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Watershed Climate Change Vulnerability Assessment
Lolo National Forest

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Northern Region (R1) & Lolo National Forest

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Watershed Climate Change Vulnerability Assessment
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This report builds on the excellent previous vulnerability work conducted by: R1 (Gallatin and Helena); R2 (Grand Mesa, Uncompahgre, Gunnison, and White); R3 (Coconino); R4 (Sawtooth); R5 (Shasta-Trinity); R6 (Umatilla); R8 (Ouachita); R9 (Chequamegon-Nicolet), and R10 (Chugach) National Forests. These pilots were compiled with additional insights by Furniss and others (2013). We also thank D. Isaak, RMRS; S. Wenger, University of Georgia; and D. Nagel, RMRS for their generous help with data interpretation and development.

A NOTE ABOUT TABLES AND FIGURES

All tables and figures with alphanumeric designations (e.g., Table F.1) can be found within the body of this report. The letter represents the first letter of the report section name (e.g., F=Findings). All tables and figures designated with a only a number (e.g., Table 1, Figure 1) are not included in the body of this report, but are listed in Appendix 1 and 2, respectively. The tables and figures themselves can be found in the supplementary materials on the accompanying CD or on-line at http://www.fs.usda.gov/main/lolo/workingtogether.

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ES. EXECUTIVE SUMMARY

INTRODUCTION

Climate change is complicating the ability of the nation's forests to "sustain the health and productivity" of forestlands (USFS mission) and secure "favorable conditions of water flows" (Organic Act of 1897) in the nation's headwaters. A recent report by the U.S. Government Accountability Office (GAO) noted that federal lands are at risk from a wide range of potential climatic impacts, and that the agency will face multiple challenges in responding (USGAO 2007). Challenges include the need for the US Forest Service (USFS) to shift from focusing on historic conditions to anticipating and managing for an uncertain future and the need for more specific guidance on climate adaptation actions.

With over 2 million acres of varied landscape providing diverse vegetation, wildlife habitat, water resources, and recreational opportunities, LNF seeks to proactively understand potential impacts from climate change to better manage its outstanding natural resources and maintain maximum ecosystem resiliency.

The LNF is part of the Columbia River Basin, where minimum air temperatures have increased by 1°C (~2°F) and maximum temperatures have increased by 1.3°C (~2.3°F) during the period 1970-2006 (Littell et al. 2010). During the same period, precipitation has shown indications of decline (Littell et al. 2010). Although the future is uncertain, reasonable scenarios of climate change suggest average annual air temperatures will increase by 1.8°C (3.2°F) by the decade of the 2040s and 3.0°C (5.3°F) by the 2080s (relative to a baseline of 1970-1999 average temperatures) (CIG 2008). These projections suggest average annual temperature will exceed the range of the 20th century variability. Average annual precipitation is not likely to exceed the range of variability of the previous century, though seasonal patterns in precipitation may shift (CIG 2008).

One of the clearest signals from climate and streamflow models is that seasonal shifts in precipitation and increased temperature will likely result in lower summer flows and, in lower elevation streams, earlier and potentially higher and more frequent peak flows (Mantua et al. 2010; Wu et al. 2012). Earlier streamflow timing has already been recorded across western North America (Stewart et al. 2005; Regonda et al. 2005). By the 2040s, spring snow water equivalent is projected to decline by 22-35% in the Columbia Basin (Littell et al. 2010).

These changes present both challenges and opportunities for forest managers. Managing for climate change will be inherently uncertain and will require a shift in thinking because managers cannot assume persistence of existing conditions, but must plan for inevitable ecological change (Stein et al. 2013). Essentially, managing for climatic change is managing for resilient ecosystems and infrastructure. To help managers prioritize actions for improving or maintaining resiliency, the goal of this assessment is to determine the relative vulnerability of three forest resources that are likely to be strongly affected by climate change: aquatics (bull trout), water supply, and infrastructure (recreation areas, trails, and roads). We also include discussion of preliminary vulnerability considerations for the western pearlshell mussel (*Margaritifera falcate*). This assessment seeks to understand the magnitude of potential climate change effects to these resource values and to proactively inform *where* resources are relatively more vulnerable and to investigate *why* they are likely to be vulnerable, thereby providing additional insight toward initial prioritization of watersheds for special management consideration.

