Analysis of climate change impacts to roads on the Mount-Baker Snoqualmie National Forest

Analysis by George Wooten, Conservation Northwest, January 2016

Executive Summary

The potential effect of changing climate was analyzed on the Mount Baker Snoqualmie National Forest (MBSNF) road system. The results were developed to build off of a December 2014 report by Ronda Strauch (University of Washington) entitled *Mt. Baker Snoqualmie National Forest Sustainable Roads System Strategy – Climate Change Analysis.* Together these two reports aim to utilize climate science to complement current condition information provided in the national forest's Sustainable Roads Strategy.

According to the Sustainable Roads Strategy report released in December 2015:

> A sustainable roads strategy is intended to identify opportunities for the National Forest transportation system to meet current and future management objectives, and to provide information that allows integration of ecological, social, and economic concerns into future decisions. To address the requirement by the 2005 Travel Management Rule for a travel analysis and subsequent minimum roads product, the Mt. Baker-Snoqualmie National Forest (MBS) developed a process called the Sustainable Roads Strategy (SRS) with the end product describing opportunities and priorities that can be used by the responsible official for identification of the forest's sustainable road system following appropriate NEPA analysis. The sustainable roads strategy is tailored to local situations and landscape/site conditions as identified by forest staff members and coupled with ongoing public input.
>
> The outcome of the Sustainable Roads Strategy process is an identification of potential opportunities for changing the way certain parts of the forest transportation system are managed to addres administrative and public issues. A thorough analysis supports subsequent National Environmental Policy Act (NEPA) processes, allowing individual projects to be more site-specific and focused, while still addressing cumulative impacts.

The key findings in Ronda Strauch's previous analysis were that:

- By 2040s, only 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 stream flows primarily in late autumn or early winter, and a lesser peak during spring snowmelt.
- Peak stream flows 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 flood levels 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.

The report reviewed potential climate change factors across the MBSNF. Several potential climate change factors were evaluated including the potential increased volume of 100-year flood levels, potential increased soil moisture, change in rain- or snow-dominant subwatershed regime and projected date of snowmelt. The objective of this study was to further the work begun by Ronda's analysis by conducting a finer scale review of potential climate effects on individual road segments using the same climate data.

Individual road segments were evaluated for their mean overlap on the potential climate change landscapes. This analysis resulted in ranking MBSNF roads by their potential for climate-induced hazards above the present level. Each road was assigned a composite climate hazard score determined from the combined potential peak 2080 flood level increase and the potential 2080 winter soil moisture increase, with the former upweighted for subwatersheds dominated by mixed rain-and-snow precipitation regimes. This document presents maps of the road climate hazard scores and describes which watersheds have the greatest mileage of roads with high hazard scores.

Another climate data set was used to evaluate the change in predicted 2040 snowmelt date, for use in prioritizing roads that are expected to open earlier, and thus provide more visitor access, as well as allow for longer periods of maintenance operations.

Stream crossing density and landslide hazard density scores were assigned to MBSNF roads, based on the number of stream crossings per unit length and the number of hazardous crossings per unit length determined by stream slope. Roads that had the highest density of hazardous stream crossings were identified.

It is hoped that by providing this information at the road segment level, the scale at which decisions are made by land managers, it can be considered in access management planning efforts that aim to create a sustainable road system today and into the future. This report is accompanied by spreadsheets and data layers. Limitations of this analysis and recommendations for future work are discussed.

Methods

Data was processed using ArcGIS 10.2 and GRASS 7.0. The MBSNF transportation geodatabase was prepared for analysis as a shapefile (RoadEvOb1083.shp). Roads are represented as linear features with start and end points (intersections) that are used to map distances along their length. Intersection points may occur where two or more roads meet or they may occur along the same road, in which case the intersection is called an "event" and the two sections of road are referred to as road segments. Events often represent a point where the road maintenance level changes, e.g., the road changes from a paved road to an unimproved surface. For these analyses, the road segment is the basic unit of analysis and segments are not allowed to overlap except at point intersections. The road layer also contains maintenance level and administrative information for each road segment.

There were 58 overlapping road segments that were removed from the original data set using the "create event table" command to recreate the routes from the start- and end-points using OBJECTID as the ID field, resulting in 2250 road segments totaling 3,688 miles. The data set included 26 road segments totaling 1 mile that produced null results when analyzed. There are a number of reasons that could cause this, e.g., topology or orientation errors can result from road segments that are looped. Null results were flagged by setting them equal to the value -100 in the results columns of the road layer.

The data for stream crossings and stream slopes is contained in layer RdEvOBMrgSplitNonOver.shp, which contains 67 additional road segments (92 miles) that were present in an earlier download from the MBSNF, but were missing from the official road layer. Some of these may have been decommissioned or may lack sufficient data to determine their maintenance level, in which case they may be referred to as "unauthorized roads"

Additional data sets used for the analysis included: the boundary of the MBSNF; slope, determined from 30m DEM data, based on 40 foot USGS contours; the National Hydrography Dataset (NHD) and the Watershed Boundary Dataset (WBD), which is bundled with the NHD. The NHD was used for mapping streams as linear features. The WBD was used to map watersheds as polygons. Watersheds are represented by hydrologic unit codes (HUC) from 2 to 12 digits long, hierarchically divided into regions, subregions, basins, subbasins, watersheds, and subwatersheds. Subwatersheds (in the narrow sense) are also referred to as "12-digit watersheds" or "HUC6 watersheds"; watersheds (in the narrow sense) are also called "10-digit watersheds" or "HUC5 watersheds". These two units are distinguished here as "watersheds" and "subwatersheds".

The climate dataset was provided courtesy of Ronda Strauch. Files were in a geodatabase in the GCS North American 1983 projection and were reprojected for these analyses to NAD 1983 UTM Zone 10 North. Climate scenarios for most data sets are projected to the year 2020, 2040, or 2080, and for each season as well for soil moisture projections. Values are relative to the period from 1916 to 2006, here referred to as the "historical" period, or relatively speaking, the "present".

Four sets of climate data were used as input to the analysis for each climate scenario, defined as follows:

1. **Precipitation regime** is a categorical classification of subwatersheds into precipitation regimes of rain-dominant, snowmelt-dominant, or mixed-rain-and-snow dominant, for each potential climate scenario. The data set used was that of the historical period and the data was contained in a vector polygon file.
2. **Peak flood level** (or simply "**peak flood**") is the projected percent increase of the 100-year flood level (Q100) over historical levels, for each potential climate scenario. Q100 is the flow magnitude with a 1% chance of occurring annually. The data set used was that of the 2080

climate scenario contained in a raster file with 90m cells. This data was analyzed at the subwatershed level, however they are summarized here at the watershed level for discussion.

3. **Soil moisture change** (or simply "**soil moisture**") is the projected change in soil moisture for each season of each climate scenario, relative to historical levels. For each climate date there are four subsets of data to represent soil moisture projections for each season, with winter and spring being wetter and summer and fall being drier. Soil moisture was used as an indicator for landslide potential. The data set used was that of the winter 2080 climate scenario which was provided in a raster file with 90m cells. From the blocky appearance of this data set, it was apparently derived by smoothing a coarser data set (blocks are approximately 5.9 km across).
4. **Snowmelt date** is the number of days earlier that snowmelt is predicted to occur relative to the present (historical period), for each climate scenario. The data set used was that of the 2040 climate scenario (there was no 2080 data set). The original data set contained 90 m cells, but according to Ronda Strauch (personal comm) it was derived from model simulations using 800 m raster data.

The climate scenarios that were selected as input layers were those that yielded the greatest amount of change across the MBSNF. These data sets were the 2080 peak flood level and the winter 2080 soil moisture increase. The 2040 snowmelt date was considered sufficient for analysis.

The peak flood, soil moisture and snowmelt data sets are all raster data sets composed of 90 m cells. These are also referred to potential climate landscapes. Prior to calculation of the peak flood climate hazard, the peak flood landscape was upweighted by a factor of 1.2 only for subwatersheds that were historically dominated by mixed rain-and-snow precipitation regimes.

For these data sets, analysis of the potential effect of climate change on road segments was determined as the mean value of the overlapping cells of the raster data set underlying each road segment. The results are referred as potential climate road hazard scores, or simply climate hazards. After the calculation of peak flood and soil moisture climate hazards, these two hazard scores were then transformed into a composite value that weighted each equally.

In addition to analyzing potential climate hazards, road segments were evaluated for current conditions and for landslide potential by determining the number of stream crossings per mile as well as the number of *hazardous* stream crossings per mile, defined as streams with a defined threshold of slope steepness.

Results of the potential climate change effects were categorized into quantiles to help describe and prioritize road system needs on the MBSNF.

Peak flood hazard determination

This analysis determined potential effects on roads from increased peak flood levels. Most landslides in this region are initiated during intense rain events. The peak flood level landscape represents the percent increase of the 100-year flood level (Q100) of each subwatershed over historical (1916-2006) levels, for each of the future climate scenarios, determined here using the 2080 climate scenario. The peak flood level is expressed as the percent above historical levels, where a value of 13 is 13% higher than the historical level.

