Mt. Baker Snoqualmie National Forest
Sustainable Roads System Strategy – Climate Change Analysis

By Ronda Strauch

Summary

Mt. Baker Snoqualmie National Forest is developing a Sustainable Roads Strategy (SRS) to ensure a long-term road network that is commensurate with funding and resource limitations. Information on changing climate is provided in this analysis to inform the planning process and to support the comprehensive longevity of the strategy. The primary pathways for climate impacts are from projected increases in extreme high flows and flooding, elevated winter and spring soil moisture and landslide risk, and increased access afforded by a longer snow-free season. Incorporation of an adaptive management system in a strategy to respond to climate change can allow decisions regarding maintenance and closures to evolve in step with changes in hydrology.


Highway 2 crossing South Fork Skykomish River

1. Introduction

The purpose of this work is to support the Sustainable Roads Strategy (SRS) being developed by Mt. Baker Snoqualmie National Forest (MBSNF) in compliance with the Travel Management Act of 2005. The process to develop the strategy began in spring 2013 and is expected to finish in December 2014. Although the process has actively engaged the public and considered several social, ecological, and economic resources and interests, the process is missing integration of climate change in its strategic development. Consequently, Conservation Northwest and The Brainerd Foundation through the Cascadia Partner Forum provided support to supply climate change information in a partner-developed climate analysis to supplement the strategy and future site-specific analyses. Formed by practitioners in Washington and British Columbia's Cascade mountains in the summer of 2012, the Cascadia Partner Forum fosters a network of natural resource practitioners working with the Great Northern and North Pacific Landscape Conservation Cooperatives to build the adaptive capacity of the landscape and species living within it. The MBSNF lies entirely within Cascadia, and access management was identified by the partner forum as a priority topic to address in climate adaptation planning.

Projected changes in climate were assessed to characterize the changes road managers and users might experience and to identify where and when roads may be affected by changing climate. Analyses focus on increases in stream flows that can damage infrastructure, enhancement of soil moisture as a proxy for reduced slope stability and landslides, and earlier snowmelt that may allow access earlier in the spring and summer than in the past. This report covers only roads, although a large number of trails also provide access throughout MBSNF. While only roads within MBSNF are included in this assessment, it is recognized that roads leading to MBSNF influence access to the forest and may be influenced by changing climate as well as by the management of other jurisdictions. Additional analysis has been performed in other studies that cover a broader geographical area that includes this study area and provides more information on climate change and access to federal lands (Strauch et al. 2014a,b).

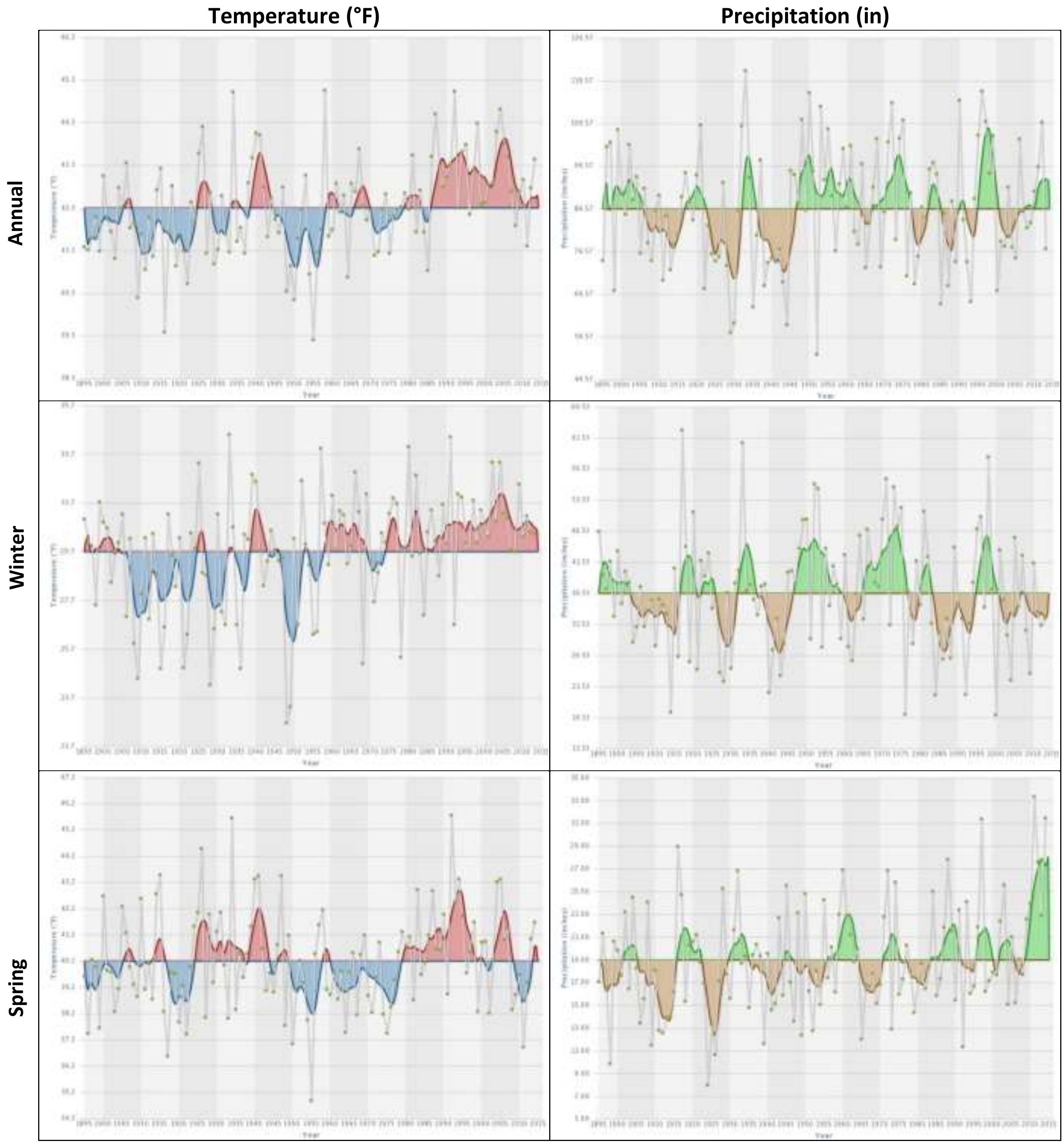
2. Climate Change Background

The state of knowledge about observed and projected changes in climate are provided in a summary prepared for Washington State by Climate Impacts Group (Snover et al. 2013), which is the bases for the information provided in this report unless otherwise noted. Observed changes in climate since the 1950s include long-term warming, lengthened frost-free season, resulting in declined glacial area and spring snowpack, and earlier peak streamflow (Table 1). These changes mirror global changes, but natural climate variability can mask or even reverse regional or local trends. Heavy downpours are increasing in most regions of the U.S. However, trends for the Pacific Northwest (PNW) are ambiguous with study findings dependent on dates and methods used in analyses. Observed annual and seasonal temperature and precipitation along the west slopes of the Cascade Mountains are shown in Figure 1. Records indicate yearly and multi-year variability in temperatures and a warming trend since the mid-1980s, annually and in all seasons except spring, with the winter warming trend beginning a decade earlier than other seasons. Precipitation records also indicate high interannual variability with multi-year dry and wet periods, both annually and seasonally. One notable standout is the exceptionally high spring precipitation during the past five years, which has been consistently above average.

