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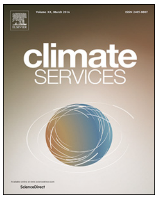

Effects of climate change on hydrology and water resources in the Blue Mountains, Oregon, USA

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ABSTRACT

In the semi-arid environment of the Blue Mountains, Oregon (USA), water is a critical resource for both ecosystems and human uses and will be affected by climate change in both the near- and long-term. Warmer temperatures will reduce snowpack and snow-dominated watersheds will transition to mixed rain and snow, while mixed rain and snow dominated watersheds will shift towards rain dominated. This will result in high flows occurring more commonly in late autumn and winter rather than spring, and lower low flows in summer, phenomena that may already be occurring in the Pacific Northwest. Higher peak flows are expected to increase the frequency and magnitude of flooding, which may increase erosion and scouring of the streambed and concurrent risks to roads, culverts, and bridges. Mapping of projected peak flow changes near roads gives an opportunity to mitigate these potential risks. Diminished snowpack and low summer flows are expected to cause a reduction in water supply for aquatic ecosystems, agriculture, municipal consumption, and livestock grazing, although this effect will not be as prominent in areas with substantial amounts of groundwater. Advanced planning could help reduce conflict among water users. Responding pro-actively to climate risks by improving current management practices, like road design and water management as highlighted here, may be among the most efficient and effective methods for adaptation.

Practical Implications

Water is a particularly valuable resource in the relatively dry landscapes of the Blue Mountains region, Oregon (USA). Most of that water is sourced from high-elevation public lands, specifically the Malheur, Umatilla, and Wallowa-Whitman National Forests. Snowpack, which is the key to downstream water supply during the summer, may already be decreasing in response to a warmer climate and will continue to decrease in future decades. This will inevitably affect ecological processes and human enterprises in the region.

A higher rain:snow ratio in the Blue Mountains is expected to cause higher peak streamflows in late autumn and winter, leading to increased frequency and magnitude of flooding downstream. This will have the potential to damage roads, especially in and near floodplains, and associated infrastructure such as culverts and bridges. Refitting this infrastructure for more severe conditions will create a financial burden for the U.S. Forest Service, other public agencies, and private landowners. Increase flooding may also reduce access for recreational activities and resource management, possibly for long periods of time. If damage is high enough, it will require a prioritization of roads that can be maintained within a sustainable transportation system, and perhaps the permanent closure of some roads.

Reduced snowpack and earlier snowmelt will reduce hydrologic recharge of both surface and subsurface flows in spring and summer. This will lead to lower streamflows in summer in both rivers and smaller streams, creating adverse conditions for coldwater fish species and other aquatic

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organisms. It will also reduce water supply for agriculture, municipal uses (drinking water), industrial uses, livestock grazing, and recreation. Reduced water supply will be an especially important issue when multiple consecutive drought years decrease water available for both aquatic ecosystems and downstream human uses.

Currently, water allocation is mostly satisfactory in the Blue Mountains region, and conflicts are occasional and localized. However, competition among different users may become acute during future drought periods, and if low water supply becomes a chronic situation, social and political solutions may be needed to resolve conflicts. Finding a balance in the near term among water allocated for ecological functions, local communities, and economic benefits will help forestall those conflicts.

1. Introduction

Water is a critical resource in arid and semi-arid forest and rangeland environments of western North America, typically limiting the distribution of plant and animal species. Water is also a critical element for human activities, affecting where and how human communities and local economies persist across the landscape (Hartter et al., 2018). The Blue Mountains of northeast Oregon and southeast Washington, most of which are located within federal land, are the primary water source for human uses, which include agriculture, drinking water, industrial uses, livestock grazing, and recreation.

Climate change is expected to alter hydrologic processes in the Pacific Northwest region of North America, thereby affecting key resources and processes including water supply, infrastructure, aquatic habitat, and access. A warmer climate will affect the amount, timing, and type of precipitation, and the timing and rate of snowmelt (Luce et al., 2012, 2013; Safeeq et al., 2013), which will in turn affect snowpack volume (Hamlet et al., 2005; Luce et al., 2014a), streamflow (Hidalgo et al., 2009; Elsner et al., 2010; Hamlet et al., 2013), and stream temperature (Isaak et al., 2012; Luce et al., 2014b; Mantua et al. 2010). Altered precipitation patterns would also affect vegetation (Kerns et al., 2018), which would in turn affect water supply (Adams et al., 2012, Vose et al., 2016).

Federal lands dominate the headwaters of the major basins in the Blue Mountains Ecoregion (Fig. 1). Understanding how climate change will affect hydrologic processes will help federal land managers and their many partners identify planning and management strategies that maintain ecosystem function, water supply, and a sustainable road system (Peterson and Halofsky, 2018). Reduced or less reliable water supply affects local economic activities, planning, and resource management. Anticipatory planning can reduce conflicts and improve economic and ecological outcomes during droughts. Damage to roads, bridges, and culverts creates safety hazards, affects aquatic resources, and incurs high repair costs. Reduced access to public lands reduces the ability of land managers to preserve, protect, and restore resources and to provide for public use of resources. Designing a less vulnerable road network would again protect both ecological and economic interests.

Here we describe hydrologic processes in the Blue Mountains of Oregon, historical trends in hydrologic parameters (snowpack, peak streamflow, low streamflow, and stream temperatures), and projected effects of climate change on these hydrologic parameters. We also identify and map key sensitivities of water supply, roads, and infrastructure to changes in climate and hydrology.

2. Effects of climate change on hydrologic processes

2.1. Methods

Hydrologic simulations of streamflow were prepared using the Variable Infiltration Capacity (VIC) model (Liang et al., 1994) to simulate streamflow driven by downscaled forcing data from global circulation models (GCMs) that have contributed to the Intergovernmental Panel on Climate Change AR4 (CMIP3) assessment (Elsner et al., 2010; IPCC, 2007). VIC projections were prepared from an ensemble of 10 GCM models using A1B emission scenarios and having the best match with observations in the historical period (Littell et al., 2011). Projections for the "2040s" cover an average from 2030 to 2059, and the "2080s" cover 2070 to 2099. Historical metrics were based on the period 1977 through 1997 (Wenger et al., 2010). VIC data were computed on a 1/16th-degree (~6 km) grid to produce daily flow data that were further routed downstream and analyzed for metrics important to aquatic ecology (Wenger et al., 2010, 2011). VIC outputs were further processed with a linear groundwater reservoir routing algorithm using the calibrated recession coefficient values of Safeeq et al. (2014) to estimate impacts to low flows, which are sensitive to groundwater dynamics.

To assess changes in snowpack, we used the model of Luce et al. (2014a), who evaluated snow sensitivity to climate at Snowpack Telemetry (SNOTEL) sites in the Pacific Northwest, developing projections for April 1 snow water equivalent (SWE) for a scenario of 3 °C warmer than the last 20 years. Validation of the model shows that it is suitable to assess climate change effects (Lute and Luce, 2017).