After upweighting rain-on-snow watersheds as described below, peak flood hazard scores were determined for each road segment in field [PkFloodPc] as the mean overlap of the road segments with the peak flood landscape (values range from 13 to 144).

Upweighting peak flood levels within a rain-on-snow regime
The value of the peak flood level was upweighted by a factor of 1.2027 for subwatersheds that were historically mixed rain-and-snow dominant. The intent of using this factor was to act as a tie-breaker for watersheds with close scores. The upweighting factor was determined as the percent standard deviation of the mean peak flood value for the 2080 climate scenario, where the mean is 1.429, the SD is 0.2896 and the SD of the mean is 0.2027%.

Increased soil moisture hazard determination
The winter 2080 soil moisture scenario was chosen for analysis because it had the greatest variation across the landscape. The original soil moisture data is expressed as the fractional difference above or below historical levels, i.e., 0.25 represents a 25% increase over historical levels. Prior to analysis, the soil moisture landscape was converted to integer percentages, ranging from -2 to +53 across the analysis landscape, which extended considerably beyond the MBSNF boundary

The soil moisture hazard scores were determined for each road segment in field [SoiMoi] as the mean overlap of the road segments with the potential winter 2080 soil moisture landscape.

Composite climate change hazard determination
In order to present the potential climate effects on roads as a single factor for management consideration, a composite score was created by equally weighing the potential peak flood level increase and the potential soil moisture increase, with the former upweighted by a factor of 1.2027 for mixed rain and snow subwatersheds.

The calculation of the composite climate change hazard score was evaluated for each road segment within the table for the road layer, after each score was calculated separately within the road layer shapefile. For ease of calculation, the peak flood and soil moisture data sets were both set to the same scale as the percent increase above present (nominally, historical) levels. The composite climate hazard score was calculated so as to apply geometrically equivalent weights to the range of scores for peak flood level and soil moisture increase. The scores for soil moisture (range 0 to 27) were first normalized to the full range of the peak flood levels (range 13 to 144) by multiplying by 144/27 in field [SoilNorm]. The values for peak flood level and normalized soil moisture increase were added together, and divided by 2 and the results were placed in field [RiskComp] (range from 10 to 144). Note that the composite score is an abstract number that should not be thought of as a value.

Earlier snowmelt date determination
The projected snowmelt date for the 2040 climate scenario was used to evaluated the effect on MBSNF road segments. The original data set was derived from 800 m raster data.

The original snowmelt data set did not completely overlap the MBSNF road layer used for these analyses. Although the missing coverage was a relatively small area at the northwestern and western boundaries of the MBSNF, a more complete overlap was necessary to prevent the GIS algorithms from miscalculating values or returning null values where roads extended beyond the layer. Therefore the 2040 snowmelt data set was extended up to 6.3 km outward from the western and northwestern edge of the original data set, using the expand command in GRASS GIS.

The snowmelt date for MBSNF road segments was determined as the mean overlap with cells in the 2040 snowmelt landscape .

Determination of road stream crossings density
In order to incorporate stream proximity into this analysis, the National Hydrography Dataset (NHD) was added to the project. The intersection of streams and MBSNF roads was used to create a point file. The road data for this analysis included an additional 92 miles that was not included in the more recent official version used for the climate analyses.

The point layer of stream crossings was joined to the roads layer by their road numbers and the number of road crossings per mile of road was determined for each road segment.

Number of hazardous stream crossings per road mile
Slope was determined from 30m DEM data, based on 40 foot USGS contour data.

A review of the literature was done to determine appropriate threshold values for ranking landslide hazard by slope (Cannon and others 2010; Iverson 2013; Clearwater-Nez Perce Forest Plan Revision (undated); Gartnera and others 2007; Stevens County Hazard Management Plan 2008). The threshold stream slope values used here are shown in Table 1 along with the number of MBSNF road crossings for each slope category.

Table 1. Landslide hazard categories assigned to stream crossings based on the slope of the stream at the point where it crosses a road on the MBSNF.

Percent Slope	Landslide Hazard
(undetermined)	0-Unknown
0 – 35	1-Infrequent
36 – 45	2-Low
46 – 55	3-Moderate
56 – 109	4-High

The point layer created from the intersection of streams and roads was overlaid on the slope landscape and each point was assigned the value of the slope at that point. These points were joined to the road segments by the road numbers and the number of hazardous stream crossings per mile was determined for each road segment.

Results

Peak flood level results
Figure 1 displays the results of the peak flood hazard analysis as a map of the potential 2080 peak flood road hazard scores, overlaid onto the watershed and subwatershed boundaries. Watersheds with more than five miles of road above the 70th percentile (peak flood level >72%) are highlighted in blue. Figure 1 also displays subwatersheds that were ranked above the 90th percentile of potential 2080 peak flood levels with yellow outlines. There is a cluster of these high-ranked subwatersheds near the eastern middle of the map, but they doesn’t significantly overlap roads on the MBSNF and therefore do not contribute to the road hazard scores in this analysis. These subwatersheds lie within the Chiwawa, Upper Suiattle, and White River-Little Wenatchee River Watersheds.

Figure 2 shows subwatersheds dominated by rain-on-snow precipitation regimes, that had their peak flood hazard scores upweighted by a factor of 1.2. The effect of this factor on the percentile rank of individual road segments was relatively small and this became even smaller when the road hazard score was converted to a composite metric, as shown by noting the similarity of the road hazard scores between Figures 1 and 2.

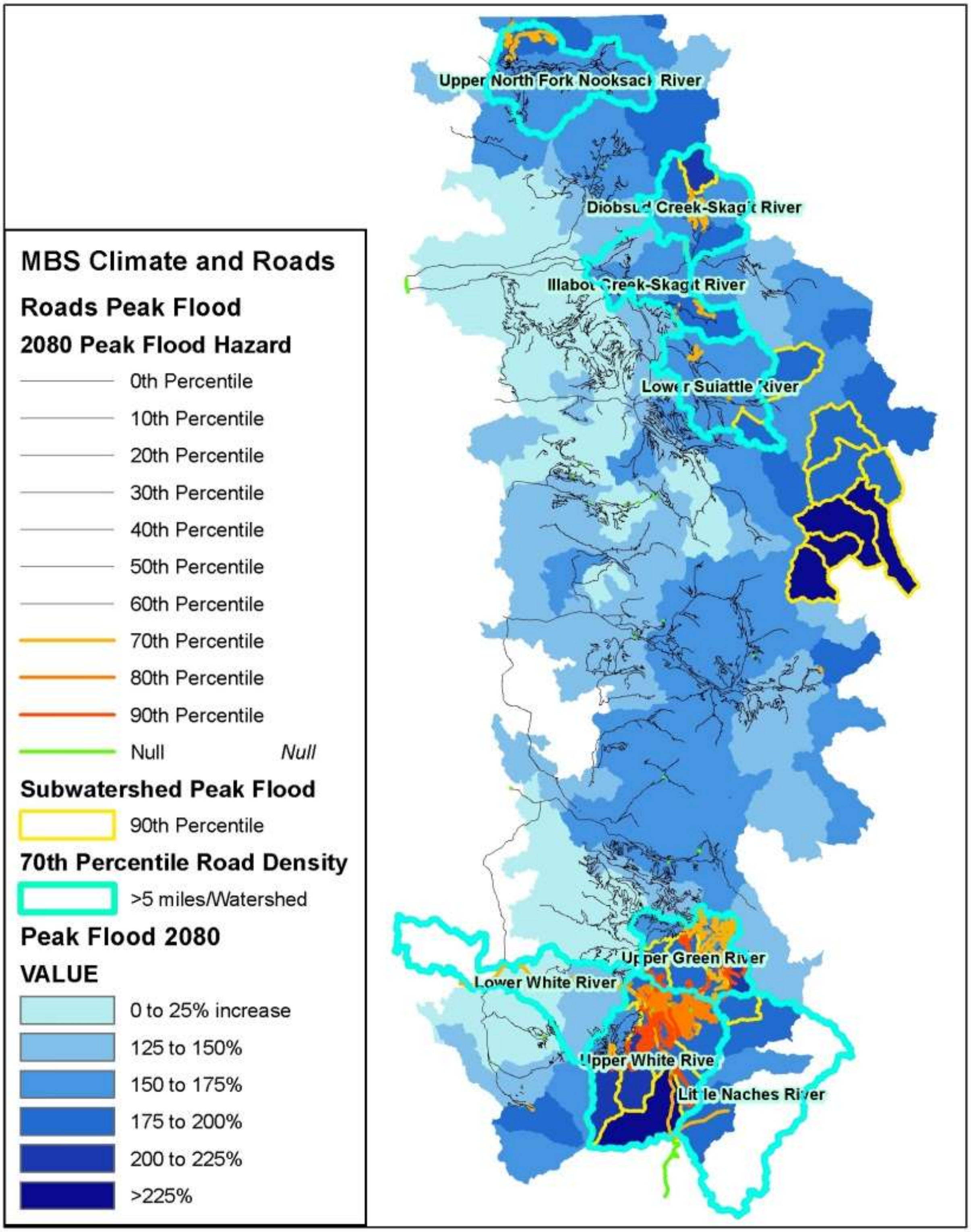

Figure 1. Potential 2080 peak flood level scores overlaid onto watershed and subwatershed boundaries. Watersheds with more than 5 miles of roads exceeding the 70th percentile are highlighted in blue. Subwatersheds with peak 2080 flood levels above the 90th percentile are outlined in yellow.