Table 1 – Observed changes in climate variables in the Pacific Northwest

Variable	Change	Timeframe	Comment
Annual Temperatures	+ 1.3°F	1895-2011	
Annual Precipitation	No significant trend	1895-2011	
Heavy downpours	Ambiguous	varies	Different trends depending on dates and methods
Snowpack	- 25%	1950-2006	Substantial year-to-year variability
Glacier	- 7% (north) - 49% (south)	1958-1998 1904-2006	Greater loss toward the south
Streamflow	0 to - 20% Earlier peak where snowmelt	1948-2006	Year-to-year variability; Due to less snowpack and earlier snowmelt

Projected changes from climate models emissions are for continued warming, increased extreme precipitation, and further decline in snowpack in Washington (Table 2). The magnitude of change after mid-century depends on the amount of greenhouse gas emissions in the coming decades, which have been identified as "what if" scenarios of plausible future emissions (Van Vuuren et al. 2011; Nakićenović et al. 2000). Warming is projected for all seasons and extreme heat events are projected to increase in frequency while extreme cold events become less frequent. Climate models project little change in annual precipitation (ranging from -4% to +14%), but seasonal precipitation is projected to change with more precipitation in autumn, winter, and spring (+2 to +7%), and less in summer (-6 to -8%; IPCC 2013; Mote and Salathé 2010). Precipitation intensity is projected to increase: the number of days with more than one inch of rain is projected to rise by +13% (±7%) by the 2050s (relative to1971-2000), for a high greenhouse gas scenario (Kunkel et al 2013; Snover et al. 2013). Spring snowpack is projected to decline further in Washington with reductions of -38 to -46% by the 2040s compared with historical averages (1970-1999; Elsner et al. 2010). Reductions are largest in warmer areas west of the Cascade Range crest and at low elevations in eastern Washington.



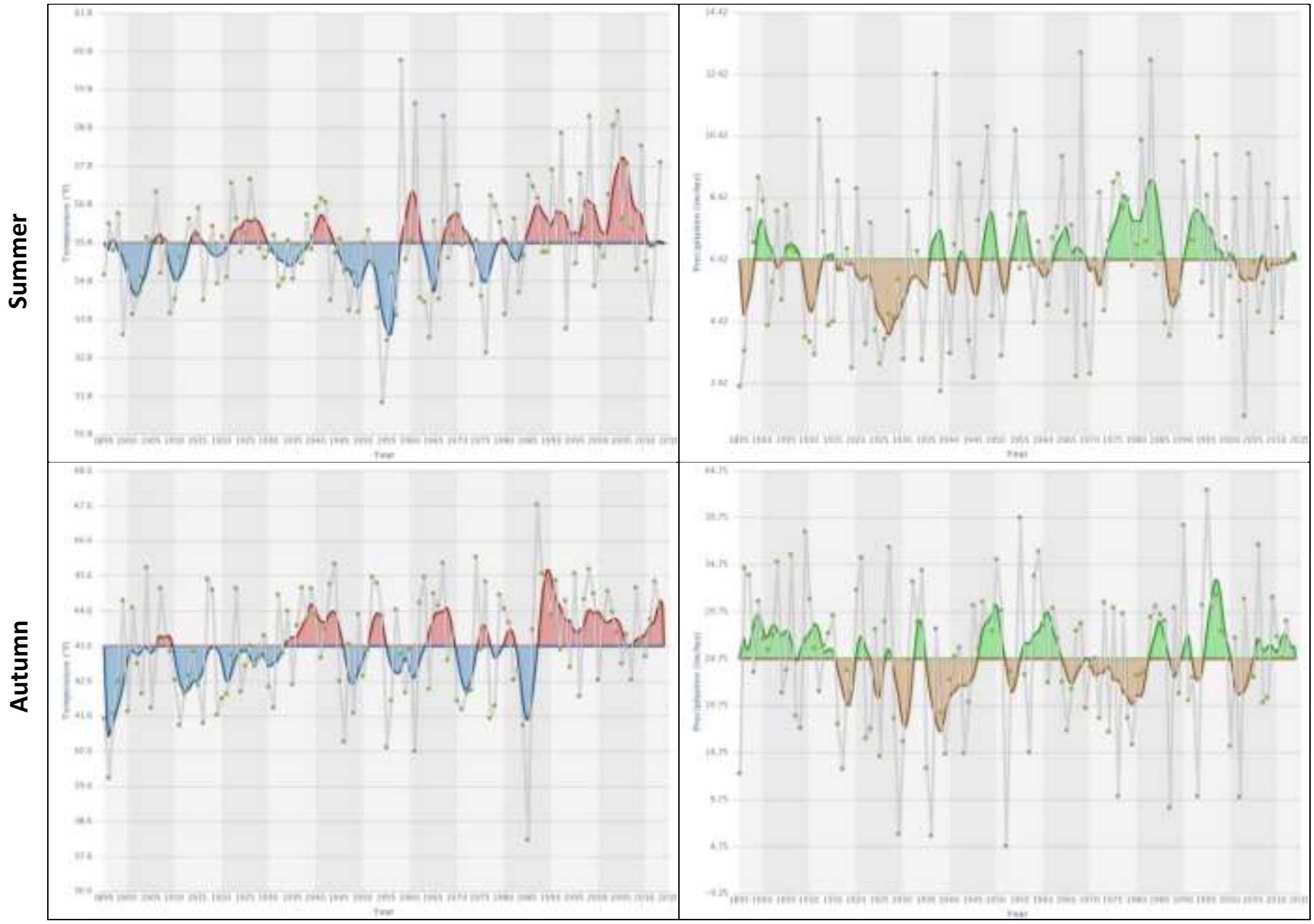


Figure 1 – Historical annual and seasonal climate trends in temperatures and precipitation for the west slopes of the Cascade Mountains compiled by National Climate Data Center datasets (http://charts.srcc.lsu.edu/trends/), broader area than MBSNF. A 5-year moving average is plotted above and below the long-term average represented by the horizontal line. Alternating shaded columns represent decades with the first full decade starting in 1900.

Table 2 – Projected changes in climate variables in the Pacific Northwest

Variable	Average	Range	GHG Emissions	Timeframe	Comment
Temperatures (Annual)	+ 4.3°F	+ 2° to + 6.7° F	Low scenario	2050s	Relative to 1950-1999
	+ 5.8°F	+ 3.1° to + 8.5° F	High scenario	2050s	Warming in all seasons
Precipitation (Annual)		− 4.3 to + 10.1%	Low scenario	2050s	Relative to 1950-1999
		− 4.7 to + 13.5%	High scenario	2050s	Annual changes small compared to year-to-year variability
Heavy downpours (Days with > 1 in)	+ 13%	± 7%	High scenario	2041-2070	Relative to 1950-1999
(Days with > 3 in)	+ 22%	± 22%	High scenario	2041-2070	

3. Climate Change Relevant to MBSNF Roads

Data Analysis

Road data were provided by MBSNF (dated June 24, 2013) and includes system roads (officially roads in the Inventory of Forest Service Infrastructure [INFRA] database that are under the jurisdiction of MBSNF) as well as nonsystem roads (40 roads considered for addition to the official MBSNF road system). Both types of roads were considered and geospatially analyzed with climate projections using ArcGIS (version 10.2). Roads within the geographic footprint of MBSNF, but not under the MBSNF jurisdiction, and roads that have been decommissioned through a signed NEPA document were excluded from these analyses.

Aligning with the current greenhouse gas emissions trajectory, the A1B scenario was used in this assessment and is a medium-high emissions scenario reflecting rapid increases in greenhouse gasses in the early 21st century followed by substantial reductions in emissions in the second half of the 21st century (Nakićenović and Swart 2000). New scenarios based on Representative Concentration Pathways (RCPs; Van Vuuren et al. 2011) were developed for the 2013 IPCC report. New, updated global climate models (GCMs) were also developed for the recent IPCC report. The new models project similar changes in climate relative to the previous IPCC; differences are in the way they were created and the new ones span a wider range of possible emissions (Snover et al. 2013). Hydrologic model simulations using these recent scenarios and the latest downscaled GCMs are still in progress. Therefore, this assessment relies on established datasets used in many studies in the PNW (Hamlet et al. 2013). The A1B scenario is similar to new RCP 8.5 through about mid-century and then follows closer to RCP 6.0 scenario by 2100 (Fig. 2).

