DEVELOPMENT OF A DISTRIBUTED HYDROLOGY MODEL FOR USE IN A FOREST RESTORATION DECISION SUPPORT TOOL TO INCREASE SNOWPACK IN THE UPPER COLUMBIA

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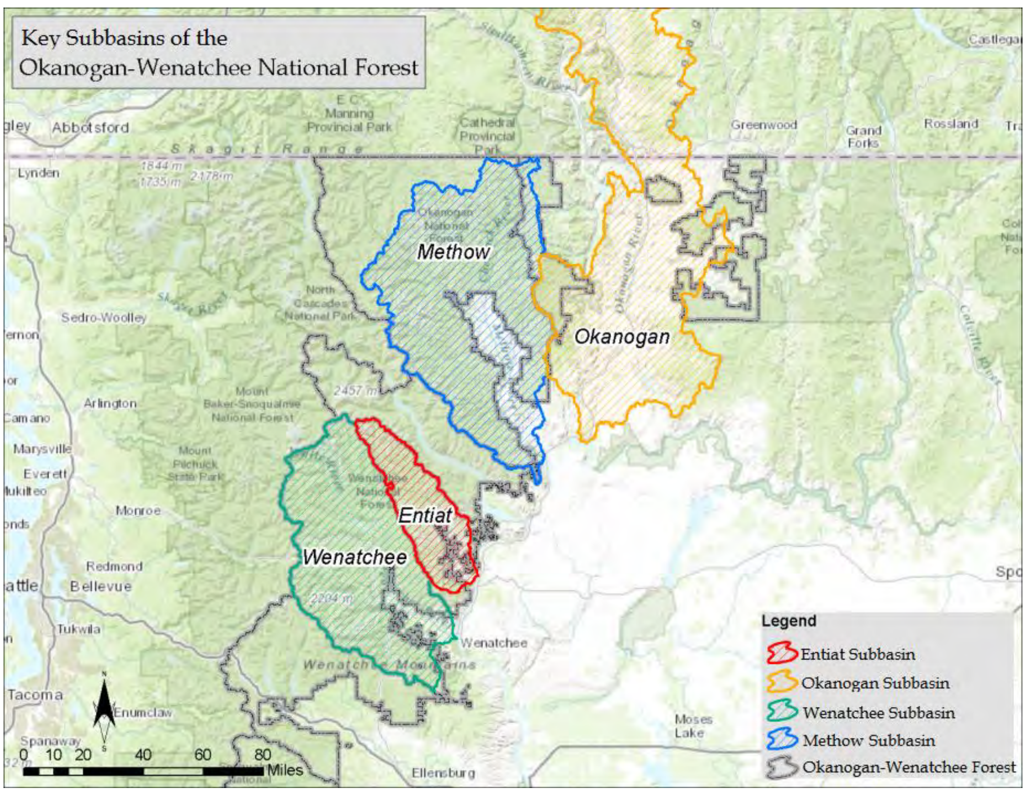

Executive Summary

Background

Management of public and private forest lands in the Upper Columbia River basin is necessary to ensure the sustainability of natural ecosystems and enhance protection and recovery of fish and wildlife populations. By 2030, summertime surface water demand is expected to significantly exceed supply in most years in many Upper Columbia tributaries; in some years, a portion of these tributaries will exceed supply even outside the summer months. Forest restoration (i.e., timber harvest, prescribed burning, thinning) reduces canopy cover and, subsequently, has been shown to increase snow accumulation and total runoff volume. Targeted forest restoration actions have the potential to help increase late season flows, while possibly reducing peak flows during the fall and winter to better meet salmonid habitat requirements.

The Okanogan-Wenatchee National Forest (OWNF), through its Restoration Strategy, is planning landscape-scale restoration of forested lands across north-central Washington with a goal of doubling the restoration footprint over the next decade. Such restoration includes conducting thinning and prescribed fires to move the forest, incrementally, back toward its historic range of variability, which is more resilient to catastrophic fire, disease, and pest epidemics. These efforts also provide an opportunity to positively influence streamflows. If tools are developed to strategically locate and design vegetation projects so that they can improve streamflow, the benefits could be significant in the watersheds of the Upper Columbia, and could help achieve both terrestrial and aquatic ecological objectives. Treatments resulting in increased snowpacks may provide hydrologic benefits for instream and out-of-stream uses, including extended runoff periods and shorter low-flow periods.

The impact of a particular forest management activity or disturbance on watershed hydrologic processes is highly variable, depending on local climate, soils, vegetation, topography, dominant basin orientation/aspect, and the spatial pattern of disturbance. Hydrologic models can be an important tool for estimating how changes in forest management practices can affect moisture states such as canopy interception storage, snow water equivalent, and soil moisture, and fluxes such as evapotranspiration, sublimation, and streamflow. They also provide a method of evaluating the likely effects of alternative forest management practices in isolation; that is, without layering in the additional complexity of variation in other basin properties and meteorological forcings.

Project Purpose

Under this project, funded by the Upper Columbia Salmon Recovery Board (UCSRB), researchers at Pacific Northwest National Laboratory evaluated the ability of a distributed hydrologic model to accurately predict hydrologic properties and changes associated with a range of precisely defined forest restoration scenarios in snow-dominated watersheds within the Wenatchee, Entiat, Methow, and Okanogan subbasins (Figure ES.1) under current and future climate conditions. As part of this effort, we evaluated whether restoration treatments of the type and magnitude anticipated for the OWNF have the potential to measurably increase flows in UCSRB priority watersheds.

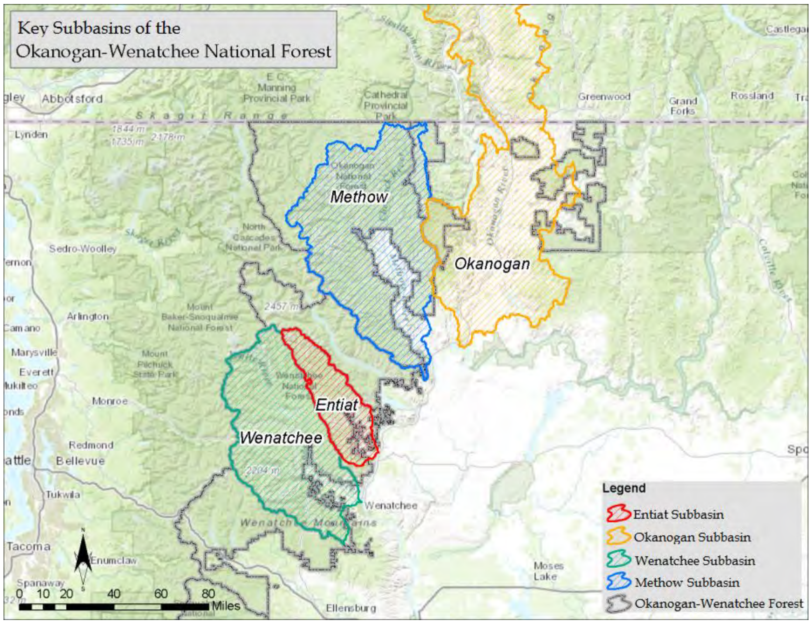

Figure ES.1. Overview of four key subbasins in the Okanogan-Wenatchee National Forest in the north-central Cascade mountain range.

Key Findings

Results derived from this study

- demonstrate the ability of the Distributed Hydrology Soil Vegetation Model (DHSVM) to accurately predict hydrologic properties and changes for select forested subbasins in the north-central Washington State.
- demonstrate the ability to prescribe realistic forest restoration scenarios in high spatial detail (90 m) within DHSVM to represent a range of management actions, including mechanical thinning and prescribed burns.
- suggest forest restoration will increase peak snow water equivalent and annual water yield (with reduction in overstory fractional coverage) under both current and future climate conditions, consistent with published paired watershed studies.
- suggest that the impact of forest restoration on the timing of snowmelt and streamflow varies from year to year and is highly dependent on local meteorological conditions (including solar radiation, downward longwave radiation, air temperature, humidity, and wind speed) and particular forest restoration scenarios (i.e., amount of overstory removed).
- suggest that under future climate conditions there will be a general increase in late fall and winter flows for all restoration scenarios and a decrease in flow during the summer and early fall relative to current climate conditions. However, forest restoration tends to decrease fall and winter flows and generally increases summer flows compared to a future climate condition no restoration baseline.

Data Inventory and Analysis

The DHSVM was selected to study the snow-dominated watersheds of the Wenatchee, Entiat, Methow, and Okanogan subbasins, because it was specifically designed to evaluate the effects of vegetation, vegetation change, and climate change on the hydrological cycle at spatial scales that are relevant for forest management practices.

We compiled a comprehensive inventory of available meteorological, snow water equivalent, and stream flow data along with digital elevation model terrain data, and SSURGO soils data to be used for model parametrization and testing. A spatial filtering process based on a geographic information system was implemented on the Wenatchee, Entiat, Methow, and U.S. portion of the Okanogan subbasins to better understand which (where and how much) forest lands are candidates for various forest management actions. We updated our analysis to include the areal extent of large 2014 wildfires (e.g., Carlton Complex) that affected the study basins, but the 2015 fires were not evaluated.

The spatial filtering process was initiated using the 8-digit Hydrologic Unit Code (HUC) boundaries for each basin, then eliminating areas within the subbasins based on a number of criteria, including National Park Service lands, U.S. Fish and Wildlife protected lands, wilderness areas, U.S. Forest Service (USFS) Category 1B and 1B-1 roadless areas, urban boundaries, developed areas, and non-forested land cover. Within these areas, lands inside and outside of USFS lands were evaluated. For the presented analysis, no slope stability (soil type, percent slope) or past mass wasting events were considered. Roadless areas were originally excluded from consideration, but are now included based on subsequent discussion with USFS staff. We identified 1,519 square miles (972,412 acres) of USFS and other lands potentially suitable for forest restoration (Table ES.1).

Table ES.1. Results of spatial filtering for four north-central Cascades subbasins, including the full subbasin area, filtered areas including only forested lands, area affected by 2014 wildfires, and roadless areas. The upper portion of the table includes total area in square miles, whereas the lower portion of the table includes percent area relative to the full subbasin area.

Area(sq mi)	Wenatchee	Entiat	Methow	Okanogan
Total Area	1328.8	418.3	1820.7	1611
USFS & Other-Forest Only	355.6	138.8	584.6	440.4
USFS only-Forest Only	329.9	128.9	548.3	152.7
Area Affected by 2014 Fires (August)	24	38.7	289.7	55.4
Area Affected by 2014 Fires (Current)	24.2	39.6	290.2	55.4
USFS & Other-Forest_Affected by 2014 Fires (Aug)	6.7	25.8	97.4	11
USFS & Other-Forest Affected by 2014 Fires (Dec)	6.7	26.5	97.5	11
Roadless Forested	167.11	60.61	164.81	13.01
Roadless Forested Affected by 2014 Fires	0.87	3.28	12.48	0

Percentage of Area(%)	Wenatchee	Entiat	Methow	Okanogan
Total Area	100%	100%	100%	100%
USFS & Other-Forest Only	26.76%	33.18%	32.11%	27.34%
USFS only-Forest Only	24.83%	30.82%	30.11%	9.48%
Area Affected by 2014 Fires (August)	1.81%	9.25%	15.91%	3.44%
Area Affected by 2014 Fires (Current)	1.82%	9.46%	15.94%	3.44%
USFS & Other-Forest Affected by 2014 Fires (Aug)	0.50%	6.17%	5.35%	0.68%
USFS & Other-Forest Affected by 2014 Fires (Dec)	0.51%	6.34%	5.35%	0.68%
Roadless Forested	12.58%	14.49%	9.05%	0.81%
Roadless Forested Affected by 2014 Fires	0.07%	0.78%	0.69%	0.00%

To identify key locations and watersheds for model application we considered available meteorological and streamflow data in conjunction with our spatial land filter and UCSRB priority areas (major spawning areas) for spring Chinook and Steelhead (Figure ES.2). Based on this analysis, we identified one watershed in each of the major subbasins: the Upper Entiat watershed (Entiat subbasin), the Chiwawa watershed (Wenatchee subbasin), the Upper Methow watershed (Methow subbasin), and the Omak Creek watershed (Okanogan subbasin).

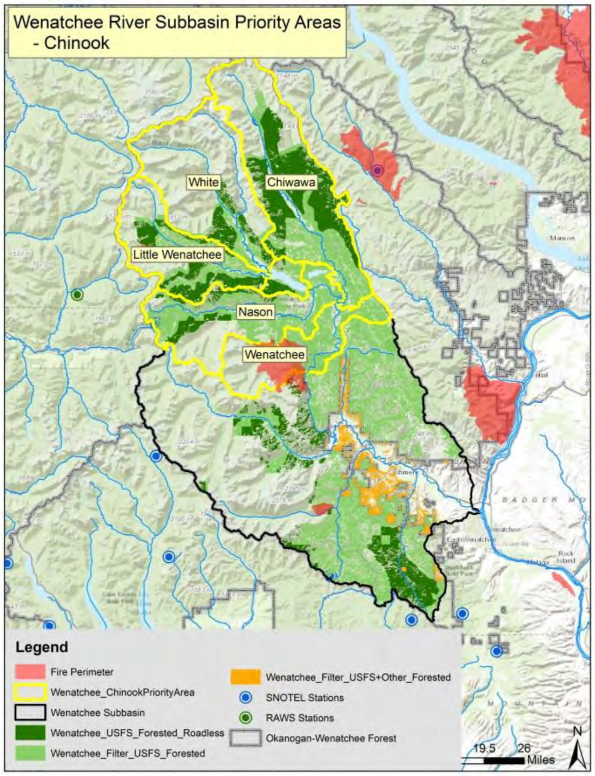

Figure ES.2. Example for Wenatchee subbasin showing UCSRB Chinook priority areas along with locations suitable for forest management and the extent of the 2014 wildfires.

Forest Restoration Strategy

Forest restoration scenarios were developed by USFS staff to be consistent with the OWNF Restoration Strategy and were spatially mapped to the DHSVM computational grid based on forest type, topographic classification, and fire index (Figure ES.3). Management actions were represented in DHSVM by changes in the overstory canopy fractional coverage in selected grid cells. Five restoration scenarios were evaluated along with two wildfire scenarios as described below:

Scenario 1a: The percentage of overstory fractional coverage of all ridgetop grid cells in both the Dry and Moist forest types (Dry/Moist forest hereafter) with overstory fractional coverage greater than 30% was reduced to 30% to represent mechanical thinning.

Scenario 1b: The percentage of overstory fractional coverage in higher elevation (top 50%) south-facing grid cells in the Dry/Moist forest with overstory fractional coverage greater than 50% was reduced to 50% to represent mechanical thinning.

Scenario 1c: The percentage of overstory fractional coverage of all south-facing grid cells in the Dry/Moist forest with overstory fractional coverage greater than 50% was reduced to 50% to represent mechanical thinning.

Scenario 2a: The percentage of overstory fractional coverage of grid cells in both the Cool and Cold forest types (Cool/Cold forest hereafter) that had a Fire Potential Index in the top 30% was reduced to zero to represent prescribed burning.

Scenario 2b: Grid cells in the Cool/Cold forest with a Fire Potential Index in the top 50% had their overstory fractional coverage reduced to zero to represent prescribed burning.

Scenario 3a: North-facing and valley bottom grid cells in all forest types with a Fire Potential Index in the top 10% had their overstory fractional coverage reduced to zero to represent loss by wildfires.

Scenario 3b: North-facing and valley bottom grid cells in all forest types with a Fire Potential Index in the top 30% had their overstory fractional coverage reduced to zero to represent loss by wildfires.

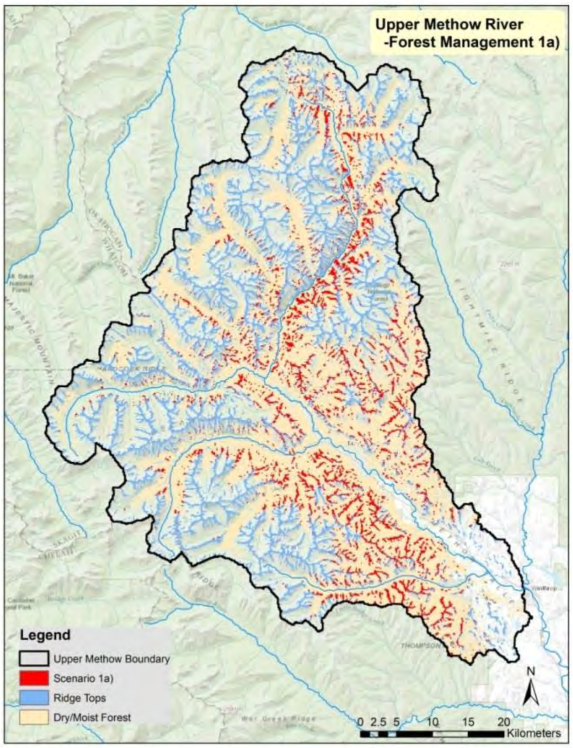

Figure ES.3. The Upper Methow watershed showing locations of forest restoration Scenario 1a with treatments on ridgetops in Dry/Moist forest types (red) where overstory fractional coverage was reduced to 30%.

Climate Change Scenarios

Our climate change scenarios are based on the Representative Concentration Pathway 8.5 (RCP8.5) emissions trajectory. This RCP is characterized by increasing greenhouse gas emissions over time, representative of scenarios in the literature that lead to high greenhouse gas concentration levels. To remove General Circulation Model (GCM) biases and apply this scenario we first calculated the difference between the monthly average temperatures of GCM gridded historic and the RCP8.5 future climate projections. The time period used to calculate historical monthly temperature data is 1975 to 2003 (29 years) and for future climate projection it is 2027 to 2055 (29 years). These differences (i.e., monthly deltas) ranged from 0.9 to 2.9°C depending on season and location, and were then added to observed meteorological station air temperature in each watershed to generate a time series of future temperature. Longwave radiation, short wave radiation, and relative humidity were then estimated based on modified temperature and corresponding precipitation data for the same period.

Results for the Upper Entiat Watershed

The DHSVM was driven at a 3-hour time step for 22 years (Water Year (WY) 1990–2011) in the Upper Entiat watershed based on meteorology generated from the Pope Ridge SNOTEL (snow telemetry) site. The model was calibrated for the period from WY 1999 to 2006. Mean daily simulated discharge was generally in good agreement with observed discharge. For the calibration period, the daily Nash-Sutcliffe Efficiency (NSE) value is 0.868 and for the validation period the NSE value was 0.737 with a total mass balance error of 0.27%.

The DHSVM was then run for all seven forest restoration scenarios plus the no restoration baseline under both current (observed) and future climate conditions. Reduction in overstory fractional coverage ranges from 1.3% to 15% depending on the scenario (Figure ES.4). An increase in water yield with forest restoration is evident under both climate scenarios ranging from 1.5–13.8 mm/yr under current climate conditions to 1.0–12.5 mm/yr under future climate conditions. Corresponding increases in annual streamflow range from 0.3–2.3% (0.2–2.1 cubic feet per second (cfs)) for current climate conditions and 0.2–2.1 % (0.6–7.4 cfs) for future climate conditions.

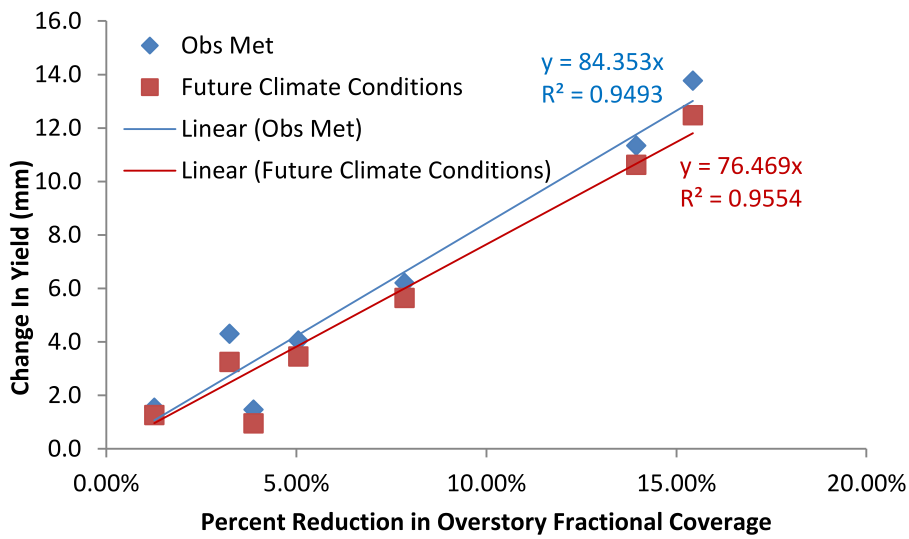

Figure ES.4. Increase in annual water yield (mm) in the Upper Entiat watershed as a function of percent reduction in overstory fractional coverage. For the current climate conditions (blue), a 1% percent reduction in fractional coverage will lead to 0.84 mm/yr increase in water yield versus 0.76 mm/yr under future climate conditions (red).

Under current climate conditions 7-day low flows are <u>increased</u> for all months (July through October) for all forest restoration scenarios except restoration in the Cool/Cold forest, which shows a general decrease relative to the no restoration baseline. Ridgetop thinning in the Moist/Dry forest shows the greatest percent increase from the current condition baseline, particularly in July with a 5% increase equal to 10 cfs above the baseline.

Under future climate conditions there is an increase in late fall and winter mean monthly flows (November through May), compared to current climate conditions for all forest restoration scenarios (including the no restoration baseline), and a decrease in flow during the summer and early fall (June through October). However, forest restoration tends to decrease fall and winter flows and generally increases summer flows compared to a future climate condition no restoration baseline.

Under future climate conditions there is an increase in late fall and winter 7-day average low flows (November through May), compared to current climate conditions for all scenarios (including the no restoration baseline), and a decrease in flow during the summer and early fall. However, forest restoration tends to decrease November through May flows and generally increase June through October low flows compared to a future climate condition no restoration baseline.

Results for the Chiwawa Watershed

The DHSVM was driven at a 3-hour time step for 4 years (WY 2011–2014) in the Chiwawa watershed within the Wenatchee subbasin. Model results are good with a NSE value of 0.808 and a total mass balance error of -2.78 %.

The DHSVM was then run for all seven forest restoration scenarios plus the no restoration baseline under both current (observed) and future climate conditions. Forest restoration scenarios in the Chiwawa watershed reduced overstory fractional coverage from 3.3% to 18.5% (Figure ES.5). A nearly identical increase in water yield with forest restoration is evident under both current and future climate conditions ranging from 2.8–23.8 mm/yr under current climate conditions, to 2.5–23.7 mm/yr under future climate conditions. Corresponding increases in annual streamflow range from 0.3–2.1% (1.4–11.9 cfs) for current climate and 0.2–2.1 % (1.3–11.9 cfs) for future climate conditions.

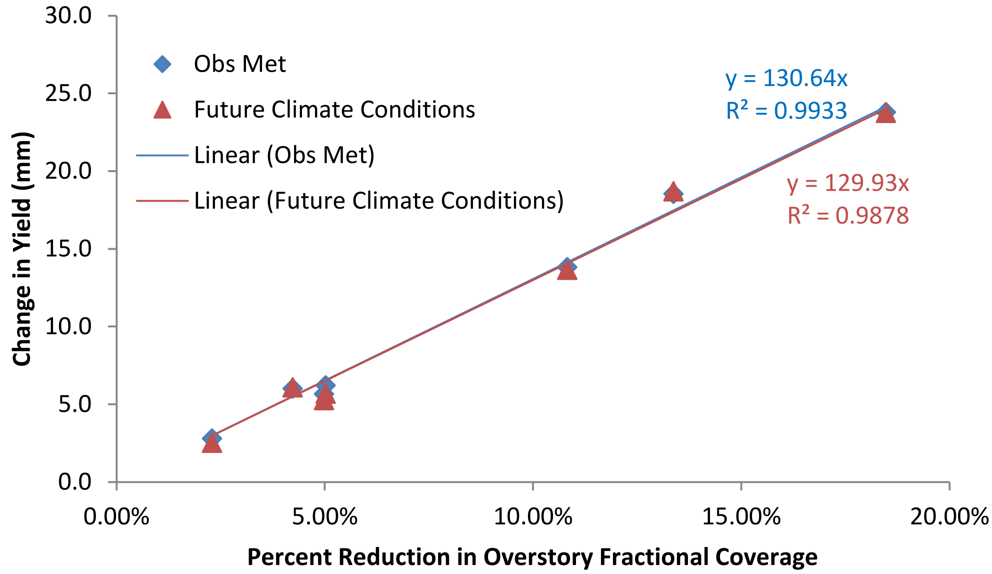

Figure ES.5. Increase in annual water yield (mm) in the Chiwawa watershed as a function of percent reduction in overstory fractional coverage. A nearly identical increase in water yield with forest restoration is evident under both current climate conditions (blue) and future climate conditions (red). In both cases, a 1% per percent reduction in fractional coverage yields a 1.3 mm/yr volume increase in water yield.

Under current climate conditions 7-day low flows are reduced for all scenarios relative to the baseline in May and increased for all scenarios in June. Scenarios 1a,b,c continue to show an increase in low flows July through August. Scenarios 2a,b and 3a,b show decreased lows flows beginning in July.

Under future climate conditions there is an increase in late fall and winter mean monthly flows (October through April), compared to current climate conditions for all scenarios (including the no restoration baseline), and a decrease in flow during the summer and early fall (May through September). However, forest restoration tends to decrease November through April flows and generally increases May through October flows compared to the future climate condition no restoration baseline.

Under future climate conditions there is an increase in late fall and winter 7-day average low flows (October through April), compared to current climate conditions for all scenarios (including the no restoration baseline), and a decrease in flow May through September. However, forest restoration tends to decrease December through April flows and generally increases May through October flows compared to a future climate condition no restoration baseline.

Results for the Upper Methow Watershed

The DHSVM was driven at a 3-hour time step for 15 years (WY 1992–2006) in the Upper Methow watershed based on meteorology generated from two National Oceanic and Atmospheric Administration stations at Mazama and Winthrop. The model was calibrated for the period from WY 1991 to 1997 and validated for the period WY 1998 to WY 2006. Model results were fair with a NSE value of 0.469 during calibration and 0.733 for the validation period. The NSE value for the entire 15 years is 0.625 with a relatively large total mass balance of -14.7%.

The DHSVM was then run for all seven forest restoration scenarios plus the no restoration baseline under both current and future climate conditions. Forest restoration scenarios in the Upper Methow watershed reduced fractional coverage from 2.6% to 9.9% (Figure ES.6). An increase in water yield with forest restoration is evident under both current and future climate conditions, ranging from 0.6–9.5 mm/yr under current climate conditions, to 0.5–10.4 mm/yr under future climate conditions. Corresponding increases in annual streamflow range from 0.1–2.3% (0.9–14.1 cfs) for current climate conditions and 0.1–2.5 % (0.8–15.3 cfs) for future climate conditions.

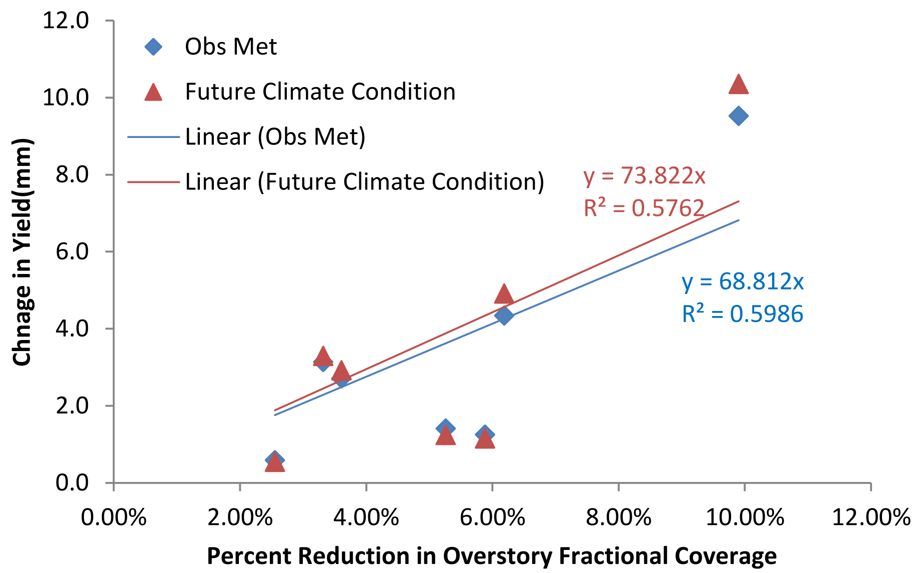

Figure ES.6. Increase in annual water yield (mm) in the Upper Methow watershed as a function of percent of the overstory fractional coverage reduced. For current climate conditions (blue), a 1% per percent reduction in fractional coverage will lead to 0.68 mm/yr volume increase in water yield; this increases slightly to 0.74 mm/yr under future climate conditions (red).

Under current climate 7-day low flows are decreased in May for all restoration scenarios. Scenario 1a (and to a lesser extent 3b) shows increased 7-day low flows June through October, while 1b and 1c show little change from baseline over the same time period. Scenarios 2a and 2b show a decrease from baseline June through August.

Under future climate conditions there is an increase in fall through spring mean monthly flows (October through May), compared to current climate conditions for all scenarios (including the no restoration baseline), and a decrease in flow during June and July. However, forest restoration tends to decrease March and April flows and generally increases June and July flows compared to the future climate condition no restoration baseline.

Under future climate conditions there is an increase in late fall through spring 7-day average low flows (November through May), compared to current climate conditions for all restoration scenarios (including no restoration baseline), and a general decrease in flow during the summer and early fall (June through October). However, forest restoration tends to decrease December–April flows and generally increases June through October flows compared to the future climate condition no restoration baseline.

Results for the Omak Creek Watershed

We faced several obstacles in the Okanogan subbasin. Meteorological data are limited and the main-stem Okanogan River is highly regulated. With limited options, we selected Omak Creek for model application based largely on the presence of forest cover and the availability of observed unregulated streamflow. However, a quality check of the data revealed several periods of missing data, and large amounts of data marked as "not yet checked" or "provisional." Furthermore, since the late 1990s, several watershed rehabilitation efforts to re-establish summer Steelhead have been implemented in Omak Creek. Those efforts include installation of instream structures, road decommissioning, and culvert replacement, making it hard to test and evaluate model performance in the basin.

We ran the model for 10 years (WY2003–2012) based on meteorology generated from the Kramer Remote Automatic Weather Station outside of the basin. No model performance statistics were calculated but visual inspection indicates poor model performance. The limited available data were entirely inadequate to conduct the diagnostic studies needed to improve the model. Consequently, we have not included Omak Creek results in this report.

Regional Application

Our analyses demonstrated the value of DHSVM modeling in identifying potential improvements in streamflow volume and timing in the pilot watersheds, our findings suggest future application of DHSVM in the wider north-central Cascade region would also benefit greatly from the following:

- targeted field measurements for model parameterization, including skyview fraction, leaf area index, and snow albedo in the open and forest during snow accumulation and melt;
- spatial canopy characteristics including tree clumps and gaps;
- improved meteorological data, including the use of gridded products to better capture spatial variability and the potential use of remote-sensing data to estimate atmospheric longwave radiation;
- additional model validation data over a range of climate zones and canopy types/fractional coverage that could include targeted use of game cameras to record the presence/absence of snow and depth. The potential use of remote sensing for the presence/absence of snow;
- an improved DHSVM radiation balance to better represent canopy vertical (light attenuation) and spatial (tree clumps and gaps) characteristics.

Acronyms and Abbreviations

°C	degree(s) Celsius
°F	degree(s) Fahrenheit
CC	Canopy Cover
Cfs	cubic feet per second
CH	canopy height
CRHM	Cold Region Hydrology Model
DEM	digital elevation model
DOE	U.S. Department of Energy
DHSVM	Distributed Hydrology Soil Vegetation Model
EVH	Existing Vegetation Height
EVT	existing vegetation type
Ft	foot (feet)
GCM	General Circulation Model
GeoMAC	Geospatial Multi-Agency Coordination Group
Hr	hour(s)
HUC	Hydrologic Unit Code
in.	inch(es)
kPa	kilopascal(s)
LAI	Leaf Area Index
LFRDB	LANDFIRE reference database
M	meter(s)
mm	millimeter(s)
mph	mile(s) per hour
NOAA	National Oceanic and Atmospheric Administration
NRC	National Research Council
NSE	Nash-Sutcliffe Efficiency
OWNF	Okanogan-Wenatchee National Forest
PNNL	Pacific Northwest National Laboratory
RAWS	Remote Automatic Weather Station
RCP8.5	Representative Concentration Pathway 8.5
RHESSys	Regional Hydro-Ecological Simulation System
SNOTEL	snow telemetry
SWC	Snow Water Content
SWE	Snow Water Equivalent
TAG	Technical Advisory Group
UCSRB	Upper Columbia Salmon Recovery Board

USFS	U.S. Forest Service
USGS	U.S. Geological Survey
WaSiM-ETH	Wasserhaushalts-Simulations-Modell
WY	Water Year
yr	year(s)

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1.0 Introduction

Management of public and private forest lands in the Upper Columbia River basin is necessary to ensure sustainability of natural ecosystems and enhance protection and recovery of fish and wildlife populations. By 2030, it is anticipated that summertime surface water demand will significantly exceed supply in most years in many Upper Columbia tributaries; in some years, a portion of these tributaries will exceed supply even outside the summer months. Forest restoration (i.e., timber harvest, prescribed burning, thinning) reduces canopy cover and subsequently has been shown to increase snow accumulation and total runoff volume. Targeted forest restoration actions have the potential to help increase late season flows, while possibly reducing peak flows during the fall and winter to better meet salmonid habitat requirements. A tool that can balance competing demands for water is needed for salmonid recovery in the Upper Columbia River basin.

In many mountainous regions, the winter snowpack is the primary source of water, which is also the foundation of many ecosystem services. In snow-dominated areas of north-central Washington, the amount of water present in the snowpack on 1 April can explain from 60 to 90% of the variation in annual runoff. Overall, as much as 95% of the total annual streamflow in higher elevations originates as melting snow, while only 3 to 5% of the rainfall becomes streamflow. In coniferous forests in these areas, roughly 25 to 35% of the winter snowpack is intercepted and lost to the atmosphere by some combination of sublimation and evaporation. Changes in interception accumulate over the course of the winter and can represent a significant change in water inputs during spring melt.

In general, basins that have been harvested produce greater water yields. Numerous studies conducted worldwide support this conclusion. Forest restoration (primarily through thinning and gap creation) can affect several processes that influence snowpack and forest water yield. On average, annual runoff has been found to increase by 1.1 to 2.5 mm for each 1% of watershed area. There is also evidence that in some forests low flows during dry periods can increase after harvesting because of increased soil and groundwater recharge. These factors can cause soil water content, groundwater, and runoff to be higher in treated vs. untreated areas. The response, however, is highly variable and is affected by factors such as climate, geology, soils, topography, and vegetation. Hydrologic models are an important tool for estimating how changes in forest management practices can affect moisture states such as canopy interception storage, snow water equivalent, and soil moisture, and fluxes such as evapotranspiration and streamflow. In addition, these models provide the only means for evaluating the likely effects of alternative forest management practices on isolation, that is, without layering in the additional complexity of variation in other basin properties and meteorological forcings.

The Okanogan-Wenatchee National Forest (OWNF), through its Restoration Strategy, is planning landscape-scale restoration of forested lands across north-central Washington with a goal of doubling the restoration footprint over the next decade. Such restoration includes thinning and prescribed fire to move the forest, incrementally, back toward its historic range of variability, which is more resilient to catastrophic fire, disease, and pest epidemics. These efforts also provide an opportunity to positively influence streamflows. If tools are developed to strategically locate and design vegetation projects so that they can improve streamflow, the benefits could be significant in the watersheds of the Upper Columbia River basin, achieving both terrestrial and aquatic ecological objectives. Treatments resulting in increased snowpacks may provide hydrologic benefits for instream and out-of-stream uses, including extended runoff periods and shorter low-flow periods.

Improvements in flow will benefit fish species that are listed under the Endangered Species Act. In the late 1990s, three fish species were listed in the Upper Columbia region: Upper Columbia spring Chinook salmon, Steelhead, and Bull Trout. Given the current trends in flow and temperature and the linkages between healthy forests and aquatic habitat quality, functional upland ecosystems will play a key role in ensuring the long-term recovery and viability of these species. Large-scale restoration of forests in areas where snowpack supplies late season flows may help increase flow during critical rearing and migration periods, while reducing peak flows in the spring and winter during incubation and emergence.

An ecohydrological perspective is critical for understanding how forest management affects water supply in north-central Washington, for predicting future vulnerabilities in water resources and for developing tools to help mitigate these vulnerabilities. Forest management may be one of a few tools to increase water supply in snow-dominated systems. Acquiring and leasing water through more traditional means is becoming controversial, costly, and challenging, and is likely to become even more difficult in the future. Conversely, forest management could be a tool that benefits multiple stakeholders and has beneficial impacts on flow. That is the focus of the research reported herein—to determine whether restoration treatments of the type and magnitude anticipated have the potential to measurably increase flows in the Upper Columbia Salmon Recovery Board's (UCSRB's) priority subbasins. Implementation and parameterization of an appropriate ecohydrological model is the first step in developing strategies to influence streamflow through forest management.

1.1 Project Objectives

Pacific Northwest National Laboratory (PNNL) evaluated the ability of a distributed hydrologic model to accurately predict hydrologic properties and changes associated with a range of precisely defined forest restoration scenarios within portions of the Wenatchee, Entiat, Methow, and Okanogan subbasins (Figure 1) under current and future climate conditions. Specific objectives of this project are to do the following:

- Evaluate and select an appropriate physics-based, distributed hydrologic model that will meet the needs and objectives of the UCSRB.
- Identify appropriate data for model parameterization and testing.
- Conduct a comprehensive review of existing data and information; identify open questions and additional data needs.
- Implement the hydrologic model in watersheds where snowpack is the primary driver for instream flow and forest restoration has the potential to influence snowpack under current and future climatic conditions.
- Provide an assessment of the ability of the model to accurately predict hydrologic properties and changes for north-central Washington.
- Assess the adequacy of existing data to expand the modeling effort to all forested watersheds of north-central Washington.

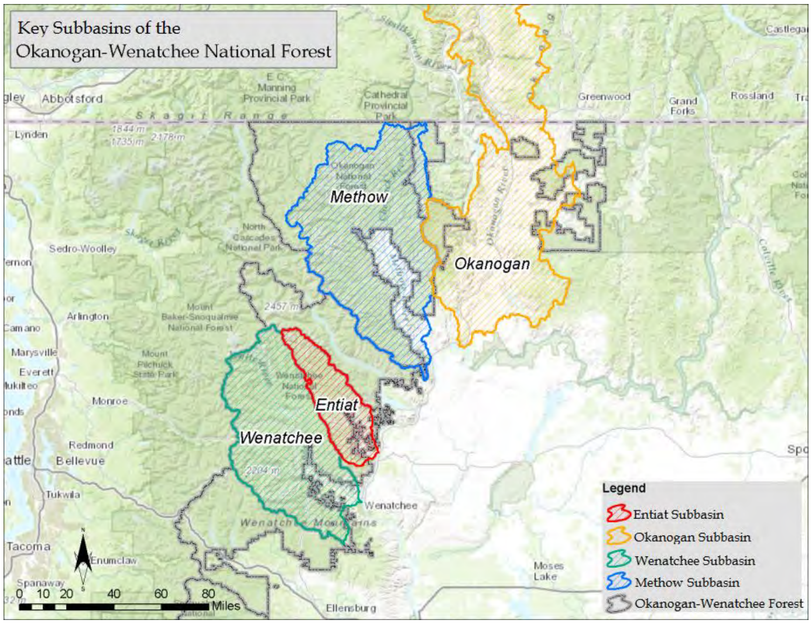


Figure 1. Overview of four key subbasins in the Okanogan-Wenatchee National Forest in the north-central Cascade Mountain range.

1.2 Technical Approach and Methodology

Project activities were coordinated with a Technical Advisory Group (TAG) composed of technical experts and relevant stakeholders. Project objectives were met through completion of the following four major tasks:

- **Task 1. Model Selection**. We evaluated existing distributed hydrologic models that incorporate snow modeling processes for their ability to address the forest management questions of this project, subject to available data (Task 2), and the soil, vegetation, and hydroclimatic conditions specific to this project and the north-central Cascades. In consultation with the TAG, the Distributed Hydrology Soil Vegetation Model (DHSVM) was selected as the best model to meet the project objectives.
- **Task 2. Data and Information Inventory**. We conducted a comprehensive review of data and information to better understand the impacts of forest management activities on hydrologic processes in the north-central Cascades, with particular focus on snow accumulation and melt. This review included previous DHSVM applications and an inventory of the best available data for hydrologic model parameterization and testing. We also identified and documented in this report open questions and information needs.
- **Task 3. Model Parameterization**. Based on the knowledge gained in Tasks 1 and 2, we identified select watersheds to determine where snowpack is the primary driver for instream flow and where forest management practices have the potential to influence snowpack. This allowed us to focus our model parameterization and testing activities in the appropriate watersheds to meet project objectives. As part of this effort, we tested and modified existing DHSVM parameterizations for the desired outputs related to forests, snowpack, and streamflow.
- **Task 4. Model Testing**. Building from Task 3, we assessed the ability of DHSVM to generate reliable simulations at multiples scales and locations using robust parameterization. The model was then used to identify locations and watershed characteristics where forest management will have the most beneficial impact. The outcome of testing was an assessment of the ability of the model to

accurately predict hydrologic properties and demonstrate the impact that specific forest management practices have on the hydrology of the north-central Washington region.

Project results are presented in the remainder of this report, as follows:

- **Chapter 2** – A scientific background describing the impacts of forest management on forest hydrology and water yield
- **Chapter 3** – The process and justification for selecting the DHSVM
- **Chapter 4 –** Baseline data and information for model parameterization, including available meteorological, snow, streamflow, soils, and vegetation data
- **Chapter 5 –** The methods used to identify locations for potential restoration, UCSRB priority areas and streamflow metrics, the impact of recent wildfire, and the seven specific spatial restoration scenarios that were considered
- **Chapter 6** – Description of climate change scenarios
- **Chapter 7** – Results of model application in the Entiat subbasin
- **Chapter 8** – Results of model application in the Wenatchee subbasin
- **Chapter 9** – Results of model application in the Methow subbasin
- **Chapter 10** – Results of model application in the Okanogan subbasin.

2.0 Scientific Background

2.1 Forest Management Impacts on Forest Hydrology

In North American forests, evaporation of precipitation intercepted by vegetation and transpiration of water in the soil (evapotranspiration) accounts for 40–85% of gross precipitation (NRC 2008). Forest management (e.g., prescribed burns, thinning, timber harvest) and forest disturbances (e.g., wildfire, disease, insect infestation) may directly affect forest canopy, understory, and soil properties. Loss of forest canopy (reduction in Leaf Area Index [LAI]) reduces the amount of precipitation that is intercepted and returned to the atmosphere through evaporation or, in the case of snowfall, sublimation. This results in a net increase of water reaching the forest floor. Reduced leaf area decreases interception rates in both rain- and snow-dominated systems; in snow-dominated systems an increase in precipitation reaching the forest floor increases water stored in the snowpack (Neary and Folliott 2005; NRC 2008; Woods et al. 2006). A reduction in leaf area, resulting from forest harvest, fire, or insect and disease outbreaks, also reduces the transpiration of soil water and increases water available for streamflow.

In forested areas, most soils readily absorb water. As a result, most water moves downslope through the soil matrix as subsurface flow. Surface overland flow is rare, except close to stream channels where the water table may intersect the soil surface, resulting in “return flow” and “saturation overland flow.” Forest management activities and forest disturbances may remove or alter the surface layers of forest soils, thereby reducing infiltration and increasing flow over the soil surface (Horton overland flow). The reduced evapotranspiration through canopy removal may result in high local water tables and increased areas of return flow.

Forests intercept snow and emit longwave radiation but also shelter the snow from wind and solar radiation relative to open areas. A **decrease** in forest density through natural or managed restoration activities

- reduces canopy snow interception and increases below-canopy snow accumulation;
- reduces canopy longwave radiation, which by itself tends to reduce below-canopy snowmelt;
- increases below-canopy shortwave (solar) radiation, which by itself will increase below-canopy snowmelt; and
- increases sensible (air-snow heat conduction) and latent heat transfer (sublimation/condensation), which can either increase or decrease below-canopy snowmelt depending on current temperature and vapor differentials between the snow and air.

Local energy balance determines whether a reduction in forest density increases below-canopy snow duration and the magnitude and timing of melt. Key biophysical properties driving the local energy balance are topography (elevation, slope, aspect, and shading), the meteorological time series (annual, seasonal, daily, and diurnal), the evolution of snow albedo, and canopy characteristics.

Lundquist et al. (2013) investigated the relationship between snowpack duration and key meteorological variables. They found that in locations with higher mean December–February air temperature (>-1°C) snow tended to persist longer in open areas than in forested areas (Figure 2). Snow tended to persist longer in the forest in locations with colder winter air temperature. As the authors note, “mountains span a wide range of elevations and microclimates within a short horizontal distance. Thus, snow at lower elevations may last longer in clearings while snow at higher elevations lasts longer under the forest, and the precise elevation where this shift occurs likely varies between years and between different forest structures.”

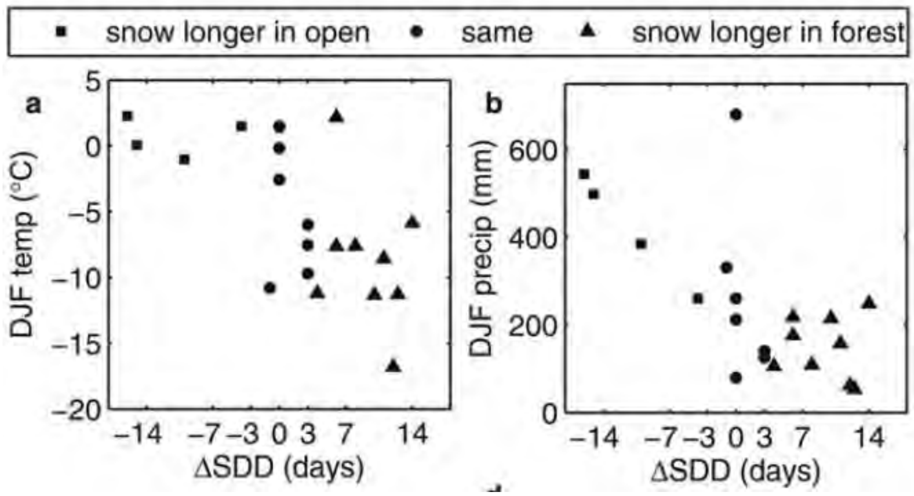


Figure 2. Comparison of snow disappearance date as a function of mean December–February (DJF) air temperature (left) and precipitation (right) (from Lundquist et al. [2013]).