Approach

The Intergovernmental Panel on Climate Change (IPCC) defines vulnerability as "the degree to which a system is susceptible to or unable to cope with, adverse effects of climate change" (IPCC 2007). Thus, *vulnerability* is a function of *exposure* (the magnitude or probability of physical changes in climate conditions), *sensitivity* (the likelihood of adverse effects to an organism or system given climate changes and potential interacting non-climate stressors), and *adaptive capacity* (the intrinsic ability for an organism or system to reduce its sensitivity by successful response to changing climate [e.g., plastic or evolutionary responses, range shifts]) (IPCC 2007) (Figure ES.1). Ultimately, the goal of a vulnerability assessment is to identify potential future impacts from climatic change and to identify vulnerable areas to provide a solid foundation for climatic change adaptation management and planning (Glick et al. 2011). *Adaptation* refers to conservation or management actions that reduce vulnerability. Here, we focus on actions that can be effected by local managers to reduce exposure (e.g., riparian shading to buffer stream warming) or sensitivity (e.g., removing culvert barriers so bull trout have access to colder waters, improving and protecting critical aquatic habitat, or monitoring water diversions to ensure sufficient water supply). We do not discuss *mitigation* as a form of adaptation, which in climate circles refers to efforts to reduce carbon emissions.

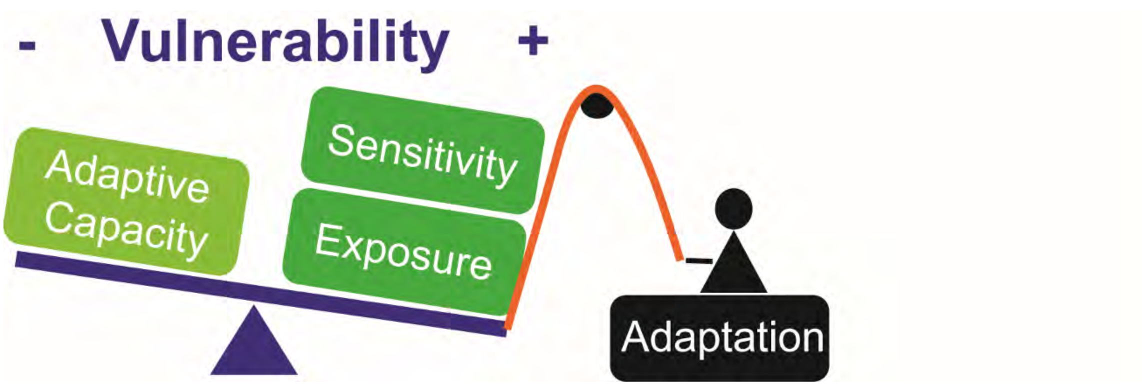

Figure ES.1. *Vulnerability is a function of climate exposure and sensitivity. Adaptive capacity (a system's intrinsic ability to reduce its sensitivity) can reduce vulnerability, although we do not address it here. The goal of the vulnerability assessment is to plan for adaptation management actions to reduce vulnerability, primarily through reducing sensitivity to climate change.*

To address vulnerability, we calculated and combined measures of climate exposure and resource sensitivity believed to be reasonable proxies for assessing the magnitude of potential climatic changes and the sensitivity of these resources to those changes. We calculated climate exposure as the degree to which stream temperature and flow are projected to change from baseline conditions (modeled average conditions for 1993-2011) under a “middle-of-the-road” scenario of carbon emissions for the period of the 2040s (2030-2059) and for the 2080s (2070-2099) for comparison. The indices we used to quantify sensitivity are proxies for intrinsic and extrinsic stressors to the resources that may increase their sensitivity to climate change. For the final vulnerability assessment, we combined all sensitivity indices into an inclusive sensitivity value and compared this against a combined exposure value for the 2040s. We did not assess 2080 vulnerability because of the significant uncertainty associated with that distant future. However, one can consider the 2080s maps as a “high” exposure scenario as compared to the 2040s, which can be considered a “moderate” mid-century exposure scenario.

The goal of this approach was to optimize trade-offs between practicality, transparency, comprehensiveness, and ecological relevance (for the aquatic species). We offer these scenarios as a general and reasonable framework to help facilitate informed management decisions. Addressing specific indicators at local scales will likely require further investigation and perhaps more time to understand and witness true ecosystem response.