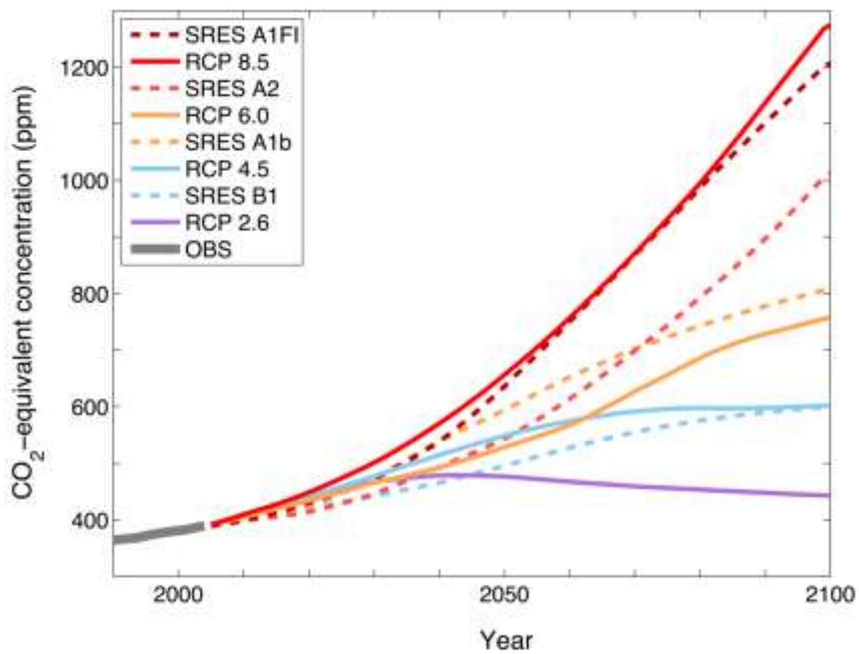


Figure 2 – Comparison radiative forcing, expressed as CO2-equivalent concentration, for greenhouse gas emission scenarios used in the IPCC 2007 and 2013 reports. Old scenarios (dashed lines) have close analogs to the new scenarios (solid lines). Measured concentrations are shown in grey for 1990 to 2010. *Figure source:* Climate Impacts Group, based on data used in IPCC 2007 and IPCC 2013 (http://sedac.ciesin.columbia.edu/ddc/sres/ [Nakićenović and Swart 2000]; http://tntcat.iiasa.ac.at:8787/RcpDb [Van Vuuren et al. 2011])

Data on projected climate change were acquired from the Pacific Northwest Hydroclimate Scenarios Project developed by an interdisciplinary research group associated with the Climate Impacts Group at the University of Washington (Hamlet et al. 2013). This dataset was selected because it was developed specifically to support comprehensive assessments, planning, and adaptation in Washington. Also, this dataset has been and continues to be used in numerous studies throughout the region (Raymond et al. 2014; Tohver et al. 2014; Elsner et al. 2010). The data are at a spatial resolution of 1/16th degree (~30 km^2) based on statically downscaled climate projections from the ten best-performing GCMs for this region forced by the A1B emissions scenario (http://cses.washington.edu/cig/data/index.shtml - anchor4). The GCM projections were used to drive the Variable Infiltration Capacity (VIC) macroscale hydrological model. The VIC model uses daily climate (i.e., temperature, precipitation, wind) as inputs to calculate hydrologic effects on river flows, snowpack, soil moisture, and other ecosystem processes (Elsner et al. 2010, Hamlet et al. 2010, Littell et al 2011, Mote & Salathé 2010). Monthly data are available for historical climate (1916-2006) and projected climate in the 2020s (2010-2039), 2040s (2030-2059), and 2080s (2070-2099). Snow simulations were produced using a special high-resolution version of the VIC model implemented at 800-m resolution for the 2040s (Safeeq et al. 2014, WHCWG 2013, Mauger 2011).

Changes in watershed type and peak flows

Flooding in Washington is largely a function of precipitation intensity and duration, the freezing elevation during storms effecting where it rains or snows, and the effects of temperature and precipitation on snowmelt and soil moisture (Hamlet and Lettenmaier 2007; Tohver et al. 2014). The flood regime is largely determined by watershed type, which can be characterized by how much of the cool season (Oct. through Mar.) precipitation remains stored in the snowpack through April 1st (Hamlet et al. 2013; Elsner et al. 2010; Hamlet and Lettenmaier 2007). Rain-dominant watersheds are rarely below freezing and snow accumulation is minimal. Therefore, peak stream flows are mainly associated with peak precipitation in late fall or early winter. Watersheds at moderate elevations can collect substantial snowpack in the winter (10 to 40% of the cool season precipitation). On the west side of the Cascade Range crest, these mixed-rain-and-snow watersheds are only a few degrees below freezing in mid-winter. Stream flows from these watersheds typically has two peaks, one during the rains of late autumn and another during the spring snowmelt. The highest elevation watersheds capture more snow (>40 % of cool season precipitation falls as snow) and these snowmelt-dominant watersheds have peak streamflows coinciding with spring snowmelt.

As the atmosphere warms, more precipitation falls as rain and the freezing elevation shifts farther upslope. Thus, peak streamflow shifts as precipitation changes, reflected in watershed type (Tohver and Hamlet 2010). The type of watershed was determined as a ratio of April 1st snow-water equivalent (e.g., the amount of water entrained in the snowpack) to cool season total precipitation simulated by VIC. There are 46 watersheds within or adjacent to MBSNF. Currently, these watersheds represent a relatively balance of all three types (Table 3). However, in the future many mixed-rain-and-snow watersheds become rain-dominant, and snowmelt-dominant watersheds shift to mixed-rain-and-snow watersheds (Fig. 3). By the 2080s, the only remaining snow dominant basin is the northeastern slope of Glacier Peak in the Upper Suiattle River watershed.

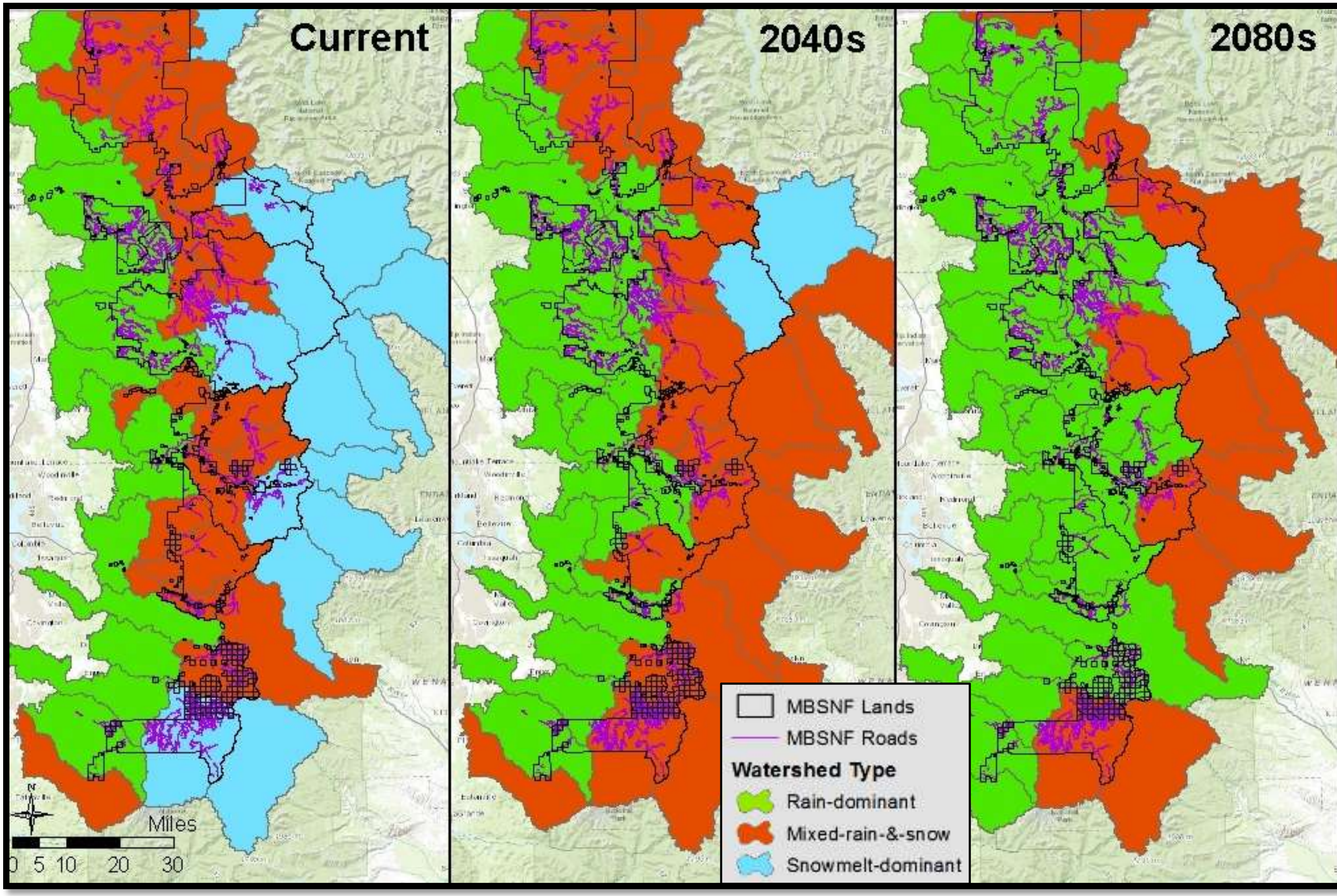


Figure 3 - Projected shift in watershed type in the MBSNF by the 2040s (2030-2059) and 2080s (2070-2099), relative to 1916-2006. Basins represent the spatial resolution of 10-digit hydrologic unit codes (HUC) as delineated by the U.S. Geological Survey. Watershed types are defined by the ratio of April 1 snow water equivalent (SWE) to cool season (Oct. – Mar.) precipitation, which represents most precipitation falling as snow or rain. Future projections were modeled using the A1B emission scenario and an ensemble of 10 global climate models (GCM). Roads within MBSNF are shown in purple.