Stream temperature changes were projected using the The NorWeST Regional Stream Temperature Database (http://www.fs.fed.us/rm/boise/AWAE/projects/NorWeST.html). NorWeST uses extensive stream temperature observations and spatial statistical models to characterize and project stream temperatures in the Blue Mountains (Isaak et al., 2015, Isaak et al., this issue). Future stream temperatures were projected based on historical conditions, model projections of future climate, and assessments of past sensitivity to climate.

2.2. Effects of climate change on snowpack

The role of snow in watershed runoff in the Pacific Northwest is determined to a great extent by mid-winter temperatures (Hamlet and Lettenmaier, 2007). Rain-dominated basins are above freezing most of the time in winter, and snow accumulation is minimal (< 10% of October-March precipitation). These basins typically have peak streamflows in winter, coinciding with peak precipitation, but may have multiple peaks associated with individual rain events. Mixed rain and snow (or transitional) basins collect substantial snowpack (10–40% of October-March precipitation), and are typically slightly below freezing in mid-winter. These basins have multiple seasonal streamflow peaks. Snow-dominated basins are cold in winter, capturing > 40% of October-March precipitation as snow and have low flows through winter, often with streamflow peaks in spring. The Blue Mountain region has all three types of basins.

Over the last 50 years, increasing temperatures in the Pacific Northwest have caused earlier snowmelt (Stewart et al., 2005; Hamlet et al., 2007), and lower spring snowpack (Mote, 2003; Hamlet et al., 2005; Mote et al., 2005). Snowpack is expected to be particularly sensitive to future temperature increases, facilitating a change from snowmelt-dominant to transitional basins, and from transitional to rain-dominant basins (Tohver et al., 2014).

Decreases in snowpack persistence and April 1 SWE will be widespread in the Blue Mountains, with the largest decreases in low to mid-elevation locations. Large areas of the ecoregion are likely to lose significant portions of April 1 SWE by the 2080s (Fig. 2). Snowpack sensitivity will be relatively high even in some of the locally higher elevation ranges such as the Strawberry Mountains, Monument Rock

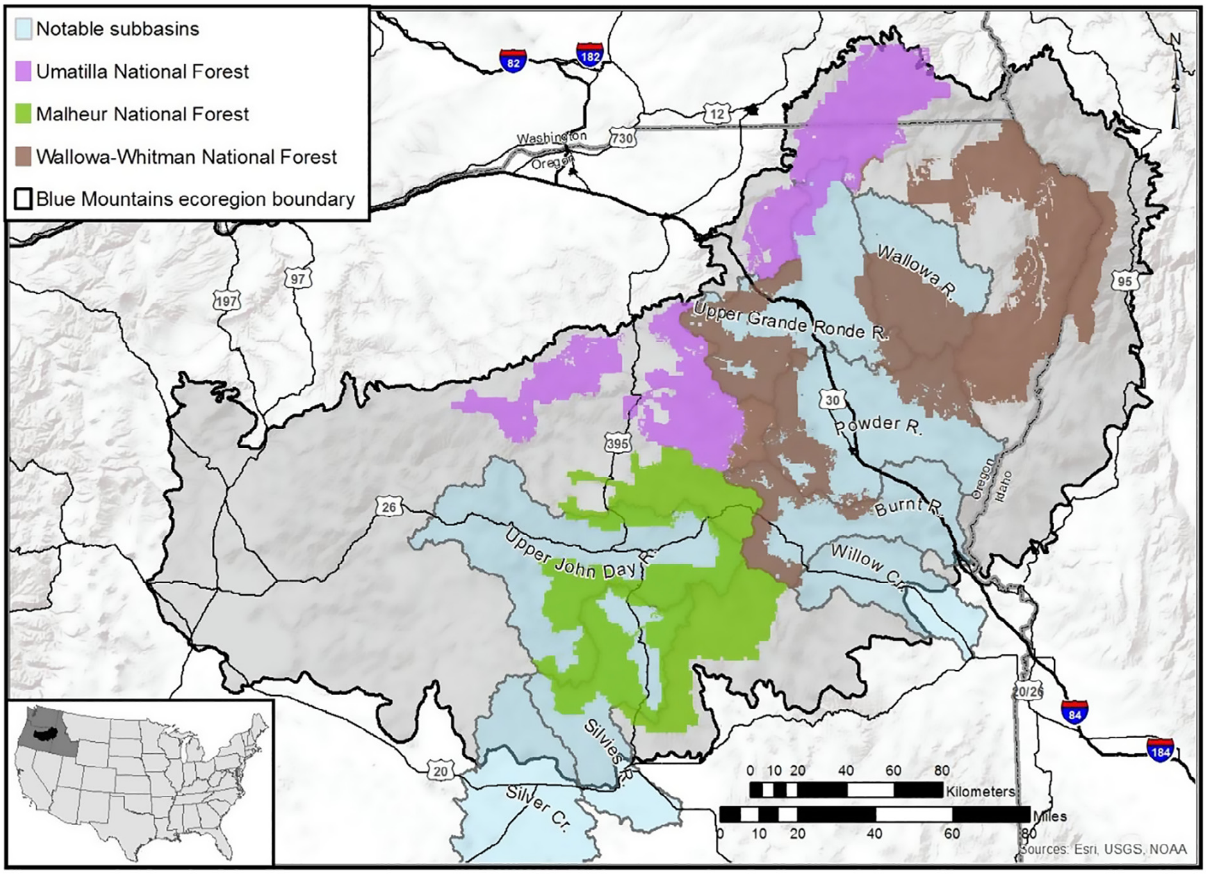


Fig. 1. National Forests and major basins in the Blue Mountains Ecoregion.

Wilderness, Wenaha-Tucannon Wilderness, and at mid-elevations in the North Fork John Day, and Hells Canyon Wilderness. Much of the Eagle Cap Wilderness, in the Wallowa Mountains, has the lowest sensitivity in the area with declines in April 1 SWE on the order of 25% by the 2080s.

2.3. *Effects of climate change on peak flows*

Flooding in mountain watersheds in the Pacific Northwest is sensitive to precipitation intensity, temperature (as it affects rain vs. snow), and the combined effects of temperature and precipitation on snow dynamics (Hamlet and Lettenmaier, 2007; Tohver et al., 2014). Floods occur during autumn and winter (associated with heavy rainfall and snowmelt) or in spring, associated with heavy snowpack and rapid snowmelt (Hamlet and Lettenmaier, 2007; Sumioka et al., 1998). Summer storms can also cause local flooding and mass wasting events (such as landslides, gullies, and debris flows), particularly after wildfire (Moody and Martin, 2009; Cannon et al., 2010; Luce et al., 2012).

Flooding can be exacerbated by rain-on-snow (ROS) events (Harr, 1986; Marks et al., 1998; McCabe et al., 2007; Eiriksson et al., 2013), and a warmer climate is expected to alter ROS flood risk depending on local conditions in different basins including elevation ranges and groundwater dynamics (e.g. Safeeq et al., 2015). In general, the ROS zone is expected shift upwards in elevation, which will tend to increase flooding in basins where much of the basin is just above the elevation where ROS is common. In contrast, in basins in which the ROS zone is already high in the basin, the upward shift in the ROS zone may reduce flooding.