2.2 Forest Management Impacts on Water Yield

Dozens of paired watershed forest harvest experiments have demonstrated that forest removal increases water yield (Bosch and Hewlett 1982; Hornbeck et al. 1997; Ice and Stednick 2004; Jones and Post 2004; Brown et al. 2005). The National Research Council (NRC 2008) provides a recent review of this topic. While noting results are highly variable depending on local conditions, several general conclusions can be made. In regions with dry summers and wet winters (western forests), the largest water yield increases occur in the late fall and early winter because of a reduction in transpiration and a resultant increase in soil moisture carryover (Jones and Post 2004). In snowmelt-dominated regions, most of the water yield increase occurs in spring because larger snowpacks accumulate in cutover areas (Harr et al. 1979; Troendle and King 1985; Troendle and Reuss 1997; Jones and Post 2004). In both eastern and western forests, water yield increases after forest harvest often occurring during seasons when water is abundant, not scarce (Harr 1983; Troendle et al. 2001).

Forest harvest experimental treatments in the NRC report ranged from 100% clearcutting to partial cuts, overstory thinning, or selective harvesting of a fraction of watershed area. In areas with more than 500 mm of mean annual precipitation (the Pacific Northwest, Northeast, and Southeast), water yield increases are roughly proportional to the amount of forest area cut (Hibbert 1967; Bosch and Hewlett 1982). Water yield increases are difficult to detect when less than 20% of the basin area has been harvested (Stednick 1996).

An extensive body of literature suggests a generally linear increase in water yield with increases in the percentage of forest removed. Bosch and Hewlett (1982) evaluated 94 paired watershed studies for the maximum increase in water yield in the first five years after treatment. They found a maximum increase of 40 mm/yr for a 10% reduction in coniferous forest. As noted by Brown et al. (2005) the use of maximum increase is also likely to be driven by climate variability because the maximum increase will generally correspond to the year of greatest rainfall (Brown et al. 2005). Sahin and Hall (1996) built on the work of Bosch and Hewlett (1982) to look at the average water yield over the same five-year period of time and found an average increase in water yield of 20–25 mm/yr for a 10% reduction in coniferous forest.

Scherer and Pike (2003) conducted a detailed literature review relevant to the potential effects of forest management on streamflow in the Okanagan Basin. Literature was considered relevant if the studied watersheds were dominated by snowmelt, and if they met the following criteria:

- predominantly covered with coniferous forest types such as lodgepole pine, Engelmann spruce, Douglas fir, white fir, subalpine fir, ponderosa pine, or grand fir
- located in central British Columbia, or east of the Rocky Mountains in Alberta, Utah, Idaho, Colorado, eastern Oregon, eastern Washington, or Arizona.

Given that the observed response of water yield to timber harvesting is highly variable and complex, the authors "found it difficult to create general quantifiable 'rules-of-thumb', or guidelines regarding how harvesting method, location, and rate of harvest will affect water yield." However, based on work by Bosch and Hewlett (1982), Reiter and Beschta (1995), Stednick (1996), and Summit Environmental Consultants Ltd. (2001), they suggest the following generalizations:

- Timber harvesting can be expected to cause the largest increases in water yield in areas where the moisture content of the soil is high during the growing season. Timber harvesting in the streamflow generation zones of a watershed (i.e., forest snowpack zone) is more likely to affect an increase in water yield.
- Streamflow responses to timber harvesting depend on the precipitation in a given year. An area with high mean annual precipitation will tend to show a larger increase in water yield than an area with low mean annual precipitation.
- As vegetation recovers, annual water yield will decrease.
- Increases in water yield are unlikely to occur as a result of timber harvesting in areas with precipitation <400 mm/yr, and the potential for increases is only marginal in areas with precipitation between 400 and 500 mm/yr.
- Increases in water yield become difficult to detect in larger basins because of variations in groundwater storage and release, tributary contributions, and differing patterns of precipitation or snowmelt across a basin.

Stednick (1996) reviewed 95 paired watershed studies and reports regression model statistics for annual water yield increase versus percent harvest area for all studies and by hydrologic region. The percent catchment area harvested was assumed to be directly proportional to basal area, thus a 25% basal area removal equated to harvesting 25% of the catchment area. No attempt was made to separate harvest area location in the catchment or harvest type on water yield, which may also account for some of the observed variability in water yield. The water yield increase was the maximum increase reported in the 5 years since treatment. A linear fit through all 95 sites with a range of forest types yielded a slope of 2.46 mm per each 1% treated (i.e., 25 mm/yr for a 10% reduction in forest cover). The Rocky Mountain/ Inland Intermountain hydrologic region is the most similar to our study site, and resulted in a slope of 0.94 mm per each 1% treated. However, these 35 sites included 9 sites that were dominated by aspen, chaparral, or the cover type was unidentified. We removed these results and found a slope of 1.14 mm/yr for each 1% treated in "conifer", larch/Douglas fir, pine/spruce, and juniper forest types (Figure 3).

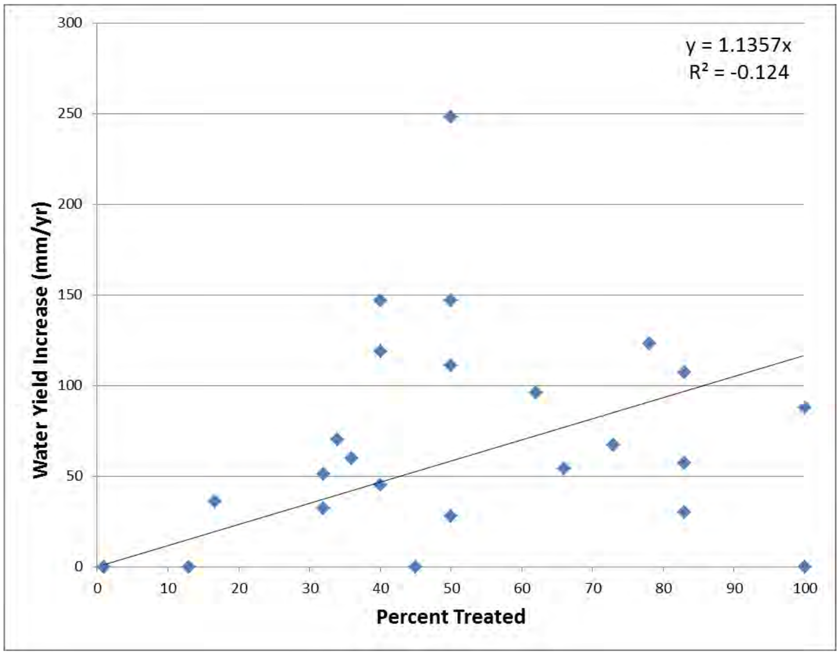


Figure 3. Annual water yield increase (mm/yr) after the percent of catchment harvested for Rocky Mountain/Intermountain hydrologic region using Table 1 of Stednick (1996), excluding locations with dominant cover of aspen, chaparral, or unknown.

3.0 Selection of a Distributed Hydrologic Model

As noted above, the impact of a particular forest management activity or disturbance on watershed hydrologic processes is highly variable, depending on local climate, soils, vegetation, topography, and the spatial pattern of disturbance. Hydrologic models can be an important tool for estimating how changes in forest management practices can affect moisture states such as canopy interception storage, snow water equivalent, and soil moisture, and fluxes such as evapotranspiration, sublimation, and streamflow. They also provide a method for evaluating the likely effects of alternative forest management practices in isolation, that is, without layering in the additional complexity of variation in other basin properties and meteorological forcings.

Beckers et al. (2009) provide a comprehensive review of hydrologic models for forest management and climate change applications in the Pacific Northwest. The authors summarized the capabilities and limitations of 30 hydrologic models for use in an operational forest management context in British Columbia and Alberta, Canada. The review brings together information contained in user manuals, technical model documentation, and in published materials that describes model applications, and emphasizes studies conducted in the Pacific Northwest. The intent of their review was to provide guidance for resource managers and practitioners to identify which models are the most appropriate for addressing their forest management questions.

The outcome of their review is presented in Figure 4 and is organized according to overall model functionality and required complexity for the forest management study. Based on their review, Beckers et al. (2009) conclude that overall, forest watershed modeling capabilities are encompassed by DHSVM, RHESSys, WaSiM-ETH, and CRHM, with the remaining high-complexity models having overlapping features but offering lower functionality for answering forest management questions. The suitability of these four models for answering forest management questions was summarized by Beckers et al. (2009) as follows:

- "DHSVM should be the preferred model for use in mountainous terrain."
- "RHESSys has capabilities not offered by DHSVM in ecohydrological areas such forest growth … however, with its daily time step, RHESSys is not as suitable as DHSVM for simulating (instantaneous) peak flows or in situations where short-duration, high-intensity precipitation events (i.e., rainfall-dominated settings) or diurnal fluctuations in meteorological conditions are important."
- "WaSiM-ETH offers a number of advantages over both DHSVM and RHESSys (detailed groundwater, glacier, lakes and reservoirs) … the model's main drawback is that its forest hydrology-specific components (e.g., forest canopy interactions with precipitation) appear not to have been tested … and that model experience, to date, only resides in Europe."
- "The CRHM was specifically developed for prairie, tundra, and boreal forest settings...the main limitation appears to be the rudimentary streamflow-routing routine, which constrains model applicability to small to medium watersheds."

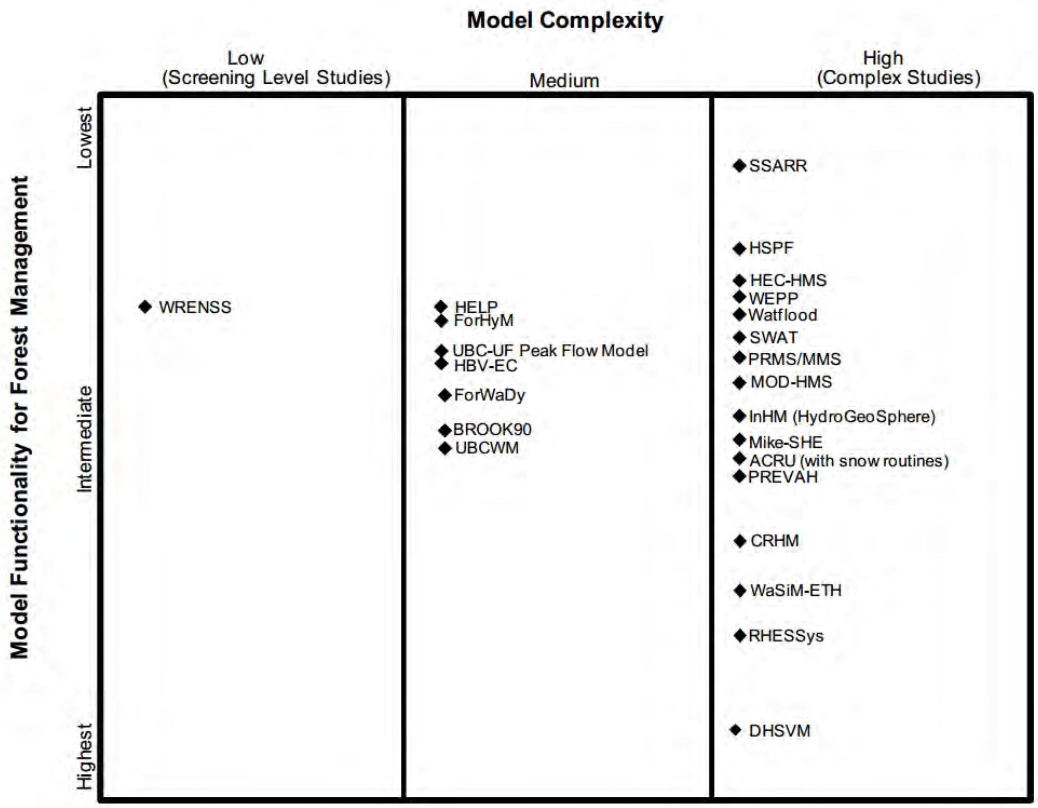


Figure 4. Hydrologic models organized according to overall functionality and complexity of the forest management study (from Beckers et al. 2009).

DHSVM is the model of choice for the questions and complexity of the project documented here based on the selection process of Beckers et al. (2009), subsequent research, and the experience of the principal investigator, Dr. Mark Wigmosta. DHSVM was originally developed by Dr. Wigmosta at the University of Washington under a U.S. Department of Energy (DOE) Global Change Distinguished Postdoctoral Fellowship (Wigmosta et al. 1994). The model was specifically designed to study the effects of vegetation, vegetation change, and climate change on the hydrological cycle at spatial scales that are relevant for forest management practices. The model was formulated using a distributed, physics-based approach to solve coupled energy and water balance equations at high spatial (10 to 90 m) and temporal (hourly) resolution. The model was designed to use physically based input parameters and allow individual model components to be tested against spatiotemporal measurements. In fact, the first DHSVM application (Wigmosta et al. 1994) evaluated the model's ability to represent, not only streamflow, but important spatiotemporal changes in snow cover over the Middle Flathead River basin in Montana.

DHSVM simulates the effects of soil, vegetation, and topography on the movement of water at and near the land surface. The model consists of a two-layer canopy representation for evapotranspiration, a two-layer energy balance model for snow accumulation and melt, a multilayer unsaturated soil model, and a saturated subsurface flow model. The canopy snow model explicitly represents the combined canopy processes that govern snow interception, sublimation, mass release, and melt. Surface land cover and soil properties are assigned to each digital elevation model (DEM) grid cell. In each model cell, the land surface (vegetation and soil) and meteorological conditions are prescribed and an independent one-dimensional (vertical) coupled energy and water balance is calculated for each cell. Moisture can then move laterally on the surface or through the subsurface and be intercepted by roads and streams. Vegetation characteristics and meteorological forcings can be manipulated to evaluate changes in forest structure (for example through potential restoration treatments) and changes in climate. Recent additions to the model include soil erosion, landsliding, sediment transport (Doten et al. 2006), and stream temperature (Sun et al. 2014).

The original DHSVM publication of Wigmosta et al. (1994) is currently the 25th most citied paper from 1965–Present in the American Geophysical Union Journal of Water Resources Research (~15,000 papers). DHSVM has been used in a number of studies that focused on prediction of streamflow, evapotranspiration, and other surface energy and moisture fluxes (Wigmosta et al. 1994; Haddeland and Lettenmaier 1995; Kenward and Lettenmaier 1997; Dubin and Lettenmaier 1999; Wigmosta and Lettenmaier 1999; Kenward et al. 2000; Westrick et al. 2001, 2002; Wigmosta et al. 2002; Cuo et al. 2008, 2009; Sun et al. 2014). The model has also been used to study the interactions between climate and hydrology (Wigmosta et al. 1995; Arola and Lettenmaier 1996; Nijssen et al. 1997; Schnur et al. 1997) and the potential impacts of climate change on water resources (Leung et al. 1996; Leung and Wigmosta 1999; Wigmosta and Leung 2001). Furthermore, the model has proven to be an important tool for assessing the effects of forest management activities on watershed processes (Storck et al. 1995; Lamarche and Lettenmaier 1998; Storck et al. 1998; Bowling et al. 2000; Storck 2000; Bowling and Lettenmaier 2001; Lamarche and Lettenmaier 2001; Wigmosta and Perkins 2001, Vanshaar and Lettenmaier 2001; Vanshaar et al. 2002; Schnorbus and Alila 2004; Thyer et al. 2004; Waichler et al. 2005; Lanini et al. 2009; Surfleet et al. 2010; Kuras et al. 2011, 2012; Green and Alila 2012; Du et al. 2013).

There have been a number of additional studies on the applicability of DHSVM for forest management planning. For example, Schnorbus and Alila (2013) used DHSVM to investigate the immediate impact of forest harvesting upon the annual-maximum peak discharge regime of 240 Creek, a snow-dominated headwater basin of low relief located in south-central British Columbia, Canada. They found DHSVM to "be successful in realistically simulating spatiotemporally variable runoff generation processes in further performance evaluations (Kuras et al. 2011) and [it] is believed to be a reliable enough tool for assessing the effects of forest harvesting on the peak flow regimes of snow-dominated watersheds."

Du et al. (2013) parameterized DHSVM for the Mica Creek Experimental Watershed in northern Idaho. Performance was assessed based on measured streamflow from nested and paired watersheds, snowpack dynamics, soil moisture, and transpiration estimated from sap flux. As part of their study, model parameters were categorized into sensitivity groups relative to streamflow responses. Overstory LAI, minimum stomatal resistance, and soil porosity were found to be the most influential, indicating model sensitivity to canopy and soil properties.

Regarding DHSVM sensitivity to variations in LAI, the authors note, "this is because LAI directly affects three key hydrological processes: evaporation and sublimation of canopy intercepted precipitation, transpiration of soil water, and snowpack energetics, specifically the radiative and turbulent heat fluxes." In DHSVM, LAI is used as a multiplier in precipitation interception, canopy conductance, canopy light penetration, and turbulent energy flux attenuation calculations (Wigmosta et al. 1994, 2002).

By design, and as noted by Du et al. (2013) and others, many of the parameters that drive DHSVM can be directly measured or derived from other measurements, including LAI, wilting point, field capacity, vapor pressure deficit threshold, snow/rain LAI multiplier, and snow interception efficiency. As a result, Du et al. (2013) note that this "makes the model parameterization relatively easy to constrain, especially for detailed studies where the research focus is on coupled hydrological and ecological processes." This was a guiding principle in the original development of DHSVM (Wigmosta et al. 1994) and has been verified in numerous subsequent studies.

Du et al. (2013) note that these analyses were specific to a snow-dominated environment characterized by moderately steep slopes and coniferous canopies, but nonetheless provide insight into potential model sensitivity at other sites. In summary, the authors concluded that "overall, DHSVM reasonably simulated streamflow, snowpack, SWC, and transpiration dynamics for a range of canopy conditions typical of second-growth managed forestlands. This calibrated version of the model hence can be used with confidence to assess the impact of land cover alterations and climate changes on hydrologic regimes."

Based on the review of Beckers et al. (2009) and our own literature review of recent publications, we recommended DHSVM as the model to meet UCSRB needs, because of its following associated features:

- high spatial and temporal resolution
- representation of overstory and understory vegetation
- coupled energy and water balance canopy snow interception and release model
- coupled energy and water balance ground (below-canopy) snow model
- numerous Pacific Northwest land use, climate change, and forest management applications
- designed for, and tested against, forest management practices (e.g., partial and clearcutting, fire)
- several detailed field studies focusing on validation of internal, spatiotemporally varying hydrologic quantities (snow water equivalent (SWE), soil moisture, transpiration, streamflow, etc.).
- model expertise of the PNNL study team.

The TAG approved the selection of DHSVM on May 23, 2014.

4.0 Data and Information Inventory

DHSVM requires DEM data to represent topography, meteorological data to drive the model, vegetation cover data to parameterize biophysical properties of the canopy, and soils data to parameterize soil hydraulic and water-holding properties.

4.1 DEM Data

The U.S. Geological Survey (USGS) DEM data files used by this project are digital representations of cartographic information in a raster form. DEMs consist of a sampled array of elevations for a number of ground positions at regularly spaced intervals.

4.2 Soils Data

The Natural Resources Conservation Service (NRCS) Soil Survey Geographic Database (SSURGO) was used to classify surface soils into a limited number of soil texture groups for input into DHSVM. An example for the Entiat subbasin is shown in Figure 5. Results for individual subbasins are presented in Chapters 7.0–10.0.

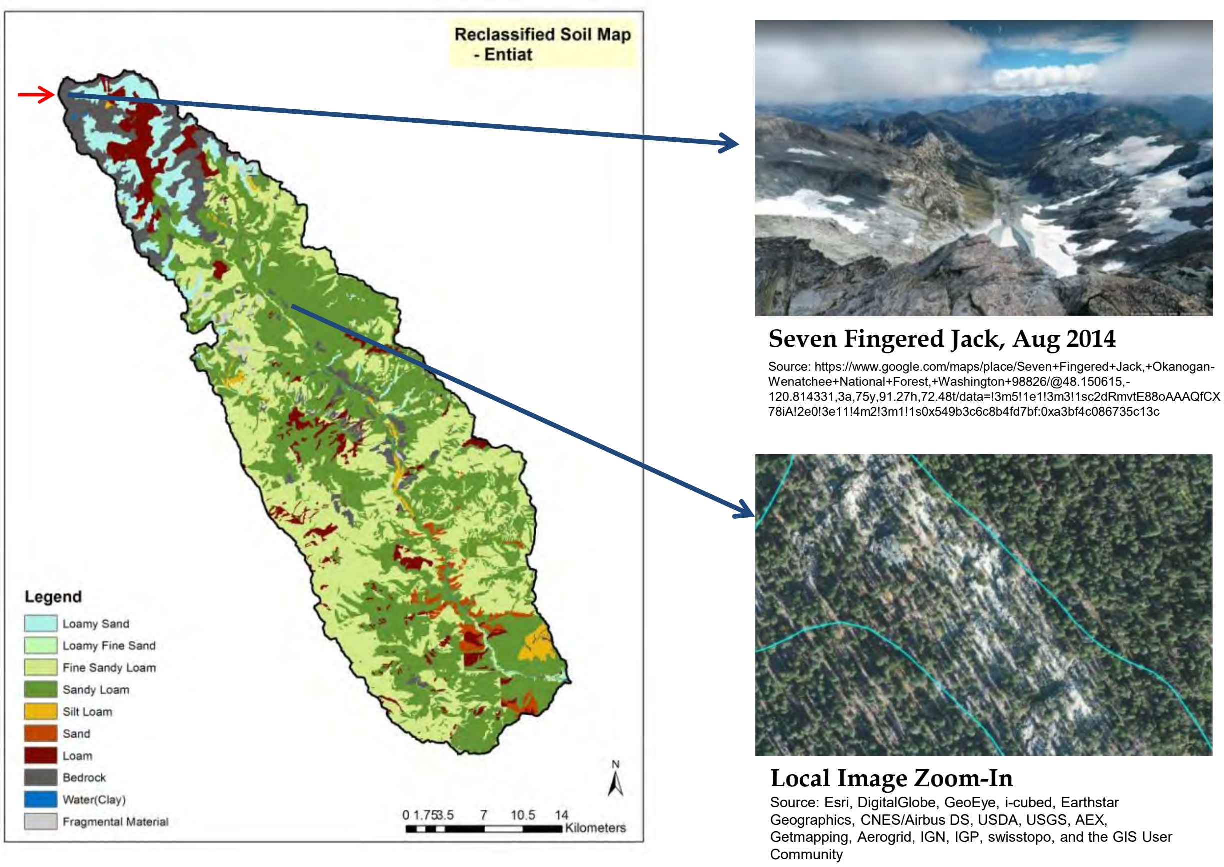


Figure 5. SSURGO-based soil texture classes for the Entiat subbasin (left). Areas of exposed bedrock are shown in the upper basin (upper-right image) as well as isolated bedrock exposure in forest (lower-right image).

4.3 Meteorological, Snow, and Streamflow Data

We compiled a comprehensive inventory of available meteorological, snow water equivalent, and stream flow data. Locations are presented separately for each subbasin in Chapters 7.0–10.0. A brief description of each data source is given below.

- **National Oceanic and Atmospheric Administration (NOAA) Summary of the Day**. Most stations provide daily values for maximum air temperature (°C), minimum air temperature (°C), and total precipitation (mm). Depending on the site, additional information may include snowfall (mm), snow depth (mm), snow water equivalent of the snowfall and on the ground (mm), and general weather conditions (fog, ice, sleet, hail, etc.)
- **Remote Automatic Weather Stations (RAWSs)**. These stations provide hourly data for the following:
  - solar radiation total (kW-hr/m^2)
  - average wind speed (m/s)
  - wind direction vector (deg)
  - wind speed gust (m/s)
  - average air temperature (°C)
  - maximum air temperature (°C)
  - minimum air temperature (°C)
  - average relative humidity (%)
  - maximum relative humidity (%)
  - minimum relative humidity (%)
  - total precipitation (mm)
- **AgriMet**. These stations provide accumulated solar radiation (Langleys) along with 15-minute data for the following:
  - average air temperature (°F)
  - maximum air temperature (°F)
  - minimum air temperature (°F)
  - precipitation w/ heated bucket (in.)
  - incremental global solar radiation (Langleys/hr)
  - average dew point temperature (°F)
  - average relative humidity (%)
  - maximum relative humidity (%)
  - minimum relative humidity (%)
  - average actual vapor pressure (kPa)
  - cumulative wind run (miles)
  - wind direction (deg)
  - peak wind gust (mph)
  - average wind speed (mph)

  Snow Telemetry (SNOTEL). The type and frequency of data will vary depending on the station and time period of interest.
  - Most stations provide daily precipitation (in.), snow water equivalent (in.), maximum air temperature (°F), and minimum air temperature (°F) for the full period of record.
  - Many stations provide hourly precipitation (in.), snow water equivalent (in.), and air temperature (°F) for recent years.

- Some stations provide hourly precipitation (in.), snow water equivalent (in.), air temperature (°C), solar radiation (watts), relative humidity (%), snow depth (in.), soil moisture (%), soil temperature (°C), vapor pressure (kPa), wind direction (deg), and wind speed (mph).

- **Northwest Avalanche Center**. This data source may have a limited period of record. Station information may include hourly air temperature (°F), precipitation (in./hr), relative humidity (%), minimum wind speed (mph), average wind speed (mph), maximum wind speed (mph), and wind direction (deg).
- **Washington State Department of Ecology – Streamflow**. This data source uses three types of stations:
  - Telemetry – data are logged every 15 minutes and transmitted every 3 hours. Measurements include stage (ft), flow (cfs), water temperature (°F), and air temperature (°F)
  - Stand Alone – logs data every 15 minutes and is downloaded periodically (once a month). Measurements include stage (ft), flow (cfs), water temperature (°F), and air temperature (°F).
  - Stage – consists of a series of periodic manual river stage readings (ft) related to a series of instream flow measurements.
- **USGS streamflow stations**. The type and frequency of data will vary depending on the station and time period of interest.
  - Most stations provide daily river stage (ft) and average discharge (cfs) for the full period of record.
  - Some stations provide 15-minute river stage (ft) and instantaneous discharge (cfs).
  - Additional information about water temperature (°F) and turbidity may be available at selected stations.

4.4 LANDFIRE Vegetation Data

Based on consultation with TAG members and conversations with U.S. Forest Service (USFS) representatives Paul Hessburg, James Dickenson, and Richy Harrod regarding available data and USFS forest restoration strategy, we selected the LANDFIRE dataset (CONUS v. 1.3.0, 2012) to help parameterize key vegetation parameters. LANDFIRE data products (http://www.landfire.gov/index.php) are created as 30 m raster grids at scales that may be useful for prioritizing and planning individual hazardous fuel reduction and ecosystem restoration projects. To generate key LANDFIRE vegetation products, biophysical gradients, Landsat imagery, and training databases from the LANDFIRE reference database (LFRDB) are used in a predictive landscape modeling environment to create maps of existing vegetation type, and existing vegetation height and canopy cover.

The LANDFIRE Existing Vegetation Type (EVT) data product represents the vegetation currently present at a given site. Map units are classified based on the dominant vegetation in plot information contained in the LFRDB. Additional attributes are provided in which LANDFIRE EVTs have been cross-walked to existing vegetation classifications. The Order, Class, and Subclass attributes are based on the Federal Geographic Data Committee – Vegetation Subcommittee's vegetation classification standard and pertain to upper physiognomic levels of the National Vegetation Classification System hierarchy. Order describes the dominant life forms (tree, shrub, dwarf shrub, herbaceous, or nonvascular) within the Vegetated Division of the hierarchy. Class describes the level in the classification hierarchy defined by the relative percent of canopy cover of the tree, shrub, dwarf shrub, herb, and nonvascular life form in the uppermost strata during the peak of the growing season. Subclass describes the predominant leaf phenology of classes defined by tree, shrub, or dwarf shrub stratum (evergreen, deciduous, mixed evergreen-deciduous), and the average vegetation height for the herbaceous stratum (tall, medium, short).

The Forest Canopy Cover (CC) layer (Figure 6) describes the percent cover of the tree canopy in a stand. Specifically, CC describes the vertical projection of the tree canopy onto an imaginary horizontal surface representing the ground's surface. CC is generated using a predictive modeling approach that relates Landsat imagery and spatially explicit biophysical gradients to calculated values of average canopy cover from field training sites and digital orthoimagery.

The forest canopy height (CH) layer (Figure 6) describes the average height of the top of the vegetated canopy and is provided for forested areas only. CH is generated using a predictive modeling approach that relates Landsat imagery and spatially explicit biophysical gradients to calculated values of average dominant height from field training sites. The EVH layer represents the average height of the dominant vegetation for a 30 m grid cell (Figure 7). CH is generated separately for tree, shrub, and herbaceous lifeforms using training data and other layers. EVH is determined by the average height weighted by species cover and based on the EVT lifeform. Decision-tree models using field reference data and Landsat, elevation, and ancillary data are developed separately for each lifeform. Decision-tree relationships are used to generate lifeform-specific height class layers, which are merged into a single composite EVH layer.

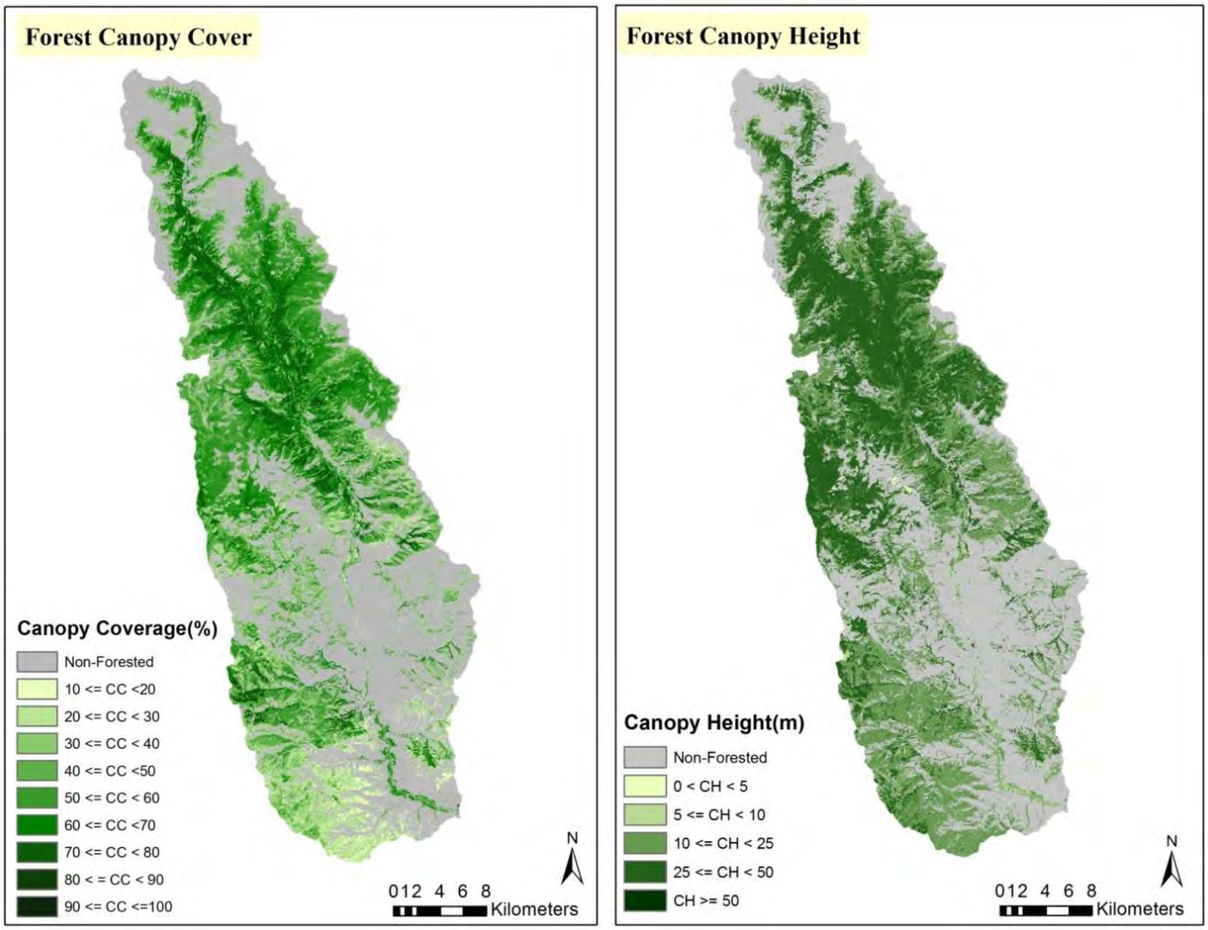


Figure 6. LANDFIRE percent forest canopy coverage (left) and forest canopy height (m) in the Entiat subbasin.

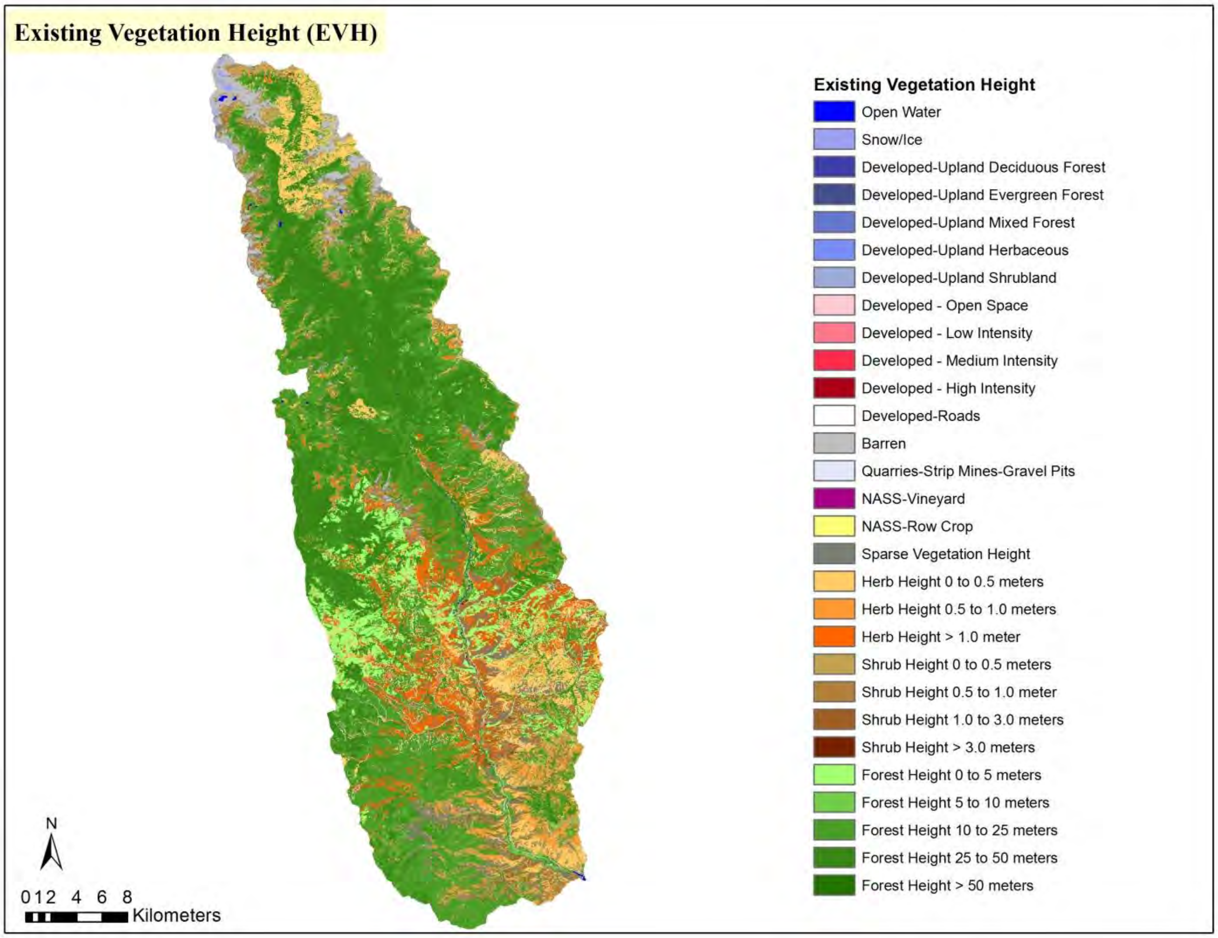


Figure 7. LANDFIRE existing vegetation height (m) in the Entiat subbasin. Values for forest height are consistent with those in Figure 6.

4.4.1 DHSVM LANDFIRE-Based Vegetation Classes

Paul Hessburg and Brion Salter (USFS) developed and provided aggregated vegetation classification of LANDFIRE data in the four study basins. Forest was classified into 160 classes based on forest type (Dry, Moist, Cool, Cold, and Deciduous), height, and fractional CC (Table 1). Shrubland and herbland were broken into two classifications each based on fractional cover. Agricultural and non-vegetated lands were broken into four and five classes respectively, based on type. Aggregated cover types are shown for each basin in Chapters 7.0–10.0. A single value for forest CC and forest CH was assigned to each class as the weighted average of all 30 m LANDFIRE values (e.g., Figure 6) within the aggregated class.

Table 1. USFS aggregated forest classification matrix of LANDFIRE data based on forest type, height, and fractional canopy coverage resulting in 160 (5×4×8) classes.

Forest Type	Forest Height	Fractional Canopy Coverage
Dry	0-5 m	0-20%
Moist	5-10 m	20%-30%
Cool	10-25 m	30%-40%
Cold	>25 m	40%-50%
Deciduous	-	50%-60%
-		
-	-	60%-70%
-	-	70%-80%
-	-	>80%

5.0 Forest Restoration

5.1 Land Filter

A spatial filtering process based on a geographic information system (GIS) was implemented on the Wenatchee, Entiat, Methow, and U.S. portion of the Okanogan subbasins to better understand which (where and how much) forest lands are candidates for various forest management actions. A number of large wildfires (e.g., Carlton Complex) have affected the study basins since this analysis. Therefore, we updated our analysis to include the areal extent of the recent 2014 fires. The 2015 fires have <u>not</u> been evaluated.

The spatial filtering process was initiated using the 8-digit Hydrologic Unit Code (HUC) boundaries for each subbasin, then eliminating areas within the subbasins based on a number of criteria, including National Park Service lands, U.S. Fish and Wildlife protected lands, wilderness areas, USFS Category 1B and 1B-1 roadless areas, urban boundaries, developed areas, and non-forested land cover (see Figure 8). Within these areas, lands inside and outside of USFS lands were evaluated. The land cover and developed area categories were sourced from the recently released 30 m 2011 National Land Cover Dataset; boundary data was sourced from the Washington Department of Ecology, USGS National Map; and roadless areas data were gathered from the USFS Geospatial Service and Technology Center. For the presented analysis, slope stability (soil type, percent slope) or past mass wasting events were not considered. Roadless areas were originally excluded from consideration. However, they are now included based on subsequent discussion with USFS staff. Boundaries of 2014 wildfires were derived from wildland fire perimeter data obtained from the Geospatial Multi-Agency Coordination Group (GeoMAC). The original data set contains separate wildland fire perimeters by individual incident for the current year.

Results for all four subbasins are presented in Table 2 representing a total area of 1,519 square miles (972,412 acres) of filtered (forested only) area on USFS and other lands with the potential for restoration. Recent wildfires affected a total of 140.9 square miles within the filtered (USFS and private forest) 1,519 square mile area, ranging from about 2% of this area in the Wenatchee and Okanogan subbasins (Figure 9, Figure 10, and Figure 15), to 17% and 19% of these lands in the Methow subbasin(Figure 13 and Figure 14) and Entiat subbasin (Figure 11 and Figure 12), respectively (lower portion of Table 2).

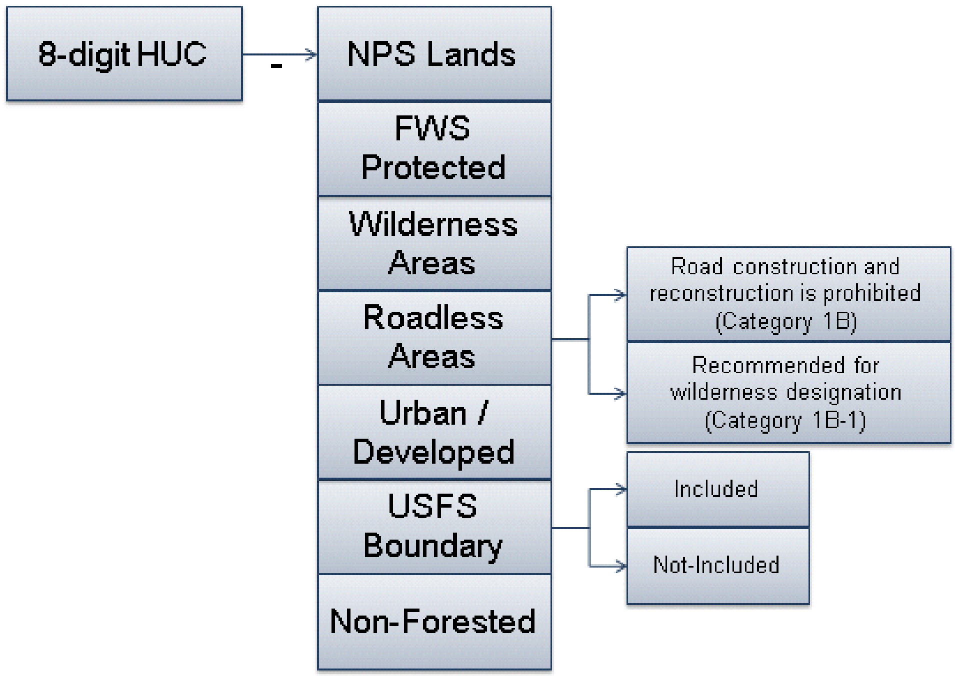


Figure 8. Workflow for spatial screening process to identify forest land with the potential for restoration.

Table 2. Results of spatial filtering for four north-central Cascades subbasins including full subbasin area, filtered areas including only forested lands, area affected by 2014 wildfires, and roadless areas. The upper portion of the table includes the total area in square miles, whereas the lower portion of the table includes percent area relative to the full subbasin area.

Area(sq mi)	Wenatchee	Entiat	Methow	Okanogan
Total Area	1328.8	418.3	1820.7	1611
USFS & Other-Forest Only	355.6	138.8	584.6	440.4
USFS only-Forest Only	329.9	128.9	548.3	152.7
Area Affected by 2014 Fires (August)	24	38.7	289.7	55.4
Area Affected by 2014 Fires (Current)	24.2	39.6	290.2	55.4
USFS & Other-Forest_Affected by 2014 Fires (Aug)	6.7	25.8	97.4	11
USFS & Other-Forest Affected by 2014 Fires (Dec)	6.7	26.5	97.5	11
Roadless Forested	167.11	60.61	164.81	13.01
Roadless Forested Affected by 2014 Fires	0.87	3.28	12.48	0

Percentage of Area(%)	Wenatchee	Entiat	Methow	Okanogan
Total Area	100%	100%	100%	100%
USFS & Other-Forest Only	26.76%	33.18%	32.11%	27.34%
USFS only-Forest Only	24.83%	30.82%	30.11%	9.48%
Area Affected by 2014 Fires (August)	1.81%	9.25%	15.91%	3.44%
Area Affected by 2014 Fires (Current)	1.82%	9.46%	15.94%	3.44%
USFS & Other-Forest Affected by 2014 Fires (Aug)	0.50%	6.17%	5.35%	0.68%
USFS & Other-Forest Affected by 2014 Fires (Dec)	0.51%	6.34%	5.35%	0.68%
Roadless Forested	12.58%	14.49%	9.05%	0.81%
Roadless Forested Affected by 2014 Fires	0.07%	0.78%	0.69%	0.00%

Forest cover in roadless areas represent 12.6, 14.5, 9.1, and <1% of the total area in the Wenatchee, Entiat, Methow, and Okanogan subbasins, respectively.

To identify key locations and subbasins for model application we combined our land filter with UCSRB priority areas (major spawning areas) for spring Chinook and Steelhead, along with locations where low flow and altered flow are an issue. Priority areas for spring Chinook are located throughout the Entiat, and in the upper portions of the Wenatchee and Methow subbasins. Priority areas for Steelhead are also located throughout the Entiat, and occupy a larger portion of the Wenatchee, Methow, and Okanogan subbasins. These data are presented in Figure 9–Figure 15, in which subbasins with Chinook or Steelhead spawning are outlined in yellow, areas with low-flow issues are outlined in black with diagonal hatching, areas with altered streamflow timing issues are outlined in black with horizontal hatching, suitable forested USFS lands are shown in green, and suitable private forested lands are shown in burnt orange.