Table 3 – Number of each watershed type within MBSNF

Watershed type*	Current	2040s	2080s
Rain-dominant	14	21	30
Mixed-rain-and-snow	18	23	15
Snowmelt-dominant	14	2	1

**Defined by how much Oct.-Mar. precipitation is entrained in April 1st snowpack (Rain = <10%; Mixed-rain-and –snow = 10 to 40%; snow = >40%)*

The shift in watershed type will adjust the proportion of MBSNF located within different watershed types. The percentage of MBSNF roads in rain-dominant watersheds will increase from 27% currently to 75% by 2080s (Fig. 4). Roads in mixed-rain-and-snow watersheds will remain the same (~50%) through the 2040s and then decline to 24% by the 2080s. Twenty three percent of MBSNF are currently located in snowmelt-dominant basins, but only about 1% will remain by 2040s. To understand where shifting watershed type may have the greatest impact on the MBSNF road network, in Figure 5 the watershed types are color coded by the density of roads within each watershed while maintaining the same color hue representing watershed type. The watersheds with the highest density of roads (>100 miles) that will shift from one type to another include: Upper White and Green rivers, South Fork Skykomish River, Upper and Lower Sauk rivers, Lower Suiattle River, Baker River, and Upper North Fork Nooksack River.

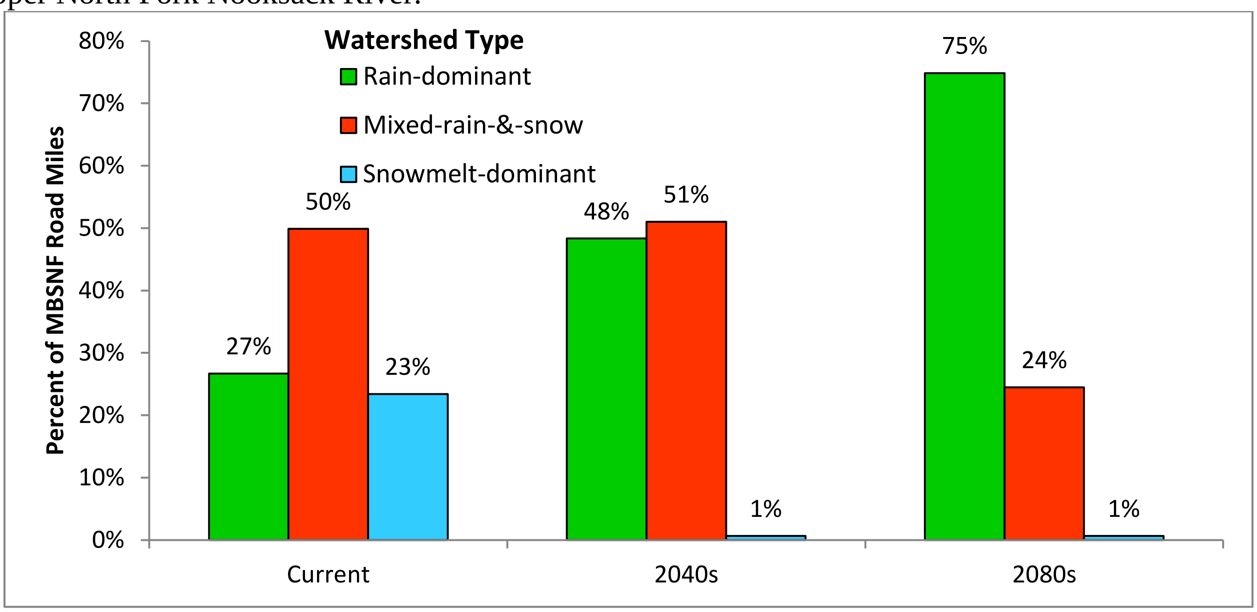


Figure 4 – Percent of MBSNF roads within different watershed types in three time periods. Watershed classification and modeling are described in Figure 3.

The changes in watershed type will influence the hydrology of the watershed and when high streamflows occur (Fig. 6). Rain-dominant watersheds will continue to have high late autumn and early winter streamflows, but these are projected to intensify. Mixed-rain-and-snow watersheds will continue to have two periods of peak flows, but the late autumn and early winter streamflows are projected to intensify and the spring peak is projected to diminish with reduced snow accumulation (Hamlet et al. 2013). Snowmelt-dominant watersheds are projected to experience higher flows in late autumn and early winter prior to substantial snowfall and earlier peak streamflows in spring associated with snowmelt.