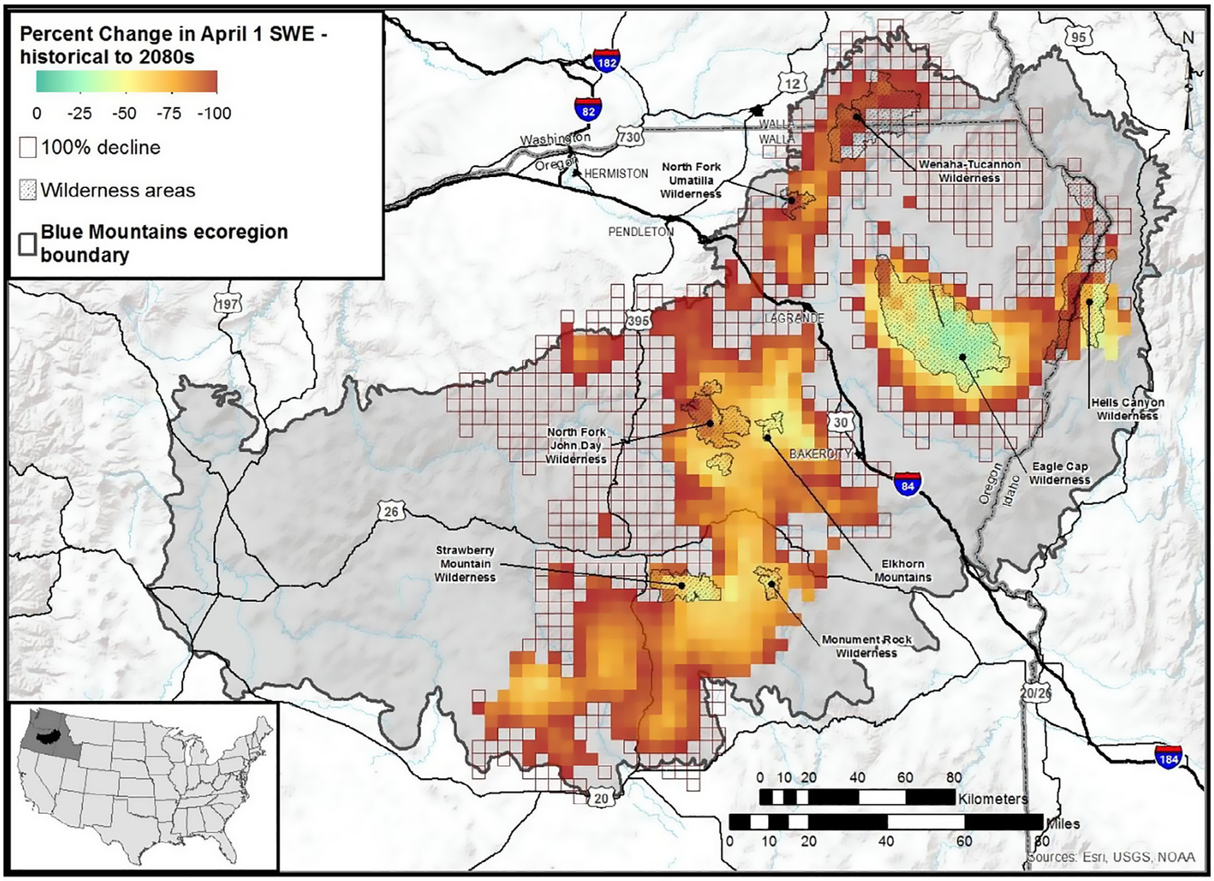
Higher temperatures in the latter half of the 20th century have caused earlier runoff in snowmelt-dominated and transitional watersheds in the western United States (Cayan et al., 2001; Stewart et al., 2005; Hamlet et al., 2007). If temperature continues to increase, possibly accentuated by increased precipitation intensity, extreme hydrologic events may become more frequent (Hamlet et al., 2013).

In the Blue Mountains, the hydrologic simulations estimate that flood magnitude will increase in the Wallowa Mountains, Hells Canyon Wilderness Area, and northeast Wallowa-Whitman National Forest by the 2080s, particularly in mid-elevation areas (Fig. 3). High flow events during winter are projected to change substantially in some areas, and areas with the largest change in flood magnitude (Fig. 3) also have altered frequency of those high flows occurring during winter months (Fig. 4), which may be damaging for fish eggs in redds (Tonina et al., 2008; Wenger et al., 2011; Goode et al., 2013; Isaak et al., this issue). Some of the largest peak flow changes are occurring in areas where the largest precipitation events (usually in November and December) now commonly fall as snow and are expected more frequently to come as rain falling on snow in the future. It is this shift in mechanism that contributes most strongly to flood magnitude increases. Other areas in the ecoregion already experience substantial rain-on-snow.

2.4. *Effects of climate change on low flows*

Earlier snowmelt over the last 50 years has reduced spring, early summer, and late summer flows in the western United States (Leppi et al., 2011; Safeeq et al., 2013; Kormos et al., 2016). The 25th percentile flows (drought year flows, 1948–2006) have become even lower across the Pacific Northwest (Luce and Holden, 2009), and large decreasing fractional flows have been documented for eastern Oregon in March-June (Stewart et al., 2005). Summer low flows are affected by both snowmelt and landscape drainage efficiency (Tague and Grant, 2009; Safeeq et al., 2013). In the Blue Mountains, which have a moderate groundwater component, summer flows decreased 21–28% between 1949 and 2010 (Safeeq et al., 2013).

Within the Blue Mountain region, snow-dominated regions with late snowmelt, such as the Wallowa Mountains, have high streamflow



Sources: Esri, USGS, NOAA

Fig. 2. Projected change in snow water equivalent from present to the 2080s in the Blue Mountains. Names indicate Wilderness areas and other high elevation ranges in the region to provide some reference for topography. Projections were modeled based on the methods of Luce et al. (2014a) using downscaled weather from Abatzoglou and Brown (2012).

sensitivity to a change in the magnitude and timing of recharge at broad spatial scales (Safeeq et al., 2014), especially in early summer. Other parts of the Blue Mountains have low-moderate sensitivity to changes in magnitude and timing of snowmelt, although sensitivity in the Wallowa Mountains is higher in early summer. Projections of future low flows using the hydrologic simulations indicate small decreases in summer streamflow (< 10%) for about half of perennial streams in the Blue Mountains by 2080 (Fig. 5), although some of the more sensitive areas (Wallowa Mountains, Elkhorn Mountains, Wenaha-Tucannon Wilderness) show > 30% streamflow decreases by 2080. Note that many of the most sensitive areas for low flows are areas that have lower sensitivity for snowpack (Fig. 2) because these are areas where late-lying snow has always been an important contributor to summer runoff, and small changes in snowpack drive large changes in low flow (Safeeq et al., 2014).