Methods Overview

For assessment of water resources and infrastructure, our study area incorporated all lands in the LNF and intervening non-Forest Service lands, for a total study area of 5,135 mi^2 (13,300 km^2) (Figure ES.2). Because there are adjoining areas of critical importance to bull trout (bull trout populations do not stop at inter-forest boundaries), we used a larger study area boundary (6,429 mi^2; 16,650 km^2) for that analysis. Study areas were defined following the boundaries of 6^{th} level hydrological unit codes (HUC 12).

For each resource value (aquatic species, water supply and infrastructure), we created a conceptual model linking exposure and sensitivity to the quantification of vulnerability (see general schematic in Figure ES.3). For each *resource area* and *resource value*, we listed the resource *needs* that describe conditions necessary for maintaining the resource value. Resource needs in blue boxes are affected by climate (*exposure*) and those in green boxes represent other stressors that increase a resources’ *sensitivity* to climate change. The *analytical unit* for exposure and sensitivity was also shown in the conceptual model. We measured exposure using various types of habitat configurations (contiguous suitable habitat, or “patch”) for aquatic species and HUC-12s for water supply and infrastructure.

For climate exposure stressors, we calculated metrics using modeled future scenarios of climate change impacts on stream temperature and flow. Sensitivity metrics were assumed to be temporally static; a necessary assumption given the inability to project changes in those stressors. We then calculated combined exposure and sensitivity *indices* by taking the geometric mean of all exposure and sensitivity metrics, respectively.