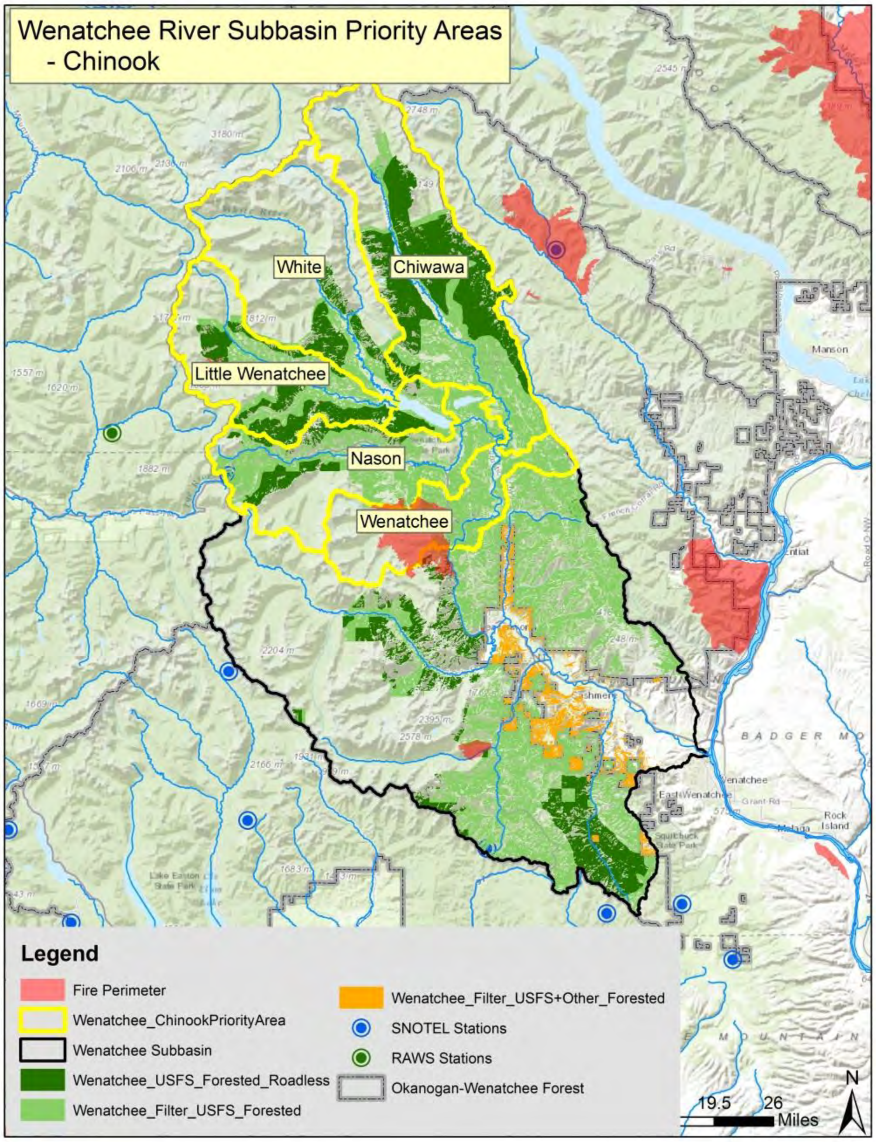


Figure 9. Wenatchee subbasin showing UCSRB Chinook priority areas along with locations suitable for forest management and the extent of 2014 wildfires.

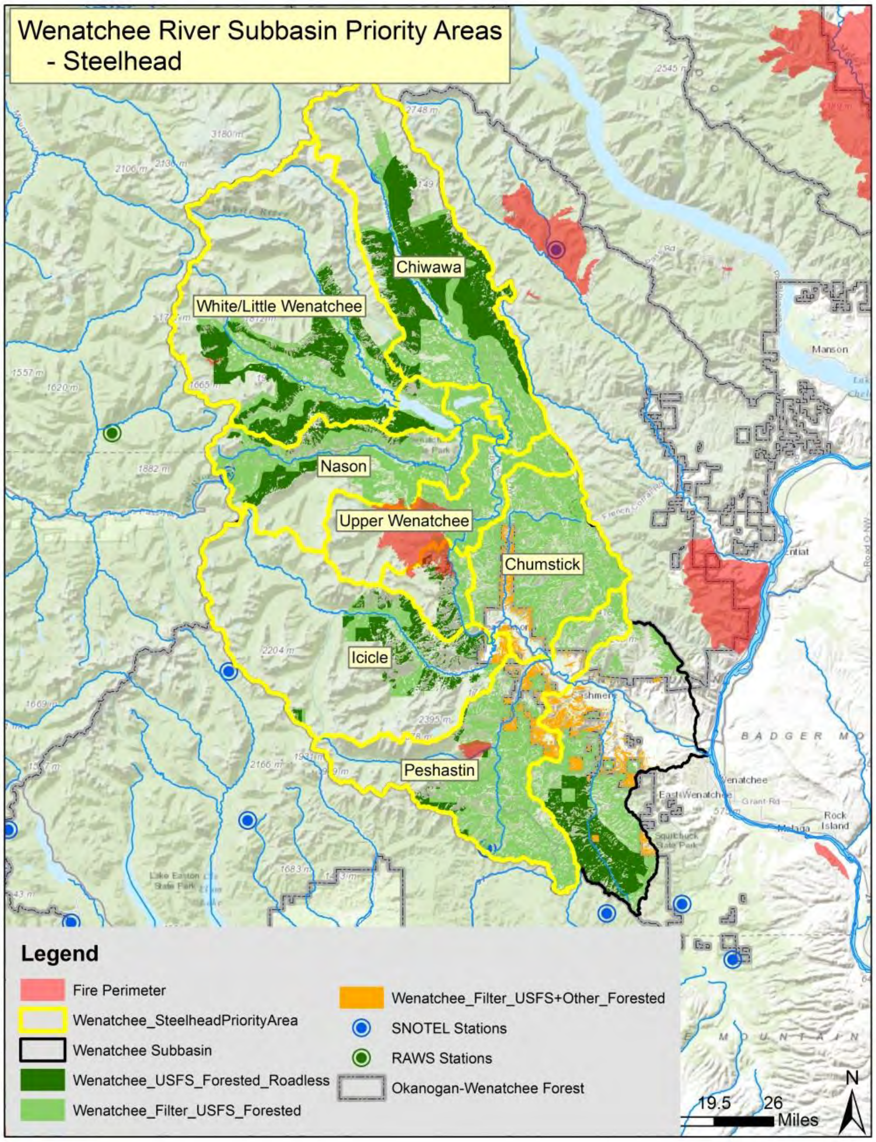


Figure 10. Wenatchee subbasin showing UCSRB Steelhead priority areas along with locations suitable for forest management and the extent of 2014 wildfires.

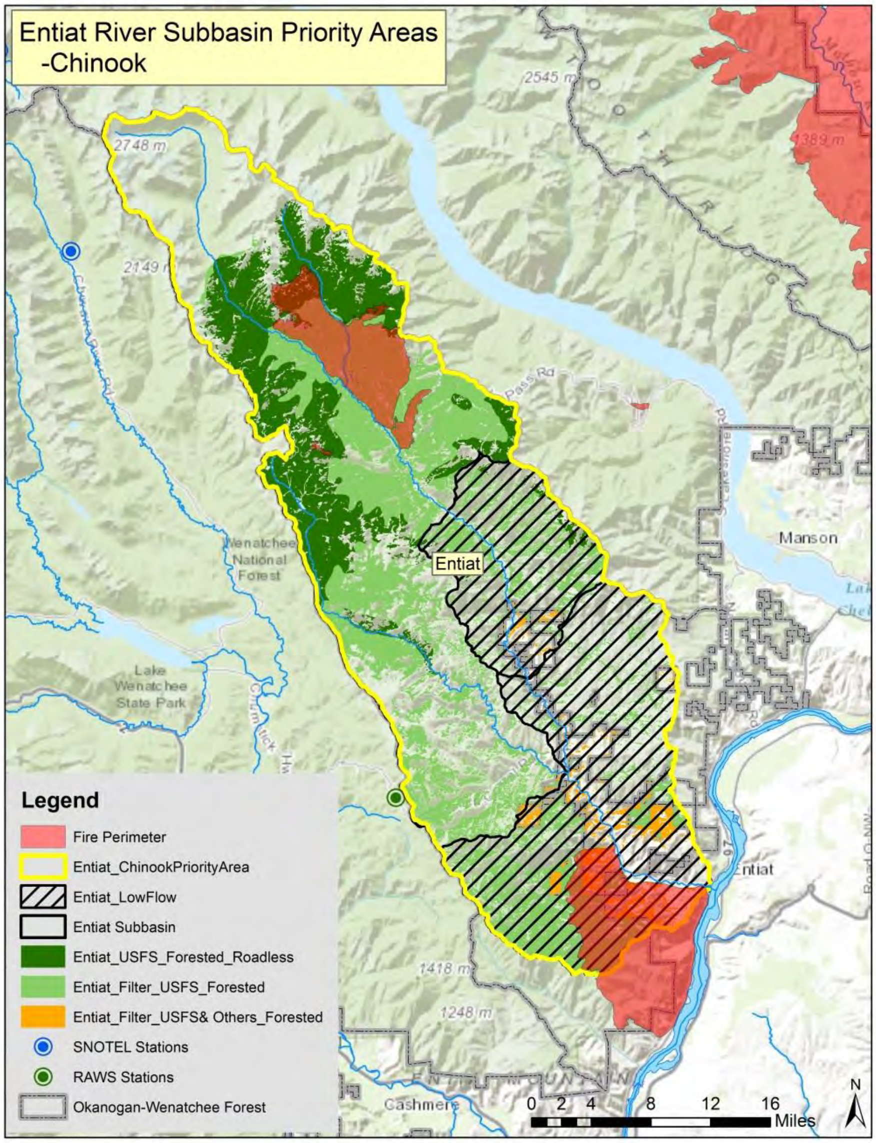


Figure 11. Entiat subbasin showing UCSRB Chinook and low-flow priority areas along with locations suitable for forest management and the extent of 2014 wildfires.

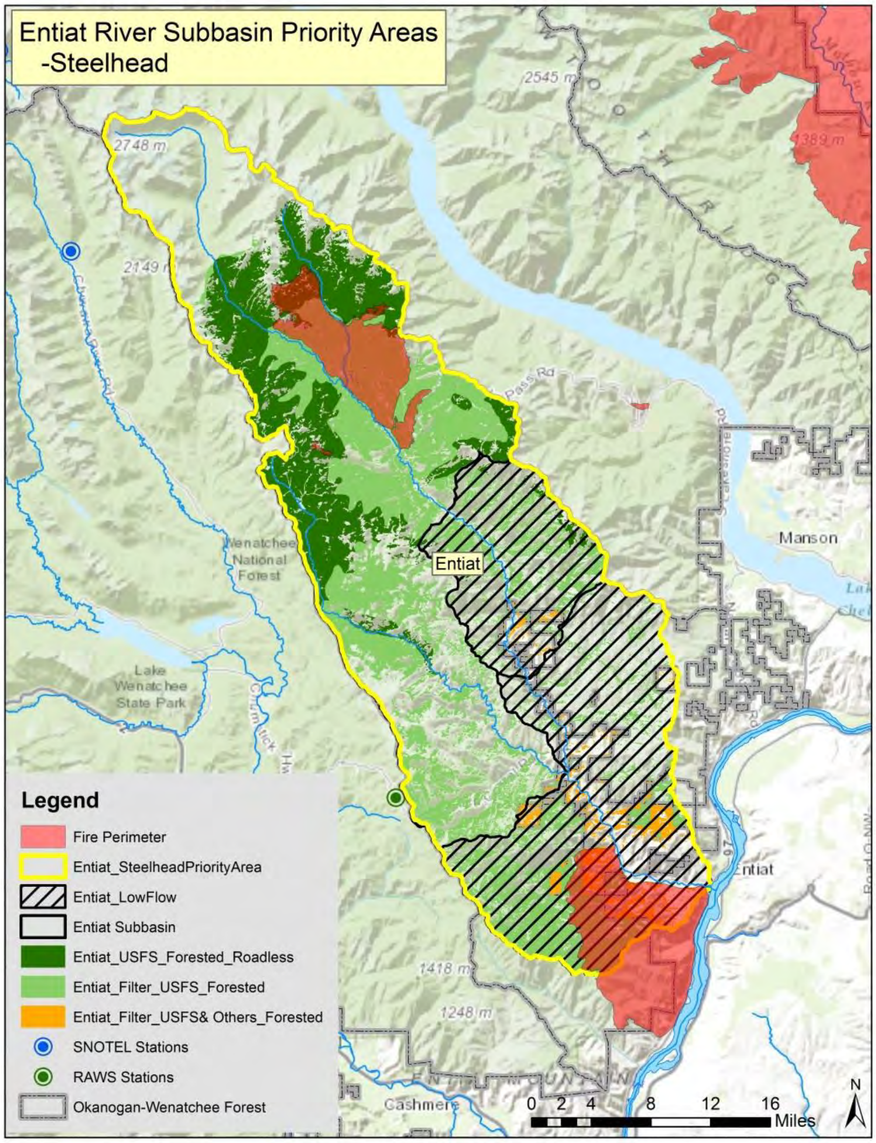


Figure 12. Entiat subbasin showing UCSRB Steelhead and low-flow priority areas along with locations suitable for forest management and the extent of 2014 wildfires.

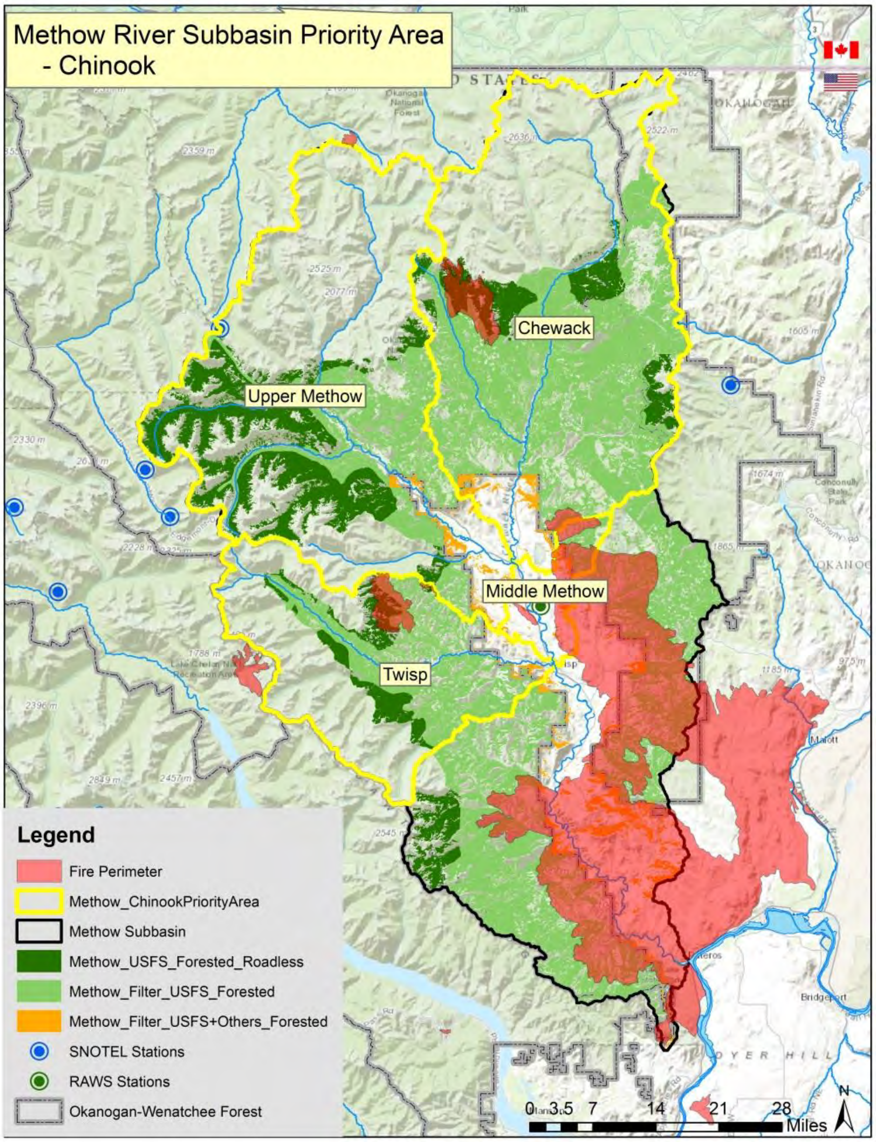


Figure 13. Methow subbasin showing UCSRB Chinook priority areas along with locations suitable for forest management and the extent of 2014 wildfires.

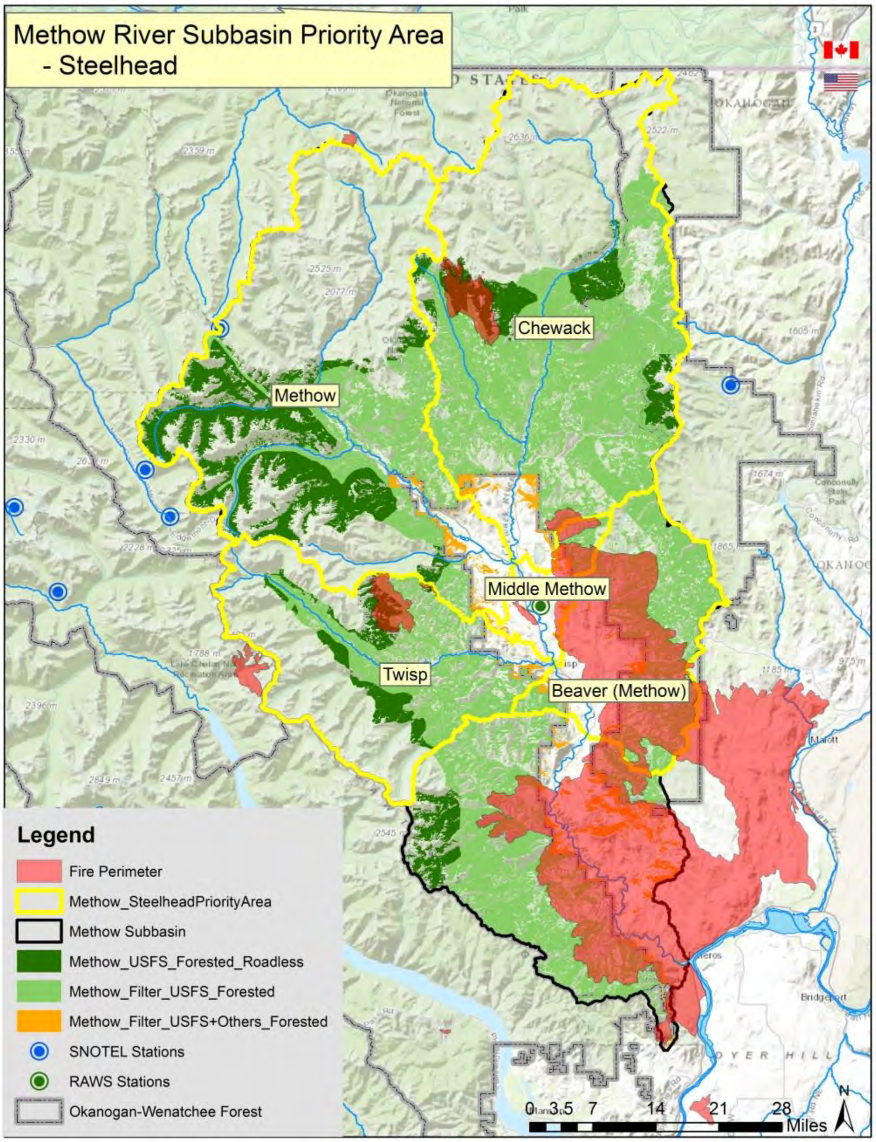


Figure 14. Methow subbasin showing UCSRB Steelhead priority areas along with locations suitable for forest management and the extent of 2014 wildfires.

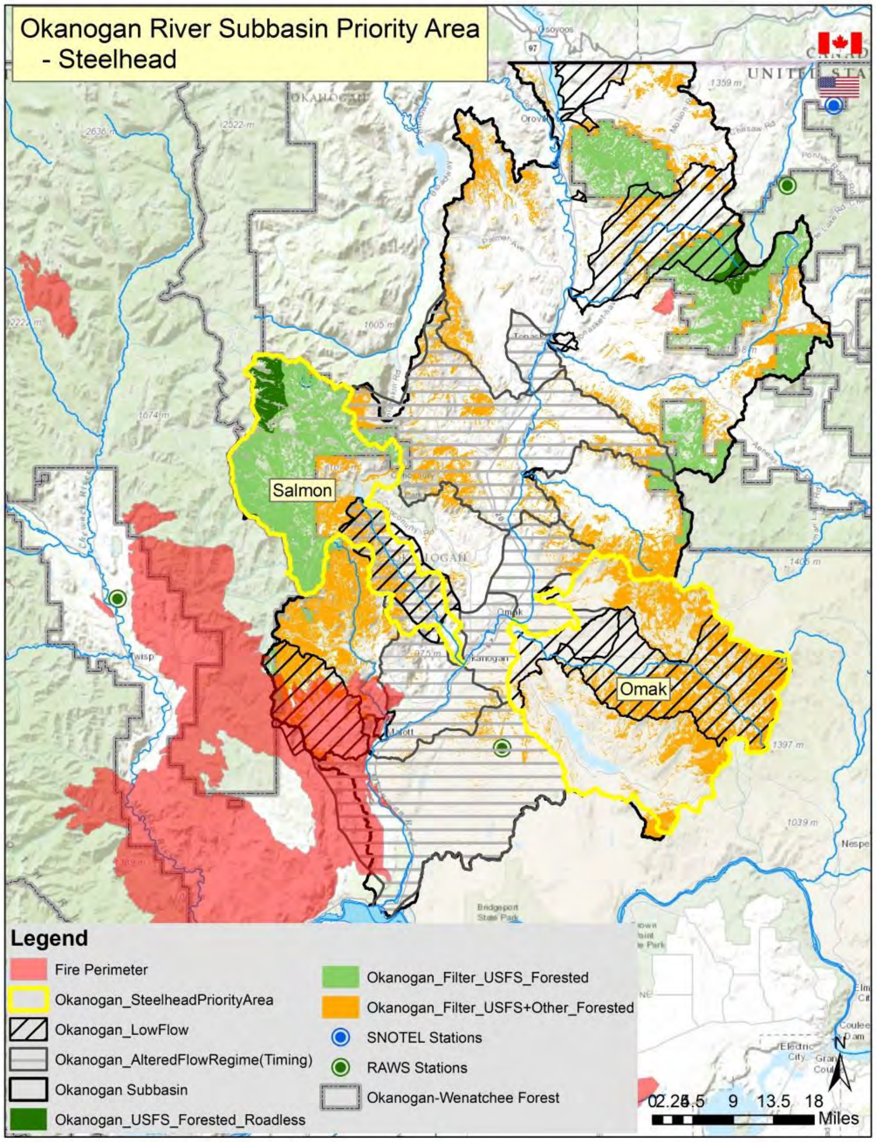


Figure 15. Okanogan subbasin showing UCSRB Steelhead and low/altered flow priority areas along with locations suitable for forest management and the extent of 2014 wildfires.

5.2 Restoration Scenarios

DHSVM simulates the effects of soil, vegetation, and topography on the transfer of water and energy at and near the land surface. The model consists of a two-layer canopy representation for evapotranspiration, a two-layer energy balance model for snow accumulation and melt, a multilayer unsaturated soil model, and a saturated subsurface flow model. The canopy snow model explicitly represents the combined canopy processes that govern snow interception, sublimation, mass release, and melt. Surface land cover and soil properties are assigned to each DEM grid cell. In each model grid cell, the land surface (vegetation and soil) and meteorological conditions are prescribed and an independent one-dimensional (vertical) coupled energy and water balance is calculated for each pixel. Moisture can then move laterally on the surface or through the subsurface and be intercepted by roads and streams. Vegetation characteristics and meteorological forcings can be manipulated to evaluate changes in forest structure (for example through potential restoration treatments) and changes in climate. Topographic influence is well represented in DHSVM through the use of high-resolution (30 or 90 m) DEM data.

Forest restoration scenarios were developed by USFS staff to be consistent with the OWNF Restoration Plan and spatially mapped to the DHSVM computational grid based on forest type (Figure 16), topographic classification (Figure 17), and fire index (Figure 18).

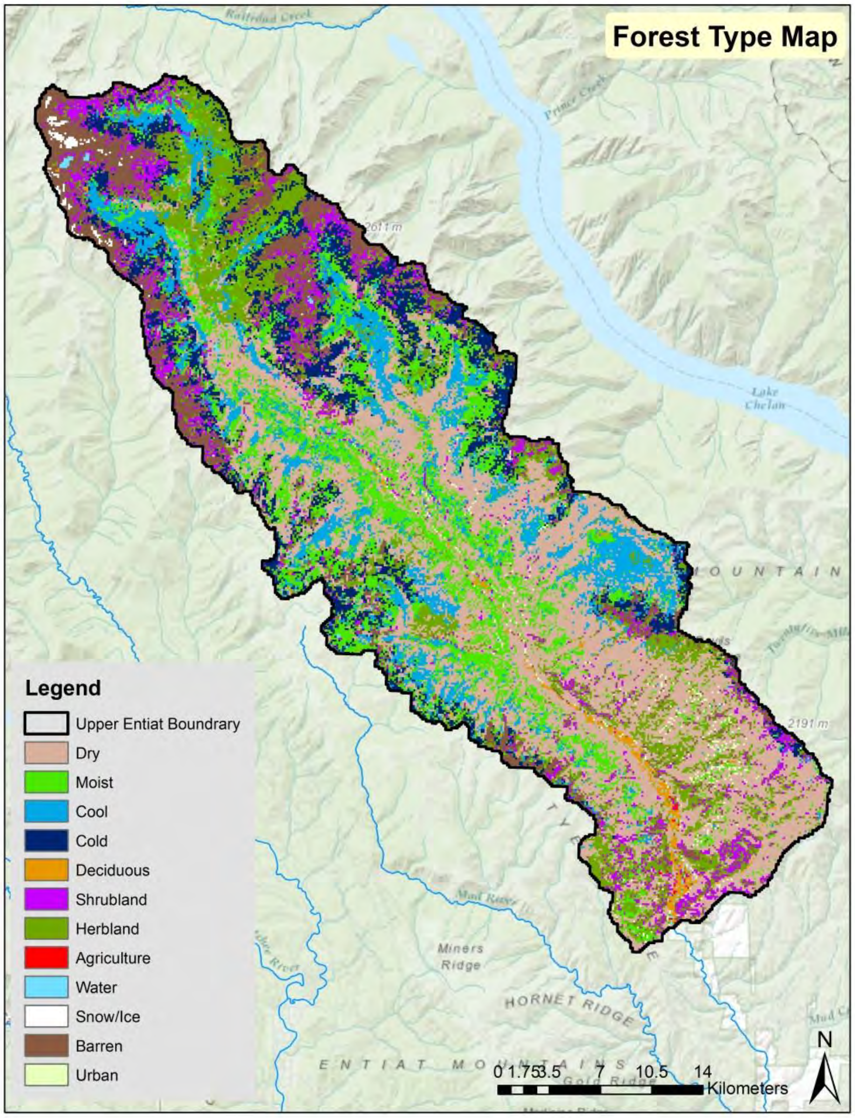


Figure 16. Forest types in the Upper Entiat watershed (data provided by Paul Hessburg and Brion Salter [USFS]).

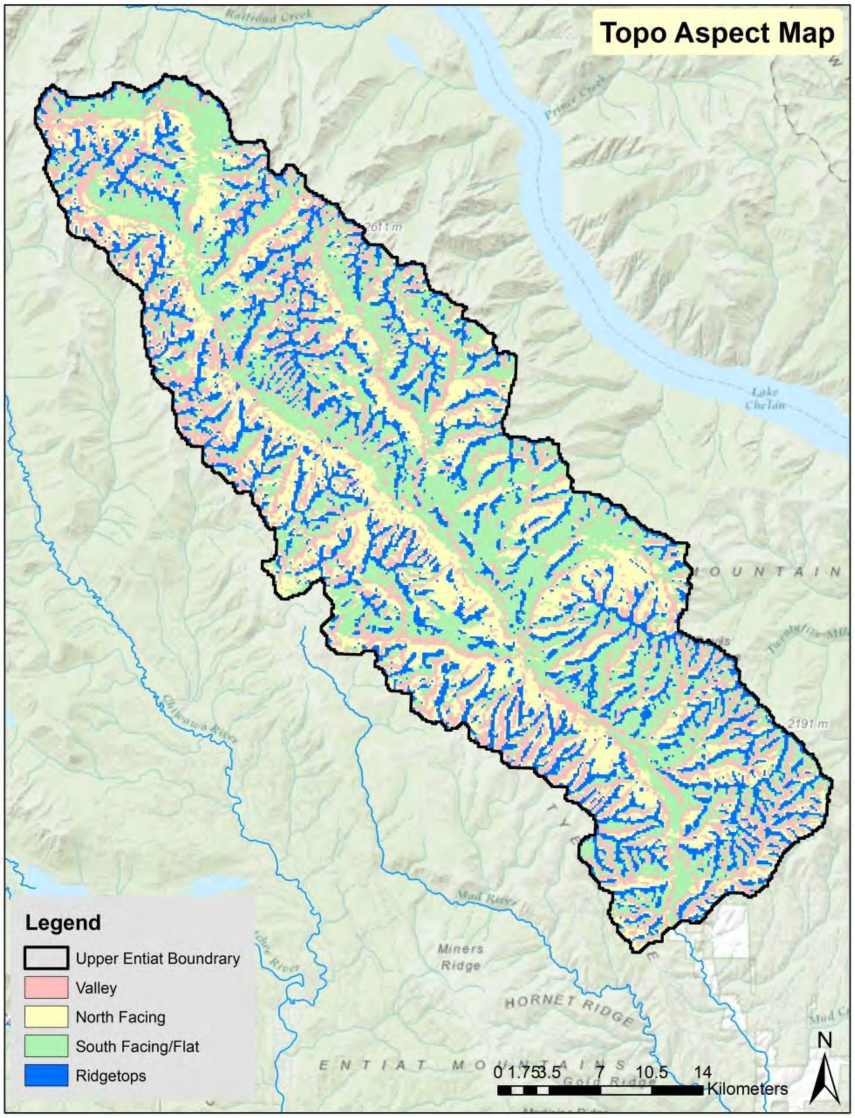


Figure 17. Topographic classes for restoration scenarios in the Upper Entiat watershed (data provided by Paul Hessburg and Brion Salter [USFS]).

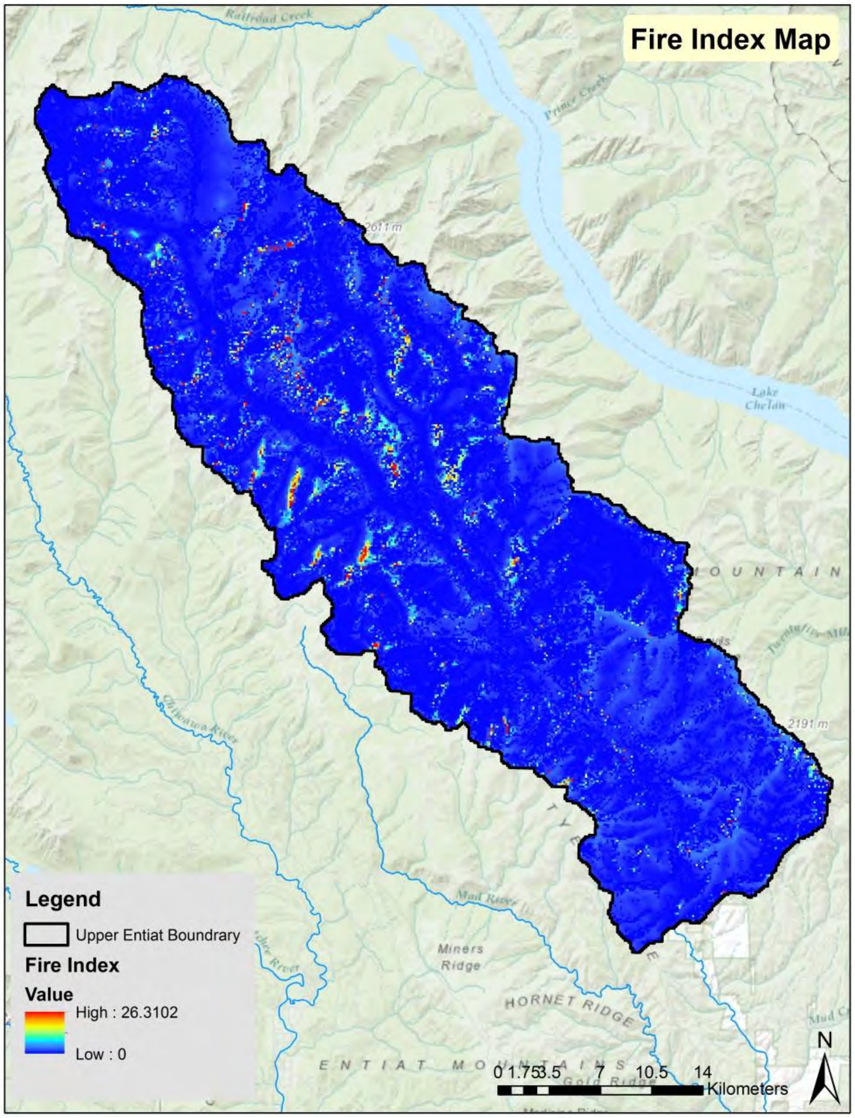


Figure 18. Fire Index in Upper Entiat watershed (data provided by Paul Hessburg and Brion Salter [USFS]).

Management actions were represented in DHSVM by changes in the overstory fractional coverage in selected grid cells (Table 3). Five restoration scenarios were evaluated along with two wildfire scenarios as described below.

Scenario 1a: The percentage of overstory fractional coverage of all ridgetop grid cells in both the Dry and Moist forest types (Dry/Moist forest hereafter) with overstory fractional coverage greater than 30% was reduced to 30% to represent mechanical thinning.

Scenario 1b: The percentage of overstory fractional coverage in higher elevation (top 50%) south-facing grid cells in the Dry/Moist forest with overstory fractional coverage greater than 50% was reduced to 50% to represent mechanical thinning.

Scenario 1c: The percentage of overstory fractional coverage of all south-facing grid cells in the Dry/Moist forest with overstory fractional coverage greater than 50% was reduced to 50% to represent mechanical thinning.

Scenario 2a: The percentage of overstory fractional coverage of grid cells in both the Cool and Cold forest types (Cool/Cold forest hereafter) that had a Fire Potential Index in the top 30% was reduced to zero to represent prescribed burning.

Scenario 2b: Grid cells in the Cool/Cold forest with a Fire Potential Index in the top 50% had their overstory fractional coverage reduced to zero to represent prescribed burning.

Scenario 3a: North-facing and valley bottom grid cells in all forest types with a Fire Potential Index in the top 10% had their overstory fractional coverage reduced to zero to represent loss by wildfires.

Scenario 3b: North-facing and valley bottom grid cells in all forest types with a Fire Potential Index in the top 30% had their overstory fractional coverage reduced to zero to represent loss by wildfires.

Table 3. Summary table of forest restoration and wildfire scenarios.

	Scenario Description			
Scenarios	Forest Type	Topography	Location	Overstory Fractional Coverage (FC)
1a)	Dry/Moist	Ridgetops	All	FC>30% to 30%
1b)	Dry/Moist	South-facing Slope	Top 50% Elevation	FC>50% to 50%
1c)	Dry/Moist	South-facing Slope	All	FC>50% to 50%
2a)	Cool/Cold	All	Top 30% Fire Index	FC to 0
2b)	Cool/Cold	All	Top 50% Fire Index	FC to 0
3a)	All	North-facing Slope and Valley Bottoms	Top 10% Fire Index	FC to 0
3b)	All	North-facing Slope and Valley Bottoms	Top 30% Fire Index	FC to 0

The forest restoration scenarios are shown spatially for each basin in Chapters 7.0–10.0.

6.0 Climate Change Scenarios

Our climate change scenarios are based on the Representative Concentration Pathway 8.5 (RCP8.5) emissions trajectory. RCP8.5 is characterized by increasing greenhouse gas emissions over time, representative of scenarios in the literature that lead to high greenhouse gas concentration levels. To remove General Circulation Model (GCM) biases and apply this scenario we first calculated the difference between the monthly average temperatures of the downscaled GCM gridded historic and the RCP8.5 future climate projections (Table 4–Table 7). The time period used to calculate historical monthly temperature data is 1975 to 2003 (29 years) and for future climate projection it is 2027 to 2055 (29 years). Inverse distance weighting (Figure 19–Figure 22) was then used to add these monthly differences (deltas) to the observed meteorological station air temperature used to run DHSVM under current climate conditions.

Analysis of precipitation for the downscaled GCM gridded historic and the RCP8.5 future climate projections showed only a minor increase in these watersheds for the future climate conditions. Therefore, to simplify the climate change simulations, we ignored changes in precipitation.

6.1.1 Upper Entiat Watershed

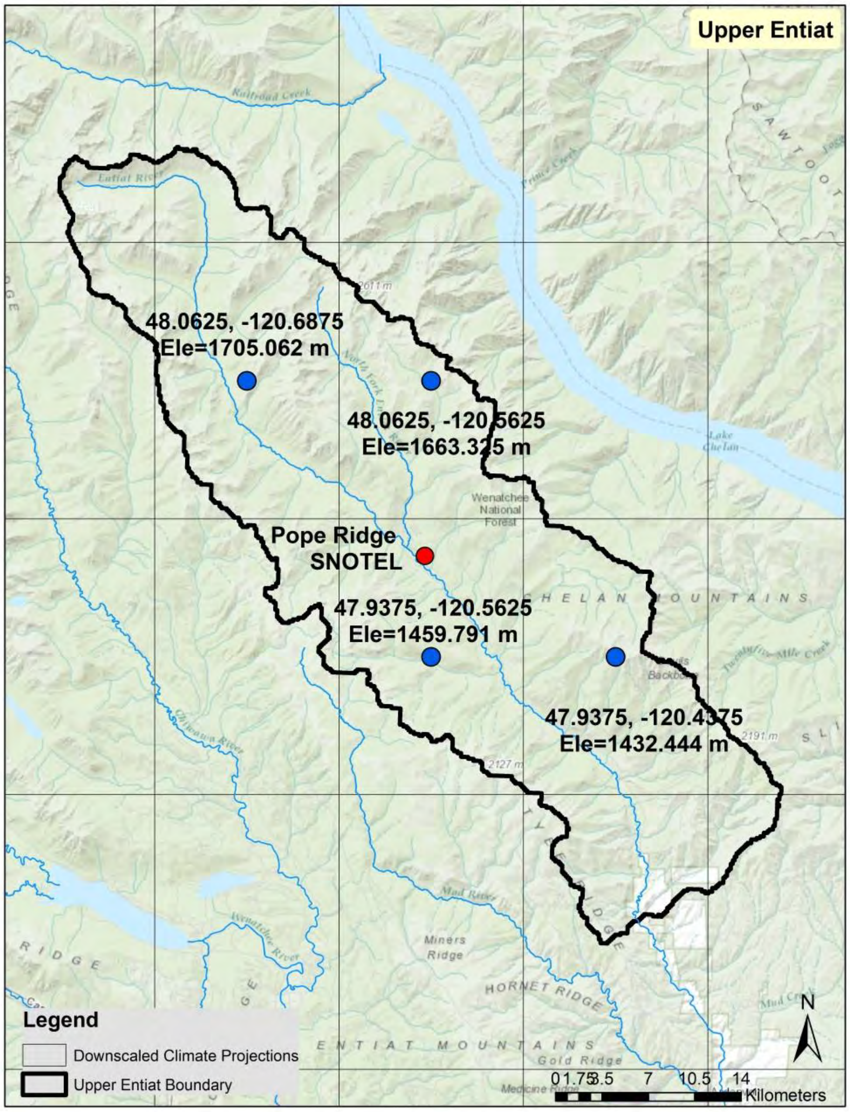


Figure 19. Downscaled GCM data points (blue) in the Upper Entiat watershed. Red dot indicates the Pope Ridge SNOTEL station used to drive the DHSVM.

Table 4. Mean monthly air temperature difference (delta) between downscaled GCM historic and RCP8.5 climate projections in the Upper Entiat watershed.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Delta	2.60	1.20	1.30	1.60	1.60	1.80	2.40	2.90	1.90	2.00	2.30	1.00

6.1.2 Chiwawa Watershed

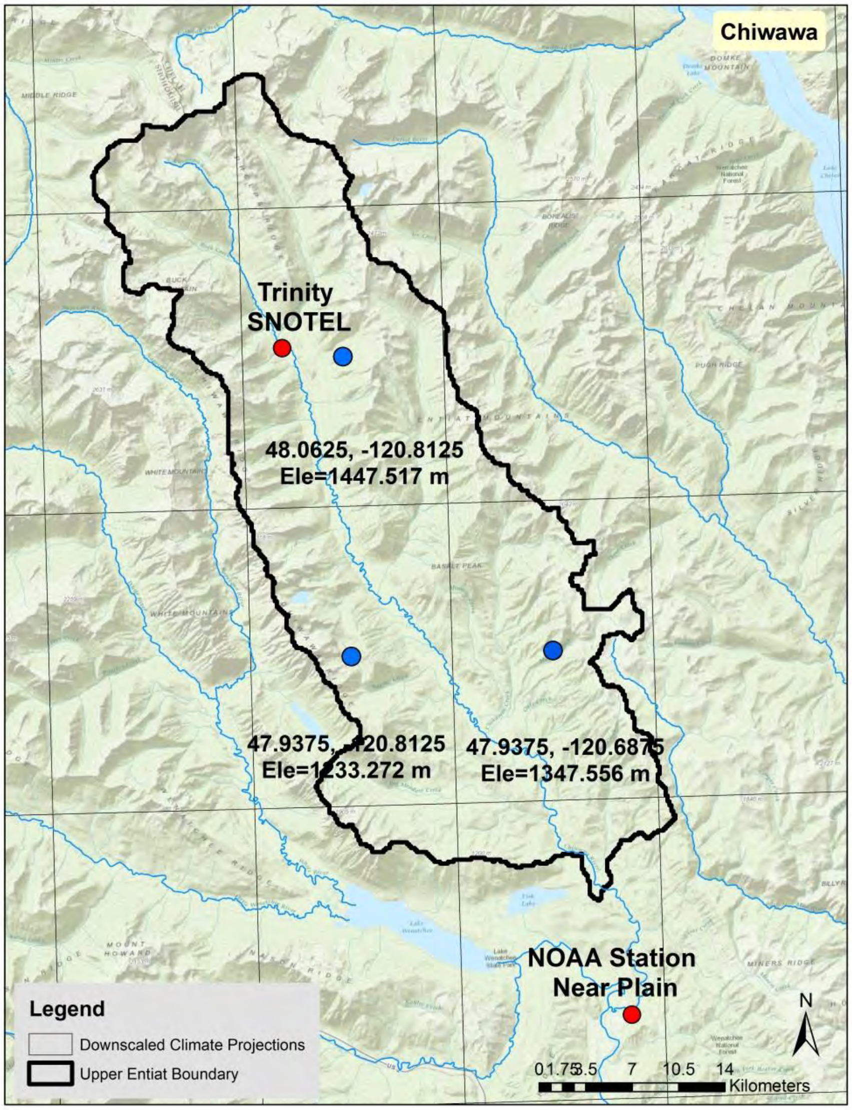


Figure 20. Downscaled GCM grid cells in the Chiwawa watershed. Red dots indicate the Trinity SNOTEL station and NOAA station near Plain used to drive the DHSVM.

Table 5. Mean monthly air temperature difference (delta) between downscaled GCM historic and RCP8.5 climate projections in the Chiwawa watershed.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Plain Delta	2.46	1.04	1.21	1.68	1.72	1.83	2.45	2.93	1.90	2.03	2.31	1.03
Trinity Delta	2.45	1.03	1.23	1.72	1.78	1.85	2.42	2.91	1.88	2.04	2.32	1.02

6.1.3 Upper Methow Watershed

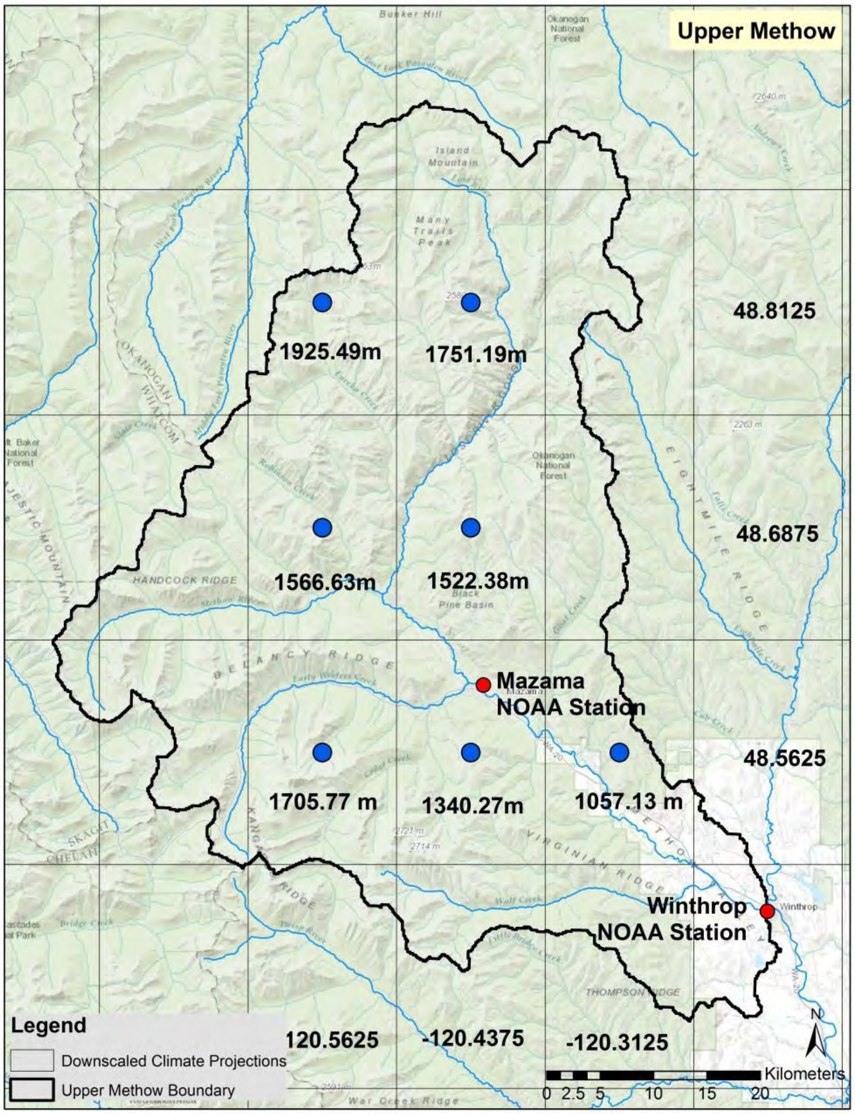


Figure 21. Downscaled GCM grid cells in the Upper Methow watershed. Red dots indicate the Mazama NOAA station and Winthrop NOAA station used to drive the model.

