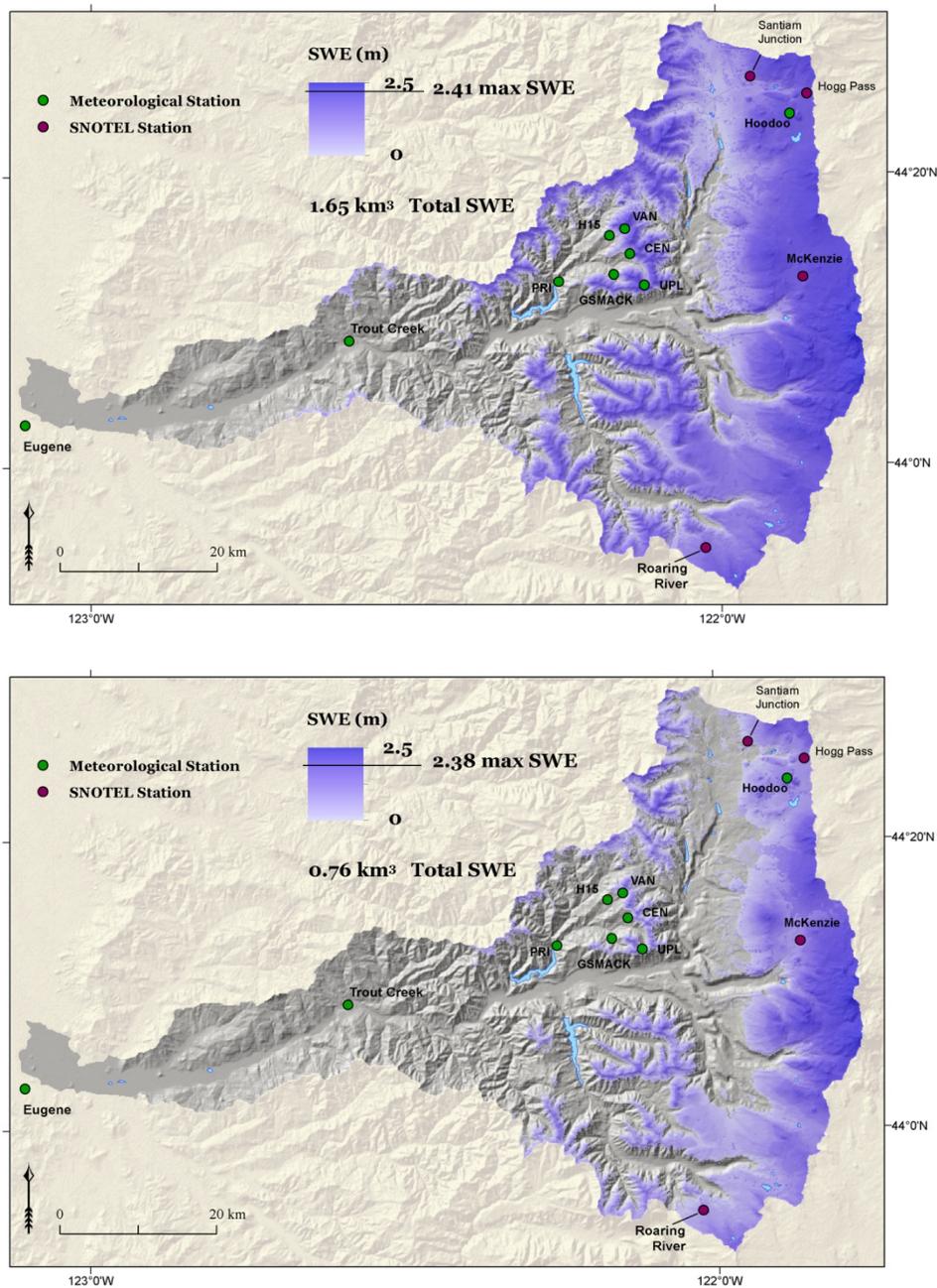
Figure 3.2: 20% Exceedance Probability of SWE (m) on April 1st
for the Reference conditions (above) and T2 conditions (below).
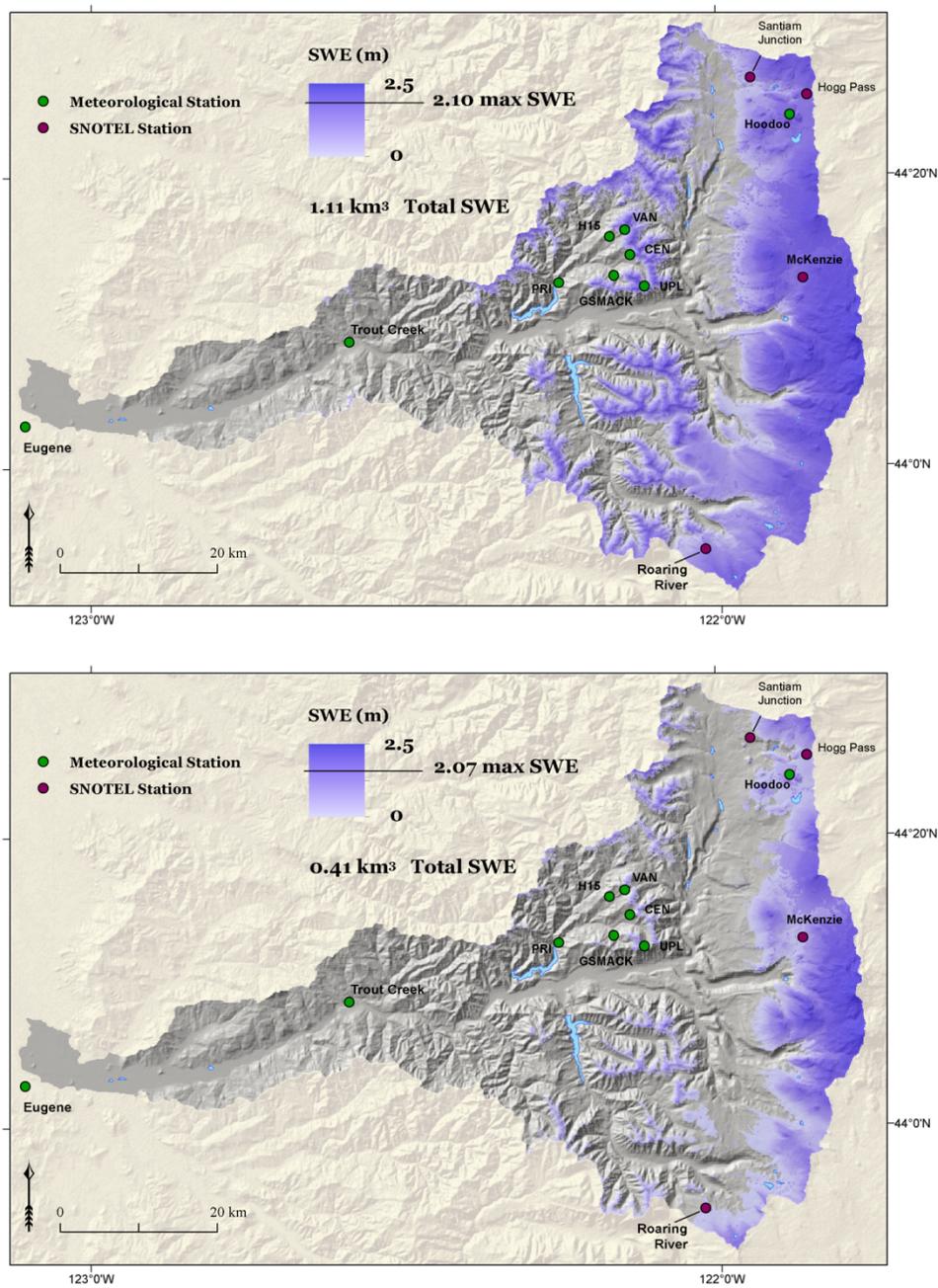
Figure 3.3: 50% Exceedance Probability of SWE (m) on April 1st
for the Reference conditions (above) and T2 conditions (below).
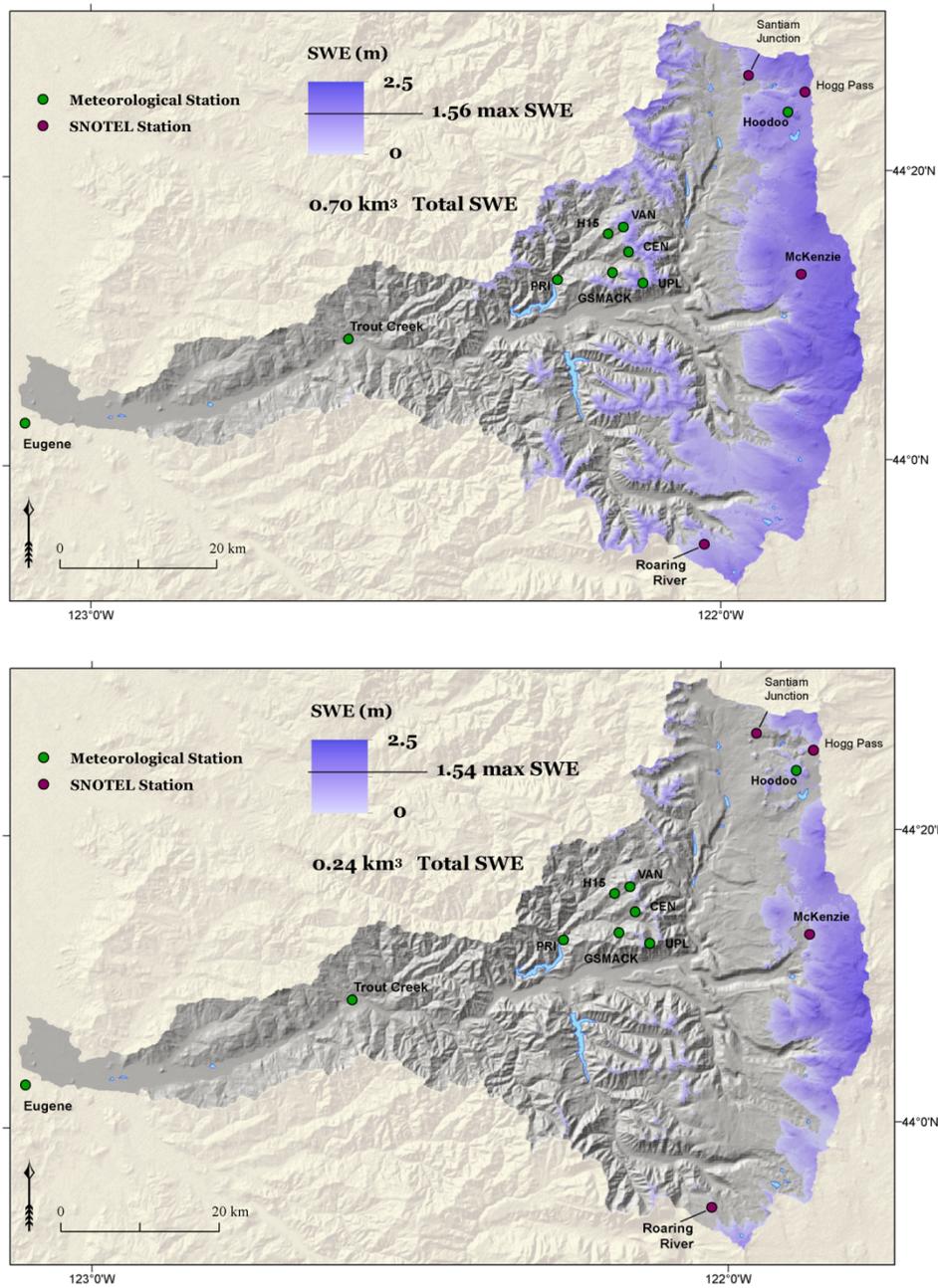
Figure 3.4: 80% Exceedance Probability of SWE (m) on April 1st for the Reference conditions (above) and T2 conditions (below).
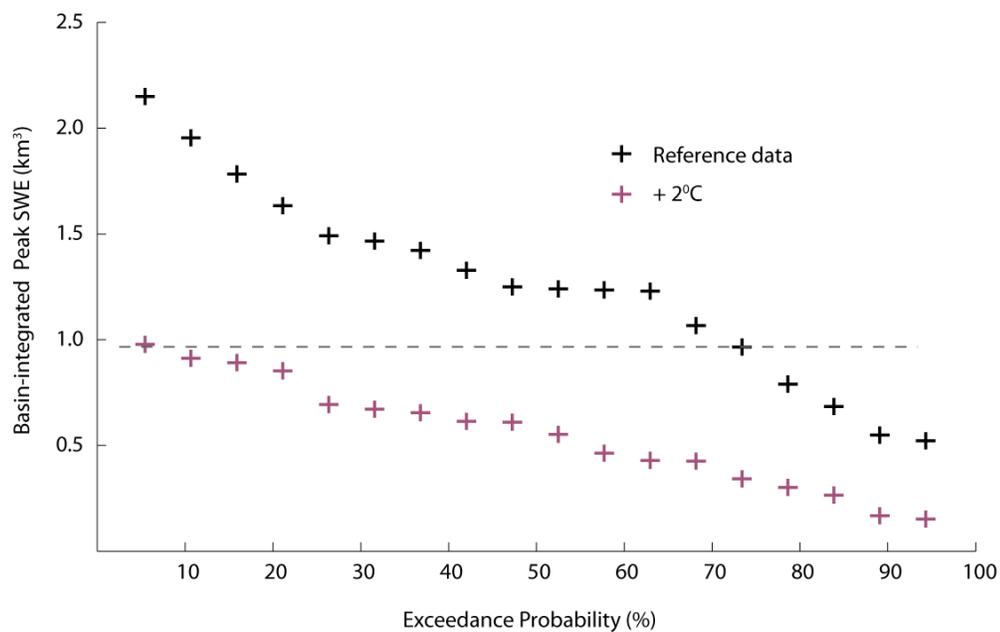
Figure 3.5: Exceedance probability for basin-wide SWE.