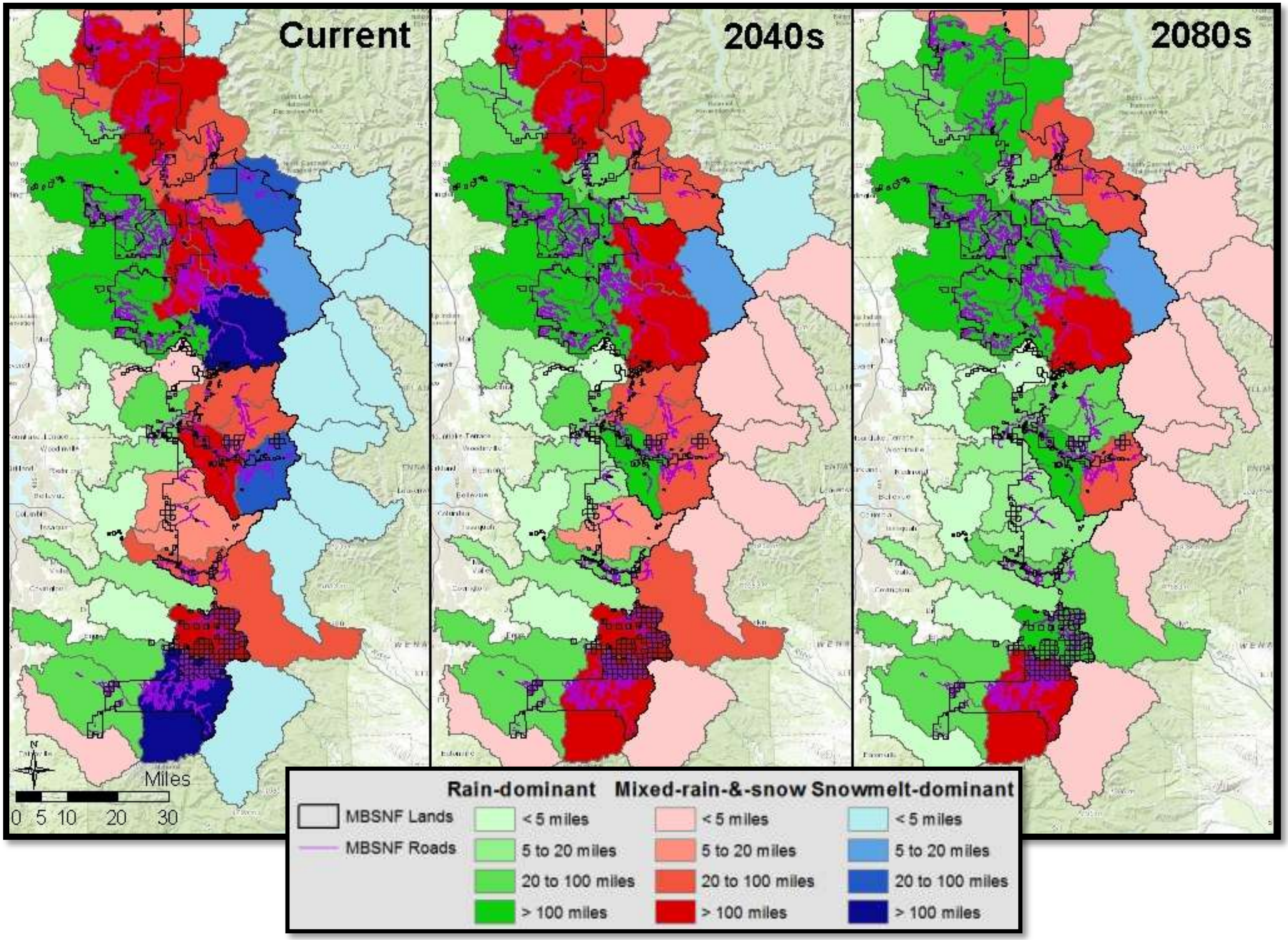


Figure 5 – Density of roads within MBSNF within watershed type projected to shift in the MBSNF by the 2040s and 2080s. Watershed types and modeling are described in Figure 3. Roads within MBSNF are shown in purple.

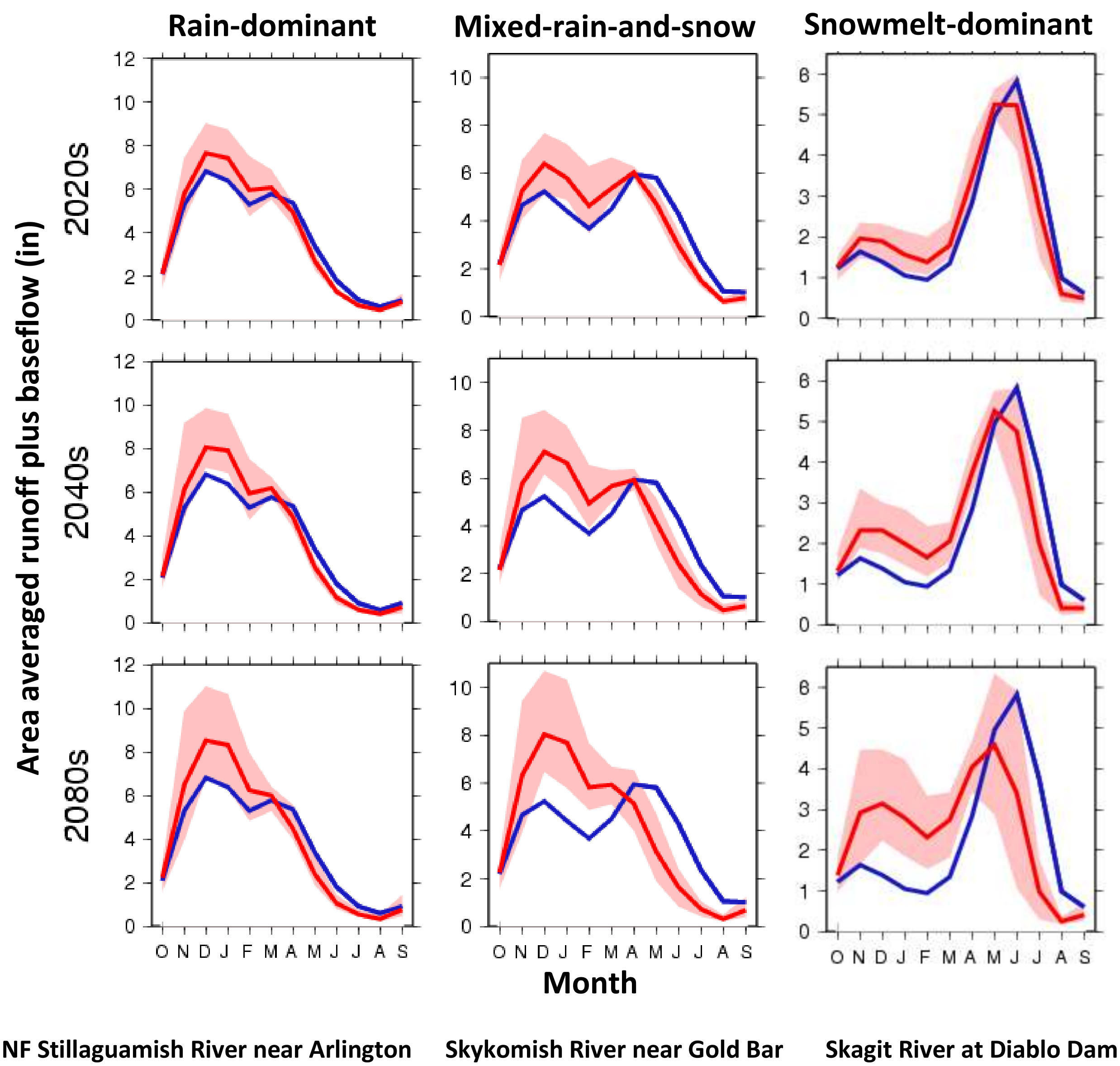


Figure 6 - Representative river hydrographs of three watershed types located west of the Cascade Range crest. Combined monthly average total runoff and baseflow over the entire basin expressed as an average depth (Units: in) is one of the primary determinants of streamflow. Blue line shows the simulated historical values, light red bands show the range of 10 GCM (ensemble) scenarios for the future time period and A1B emissions scenario. Dark red lines show the ensemble average.

Extreme flooding can be defined as the 100-year flood (the annual peak streamflow with a 1% probability of exceedance, or Q100) and changes to Q100 reported as a ratio of future Q100 to historical Q100 provide an indication of how extreme flows may change (Tohver et al. 2014). All watersheds in MBSNF jurisdiction are projected to experience an increase in peak flooding and the changes in flooding are projected to increase in time (Fig. 7). The largest increases in floods in the PNW have been projected in mixed-rain-and-snow watersheds (Hamlet et al. 2013). While little flood impact is projected by 2020s, more than 300 miles of MBSNF roads are located in watersheds projected to see more than a 50% increase in 100-year floods by 2040s (Fig. 7). This mile-impacted number doubles by 2080s. Roads in the Upper Green and White rivers, Cascade River, and Illabot Creek are projected to be most at risk from increasing peak flows.

Changes in soil moisture and landslide risks

Most landslides, including debris flows and torrents, are initiated during intense rain events or during less intense events preceded by persistent rain over a prolonged period (high antecedent soil moisture), rapid snow or ice melt, or low evaporation that increases soil moisture (Braum et al. 1998, Brooks et al. 2004, Crozier 1986). The steep topography and intense precipitation, especially in winter, make the PNW particularly susceptible to slope stability failures and landslides. Landslides also occur frequently after rapid snowmelt, particularly rain-on-snow events in the mixed-rain-and-snow watersheds (Harp1997, Wu and Merry 1990). Most landslides in the PNW occur during the rainy season between October and May (Baum et al. 2007), and hundreds of slides may occur in the region during an intense storm (Chatwin et al. 1994). The PNW typically experiences highest precipitation in November and December, and climate models project increases in future autumn precipitation in Washington (Mote and Salathé 2010).

Projected changes in soil moisture caused by changes in seasonal precipitation and snow accumulation could influence slope stability. Climate projections support the hypothesis that landslide-triggering conditions may increase in winter because 1) more precipitation is projected to fall as rain rather than snow, 2) loss of snowpack and increased soil infiltration in autumn and early winter, and 3) increasingly intense winter storms are projected (Salathé et al. 2014; Hamlet et al. 2013; Dominguez et al. 2012). Although VIC does not simulate slope stability failures or landslides, projections of soil moisture from VIC were used as an indicator of landslide hazard (Hamlet et al. 2013). The percent change in VIC projections of total column soil moisture, averaged over seasons (summer-JJA, autumn-SON, winter-DJF, and spring-MAM) for 2040s and 2080s compared to historical simulations of soil moisture, were used to indicate future slope stability associated with elevated soil moisture.