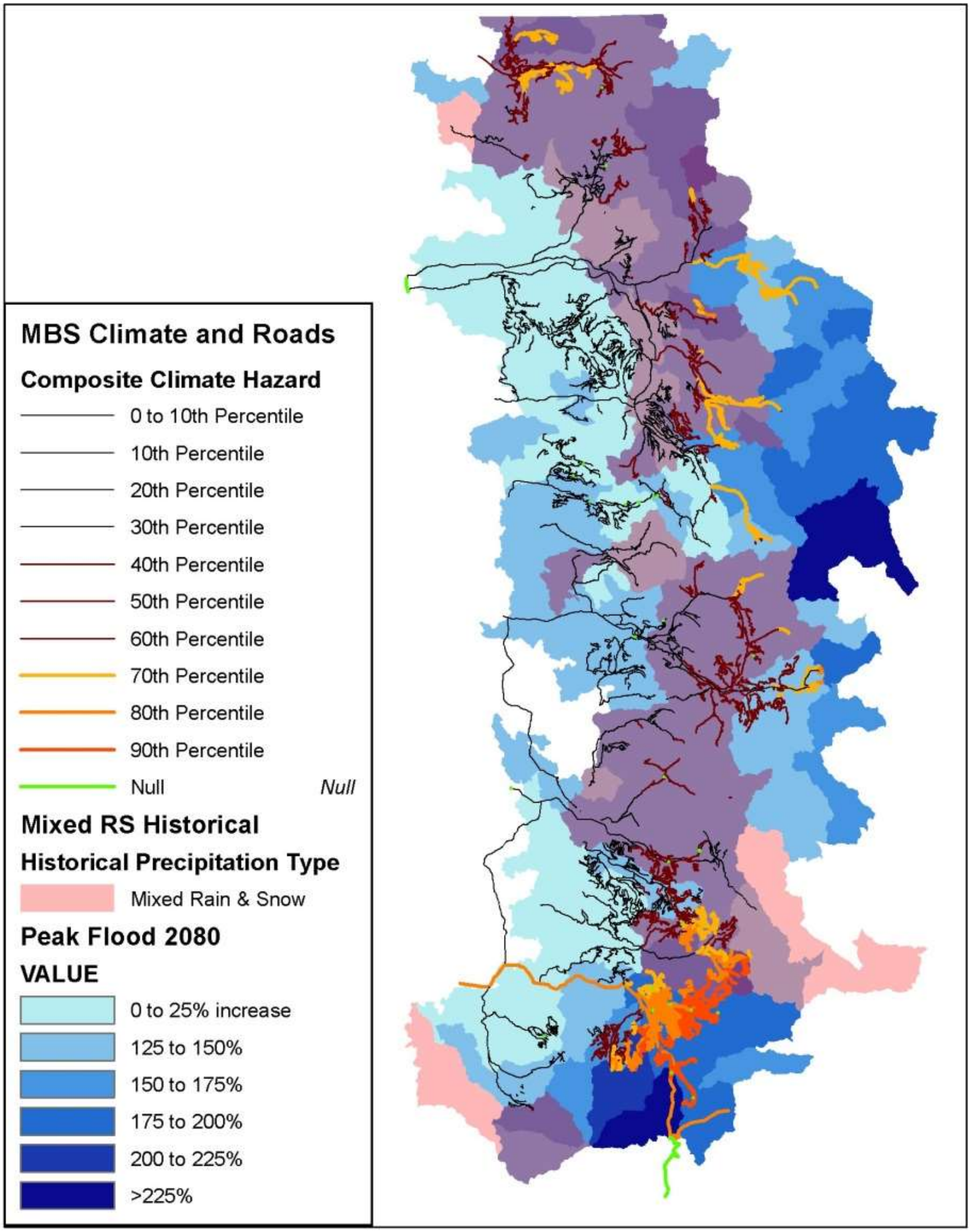

Figure 2. Composite road hazard scores overlaid on the potential 2080 peak flood level percent increase for each subwatershed, with mixed rain-and-snow subwatersheds shaded darker.

The mileage of roads with peak flood levels above the 70th percentile are summarized by watershed in Table 2. There were 526 road segments with 2080 peak flood level scores above the 70th percentile (623 miles or 28% of MBSNF road system). Watersheds with more than five miles of road above the 70th percentile were the Upper White River, Upper Green River, Upper North Fork Nooksack, Diobsud Creek-Skagit River, Lower White River, Little Naches River, Illabot Creek-Skagit River, Lower Suiattle River, with the first two watersheds having about five times the mileage of all of the other roads combined.

Table 2. Mileage of roads with peak flood increases above the 70th percentile by watershed, sorted from highest to lowest number of miles.

Summary of Miles by Watershed	**Miles**
Upper White River	343.3853
Upper Green River	156.5782
Upper North Fork Nooksack River	32.51902
Diobsud Creek-Skagit River	29.22454
Lower White River	23.73768
Little Naches River	11.57607
Illabot Creek-Skagit River	9.31546
Lower Suiattle River	7.37126
Headwaters Cowlitz River	3.23687
Lower Chilliwack River	1.37865
Upper Puyallup River	1.16416
Lower Puyallup River	0.89772
Lower Green River	0.82854
Nason Creek	0.64914
Kachess River-Yakima River	0.51591
Carbon River	0.41176
Tye River	0.24294
Cedar River	0.19396
Lower Sauk River	0.17023
TOTAL	**623.3974**

Effect of upweighting factor for rain-on-snow subwatersheds

The effect of upweighting the peak flood level by a factor of 1.2027 for rain-on-snow dominated subwatersheds is slight, and this becomes even slighter once the composite road scores are calculated. Affected subwatersheds are displayed in Figure 2 which shows that rain-on-snow dominated subwatersheds tend to be at middle elevations, where the effect is to raise the scores at middle elevations relative to higher elevations, where the highest peak flood scores are found. Interestingly, most of the roads exceeding 70th percentile hazard scores that are clustered at the south end of the MBSNF had high scores without being upweighted by being within rain-on-snow subwatersheds.

Admittedly the upweighting factor is somewhat arbitrary. It was determined as the percent standard deviation of the mean peak flood value, so that it would be quantitative. The use of a relatively small upweighting factor is that it acts as a tie-breaker for close cases. Figure 3 shows the distribution of peak flood scores after upweighting. In this figure, the lowest values within the 70th, 80th, and 90th percentile bins are highlighted in red to indicate where some of scores changed rank from a lower percentile.

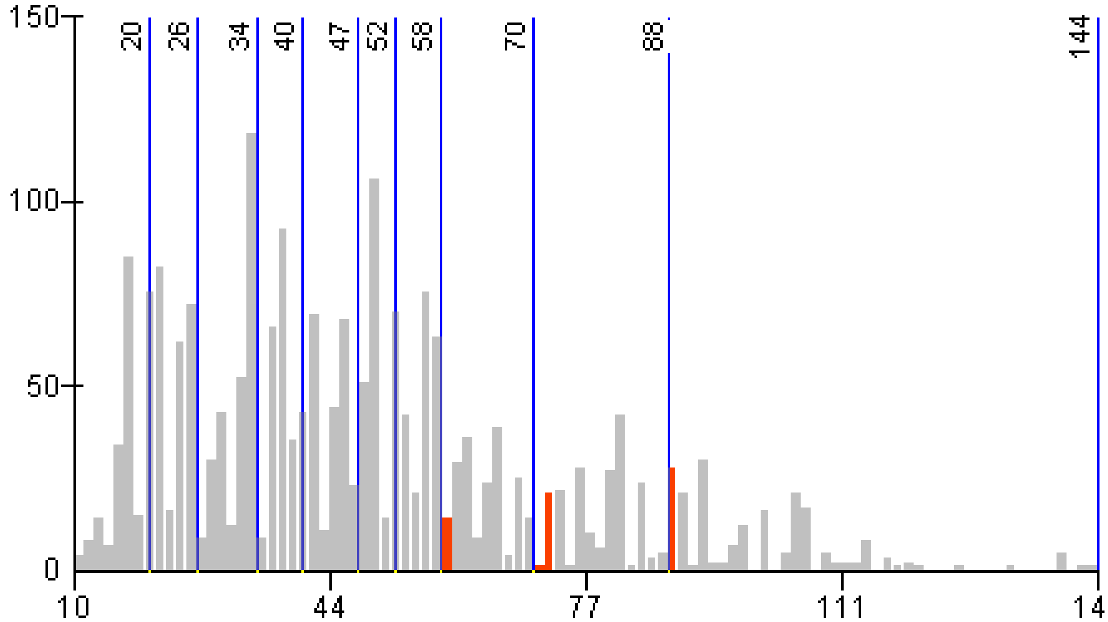

Figure 3. The distribution curve of the 2080 peak flood levels after applying the upweighting factor of 1.2027. Red highlights indicate scores that increased rank due to the factor. Highlights are only shown for the 70th, 80th, and 90th percentiles.