The dashed line highlights the similar magnitudes of a p75 (common) snowpack in the Reference conditions to a p5 (rare) for T2 conditions.
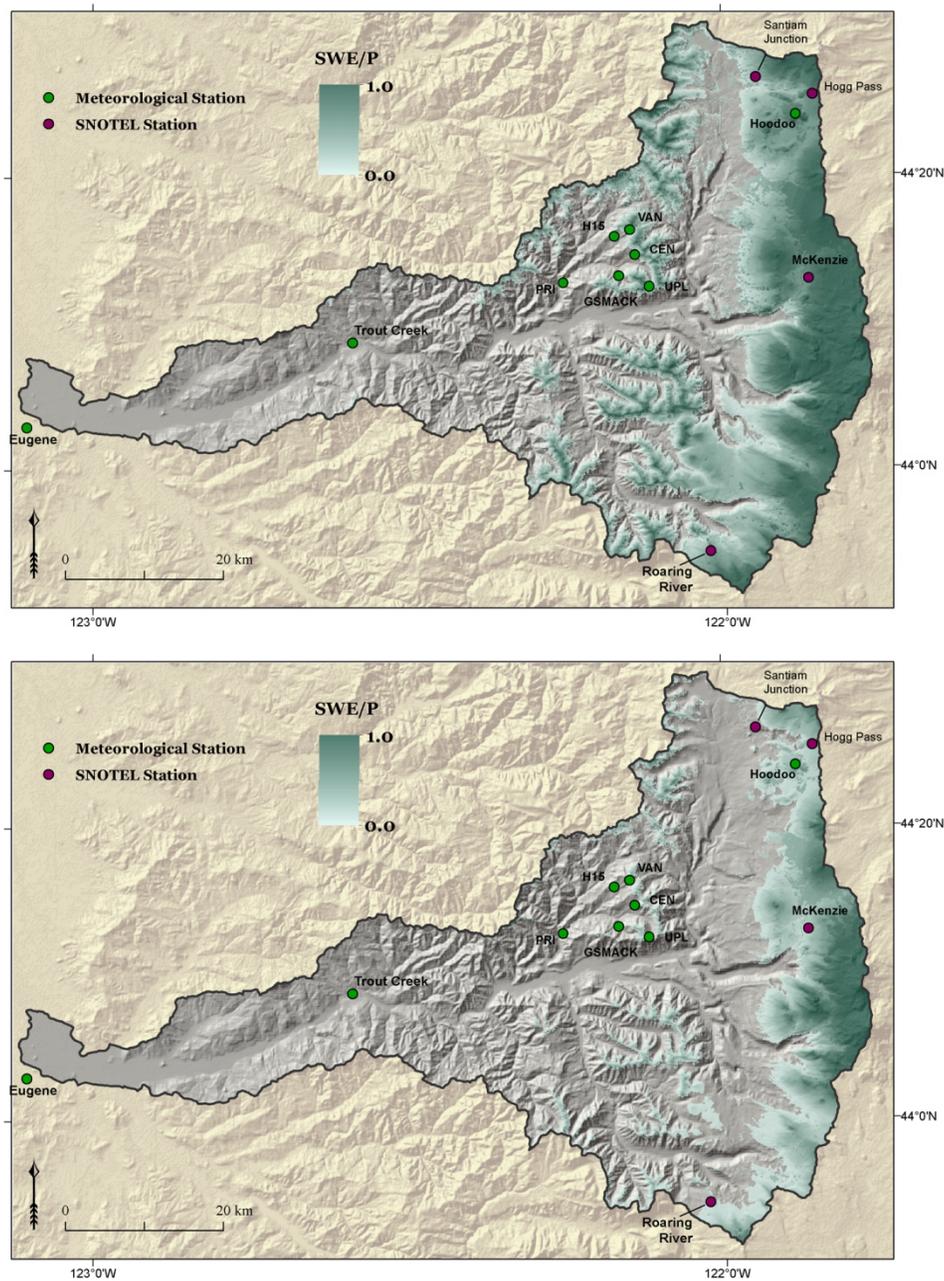
Figure 3.6: 50% Exceedance Probability of SWE/P on April 1st
for the Reference conditions (above) and T2 conditions (below).
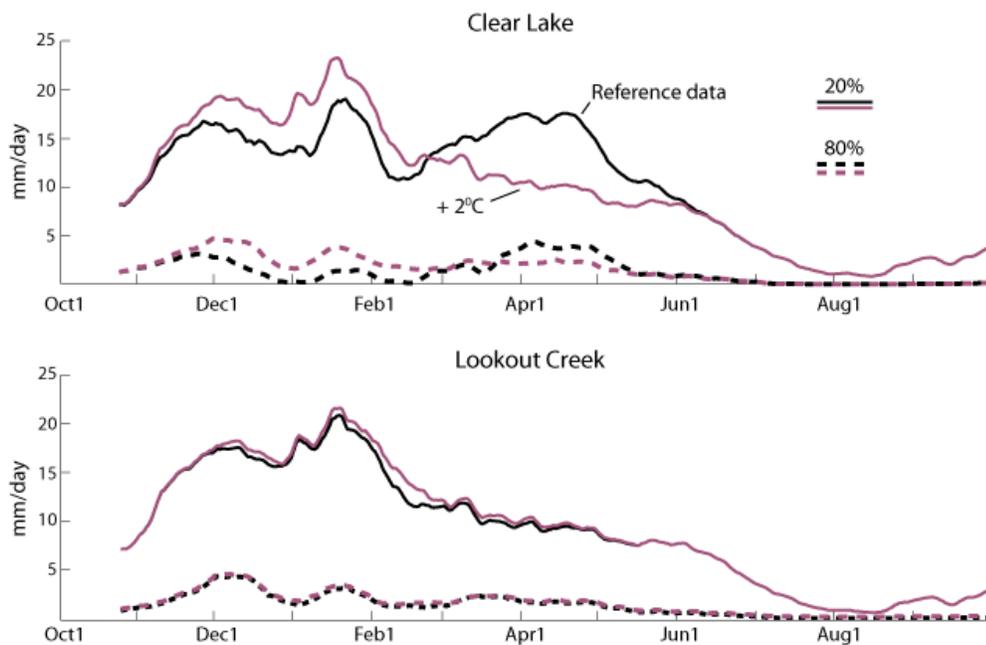
Figure 3.7: The 20% and 80% Exceedance Probabilities for WAR in Clear Lake and Lookout Creek in the Reference data and with a 2°C temperature increase.
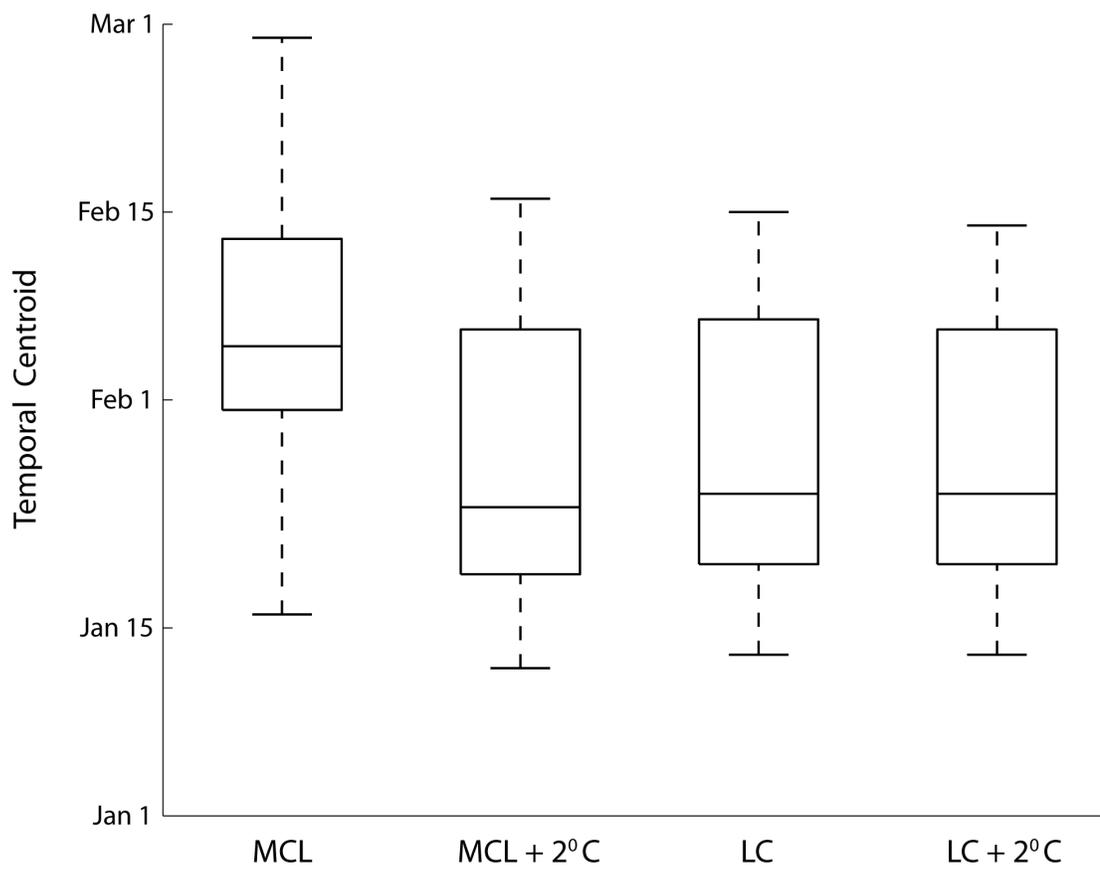
Figure 3.8: Temporal centroid for water available for runoff in the Reference data and with a 2°C temperature increase. MCL is the McKenzie River above Clear Lake and LC is Lookout Creek.