In the MBSNF by the 2040s, summer and autumn soil moisture is projected to decline throughout MBSNF by between 10 to 25% (Fig. 8). However, winter and spring soil moisture is projected to rise, predominantly less than 10%, and some lower elevations are even projected to be drier (<10%). By the 2080s, patches of MBSNF become even drier (>25% decline) during summer and autumn, particularly in the rainshadow Mount Rainier (Fig. 9). The winters and springs of the 2080s are projected to become even wetter with the higher elevations of MBSNF projected for 10 to 25% increases in soil moisture. However, projected soil moisture in the spring varies considerably with elevation, ranging from drier (declines up to 10%) at lower elevations to increases of more than 25% at the highest elevations on the west side of MBSNF. Decreases in summer precipitation and warmer temperatures reduce the actual evapotranspiration and enhance summer soil drying.

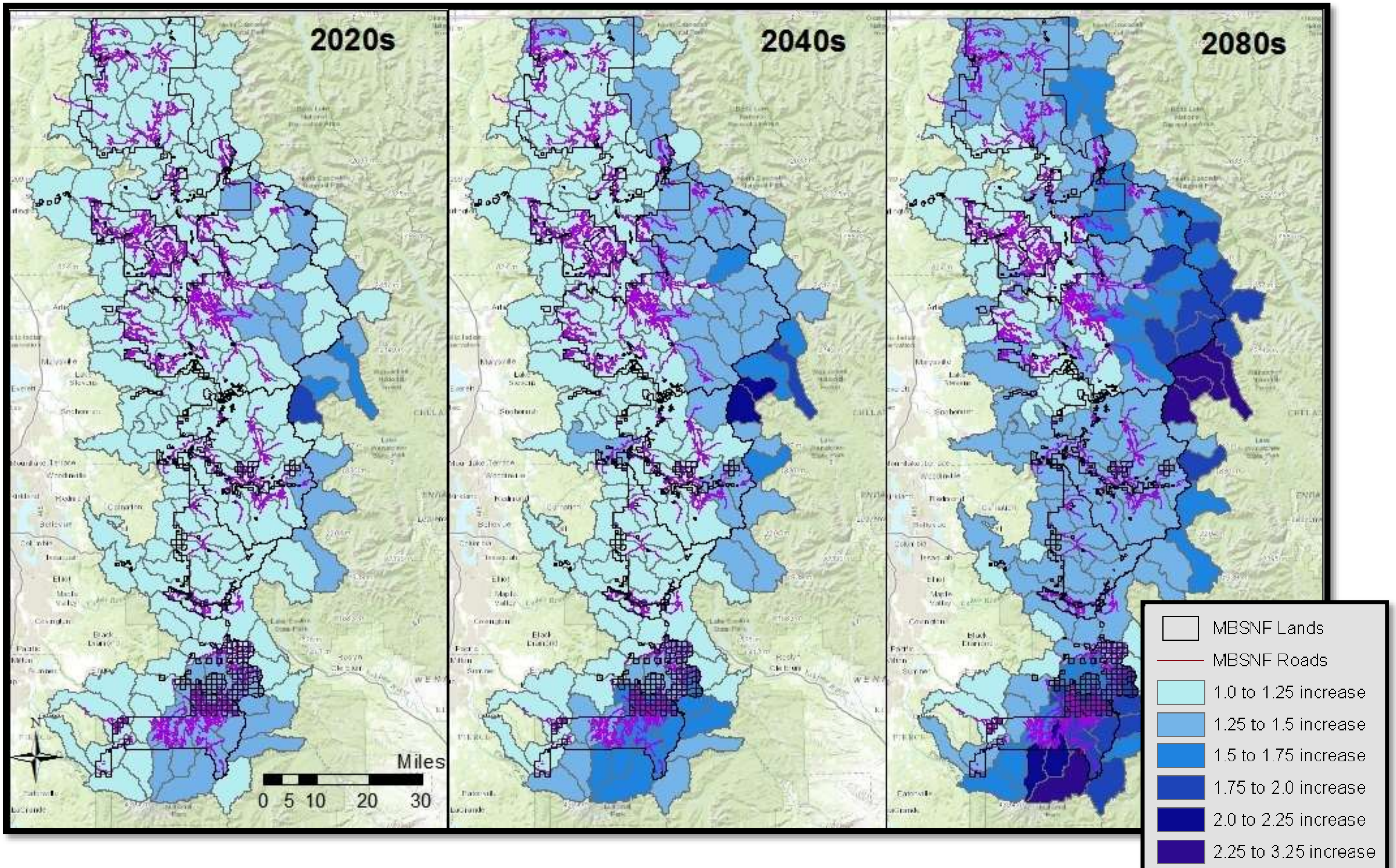


Figure 7 - Shifting trend in the 100-year flood statistic in watersheds of MBSNF. Flood level is designated as the annual peak flow with an estimated 100-year return frequency (Q100). The flood statistic represents the ratio of Q100 in 2020s, 2040s, and 2080s to historical (1916-2006) levels. Ratios > 1 indicate increasing peak flows in the future and no ratios were < 1. For example, a 1.5 increase indicates a 50% increase in Q100. Roads within MBSNF are shown in purple.

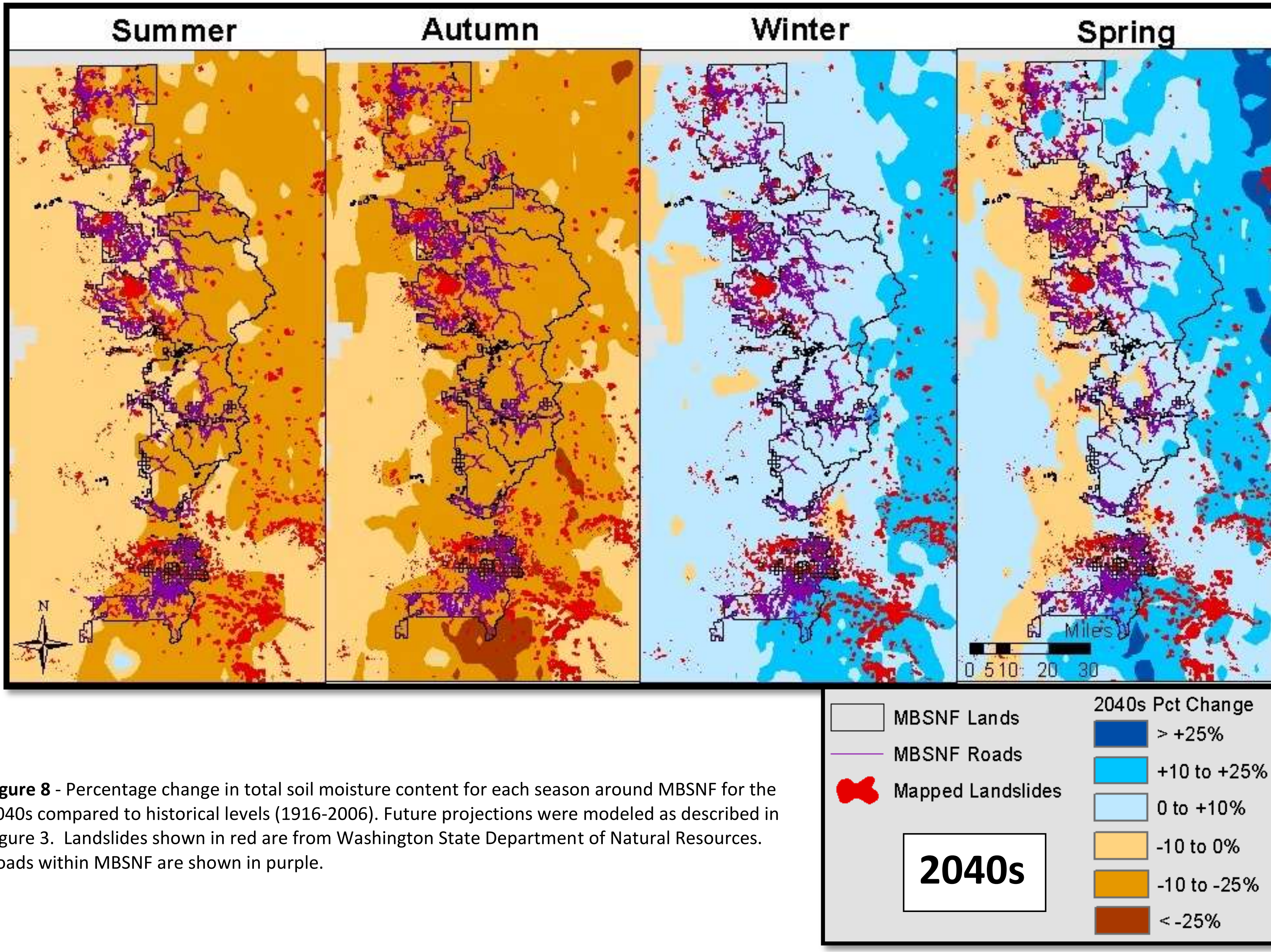


Figure 8 - Percentage change in total soil moisture content for each season around MBSNF for the 2040s compared to historical levels (1916-2006). Future projections were modeled as described in Figure 3. Landslides shown in red are from Washington State Department of Natural Resources. Roads within MBSNF are shown in purple.