Increased soil moisture results

The soil moisture hazard scores for individual road segments was determined as the mean overlap of road segments with the soil moisture landscape. The results in field [SoiMoiPc] ranged in value from 0 to 27. Figure 4 shows a map of the 2080 winter soil moisture increases for each road segment, along with watersheds having more than 5 miles of roads ranked above the 70th percentile soil moisture (values > 11).

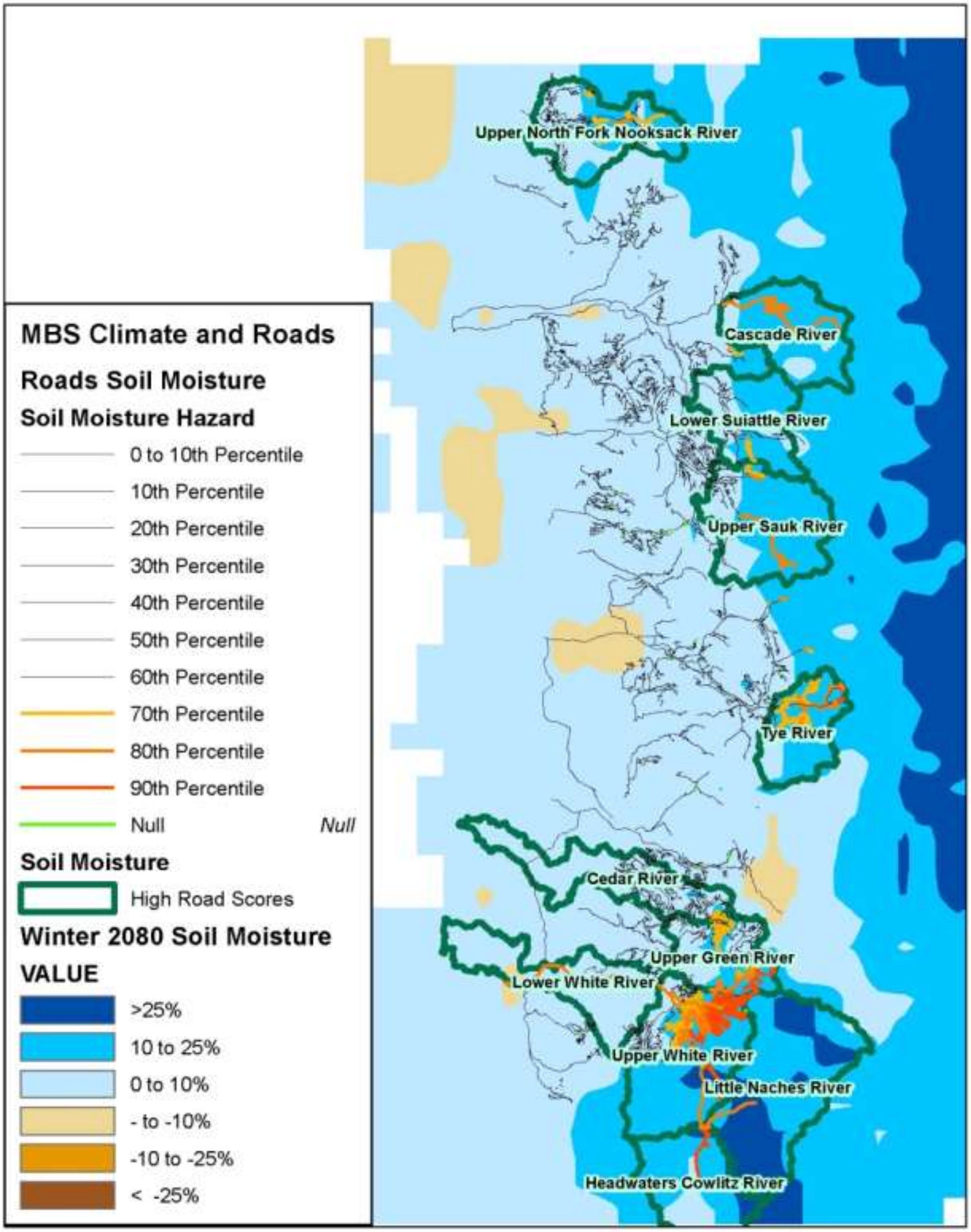

Figure 4. Roads ranked by potential 2080 soil moisture increase overlaid on the landscape of potential winter 2080 soil moisture increase. Watersheds with significant mileage of roads with high scores are outlined in dark green.

The mileage of roads with 2080 winter soil moisture increases above the 70th percentile within each watershed is shown in Table 3, sorted from highest to lowest number of miles per watershed. Watersheds with more than five miles of road above the 70th percentile (values > 11) are the Upper White River, Upper Green River, Tye River, Cascade River, Upper North Fork Nooksack River, Upper Sauk River, Lower White River, Headwaters Cowlitz River, Cedar River (uppermost part), Little Naches River, and Lower Suiattle River, with the first watershed having highest concentration of roads with high hazard scores.

There are 635 miles of road ranked above the 70th percentile for 2080 winter soil moisture increase. From Figure 4 it can be seen that the influence of potential 2080 spring soil moistures on road climate hazard scores becomes strongest where potential soil moisture increases exceed 10%. The distribution of the potential 2080 winter soil moisture increase is somewhat similar to the peak flood level landscape in that it tends to increase from low to higher elevations and has a pronounced effect in the Upper White River and Upper Green River Watersheds.

Table 3. Location of roads exceeding the 70th percentile winter 2080 soil moisture by watershed, sorted from highest to lowest number of miles per watershed.

Watershed	**Miles**
Upper White River	272.3867
Upper Green River	85.21848
Tye River	75.28205
Cascade River	55.33492
Upper North Fork Nooksack River	37.18979
Upper Sauk River	29.70408
Lower White River	23.73768
Headwaters Cowlitz River	14.11405
Cedar River	12.13669
Little Naches River	11.57607
Lower Suiattle River	6.9513
Illabot Creek-Skagit River	3.32462
North Fork Skykomish River	1.77989
Beckler River	1.67885
Kachess River-Yakima River	1.42486
Nason Creek	0.94891
Lower Puyallup River	0.89772
Lower Green River	0.82854
Diobsud Creek-Skagit River	0.40776
Carbon River	0.28087
TOTAL	**635.2038**

Composite climate change hazard score results

The composite climate hazard scores calculated for each road segment ranged from 10 to 144.

Figure 5 displays a map of the composite road hazard scores with ranks exceeding the 70th percentile (values >58) highlighted, overlaid on watersheds with more than 10 miles of road exceeding the 70th percentile of hazard scores. Tenth-percentiles break values are 20, 26, 34, 40, 47, 52, 58, 70, 88, and 144. There were 28 segments with null scores, mostly due to extension beyond the analysis landscape.