2.5. *Effects of climate change on water quality*

Historical temperatures in unregulated streams across the Pacific Northwest paralleled air temperature trends at nearby weather stations from 1980 to 2009 (Isaak et al., 2010, 2012), and stream temperatures increased significantly in summer, autumn, and winter, with the highest rates of warming in summer (reconstructed trend of 0.22 °C per decade). A significant stream cooling trend occurred during spring, associated with a regional trend of cooler air temperature (Isaak et al., 2012; Abatzoglou et al., 2014). Most of the variation in long-term stream temperature (80–90%) was explained by air temperature trends and a smaller proportion by discharge (10–20%). A separate study of stream data found variable trends in stream temperature, with increased temperature at some sites in the Pacific Northwest (28–44%) and decreased temperature at others (22–33%) (Arismendi et al., 2012). Discrepancies are attributed to differences in length of record and location relative to dams, with warming more apparent in the longer datasets. Cold streams were generally not as sensitive as warm streams to varying climatic conditions (Luce et al., 2014b; Isaak et al., 2016). Therefore, the relatively warm streams in the Blue Mountains are expected to be quite sensitive to a warmer climate.

Decreasing summer moisture and warming temperatures in dry forests of the western United States may contribute to forest mortality in some locations (e.g., Meddens and Hicke, 2014; Allen et al., 2015; McDowell et al., 2015; Luce et al., 2016) and increased wildfire area burned (Littell et al., 2009; Littell et al., 2016). Increased wildfire, particularly if it occurs in riparian areas, would contribute to stream temperature increases (Dunham et al., 2007; Isaak et al. 2010). These risks are not characterized in the projections in this region, but illustrate that care in riparian management and land management that reduces wildfire spread can ameliorate projected warming.

Projections estimate that basin-wide average August stream temperatures in the Blue Mountains will increase 1 °C by 2040 and nearly 2 °C by 2080 in response to higher air temperature, with warmer streams in the basin likely to warm faster than cooler ones.

3. Consequences of hydrologic changes for water management

In the dry climate of the Blue Mountains region, many different parties lay claim to use of water resources to support habitation and economic enterprises. About 6800 water rights claims are located on National Forest lands: 43% for domestic livestock, 32% for instream

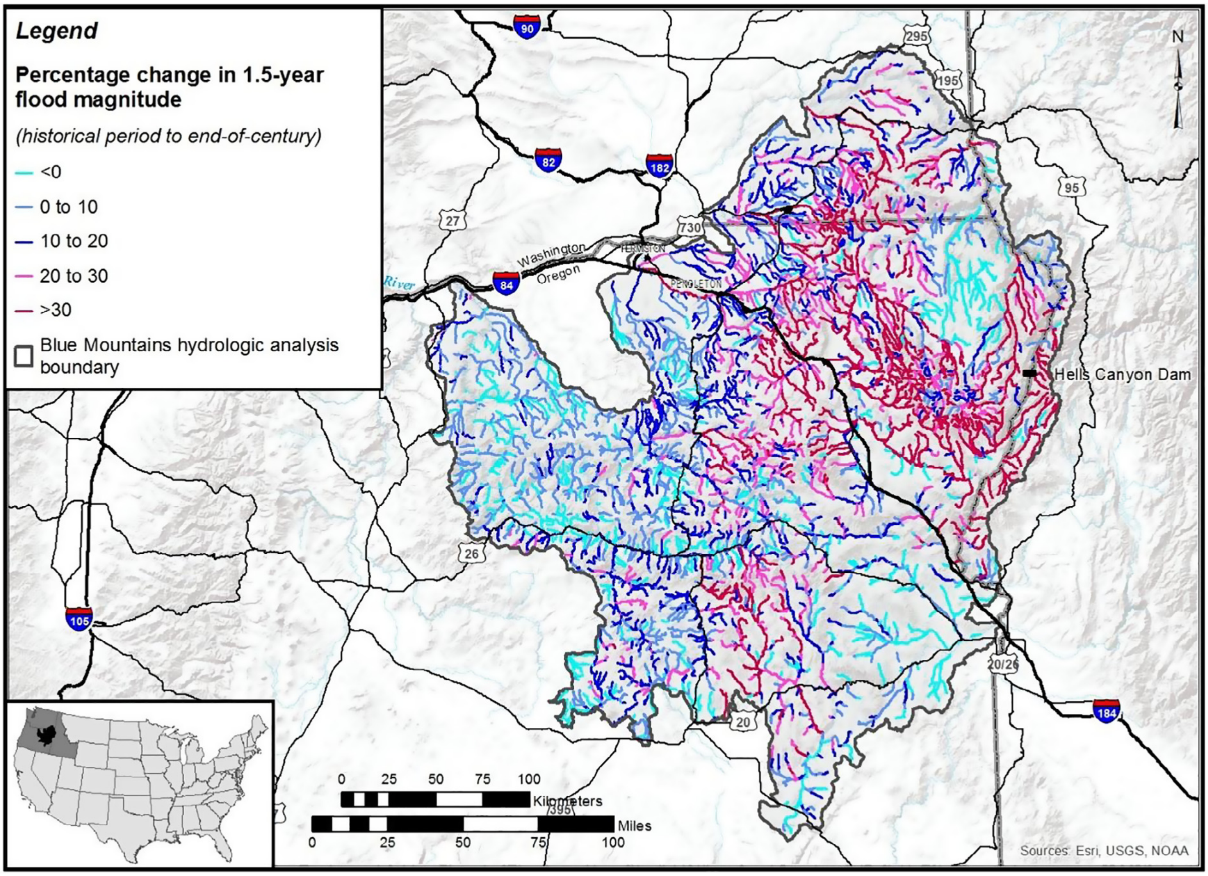


Fig. 3. Projected change in the 1.5-year flood magnitude between the historical period (1970–1999) and the 2080s for the Blue Mountains region.

flows, 9% for wildlife, 5% for irrigation, and 3% for domestic use (320 points of diversion) (Gecy, 2014). Instream flows account for 75% of water rights by volume. Six larger towns rely directly on the national forests for water supply, and 20 small communities rely on surface water or groundwater from the Blue Mountains for drinking water. Water is critical for livestock in national forests and surrounding lands, with grazing occurring in 80% of sub-watersheds in the Blue Mountains.

Water in national forest basins is fully allocated in summer, and although it is typically available for campgrounds, administrative sites, and other uses (e.g., livestock and wildlife), water may be limited in dry years. Dams and stream diversions affect local hydrology and in some cases ecological functions (Dwire et al., 2018). It is uncertain how long-term warming or short-term droughts will affect permitted water use, although significant changes in water use on the National Forests during the next decade are unlikely.