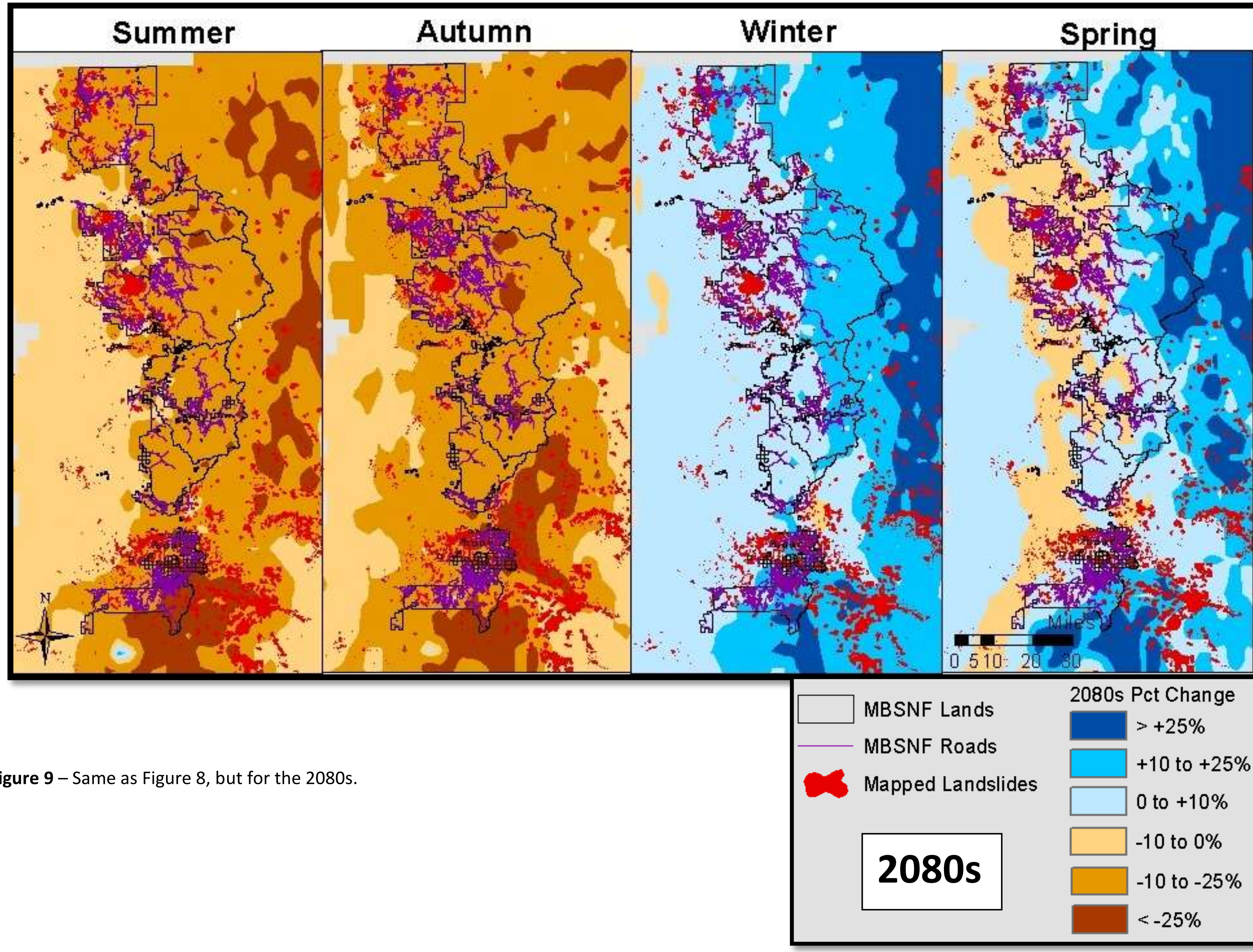


Figure 9 – Same as Figure 8, but for the 2080s.

The shift from drier soil conditions to wetter soil conditions between autumn and winter likely reflect the decrease in summer precipitation and less snowmelt, which draws down the soil moisture and increases the time necessary to recharge the soil moisture from autumn rains. Consequently, the effect of autumn precipitation is not reflected in soil moisture until winter as defined by starting December 1st. Additionally, higher soil moisture is driven by warmer temperatures in winter, which increase the amount of precipitation that falls as rain rather than snow, causing soil moisture recharge for a longer period in autumn and early winter before significant snow accumulation. Reduced snowpack will increase antecedent soil moisture in winter because more soil is directly exposed to rainfall. Additionally, warmer temperatures can increase midwinter snowmelt. Studies have already found statistically-significant increase in nighttime heat events west of the Cascades Range (1901-2009) (Bumbaco et al. 2013). Additionally, soil moisture recharge is already occurring earlier in spring and is now higher on April 1 than it was prior to 1947 (Hamlet and Lettenmaier 1999, Hamlet et al. 2007). High spring soil moisture likely reflects increased precipitation falling as rain at higher elevations and some persistent snowmelt. Landslides occur frequently after rapid snowmelt, particularly rain-on-snow events in the transient snow zone (Harp1997, Wu and Merry 1990). However, reduced snow accumulation reduces soil moisture at lower elevations, which might historically have been higher from snowmelt-recharged groundwater progressing downslope.

Figures 8 and 9 also include existing landslides maintained in a database by Washington State Department of Natural Resources. Many landslides occur in approximately the same areas and with the same relative abundance as they did previously (Crozier 2010, Braum et al. 1998). Using projected soil moisture as a proxy for landslide risk, projections suggests declining landslide risks during summer and autumn throughout MBSNF and higher risk at many locations during winter and spring. Both these changes are projected to intensify over time. The aggregation of data at the seasonal level neglects the potential for thunderstorms, which can rapidly elevate soil moisture in areas with high infiltrating soils even during summer. The overlay of mapped landslides and roads on projected soil moisture changes suggest that roads in the Upper White and Green rivers, Tye River, and Upper North Fork Nooksack River may be particularly vulnerable to landslides, especially in the winter.

Changes in snowpack and meltout

Temperatures-induced reductions in snowpack not only affect streamflow and soil moisture, but also the timing of access for many roads in the PNW. Snowpack has declined over the 20th century, although decadal climatic variability affects snowpack on shorter time scales (Hamlet et al. 2005, Mote et al 2008). In near-coastal areas such as the western Cascade Range, snowpack is sensitive to warming in winter and spring (Hamlet et al. 2005). Throughout the MBSNF area, snowmelt is projected to melt out earlier by 2040s (Fig. 10). More than 300 miles of roads are projected to melt out more than three weeks earlier than currently, primarily just south of Concrete and Snoqualmie Pass, and southeast of Darrington. Roads where substantial additional access maybe provided by this earlier snowmelt include those in the Finney Creek-Skagit River, North Fork Stillaguamish River, Tye River, and Upper Green River watersheds. Reduced snowpack and earlier snowmelt could allow earlier access for visitors to higher elevations and a longer “warm” recreation season (Michalak and Lawler 2013; Albano et al. 2013).