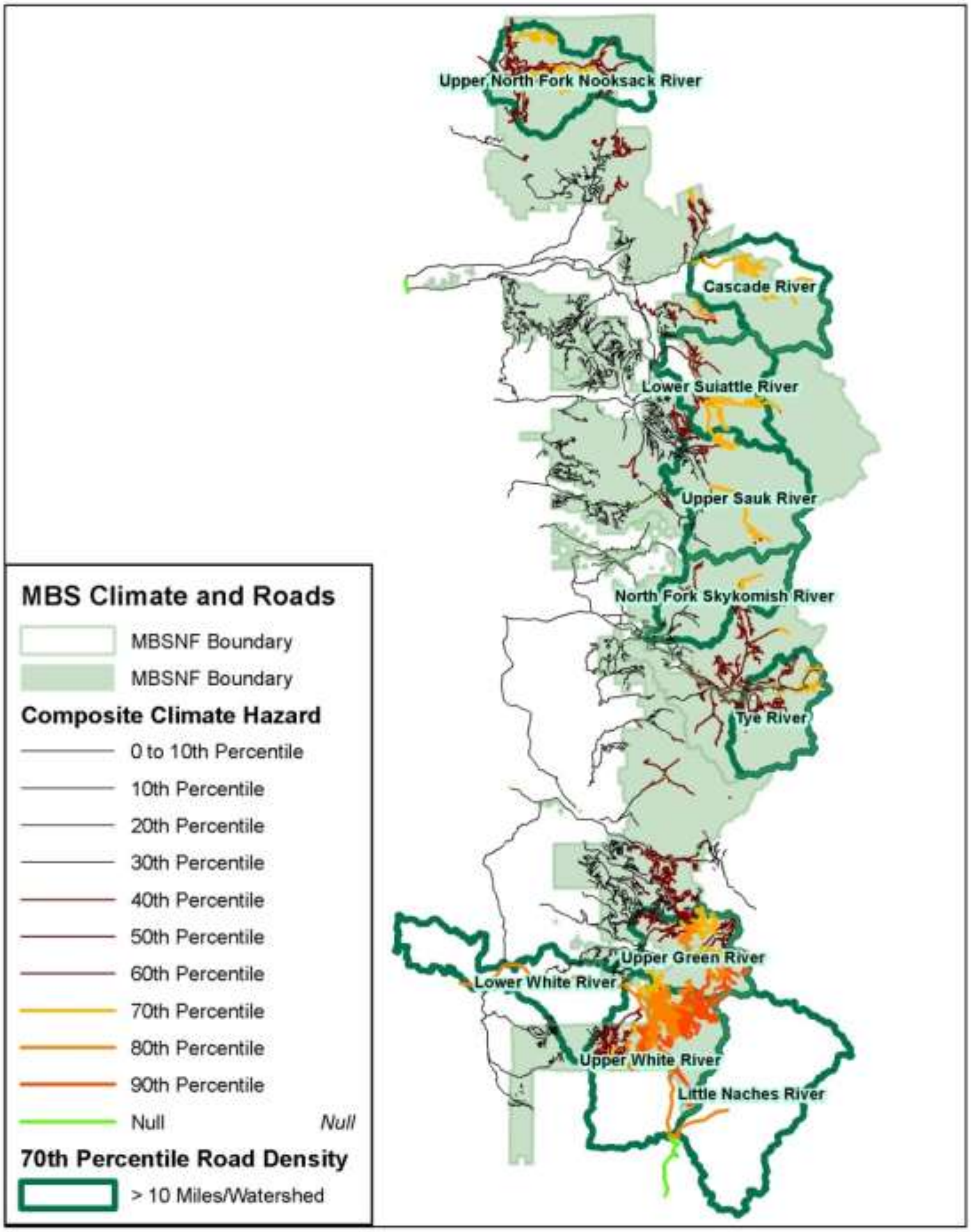

Figure 5. Composite climate hazard scores for road segments on the MBSNF. Watersheds with more than 10 miles of road exceeding the 70th percentile scores are outlined in dark green.

Watersheds containing roads with composite climate scores above the 70th percentile are shown in Table 4. Watersheds with more than ten miles of road with 70th percentile scores are the Upper White River, Upper Green River, Upper North Fork Nooksack River, Cascade River, Lower Suiattle River, Upper Sauk River, Lower White River, Tye River, and Little Naches River, with the first two watersheds having the highest concentration of roads with high hazard scores, and practically all of the roads ranked above the 80th percentile. There were 440 miles of road above the 80th percentile (20% of the total MBSNF mileage) and an additional 304 miles of road between the 70th and 80th percentiles (14% of the total mileage).

Table 4. Watersheds containing roads with composite climate scores above the 70th percentile, sorted by number of miles per watershed. These scores are compared with the potential 2080 peak flood percentile mileage in column Peak Flood and potential 2080 winter soil moisture percentile mileages in column Soil Moisture, showing only scores where mileages were in excess of 5 miles within the watershed.

Watershed	Composite (Miles)	Peak Flood (Miles)	Soil Moisture (Miles)
Upper White River	342.87806	343.3853	272.3867
Upper Green River	133.67117	156.5782	85.21848
Upper North Fork Nooksack River	56.79534	32.51902	37.18979
Cascade River	55.33492		55.33492
Lower Suiattle River	38.21559	7.37126	6.9513
Upper Sauk River	27.964		29.70408
Lower White River	23.73768	23.73768	23.73768
Tye River	22.19591		75.28205
Little Naches River	11.57607	11.57607	11.57607
North Fork Skykomish River	7.85		
Illabot Creek-Skagit River	6.21131	9.31546	
Diobsud Creek-Skagit River	3.79357	29.22454	
Headwaters Cowlitz River	3.23687		14.11405
Upper Suiattle River	2.36874		
Kachess River-Yakima River	2.04856		
Beckler River	1.67885		
Nason Creek	0.94891		
Lower Puyallup River	0.89772		
Lower Green River	0.82854		
Cedar River	0.68254		12.13669
Carbon River	0.28087		
TOTAL	**743.19522**		

Differences in Table 4 occur where one or the other input values is high and the composite score is not, for instance in the Headwaters Cowlitz River Watershed and the Diobsud Creek-Skagit River Watershed. In these cases, the ranks of the input data may warrant greater attention than the composite score indicates. Inspection of the roads in the Headwaters Cowlitz River Watershed reveals that the high soil moisture score is due to a bonafide high score for State Highway SR-123. But the peak flood score for this road was null due to incomplete coverage of the peak flood landscape. In contrast, the difference in scores for the Diobsud Creek-Skagit River Watershed is due to inverse correlation between the two input data sets, with soil moisture dipping as peak flooding increases.

Earlier snowmelt date results

The snowmelt date for MBSNF road segments under the 2040 climate scenario is shown in Figure 6. Roads are ranked by percentile, with ranks above the 70^{th} percentile (more than 20 days earlier) highlighted.

Roads exceeding the 70^{th} percentile score for predicted 2040 snowmelt date are widely distributed across the MBSNF, primarily at moderate elevations. Two concentrations of roads with 70^{th} percentile scores are in the Cedar River Watershed and on ridges to the southeast of Darrington and northwest of Darrington (North Mountain) extending to Sedro Wooley.

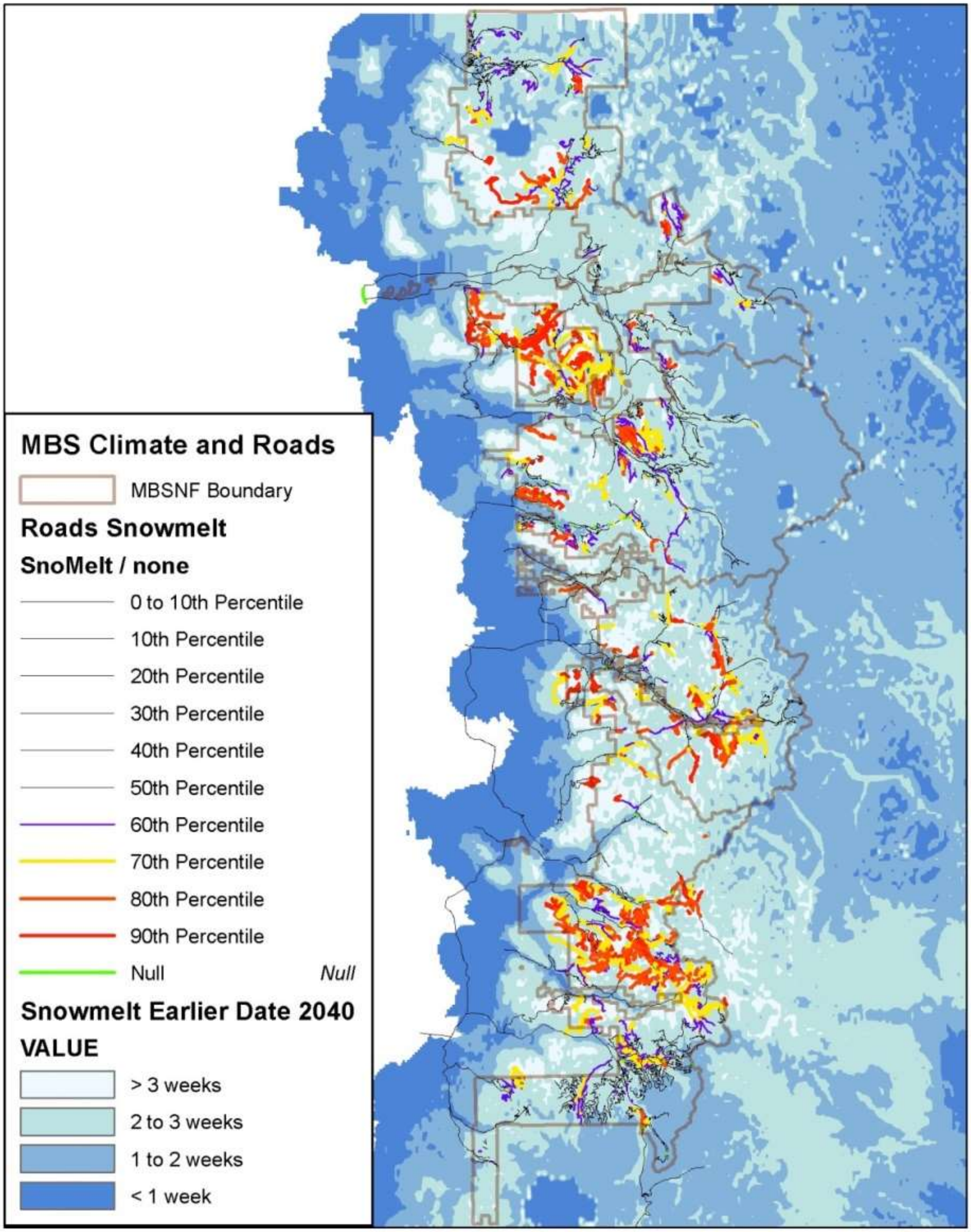

Figure 6. Projected 2040 snowmelt dates for MBSNF roads, overlaid on the projected 2040 snowmelt date landscape. Roads above the 70th percentile (more than 20 days earlier) are highlighted.