Table 6. Mean monthly air temperature difference (delta) between downscaled GCM historic and RCP8.5 climate projections in the Upper Methow watershed.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Winthrop Delta	2.45	1.00	##	1.51	1.81	1.88	2.30	2.78	1.71	2.19	2.26	1.07
Mazama Delta	2.42	0.99	##	1.49	1.86	1.89	2.29	2.77	1.70	2.20	2.24	1.07

6.1.4 Omak Watershed

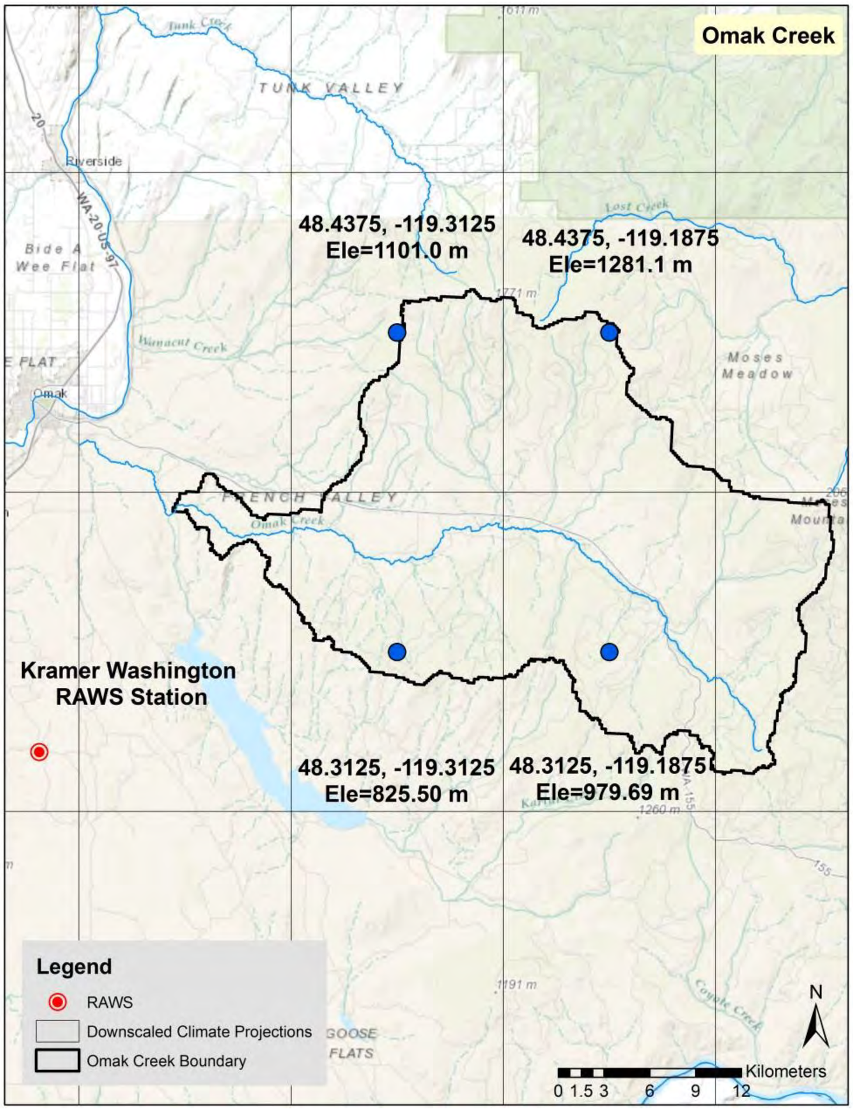


Figure 22. Downscaled GCM grid cells in the Omak Creek watershed. Red circled dot indicates the Kramer RAWS used to drive the model.

Table 7. Mean monthly air temperature difference (delta) between downscaled GCM historic and RCP8.5 climate projections in the Omak Creek watershed.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Delta	2.75	0.94	1.11	1.41	1.43	1.73	2.44	2.72	1.87	1.98	2.32	1.17

7.0 Model Application in the Entiat Subbasin

7.1 Calibration and Validation

DHSVM was driven at a 3-hour time step for 22 years (WY1990–2011) in the Upper Entiat watershed

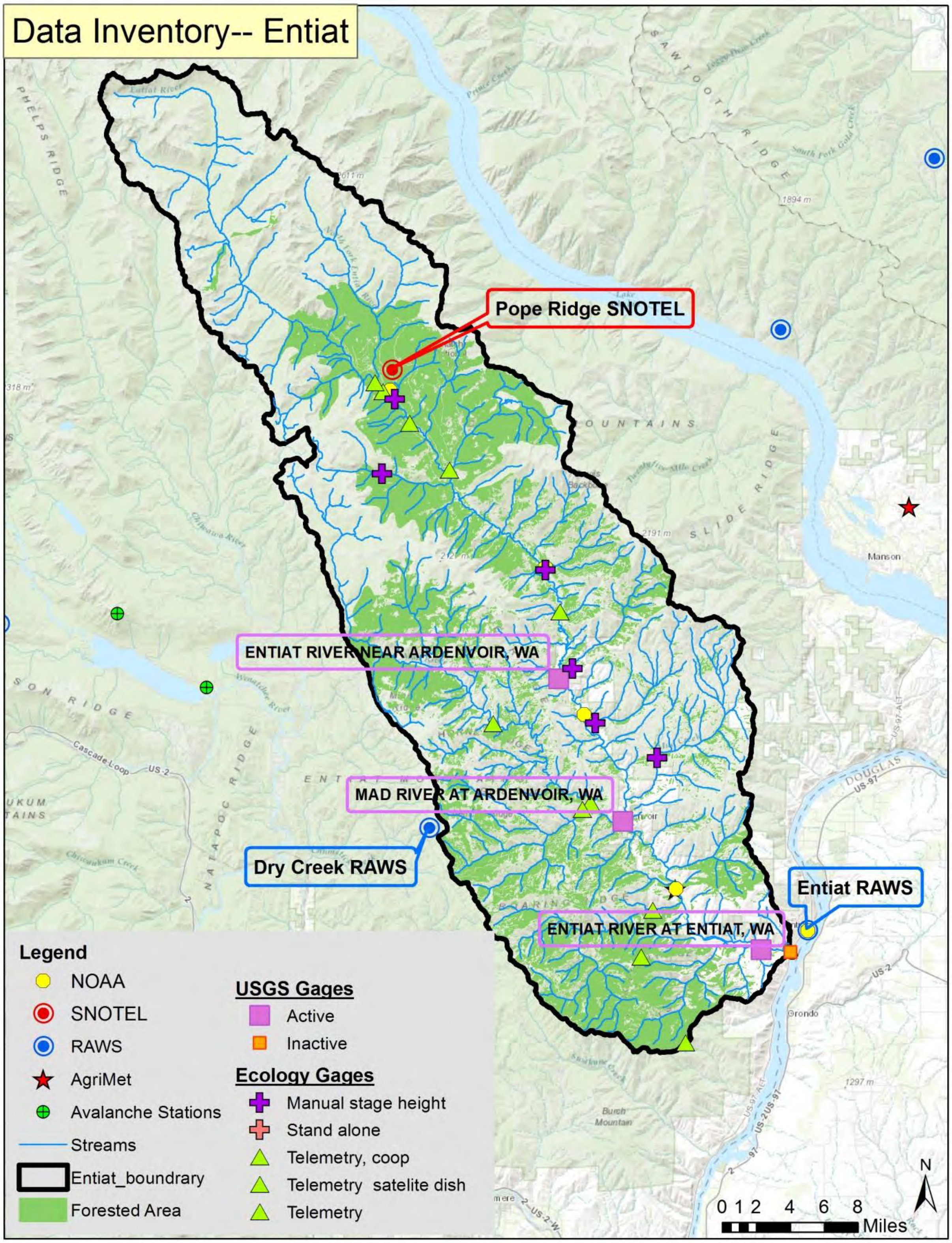


Figure 24) using SSURGO-based soils (Figure 25) and USFS-derived vegetation classes (Figure 26). The model was calibrated for the period from WY 1999 to 2006 using measured streamflow from the USGS

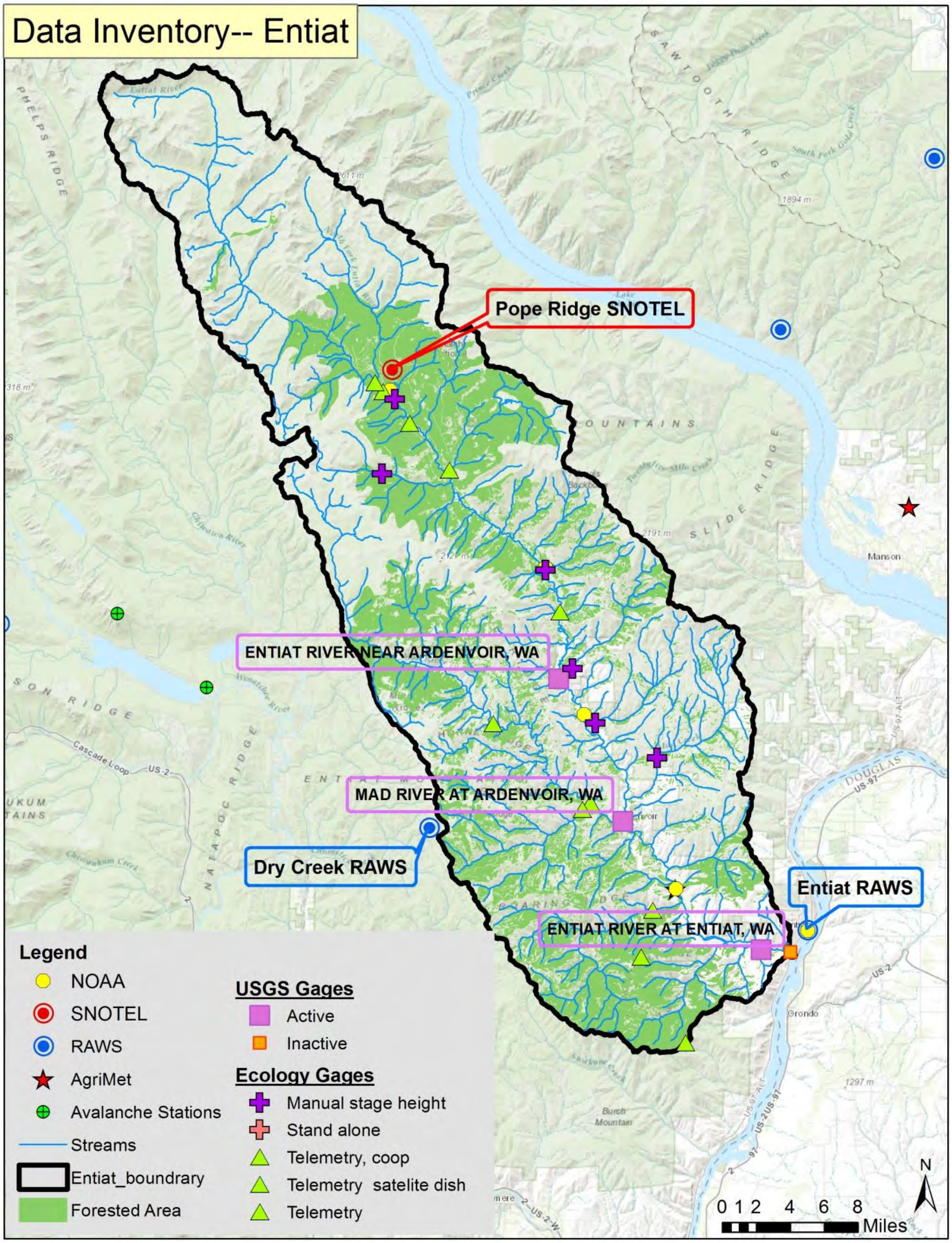


Figure 24). Mean daily simulated discharge was generally in good agreement with observed discharge rates. For the calibration period, the daily Nash-Sutcliffe Efficiency (NSE) value is 0.868 and the NSE for the entire 22 years was 0.737 (Figure 27) with a total mass balance error of 0.27%.

The NSE value can range between negative infinity and 1. An efficiency of 1 (NSE = 1) corresponds to a perfect match of modeled discharge to the observed data. An efficiency of 0 (NSE = 0) indicates that the model predictions are as accurate as the mean of the observed data, whereas an efficiency less than zero ($E < 0$) occurs when the observed mean is a better predictor than the model. Ideally, the NSE value should exceed 0.7 and the mass balance error should be between plus or minus 5%.

Monthly average flow was also checked to evaluate model performance (Figure 28). Simulated and observed monthly flows are generally in good agreement, except for a slight model under-simulation February–April and an over-simulation in June.

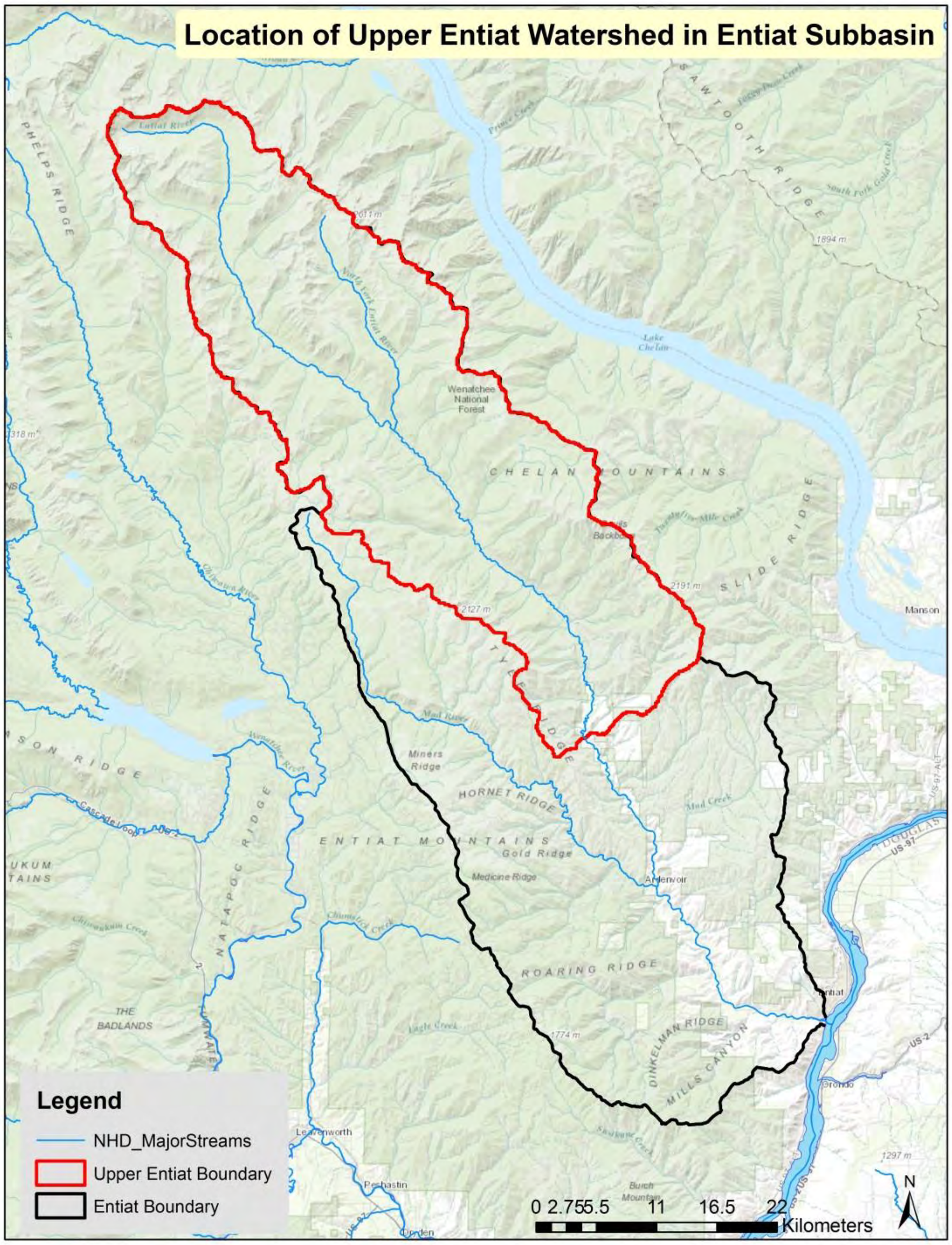


Figure 23. Location of the Upper Entiat watershed in Entiat subbasin.

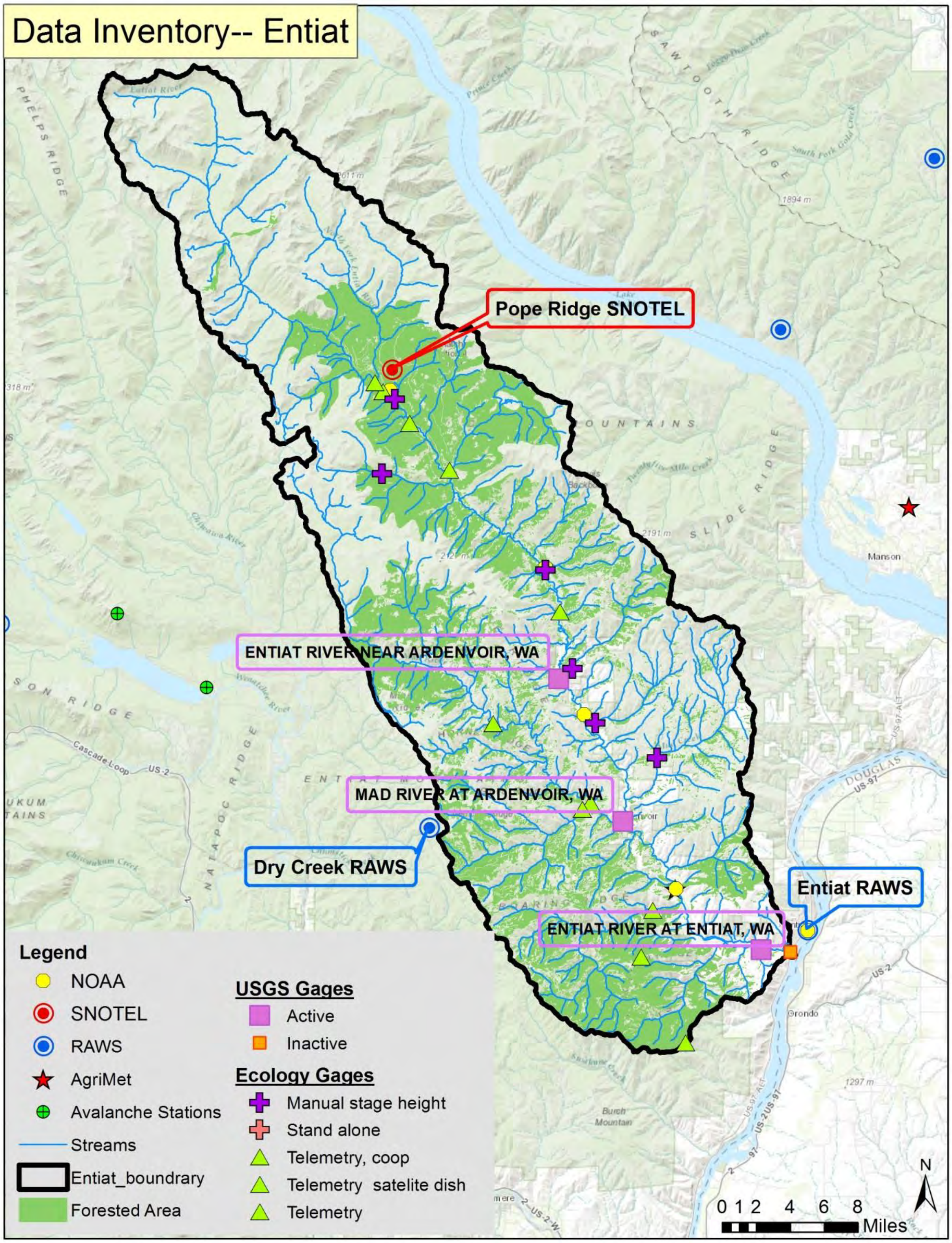


Figure 24. Available meteorological, snow, and streamflow monitoring stations in the Entiat subbasin along with areas that may be suitable for forest restoration.

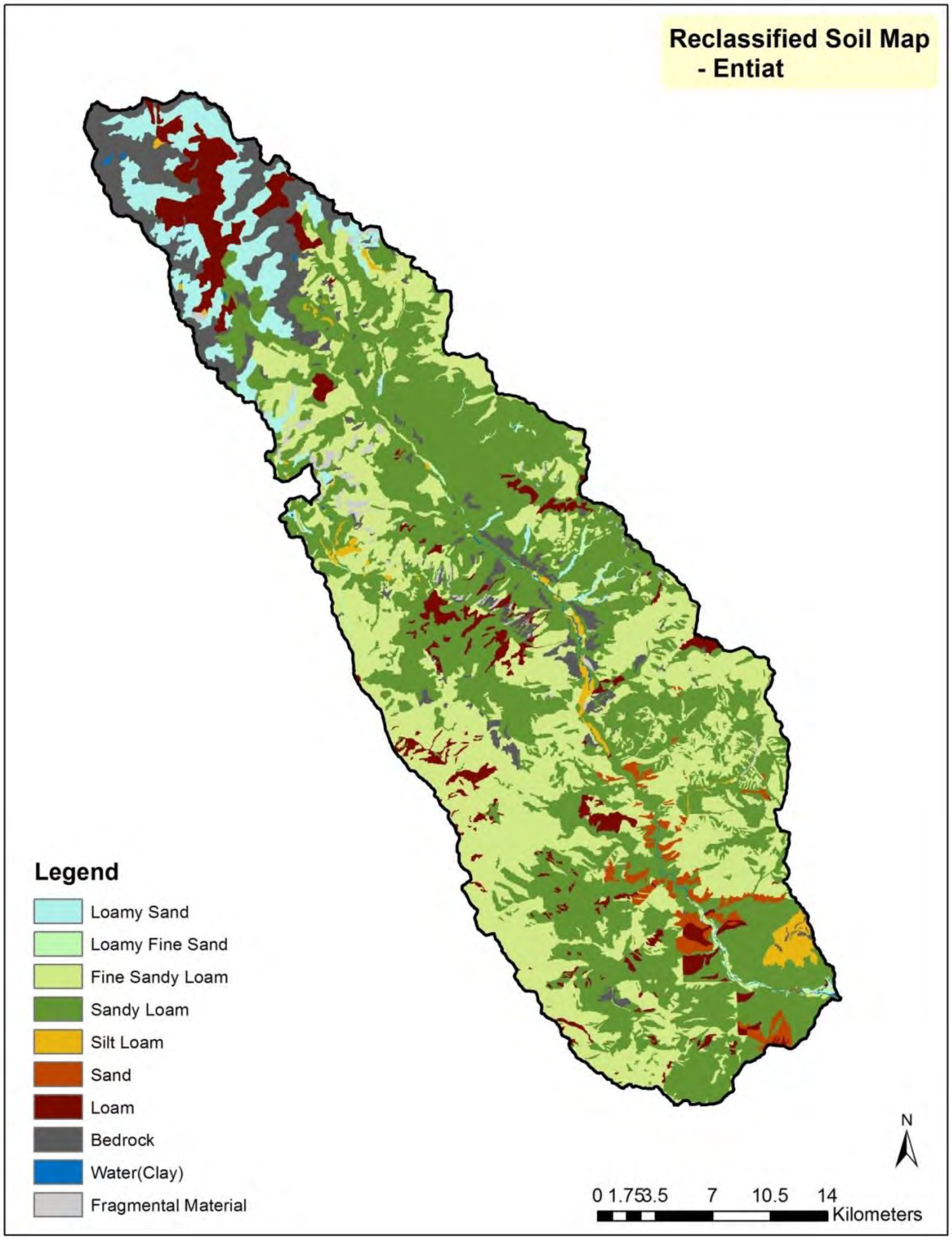


Figure 25. SSURGO-based soil texture classes for the Entiat subbasin.

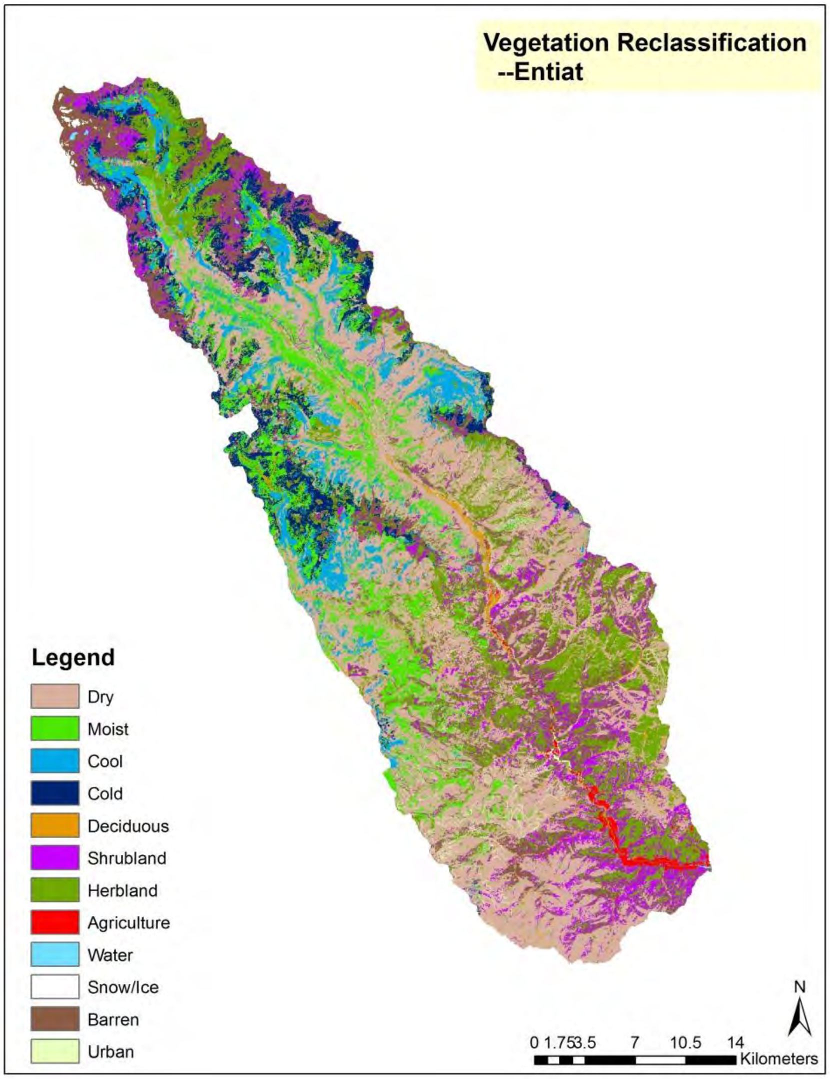


Figure 26. USFS-derived vegetation type based on LANDFIRE data in the Entiat subbasin.

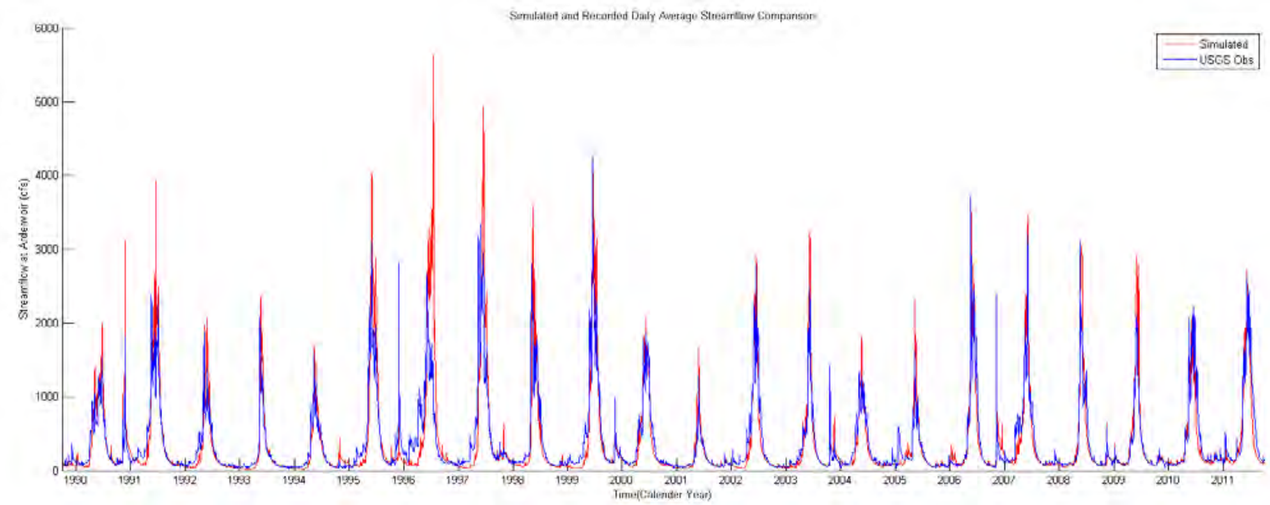


Figure 27. Simulated (red) and observed (blue) mean daily flow in the Upper Entiat watershed at Ardenvoir, Washington.

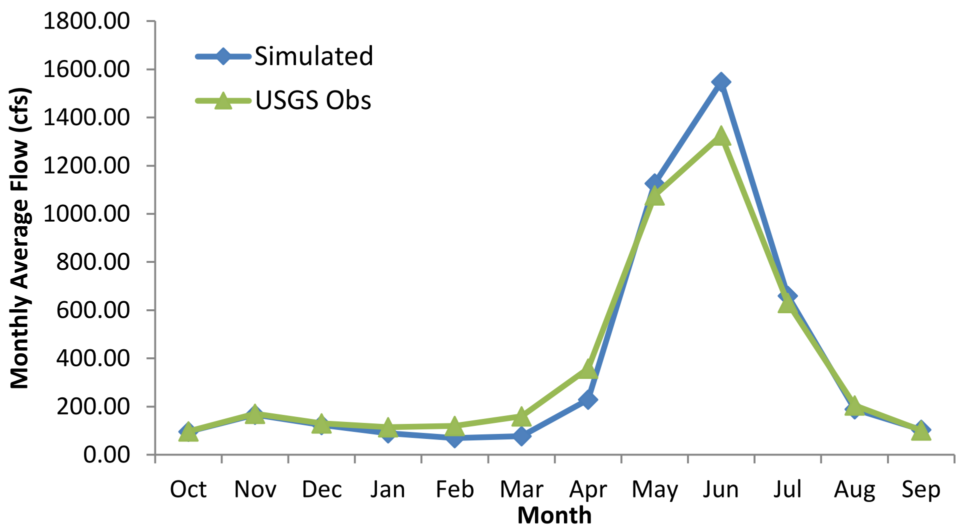


Figure 28. Simulated (blue) and observed (green) mean monthly flow for the Upper Entiat watershed.

7.2 Forest Restoration

Restoration locations in the Upper Entiat watershed are presented by scenario in Figure 29 to Figure 35.

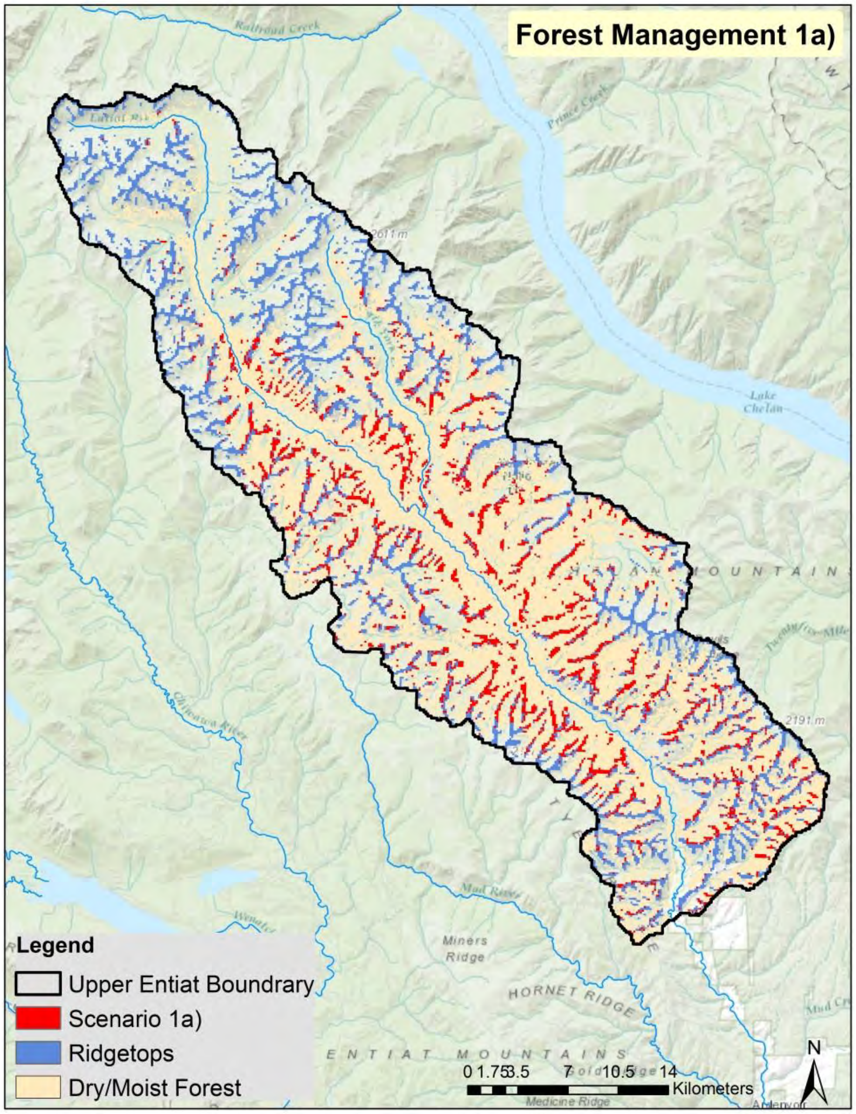


Figure 29. Locations of forest restoration Scenario 1a (red) in the Upper Entiat watershed with treatments on ridgetops in Dry/Moist forest where overstory fractional coverage was reduced to 30%.

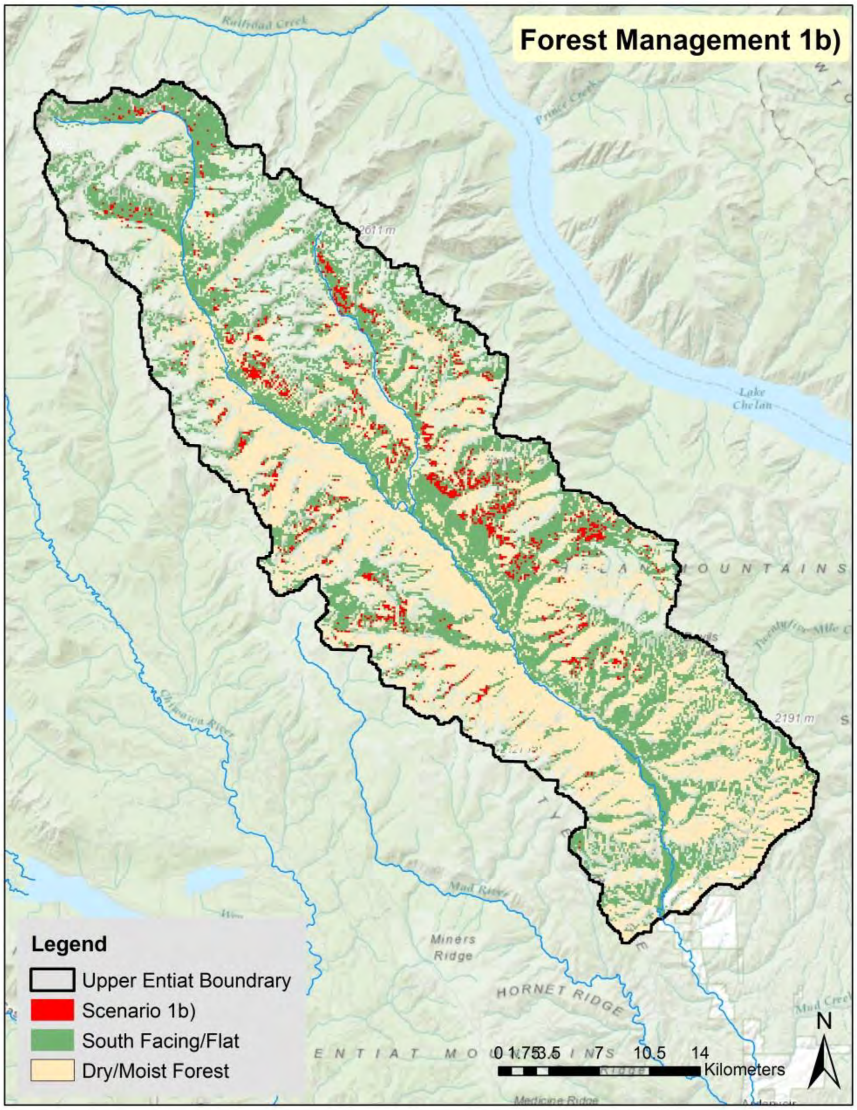


Figure 30. Locations of forest restoration Scenario 1b (red) in the Upper Entiat watershed with treatments on the upper elevation (top 50%) south-facing hillslopes in Dry/Moist forest where overstory fractional coverage was reduced to 50%.

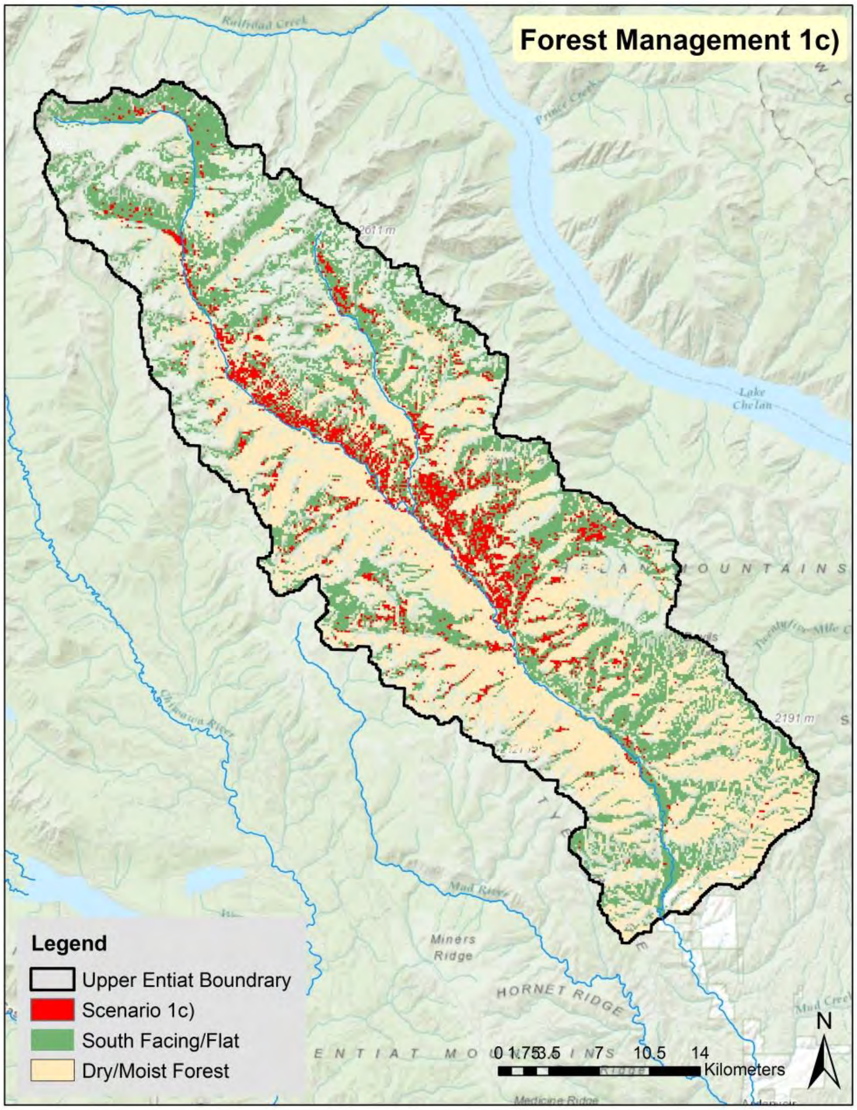


Figure 31. Locations of forest restoration Scenario 1c (red) in the Upper Entiat watershed with treatments on all south-facing hillslopes in Dry/Moist forest where overstory fractional coverage was reduced to 50%.

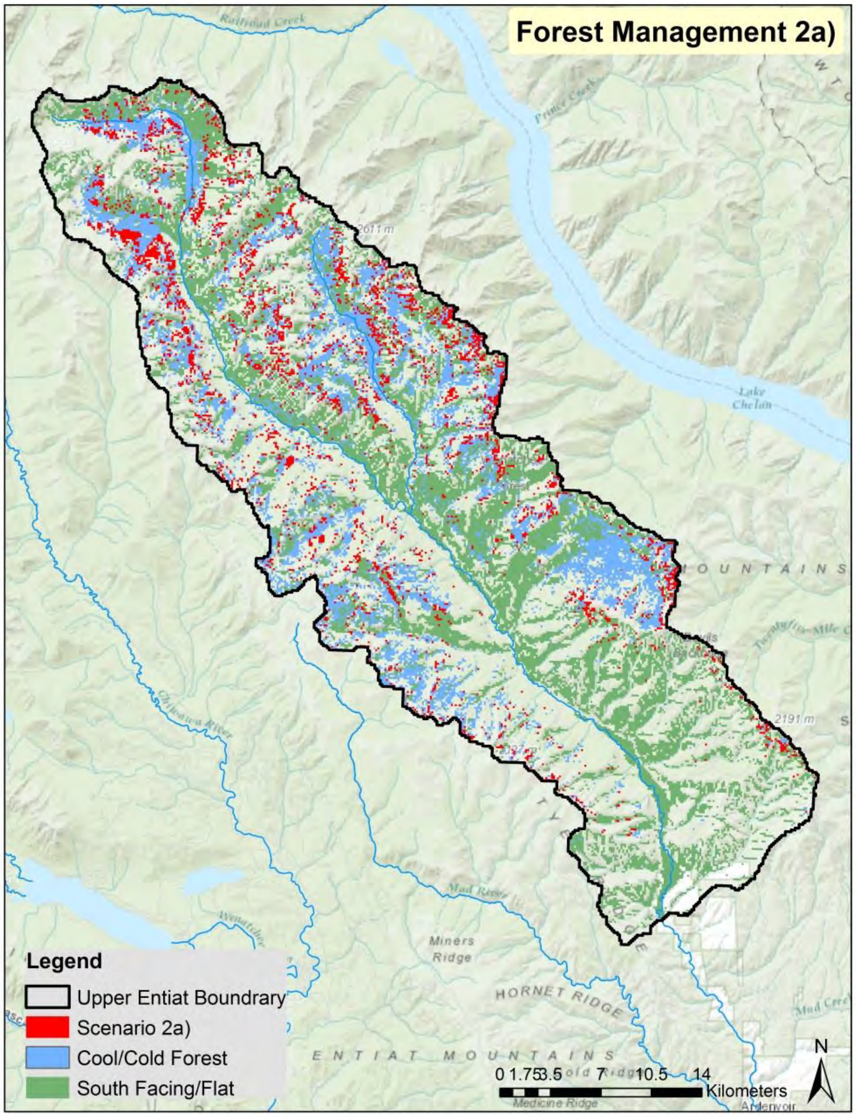


Figure 32. Locations of forest restoration Scenario 2a (red) in the Upper Entiat watershed with overstory removal via prescribed burning on locations in Cool/Cold forest with a Fire Potential Index in the top 30%.

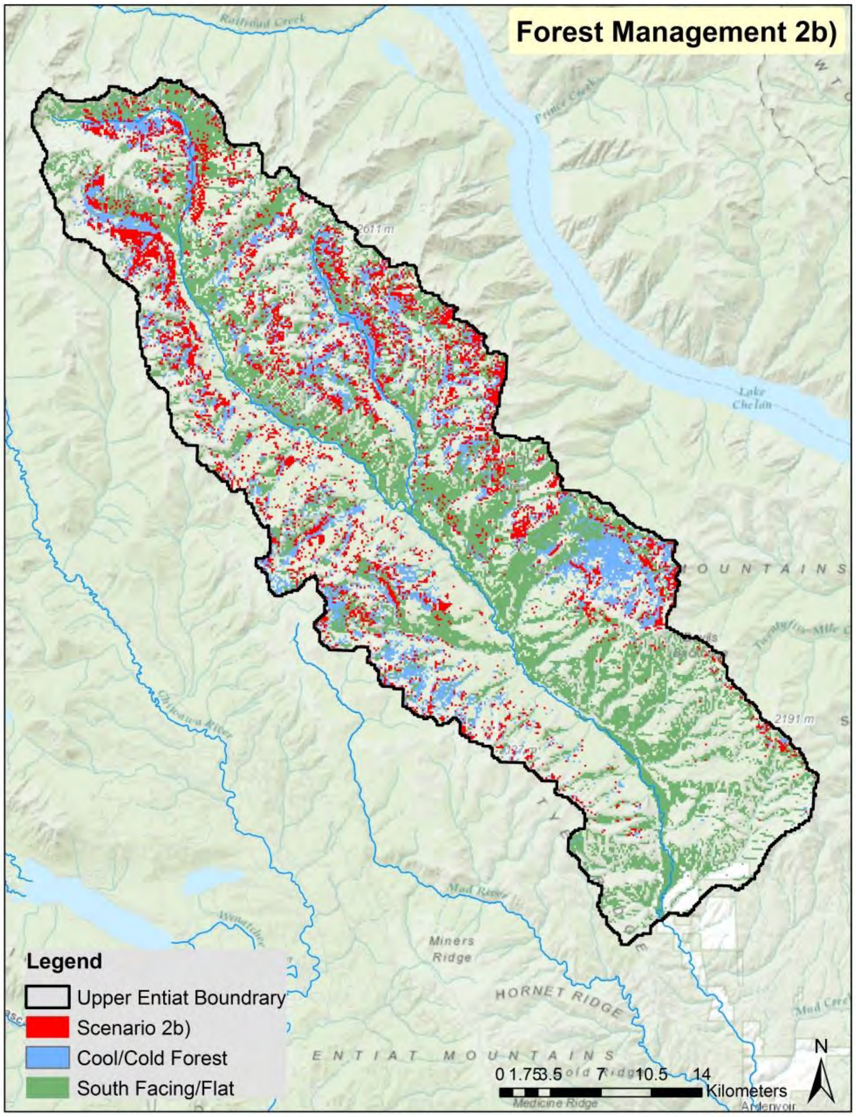


Figure 33. Locations of forest restoration Scenario 2a (red) in the Upper Entiat watershed with overstory removal via prescribed burning on locations in Cool/Cold forest with a Fire Potential Index in the top 50%.