As discussed above, warming temperatures will lead to decreased snowpack and earlier snowmelt, altering streamflow patterns and decreasing water availability in summer. Most precipitation in the Blue Mountains falls during winter when consumptive demand is low. Rain is infrequent, and streams depend on groundwater to maintain flows in summer. Because water supply in summer is limited, climate change may make it difficult to meet current demands during extreme drought years and following consecutive drought years, especially after the mid 21st century. Current conflict over water use in the Blue Mountains region is not a prominent issue, although future water shortages caused by declines in dry season flows may create social and political tension if different sectors (e.g., agriculture and municipal) compete for water.

Declining summer flows caused by reduced snowpack accumulation and earlier snowmelt in the Blue Mountains could affect water availability during peak summer demand. Diversions from streams draining high elevation areas may show the greatest changes (Fig. 6) even though the snowpacks there are the most resilient. Summer flows are so dependent on snow inputs in mid-summer that the declines in snowpack will be felt most strongly there. In contrast, basins with little snow in summer already are less likely to be affected by large snowpack declines. The Burnt, Powder, Upper Grande Ronde, Silver, Silvies, Upper John Day, Wallowa, and Willow sub-basins (Fig. 1) are at highest risk for summer water shortage associated with low streamflow. Widespread diversions increase water extraction across the landscape, with aging (leaky) infrastructure contributing to water loss.

Water availability is an important attribute of the Watershed Condition Framework (WCF) classification system used to rate watershed condition in national forests (Potyondy and Geier, 2011). Most sub-watersheds in the Blue Mountains are rated as "functioning" or "functioning at risk," based on flow alterations from diversions, withdrawals, and dams relative to natural flows and groundwater storage. The Burnt, Powder, Upper Grande Ronde, and Wallowa sub-basins have the most sub-watersheds with "impaired function" for water quantity. The highest off-forest consumptive uses are in the Burnt, Malheur, Powder, Silver Creek, Silvies, Umatilla, and Walla Walla basis (Gecy, 2014), most of which are expected to have moderate to high changes in summer flows (Fig. 6).

4. Consequences of hydrologic changes for roads, infrastructure, and access

Roads, trails, bridges, and other infrastructure in the Blue Mountains have historically provided access for land managers, mineral prospectors, loggers, hunters, and recreationists. The U.S. Forest Service is mandated to provide multiple resources across this landscape, and access to water resources, timber and range resources, wildlife, and enjoyment by the public has largely determined where these activities occur. Sustainable management of access promotes use, stewardship,

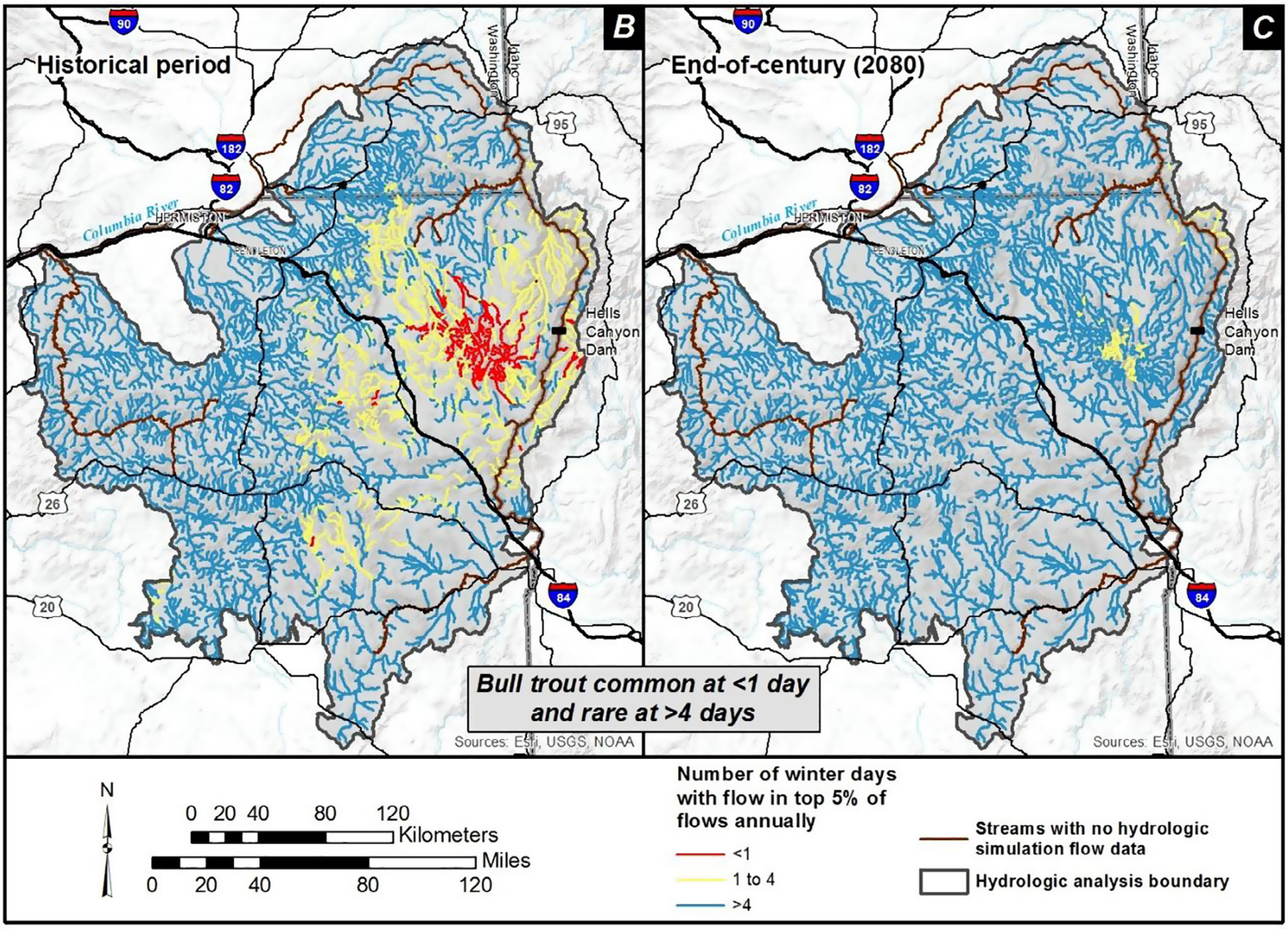


Fig. 4. The average number of winter days each year that are in the top 5% (18 days) for that year based on flow. This addresses whether high flow events typically occur in winter (December-March), when fall spawning fish have eggs in the gravel, or in other months. Values are displayed the historical period (1970–1999) (left) and projected for 2080 (right).

and appreciation of public lands for their social and economic values (Louter, 2006).

The three national forests assessed here, the Malheur, Umatilla, and Wallow-Whitman National Forests, contain 37,500 km of roads: 800 km paved, 17,800 km gravel, and 18,900 km native-surface (Table 1). Road density is highest at low elevations and near mountain passes. Roads and trails cross many streams, with 96% of crossings being culverts installed decades ago. Some crossings are being replaced, but many have not been inventoried and conditions are unknown. Older roads are more likely to be near streams, thus increasing risks for damage to roads and aquatic resources.