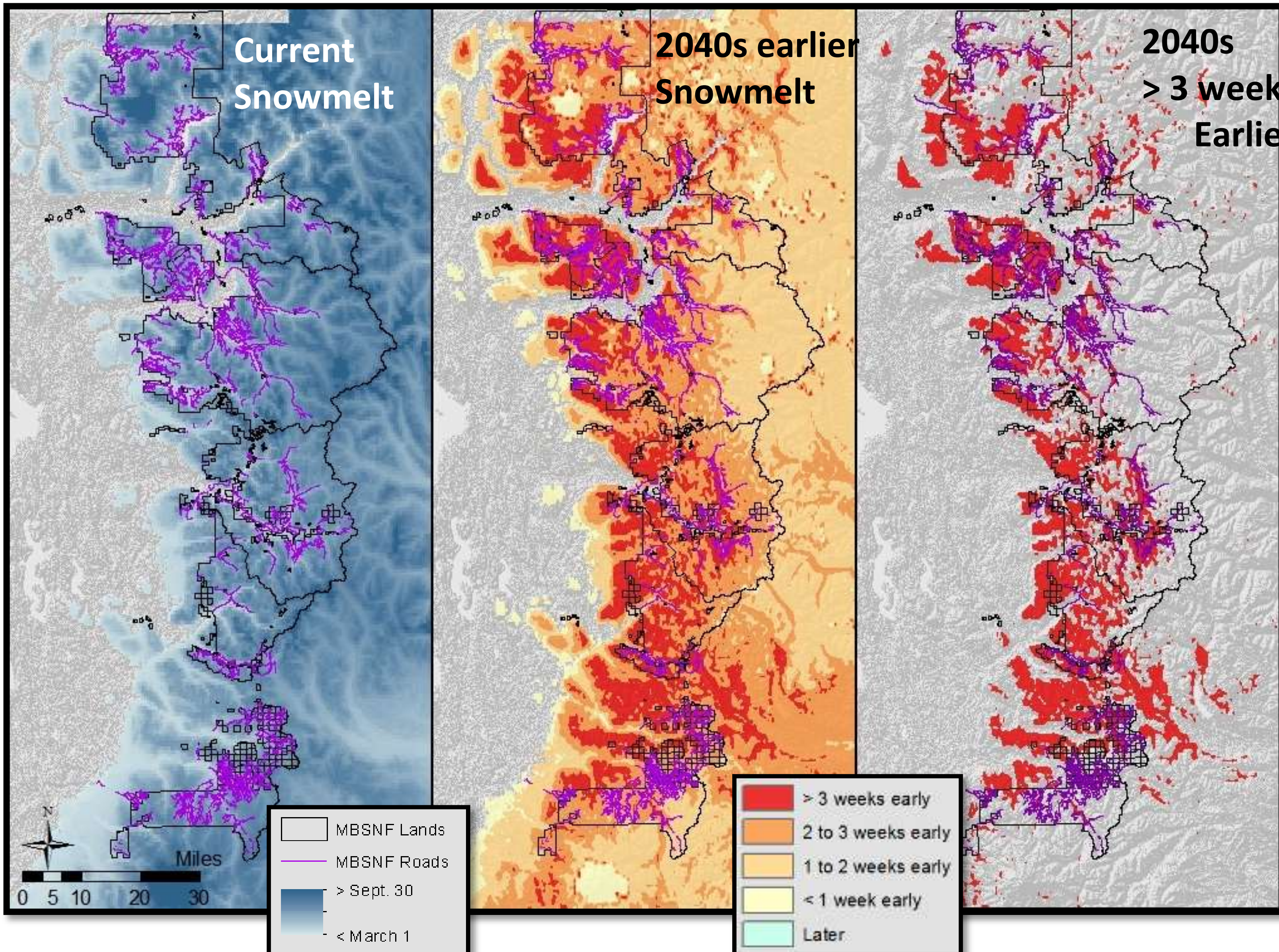


Figure 10 – Current snowmelt date around MBSNF and the average change in date b 2040s at which 90 percent of the snow water equivalent is melted compared to historical dates (1916-2006). Third panel shows only areas where snowmelt is projected more than three weeks earlier (red). Future projections were modeled as described in Figure 3. Roads within MBSNF are shown in purple. Data are resolved at 30 arc-sec (approximately 800 m) resolution from Mauger (2011).

4. Adaptation

During the development and implementation of the SRS, integration of projected location and timing of impacts related to climate change can help strengthen the longevity of the strategy. Roads in locations with higher risk of flooding or unstable slopes may coincide with areas of lower density public destinations, making closure or removal more amenable and justifiable. Alternatively, in areas with high destination density and road density, climate hazards can be used to select roads that have lower probability of future damage as more sustainable in the long-term. For example, a road located outside the floodplain with access to a popular destination could be retained while a redundant road in the floodplain with higher risk of flood damage is decommissioned. Similarly, a co-beneficial operational strategy to remove or modify infrastructure to allow channels to migrate within floodplains may also reduce the potential for damage to other upstream structures, which could be impacted by potentially expanded flood inundation in the future if obstructions were not removed.

When considering roads to retain in the MBSNF system, the SRS process can benefit from including the future risk of damage. Roads retained in areas with high climate hazard may commit MBSNF and the public to long-term cost for maintenance/repairs. Climate change integration into the SRS process can help explain the risks/costs of retaining certain roads in MBSNF's inventory, balancing with the desires of public access. These costs can include: persistent maintenance of troublesome areas, culvert upgrades, streambank and slope stabilization, surface treatments, and future reroutes probabilities due to repeated damage.

The SRS process may also benefit from considering anticipate shifts in access as temperatures warm during shoulder seasons in spring and autumn. For example, if certain roads are snow-free earlier, can maintenance crews get in and clear debris or inspect the roadbed and crossing structures, before visitors advocate for access? The timing and resource needs of maintenance may need to account for opening roads up earlier, when weather permits, or roads may need to be closed to visitors until crews can establish that the road is safe for access. Incorporating an adaptive management approach into the SRS will provide flexibility to implement or adjust decisions and priorities regarding closures, network revisions, and maintenance as conditions change in the near and distant future. For instance, if a road is located in a high risk area for future flood damage, it could be designated to remain open until a storm damages or destroys the roadbed or stream crossing structure. At that time the road would then be closed and decommissioned, rather than repaired or rebuilt.

Additional geospatial analysis with ArcGIS could be carried out to step this analysis down to more site-specific information and decision making. This analysis could identify individual road segments with higher flooding and/or landslide hazard. For example, road segments could be assigned a categorical flood hazard based on the shifting Q100 flood statistic, weighted higher for rain-and-snow dominated watersheds. Similarly, a relative landslide hazard could be generated based on soil moisture percent change and assigned to individual road segments. The adjacency of streams and presence of steep slopes could also be incorporated into a risk equation (e.g., road distance from streams and increasing peak flows; higher soil moisture coinciding with steep slopes). With this analysis, a list of road segments that have high climate-related hazard could be made and/or mapped, where the road line width or color corresponded to higher hazard exposure. Earlier snow-free projections could be looked at separately from these hazards as a factor likely to increase demand on high density destinations or on currently less-used destinations. By also examining road segments, this information could be used to understand where public access pressures may change and to plan the priority and timing of road removal activities (i.e., start decommissioning, duration of construction season).

Conclusions

In support of the SRS being developed by MBSNF, a climate-change assessment was carried out using state-of-the-art predictions of future changes in climate from statistically downscaled GCM simulations and process-based VIC hydrologic model results. Key findings from this assessment include:

- By 2040s, approximately 1% of roads in MBSNF will remain in snowmelt-dominated watersheds, which typically have peak streamflows coinciding with spring snowmelt.
- By 2080s, approximately 75% of roads in MBSNF will reside in rain-dominated watersheds, which have peak streamflows primarily in late autumn or early winter, and a lesser peak during spring snowmelt.
- Peak streamflows from snowmelt will likely be earlier in spring than historically.
- More than 300 miles of MBSNF roads are located in watersheds projected to experience a 50% increase in 100-year floods by 2040s.
- Increases in precipitation falling as rain, reduced snowpack, and more intense winter storms drive projections for higher soil moisture and increasing landslide hazard during winter and in spring at higher elevations.
- By 2040, reduced snowpack is projected to allow access to some areas more than three weeks earlier than historically and to extend the snow-free season later into autumn.

Projections of climate change and associated shifts in hydrology specific to MBSNF provide reinforcement for the importance of the SRS process. The planning process is a critical mechanism for incorporating these projections and balancing future climate-related impacts with demands for access. In a transportation network analysis, climate hazard information can help minimize future costs and resource damage as well as maximize public and agency access.

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