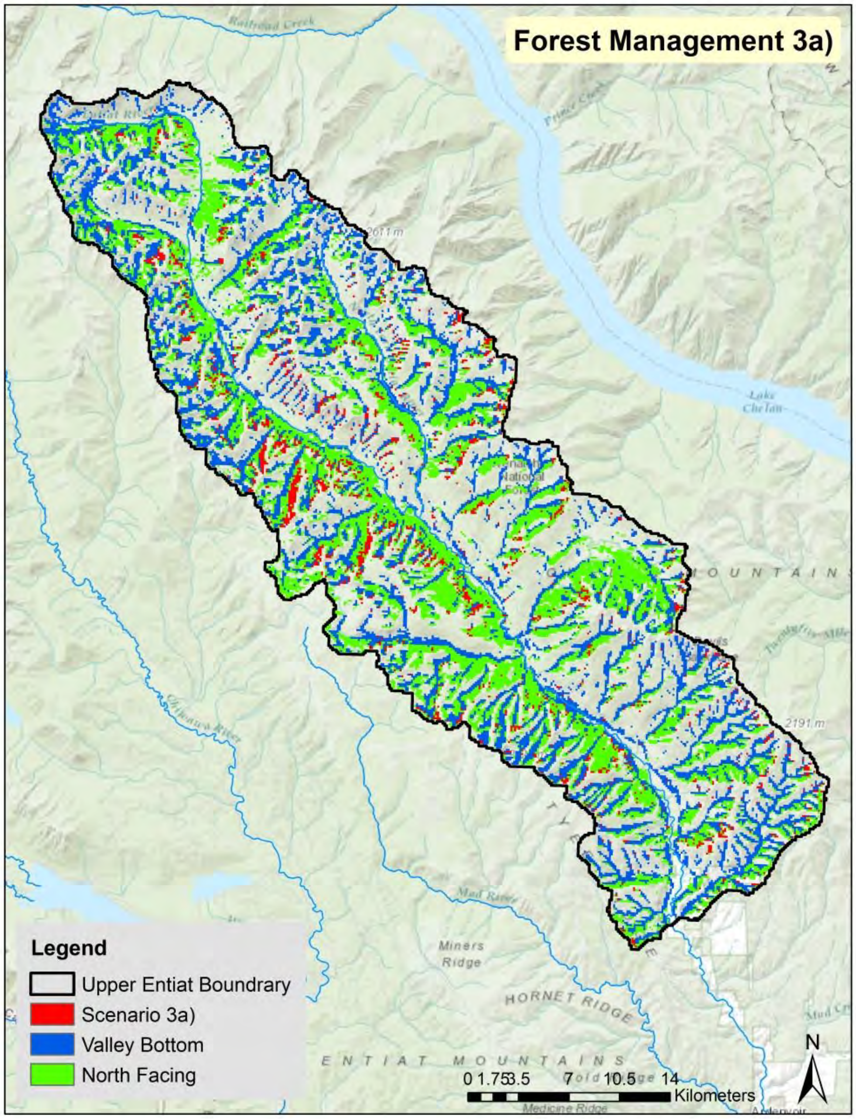


Figure 34. Locations of forest restoration Scenario 3a (red) in the Upper Entiat watershed with overstory removal via natural wildfire on north-facing slopes and valley bottoms with a Fire Potential Index in the top 10%.

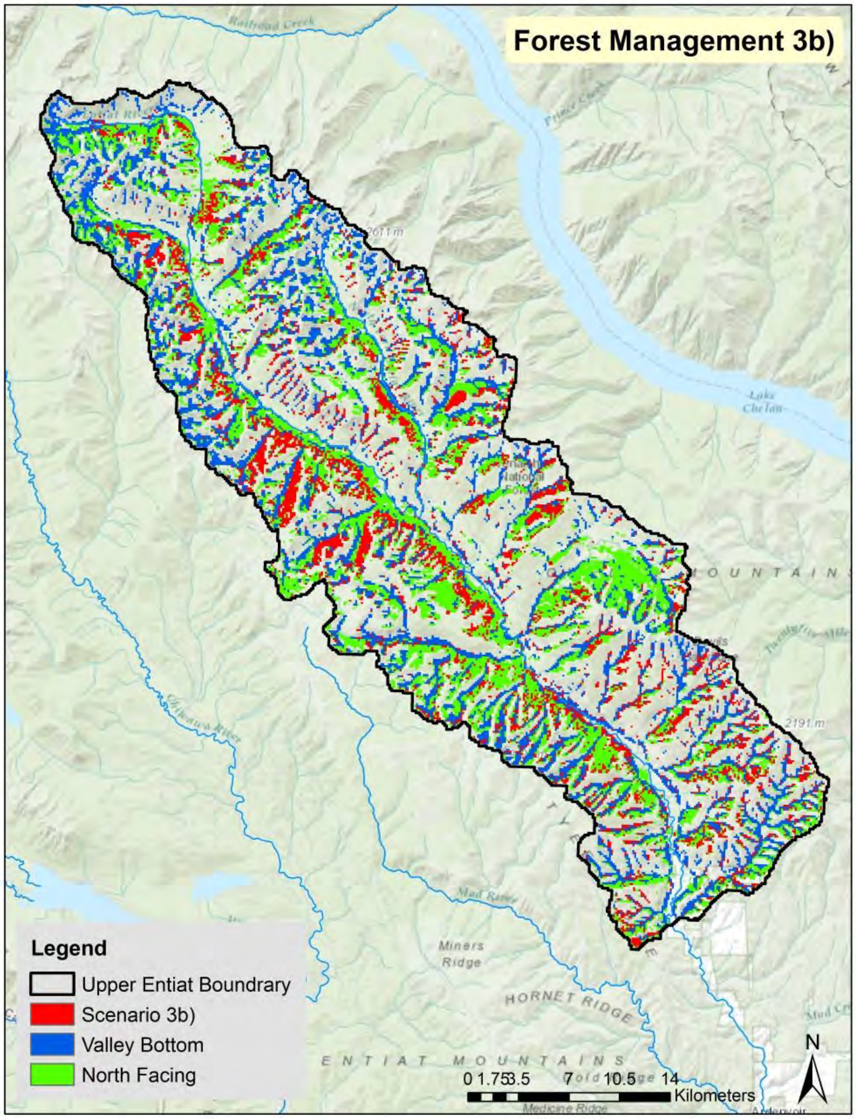


Figure 35. Locations of forest restoration Scenario 3b (red) in the Upper Entiat watershed with overstory removal via natural wildfire on north-facing slopes and valley bottoms with a Fire Potential Index in the top 30%.

7.3 Forest Restoration Results

7.3.1 Restoration Results under Current Climate

DHSVM was driven at a 3-hour time step for 22 years (WY 1990–2011) based on meteorology generated from the Pope Ridge SNOTEL site for all 7 forest restoration scenarios and the current condition no restoration baseline. Reduction in overstory fractional coverage ranges from 1.3% to 15% depending on the scenario (Table 8). While these results reflect historic climate variability, we assumed no vegetation regrowth. DHSVM scenario results are generally consistent with the Rocky Mountain/Inland Intermountain hydrologic region of Stednick (1996), showing mean increases in annual water yield ranging from 1.5 to 14.0 mm/yr (Figure 36 and Table 8). Corresponding increases in annual streamflow range from 0.3 to 2.3 %, or 0.9 to 8.1 cfs.

We also evaluated the UCSRB streamflow metrics and present selected results below. Seven-day average high flows are decreased in all scenarios relative to the baseline in April (Figure 37). By June, all scenarios show an increase in 7-day average high flows, with Scenarios 2a and 2b showing the greatest increase. In July, Scenarios 1a-c, and 3a,b still show an increase, while Scenarios 2a and 2b show a decrease relative to the current condition baseline.

Seven-day low flows are decreased in May for all scenarios and are increased June–October for all scenarios except 2a and 2b (Figure 38). Ridgetop thinning in the Moist/Dry forest (Scenario 1a) shows the greatest percent increase from the current condition baseline, particularly in July with a 5% increase equal to 10 cfs above the baseline. Burning in the Cool/Cold forest shows a general decrease relative to the baseline.

Table 8. Summary of forest restoration scenarios and results in the Upper Entiat watershed

Scenarios	Scenario Description				Pct FC reduced	% change in annual streamflow	Change in Yield (mm)	Change in Streamflow (cfs)
	Forest Type	Topo	Location	Fractional Coverage (FC)				
1a)	Dry/Moist	Ridgetops	All	FC>30% to 30%	3.87%	0.28	1.5	0.9
1b)	Dry/Moist	South-facing Slope	Top 50% Elevation	FC>50% to 50%	1.27%	0.26	1.5	0.9
1c)	Dry/Moist	South-facing Slope	All	FC>50% to 50%	3.25%	0.71	4.3	2.5
2a)	Cool/Cold	All	Top 30% Fire Index	FC to 0	7.85%	1.00	6.2	3.7
2b)	Cool/Cold	All	Top 50% Fire Index	FC to 0	13.94%	1.84	11.3	6.7
3a)	All	North-facing Slope and Valley Bottoms	Top 10% Fire Index	FC to 0	5.05%	0.66	4.0	2.4
3b)	All	North-facing Slope and Valley Bottoms	Top 30% Fire Index	FC to 0	15.43%	2.26	13.8	8.1

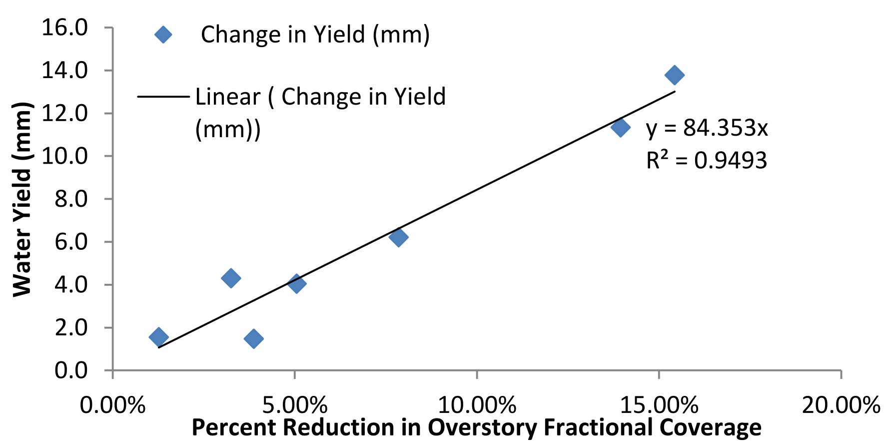


Figure 36. Increase in annual water yield (mm) in the Upper Entiat watershed as a function of percent reduction in overstory fractional coverage.

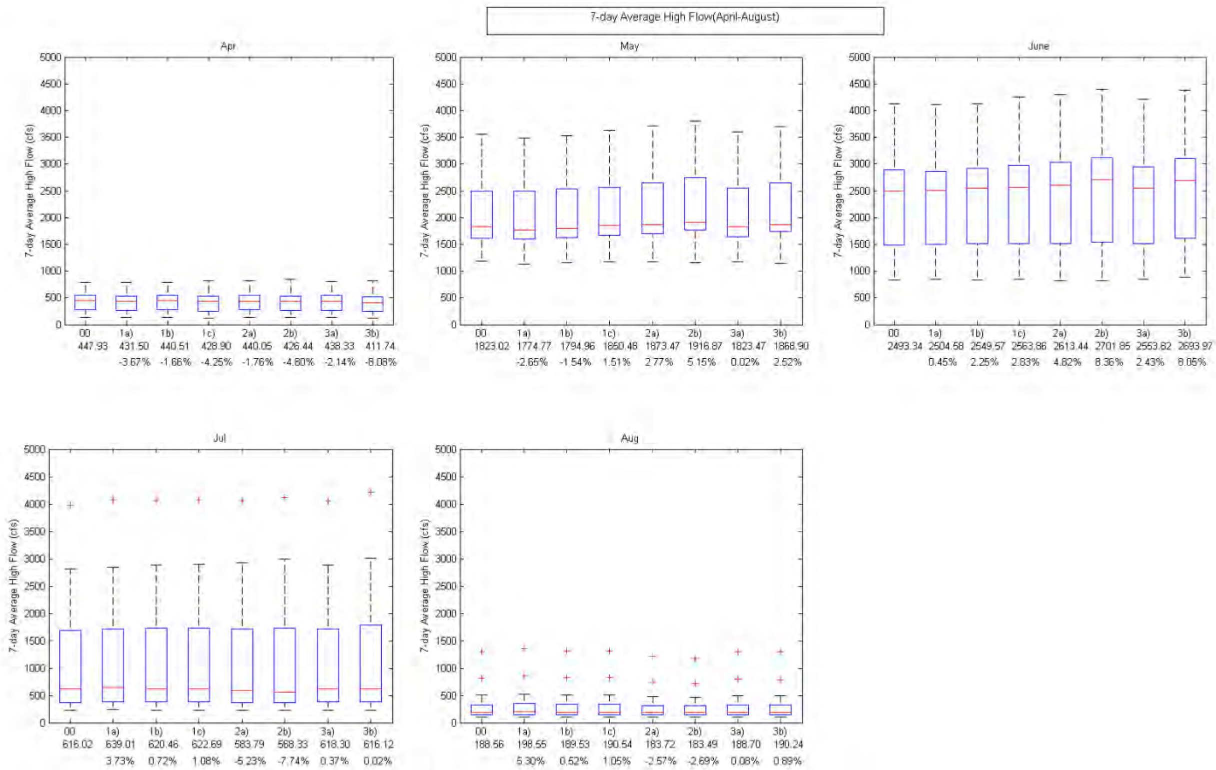


Figure 37. UCSRB 7-day high flow metric for April–August by forest restoration scenario based on 22 years in the Upper Entiat watershed. Scenario 00 in each plot (far left) represents the no restoration baseline. Median flow (cfs) for each scenario is given directly below each plot, and the percent change in flow from the no restoration scenario is provided in the next line. In the box-and-whisker plots, the red line represents the median; the lower and upper portion of the box is at the 75% and 25% exceedance, respectively. The lengths of the whiskers are 1.5 times the difference between the median and the corresponding exceedance. Red crosses are outliers.

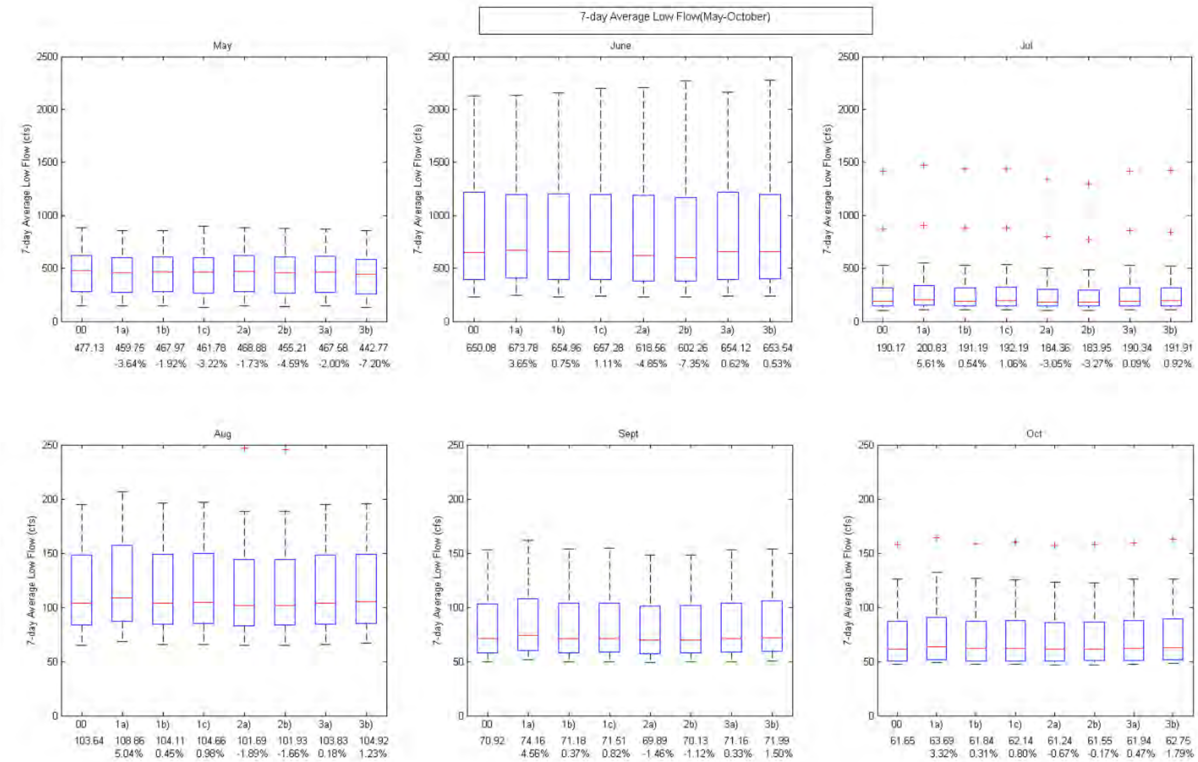


Figure 38. UCSRB 7-day low-flow metric for May–October by forest restoration scenario based on 22 years in the Upper Entiat watershed. Scenario 00 in each plot (far left) represents the no restoration baseline. Median flow (cfs) for each scenario is given directly below each plot, and the percent change in flow from the no restoration scenario is provided in the next line. In the box-and-whisker plots, the red line represents the median; the lower and upper portion of the box is at the 75% and 25% exceedance, respectively. The lengths of the whiskers are 1.5 times the difference between the median and the corresponding exceedance. Red crosses are outliers.

7.3.2 Restoration Results under Climate Change

Higher temperatures associated with future climate conditions produce an increase in fall and winter flows, an earlier snowmelt peak, and decreased summer flows compared to the corresponding current climate no restoration baseline (Figure 39).

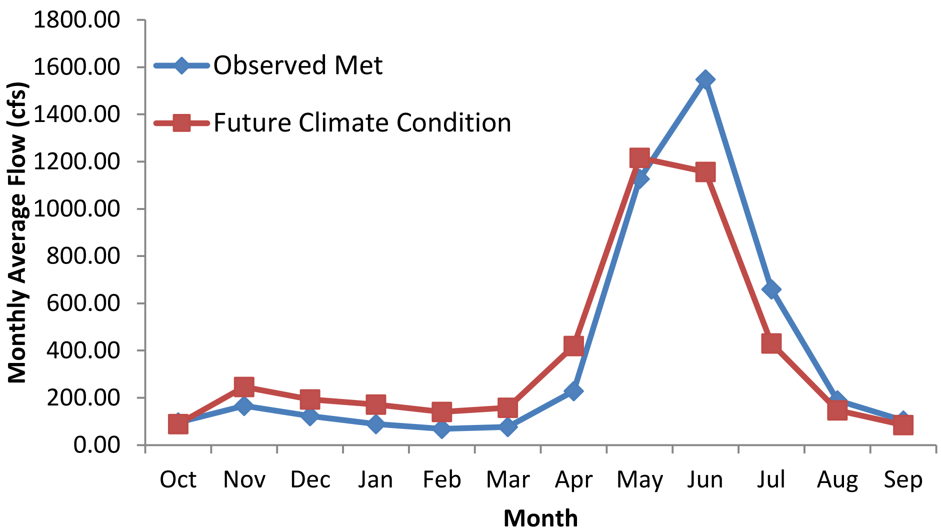


Figure 39. DHSVM-simulated mean monthly flow based on observed meteorology (blue) and future climate conditions (red) under the no restoration baseline in the Upper Entiat watershed.

The mean increase in annual water yield with forest restoration under climate change ranges from 1.0 mm/yr to 12.5 mm/yr (Figure 40 and Table 9) over the future climate condition no restoration baseline (i.e., future climate condition with current existing vegetation). Corresponding increases in annual streamflow range from 0.2 to 2.1 %, or 0.6 to 7.4 cfs.

Table 9. Comparison of restoration results between current (observed) and future climate conditions in the Upper Entiat watershed.

		% Change in Annual Streamflow		Change in Yield (mm)		Change in Streamflow (cfs)	
Scenarios	Pct FC reduced	Obs Met	Future Climate Condition	Obs Met	Future Climate Condition	Obs Met	Future Climate Condition
1a)	3.87%	0.28	0.19	1.5	1.0	0.9	0.6
1b)	1.27%	0.26	0.21	1.5	1.3	0.9	0.7
1c)	3.25%	0.71	0.54	4.3	3.3	2.5	1.9
2a)	7.85%	1.00	0.92	6.2	5.6	3.7	3.3
2b)	13.94%	1.84	1.75	11.3	10.6	6.7	6.3
3a)	5.05%	0.66	0.57	4.0	3.5	2.4	2.0
3b)	15.43%	2.26	2.08	13.8	12.5	8.1	7.4

Linear trend lines were calculated to examine the relationship between annual water yield (mm) in the Upper Entiat watershed and percent reduction in overstory fractional coverage (Figure 40). Under current (observed) climate, a 1% reduction in fractional coverage produces a 0.84 mm/yr volume increase in water yield versus a 0.76 mm/yr increase for future climate conditions.

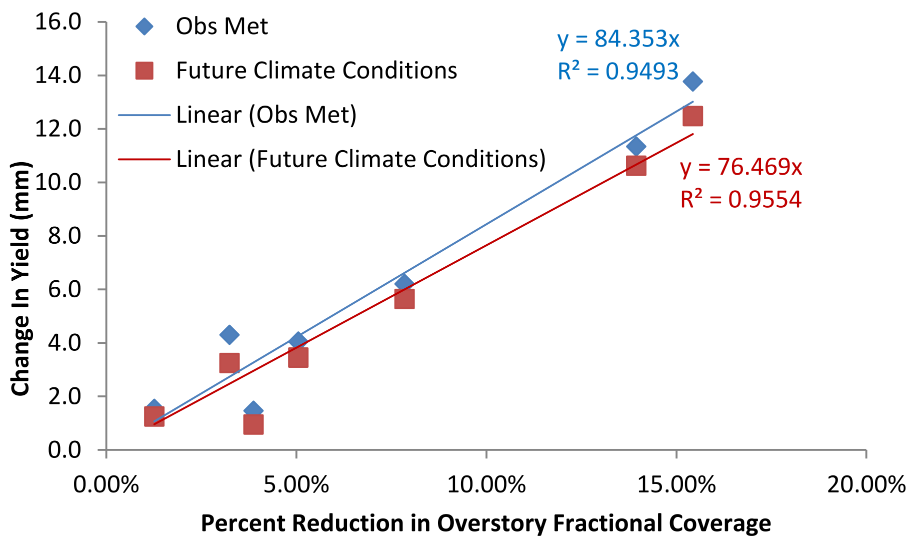


Figure 40. Increase in annual water yield (mm) in the Upper Entiat watershed under current (observed) climate (blue) and future climate conditions (red) as a function of the percent reduction in overstory fractional coverage.

Flow metrics results for climate change are presented in Table 10–Table 13 below. Comparing the top (Observed Met) and bottom panels (Future Climate Condition) in Table 10 shows that under future climate conditions there is an increase in late fall and winter mean monthly flows (November through May), compared to current climate conditions for all forest restoration scenarios (including the no restoration baseline), and a decrease in flow during the summer and early fall (June through October). However, forest restoration tends to decrease fall and winter flows and generally increases summer flows compared to a future climate condition no restoration baseline (bottom panel).

Comparing the top (Observed Met) and bottom panels (Future Climate Condition) in Table 11 shows that under future climate conditions there is an increase in late fall and winter 7-day average low flows (November–May), compared to current climate conditions for all forest restoration scenarios (including the no restoration baseline), and a decrease in flow during the summer and early fall. However, forest restoration tends to decrease December through May flows and generally increase June through October low flows compared to a future climate condition no restoration baseline (bottom panel).

Comparing the top (Observed Met) and bottom panels (Future Climate Condition) in Table 12 shows that under climate change there is an increase in late fall and winter 7-day average high flows (November through April), compared to current climate conditions for all forest restoration scenarios (including no restoration baseline), and a decrease in flow during the summer and early fall. However, forest restoration tends to decrease December through April flows and generally increase May through November flows compared to a future climate condition no restoration baseline (bottom panel).

Comparing the top (Observed Met) and bottom panels (Future Climate Condition) in Table 13 shows that under climate change there is an increase in late fall and winter 1-day average high flows (November through April), compared to current climate conditions for all forest restoration scenarios (including no restoration baseline), and a decrease in flow during the summer and early fall. However, forest restoration tends to decrease January through April flows and generally increase May through October flows compared to a future climate condition no restoration baseline (bottom panel).

Table 10. Comparison of mean monthly flow in the Upper Entiat watershed for forest restoration scenarios under current and future climate conditions.

Monthly Average Flow(cfs) – Entiat													
		Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Observed Met	No MGMT	96.28	165.83	123.32	89.63	68.82	77.19	228.59	1126.87	1548.33	659.46	189.06	103.93
	1a	99.75	167.77	122.87	88.73	67.80	75.55	220.59	1102.44	1554.71	679.33	199.00	109.04
	1b	96.56	165.48	122.87	89.32	68.59	76.72	225.01	1117.40	1563.47	668.45	190.13	104.39
	1c	96.97	163.93	120.94	86.95	65.41	70.57	210.24	1138.49	1585.74	672.14	191.12	104.95
	2a	95.45	164.71	122.41	89.00	68.32	76.46	225.26	1153.18	1590.51	652.12	182.26	101.87
	2b	95.78	163.58	121.68	88.45	67.87	75.41	219.04	1170.61	1620.65	651.36	181.29	102.14
	3a	96.77	165.50	122.43	88.74	67.96	75.90	223.52	1128.59	1577.22	666.50	188.80	104.18
	3b	97.98	163.15	119.42	85.79	65.18	71.26	207.44	1145.69	1644.04	680.07	189.63	105.30
Future Climate Condition	No MGMT	89.14	246.70	193.79	171.36	140.30	158.12	420.15	1216.80	1156.79	430.16	147.75	85.38
	1a	92.58	249.16	192.69	168.59	136.40	152.67	404.86	1198.75	1172.63	447.85	156.67	90.12
	1b	89.45	246.02	192.99	170.40	139.17	156.09	410.41	1219.64	1172.48	434.23	148.56	85.79
	1c	89.94	246.01	190.74	164.58	131.88	146.59	408.86	1245.68	1182.77	435.97	149.41	86.30
	2a	89.28	246.02	192.64	169.68	138.40	155.58	414.00	1250.47	1184.52	425.28	145.37	84.81
	2b	90.15	244.73	191.32	167.46	136.24	151.84	403.03	1280.55	1208.39	425.68	145.97	85.53
	3a	90.35	246.99	192.49	168.96	137.50	154.66	411.98	1221.09	1182.25	438.05	149.86	86.58
	3b	92.46	245.48	187.79	160.83	129.22	143.72	389.46	1257.87	1245.43	450.62	152.76	88.34

Examples of Table font format

Example	**Explanation**
Font in Red	Smaller flow compared to current non-restoration flow
Font in Black	Larger flow compared to current non-restoration flow
	Larger flow compared to non-restoration flow within its own climate scenario
	Smaller flow compared to non-restoration flow within its own climate scenario

Table 11. Seven-day average low-flow monthly median in the Upper Entiat watershed under current and future climate conditions.

7-Day Average Low-Flow Monthly Median(cfs) – Entiat													
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Observed Met	No MGMT	**61.34**	**59.15**	**55.13**	**80.67**	**477.13**	**650.08**	**190.17**	**103.64**	**70.92**	**61.65**	**72.53**	**75.07**
	1a	60.63	58.72	54.11	78.64	459.75	673.78	200.83	108.86	74.16	63.69	74.00	74.60
	1b	60.98	59.04	54.88	80.39	467.97	654.96	191.19	104.11	71.18	61.84	72.47	74.82
	1c	59.77	57.47	51.73	72.37	461.78	657.28	192.19	104.66	71.51	62.14	72.42	73.29
	2a	61.65	58.85	54.81	79.82	468.88	618.56	184.36	101.69	69.89	61.24	72.56	74.57
	2b	61.66	58.61	54.52	78.97	455.21	602.26	183.95	101.93	70.13	61.55	72.93	74.54
	3a	61.18	58.77	54.40	79.14	467.58	654.12	190.34	103.83	71.16	61.94	73.28	74.48
	3b	59.98	57.14	52.23	74.56	442.77	653.54	191.91	104.92	71.99	62.75	74.74	74.21
Future Climate Condition	No MGMT	114.91	103.41	107.60	189.83	667.91	444.36	163.01	87.13	60.06	52.70	81.35	134.36
	1a	113.48	100.47	103.15	183.97	650.04	463.96	172.26	92.05	62.91	54.86	82.97	132.66
	1b	114.71	102.99	106.55	188.60	651.98	446.86	163.77	87.57	60.33	52.88	81.35	133.41
	1c	109.98	94.76	97.93	168.93	674.13	449.08	164.80	88.11	60.71	53.17	82.13	131.98
	2a	114.59	102.17	105.64	187.23	660.96	432.34	160.98	86.68	60.20	52.71	82.45	133.63
	2b	114.12	100.74	103.44	182.88	653.33	429.18	161.88	87.36	60.78	53.23	83.34	132.71
	3a	113.68	101.19	104.70	185.78	660.45	452.84	165.41	88.28	61.19	53.44	82.87	133.29
	3b	109.81	94.87	96.18	171.24	655.10	462.76	168.80	90.05	62.48	54.57	86.26	129.77

Table 12. Seven-day average high flow monthly median in the Upper Entiat watershed under current and future climate conditions.

7-Day Average High Flow Monthly Median(cfs) -Entiat													
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Observed Met	No MGMT	**91.18**	**81.03**	**91.11**	**447.93**	**1823.02**	**2493.34**	**616.02**	**188.56**	**107.54**	**94.38**	**139.71**	**124.03**
	1a	89.75	80.19	89.18	431.50	1774.77	2504.58	639.01	198.55	112.37	98.15	143.17	122.96
	1b	90.65	80.75	90.74	440.51	1794.96	2549.57	620.46	189.53	107.98	94.69	139.62	123.23
	1c	85.90	77.29	80.29	428.90	1850.48	2563.86	622.69	190.54	108.59	95.24	138.42	121.02
	2a	91.24	80.89	90.47	440.05	1873.47	2613.44	583.79	183.72	106.02	93.91	137.69	123.54
	2b	90.85	80.71	89.77	426.44	1916.87	2701.85	568.33	183.49	106.47	94.50	136.53	122.90
	3a	90.38	80.32	89.50	438.33	1823.47	2553.82	618.30	188.70	107.85	95.24	139.60	123.29
	3b	86.49	77.13	83.66	411.74	1868.90	2693.97	616.12	190.24	109.21	96.83	138.44	119.72
Future Climate Condition	No MGMT	203.22	157.48	192.97	689.69	1671.68	1639.73	436.93	158.54	91.84	86.60	229.31	234.52
	1a	199.33	152.57	187.24	664.81	1646.90	1657.77	456.03	167.54	96.88	91.17	233.27	234.19
	1b	202.33	156.62	192.20	670.57	1681.73	1666.29	439.12	159.29	92.23	86.97	229.52	233.61
	1c	189.10	143.68	173.46	685.88	1724.29	1671.06	441.61	160.29	92.89	87.52	231.58	232.61
	2a	201.70	155.34	190.47	678.08	1741.03	1713.78	425.85	156.61	91.55	86.33	229.92	234.04
	2b	199.47	152.53	187.04	660.91	1825.56	1773.54	423.99	157.46	92.49	87.26	229.50	233.02
	3a	199.98	153.71	188.82	676.96	1686.37	1678.21	444.81	160.87	93.16	87.83	231.85	234.08
	3b	187.47	140.92	175.26	654.08	1766.62	1798.17	452.41	164.13	95.30	89.74	235.99	228.52

Table 13. One-day average high flow monthly median in the Upper Entiat watershed under current and future climate conditions.

1-Day Average High Flow Monthly Median(cfs) – Entiat													
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Observed Met	No MGMT	**98.19**	**87.35**	**105.82**	**493.82**	**2107.82**	**2844.33**	**659.95**	**193.01**	**119.90**	**127.88**	**204.67**	**149.88**
	1a	96.74	86.85	104.19	477.56	2069.02	2853.11	684.49	203.23	124.95	133.18	207.44	148.18
	1b	97.76	87.27	105.71	484.13	2109.77	2913.02	664.51	194.00	120.47	128.32	203.97	148.92
	1c	91.45	83.45	95.03	470.69	2143.25	2929.22	666.87	195.00	121.49	129.23	200.88	143.24
	2a	98.21	87.22	105.07	487.38	2168.79	2982.82	619.92	188.09	118.96	126.16	204.37	149.97
	2b	97.81	87.00	104.28	472.23	2251.33	3075.17	602.55	187.88	119.94	126.69	202.79	149.50
	3a	97.36	86.52	104.11	485.04	2123.61	2912.96	657.69	193.17	120.63	128.45	204.57	148.77
	3b	92.25	82.47	97.60	458.80	2210.94	3075.78	651.13	194.71	122.50	130.06	198.35	142.95
Future Climate Condition	No MGMT	270.05	175.70	227.95	762.77	1889.61	1807.19	459.75	165.46	98.04	105.94	324.01	240.88
	1a	266.20	170.36	220.35	745.67	1879.16	1822.59	480.49	175.31	103.69	111.74	330.67	242.15
	1b	269.30	174.67	225.80	746.56	1935.13	1839.20	462.04	166.33	98.56	106.41	325.05	239.35
	1c	257.24	159.08	205.48	780.82	1948.48	1844.99	464.42	167.33	99.20	107.28	328.92	237.92
	2a	268.47	173.21	224.24	755.44	1970.55	1878.77	447.78	163.37	97.11	105.76	325.95	242.08
	2b	266.41	169.76	218.50	740.64	2064.30	1926.29	445.55	164.28	97.92	107.23	327.51	239.99
	3a	267.24	171.36	222.57	759.19	1898.60	1851.78	469.46	167.67	99.29	107.68	328.76	241.85
	3b	254.54	156.28	204.58	748.24	1991.42	1975.84	479.97	171.18	101.35	110.42	332.27	241.50

8.0 Model Application in the Wenatchee Subbasin

8.1 Calibration and Validation

DHSVM was driven at a 3-hour time step for 4 years (WY 2011–2014) in the Chiwawa watershed within the Wenatchee subbasin (Figure 41) based on meteorology generated from the Trinity SNOTEL and the NOAA station near Plain (Figure 42) using SSURGO-based soils (Figure 43) and USFS-derived vegetation classes (Figure 44). Due to the limited meteorological record, the model was calibrated using the full period from WY 2011 to 2014. Calibration model results are good with a NSE value of 0.808 and a total mass balance error of -2.78%. Simulated and observed mean monthly flows are in general agreement, except that the simulated snowmelt peak is lower and earlier than observed (Figure 46).

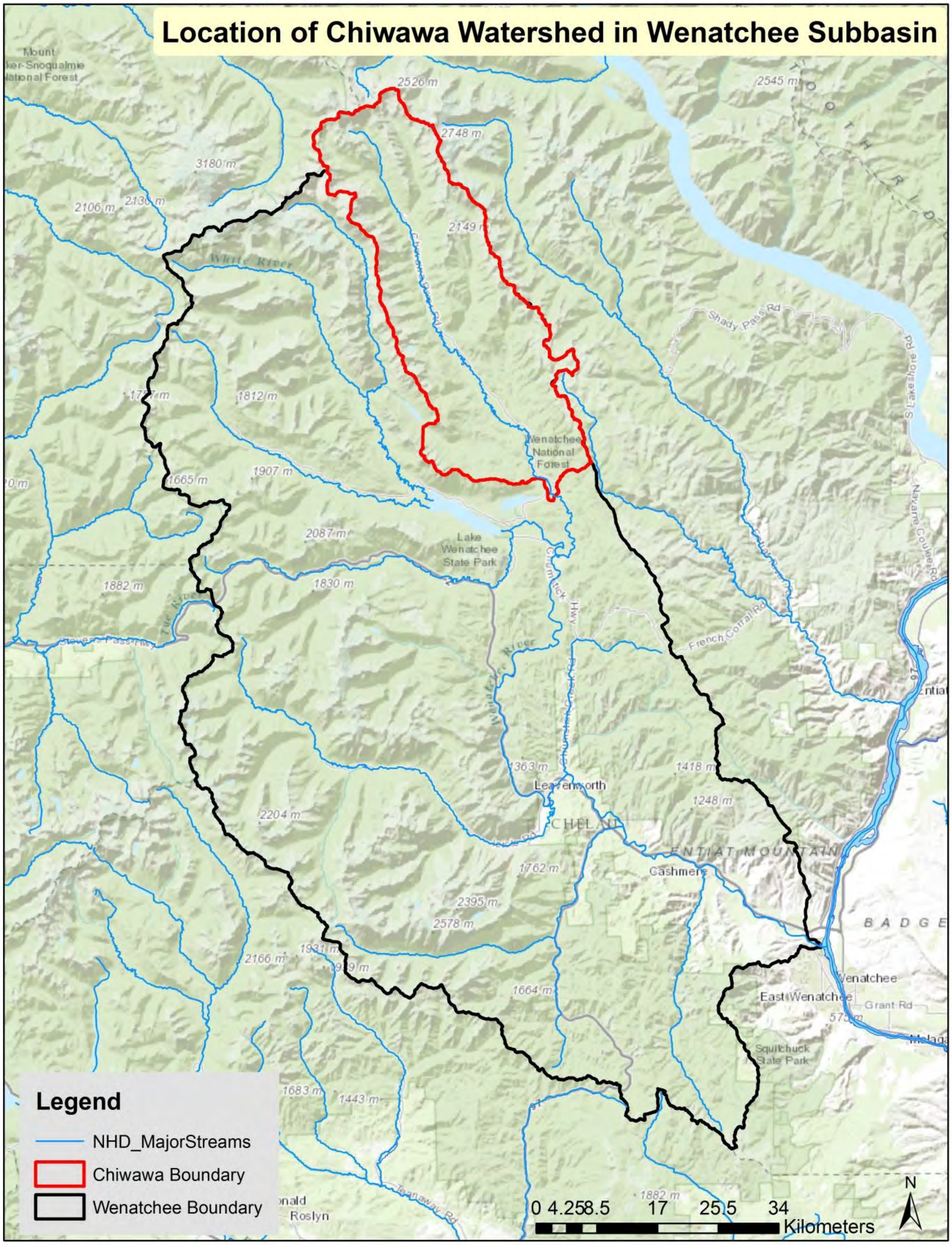


Figure 41. Location of Chiwawa watershed within the Wenatchee subbasin.

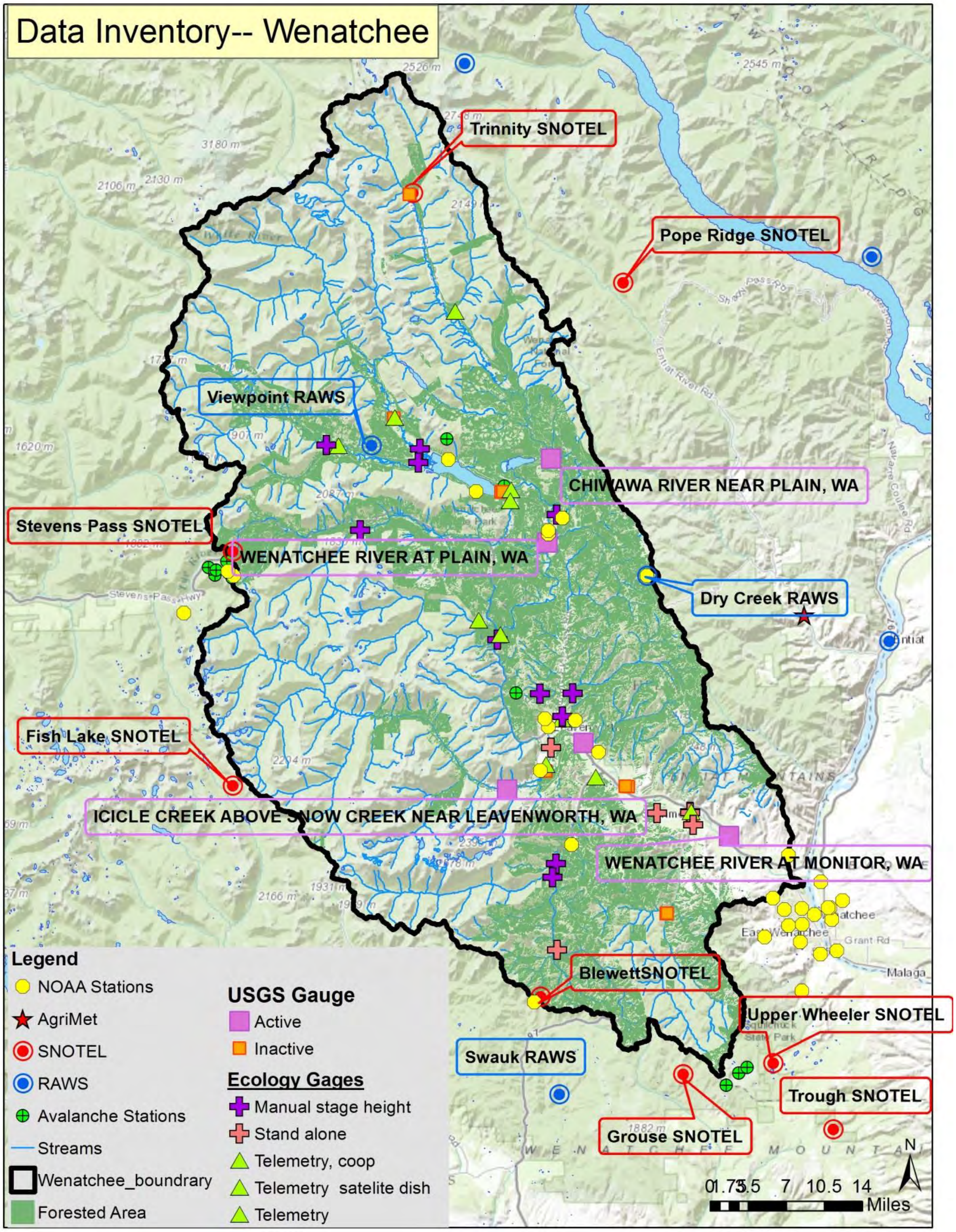


Figure 42. Available meteorological, snow, and streamflow monitoring data for stations in the Wenatchee subbasin along with areas that may be suitable for forest restoration.

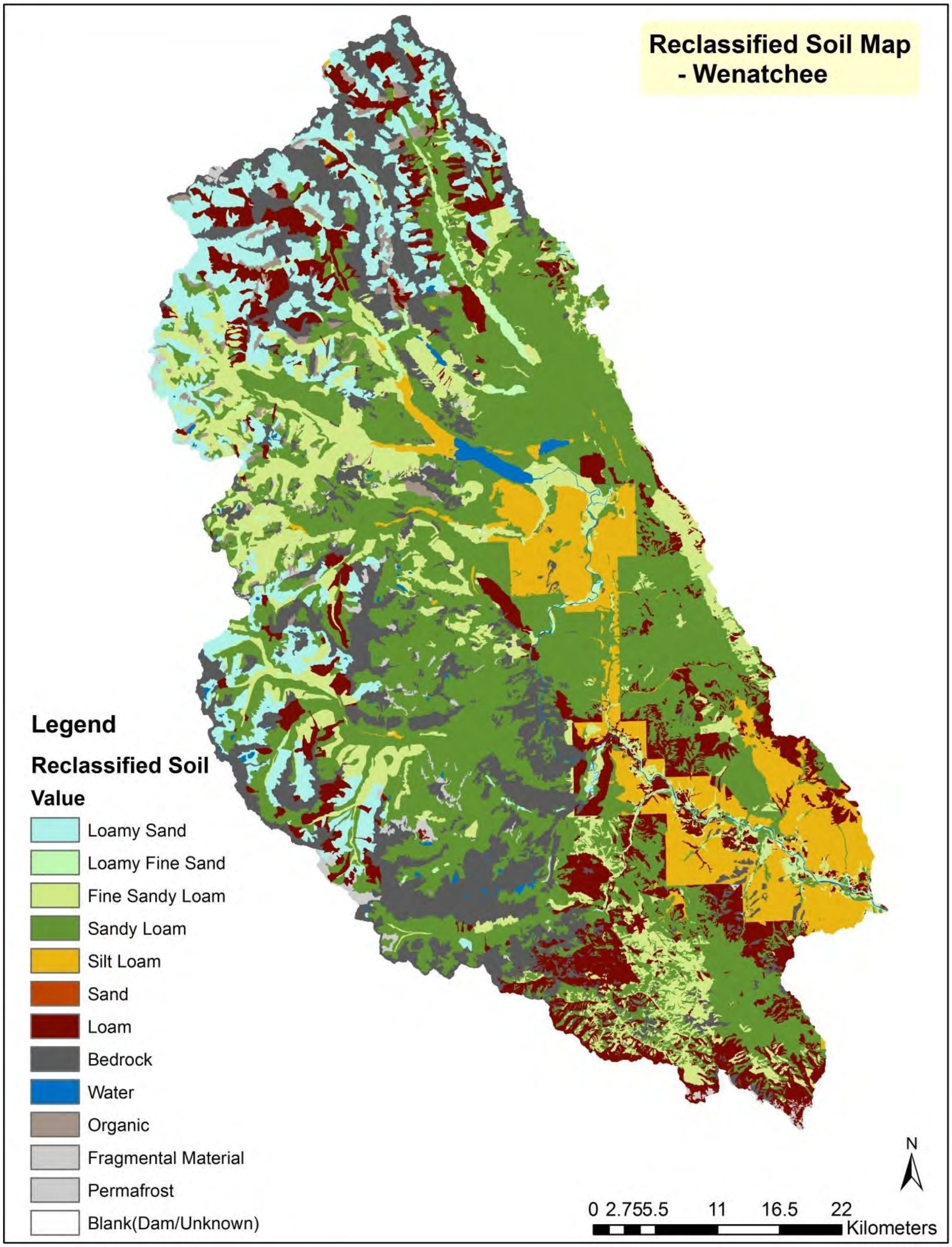


Figure 43. SSURGO-based soil texture classes for the Wenatchee subbasin.