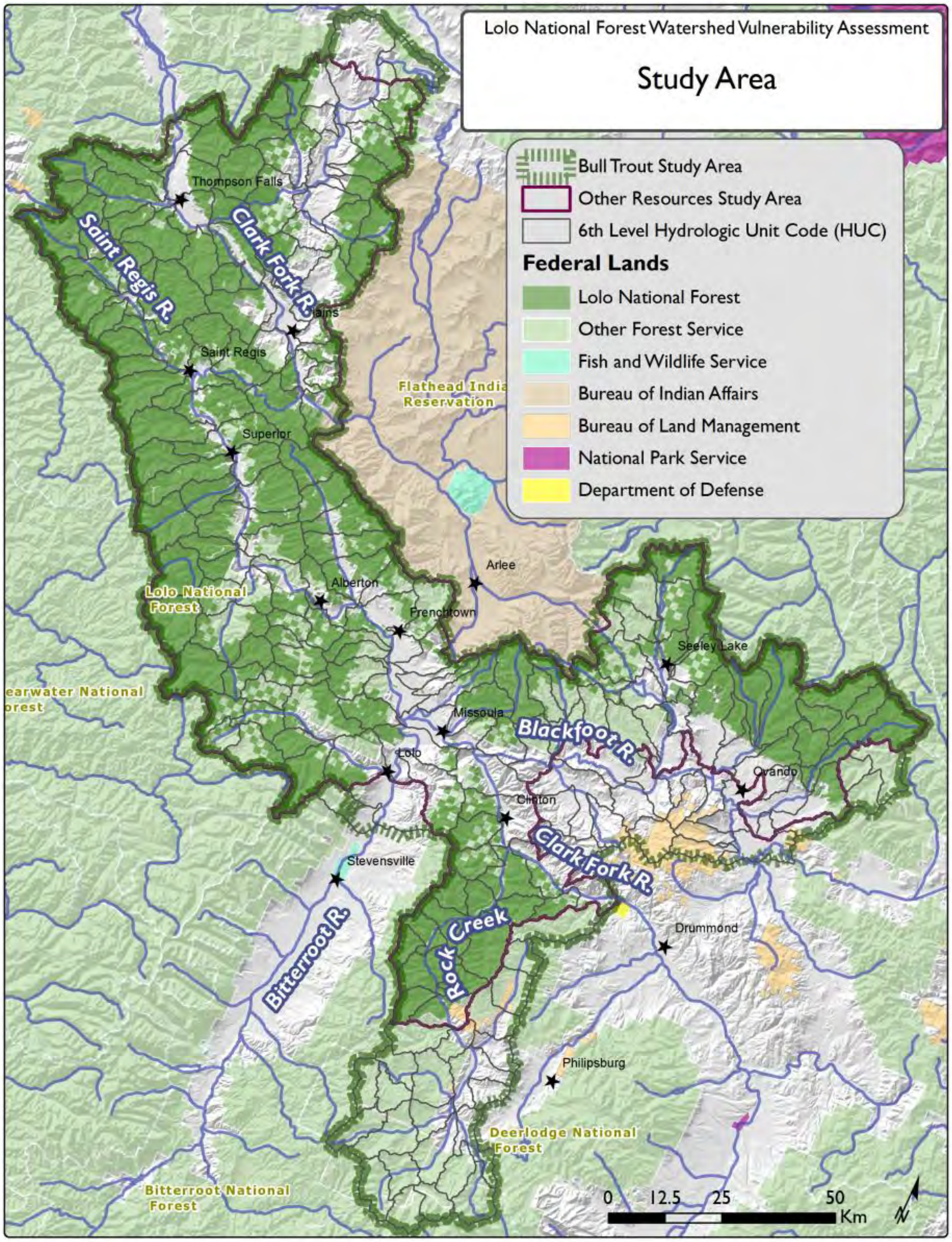

Figure ES.2. *Study area for the Lolo National Forest (LNF) Watershed Vulnerability Assessment. For the bull trout analysis, the study area incorporated all of the LNF lands and neighboring watersheds of particular interest for bull trout. For other resource areas and values, we only considered watersheds covering LNF and intervening private lands.*