3.8 Tables

Table 3.1: Temporal Centroid of Water Available for Recharge (WAR)

	McKenzie River above Clear Lake	**Lookout Creek**
Area (km^2)	64	239
Elevation Range (m)	410 – 1630	920 – 2035
Mean Elevation (m)	980	1271
Temporal Centroid (WAR - Reference)	Feb 5	Jan 27
Temporal Centroid (WAR - T2)	Jan 26	Jan 26

Table 3.2: Description of exceedance probability ranks

Rank	p	Description
1	5%	Low likelihood large magnitude
2	10%	
3	15%	
4	20%	
5	25%	
6	30%	
7	35%	
8	40%	
9	45%	Moderate likelihood, moderate magnitude
10	50%	
11	55%	
12	60%	
13	65%	
14	70%	
15	75%	
16	80%	
17	85%	High likelihood, small magnitude
18	90%	
19	95%	

Table 3.3: Volumetric SWE by Exceedance
Probability

	p20	p50	p80
Reference (km³)	1.65	1.11	0.69
T2 (km³)	0.76	0.41	0.24
% Change	54	63	65

Table 3.4: Mean elevation (m) of SWE/P

	SWE/P					
Exceedance	0.1	0.2	0.3	0.4	0.5	0.6
Probability	**Reference period**					
p20	1029	1094	1145	1207	1271	1384
p50	1188	1247	1294	1358	1427	1494
p80	1331	1359	1384	1445	1520	1582
	T2					
p20	1317	1408	1452	1522	1580	1673
p50	1473	1518	1571	1604	1700	1758
p80	1610	1627	1641	1653	1791	1820
	Shift in elevation					
p20	288	314	307	315	309	289
p50	285	271	277	246	273	264
p80	279	268	257	208	271	238

4 Developing and Assessing a Snowpack Visualization Decision Support Tool for Water Resources Research

4.1   Abstract

Assessment of a web-based decision support tool and insight gained from focus groups were used to identify methods of improved engagement and communication between the water resources researcher and practitioner communities. The topic of transitioning knowledge water resources into action is timely as professionals in the public and private arena increasingly incorporate projected climate change into water resources planning. Practitioners often find challenges and questions regarding climate change and water resources that do not have clear answers. While practitioners would readily apply knowledge garnered from the research community into practical applications, they often find the traditional dissemination of scientific research through peer-reviewed literature as inefficient for their needs. The outcomes provide insights on how to improve communication and knowledge transfer between these two groups.

4.2   Introduction

4.2.1   Significance and Motivation

Climate has changed over the last several decades and will continue to change in the future (Randall et al., 2007). This change affects the timing and availability of water resources, especially in areas where snow is a major contributor to streamflow (Barnett et al., 2005; Dozier, 2011). These changes in climate and streamflow have increased the demand for decision makers in public and private arenas to incorporate climate change impacts into near and long term planning for water resources (National Research Council, 2009; California Department of Water Resources, 2006). The inclusion of climate change represents a shift in the planning process from a perspective based on a fixed climate to one based upon a climate in transition (Milly et al., 2008), requiring new insights and information with regards to water resources. Failure to translate research results into management-useable knowledge from which managers can base decisions and actions does not maximize the value of costly and time-consuming research. However the present method of knowledge dissemination relies heavily on peer-reviewed literature. Shortcomings of peer-reviewed literature are the lengthy review and publication process, lack of ready access, and high journal subscription costs (Figure 4.1). This increases the difficulty of converting scientific data into useful information for managers.

Improvements in the transfer of knowledge from the scientific research community require modification of its existing dissemination model to incorporate better decision support. In his presidential address to the American Association for the Advancement of Science, Peter H. Raven commented on the need for scientists to provide an accessible, integrated approach to contribute knowledge to a sustainable society. Before that can happen, however, significant advances in understanding, social capacity, technology, and political will are needed (Raven, 2002). The National

Research Council published similar conclusions, stating that decision makers need new kinds of climate information and that science should adapt to these demands by providing improved means of knowledge transfer (National Research Council, 2009).

Decision support tools (DSTs) provide technological advances that address these concerns. DSTs are computer applications that distill complex scientific findings into a more easily understood format and help expedite the knowledge transfer process in terms of time and fiscal efficiency ((Turban et al., 2008)). While well intended, DSTs often do not have their expected impact with the end users as regularly they are involved too late in the development process (Ceccato et al., 2011). Geurts and Joldersma (2001) found that open dialogue between scientists, decision makers, and stakeholders improved the ability to incorporate science into decision making by shifting scientific knowledge in to a consensus-based understanding. The modified dissemination model of scientific information should not provide a one-way transfer of information from researchers to decision makers, but rather an open dialogue between groups at all stages of the development process. This type of dialogue promotes the exchange of ideas and technical knowledge, and identifies relevant scientific questions that should be addressed (Ceccato et al., 2011).

This research works to improve decision support for practitioners by:

3. Developing a web-based DST (SnowDash) that includes features, functionality, and information requirements based upon the feedback from practitioners.
4. Assessing the features and functionality of SnowDash, its overall effectiveness, and understand how users interact with the DST.
5. Obtaining feedback from users to identify supplemental features, functionality and information that will improve the DST.

4.2.2   Means of Improving Communication Between Researcher and Practitioner

Components of human resources are partially responsible for inefficiencies that exist in the communication of science to practitioners. Traditionally knowledge transfer between researchers has focused primarily on the dissemination of peer-reviewed literature within the scientific community. Researchers often lack the training and incentive for working at the interface of science, policy, and applied decisions (National Research Council, 2009). This lack of cross-institutional knowledge transfer stands in contrast to an increased demand for better communication between science and decision makers. This is especially pertinent to the development and use of water resources where the effects of warmer climate are impacting the timing of streamflow (Service, 2004; Nogués-Bravo et al., 2007; Stewart, 2009). The disconnect between supply (capable scientific researchers) and an increased demand (decision support) could only complicate the human resources problem (National Research Council, 2006).

There are multiple methods and pathways for communication between researcher and practitioner, however this paper will concentrate on web-based decision support tools and focus groups. DSTs focus on a single topic with the goal of providing the end user with an improved understanding of the question. In the past, the World Wide Web or through an intranet (a private intra-organizational network) has commonly provided access to DSTs (Shim et al., 2002). DSTs date back to the 1970s and have approached an array of topics (Mysiak et al., 2005). More recent technological advances have led to access of DSTs through mobile devices and cloud technology (Zurita et al., 2008). DSTs have commonly been used in water resources in an operational capacity (Mysiak et al., 2005), for instance dam operators monitoring reservoir levels and releases. Recently researchers have begun to use

DSTs to disseminate their findings, but often with limited success. End users often find the tools are tailored to the data of the researcher rather than to the needs of the decision maker (Mysiak et al., 2005).

One way to better understand the needs of the user is through focus groups, which provide a forum to obtain feedback from the decision maker and identify the most useful components of a DST. Focus groups are common to marketing and consumer feedback, and have become more frequent in the social sciences, but have a limited history in the sciences. They are comprised of a small number of participants (between four and eight people) that generally meet once. Participants are invited by a moderator to discuss a specific topic (Bedford and Burgess, 2001). While there is no definitive answer for the number of participants needed, published literature suggests between four and ten individuals (Bedford and Burgess, 2001; Krueger and Casey, 2009). While larger groups provide input from more people, it has also been noted that smaller groups provide more detail and dialogue (Hopkins, 2007). A strength of focus groups is the facilitation of dialogue and the exchange of ideas between participants in a semi-structured environment (Hopkins, 2007). Focus groups switch the flow of information to the moderator (who is often the researcher) providing insight into the focus group topic from the participants through dialogue.

Focus groups move knowledge to the researcher and DSTs move knowledge to the practitioner. So why combine two disparate ways of knowledge transfer? The answer has process and practical considerations. The open dialogue that originates from focus groups combines scientific knowledge with contextual insights (Geurts and Joldersma, 2001) helping guide DST development to represent an end-to-end system where pertinent research questions and the tools to address them co-develop (Mysiak et al., 2005; Giupponi, 2007; Ceccato et al., 2011). Focus groups may provide the research community with an understanding of what components should be

included in a DST by reflecting the needs of the practitioner. Practitioners are able to identify pertinent research questions and what types of information would be most the most beneficial to their organization (Ceccato et al., 2011). Focus groups also help establish connections between researchers and professionals fostering multidisciplinary ties across organizations (National Research Council, 2009).

On a practical level research proposals are increasingly requiring data management plans that highlight how data will be stored and disseminated (National Science Foundation, 2012). Similarly recent evaluations of funded research that involve the development of decision support tools have a much higher likelihood of gaining funding if they include product evaluation (National Research Council, 2009). All proposals submitted to the National Science Foundation are reviewed with regards to their intellectual merit and broader impacts. The National Science Foundation's Review Criteria on broader impacts place value on contributions to society such as enhancing education, research, and partnerships (National Science Foundation, 2012), and DSTs could help accomplish all of those goals.

4.3 Methods

4.3.1 SnowDash

SnowDash is a web-based interactive decision support tool developed by the author to distill complex research results into a single interface. SnowDash provides multiple datasets visualized through an interactive map and charting tool. The goals for SnowDash are simple: (1) provide a content-rich interface for water resource professionals that transitions data display to data interaction; and (2) assess the features, functions, and user interactions to provide a better understanding of how users interact with of SnowDash.

Description of Data Used in SnowDash

In total nine map layers and three time series graphs were generated from validated simulations of snowpack from the work of Sproles and Nolin (2012) (Table 4.1). The map layers show the snow water equivalence (SWE) at 100-m grid cell resolution for the McKenzie River basin on April 1st. SWE is a measure of the amount of water stored in the form of snow and April 1st is considered to be the day of peak snowpack in the western United States (Serreze et al., 1999). The McKenzie River is a snowmelt-dominated basin with 35% of annual precipitation accumulating as snow (Jefferson et al., 2008). Watershed scale maps of SWE, derived from a spatially distributed snow were provided for years of average, below and above average snow conditions. Additionally maps of SWE were provided for the simulated loss of SWE in projected climates. Climate projections are downscaled Intergovernmental Panel on Climate Change-AR4 (Randall et al., 2007) values for changes to temperature and precipitation input data. These values reflect an A1B emissions scenario for the 2020s (approximately a 1°C mean temperature increase and winters with 2% more precipitation) and 2040s (approximately a 2°C mean temperature increase and winters with 3% more precipitation) (Salathé et al., 2010).