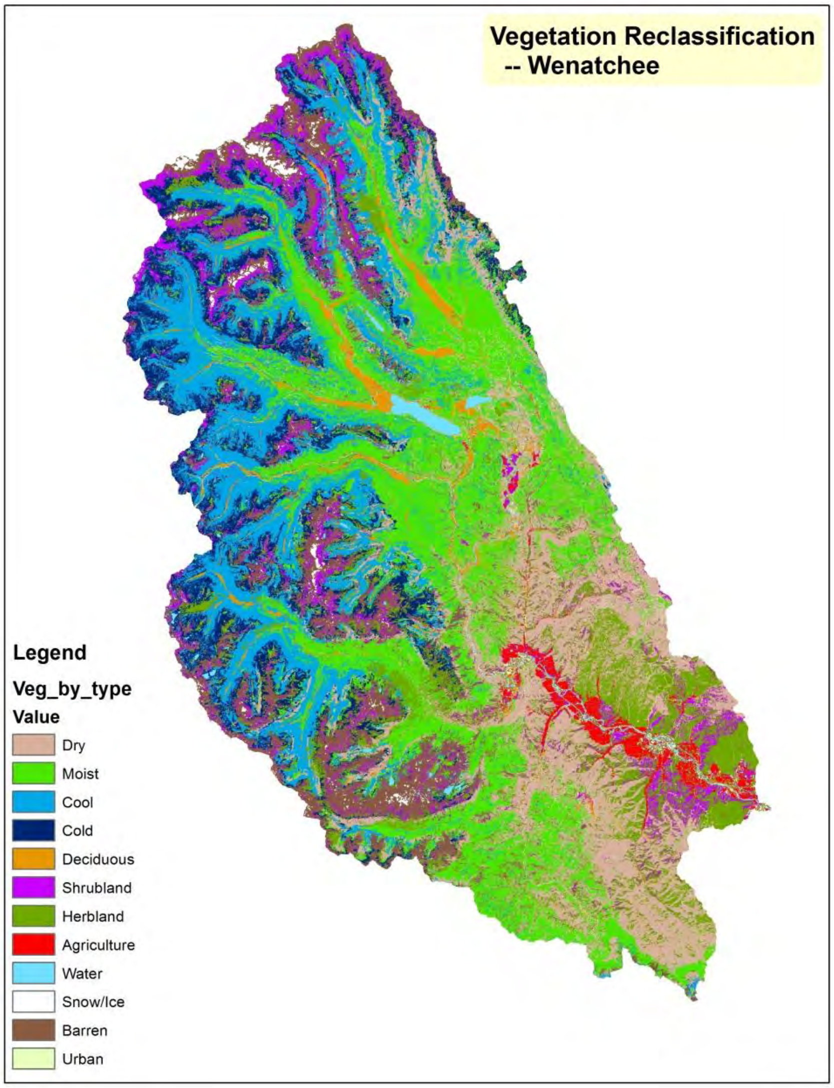


Figure 44. USFS-derived vegetation types based on LANDFIRE data in the Wenatchee subbasin.

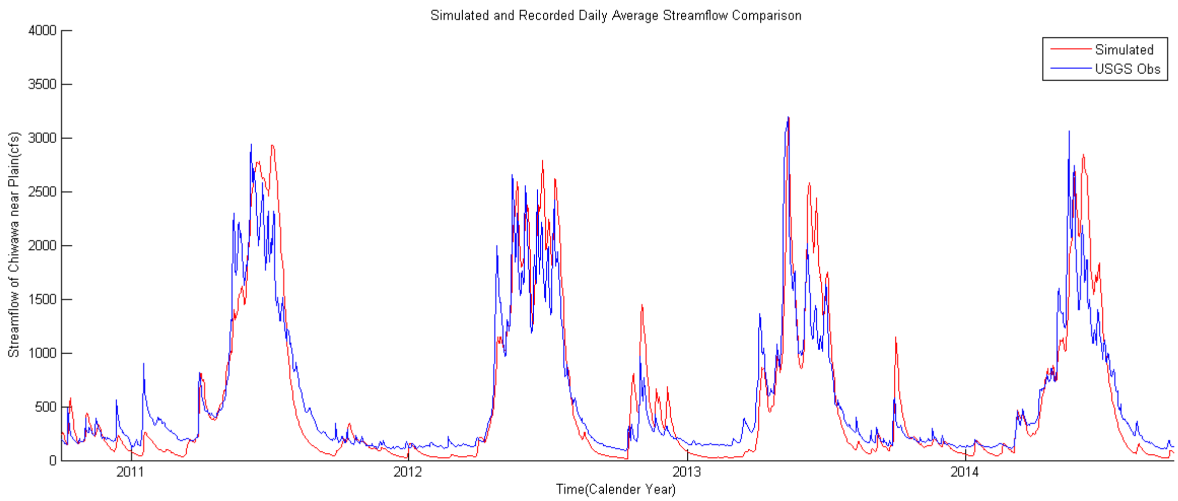


Figure 45. DHSVM-simulated (red) and USGS-observed (blue) mean daily streamflow in the Chiwawa watershed.

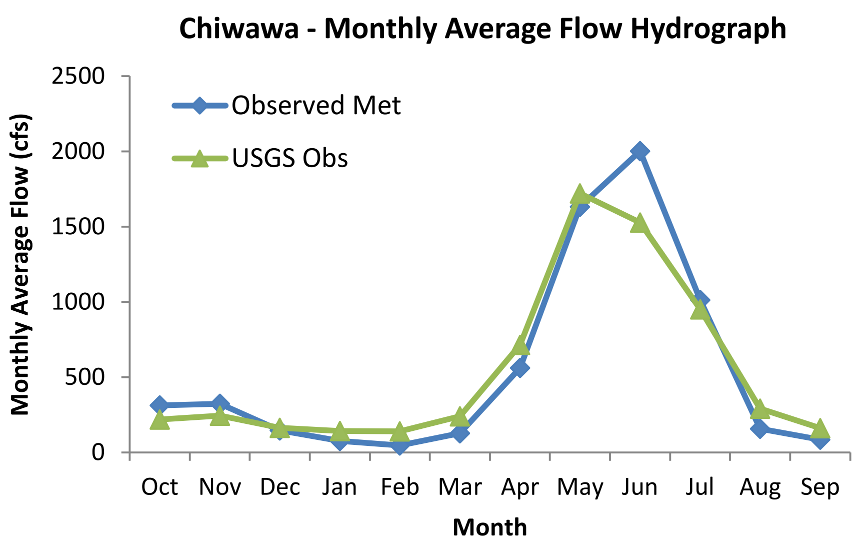


Figure 46. DHSVM0simulated (blue) and USGS-observed (green) mean monthly streamflow for the Chiwawa watershed.

8.2 Forest Restoration

Restoration locations in the Chiwawa watershed are presented by scenario in Figure 47–Figure 53.

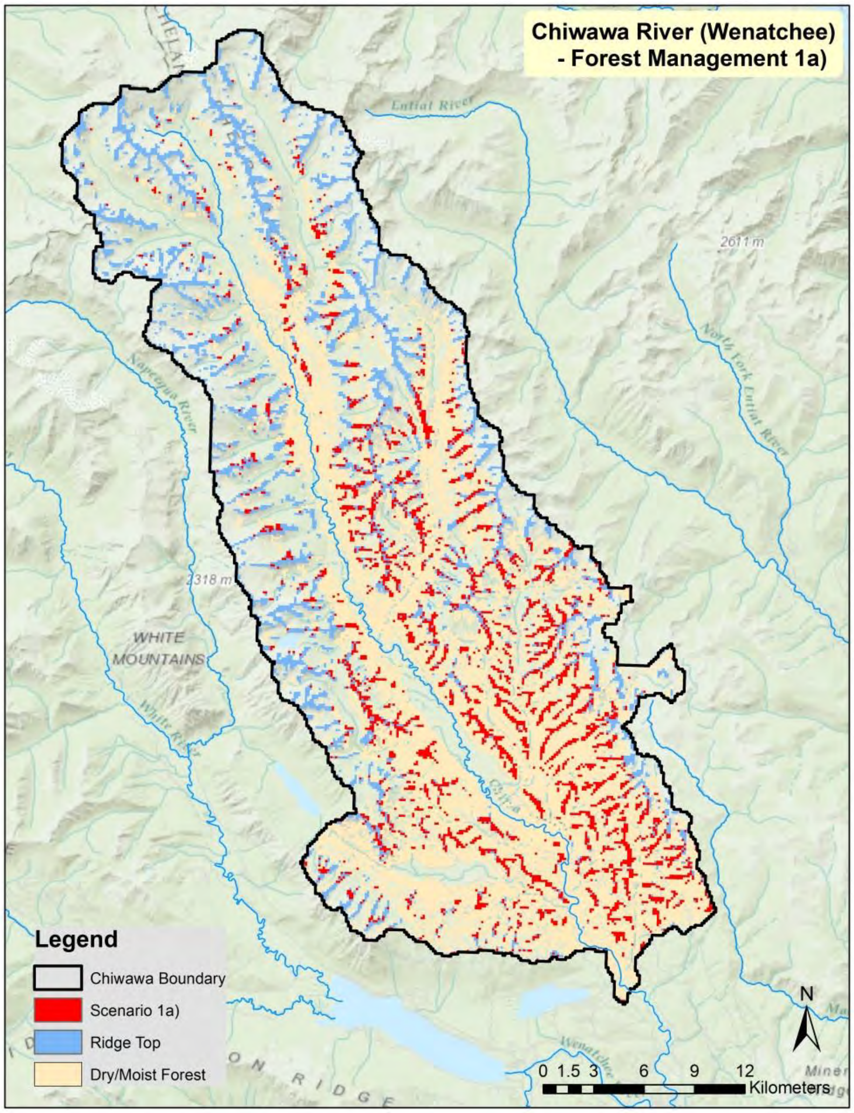


Figure 47. Locations of forest restoration Scenario 1a (red) in the Chiwawa watershed with treatments on ridgetops in Dry/Moist forest where overstory fractional coverage was reduced to 30%.

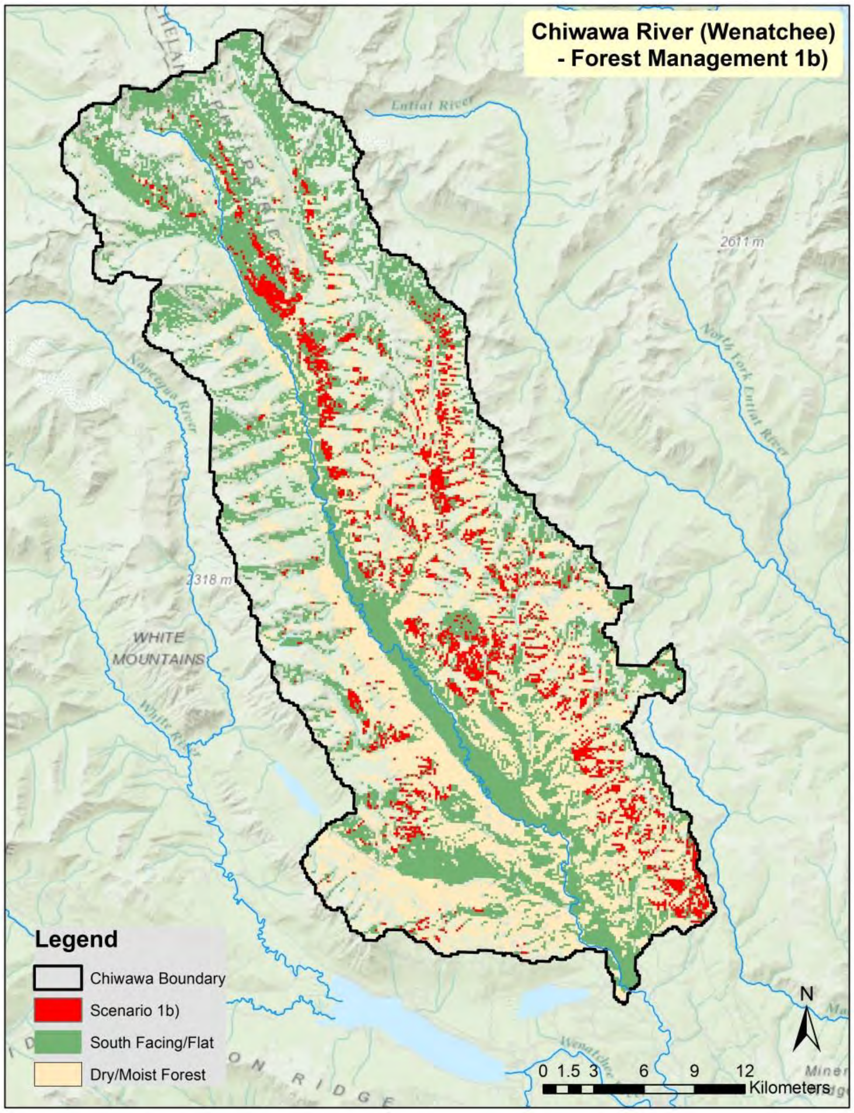


Figure 48. Locations of forest restoration Scenario 1b (red) in the Chiwawa watershed with treatments on upper elevation (top 50%) south-facing hillslopes in Dry/Moist forest where overstory fractional coverage was reduced to 50%.

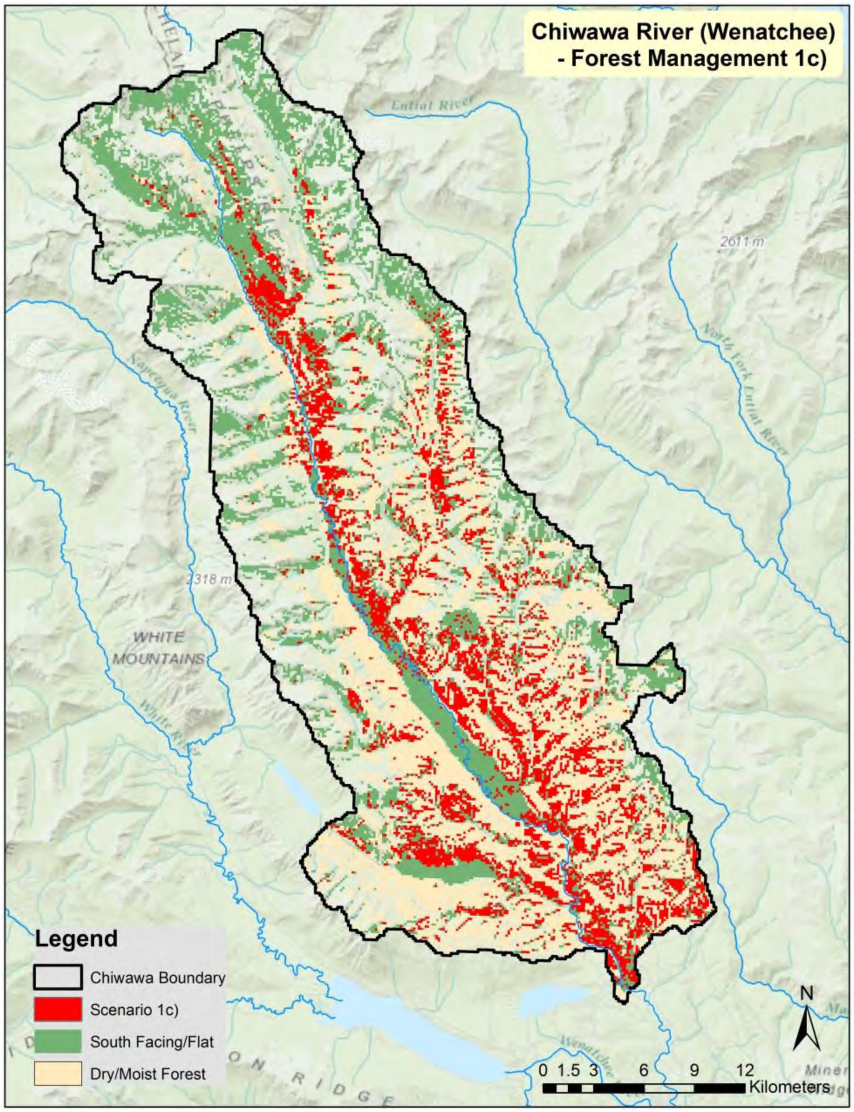


Figure 49. Locations of forest restoration Scenario 1c (red) in the Chiwawa watershed with treatments on all south-facing hillslopes in Dry/Moist forest where overstory fractional coverage was reduced to 50%.

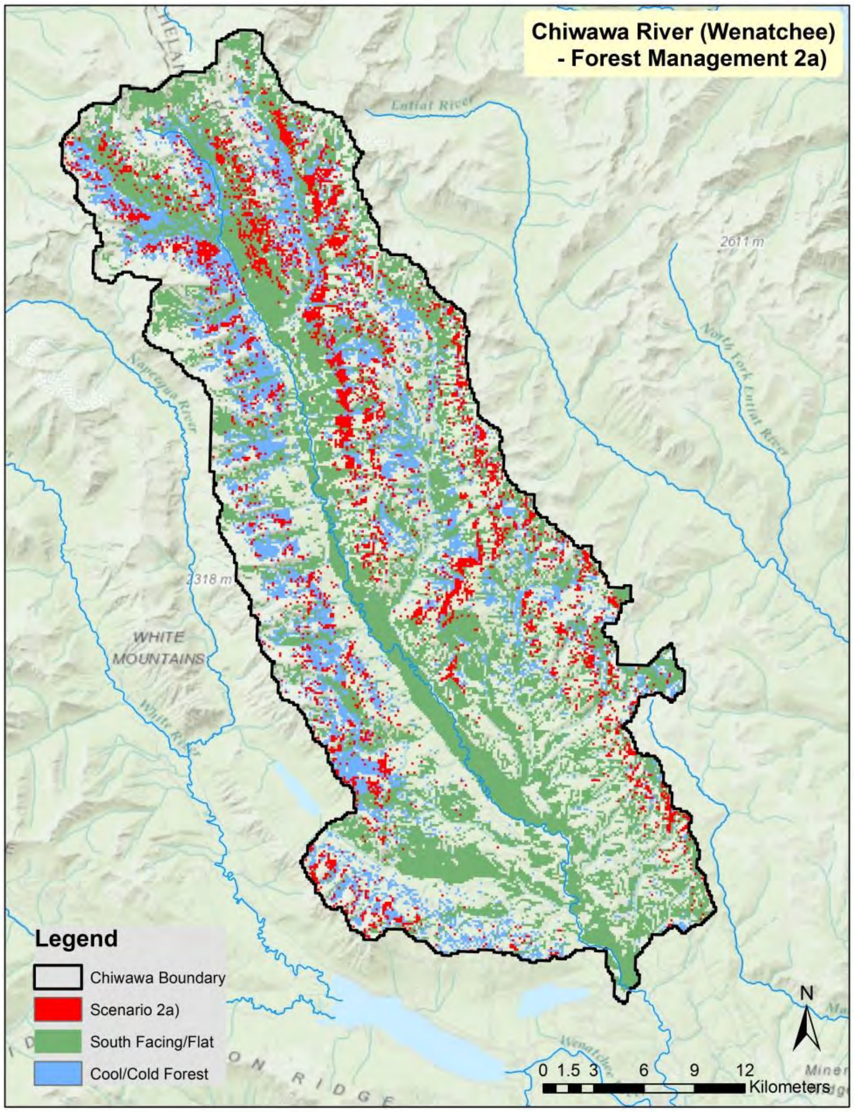


Figure 50. Locations of forest restoration Scenario 2a (red) in the Chiwawa watershed with overstory removal via prescribed burning on locations in Cool/Cold forest with a Fire Potential Index in the top 30%.

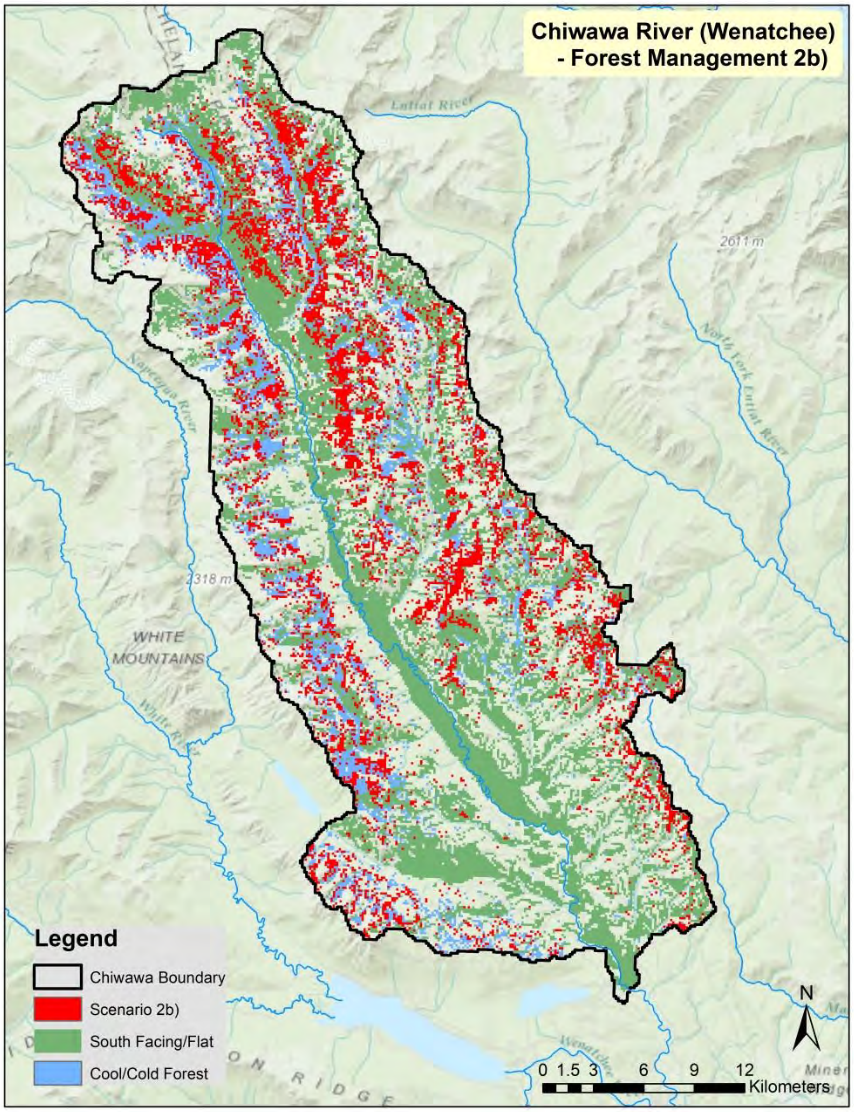


Figure 51. Locations of forest restoration Scenario 2a (red) in the Chiwawa watershed with overstory removal via prescribed burning on locations in Cool/Cold forest with a Fire Potential Index in the top 50%.

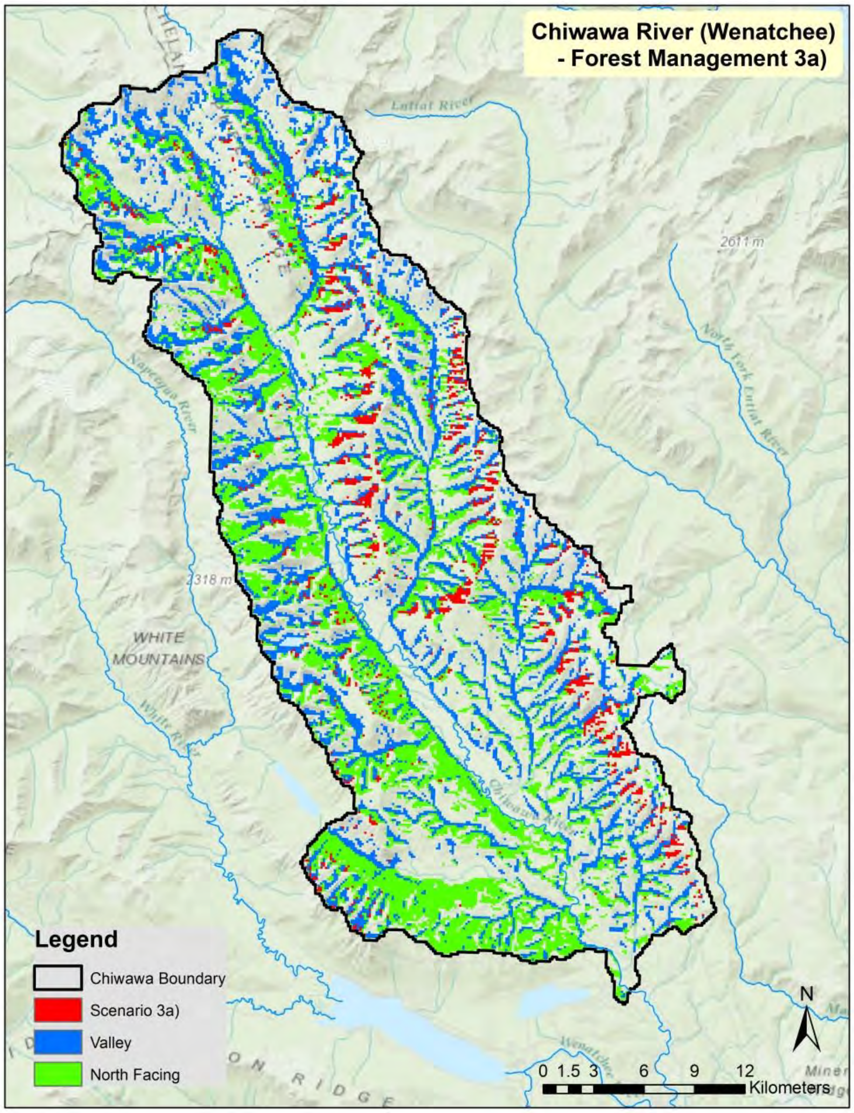


Figure 52. Locations of forest restoration Scenario 3a (red) in the Chiwawa watershed with overstory removal via natural wildfire on north-facing slopes and valley bottoms (red) with a Fire Potential Index in the top 10%.

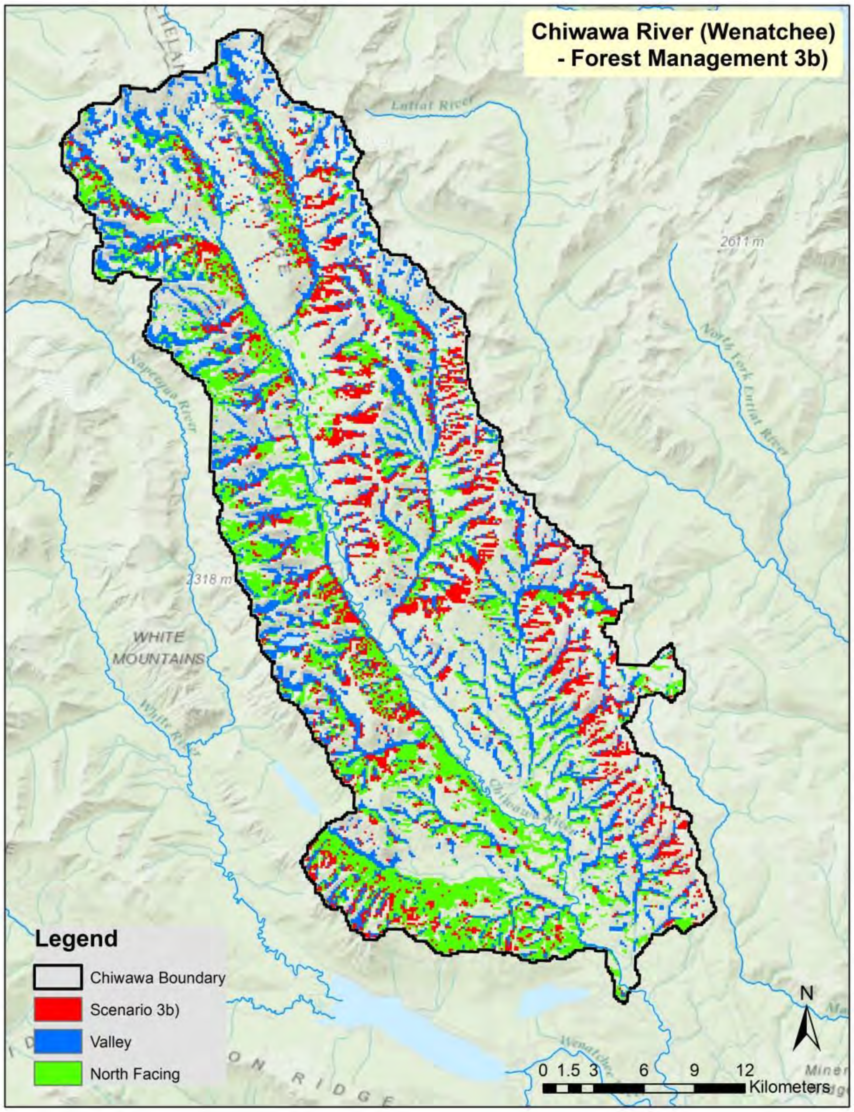


Figure 53. Locations of forest restoration Scenario 3b (red) in the Chiwawa watershed with overstory removal via natural wildfire on north-facing slopes and valley bottoms (red) with a Fire Potential Index in the top 30%.

8.3 Forest Restoration Results

8.3.1 Current Climate

Forest restoration scenarios in the Chiwawa watershed reduced overstory fractional coverage from 3.3% to 18.5% (Table 14). While these results reflect historic climate variability, we assumed no vegetation regrowth. DHSVM scenario results are generally consistent with the Rocky Mountain/Inland Intermountain hydrologic region of Stednick (1996), but greater than those for the Upper Entiat, showing mean increases in annual water yield ranging from 2.8 to 23.8 mm/yr (Table 14 and Figure 54). Corresponding increases in annual streamflow range from 0.3 to 2.1 %, or 1.4 to 11.9 cfs.

We also evaluated the UCSRB streamflow metrics and present selected results below. Seven-day average high flows are decreased in all scenarios relative to the baseline in April (Figure 55). By June, all scenarios show an increase in 7-day average high flows, and Scenarios 2a and 2b showed the greatest increase. In July, all scenarios except 2b still show an increase.

Seven-day low flows are reduced for all scenarios relative to the baseline in May and increased for all scenarios in June (Figure 56). Scenario 1a continues to show an increase in low flows July–October, while Scenarios 1b and 1c show increased low flows through August. Scenarios 2a, 2b, 3a, and 3b show deceased lows flows beginning in July.

Table 14. Summary of forest restoration scenarios and results in the Chiwawa watershed.

Scenarios	Scenario Description				Pct FC reduced	% change in annual streamflow	Change in Yield (mm)	Change in Streamflow (cfs)
	Forest Type	Topo	Location	Fractional Coverage (FC)				
1a)	Dry/Moist	Ridgetops	All	FC>30% to 30%	4.99%	0.51	5.7	2.8
1b)	Dry/Moist	South-facing Slope	Top 50% Elevation	FC>50% to 50%	2.29%	0.25	2.8	1.4
1c)	Dry/Moist	South-facing Slope	All	FC>50% to 50%	5.02%	0.55	6.2	3.1
2a)	Cool/Cold	All	Top 30% Fire Index	FC to 0	10.82%	1.22	13.8	6.9
2b)	Cool/Cold	All	Top 50% Fire Index	FC to 0	18.47%	2.11	23.8	11.9
3a)	All	North-facing Slope and Valley Bottoms	Top 10% Fire Index	FC to 0	4.23%	0.53	6.0	3.0
3b)	All	North-facing Slope and Valley Bottoms	Top 30% Fire Index	FC to 0	13.37%	1.65	18.5	9.3

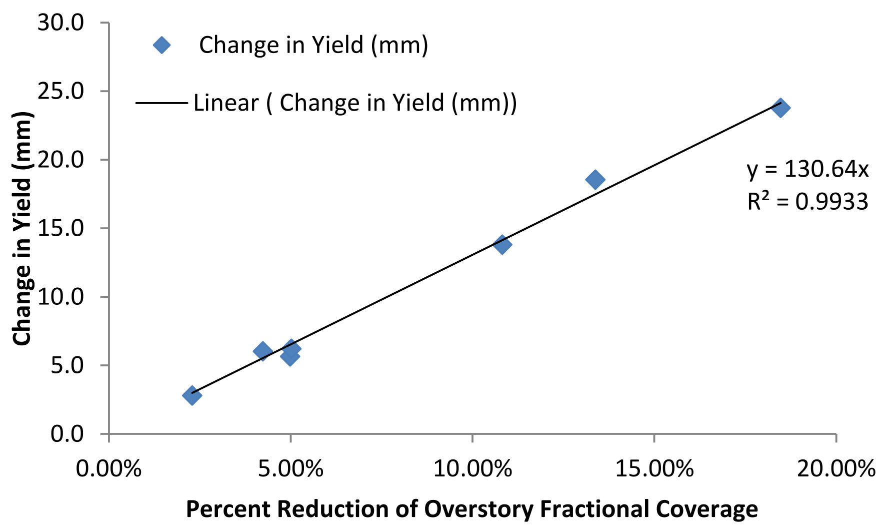


Figure 54. Increase in annual water yield (mm) in the Chiwawa watershed as a function of percent reduction in overstory fractional coverage.

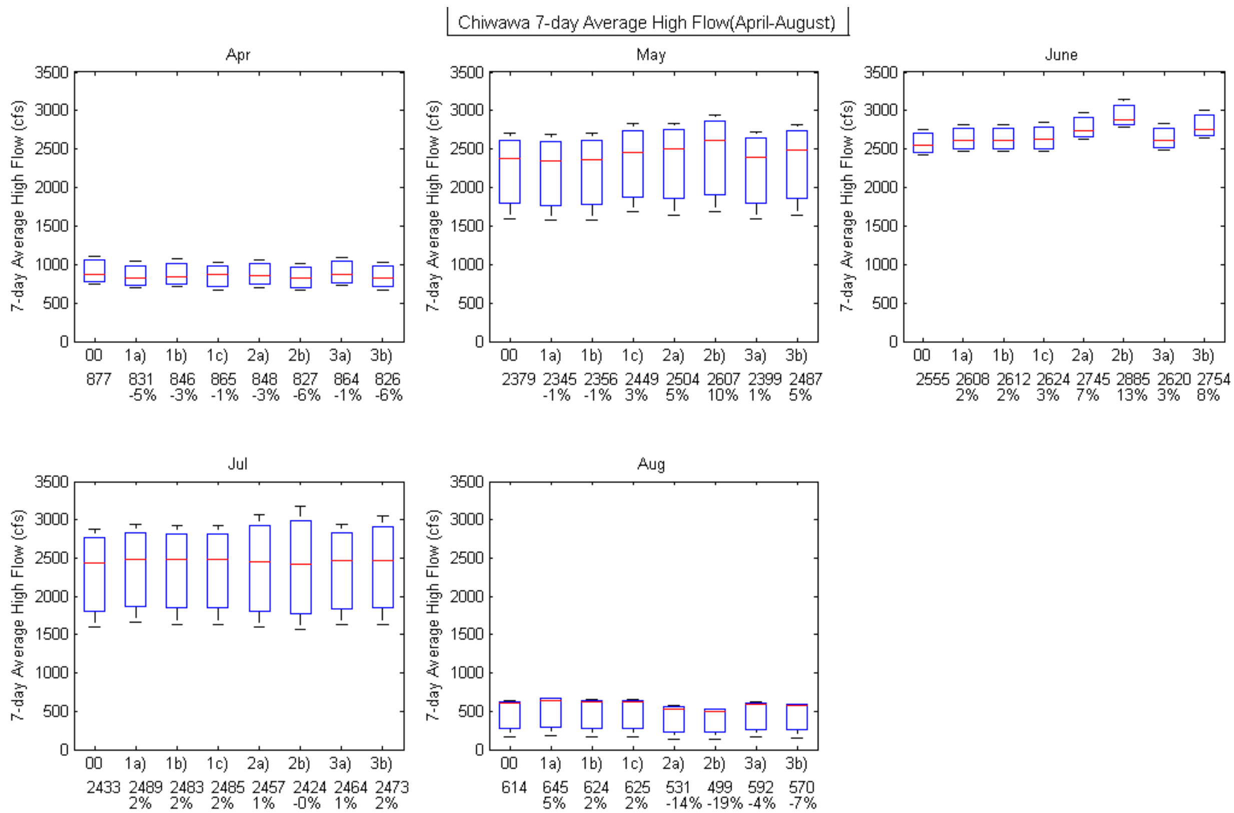


Figure 55. UCSRB 7-day high flow metric for April–August by forest restoration scenario based on 4 years in the Chiwawa watershed. Scenario 00 in each plot (far left) represents the no restoration baseline. Median flow (cfs) for each scenario is given directly below each plot, and the percent change in flow from the no restoration scenario is provided in the next line. In the box-and-whisker plots, the red line represents the median; the lower and upper portion of the box is at the 75% and 25% exceedance, respectively. The lengths of the whiskers are 1.5 times the difference between the median and the corresponding exceedance. Red crosses are outliers.

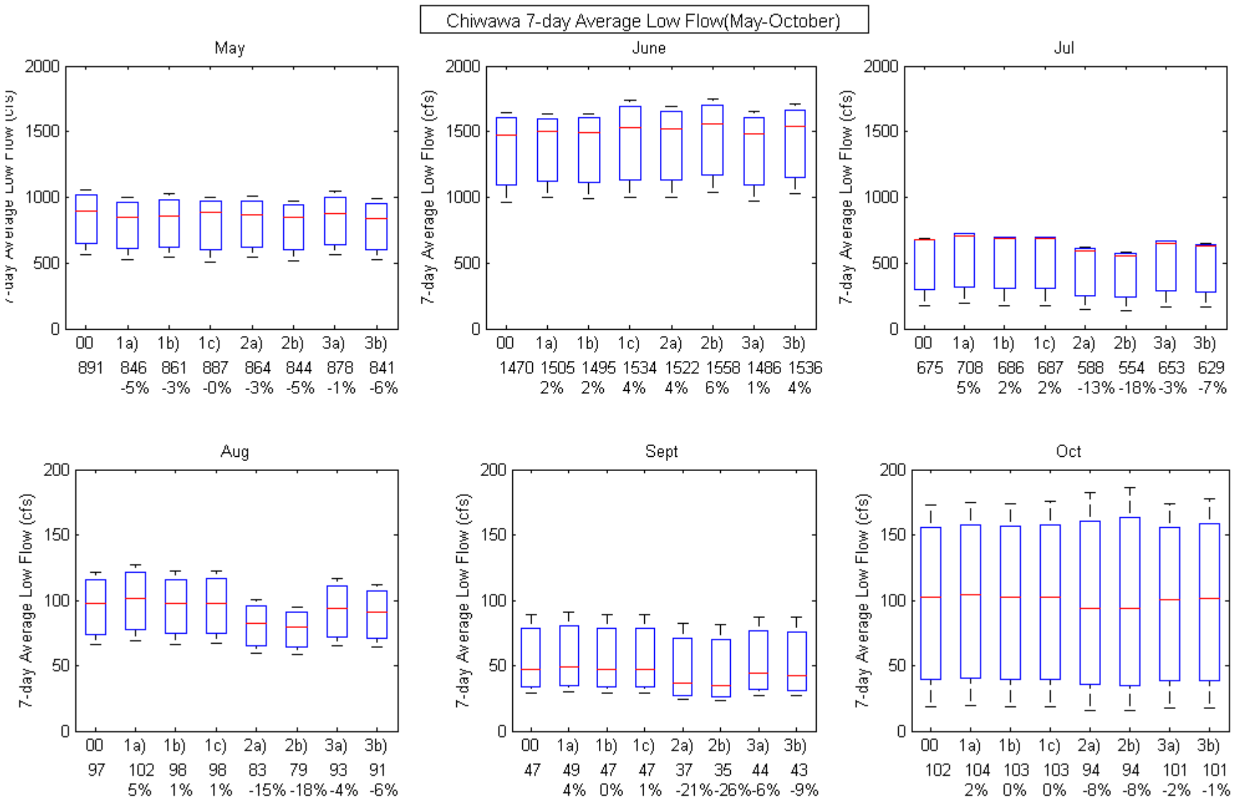


Figure 56. UCSRB 7-day low-flow metric for May–October by forest restoration scenario based on 4 years in the Chiwawa watershed. Scenario 00 in each plot (far left) represents the no restoration baseline. Median flow (cfs) for each scenario is given directly below each plot, and the percent change in flow from the no restoration scenario is provided in the next line. In the box-and-whisker plots, the red line represents the median; the lower and upper portion of the box is at the 75% and 25% exceedance, respectively. The lengths of the whiskers are 1.5 times the difference between the median and the corresponding exceedance. Red crosses are outliers.

8.3.2 Future Climate

Higher temperature in the future climate condition result in an increase in mean monthly fall and winter flows, a lower snowmelt peak, and decreased summer flows compared to the corresponding current climate no restoration baseline (Figure 57).

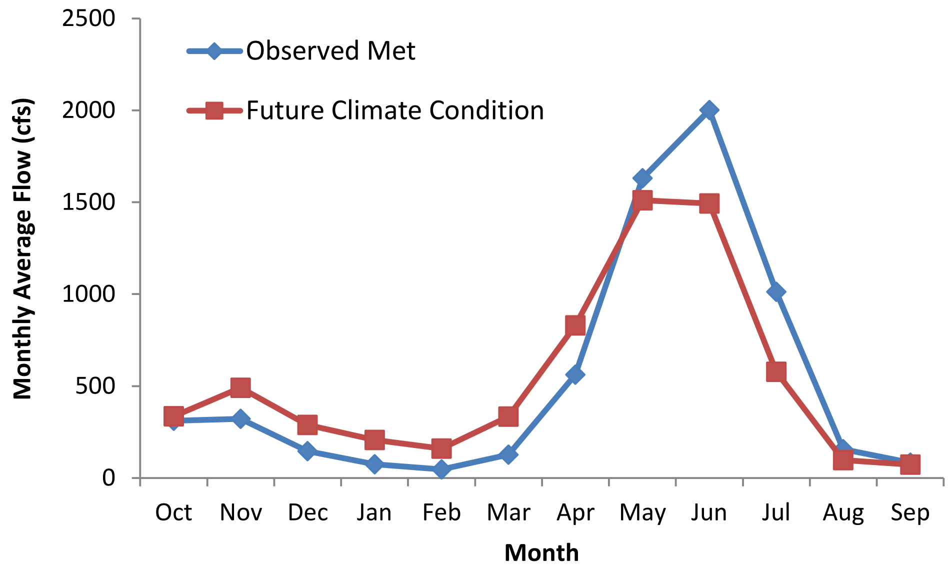


Figure 57. Mean monthly flow for current climate (blue – observed met) and future climate conditions (red) in the Chiwawa watershed.

The mean increase in annual water yield with forest restoration under future climate conditions ranges from 2.5 mm/yr to 23.7 mm/yr (Table 15 and Figure 58) over the no restoration baseline (i.e., future climate with current existing vegetation). This corresponds to increases in annual streamflow from 0.2 to 2.1 %, or 1.3 to 11.9 cfs.

Table 15. Comparison of forest restoration results between current and future climate conditions in the Chiwawa watershed.

		% Change in Annual Streamflow		Change in Yield (mm)		Change in Streamflow (cfs)	
Scenarios	Pct FC reduced	Obs Met	Future Climate Condition	Obs Met	Future Climate Condition	Obs Met	Future Climate Condition
1a)	4.99%	0.51	0.48	5.7	5.3	2.8	2.6
1b)	2.29%	0.25	0.23	2.8	2.5	1.4	1.3
1c)	5.02%	0.55	0.51	6.2	5.7	3.1	2.8
2a)	10.82%	1.22	1.23	13.8	13.7	6.9	6.8
2b)	18.47%	2.11	2.13	23.8	23.7	11.9	11.9
3a)	4.23%	0.53	0.55	6.0	6.1	3.0	3.0
3b)	13.37%	1.65	1.69	18.5	18.7	9.3	9.3

Linear trend lines were calculated to examine annual water yield (mm) in the Chiwawa watershed as a function of percent reduction in overstory fractional coverage (Figure 58). For the current climate scenario (observed met), a 1% reduction in overstory fractional coverage produces a 1.3 mm/yr volume increase in water yield. Results are nearly identical under future climate conditions.

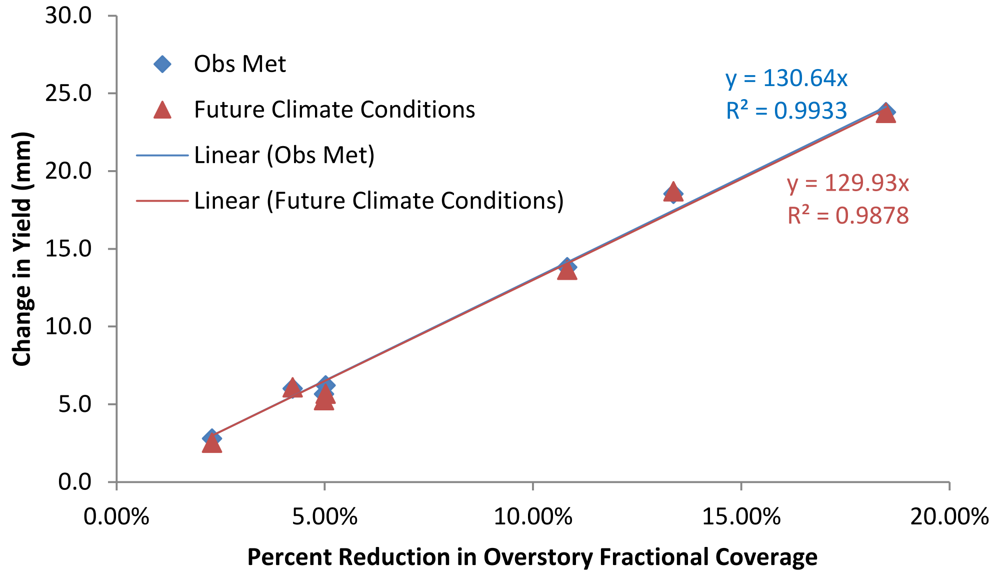


Figure 58. Increase in annual water yield (mm) under current and future climate conditions in the Chiwawa watershed as a function of the percent reduction in overstory fractional coverage.

Flow metrics results for climate change are presented in Table 16–Table 19 below. Comparing the top (Observed Met) and bottom panels (Future Climate Condition) in Table 16 shows that under future climate conditions there is an increase in late fall and winter mean monthly flows (October through April), compared to current climate conditions for all forest restoration scenarios (including no restoration baseline), and a decrease in flow during the summer and early fall (May through September). However, forest restoration tends to decrease November–April flows and generally increase May through October low flows compared to a future climate condition no restoration baseline (bottom panel).