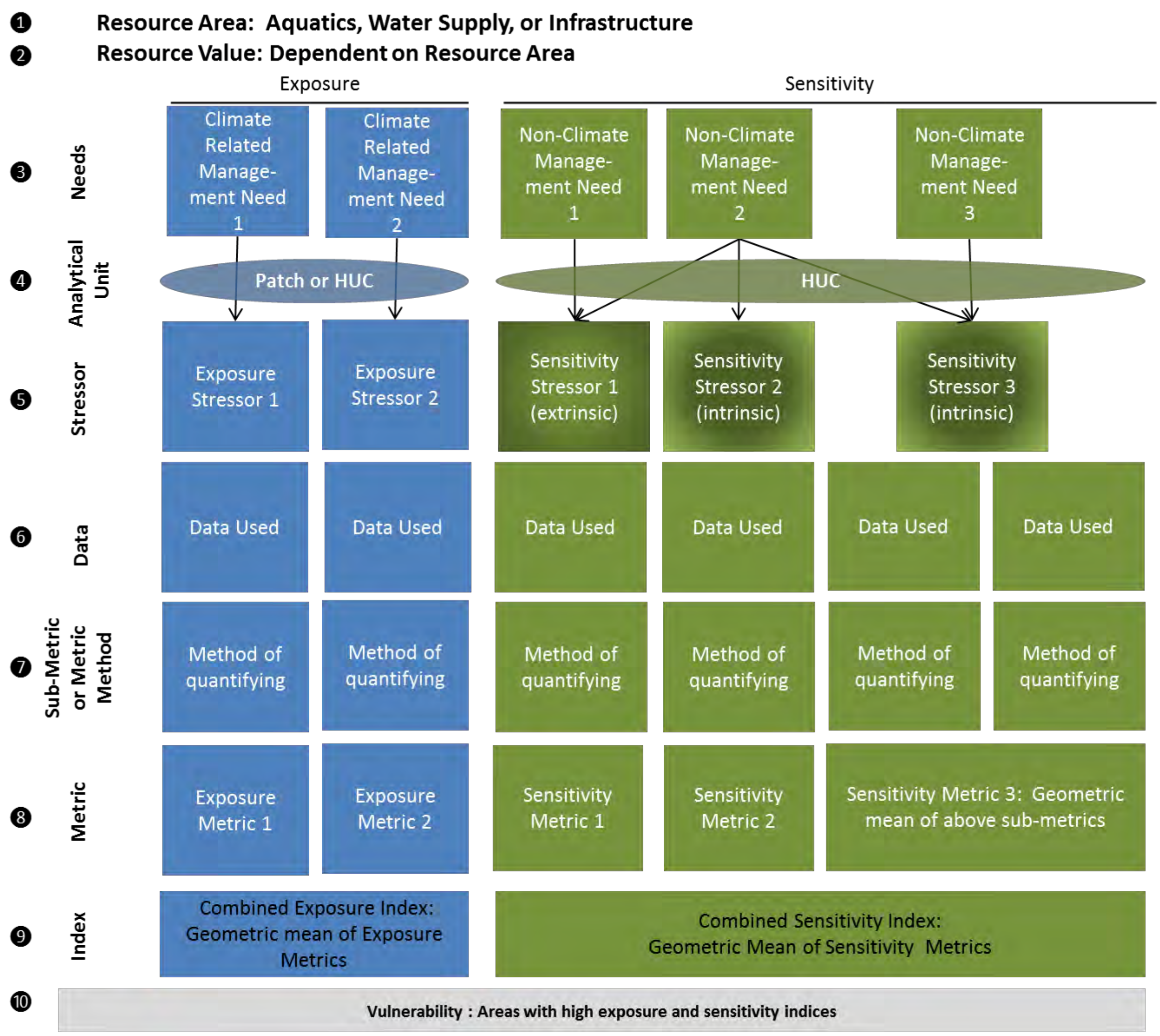

Figure ES.3. *Schematic of conceptual models used to link resource needs to each metric calculated in this analysis for each resource value analyzed.*

Finally, we mapped relative vulnerability for each resource by comparing exposure and sensitivity indices, which we placed into "clusters" (1-5) by minimizing within-group and maximizing between-group variations (based on the algorithm by Jenks 1977). We assumed exposure index values in clusters 1 or 2 had low, cluster 3 had moderate, and clusters 4 and 5 had high exposure stress. For sensitivity, we assumed sensitivity index values in clusters 1 or 2 had low and in clusters 3, 4, or 5 had high sensitivity to exposure. Thus, we mapped vulnerability as follows:

<table>
<tr><td></td><td></td><td colspan="5">Sensitivity</td></tr>
<tr><td>cluster</td><td></td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td></tr>
<tr><td rowspan="5">Exposure</td><td>1</td><td colspan="5" rowspan="2">Low Exposure</td></tr>
<tr><td>2</td></tr>
<tr><td>3</td><td colspan="2">Moderate Exposure,
Low Sensitivity</td><td colspan="3">Moderate Exposure,
High Sensitivity</td></tr>
<tr><td>4
5</td><td colspan="2">High Exposure,
Low Sensitivity</td><td colspan="3">High Exposure,
High Sensitivity</td></tr>
</table>

Exposure and sensitivity metrics for bull trout, water supply, and infrastructure used in this analysis (see main report for detail):

Bull Trout

- Exposure
  - Reduction in thermally suitable habitat patch
  - Winter flood scour
  - Reduced summer mean flow
- Sensitivity
  - Low population size/viability
  - Low stream connectivity
  - Increased sediment
    - Road crossings
    - Parallel roads near streams
  - Low channel complexity
    - Riparian cover
    - Roads near streams (2 metrics)
    - Grazing allotments near streams
  - Water diversions
  - Low stream-floodplain connection (valley confinement)
  - Presence of brook trout

Water Supply

- Exposure
  - Reduced summer mean flow
  - Change in timing of center of flow mass
- Sensitivity
  - Water diversions

Infrastructure (Recreation sites, trails, roads)

- Exposure
  - Winter flooding
- Sensitivity
  - Location in floodplain
  - Location in area of high geologic hazard or alluvial fan
  - Culverts per mile (road infrastructure only)

All exposure analyses relied on two climate datasets, the NorWeST temperature dataset (Isaak et al. 2015a) and the Western US Stream Flow Metric dataset (Wenger et al. 2010; Wenger & Luce 2011). The NorWeST dataset provides modeled August mean stream temperature (AMT) (Figure ES.4).

We used the Western US Stream Flow Metric dataset (Wenger et al. 2010; Wenger & Luce 2011) to calculate all stream flow exposure indices. To represent high flow effects, we used the winter 95 (W95) flow metric, which represents the number of days in winter in which flows are amongst the highest 5% for the year (Figure ES.5).

To represent low flows, we used the mean summer (MS) flow metric, in units of cubic feet per second (cfs) (Figure ES.6).

To represent shifts in timing of flow regimes, we used the center of flow mass (CFM) metric, with units of day of the water year (Figure ES.7). CFM represents the day of the water year at which 50% of the year's flow has passed; also known as the center of the flow mass or the center of timing.

Findings

Results of the vulnerability assessment should be interpreted as hypotheses about relative impacts from potential climatic exposure and the potential sensitivity to that exposure. As with all initial hypotheses, they should be reassessed as additional information becomes available. The vulnerability assessment results are relative within the study area, and results are dependent on the assumptions made herein. Vulnerability maps are best viewed alongside the exposure and sensitivity maps on which they are based, and all metrics and indexes should be verified with on-the-ground knowledge for management purposes. Results presented here are for the 2040s. Detailed results are presented in tables and figures listed in Appendix 1 and 2 (including results for the 2080s), respectively, and can be found in the supplementary materials on the accompanying CD or on-line at http:/www.fs.usda.gov/main/lolo/workingtogether.