The time series graphs show daily values extracted for three locations in the McKenzie River basin at elevations of 1000 m, 1500 m, and 2000 m. The 1000-m elevation is in the lower elevation portion of the snow zone, where precipitation falls as rain and snow during the winters. At 1500 m, rainfall is less frequent and at 2000 m, winter precipitation falls predominantly as snow. The charts extend for water years 2001 to 2009. A water year (WY) is the 12-month period beginning on October 1. The charts show modeled SWE for present-day and projected future climate conditions in the decades of the 2020s and 2040s for the A1B scenario.

Underlying Technology of SnowDash

Technology that was customizable and free of charge was sought when possible to alleviate costs and provide a technological framework that can be transitioned to other projects with minimal configuration and cost. The maps of snowpack were created using GIS software (ESRI, 2010) and displayed on the internet using the Google Maps Application Programming Interface (API) (Google, 2010). Google was chosen as the platform because it is free, provides an editable API, and robust online documentation and support for users. Also the Google Maps API is not blocked from governmental organizations, where map services that use a Flash-based technology may be blocked for use by employees (DenOuden, 2010; Morgenstern, 2010). The graphs were created using Dygraph (Dygraph, 2011), an open-source visualization library that uses JavaScript. Dygraph was chosen because it comes at no cost to the user and runs on JavaScript. Dygraphs is easily customizable and has a high level of graphic quality, and also maintains a user forum that is quite active and provides support for its users.

Data layers and graphs were compiled into a single HTML webpage and accessed over the Internet (Figure 4.2: http://tinyurl.com/snowdash). The beta version of the webpage was tested on multiple platforms and multiple browsers and efforts were made to address all technical problems. Staff at a local utility conducted beta testing on SnowDash to assess how the technologies would work. This organization has very stringent internet security protocols (DenOuden, 2010).

4.3.2   Assessment of SnowDash

In the fall of 2011 an email was sent to water resource professionals requesting participation in an online assessment of SnowDash. The requests were sent to two listservs (a private set of email addresses that targets and organized group with a common focus) and to an email list maintained by the researchers. While no exact

number can be tallied (due to the privacy of the listservs) it is estimated that the email was sent out to at least 1000 water resource professionals. The email requested participation in an online survey and assessment of SnowDash. The survey was conducted using Survey Monkey, an online software application that specializes in surveys (SurveyMonkey.com, 2011).

In total, the survey was composed of 25 questions (Appendix 2). Participants were queried about their background (gender, age, education) but retained their anonymity. The second portion of the survey led respondents through SnowDash, and asked them a series of questions requiring interaction with the DST. The format of the survey requested basic interaction with SnowDash, but encouraged participants to interact with both the mapping and the graphing functions. This provided a comparison of user experience/preference and interpretation of results. Participants were provided with an open forum to provide anonymous, qualitative feedback on the site and how to improve the survey and SnowDash.

A second, embedded method to better understand how participants interacted with SnowDash was also enabled. This monitoring technology captured mouse movements and clicks of website users, providing a visual and quantitative understanding of how participants were using SnowDash. Monitoring was disclosed to all participants prior to initializing SnowDash. For monitoring, we used Click Tale, a proprietary software company that specializes in web site analytics (Click Tale, 2011). Click Tale results provide a graphical display of user interactions through a series of maps of the website interface. These maps show both mouse movement and clicks that identify how users engaged with the website. There is an ~85% correlation between a user's mouse movement and eye movement while using a website (Chen et al., 2001; Cooke, 2005). This allows mouse tracking to serve as a proxy for the user's visual engagement with the SnowDash.

4.3.3 Focus Groups

The development and assessment of SnowDash was the primary goal of this research, and focus groups were employed to recognize and incorporate practitioner's needs from the outset. A secondary goal of the focus groups was to identify ways to improve communication between the water resources research and practitioner communities.

Invitations to participate in one of two focus groups were emailed to water resource professionals and policy makers in the region. Water resource professionals were the target audience for the sessions as the goal was to identify the ideas and needs of a professional community. Invitations were sent to non-profits, private companies, political offices, water districts, public utilities, and local, state, and federal agencies. In total 55 invitations to participate were emailed. The focus groups were scheduled one week apart with one in Eugene, Oregon and the other in Portland, Oregon. Each focus group lasted two hours, with the same moderator and dedicated note taker staffing each focus group. The Eugene session had six participants and the Portland session had three participants (Table 4.2). Initially the Portland session was scheduled for four participants, but one had to cancel the day of the session. A follow up phone interview was conducted with this person. Some of the participants knew each other on a casual basis, but most individuals met for the first time. The lack of social connections provides a more spontaneous conversation as compared to a group from a single agency which may trend toward a reflection of organizational experiences (Hopkins, 2007).

One of the strengths of focus groups over individual surveys is the interaction between participants (Kitzinger, 1994), and conversations between participants were encouraged. The moderator followed the same general framework of questions (Appendix A) to lead participants *into* discussions structured around a topic but

were kept on track. Notes from both sessions were compiled into a single digital document that synthesized both groups. This synthesis report was sent to participants for review and clarification, however no responses were received. An abbreviated report is contained in the Results section of this document.

4.4 Results

4.4.1 SnowDash

Profile of Participants

The email requesting participation in the online survey and assessment of the decision support tool (DST), SnowDash, was sent to over 1000 water resource professionals. Of these 1000+, 115 people began the survey and assessment. The geographic locations of participants who accessed the site were primarily from the western United States. Of the 115 people that accessed SnowDash during the survey period, 71% accessed the site from Oregon, 8% from New Mexico, 5% from Washington and Idaho, and the remaining 16% from 15 other states. The demographics of participants are described in Table 4.3. *The results discussed in the remainder of this section represents only completed survey and assessments*.

The majority of respondents were women younger than 45-years old. This research did not set out to analyze gender or age with regard to water resource topics. However, the demographic characterization of the respondent pool provides context to the results.

The group of respondents was primarily a well-educated group of water resource professionals (Table 4.4). Of the completed responses 80% are professionals, with the remainder students. Over 75% of participants use water resource data on a weekly or daily basis for school or work (Table 4.5). This reflects the nature of the

requests for participation. This is also a well-educated group, with 76% having a master's or professional degree.

Respondents who classified themselves as professionals (rather than students) were asked whether climate change impacts on water variability was a topic in their workplace. Over 65% of responses stated that such discussions are in a nascent or early phase, while only 18% stated that measures have been implemented (Figure 4.3). This trend shows a similar pattern as compared to a 2007 study (Bartleson and Doppelt, 2007) that surveyed municipal water districts that rely on snowmelt for water supply. In that study only 5 out of 35 respondents only 5 (14%) had begun to formally plan for climate change. The absence of planning for projected climate change does not reflect respondents' belief that climate change will affect snowpack. Over 70% of respondents understood that projected climate change would affect snowpack in the Northwestern United States.

Analysis of Maps and Graphs
Respondents were asked a series of questions that required interaction with SnowDash. Based on the results from the map analysis questions (11 -16), respondents demonstrated the ability to infer correct answers from SnowDash that contain complex patterns of data such as SWE distribution and quantity. Respondents were also able to compare patterns that exist across reference years very effectively and showed a high ability for recognition of spatial patterns and correlations with an accuracy of over 75%. The survey requested that participants compare snowpack in two projected climate scenarios, however participants examined on average 2.5 snowpack scenarios per respondent. These statistics portray an audience that has advanced skills and can interpret complex information and data using web-based tools. The results were proportionally similar across age groups and gender. When asked to compare the impacts of projected climate across

years using the interactive chart, respondents had a similar level of comprehension compared to the map and most respondents chose the correct answer.

So what was more useful to participants, a map or a graph? 43% of respondents stated that both were equally as useful, while 38% found more value in the map. There were no distinct differences with regard to gender or age regarding which format was perceived as more valuable (Figure 4.4). Overall participants found SnowDash to be useful with an average rating of 5.7 out of 10 (Figure 4.5). Participants aged 35 and under found SnowDash to be more useful (6.6 rating) as compared to respondents over age 35. Despite the average rating of 5.7, participants found merit in SnowDash and a web-based DST with over 75% of respondents answering positively that they would like to have a similar website for their work.

Qualitative Comments from Participants

Respondents were given an opportunity to provide their input, which provided insight into why the average rating of 5.7 was not higher. One common response (5 responses) was the map and graphs were too small for analysis in the survey. Another participant noted that it was challenging to use both the survey and SnowDash using the same monitor. This statement represents one of the technical challenges in designing the survey and SnowDash – making each one big enough on a monitor to be functional, but not dominate the screen. Another recurring topic was technological limitations (4 responses). In order to serve web-based maps and an interactive chart, SnowDash implemented several open-source web technologies (as discussed in the Methods section). Because some government organizations block various technological components employed in SnowDash, some participants did not have full functionality of the DST. For instance the dynamic graph did not load for users that only had Internet Explorer 7.x as a web browser. Participants noted this as a source of frustration (4 responses).

Another common comment from participants was that the survey needed more background in terms of the research methodology and terminology and simpler phrasing of the questions. Contrary to this emphasis on more information were comments that the survey was too long and needed to be more condensed. These comments are important as SnowDash is intended to be a tool for a wide user base and highlight the fact that attention to making information accessible to the user base is key to having a successful DST. However, they also show that designing a tool and assessment that meets all participants' needs is exceedingly difficult.

User Interaction with SnowDash

Participants' interaction with SnowDash was passively recorded for all participants. SnowDash had 118 unique users over 10 days from the time of the initial request, corresponding well to the 115 surveys that were initiated. All of the figures and statistics in the remainder of this section will reflect the combined movement of all 118 participants. The web interface programming of SnowDash required interactions with charts to be recorded separately from the mapped portion. Results from the map area will be introduced first.

User interaction was analyzed for the order of progression of mouse movement while initiating use of SnowDash. Using mouse movement as a proxy for eye movement (Chen et al., 2001), the order of progression indicates how users visually ordered their interactions with SnowDash. The participants followed a cross scanning progression, first looking at the title then the map before looking at the data layers and interactive features. In the final measured step, the user went back to the map (Figure 4.6). The movements by users of SnowDash are remarkably similar to similar studies in the 1980s that tracked eye movement on paper maps (Antes et al., 1985; Steinke, 1987). The mouse movements show that users' first survey the available information across the entire screen, interpret data available, and then engage with the interface of the SnowDash.

Mouse movements also highlighted which features of the map were used most frequently. While the survey guided participants through SnowDash, the user was encouraged to explore the interface and interact with map layers. Figure 4.7 divides the map portion of the screen into eight regions on the map and four regions that make up the menu layers and legend. The most common interaction with SnowDash was the use of the menu to add map layers. This feature had over 20% of the user interaction (Region 11). The four central regions that occupy the center of the map (2, 3, 6, 7) engaged users for 27% of overall interaction with the map. While users interaction is notable, it is also notable what users did not use. The drop down menu for the graph had only 6% of user interaction. This number is significantly lower than the same feature for the map. It should be noted that there were three options for the graph menu and nine options for the map menu. The 3:1 ratio of options is similar to the 20:6 ratio of user interaction. The zoom tool (Region 1) had 7% of user interaction while the map background feature (Region 4) had minimal use with less than 1% of total user interaction. Adding or removing the context layers (Region 2) of contour lines and graph locations had less than 4% of the user interaction. Based on the comments of the respondents, the zoom tool was not easy to find in the interface. Several respondents stated that the ability to examine the map more closely would have enhanced their interaction. To summarize participant interaction with the map section, the menu to add layers of SWE was the most commonly used region of the map. The combined area of the center of the map also had considerable engagement by users. The other features had minimal use by users.