Comparing the top (Observed Met) and bottom panels (Future Climate Condition) in Table 17 shows that under future climate conditions there is an increase in late fall and winter 7-day average low flows (October through April), compared to the current climate for all forest restoration scenarios (including the no restoration baseline), and a decrease in flow May through September. However, forest restoration tends to decrease December through April flows and generally increases May and June flows compared to a future climate condition no restoration baseline. However, forest restoration tends to decrease December–April flows and generally increases May and June flows compared to a future climate condition no restoration baseline (bottom panel). Scenarios 1a, 1b, and 1c increase flows during the entire June through October time period.

Comparing the top (Observed Met) and bottom panels (Future Climate Condition) in Table 18 shows that under future climate conditions there is an increase in late fall and winter 7-day average high flows (November through April), compared to current climate conditions for all forest restoration scenarios (including no restoration baseline), and a decrease in flow during the summer and early fall. However, forest restoration tends to decrease November through April flows and generally increases May through July flows compared to a future climate condition no restoration baseline (bottom panel). Scenarios 1a, 1b, and 1c increase flows during the entire May through October time period.

Comparing the top (Observed Met) and bottom (Future Climate Condition) in Table 19 shows that under future climate conditions there is an increase in late fall and winter 1-day average high flows (November through April), compared to current climate conditions for all forest restoration scenarios (including no restoration baseline), and a decrease in flow during the summer and early fall. However, forest restoration tends to decrease November through April flows and generally increases May through July flows compared to a future climate condition no restoration baseline (bottom panel). Scenarios 1a, 1b, and 1c increase flows during the entire May through October time period.

Table 16. Mean monthly flow in the Chiwawa watershed for forest restoration scenarios under current and future climate conditions.

Monthly Average Flow(cfs) – Chiwawa													
		Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Observed Met	No MGMT	310.92	321.73	145.21	75.16	45.97	126.73	561.12	1630.58	2001.89	1012.21	155.77	83.19
	1a	315.39	319.04	140.90	72.63	44.57	120.94	523.97	1615.75	2050.98	1051.54	163.74	85.79
	1b	312.84	319.57	141.40	72.89	44.44	120.84	534.53	1626.70	2040.53	1032.84	157.19	83.82
	1c	314.59	319.17	136.80	68.63	39.71	106.79	500.54	1688.07	2055.80	1034.15	157.53	84.12
	2a	317.04	316.61	140.89	72.99	44.84	120.75	533.80	1676.73	2139.18	971.47	133.98	80.09
	2b	323.49	311.96	136.29	70.47	43.35	114.10	505.60	1717.07	2228.51	948.13	128.72	80.42
	3a	313.52	318.95	143.77	74.43	45.55	124.74	552.25	1636.52	2051.15	1010.87	150.15	83.26
	3b	322.30	312.76	137.65	70.65	42.98	115.25	512.97	1675.95	2152.31	1005.50	146.72	85.05
Future Climate Condition	No MGMT	335.87	490.20	288.83	206.26	159.01	334.01	829.49	1511.47	1493.01	577.88	96.50	72.05
	1a	342.31	490.39	281.58	199.33	152.75	316.35	786.79	1533.71	1539.29	606.83	102.29	74.35
	1b	338.81	490.10	284.39	200.83	152.44	320.03	805.53	1542.49	1519.50	585.35	96.95	72.52
	1c	341.08	493.10	281.39	193.65	140.62	293.89	827.48	1577.72	1522.68	586.01	97.19	72.81
	2a	346.42	482.13	278.49	197.70	151.89	317.15	786.53	1598.03	1598.46	554.01	88.94	72.88
	2b	355.61	475.84	269.39	189.51	144.59	299.92	753.83	1681.32	1656.36	543.16	87.90	74.53
	3a	341.56	486.28	285.36	203.30	156.59	328.34	811.98	1527.93	1536.84	582.72	95.85	73.64
	3b	354.62	480.82	274.35	192.60	145.79	305.50	768.06	1614.73	1612.68	582.93	96.13	76.82

Table 17. Seven-day average low-flow monthly median in the Chiwawa watershed for forest restoration scenarios under current and future climate conditions.

7-Day Average Low-Flow Monthly Median(cfs) – Chiwawa													
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Observed Met	No MGMT	**34.54**	**24.37**	**32.09**	**160.84**	**891.14**	**1469.53**	**674.72**	**97.27**	**46.94**	**102.37**	**129.49**	**61.05**
	1a	33.47	23.96	31.27	151.28	846.06	1504.65	708.17	101.83	48.72	104.15	131.76	59.11
	1b	33.41	24.17	31.15	150.08	861.11	1494.84	685.96	97.87	47.15	102.57	130.04	59.22
	1c	31.53	20.95	25.68	116.65	886.80	1534.06	686.73	98.09	47.29	102.70	131.00	54.79
	2a	33.81	24.09	31.72	155.33	863.63	1521.85	588.08	82.63	37.00	94.13	132.97	60.05
	2b	32.86	23.76	30.94	148.02	843.61	1557.79	554.09	79.47	34.77	94.05	133.44	58.63
	3a	34.36	24.29	31.94	158.84	878.31	1485.51	652.89	93.35	44.19	100.52	129.52	60.70
	3b	33.21	23.78	30.44	146.32	840.88	1535.63	629.06	91.17	42.58	101.19	130.22	58.24
Future Climate Condition	No MGMT	88.38	77.99	105.35	549.77	784.03	1301.22	334.27	67.86	33.78	110.49	145.45	105.30
	1a	85.60	75.86	101.20	524.24	796.20	1347.47	359.10	71.49	35.21	111.88	147.96	102.25
	1b	85.74	74.62	99.41	526.38	777.38	1334.34	336.80	68.14	33.90	110.59	146.76	101.97
	1c	82.73	66.66	83.00	482.00	825.35	1340.48	337.26	68.31	34.02	110.70	148.29	98.82
	2a	85.47	75.44	102.09	517.89	826.42	1386.60	292.13	61.00	27.33	105.46	149.48	101.09
	2b	82.47	72.19	97.85	484.96	883.44	1452.10	280.52	60.24	26.00	106.94	152.22	97.46
	3a	87.57	77.18	104.19	538.76	774.89	1324.82	328.64	66.70	32.43	110.00	146.31	103.99
	3b	83.94	72.74	97.38	495.20	846.30	1398.46	321.55	66.65	31.65	111.74	150.32	98.77

Table 18. Seven-day average high flow monthly median in the Chiwawa watershed for forest restoration scenarios under current and future climate conditions.

7-Day Average High Flow Monthly Median(cfs) – Chiwawa													
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Observed Met	No MGMT	**142.09**	**46.50**	**127.71**	**876.51**	**2379.05**	**2555.32**	**2433.33**	**614.08**	**116.48**	**913.26**	**190.23**	**166.32**
	1a	137.19	45.36	120.85	830.64	2345.15	2607.73	2488.78	645.47	122.03	928.95	183.81	159.81
	1b	136.95	45.24	119.41	846.27	2355.94	2612.40	2482.71	624.26	117.12	922.23	184.26	161.09
	1c	129.49	37.55	94.08	865.15	2448.81	2623.65	2484.62	624.99	117.40	927.80	179.98	155.03
	2a	136.20	45.81	123.85	848.03	2503.75	2744.66	2456.80	530.58	95.75	913.11	186.16	161.89
	2b	129.81	44.53	118.51	826.76	2606.91	2885.29	2424.22	499.38	90.82	910.82	181.45	156.58
	3a	139.81	46.16	126.32	863.98	2398.82	2619.63	2463.55	592.30	111.26	918.47	188.31	164.68
	3b	128.95	43.12	116.97	825.68	2486.61	2753.73	2473.08	570.31	107.39	918.60	180.57	156.74
Future Climate Condition	No MGMT	394.10	199.11	476.29	1409.33	2303.05	2001.84	1715.68	304.13	100.23	1135.47	466.44	411.07
	1a	380.98	190.74	454.40	1349.08	2338.39	2052.15	1762.89	327.17	101.59	1156.19	455.47	398.99
	1b	384.60	191.49	455.33	1371.63	2357.15	2042.67	1749.00	306.35	100.33	1147.06	454.60	399.55
	1c	368.96	172.22	413.47	1343.98	2375.77	2052.78	1750.75	306.80	100.44	1153.89	445.12	389.07
	2a	375.85	190.17	449.70	1339.66	2447.74	2159.52	1822.52	264.77	94.34	1158.23	439.42	387.68
	2b	358.76	180.30	421.31	1275.66	2586.55	2271.53	1863.44	254.25	95.10	1177.20	413.44	365.64
	3a	387.80	195.78	466.93	1383.13	2328.25	2057.42	1763.56	298.55	99.41	1151.85	456.64	403.04
	3b	364.50	179.45	429.05	1303.72	2470.08	2167.73	1828.01	292.16	100.49	1185.70	426.88	378.26

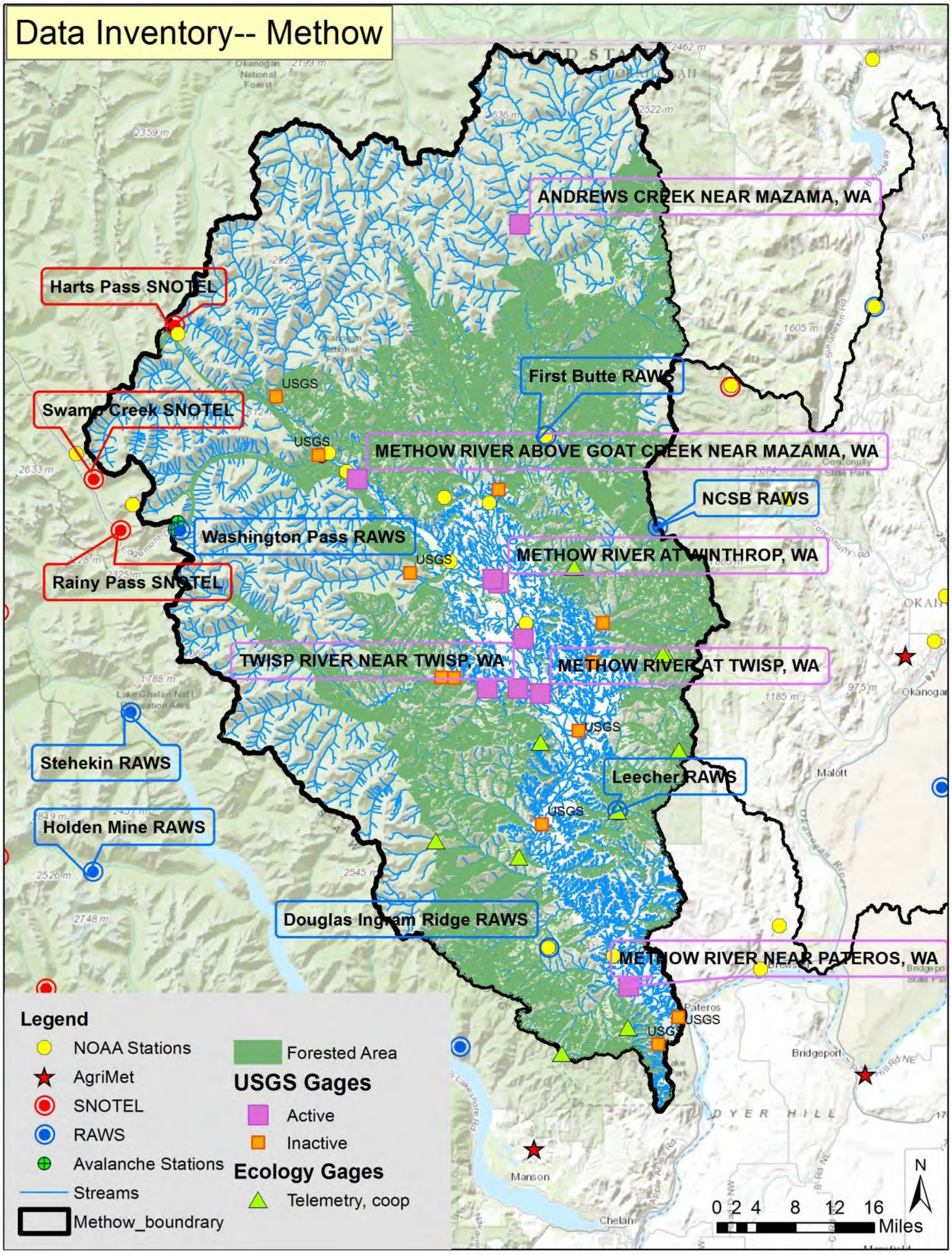
Table 19. One-day average high flow monthly median in the Chiwawa watershed for forest restoration scenarios under current and future climate conditions.

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1-Day Average High Flow Monthly Median(cfs) – Chiwawa													
Observed Met	No MGMT	**152.41**	**48.83**	**104.33**	**966.43**	**2587.54**	**2779.20**	**2617.18**	**599.87**	**118.18**	**881.60**	**207.16**	**183.45**
	1a	147.69	47.64	99.49	916.51	2559.26	2838.71	2669.69	631.22	123.65	876.84	201.01	176.79
	1b	147.09	47.63	97.74	933.45	2568.43	2843.68	2668.74	610.01	118.81	874.99	200.68	177.58
	1c	139.28	39.34	80.49	953.47	2670.55	2855.71	2670.88	610.74	119.09	881.02	196.32	171.23
	2a	145.78	48.09	101.82	933.73	2755.37	2986.14	2685.70	514.91	97.21	873.89	202.73	178.49
	2b	139.03	46.75	97.94	912.18	2879.74	3133.80	2659.62	484.41	92.32	861.96	195.88	172.31
	3a	149.92	48.47	103.40	952.58	2619.53	2853.38	2661.06	577.62	112.86	876.70	204.90	181.48
	3b	137.64	45.08	96.54	911.27	2728.51	2994.81	2696.48	555.85	108.91	862.97	194.10	172.41
Future Climate Condition	No MGMT	434.40	215.53	541.28	1575.53	2480.68	2125.12	1754.11	296.84	120.48	1135.70	509.41	422.39
	1a	423.13	206.68	516.52	1493.41	2517.13	2171.64	1801.16	319.74	121.93	1142.31	495.82	409.38
	1b	425.21	207.45	515.29	1530.81	2542.55	2161.72	1788.46	298.97	120.58	1141.22	496.12	409.85
	1c	408.56	186.57	455.40	1515.38	2591.57	2164.15	1790.09	299.41	120.69	1149.36	484.00	398.43
	2a	414.24	205.26	513.40	1483.40	2662.55	2287.22	1855.58	257.31	112.94	1133.22	478.75	398.27
	2b	394.63	194.30	479.54	1411.90	2796.92	2400.60	1890.96	247.13	112.43	1130.94	449.33	375.36
	3a	426.37	211.59	531.33	1536.88	2526.36	2184.24	1801.55	291.11	118.99	1134.57	498.80	413.96
	3b	399.01	192.76	484.96	1444.44	2673.07	2289.54	1860.85	284.89	119.39	1142.53	464.83	388.50

9.0 Model Application in the Methow Basin

9.1 Calibration and Validation

DHSVM was driven at a 3-hour time step for 15 years (WY 1992–2006) in the Upper Methow watershed



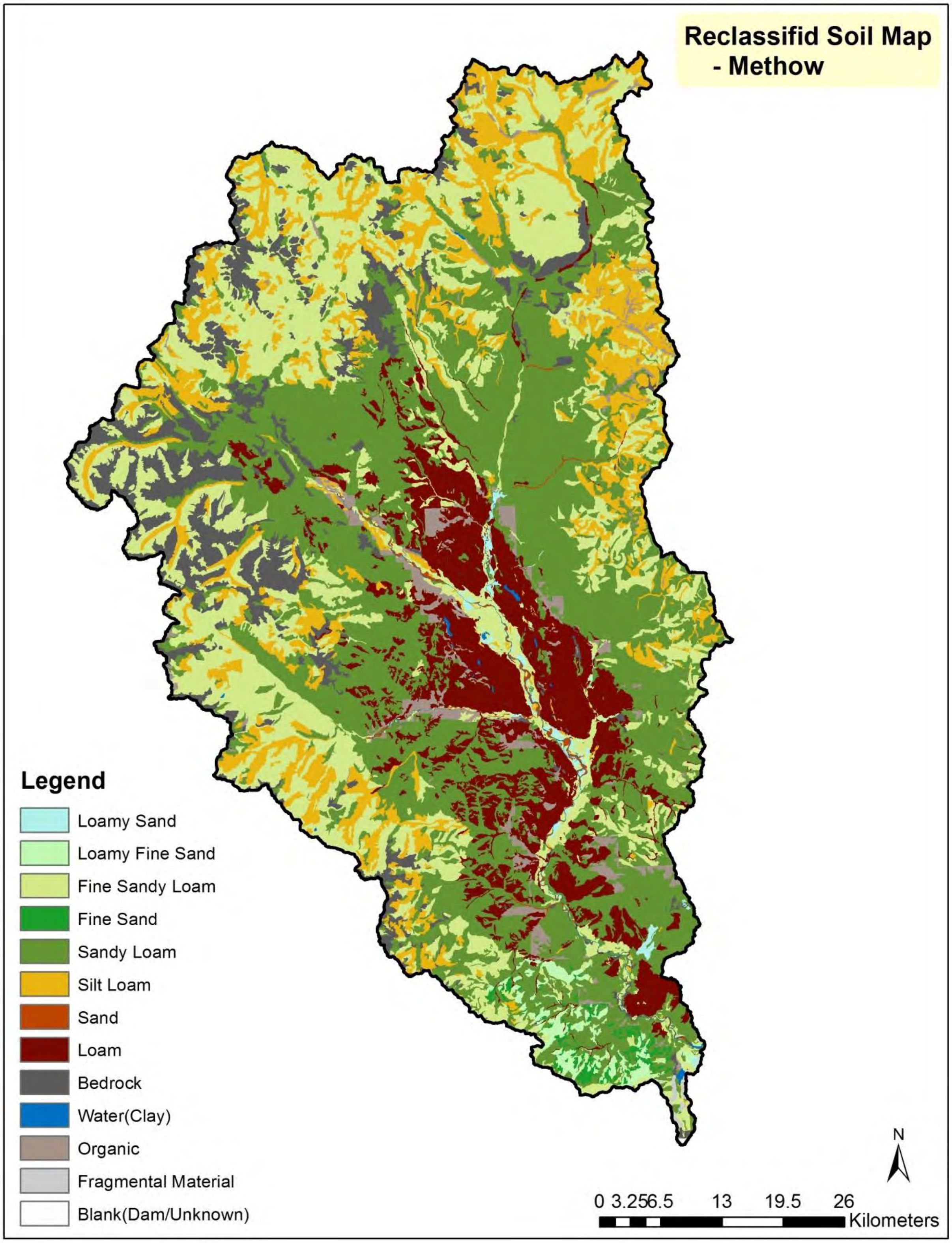

Reclassifid Soil Map
- Methow
Legend
Loamy Sand
Loamy Fine Sand
Fine Sandy Loam
Fine Sand
Sandy Loam
Silt Loam
Sand
Loam
Bedrock
Water(Clay)
Organic
Fragmental Material
Blank(Dam/Unknown)
N
0 3.256.5 13 19.5 26
Kilometers

Figure 61) and USFS-derived vegetation classes (Figure 62). The model was calibrated for the period from WY 1991 to 1997 and validated for the period WY 1998 to 2006. The NSE value is 0.469 and 0.733 for the calibration and validation periods, respectively. The NSE value for the entire 15 years of the run is 0.625 with a total mass balance of -14.7% compared to USGS observations. Simulated mean monthly flow shows general agreement with observed flow, except for lower flow in April and higher flow in June (Figure 64).

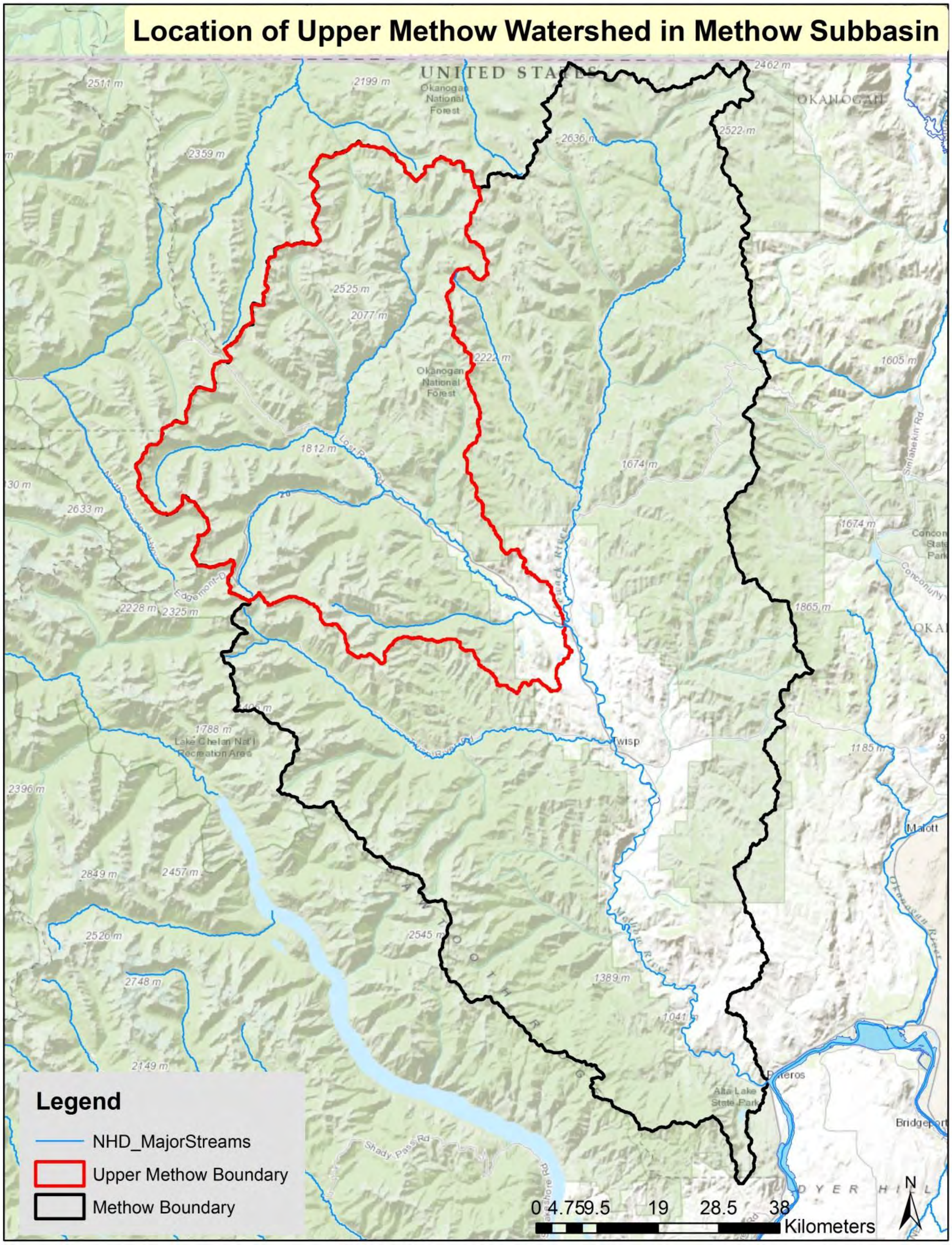


Figure 59. Location of the Upper Methow watershed in the Methow subbasin.

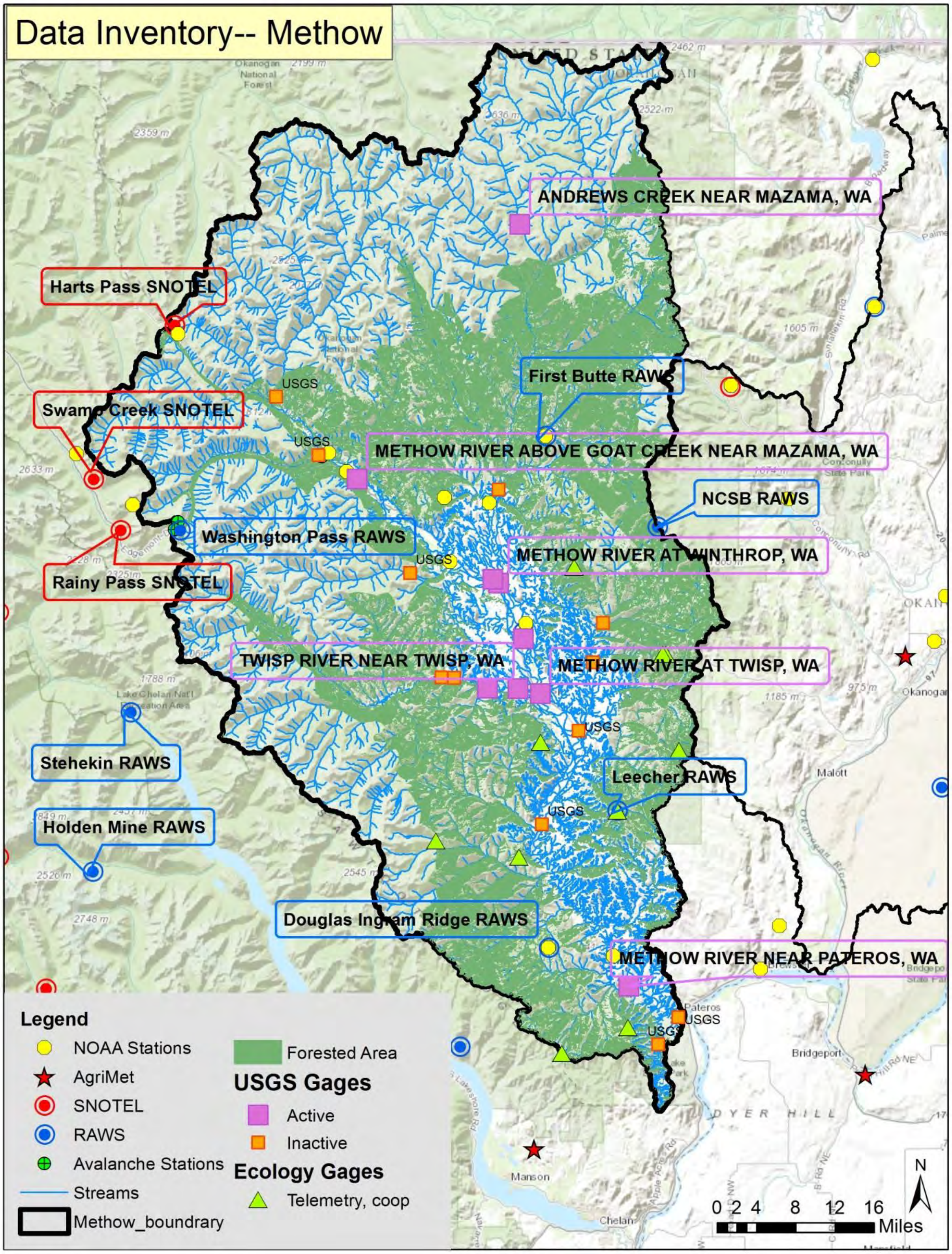


Figure 60. Available meteorological, snow, and streamflow monitoring data for stations in the Methow subbasin along with areas that may be suitable for forest restoration.

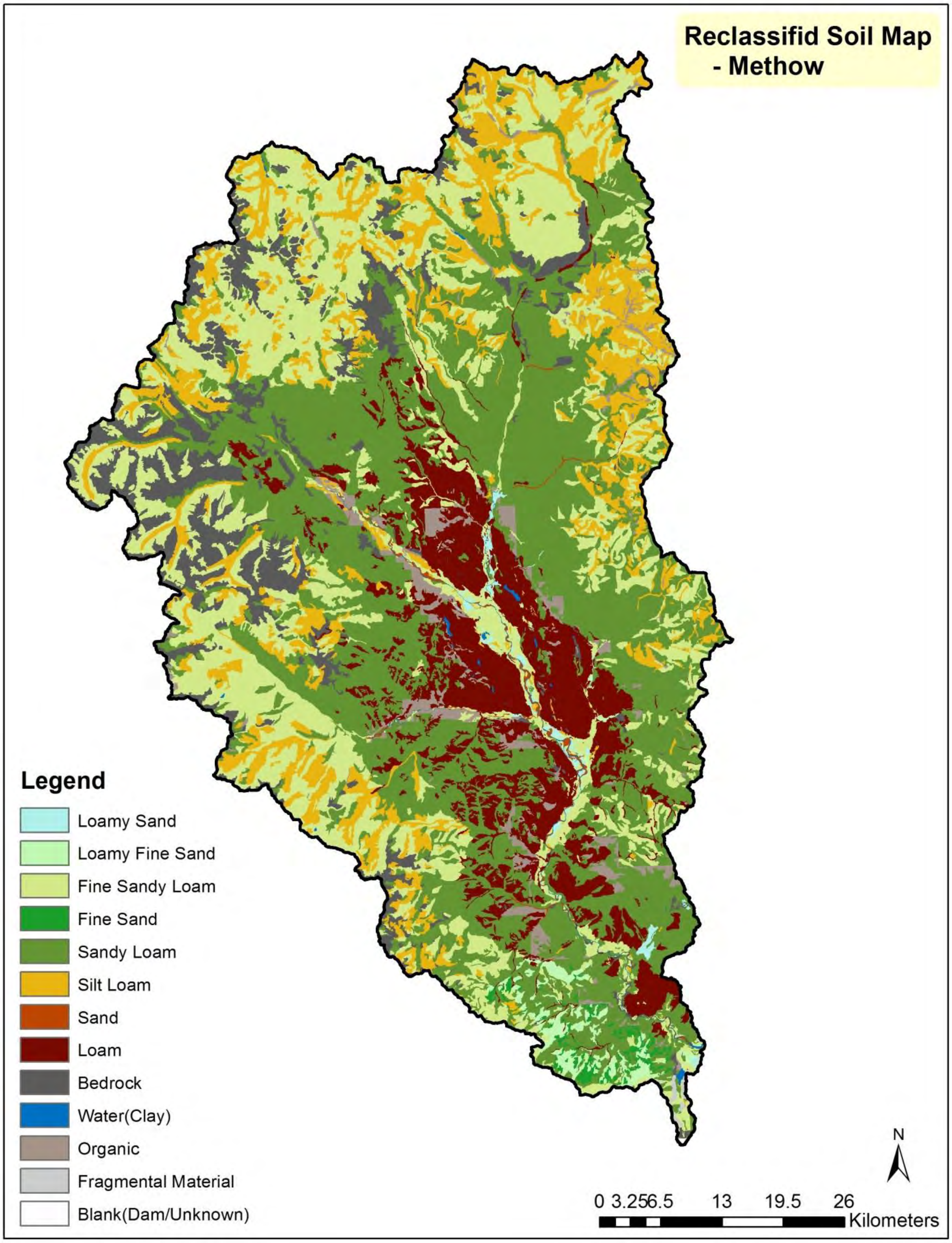


Figure 61. SSURGO-based soil texture classes for the Methow subbasin.

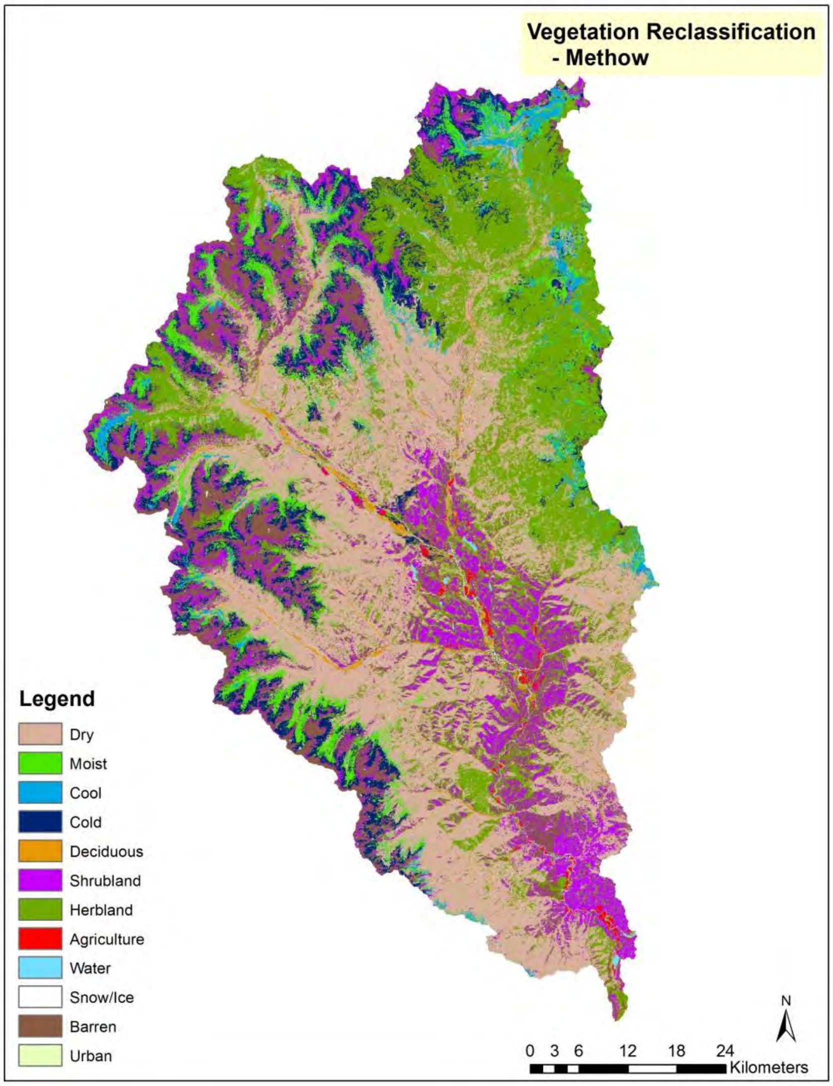


Figure 62. USFS-derived vegetation type based on LANDFIRE data in the Methow subbasin.

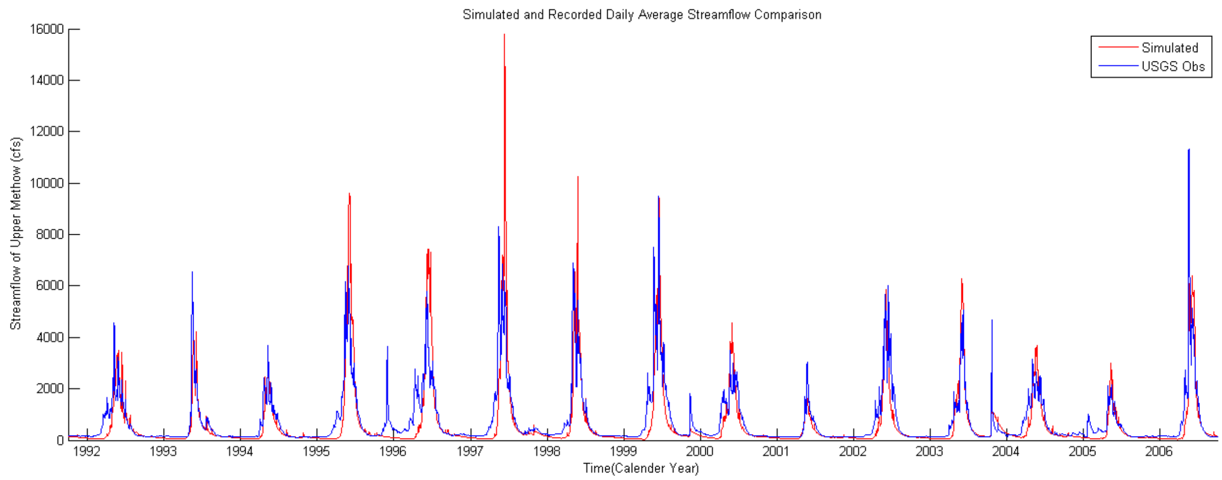


Figure 63. Simulated (red) and USGS-observed (blue) mean daily streamflow for the Upper Methow watershed.

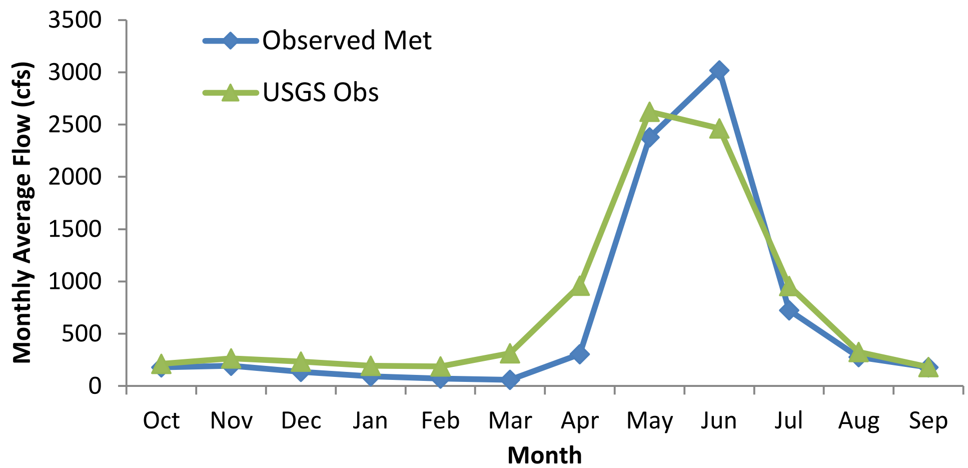


Figure 64. Simulated (blue) and USGS-observed (green) mean monthly flow for the Upper Methow watershed.

9.2 Forest Restoration

Locations of forest restoration in the Upper Methow watershed are presented by scenario in Figure 65–Figure 71.

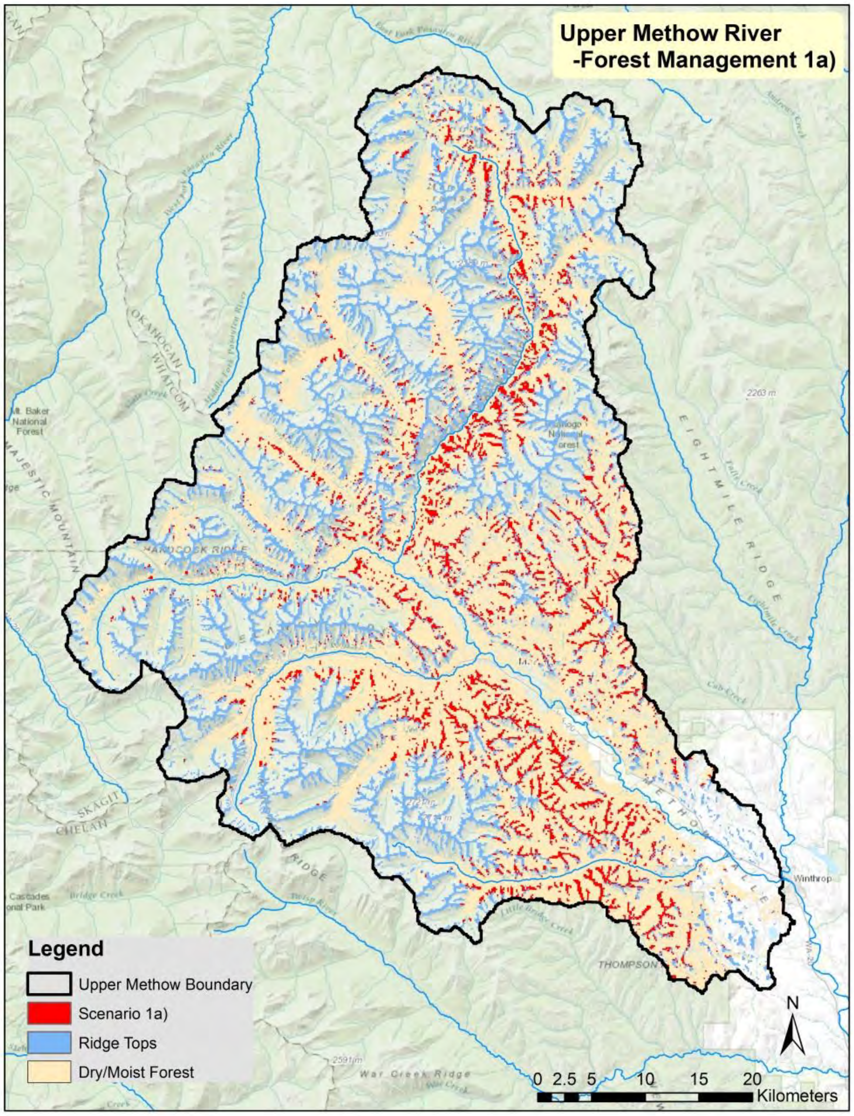


Figure 65. Locations of forest restoration Scenario 1a (red) in the Upper Methow watershed with treatments on ridgetops in Dry/Moist forest where overstory fractional coverage was reduced to 30%.

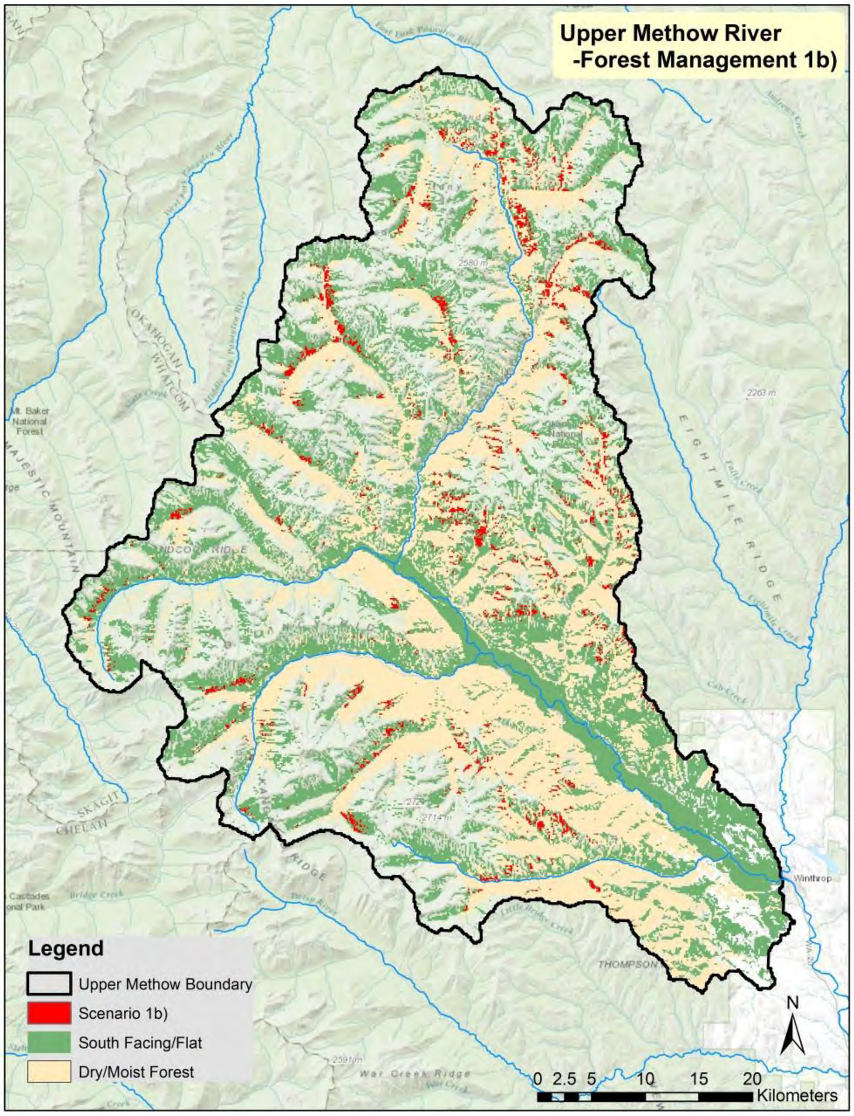


Figure 66. Locations of forest restoration Scenario 1b (red) in the Upper Methow watershed with treatments on upper elevation (top 50%) south-facing hillslopes in Dry/Moist forest where overstory fractional coverage was reduced to 50%.

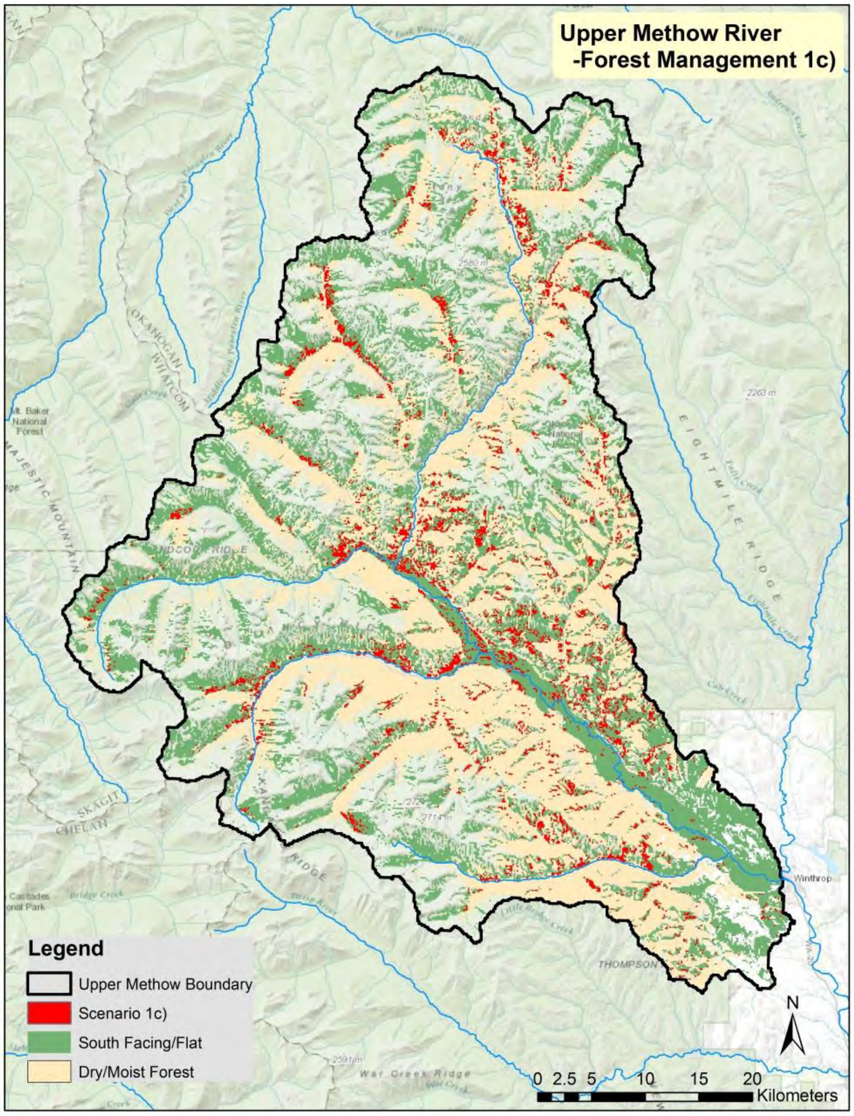


Figure 67. Locations of forest restoration Scenario 1c (red) in the Upper Methow watershed with treatments on all south-facing hillslopes in Dry/Moist forest where overstory fractional coverage was reduced to 50%.