A Note about Uncertainty

There is inherent uncertainty in the findings of this analysis because:

- climate projections from global circulation models (GCMs) are inherently uncertain;
- translating GCM outputs into measures of in-stream temperature and flow requires additional models with additional assumptions leading to associated increases in uncertainty;
- this assessment relies on proxy measures that we assume relate exposure and sensitivity to actual potential impacts from climatic change;
- all spatial data are imprecise, and there are errors inherent to all data.

We have detailed the uncertainty of specific metrics in the Methods sections and in figure captions of the main report.

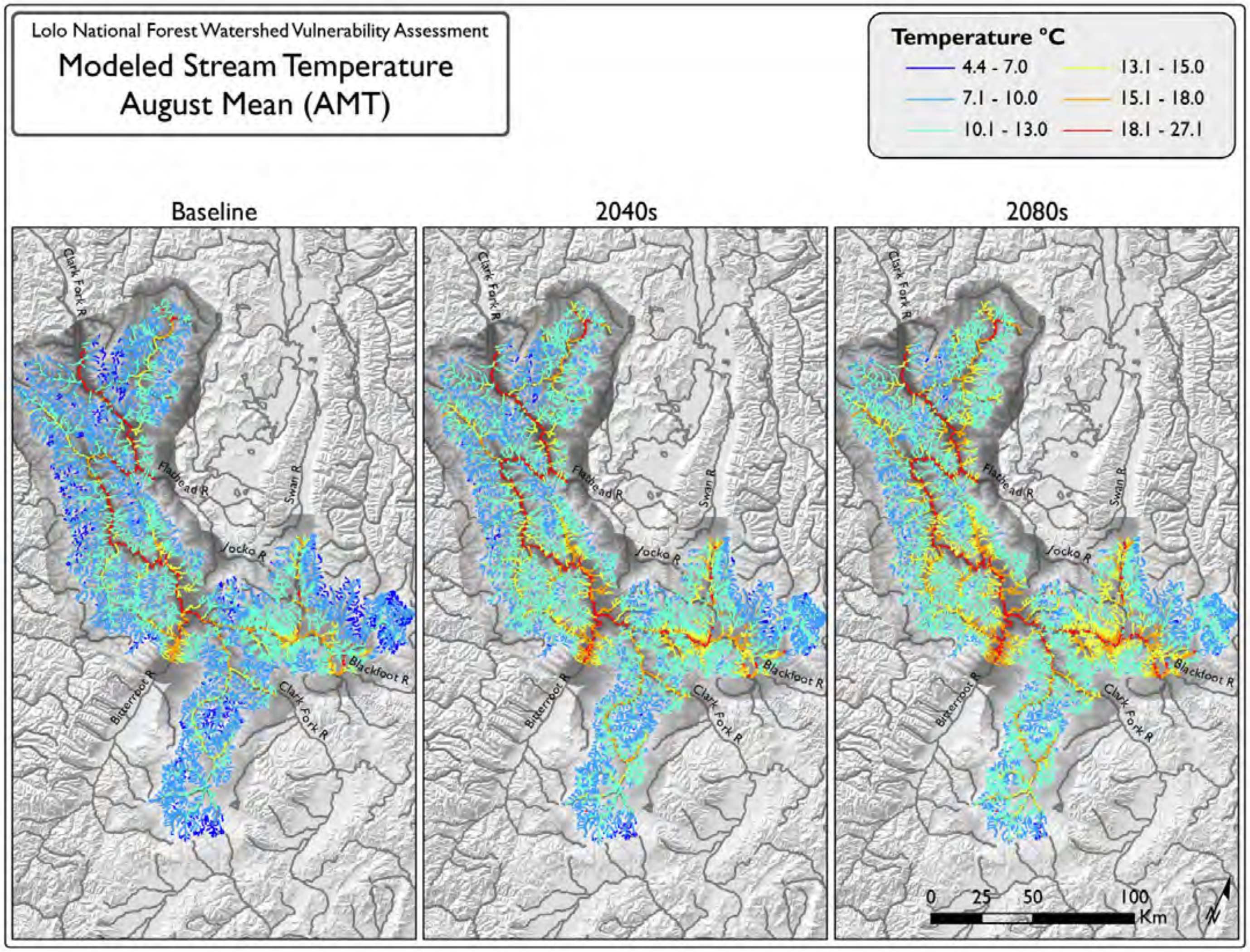

Figure ES.4. *NorWeST modeled August mean stream temperature (AMT) data for baseline (1993-2011) and for the 2040s (2030-2059) and 2080s (2070-2099).*