Although the need for roads for timber harvest has decreased greatly in the past 20 years, demand for roads for recreational activities has increased. Hiking and camping are the most popular warm-weather activities, with greater than 60% of trips to national forests lasting 6 h or less (USFS, 2010), thus concentrating human impacts on areas that are easily accessible. Demand is increasing for trail use by mountain bikes, off-highway vehicles, and winter recreation.

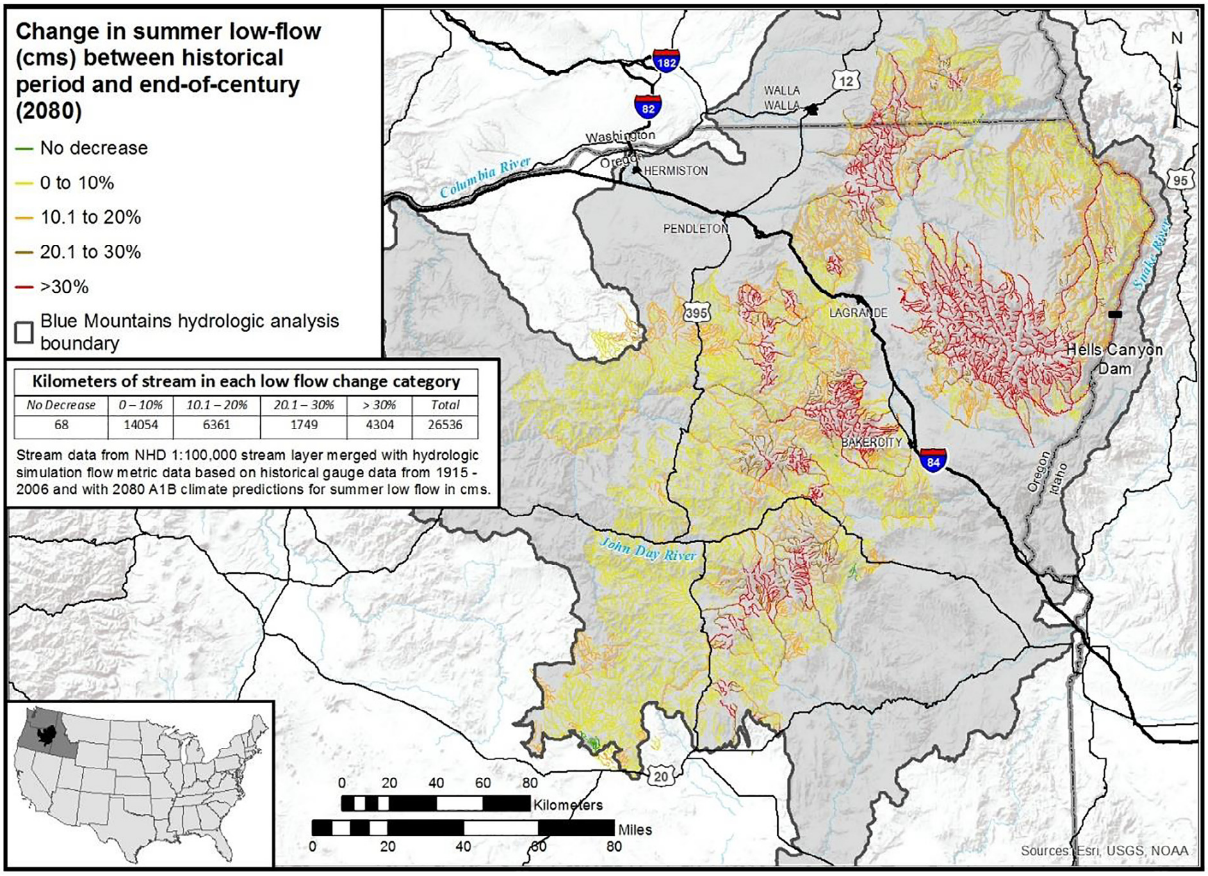
4.1. Road management

The condition of roads and trails in the Blue Mountains is a function of their age, design, maintenance practices, and location. Culverts were typically designed to withstand a 25-year flood. Road construction has declined since the 1990s, with few new roads being added. Roads accelerate runoff rates and decrease late-season flows, increase peak flows, and increase erosion rates (e.g. Wigmosta and Perkins, 2001; Lamarche and Lettenmaier, 2001; Bowling, 2001; Wemple and Jones, 2003). Impacts are greater for roads near streams, although roads in uplands also affect surface and subsurface flows and erosion (Luce, 2002; Trombulak and Frissell, 2000).

National forest engineering staff are charged with operating a sustainable transportation system that is safe, responsive to public needs, and causes minimal environmental impact. Potential management actions include reducing road maintenance levels (e.g. Luce and Black, 2001), storm-proofing roads, upgrading drainage structures and stream crossings, reconstructing and upgrading roads, decommissioning roads, and converting roads to alternative modes of transportation. Activities that are critical to health and safety receive priority in decisions about which roads to repair and maintain, balanced with consideration for access and aquatic habitat (Luce et al., 2001; Trombulak and Frissell, 2000).

The Malheur, Umatilla, and Wallow-Whitman National Forests are currently identifying a sustainable road network that is ecologically and fiscally sustainable in accordance with the 2001 Road Management Rule (36 CFR 212, 261, 295). Their transportation analysis assesses the condition of existing roads, including options for removing damaged or unnecessary roads, and maintaining and improving necessary roads. This process increases the agency's ability to acquire funding for road improvement and decommissioning, provides a framework for annual maintenance costs, facilitates agreement with regulatory agencies, and increases financial sustainability.

Reconstruction and decommissioning of roads and trails require an environmental assessment and public involvement. The Water and



Kilometers of stream in each low flow change category

No Decrease	0 – 10%	10.1 – 20%	20.1 – 30%	> 30%	Total
68	14054	6361	1749	4304	26536

Stream data from NHD 1:100,000 stream layer merged with hydrologic simulation flow metric data based on historical gauge data from 1915 - 2006 and with 2080 A1B climate predictions for summer low flow in cms.

Fig. 5. Projected change in mean summer streamflow from the historic time period (1970–1999) to the 2080s for streams in the Blue Mountains region. Projections created by modifying standard VIC projections (following Wenger et al., 2010) routed through a linear groundwater reservoir model, using calibrated recession parameters for each watershed from Safeeq et al. (2014).

Erosion Predictive model (Flanagan and Nearing, 1995), Geomorphic Road Analysis and Inventory Package (GRAIP) (Black et al., 2012; Cissel et al., 2012), and NetMap (Benda et al., 2007) are often used to identify hydrologic impacts and guide management on projects. For example, the Wall Creek watershed GRAIP analysis in the Umatilla National Forest determined that 12% of the road system contributed 90% of the sediment, providing the information needed to prioritize critical sites (Nelson et al., 2010).