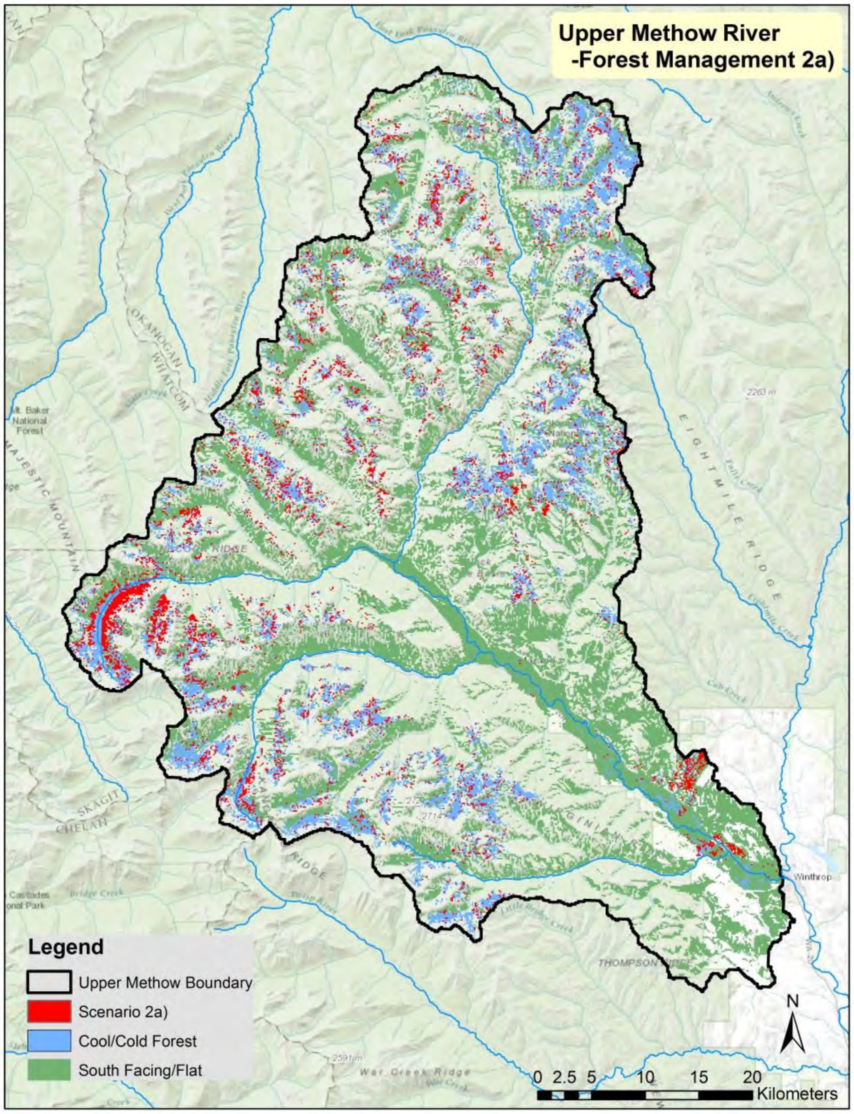


Figure 68. Locations of forest restoration Scenario 2a (red) in the Upper Methow watershed with overstory removal via prescribed burning on locations in Cool/Cold forest with a Fire Potential Index in the top 30%.

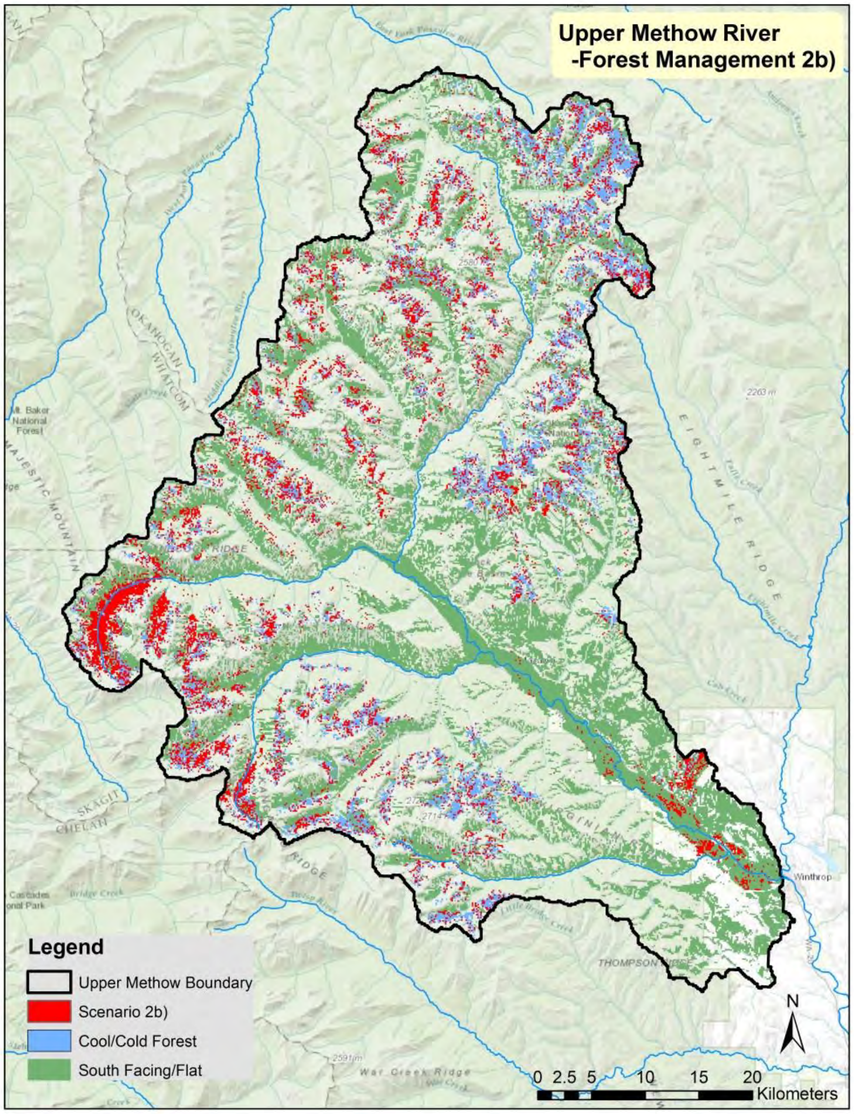


Figure 69. Locations of forest restoration Scenario 2a (red) in the Upper Methow watershed with overstory removal via prescribed burning on locations in Cool/Cold forest with a Fire Potential Index in the top 50%.

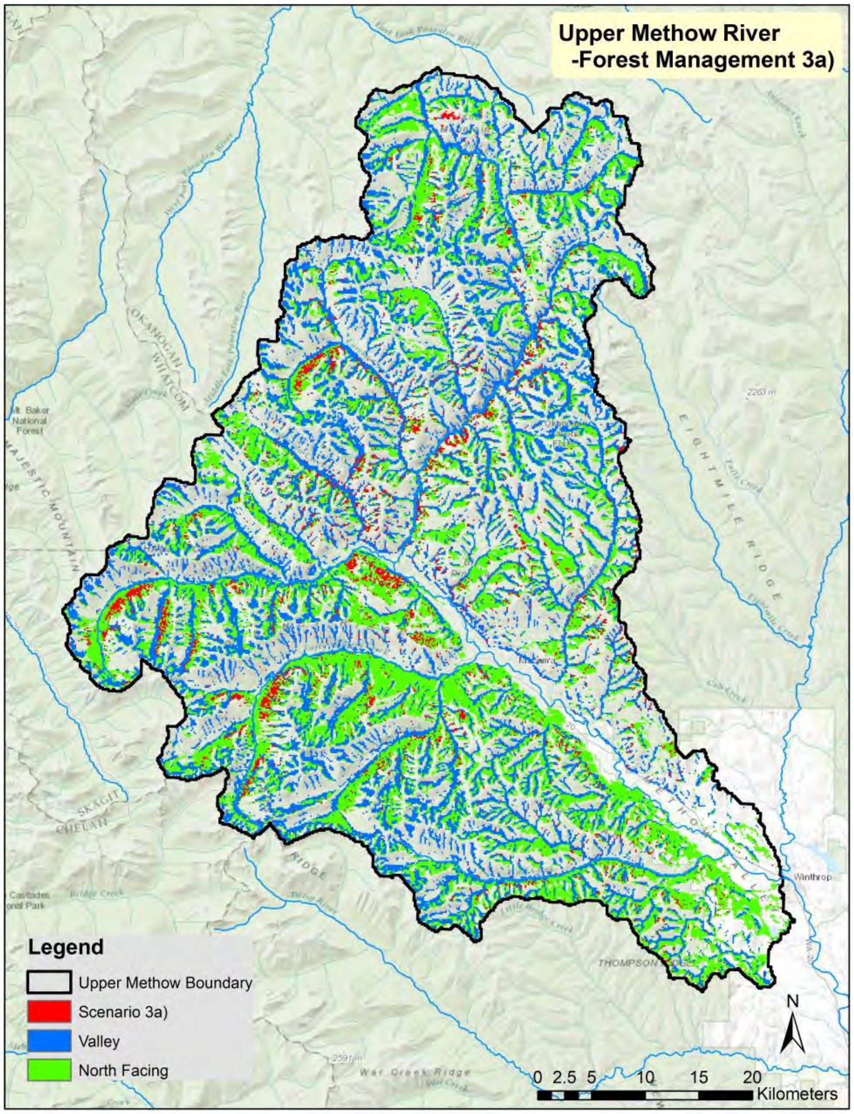


Figure 70. Locations of forest restoration Scenario 3a (red) in the Upper Methow watershed with overstory removal via natural wildfire on north-facing slopes and valley bottoms with a Fire Potential Index in the top 10%.

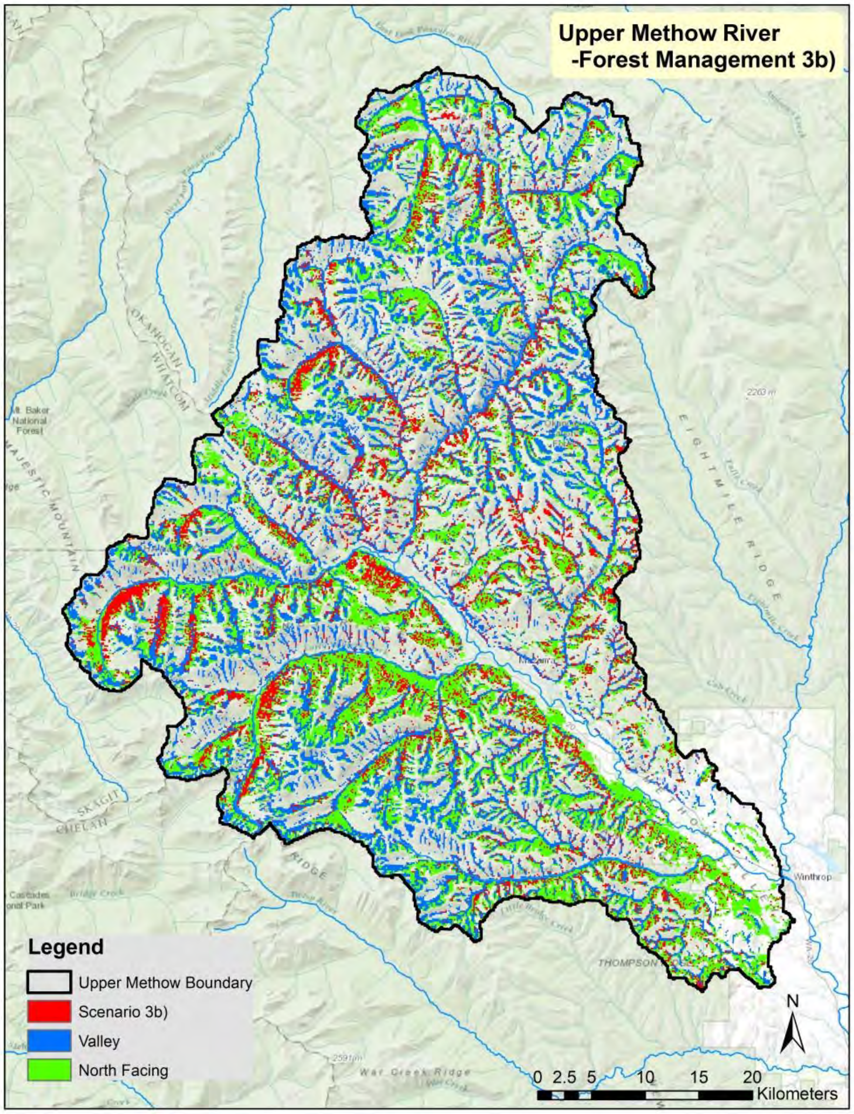


Figure 71. Locations of forest restoration Scenario 3b (red) in the Upper Methow watershed with overstory removal via natural wildfire on north-facing slopes and valley bottoms with a Fire Potential Index in the top 30%.

9.3 Forest Restoration Results

9.3.1 Historic Climate

DHSVM was driven at a 3-hour time step for 15 years (WY 1992–2006) based on meteorology generated from two NOAA stations at Mazama and Winthrop for all seven scenarios and the no restoration baseline. Forest restoration reduced overstory fractional coverage between 2.6% and 9.9%. While these results reflect historic climate variability, we assumed no vegetation regrowth. DHSVM forest restoration results show mean increases in annual water yield ranging from 0.6 to 9.5 mm/yr (Table 20 and Figure 72). Corresponding increases in annual streamflow range from 0.1 to 2.3 %, or 0.9 to 14.1 cfs.

We also evaluated the UCSRB streamflow metrics and present selected results below. Seven-day average

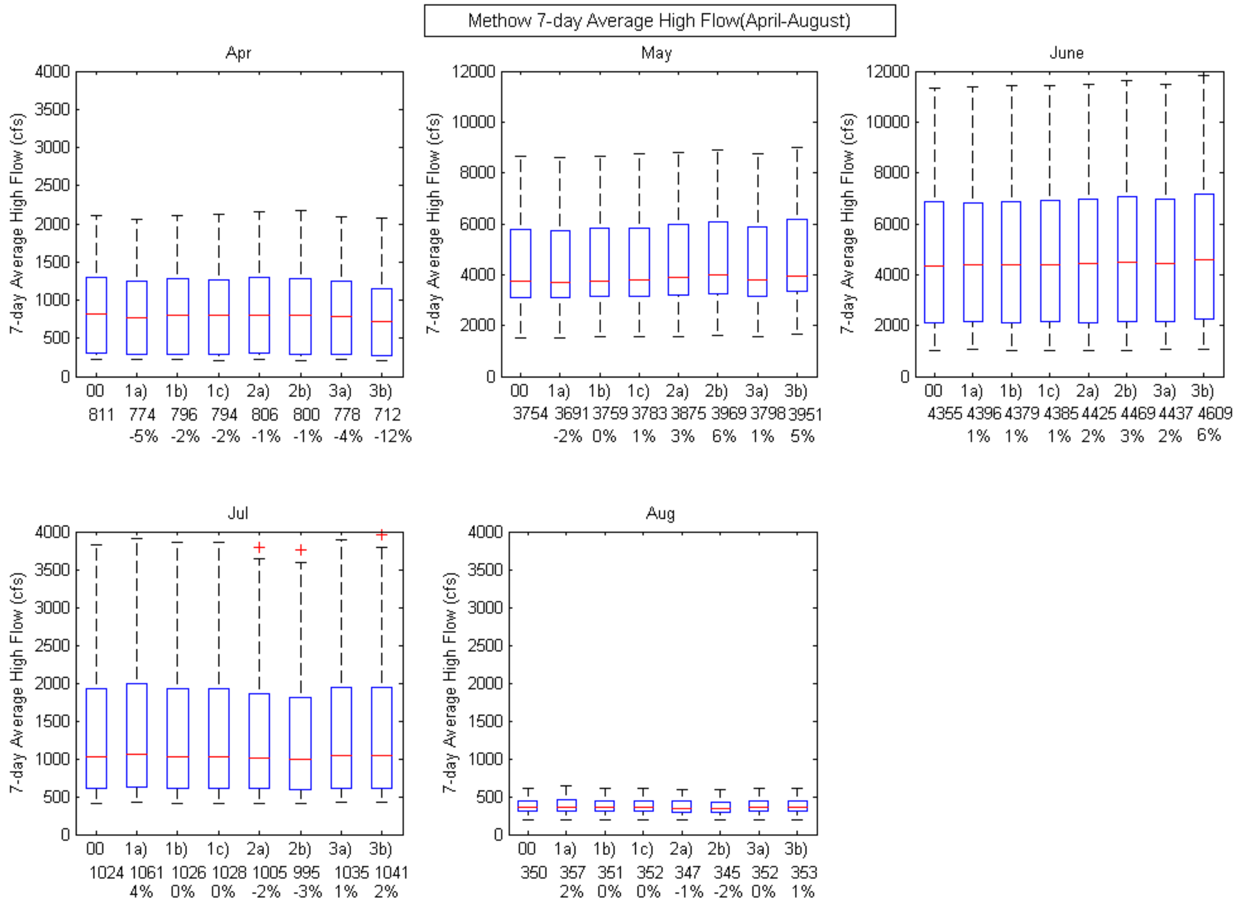


Figure 73). By June, all scenarios show an increase in 7-day average high flows, and Scenario 3b shows the greatest increase. In July, Scenarios 1a and 3a,b still show an increase, while the remaining scenarios show no change or a decrease relative to the current condition baseline.

Seven-day low flows are decreased in May for all scenarios (Figure 74). Scenario 1a (and to a lesser extent 3a) shows increased 7-day low flows June–October, while 1b and 1c show little change from the baseline over the same time period. Scenarios 2a and 2b show a decrease from the baseline June–August.

Table 20. Summary of forest restoration scenarios and results in the Upper Methow watershed.

Scenarios	Scenario Description				Pct FC reduced	% change in annual streamflow	Change in Yield (mm)	Change in Streamflow (cfs)
	Forest Type	Topo	Location	Fractional Coverage (FC)				
1a)	Dry/Moist	Ridgetops	All	FC>30% to 30%	5.88%	0.33	1.3	1.9
1b)	Dry/Moist	South-facing Slope	Top 50% Elevation	FC>50% to 50%	2.55%	0.14	0.6	0.9
1c)	Dry/Moist	South-facing Slope	All	FC>50% to 50%	5.26%	0.33	1.4	2.1
2a)	Cool/Cold	All	Top 30% Fire Index	FC to 0	3.61%	0.64	2.7	4.0
2b)	Cool/Cold	All	Top 50% Fire Index	FC to 0	6.19%	1.02	4.3	6.4
3a)	All	North-facing Slope and Valley Bottoms	Top 10% Fire Index	FC to 0	3.32%	0.75	3.1	4.6
3b)	All	North-facing Slope and Valley Bottoms	Top 30% Fire Index	FC to 0	9.90%	2.29	9.5	14.1

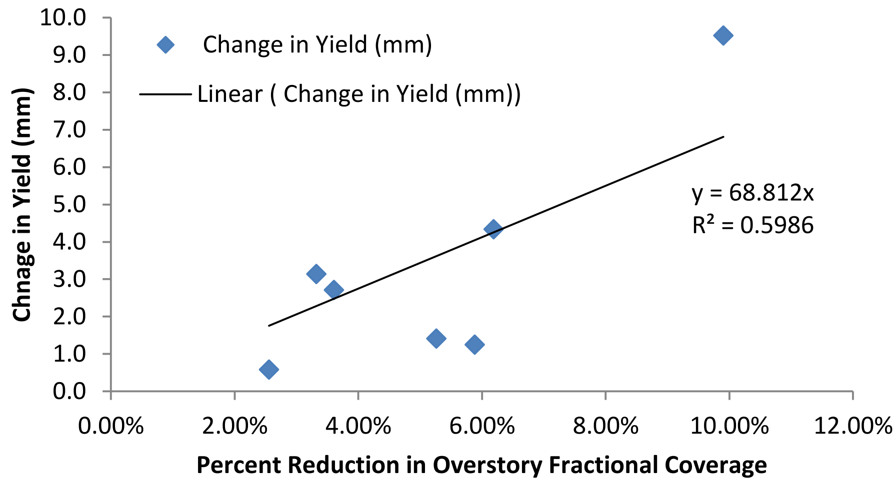


Figure 72. Increase in annual water yield (mm) in the Upper Methow watershed as a function of percent reduction in overstory fractional coverage.

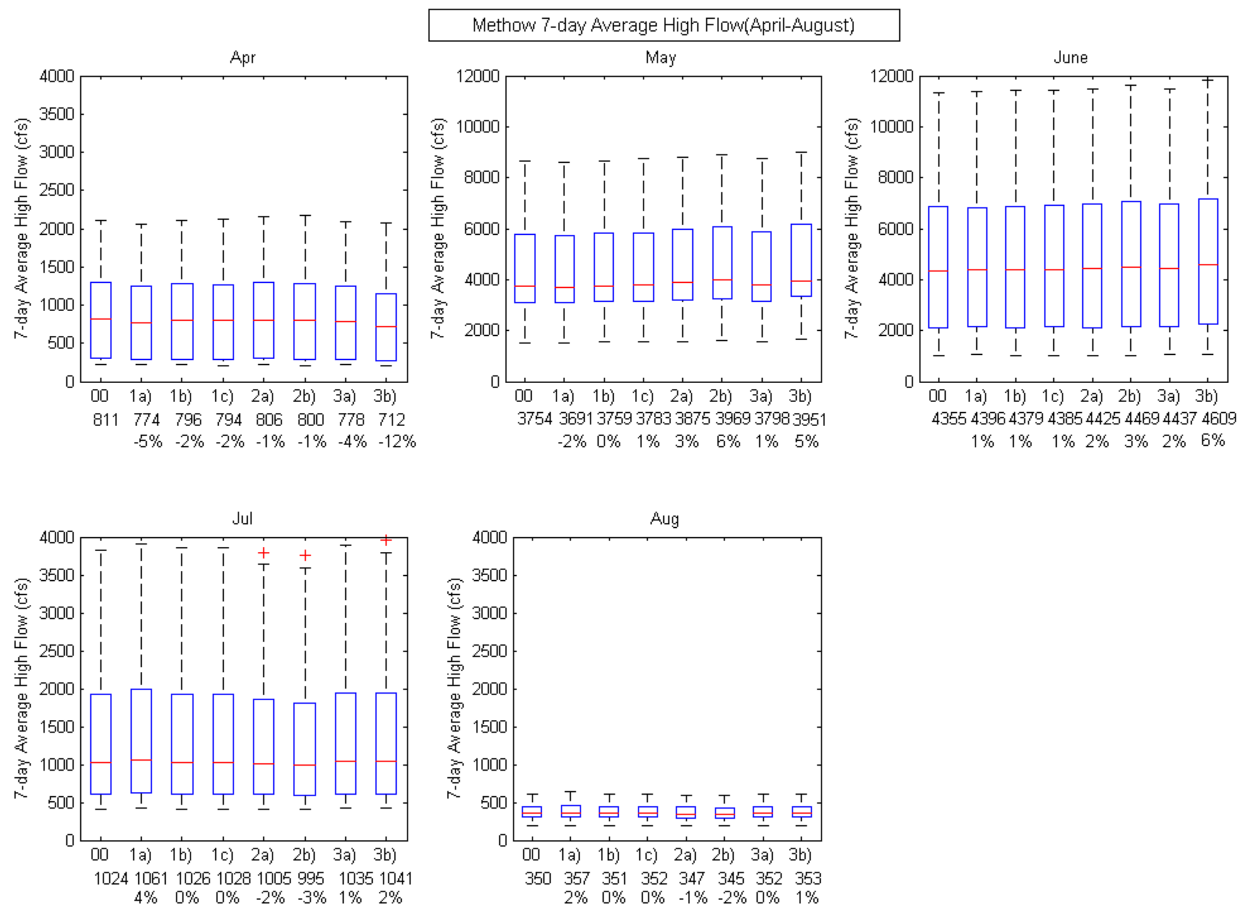


Figure 73. UCSRB 7-day high flow metric for April–August by forest restoration scenario based on 15 years in the Upper Methow watershed. Scenario 00 in each plot (far left) represents the no restoration baseline. Median flow (cfs) for each scenario is given directly below each plot, and the percent change in flow from the no restoration scenario is provided in the next line. In the box-and-whisker plots, the red line represents the median; the lower and upper portion of the box is at the 75% and 25% exceedance, respectively. The lengths of the whiskers are 1.5 times the difference between the median and the corresponding exceedance. Red crosses are outliers.

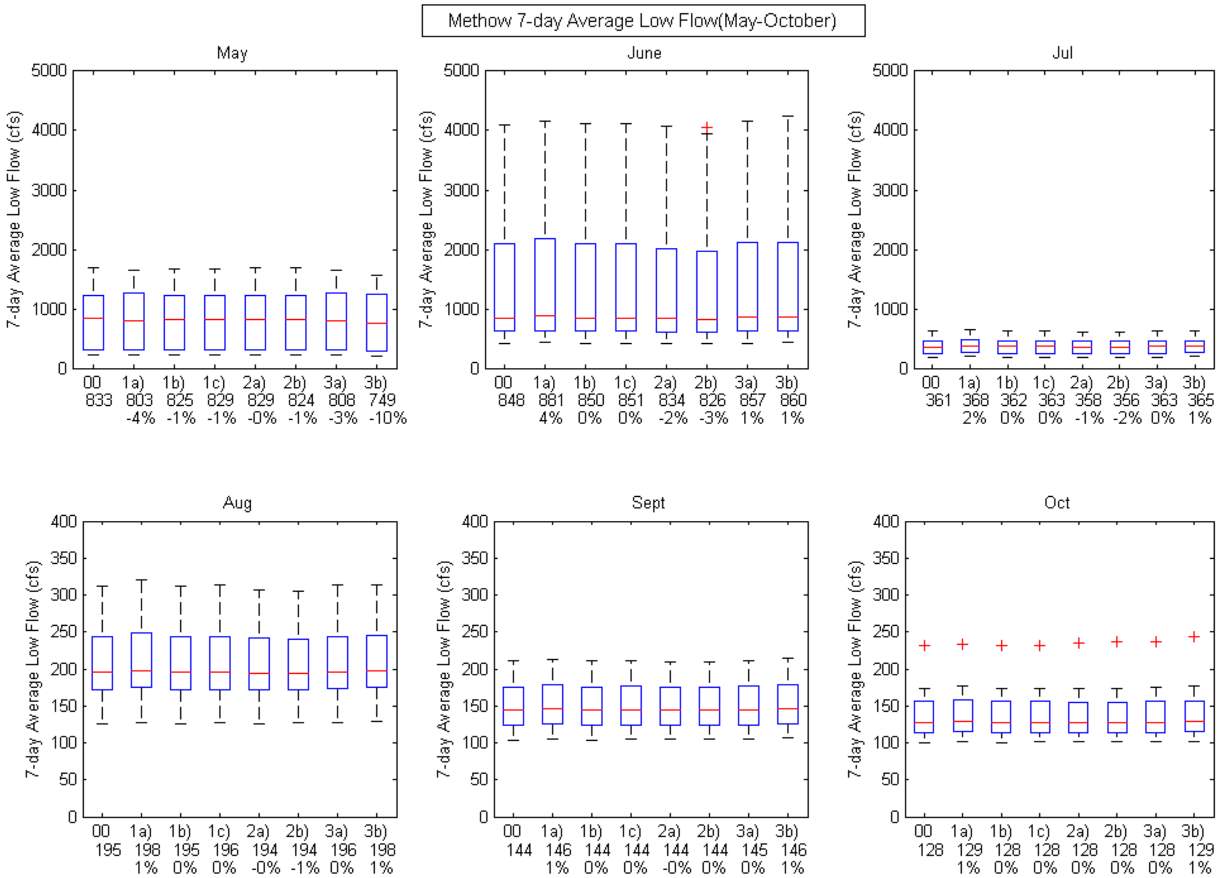


Figure 74. UCSRB 7-day low-flow metric for May–October by forest restoration scenario based on 15 years in the Upper Methow watershed. Scenario 00 in each plot (far left) represents the no restoration baseline. Median flow (cfs) for each scenario is given directly below each plot, and the percent change in flow from the no restoration scenario is provided in the next line. In the box-and-whisker plots, the red line represents the median; the lower and upper portion of the box is at the 75% and 25% exceedance, respectively. The lengths of the whiskers are 1.5 times the difference between the median and the corresponding exceedance. Red crosses are outliers.

9.3.2 Future Climate

Higher temperatures under the future climate condition reduce the June snowmelt peak relative to current climate but produce only minor changes in streamflow in other months (Figure 75).

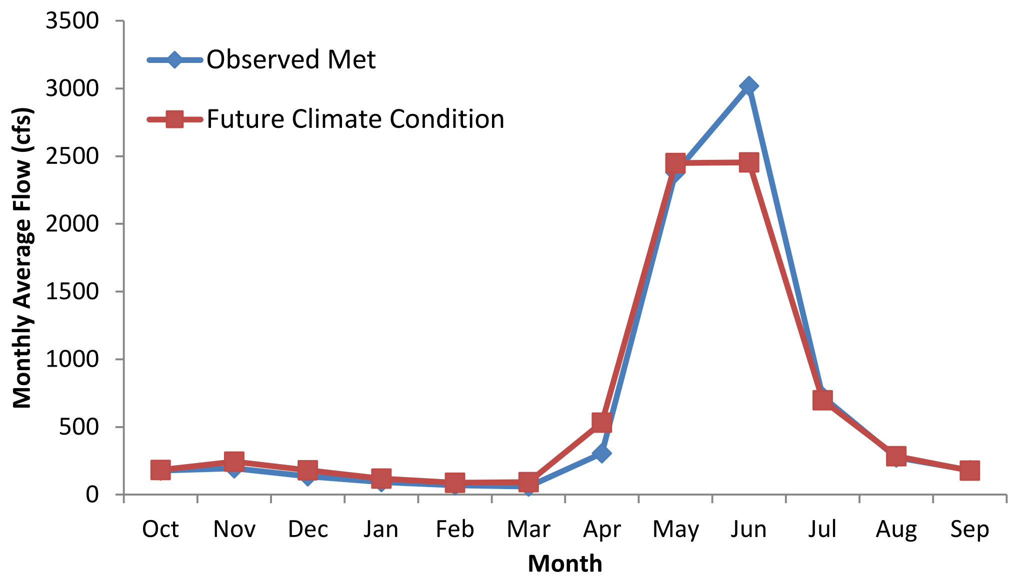


Figure 75. Mean monthly flow under current (blue) and future climate (red) conditions in the Upper Methow watershed.

The mean increase in annual water yield with forest restoration under climate change ranges from 0.5 mm/yr to 10.5 mm/yr (Table 21 and Figure 76) over the future climate condition no restoration baseline (i.e., future climate with current existing vegetation). Corresponding increases in annual streamflow range from 0.2 to 2.5%, or 0.8 to 15.3 cfs.

Table 21. Summary of forest restoration scenarios and results in the Upper Methow watershed under current and future climate conditions.

		% Change in Annual Streamflow		Change in Yield (mm)		Change in Streamflow (cfs)	
Scenarios	Pct FC reduced	Obs Met	Future Climate Condition	Obs Met	Future Climate Condition	Obs Met	Future Climate Condition
1a)	5.88%	0.33	0.31	1.3	1.2	1.9	1.7
1b)	2.55%	0.14	0.13	0.6	0.5	0.9	0.8
1c)	5.26%	0.33	0.29	1.4	1.2	2.1	1.8
2a)	3.61%	0.64	0.70	2.7	2.9	4.0	4.3
2b)	6.19%	1.02	1.19	4.3	4.9	6.4	7.3
3a)	3.32%	0.75	0.81	3.1	3.3	4.6	4.9
3b)	9.90%	2.29	2.53	9.5	10.4	14.1	15.3

Linear trend lines were calculated to examine annual water yield (mm) in the Upper Methow watershed as a function of percent reduction in overstory fractional coverage (Figure 76). For current climate conditions (observed meteorology), a 1% reduction in overstory fractional coverage will lead to 0.68 mm/yr volume increase in water yield; this increases slightly to 0.74 mm/yr under future climate conditions.

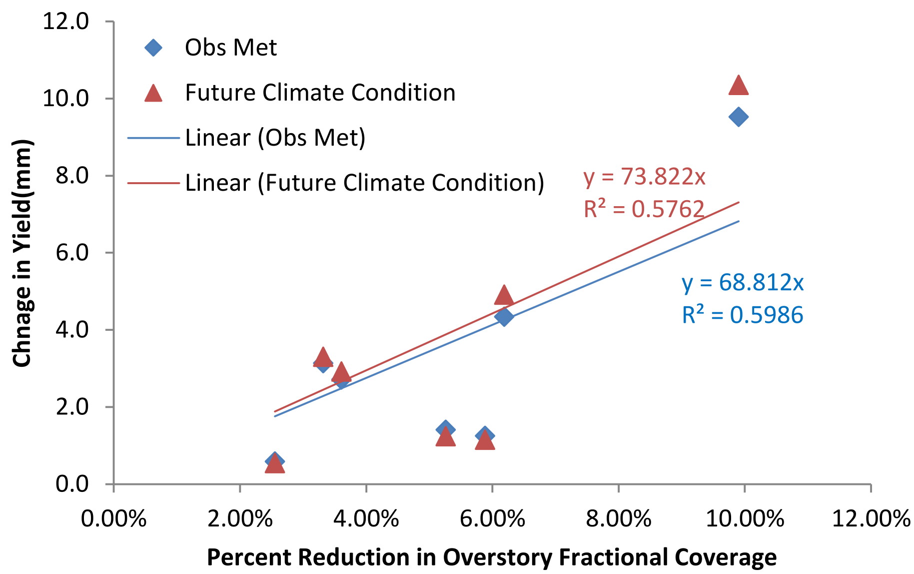


Figure 76. Increase in annual water yield (mm) in the Upper Methow watershed as a function of percent reduction in overstory fractional coverage under current and future climate conditions.

Flow metrics results for climate change are presented in Table 22–Table 25 below. Comparing the top (Observed Met) and bottom panels (Future Climate Condition) in Table 22 shows that under future climate conditions there is an increase in fall through spring mean monthly flows (October through May), compared to current climate conditions for all forest restoration scenarios (including the no restoration baseline), and a decrease in flow during June and July. However, forest restoration tends to decrease March and April flows and generally increases June and July flows compared to a future climate condition no restoration baseline (bottom panel).

Comparing the top (Observed Met) and bottom panels (Future Climate Condition) in Table 23 shows that under future climate conditions there is an increase in late fall through spring 7-day average low flows (November through May), compared to the current climate for all forest restoration scenarios (including no restoration baseline), and a general decrease in flow during the summer and early fall (June through October). However, forest restoration tends to decrease April and May flows and increases June through October flows compared to a future climate condition no restoration baseline (bottom panel).

Comparing the top (Observed Met) and bottom panels (Future Climate Condition) in Table 24 shows that under climate change there is an increase in late fall through spring 7-day average high flows (October through April), compared to the current climate for all forest restoration scenarios (including no restoration baseline), and a decrease in flow May through July. However, forest restoration tends to decrease March and April flows and increases May through November flows compared to a future climate condition no restoration baseline (bottom panel).

Comparing the top (Observed Met) and bottom panels (Future Climate Condition) in Table 25 shows that under climate change there is an increase in late fall through spring 1-day average high flows (November through April), compared to the current climate for all forest restoration scenarios (including no restoration baseline), and a decrease in flow May through July. However, forest restoration tends to decrease March and April flows and increases May through October flows compared to a future climate condition no restoration baseline (bottom panel).

Table 22. Mean monthly flow in the Upper Methow watershed for forest restoration scenarios under current and future climate conditions.

Monthly Average Flow(cfs) – Methow													
		Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Observed Met	No MGMT	178.50	193.63	134.15	93.93	70.26	59.52	304.84	2379.03	3019.01	723.29	275.76	179.43
	1a	180.01	194.25	134.14	93.99	70.36	59.59	297.11	2339.61	3053.01	748.07	282.42	182.00
	1b	178.59	193.55	134.05	93.89	70.25	59.50	301.81	2376.70	3033.01	724.79	276.13	179.59
	1c	178.92	193.50	133.94	93.86	70.23	58.57	293.82	2388.66	3041.98	726.05	276.70	179.93
	2a	178.91	194.38	134.55	94.12	70.34	59.53	304.11	2421.65	3041.51	708.36	273.21	178.80
	2b	179.61	194.63	134.73	94.21	70.38	59.42	301.91	2449.85	3053.28	698.83	272.21	179.11
	3a	179.47	194.38	134.44	94.11	70.36	59.48	296.75	2383.34	3068.52	729.60	277.03	180.12
	3b	181.86	195.60	134.97	94.41	70.53	59.16	277.67	2422.48	3151.59	731.76	279.15	182.13
Future Climate Condition	No MGMT	181.74	244.97	179.80	119.13	88.98	93.08	531.31	2449.77	2454.52	697.82	284.37	178.16
	1a	183.63	246.64	179.56	119.05	88.91	92.36	511.63	2408.90	2497.66	723.66	291.96	181.04
	1b	181.88	244.91	179.64	119.07	88.96	92.92	524.32	2453.49	2466.12	698.85	284.71	178.31
	1c	182.24	245.16	179.44	118.80	88.38	89.64	517.16	2470.07	2470.36	699.99	285.26	178.66
	2a	182.81	245.81	180.40	119.49	89.16	92.98	527.78	2473.97	2482.45	698.32	284.29	178.44
	2b	184.02	245.81	180.59	119.60	89.17	92.35	522.40	2490.91	2504.29	698.51	284.56	179.27
	3a	183.51	246.79	179.95	119.29	88.95	92.11	512.54	2444.80	2510.23	716.73	288.29	179.58
	3b	187.45	249.16	180.18	119.47	88.68	89.14	471.55	2477.06	2614.01	736.21	293.09	182.46

Table 23. Seven-day average low flow in the Upper Methow watershed for forest restoration scenarios under current and future climate conditions.

7-Day Average Low-Flow Monthly Median(cfs) – Methow													
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Observed Met	No MGMT	**66.94**	**53.06**	**47.12**	**51.02**	**832.85**	**848.03**	**361.44**	**194.90**	**144.17**	**127.74**	**112.20**	**88.49**
	1a	66.98	53.20	47.39	51.14	802.75	880.69	368.16	197.79	146.03	128.76	112.57	88.46
	1b	66.92	53.05	47.13	51.02	825.42	849.51	362.04	195.10	144.26	127.80	112.14	88.46
	1c	66.85	53.04	46.87	49.15	828.60	851.01	363.07	195.52	144.50	128.00	112.04	88.31
	2a	67.03	53.14	47.10	51.05	828.69	834.10	358.03	194.12	143.89	127.74	112.75	88.72
	2b	67.10	53.21	47.08	50.86	824.08	825.58	355.56	193.92	144.26	128.10	113.17	88.85
	3a	67.10	53.21	47.17	50.99	807.85	856.72	362.88	195.68	144.69	128.13	113.05	88.77
	3b	67.45	53.52	47.22	50.35	748.78	860.28	364.72	197.58	146.29	129.35	114.79	89.21
Future Climate Condition	No MGMT	88.28	75.01	72.53	128.58	1076.91	819.13	360.36	193.69	137.55	121.39	132.55	115.89
	1a	88.93	74.92	72.33	128.19	1059.05	853.42	371.64	196.90	139.49	122.76	133.47	116.84
	1b	88.28	75.01	72.52	128.25	1063.79	820.73	360.78	193.89	137.65	121.46	132.55	115.89
	1c	87.93	73.70	71.72	120.48	1073.74	822.07	361.37	194.30	137.88	121.66	132.45	115.82
	2a	88.79	75.26	72.98	128.17	1076.86	821.47	360.41	193.94	137.94	121.87	132.85	116.95
	2b	88.95	75.24	73.00	126.10	1076.17	820.87	361.22	194.47	138.65	122.79	133.14	117.44
	3a	88.83	74.78	72.54	127.25	1074.36	845.70	365.73	195.23	138.43	122.07	132.79	116.95
	3b	89.60	74.01	71.76	121.19	1028.39	869.12	372.26	198.32	140.77	124.01	134.08	118.51

Table 24. Seven-day average high flow in the Upper Methow watershed for forest restoration scenarios under current and future climate conditions.

7-Day Average High Flow Monthly Median(cfs) – Methow													
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Observed Met	No MGMT	**87.65**	**66.37**	**59.54**	**810.70**	**3754.30**	**4354.57**	**1024.26**	**350.26**	**192.81**	**164.83**	**145.41**	**118.55**
	1a	87.62	66.41	59.83	773.51	3691.22	4396.40	1061.49	356.70	195.91	166.35	146.64	118.06
	1b	87.62	66.36	59.54	796.27	3759.14	4378.77	1026.22	350.84	193.00	164.89	145.44	118.44
	1c	87.47	66.29	59.50	793.59	3782.83	4384.84	1028.36	351.83	193.36	165.19	145.73	117.98
	2a	87.88	66.46	59.53	805.69	3874.86	4425.41	1005.27	346.95	192.33	164.74	145.28	119.04
	2b	88.01	66.52	59.54	800.43	3968.57	4469.44	994.71	344.51	192.88	164.69	145.13	119.29
	3a	87.93	66.53	59.60	777.63	3798.07	4436.53	1035.00	351.63	193.66	165.50	145.76	118.79
	3b	88.35	66.88	59.69	711.79	3951.12	4608.98	1040.60	353.32	196.29	167.07	147.27	119.53
Future Climate Condition	No MGMT	114.73	96.22	116.27	1211.80	3440.77	3417.95	926.42	352.96	191.05	175.03	182.56	155.22
	1a	115.67	96.63	116.07	1172.08	3442.49	3440.41	967.27	362.73	194.96	177.75	184.97	156.88
	1b	114.73	96.21	116.02	1201.94	3472.63	3440.57	927.95	353.38	191.24	175.18	182.58	155.21
	1c	114.66	94.36	109.05	1203.84	3477.56	3445.04	929.41	354.16	191.59	175.48	182.69	155.07
	2a	115.77	96.63	116.03	1216.22	3526.83	3488.10	930.50	353.05	191.31	174.98	184.20	157.04
	2b	116.24	96.59	114.33	1217.27	3594.41	3547.24	931.93	353.84	192.27	175.53	185.20	157.97
	3a	115.76	96.50	115.33	1182.87	3486.49	3479.80	962.88	358.18	192.79	176.14	186.01	157.44
	3b	117.29	96.35	110.74	1125.50	3669.01	3674.49	996.62	364.91	196.27	178.42	191.49	160.76

Table 25. One-day average low flow in the Upper Methow watershed for forest restoration scenarios under current and future climate conditions.

1-Day Average High Flow Monthly Median(cfs) - Methow													
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Observed Met	No MGMT	**87.62**	**66.37**	**60.70**	**806.49**	**3926.57**	**4625.85**	**1217.49**	**419.33**	**221.32**	**212.54**	**162.34**	**118.59**
	1a	87.60	66.41	61.08	775.60	3871.25	4659.70	1262.65	426.15	224.12	215.00	163.96	118.09
	1b	87.60	66.35	60.69	793.14	3921.54	4655.83	1220.08	419.92	221.53	212.67	162.23	118.47
	1c	87.45	66.29	59.73	780.42	3960.23	4662.74	1223.01	421.13	222.08	213.17	161.97	118.03
	2a	87.85	66.46	60.70	800.49	4060.10	4715.94	1199.90	416.86	221.07	211.98	162.64	119.07
	2b	87.98	66.52	60.51	795.27	4152.42	4770.22	1190.72	416.43	221.89	212.52	162.56	119.33
	3a	87.90	66.53	60.80	772.94	3961.78	4714.61	1232.37	421.38	222.31	213.09	163.92	118.83
	3b	88.33	66.89	60.70	701.61	4187.67	4912.09	1244.41	426.13	225.43	215.27	166.04	119.57
Future Climate Condition	No MGMT	114.72	100.18	123.55	1183.40	3720.21	3659.87	1089.68	421.98	213.89	212.28	194.73	155.20
	1a	115.65	100.27	123.78	1143.47	3733.01	3731.85	1132.29	429.14	216.30	214.91	197.24	156.86
	1b	114.72	100.09	123.37	1172.83	3748.73	3667.96	1091.71	422.55	214.07	212.42	194.70	155.19
	1c	114.65	99.40	112.90	1173.87	3754.46	3674.65	1094.18	423.82	214.58	212.97	194.61	155.05
	2a	115.76	100.69	123.25	1187.89	3797.42	3699.52	1093.15	423.05	214.54	213.02	195.65	157.02
	2b	116.23	100.81	120.77	1189.43	3860.30	3736.65	1094.47	425.02	215.62	215.00	195.45	157.94
	3a	115.75	100.47	122.57	1154.09	3777.78	3756.03	1124.98	426.87	215.46	213.64	197.86	157.42
	3b	117.27	100.61	117.52	1100.39	3935.55	3929.57	1158.46	435.53	219.08	217.52	202.16	160.74

10.0 Model Application in the Okanogan Basin

10.1 Calibration and Validation

We faced several obstacles in the Okanogan basin. Meteorological data are limited and the main-stem Okanogan River is highly regulated. With limited options, we selected Omak Creek for model application based largely on the presence of forest cover and the availability of observed unregulated streamflow. However, a quality check of the data revealed several periods of missing data, and large amounts of data marked as “not yet checked” or “provisional.” Furthermore, since the late 1990s, several watershed rehabilitation efforts to re-establish summer Steelhead have been implemented in Omak Creek. Those efforts include installation of instream structures, road decommissioning, and culvert replacement, making it hard to test and evaluate model performance in the basin.

We ran the model for 10 years (WY 2003–2012) based on meteorology generated from the Kramer RAWS outside of the basin. No model performance statistics were calculated but visual inspection indicates poor model performance. The limited available data were entirely inadequate to conduct the diagnostic studies needed to improve the model. Consequently, we have not included Omak Creek results here.

11.0 References

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