Before presenting the results of the graphs, it is important to note that many users were not able to see or interact with the graphs due to technical limitations. Because of this, *quantifiable numbers were not reliable*, and values will be given only in percentages. User interaction on the graphs was consistent across all three elevations. The users' interaction focused on the body of the graph Figure 4.9.

Surprisingly there was more interaction with the timeline on the x-axis than with SWE values on the y-axis. An interactive display of SWE values and dates were displayed in the upper portion of the graph. Approximately 20% of the users interaction focused on the interactive date range at the bottom of the graph. It is of note that several comments in the survey requested that some sort of date range be available.

4.4.2   Focus Groups

Participants noted that collaboration between the research and practitioner communities is very important, and that improved communication would be beneficial to their job functions. Tables 4.6 and 4.7 summarize suggestions on how to improve communications, and the central points of discussion from the focus groups are presented below.

All participants agreed they would welcome DSTs that provide access to the results of scientific research. Some of the more frequently identified features that DSTs should include are interactive mapping, access to the underlying data, and the ability to chart data. The desired level of access to data corresponded to the technical level of participants' job functions. For instance engineers would want access to the raw data and the underlying science behind the research. By contrast the people working in education or policy need access to graphics and information that explains the research in lay terms. DSTs were also recognized as a desirable means of knowledge transfer within and across organizations. While participants noted the benefits of knowledge transfer, they agreed that few tools exist to facilitate the process. All participants would welcome access to tools that aid in knowledge transfer both in terms of content and data.

Practitioners noted the value of communication with the research community, which helps direct their attention to the most relevant studies. While participants valued peer–reviewed academic articles, they described journal articles as too often written for an academic audience and too dense for practical use. The articles are primarily used as a tool to reference research that has been conducted on a specific topic or location. Additionally peer-reviewed literature is often restrictive to practitioners, as many have limited access to journal publications that causes potentially relevant research to go unknown. All participants in both groups agreed that a short summary paper (1-2 page) would improve their ability to identify relevant research. This format would be especially effective for unpublished, yet relevant research about a particular place or topic (ex. Master's Thesis). Participants described a paper resembling an executive summary, which contains key figures and maps, and provides information on how to gain more details.

Participants also noted that access to data created by the research community is limited. The main obstacle to implementing research data into applications is simply not knowing what data exists. To quote one participant, "If the research community provides data, I can use it. But if it doesn't exist, I can't." This response elicited approval from the other members of the focus group. Both focus groups also commented that providing access to the data improves the value of the research. A searchable catalog that provides a simple description of what research data is available and contact information was identified as a valuable first step towards improving data dissemination. Ideally data would be available for download through the catalog, and would contain metadata, tabular and spatial data, and be organized spatially and in an indexed listing. Participants also agreed that improved access to relevant graphs, charts, and maps from academic research would better enable them to incorporate this data into their daily work functions. Material on the Internet has helped to bridge this access gap, but often graphic data is only available in journal

publications. The complexity of the research findings, data, and graphics requested by practitioners varied by the technical level of a participant's job function. For instance, the engineer explained that evaluating hydrologic structures requires in-depth statistical analysis such as recurrence intervals and associated streamflow, while the policy coordinator uses a more qualitative approach that is better understood by a lay audience.

Participants identified a need for the research community to include possible research implications of their results into scientific papers and reports. The inclusion of differential effects allows the practitioner to connect the research to relevant applications, especially when provided within a regional context. It was stated that the geographic context of water resource research is essential to incorporating findings into daily operations. One participant identified the maximum scale for effective place-based research was noted as a 6th-field Hydrologic Unit Code (ex. the Willamette River Basin in Oregon).

4.5   Discussion

This research combined two methodologies to address one goal — improving the transfer of knowledge between the water resources research and practitioner communities through the development and assessment of a web-based DST, SnowDash. This goal is timely as water resource practitioners begin to design and implement climate change strategies (National Research Council, 2005, 2006, 2009). This project worked with practitioners, the end users, and incorporated their needs into the development SnowDash. Further insights were gained through the assessment of user interaction with the product. The results suggest methods to improve the effectiveness of web-based DSTs to disseminate water resources research. While DSTs provide new opportunities for knowledge-to-action networks,

they will not replace peer-reviewed research and professional relationships. But rather supplement them and potentially open new collaborative research opportunities.

A web-based interactive DST like SnowDash that has mapping and graphing capabilities provides a complimentary framework for many new emerging technologies and requirements by funding agencies. For instance, open-access journals disseminate peer-reviewed research over the Internet at no or minimal cost, have a shorter publication time, and to link to research findings and data provided in a DST. This combination increases access to findings and data while reducing publication time and costs—the primary obstacles described in the focus groups that limit practitioners' ability to incorporate new research and data into their work. Smaller organizations with limited fiscal resources would especially benefit from this improved dissemination of research information. These organizations are unable to fund research staff, but are tasked with making management decisions that could be improved with insight from research at the regional scale. Research requires a financial investment. The value of this investment increases if it can be applied in practice.

Additionally, DSTs are no longer restricted to a desktop computer, allowing mobile and cloud computing technologies to provide data sources for mobile DSTs that implement spatio-temporal information (need citation). This trend is already being implemented in the health care professions (need citation). Demographics will also play a role in the increase of DSTs, as the workforce will increasingly reflects practitioners whose education and personal lives incorporate the Internet and mobile technologies. While the sample size was limited, Figure 4. 5 reflected this trend.

Web-based DSTs integrate well with new National Science Foundation policies that require funded research to provide a data management plan in all proposals (National Science Foundation, 2012). The framework provided by a web-based DSTs helps manage and improve access to research data. A well-designed framework would be scalable, allowing complimentary research in the future to be incorporated into a single data management plan. This is turn would in turn minimize the time invested in creating a unique plan for each project. It is of note that the water resource community is increasingly addressing the demand for data storage and retrieval. For example, the Hydrologic Information System (HIS) developed by Consortium of Universities for the Advancement of Hydrologic Science, Inc. (CUAHSI) provides a common format for the storage and retrieval of water resource data (Consortium of Universities for the Advancement of Hydrologic Science Inc, 2011).

4.6 Conclusions

Developing an end-to-end knowledge system in water resources helps transform research into practical applications. The goals of this research were to examine and evaluate the perspectives of water resource practitioners on how this end-to-end system can be improved.

With regard to SnowDash:

1) The mapping features of SnowDash were the most popular feature, however users requested more interactive features associated with the maps.

2) While DSTs are intended to leverage technology there are distinct technological limitations, especially in government agencies with access to a single version of Internet software.

3) Practitioners aged 35 and under found SnowDash to be of greater value than the other age groups. This simple statistic is important this as this age demographic begins to be a larger part of the water resource community.

From focus groups:

4) Practitioners welcome researchers' insights when developing practical applications, but felt that the dissemination of research findings through peer-reviewed journal articles is not highly effective. Shorter more regionally focused summary papers were identified as more effective for providing key research findings.

5) Practitioners will apply relevant research finding to practical applications. The lack of a list of available data or a data archive limits access from a practical perspective.

While most research provides recommendations for future work, the nature of this research supplies recommendations for implementation. The version of SnowDash that was used in this research is considered a prototype. Further improvements will be made to SnowDash based on insights from the focus groups, survey results, and survey comments. An improved version of SnowDash will be developed that includes download access to the underlying SWE data used in the maps. Additionally an active role will be assumed at the organizational level with regards to connecting researcher and practitioner.

Climate change presents distinct challenges and questions to water resource managers and practitioners to which there may be not clear answers (National Research Council, 2009). Improving the knowledge-to-action network that exists between researchers and practitioners will improve the ability to make better-informed decisions. Raven (2002) and the National Research Council (2009) called on the scientific community to create a more accessible and integrated approach to knowledge transfer. This research worked with practitioners throughout the project to help improve the knowledge-to-action network that exists between researchers and practitioners. While the findings from this project can help with the

dissemination of research, it is ultimately up to the individual members of the collective water resources community to develop the interpersonal and technological infrastructure to make a knowledge-to-action network fully realized.