Road stream crossings density

The point file of road-stream intersections is shown in Figure 7. Many more stream crossings and culverts likely exist than indicated by this approach. Because the number of stream crossings (10,440 points) was about five times the number of road segments, the data was judged to be sufficiently dense to accurately represent a measure of stream proximity for most MBSNF roads.

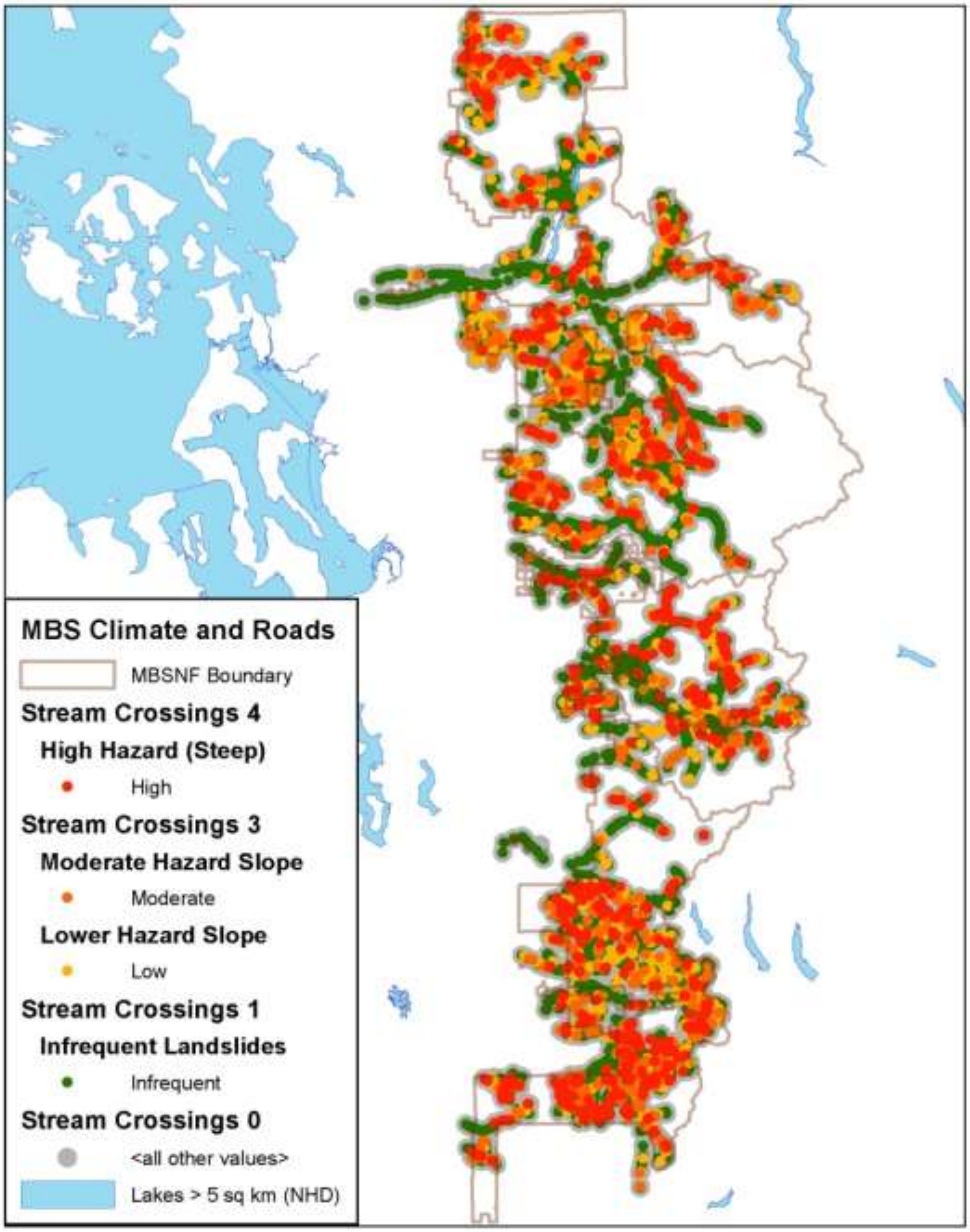

Figure 7. Road-stream crossings on the MBSNF. The hazard ranks were determined based on slope as explained in the section on hazardous stream crossings.

Figure 8 shows MBSNF roads classified by stream crossing density.

There were 1,462 roads with at least one stream crossing, ranging from 0.1 to 24.4 stream crossings per mile. The join produced 855 nulls, of which 146 were data processing artifacts and 709 were roads that did not have any stream crossings. The stream crossings are widely distributed across the MBSNF, without much correlation with elevation or directional position.

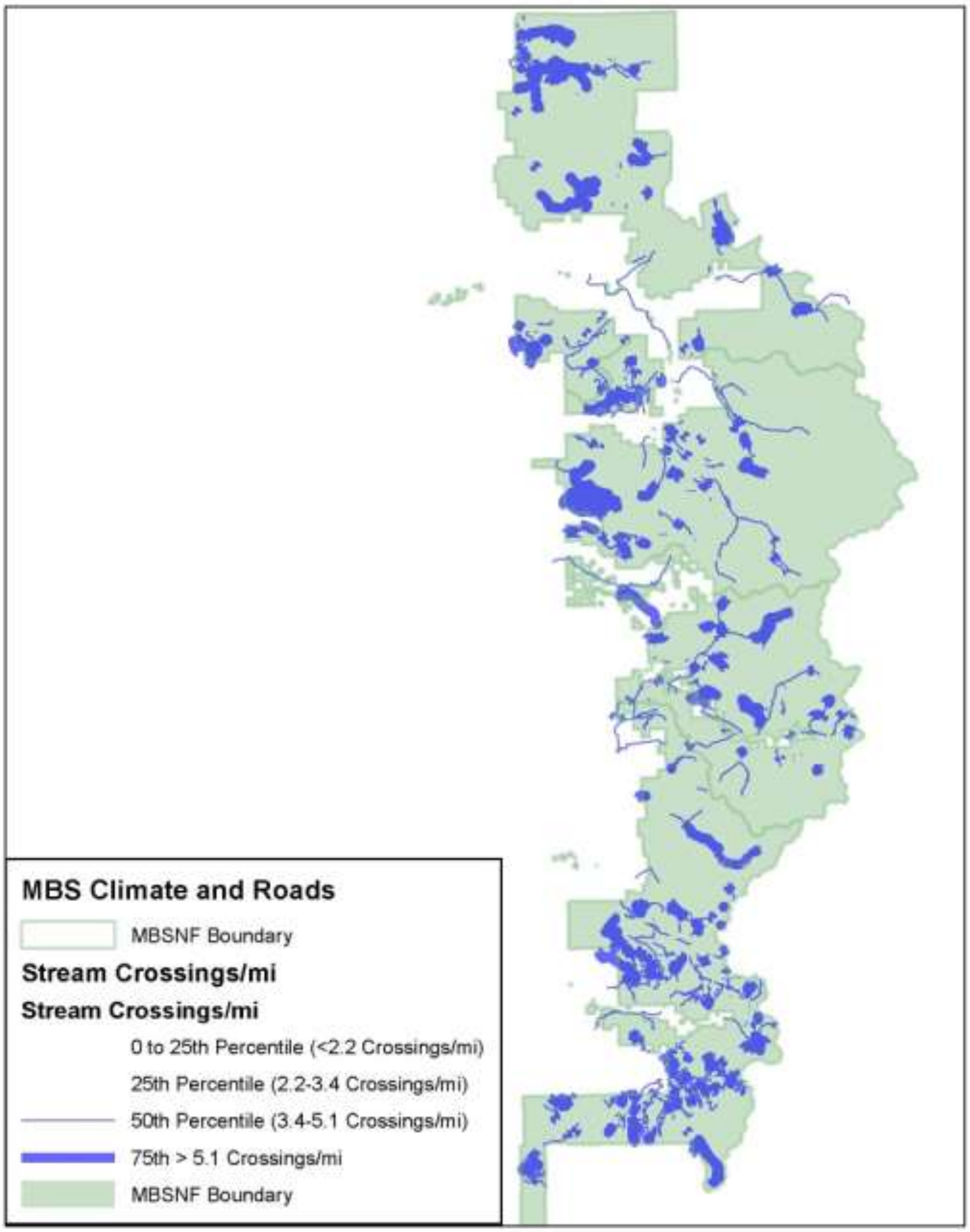

Figure 8. Stream crossings per mile of road. Roads with > 5.1 stream crossings per mile (75th percentile) are shown in heavy blue. Roads below the 50th percentile of crossings per mile are not shown.