4.2. Climate change effects on transportation systems

Climate and hydrology will influence the transportation system in the Blue Mountains through reduced snowpack, resulting in a longer season of road use, higher peak flows and flood risk (Fig. 7), and increased landslide risk (Strauch et al., 2014). Increased wildfire disturbance (Kerns et al., 2018) plus higher peak flows may contribute to increased erosion and landslides (Goode et al., 2012). Direct (physical) effects of climate change occur from floods, snow, landslides, extreme temperatures, and wind, whereas indirect effects include secondary influences on access related to public safety and visitor use patterns. Effects on roads will be related to weather events (e.g., a single storm), but the risks of such events are a characteristic of the climate. An increase in the size of rare events will have major effects on hydrologic systems and may require changes of current design standards for infrastructure.

In the highly dissected northern Blue Mountains, more intense winter storms and more rain-on-snow events (Salathé et al., 2014) may cause shallow debris slides to become more frequent, potentially damaging infrastructure and reducing access. In addition, reduced snowpack is expected to increase antecedent soil moisture in winter (Hamlet et al., 2013).

Vulnerability of roads to erosion and mass wasting (e.g. landslides and gullies) processes varies depending on topography, geology, slope stability, age, design, location, and use (Luce and Wemple, 2001; Wemple et al., 2001). Roads and trails built decades ago have often deteriorated, and many infrastructure components are near the end of their design lifespan. Culverts were typically designed to last 25–75 years, and if they are beyond their design life, rust and wear make them less resilient to high flows and bed load movement and more susceptible to structural and piping failure. Even storms of low to moderate intensity can damage roads and trails that are already compromised. Roads and trails built on steep slopes are particularly vulnerable to erosion and mass failures. The road network built to facilitate past timber harvesting has contributed to the sensitivity of roads and other infrastructure by increasing storm runoff and peak flows (Schmidt et al., 2001; Croke and Hairsine, 2006). Roads and trails in valley bottoms are built on gentle grades, but proximity to streams increases sensitivity to flooding, channel migration, and bank erosion. Most road-stream crossings use culverts rather than bridges, and culverts are more sensitive to high streamflows and debris movement. Highways in the Blue Mountains, with higher design and maintenance standards, will be less vulnerable to climate change than unpaved roads in national forests. Currently, budgets are often insufficient to maintain and repair infrastructure, thus increasing the susceptibility of the transportation system.

New or replaced infrastructure could increase resilience to climate change because materials and standards have improved in recent years. For example, new culverts and bridges are often wider than the original structures, and open-bottomed, arched culverts are now often used in the Blue Mountains to improve fish passage and stream function.

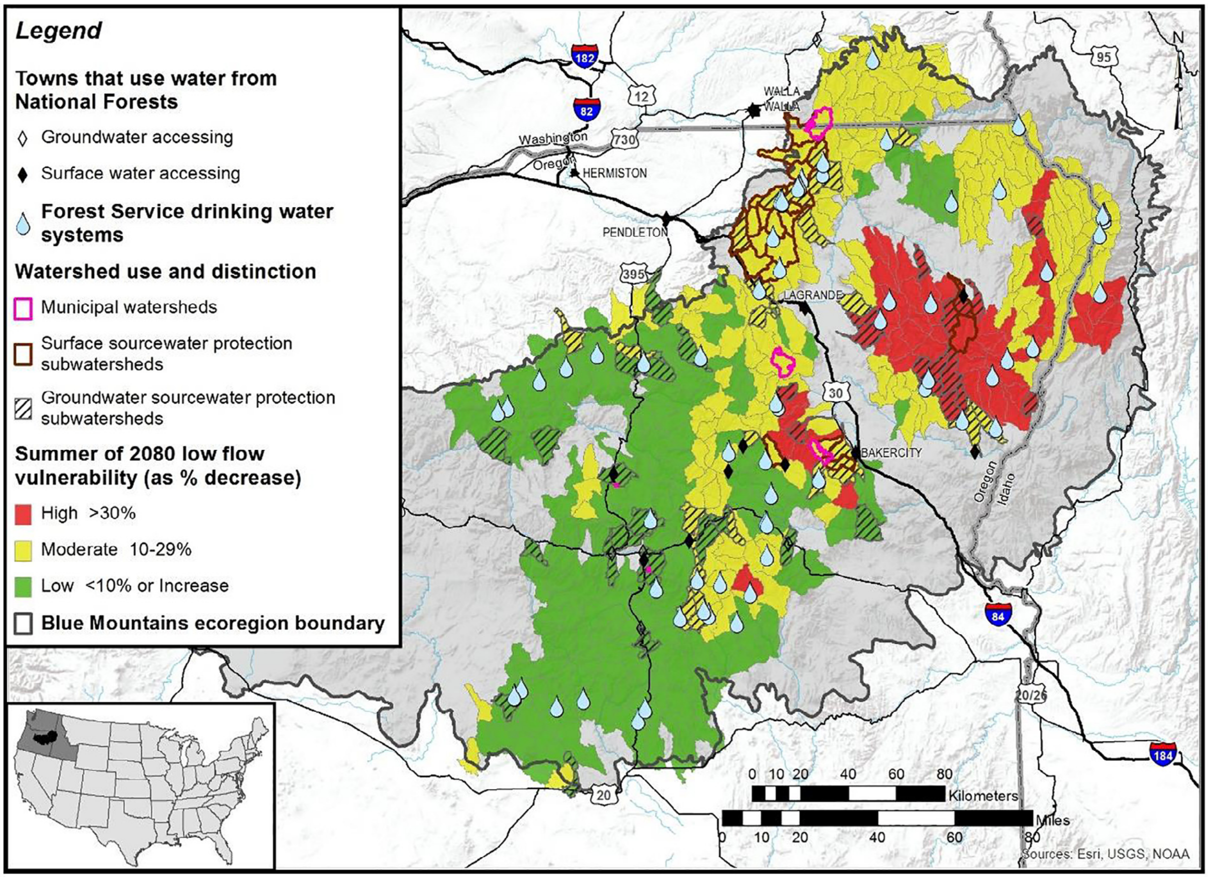


Fig. 6. Projected risk of summer water shortage in the Blue Mountains region, based on low streamflows for 2080s. The data in Fig. 5 were used to calculate differences averaged over each watershed.

Table 1
Kilometers of road by maintenance level in national forests in the Blue Mountains.

Operational maintenance levels	National forests		
	Malheur	Umatilla	Wallowa-Whitman
	Kilometers		
Basic custodial care (closed)	6059	3543	7216
High-clearance cars/trucks	8814	3131	6719
Suitable for passenger cars	587	545	435
Passenger car (moderate comfort)	0	114	29
Passenger car (high comfort)	0	132	210
All roads	15,460	7465	14,609

Natural channel design, which mimics upstream and downstream conditions, is often used at stream crossings, and helps pass larger pieces of wood.

4.3. Short-term climate change effects on other infrastructure and access

In the short-term changes in runoff and geomorphology will directly challenge the road network integrity. Higher peak flows in winter increase the potential impacts of flooding roads, trails, campgrounds, and structures (Walker et al., 2011; MacArthur et al., 2012). Increased risk of landslides in some areas will contribute to flooding by diverting water, blocking drainage, and filling channels with debris (Crozier, 1986; Chatwin et al., 1994; Schuster and Highland, 2003).