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4.8 Figures
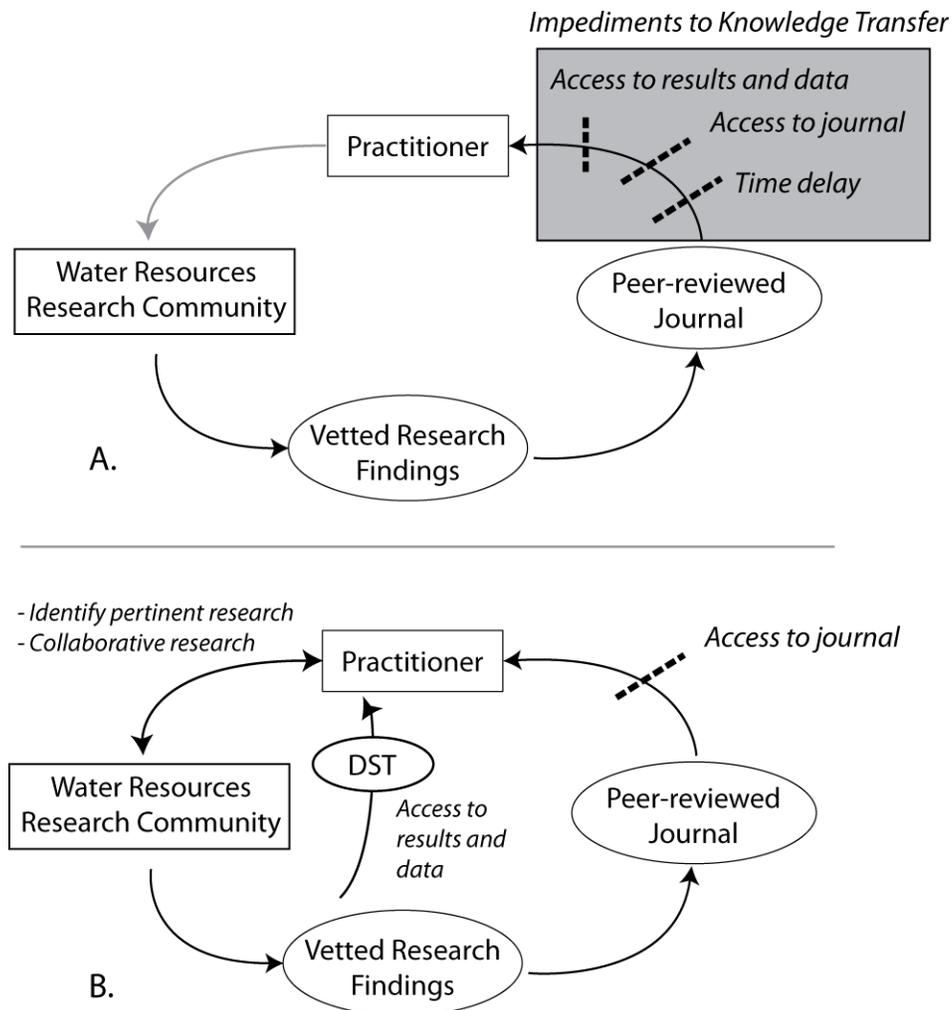
Figure 4.1 A: The process of transferring research knowledge to practitioners through a traditional peer review approach. Figure 4.1B The development of a DST streamlines the knowledge to action process, eliminating many of the impediments created by using only peer-reviewed journals.
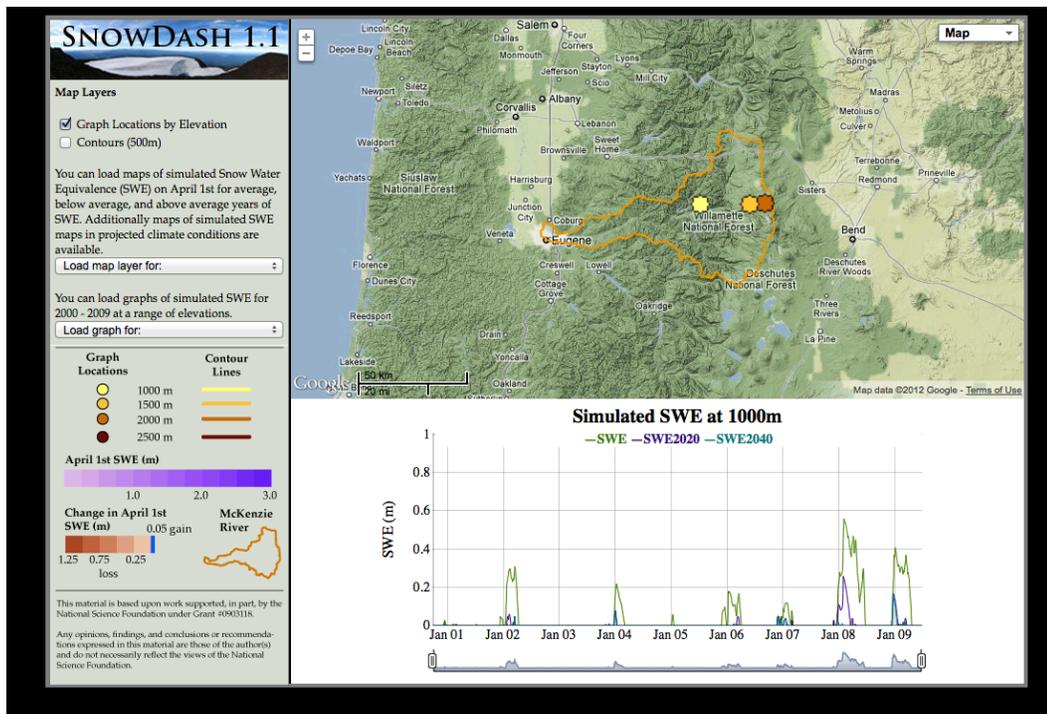
Figure 4.2: The interface of SnowDash.
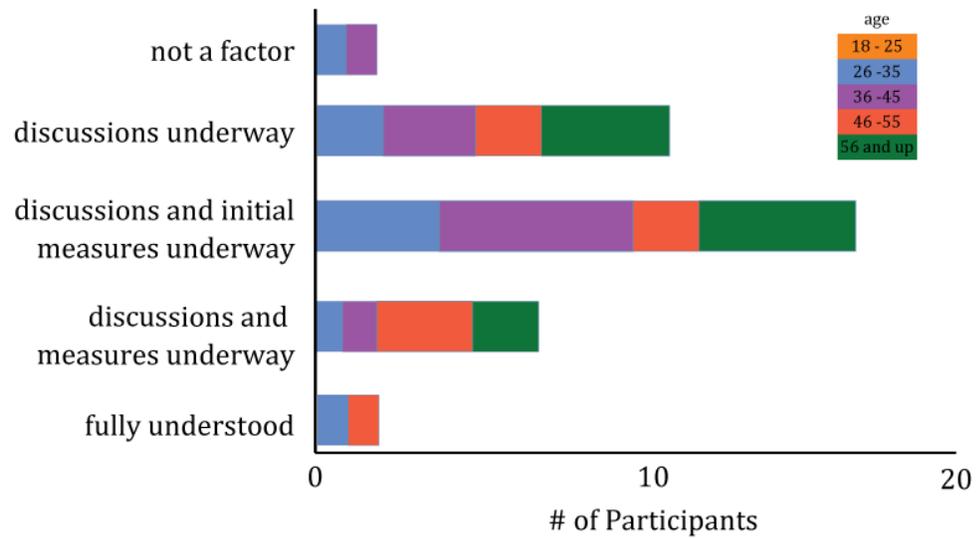
Figure 4.3: Discussions of climate change impacts on water availability are in the early phases for most participants' work place.
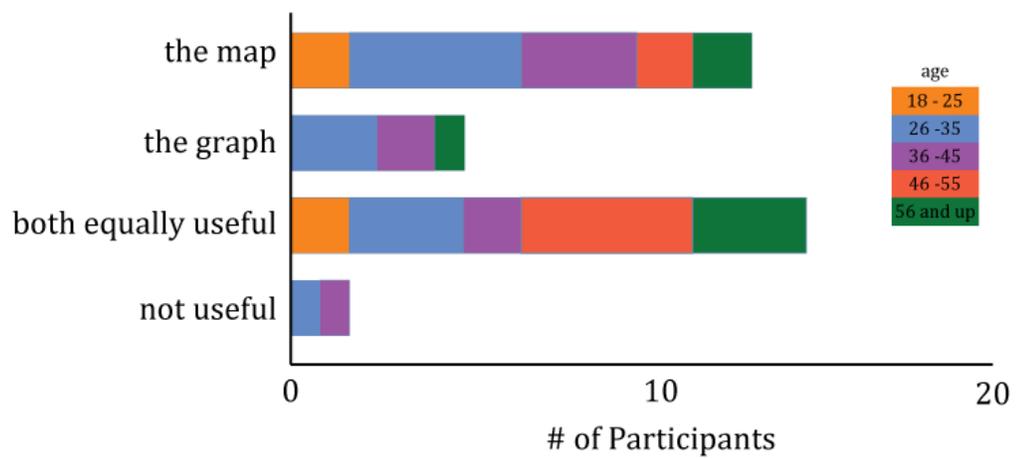
Figure 4.4: Participant rating of the usefulness of the map and graph.
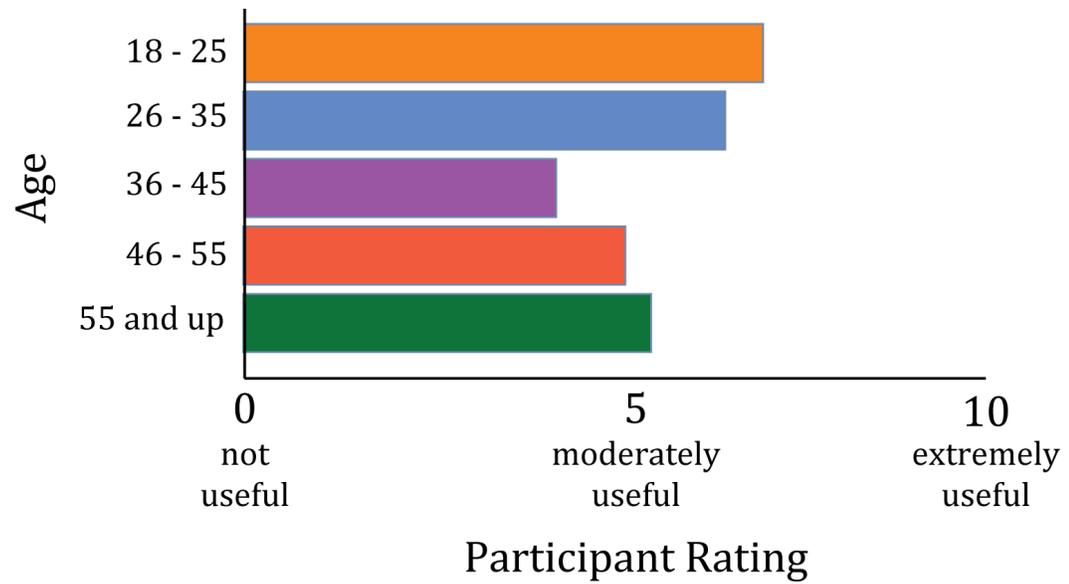
Figure 4.5: Participant rating of the usefulness of SnowDash. The mean score for the usefulness of SnowDash was 5.7; however mean score for 35 and under was 6.6.
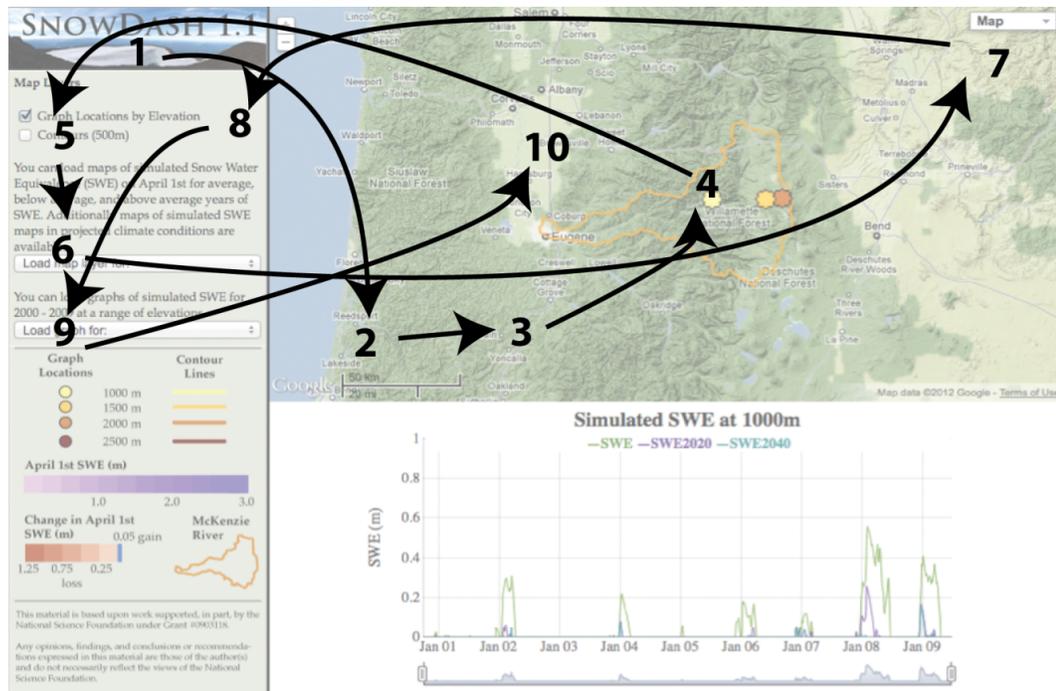
Figure 4.6: The movement of the mouse was analyzed to show the visual sequence of users. Users started in the upper left corner at the title, and moved through the interface. This order is a composite of the 118 users.
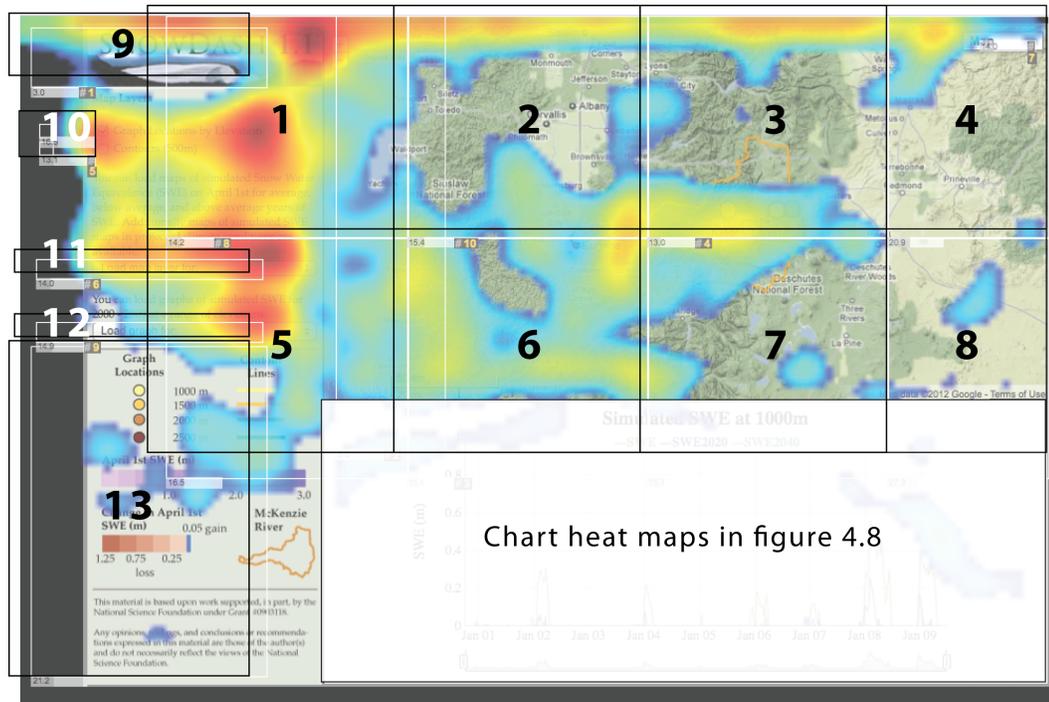
Figure 4.7: User interaction with the SnowDash map. The darker colors show more interaction. You see that users were much more likely to use the map layers in areas 1 and 5 than the map. This shows that the data was a priority. This is a composite of the 118 users.
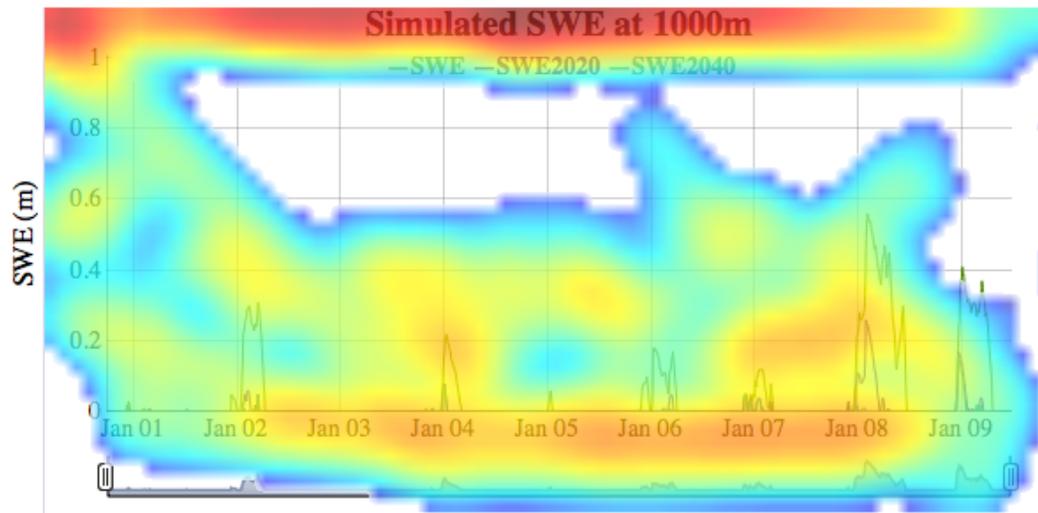
Figure 4.8: User interaction with the SnowDash chart. The darker colors show more interaction with the chart. The dark colored band at the top is due to its proximity to the map, which can capture map users and graph users. Movements. This is a composite of the 118 users.