Hazardous stream crossings

The density of hazardous stream crossings provides a measure of the current landslide hazard that is independent of the potential climate change. The total number of stream crossings on the MBSNF ranked by their landslide hazard potential is shown in Figure 7 and Table 5.

Table 5. Number of stream crossings for MBSNF road segments by hazard category based on the slope of the stream at the point where it crosses a road on the MBSNF.

Percent Slope	Landslide Hazard	Number of Road Crossings
(undetermined)	0-Unknown	146
0 – 35	1-Infrequent	6,459
36 – 45	2-Low	1,805
46 – 55	3-Moderate	1,271
56 – 109	4-High	1,076

The number of hazardous stream crossings per mile of road was calculated as an indicator of current landslide hazards for MBSNF road segments. When this layer is overlaid onto the climate change road hazard score map, it provides additional information for the long-term road system strategy. Figure 9 displays a map of stream crossings with high landslide hazard potential, displayed as the 75th percentile of hazardous stream crossing density (greater than or equal to 1.4554 crossings per mile).

There were 167 roads above the 75th percentile of hazardous stream crossing density, totaling 879 miles. There were 399 roads segments with at least one hazardous stream crossing. The density of crossings ranged from 0.02 to 20.2 hazardous crossings per mile. As with the full stream crossing data join, there were 855 nulls, of which 146 were data processing artifacts and 709 represented roads that did not have any stream crossings.

Figure 9 shows that roads with a high density of hazardous stream crossings (>75th percentile) tend to be shifted toward higher elevations compared to roads with high densities of all stream crossings. This results in a tendency to overlap roads with high climate hazard scores, which are also skewed toward higher elevations.

There were 42 road segments totaling 59 miles that had a both high density of hazardous stream crossings and high hazard scores. The watersheds that contained these road segments were the Upper North Fork Nooksack River, Illabot Creek-Skagit River, Cascade River, Lower Suiattle River, Upper Sauk River, North Fork Skykomish River, Upper Green River and Upper White River Watersheds, with the latter having the greatest number and mileage of those roads.

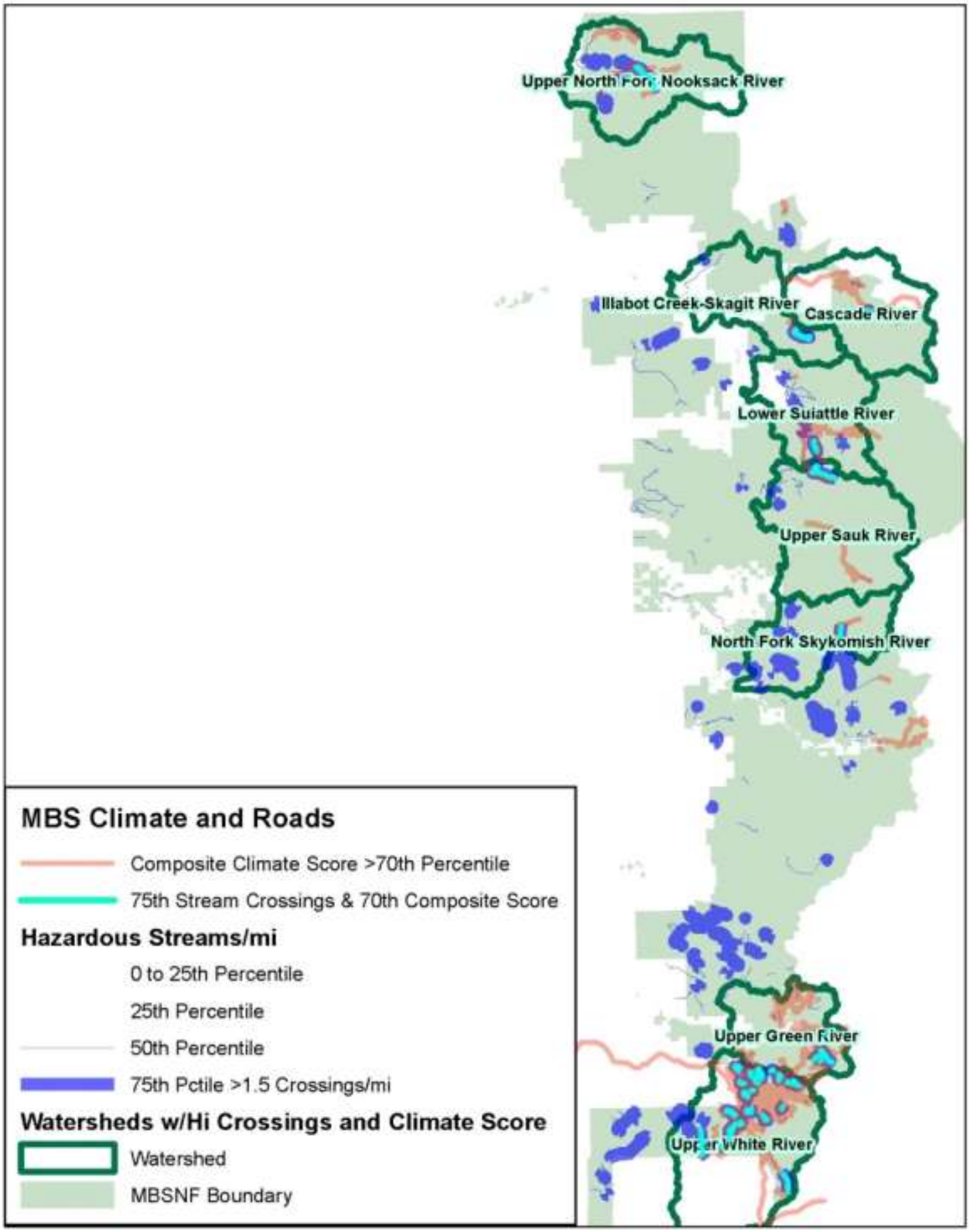

Figure 9. Roads ranked by the 75th percentile of the density of hazardous stream crossings per mile (thick blue lines), overlaid by the 70th percentile composite road hazard scores (thick red line). Bright blue lines outlined in purple indicate roads that have both high density of hazardous crossings and high hazard scores. Watersheds that contain these overlapping roads are outlined in dark green.

Discussion

In this study we analyzed the potential effect of changing climate on the MBSNF road system as the mean overlap of road segments on the potential climate change landscapes. Climate hazard scores are ranked using percentiles as a way of prioritizing management needs.

A composite climate hazard score was calculated to reduce the complexity of interpreting results. The composite climate hazard score was calculated so as to apply geometrically equivalent weights to the range of scores for peak flood level and soil moisture increase. Admittedly the use of equal weighting is arbitrary, so the analyses should be considered separately as well, at least for the highest hazard scores.

We identified which watersheds contained roads with high composite hazard scores and sorted them by those with the greatest mileage (Figure 5 and Table 3). There were 662 road segments ranked at the 70th percentile of the composite climate hazard scores, totaling 743 miles.

Table 3 compares the distribution of the composite climate scores with the potential changes in peak flooding and soil moisture. Overall there are more similarities than differences within watersheds. This strengthens the confidence that the composite climate scores are a realistic measure for ranking climate hazards of roads.

Watersheds with more than ten miles of road with 70th percentile scores are located in the Upper White River, Upper Green River, Upper North Fork Nooksack River, Cascade River, Lower Suiattle River, Upper Sauk River, Lower White River, Tye River, and Little Naches River. There were 440 miles of road above the 80th percentile (20% of the total MBSNF mileage) and an additional 304 miles of road between the 70th and 80th percentiles (14% of the total mileage).

The greatest concentration of roads with high potential climate hazard scores were located in the headwaters of the Upper White River and Green River Watersheds at the south end of the MBSNF. Roads within these two watersheds dominate the hazard scores down to the 80th percentile. This cluster of roads had high scores for both peak flooding as well as soil moisture. Interestingly, most of the roads in this cluster had high composite climate hazard scores without being upweighted by being within rain-on-snow subwatersheds.

If only the 2080 peak flood level was considered for ranking potential climate effects on roads, then there would be more roads with high hazard scores at the north end of the MBSNF where they overlap watersheds with high 2080 peak flood levels. These watersheds are the Upper North Fork Nooksack, Diobsud Creek-Skagit River, Illabot Creek-Skagit River, and the Lower Suiattle River.

The potential 2080 winter soil moisture increase was used as a surrogate for landslide risk. The winter soil moisture scenario was chosen as the input data set because it had the greatest magnitude of change across the MBSNF. The choice of the winter season is also supported by Strauch (2014, p. 11): "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)."