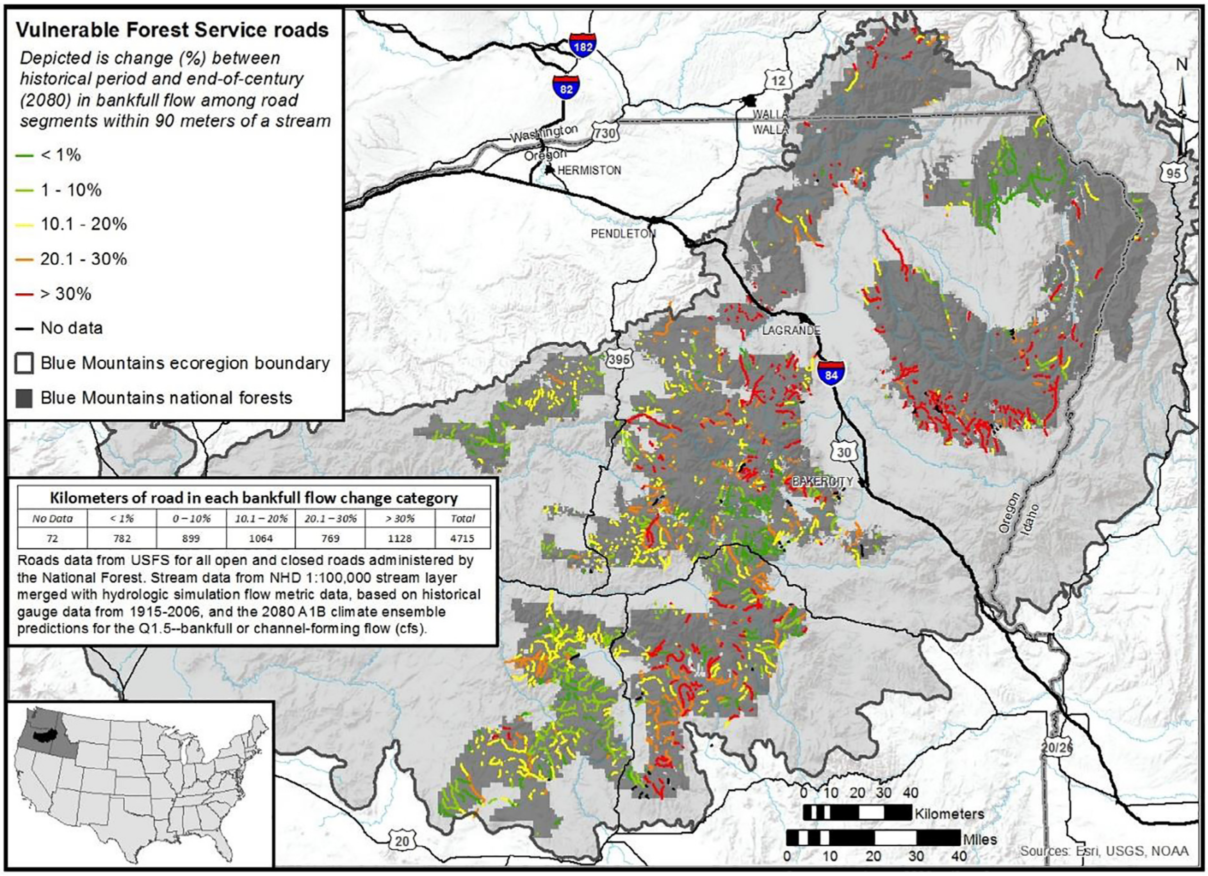
In addition, altered hydrologic regimes in the Blue Mountains may contribute to safety hazards. Damaged roads reduce access for responding to emergencies, and higher streamflows could create hazardous conditions for river recreation and campers. More wildfires (Kerns et al., 2018) would further restrict emergency access by increasing downed logs and road damage, reducing agency capacity to respond to additional fires and to emergency needs in local communities (Strauch et al., 2014).

4.4. Medium and long-term effects on access

As change progresses, runoff and geomorphic impacts could become more severe and widespread, and accumulated minor impacts will exacerbate the outcomes. More frequent flooding will continue to increase sediment and debris transport, damaging stream-crossing structures. Shifting channel dynamics caused by increased flow and sediment may compound problems, even if crossing structures are upgraded to accommodate higher flows. Repeated landslides can cause aggradation in streams, thus elevating future flood potential, and culverts blocked with debris can cause flooding and associated damage to roads, trails, and campgrounds (Halofsky et al., 2011).

In the long term, higher winter soil moisture may increase the risk of landslides in autumn and winter, especially in areas that have experienced high-severity wildfire and insect outbreaks (Montgomery et al., 2000; Schmidt et al., 2001; Istanbulluoglu et al., 2004). Although floods and landslides will continue to be more common in areas with known susceptibility (e.g., high density roads, steep slopes), they may also occur in higher elevation locations currently covered by snowpack for much of the year (MacArthur et al., 2012).

A longer snow-free season will extend visitor use in spring and autumn, especially at higher elevations (Rice et al., 2012). Trailheads at lower elevations may be accessible earlier, but hazards associated with snow bridges and avalanche chutes may persist along trails. River rafters may encounter unfavorable conditions from lower streamflows in



Kilometers of road in each bankfull flow change category						
No Data	*< 1%*	*0 – 10%*	*10.1 – 20%*	*20.1 – 30%*	*> 30%*	*Total*
72	782	899	1064	769	1128	4715

Roads data from USFS for all open and closed roads administered by the National Forest. Stream data from NHD 1:100,000 stream layer merged with hydrologic simulation flow metric data, based on historical gauge data from 1915-2006, and the 2080 A1B climate ensemble predictions for the Q1.5--bankfull or channel-forming flow (cfs).

Fig. 7. Projected change in bankfull flow for roads within 90 m of a stream for the 2080s. The Variable Infiltration Capacity model was used to calculate differences in Q1.5-bankfull flow between historic data (1915–2006) and the 2080s. Not all vulnerable roads are represented; some roads intersect smaller intermittent streams.

late summer (Mickelson, 2009), as well as hazards associated with deposited sediment and woody debris from high winter flows. Warmer winters may shift river recreation to times of the year when risks of extreme weather and flooding are higher.

Some benefits to access and transportation in the Blue Mountains may accrue from the effects of climate change. Lower snow cover will reduce the cost of snow removal from roads, and allow earlier access for snow removal and maintenance in low-mid elevation areas and a longer construction season at higher elevations (e.g., installation of temporary trail bridges). As noted above, less snow may increase access for warm-weather recreation, but may reduce opportunities for winter recreation (Joyce et al., 2001; Morris and Walls, 2009). The highest elevations of the Blue Mountains are expected to retain a significant amount of snow, at least for the next few decades, which may focus snow-based activities in fewer areas as snow at lower elevations decreases.

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