4.9   Tables

Table 4.1: The SWE datasets available in SnowDash. An A1B climate projection represents a global approach to energy that balances fossil-based fuels and renewable energy sources and is a conservative estimation of greenhouse gas emissions (Randall et al., 2007). For more information on how the data were downscaled please refer to (Salathé et al., 2010).

| Data	Type	Description
Average Year (SWE)	Map Layer	Simulated SWE for 2007
Below Average (SWE)	Map Layer	Simulated SWE for 2001
Above Average (SWE)	Map Layer	Simulated SWE for 2008
2020s Average (SWE)	Map Layer	Projected change in SWE for 2007 2020A1B climate projection applied
2020s Below Average (SWE)	Map Layer	Projected change in SWE for 2001 2020A1B climate projection applied
2020s Above Average (SWE)	Map Layer	Projected change in SWE for 2008 2020A1B climate projection applied
2040s Average (SWE)	Map Layer	Projected change in SWE for 2007 2020A1B climate projection applied
2040s Below Average (SWE)	Map Layer	Projected change in SWE for 2001 2020A1B climate projection applied
2040s Above Average (SWE)	Map Layer	Projected change in SWE for 2008 2020A1B climate projection applied
SWE at 1000m	Graph	Simulated SWE at 1000 m extracted at a single location for 2007 and 2007 with the 2020A1B and 2040A1B climate projections applied
SWE at 1500m	Graph	Simulated SWE at 1500 m extracted at a single location for 2007 and 2007 with the 2020A1B and 2040A1B climate projections applied
SWE at 2000m	Graph	Simulated SWE at 2000 m extracted at a single location for 2007 and 2007 with the 2020A1B and 2040A1B climate projections applied

Table 4.2: Description of focus group participants' employment.

Participant's Job Title	Type of organization	Meeting Venue
Stream restoration ecologist	Nonprofit	Eugene
Environmental scientist	Public utility	Eugene
Hydropower engineer	Public utility	Eugene
Freshwater scientist	Federal agency	Eugene
Water conservation technician	Independent	Eugene
Geomorphologist	Watershed council	Eugene
Fisheries biologist	Federal agency	Portland
Outreach and education coordinator	Public utility	Portland
Global water analyst	Private engineering firm	Portland
Water policy analyst	State agency	Phone interview

Table 4.3: Age of respondents and % of respondents that completed the survey.

Age Range	Initial Respondents	Completed Respondents	Completion Rate
18-25	5	4	80%
26-35	29	15	52%
36-45	26	11	42%
46-55	28	8	29%
56 and up	21	13	62%

Table 4.4: Educational level of participants

Education level	% of Respondents
High School	0
Undergraduate	4
20	6
Master's or professional degree	66
PhD	10

Table 4.5: Frequency of how often participants use water resource data.

Frequency	% of Respondents
Daily	48
Weekly	24
Monthly	6
A few times a year	7
Once a year	0
Not often	2

Table 4.6: Suggestions from focus groups on how to improve access and usability of research data by practitioners.

Means to improve access to data from academic research
- searchable data catalog
- downloadable
- organized geographically
- tabular and geographic data
- meta data
- pertinent graphs, charts and figures

Table 4.7: Suggestions from focus groups on how to improve the integration of the research practitioner communities.

- improved communication between groups (informal)
- work with practitioner to identify pertinent research questions
- improved access to data
- regional context of research
- not rely solely on peer reviewed literature for the dissemination of research
- development of summary papers that describe research (especially for unpublished research)

4.10 Appendices

Appendix A: Questions used in the focus group sessions

Role	Time	Question
Introduction to project	5	(Goal) Introductions of myself and notetaker, reading of the project (per IRB), and introduction of the continuum of information to knowledge.
Questions to ask the group		
Introduction	10	You have been selected because you make decisions based on water resources. Please tell us your name and organization. Also, describe what kind of decisions you make in your position.
Background	5	Do those decisions ever involve statistics? If so to what level?
Transition	10	Describe the types of information that have helped you the most in your decision-making?
Key	15	There are many ways to get scientific information. How do you like to get that information?
Key	15	Think back to a time when you encountered a gap between scientific information and applicable knowledge. What would you need to avoid this problem in the future?

Key	15	How is knowledge transferred within your organization? Are their tools in place to aid with the transfer?
Key	15	If you were in charge of designing a decision support tool, what would it include?
Ending	10	Is there anything that we should have talked about, but did not?

Appendix B: Introduction and questions used in the online assessment of Snowdash

This is to inform you that you are participating in a project funded by the National Science Foundation and administered by faculty and students at Oregon State University. The focus of the project is to better understand how to connect scientific research to students and practitioners. As part of the project, we would like you to participate in an accompanying survey. The results from the assessment will be use to understand how these technologies help connect the research, student, and professional communities. The survey is not long, and accompanies a hydrologic "dashboard" focusing on snow water resources.

Any personal or identifying information from will be removed and will not be included in reports or publications. This site uses ClickTale web analytics service and may record mouse clicks, mouse movements, and scrolling activity **on this website only**. We are using the information collected to better connect research to students and practitioners. We do not collect any personally identifiable information. You can choose to disable the Service at http://www.clicktale.net/disable.html. ClickTale does not track your browsing habits across web sites which do not use ClickTale services. For more information see Privacy Policy for Information Collected by the ClickTale Web Analytics Service (http://www.clicktale.com/privacy_service.aspx).

Participation in the survey is voluntary. Thank you for your time and effort.

Respectfully,
Dr. Anne Nolin, Principal Investigator
Eric A. Sproles, Co-Principal Investigator

The goal of this website, SnowDash, is to improve the communication of scientific research results to students and practitioners. The maps and data that are incorporated in this web-based tool represent simulated results of Snow Water Equivalence (SWE). SWE represents the amount of water represented by the snowpack. These are validated model results for the McKenzie River Basin, located on the western slope of the Oregon Cascades.

Please answer the following questions before going to the map.

1. What is your age?
    a. 18-25
    b. 25-35
    c. 35-45
    d. 45-55
    e. 55-65
    f. 65+

2. What of the following best represents your highest educational level?
    a. Presently an undergraduate
    b. Bachelor's degree
    c. Master's or professional degree
    d. Ph.D.

3. Gender?
    a. Female
    b. Male

4. How often do you use water resource data for school or work?
    a. Daily
    b. Weekly
    c. Monthly
    d. A few times a year
    e. Once a year
    f. Not often

5. Do you use water resource data for school or professionally?
   a. School
   b. Professionally

Here the users will be led to additional questions that branch into another two

questions depending on their previous answer:

Student:

6. Do you plan to use your apply your education to a job in the water resources field?

7. On a scale of 1-10, with 10 representing full knowledge, rate your understanding of where your drinking water comes from?