If only the potential 2080 soil moisture increase was taken into account, then the Headwaters Cowlitz River and Cedar River Watersheds would be ranked higher. In addition to prioritizing roads with high composite hazards within the long term road strategy, it is important that these other watersheds with high peak flood or soil moistures are taken into consideration.

Subwatersheds with high potential 2080 peak flood levels that do not overlap roads on the MBSNF should also be considered. They may still pose high landslide potential to other jurisdictions, as well as posing threats of downstream movements onto the MBSNF. These subwatersheds lie within the Chiwawa, Upper Suiattle, and White River-Little Wenatchee River Watersheds.

The potential for an area to incur landslides and debris flows is related to the topographic slope. According to Iverson (2013, p. 574):

> Debris flows typically originate from discrete or distributed source areas that have slopes > 30% mantled with soil and fragmented rock. This debris becomes thoroughly wet through introduction of surface water or groundwater, commonly as a result of intense rain or snowmelt. The water-laden debris starts to move downslope when frictional forces no longer can resist driving forces, and it then liquefies and begins to flow.

Strauch (2014) suggested that slope and stream proximity could be incorporated into a risk equation:

> 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). (Strauch 2014, p. 17)

As a measure of stream proximity, we determined the density of stream crossings on MBSNF roads. As a measure of currently existing landslide hazards we also determined the density of hazardous stream crossings, defined as crossings with steep slopes. There were 167 roads above the 75^{th} percentile of hazardous stream crossing density, totaling 879 miles.

The hazardous stream crossing density represents currently existing landscape features, in contrast to the climate hazard scores that represent future hazards. In theory, the total future hazard should be the sum of the current hazards plus that from projected climate change. By intersecting these two layers, we identified 42 road segments totaling 59 miles that had both high density of hazardous stream crossings and high composite climate hazard scores, that should be ranked as the highest priority for consideration under the long term road strategy.

Several assumptions that went into this analysis bear discussion.

The use of road-stream intersection points resulted in a rapid assessment of stream density and landslide hazard. Originally the intent was to determine the distance of road segments from all hazardous slopes, but over half of the MBSNF has steep slopes that would be complicated to prioritize for road management on that basis. In contrast, point intersections were readily calculated and they have the practical advantage that the result gives the exact location of stream crossings, which are where hazards and maintenance costs interact most strongly. The road-stream-slope point intersection method could be evaluated on other jurisdictions as a rapid assessment tool for maintenance costs and landslide hazards.

The projected snowmelt date for the 2040 climate scenario was evaluated for MBSNF road segments as a tool for prioritizing road maintenance for roads that might open earlier, and thus provide better visitor access as well as earlier inspection and maintenance periods during the season. Ronda Strauch's previous report raised this issue with the following statements:

> ... 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? (Strauch 2014, p. 17)
>
> 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. (Strauch 2014, p. 18)

The results showed that roads that become clear more than 20 days earlier under the 2040 climate scenario are widely distributed across the MBSNF, however several clusters may help guide more efficient maintenance changes.

In considering the practical use of this information beyond this study, the following points should be considered:

- Consider whether the soil moisture landscape might be improved by the use of a different season, such as spring, or by a calculating a composite of both spring and winter. An initial analysis used a composite of the 2040 spring and winter scores, resulting in greater variability at middle elevations, in contrast to the relatively even west-to-east increase presented here.
- Consider acquiring a more complete snowmelt coverage that covers all of the roads extending approximately seven km beyond the boundary of the MBSNF.
- Consider developing a more rigorous stream proximity and slope landscape, perhaps using high resolution DEMs, or by smoothing the slope data.
- Consider combining the stream crossing data with the climate hazard scores.
- Consider developing a culvert location database for all roads on the MBSNF. According to USGS Geologist Stephen Slaughter (pers. comm.), this would help determine road costs as well as the location and number of stream crossings and stream crossings on steep slopes.

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Appendix A. Data files created for this project

This section lists some of the main files used or created for the climate analysis of roads on the MBSNF. These files are available for sharing between partners. Many of the files are contained in subfolders within zip files in order to reduce the file size, reduce the number of files, and to give them more meaningful names.

Spreadsheet **MBS-road-climate-risk2015-final.xlsx**. This files contains data and calculations made for the climate analysis. The tabs are described as follows:

- Road Composite Risk - Composite road climate hazard scores.
- PeakFlood70thPercentile – Roads exceeding the 70th percentile scores for 2080 peak flood levels.
- SoilMoisture70th – Roads exceeding the 70th percentile for winter 2080 soil moisture increases.
- Composite70th – Roads exceeding the 70th percentile of composite climate hazard scores.
- 75th hazardous xings – Roads exceeding the 75th percentile of density of hazardous stream crossings

Input polygon files (asterisked files also contain KMZ files for viewing in GoogleEarth)
BasinType.zip/BasinType/**BasinType.shp***. This file contains the **precipitation regime** of the 12-digit subwatersheds for the historical period and each of the climate scenarios.

Input raster files
Q100Flood.zip/Q100Flood/ras/q100ras. This the original data set containing the **100-year flood volume** (the annual peak streamflow with a 1% probability of exceedance or Q100) for the historical period. The units are unspecified. This file was not used for this project. It was the basis for determining the changed peak flood level for the climate scenarios.

Snomout.zip/snomout/sn2040e. This file contains the date of **snowmelt** for the 2040 climate scenario.

Spr40soil.zip/spr40/spr40p. This file contains the **soil moisture** percent change for the spring 2040 climate scenario.

Win40soil.zip/win40/win40p. This file contains the **soil moisture** percent change for the winter 2040 climate scenario.

Win80.zip/win80/soiwin80. This file contains the **soil moisture** percent change for the winter 2080 climate scenario.

Road Climate Hazard Scores

Road-Climate-Hazard-Scores-Brief.zip/ Road-Climate-Hazard-Scores-Brief/**RoadEvOB1083.shp***. this is a linear feature file created as an event layer from the official map of roads on the MBSNF, with field [OBJECTID] as the unique name field for the events (2250 segments). It is projected into UTM Zone 10 NAD 1983. Most of the original fields contained in the official road layer have been removed to simplify analysis, however the original road designation fields are restored in shapefile RoadEvOB1083full.shp. An abbreviated set of fields summarizes the road data as follows:

[Level] – This is the road maintenance level.

[Level2] - This is the road maintenance level preceded by a code for the Administrating agency ("FS" represents Forest Service).

[Topo] – This field indicates the source of the data which required splitting and merging overlapping road segments froman early analysis done on a different set of MBSNF road layers.

[NAME] – This is the name of the road.

[LenMi] – This is the length of the road in miles.

[PkFlood] - Peak flood hazard scores determined as the mean overlap of the road segments with the peak flood landscape. Data was calculated as integer percent by multiplying the original floating point factors by 100 [PkFlood].

[PkFloodPc] - Peak flood hazard scores calculated only for the percent increase above historical levels by subtracting 100 from [PkFlood].

[SoiMoi] - The soil moisture hazard scores determined as the mean overlap of the road segments with the potential winter 2080 soil moisture landscape. Data is in floating point.

[SoiMoiPc] - The soil moisture hazard scores based on [SoiMoi] converted to the nearest integer values.

[SoilNorm] - The scores for soil moisture normalized to the full range of the peak flood levels by multiplying by 144/27.

[RiskComp] - The composite climate hazard score calculated as mean of the peak flood level increase in [PkFloodPc] plus the normalized soil moisture increase in [SoiMoiPc].

[SnoMelt] - This the projected 2040 snowmelt date given in days earlier than the present snowmelt date.

Road-climate-scores-sent-November.zip/ Road-climate-scores-sent-November/RoadEvOB1083full.shp. This is a linear feature file with the same features contained in RoadEvOB1083.shp, but with the full set of fields restored by joining to the original MBSNF data by linking field [OBJECTID2] to field [OBJECTID]. The climate hazard scores have the same names and meaning as described for file RoadEvOB1083.shp. A version of this file was shared with the MBSNF under the name RoadEvOB1183.shp, which incorrectly indicated the file occurred in a different projection.

Road-stream-crossings.zip/ Road-stream-crossings/**RdEvOBMrgSplitNonOver.shp***. This file contains the density of streams per mile, in field [StrmsPMi] and hazardous streams per mile, in field [HazStrmPMi]. [Name] is the road name and other fields are defined as described above. This table can be joined to the original road maintenance data table by joining [OBJECTID2] to [OBJECTID], but this join will not include road segments that were not contained in the original official road layer.

These additional "unofficial" roads came from a 2012 download from the MBS. Those unofficial road segments can be identified by having a non-blank value in RTE_NO.

HazardousRoadXStreamXings.zip/ HazardousRoadXStreamXings/**HazStrmInt70thComp.shp***. This file is an export from the above file of roads with stream crossing density (RdEvOBMrgSplitNonOver.shp) that only includes those road segments that had > 75th percentile stream hazard category and > 70th percentile climate hazard score.