Natural Resource Professional:

6. Which statement best describes the topic of climate impacts on water variability at your work?
   a. Climate change is not really a factor at our work.
   b. Discussions about the impacts of climate variability on water supply.
   c. Discussions and initial measures to better understand the impacts of climate variability are under way.
   d. Discussions and measures to better understand climate variability have been implemented.
   e. Investigations on the impacts of climate are fully understood.

7. In your area, approximately how much of your source water originates from snow?
   a. None
   b. 11-20%
   c. 21-40%
   d. 41-60%
   e. 61-80%
   f. 81-100%

Please answer the following questions:

8. Select the answer that best describes your understanding of projected climate on snowpack in the Northwestern United States:
   a. I am not familiar with the impacts of projected climate on snowpack in this region.
   b. There will be little to no change in snowpack.
   c. Changes in snowpack will vary from winter to winter and across watersheds.
   d. Changes in snowpack will be consistent across watersheds.
   e. Changes in snowpack will be consistent from winter to winter.
   f. Changes in snowpack will have a greater relative effect on snowpack at higher elevations.

http://tinyurl.com/snowdash

The map shows the McKenzie River Watershed, outlined in orange. The available layers are listed on the left of the map, and a corresponding legend is just below the list of layers.

April 1st is assumed to be the approximate date for peak SWE in the mountains of the western US. All of the map layers show simulated snow on April 1st.

Load any of the years of simulated SWE for 2009 using the Drop down menu labeled "LOAD MAP LAYERS".

9. Over what elevations are the greatest amounts of SWE located?
    a.   The same at all elevations
    b.   Lower elevations
    c.   Middle elevations
    d.   Upper elevations
    e.   Not sure

Load at least one other year and examine how SWE is distributed across the map.

10. What year(s) did you examine?
    Check boxes with the years that were available (2001 – 2009).

11. How does this (do these) year(s) compare with the first year that you examined?
    a.   There is little or no change in the spatial pattern of SWE.
    b.   There is little or no change in the maximum depth of SWE.
    c.   There is little or no change in both the spatial pattern and maximum depth of SWE.
    d.   The spatial pattern of SWE is different.
    e.   The maximum depth of SWE is different.
    f.   The spatial pattern and maximum depth of SWE are both different.
    g.   I cannot really tell from the map.

This website also provides map layers of snowpack simulations for a projected future climate scenario and the associated loss of SWE (link to information about climate simulations).

Using the same drop-down box, select "SWE Loss for Average Year 2020s"

12. Where is the greatest most amount of SWE lost?
   a. There will be little to no change in the amount of SWE
   b. Lower elevations
   c. Middle elevations
   d. Upper elevations
   e. Cannot really tell from this map

Load one of the following maps layers:
- SWE Loss for Below Average Year 2020s
- SWE Loss for Above Average Year 2020s
- SWE Loss for Average Year 2040s
-
13. How does this year(s) compare with the first year that you looked at?
   a. There will be little to no change in snowpack.
   b. The same with regards to pattern of SWE Loss.
   c. The same with regards to depth of SWE Loss.
   d. Same with regards to pattern and depth of SWE Loss.
   e. Different with regards to pattern of SWE Loss.
   f. Different with regards to depth of SWE Loss.
   g. Different with regards to pattern and depth of SWE Loss.
   h. Cannot really tell from this map.

Examine other map layers if you like.

14. What SWE Loss maps did you examine?
    a. SWE Loss for Average Year 2020s
    b. SWE Loss for Below Average Year 2020s
    c. SWE Loss for Above Average Year 2020s
    d. SWE Loss for Average Year 2040s
    e. SWE Loss for Below Average Year 2040s
    f. SWE Loss for Above Average Year 2040s

There is also a chart at the bottom of the page that allows you to examine the projected impacts of climate change on snowpack in the McKenzie.

You can adjust the slider bar at the bottom to adjust the time frame that is visible.

15. Comparing years, what observations can you make regarding the projected climate change impacts on snowpack?
    a. There will be little to no change in snowpack.
    b. Projected climate will impact all years the same.
    c. Projected climate will impact years with smaller snowpacks more than years with larger snowpacks.
    d. Projected climate will impact years with larger snowpacks more than years with larger snowpacks.
    e. Cannot really tell from this graph.

16. Using the graph, which year's snowpack was most significantly impacted by projected climate?
    • Drop down list

You can also load a graph for individual stations throughout the McKenzie Basin. Compare the difference between points A, B, and C (low, middle, and upper elevations).

17. Comparing elevations and years, which of the following statements are true? You may select as many as you like.
    a. There will be little to no change in snowpack.
    b. Projected climate will impact all elevations in the same way.
    c. Projected climate will impact all years in the same way.
    d. Projected climate will impact elevations differently.
    e. Projected climate will impact years in the same way.
    f. The date that all snow has melted away does not vary with elevation.
    g. Cannot really tell from the graphs.
    h. None of the above.

18. Select the answer that best describes your understanding of projected climate change on snowpack in the Northwestern United States:
    a. There will be little to no change in snowpack.
    b. Changes in snowpack will vary proportionally from winter to winter and across watersheds.
    c. Changes in snowpack will be proportionally consistent across watersheds.
    d. Changes in snowpack will be proportionally consistent from winter to winter.
    e. Changes in snowpack will have a greater relative effect on snowpack at lower elevations.
    f. Changes in snowpack will have a greater relative effect on snowpack at higher elevations.

19. What feature of this website did you find most useful?
    a. The map.
    b. The graph.
    c. Both were equally useful.
    d. It was not useful.

20. On a scale of 1-10, with 10 being most useful, would you rate the ability of this website to convey the results of research?

21. What features would you like to see added in the future?

22. Please provide any other general comments below:

For professionals:

23. Would you be able to use a similar website in your work (not necessarily pertaining to snow)?
    a. Yes
    b. No

If you would like access to the data used to generate these map layers and graphs, please contact Eric Sproles @ sprolese@geo.oregonstate.edu.

Thank you for your time in participating in this survey. Your contributions are greatly appreciated.

5   Future Research Directions, Management Implications, and Conclusions

5.1　Conclusions

This dissertation presents a knowledge-to-action approach to water resources science research that includes snow surveys, distributed and probabilistic modeling of watershed-scale snowpack, and the development and assessment of a snowpack decision support tool. Each of the preceding chapters applies a combination of methods and tools to improve our understanding of snowpack in the McKenzie River Basin (MRB) and how projected climate change will affect this resource.

Chapter 2 provided a detailed understanding of snowpack in the MRB for present-day and future climate scenarios. A spatially distributed, process-based model was modified to reflect the climate conditions of the maritime Oregon Cascades mountain range. Model calibration focused first on achieving optimal accuracy for distributed precipitation and temperature, both of which are first order controls on snowpack. Calibration then focused on optimal simulations of SWE. This order of operations establishes baseline accuracy for model forcing variables before focusing on SWE simulations. This approach also provides confidence in model predictive skill so that simulations of SWE are accurate for the right reasons (Kirchner, 2006). Therefore, the datasets generated in this dissertation are robust and provide the opportunity to be incorporated into further analysis .

The sensitivity analysis identified temperature as the primary control on snowpack in the MRB. While precipitation does influence accumulation of SWE, it is relatively minor in comparison to temperature. This is not surprising as the upper reaches of the basin can receive up to 3500 mm of precipitation annually. Supply is not an issue. Snowpack in the middle elevations (1000 -1800 m) was the most sensitive with a 2°C increase applied to daily temperature inputs. Basin wide, the peak volumetric

storage of SWE was reduced an average of 56% and occurred 12 days earlier. The
effects of the A1B and B1 emissions scenarios applied to meteorological inputs began
to distinguish themselves in the 2040 perturbations. Simulations of SWE with the
2080 perturbations showed significant differences between the A1B and B1
emissions scenarios, however both showed significant losses of volumetric SWE. The
results of Chapter 2 are not intended to serve as a deterministic indicator of what
snowpack in the MRB will look like in the future. Rather, they are intended to
provide a way to understand watershed-scale trends of snowpack in present
conditions and how these trends may shift in the future.

Chapter 3 developed a fresh approach to understanding the impacts of projected
climate change on snowpack in mountain watersheds. A probabilistic approach to
the timing and spatial distribution of snowpack at the watershed scale was
developed. These results account for the range of statistical outcomes found over the
reference period. A 2°C increase in temperature inputs describe a change in
statistical outcomes, with the present rain/snow patterns shifting 260 m up in
elevation.

Shifts in the timing of water available for runoff (WAR) in two sub-basins of the
McKenzie River due to a 2°C increase were assessed probabilistically. WAR in the
lower elevation basin that is more heavily influenced by rain, shows a small
sensitivity to increased temperature. However in the sub-basin that is more reliant
on snowmelt, the timing WAR shifts approximately 10 days earlier. This shift shows
increases of WAR during the winter months and decreases during the spring and
early summer.

Chapter 4 addressed the growing need for decision makers, both in public and
private arenas, to incorporate climate change impacts into near and long term

planning for water resources by connecting practitioners to research data. This final component of the dissertation provided suggestions and a decision support tool (DST) for accomplishing this goal. The DST, SnowDash, was developed to provide access to the data from Chapter 1. The development of SnowDash included the insight of practitioners throughout the process. During the initial stages of the research, focus groups helped identify components of a DST that would be of most use to practitioners. Qualitative assessment of SnowDash by practitioners provided a better understanding of how user's interacted with the tool.

A secondary goal of the focus groups was on the topic of improved communications between the research and practitioner communities. Focus group participants commented that the present model of dissemination through peer-reviewed journals is inefficient for their needs. Both groups noted that research data is often underutilized because practitioners are unaware of its existence or unsure of how to gain access to the data. However, both groups stated that if ready access to research data were provided, the practitioner community would apply the data into their work.

While this phase of dissertation research is complete, it provides a catalyst for future research efforts. Chapter 2 provided robust results for precipitation, temperature and SWE. The spatial interpolation of temperature could be improved through a sub-model that calculates lapse rates on a time step basis rather than relying on prescribed monthly values. This would address the problems with associated lapse rate variability with regards to moisture content of a storm and also cold air drainage. The model outputs from Chapter 2 provide an excellent data set for further analysis or as inputs for other hydrologic models. These models could incorporate the probabilistic results from Chapter 3 to provide statistical thresholds for streamflow in project climatic conditions.

These data could be also used to analyze how warmer winter temperatures might affect the human, economic, and ecologic resources associated with mountain snowpack. For instance, results of the streamflow model would reflect shifts in timing and magnitude of discharge due to projected climate. Natural resource economists could use these results to develop pricing schemes that reflect the new supply model. Wildlife researchers could use these data to explore migration patterns of elk species, which are strongly influenced by the spatio-temporal distribution of snow.

This dissertation provides tangible results that represent a significant advance in the understanding of snowpack in the MRB and in the region. Working with the water resource practitioner community throughout the process helped to develop research questions and answers that can be readily adapted into management strategies. Results have already helped water resource professionals identify a site for a new SNOTEL station and develop strategies for municipal water use. Methods of improved dissemination identified in this research will be employed to improve access to the results in the future.

The research presented in this dissertation links relevant research findings to the decision maker through a knowledge-to-action framework. This research model addresses the need for water resources research to be more proactively shared with practitioners. Making improvements to this dissemination model and applying it in practice will only increase the value of water resources research and also provide relevant, timely information for climate change adaptation strategies.

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