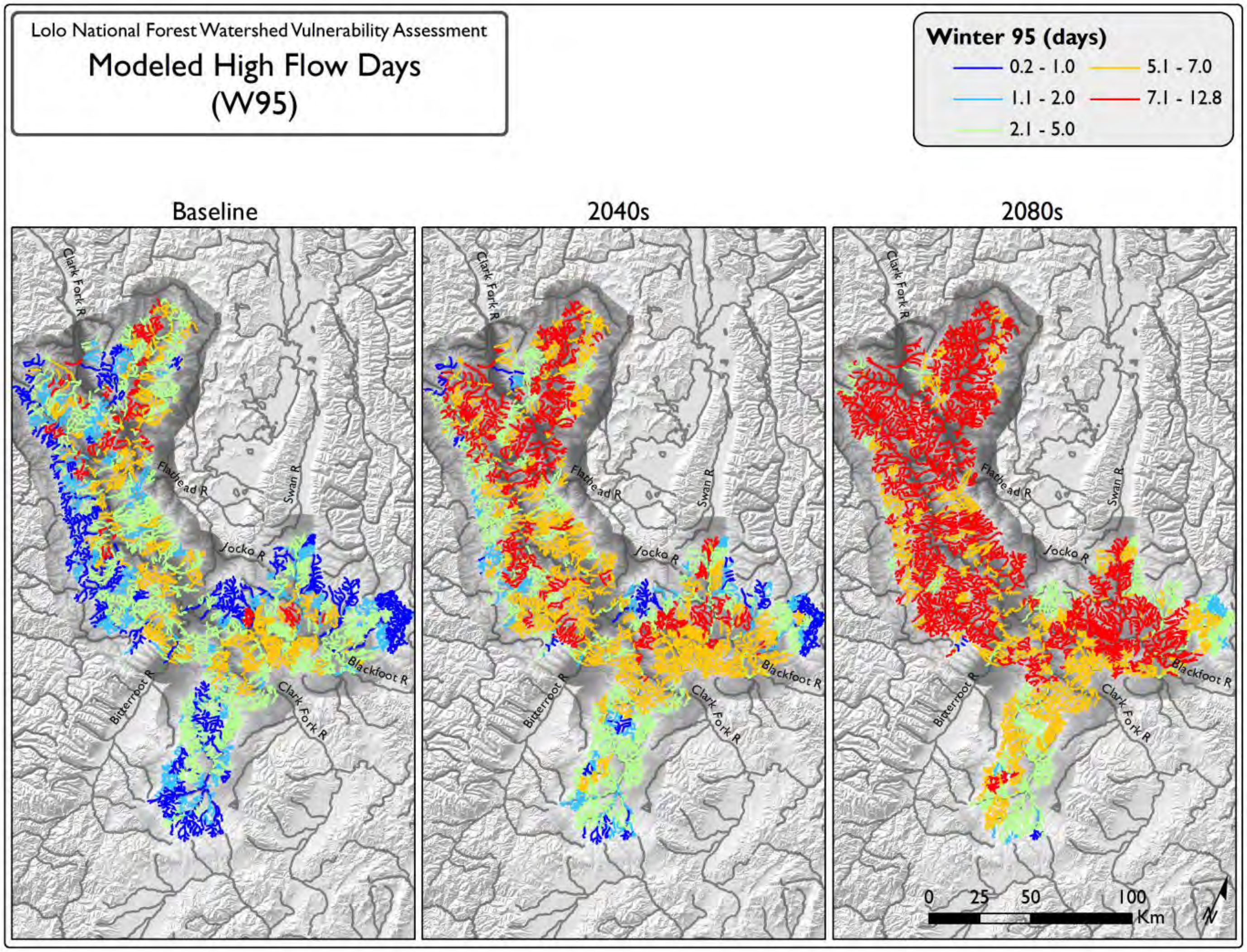

Figure ES.5. *Modeled high flow days (W95) for baseline and for the 2040s and 2080s.*

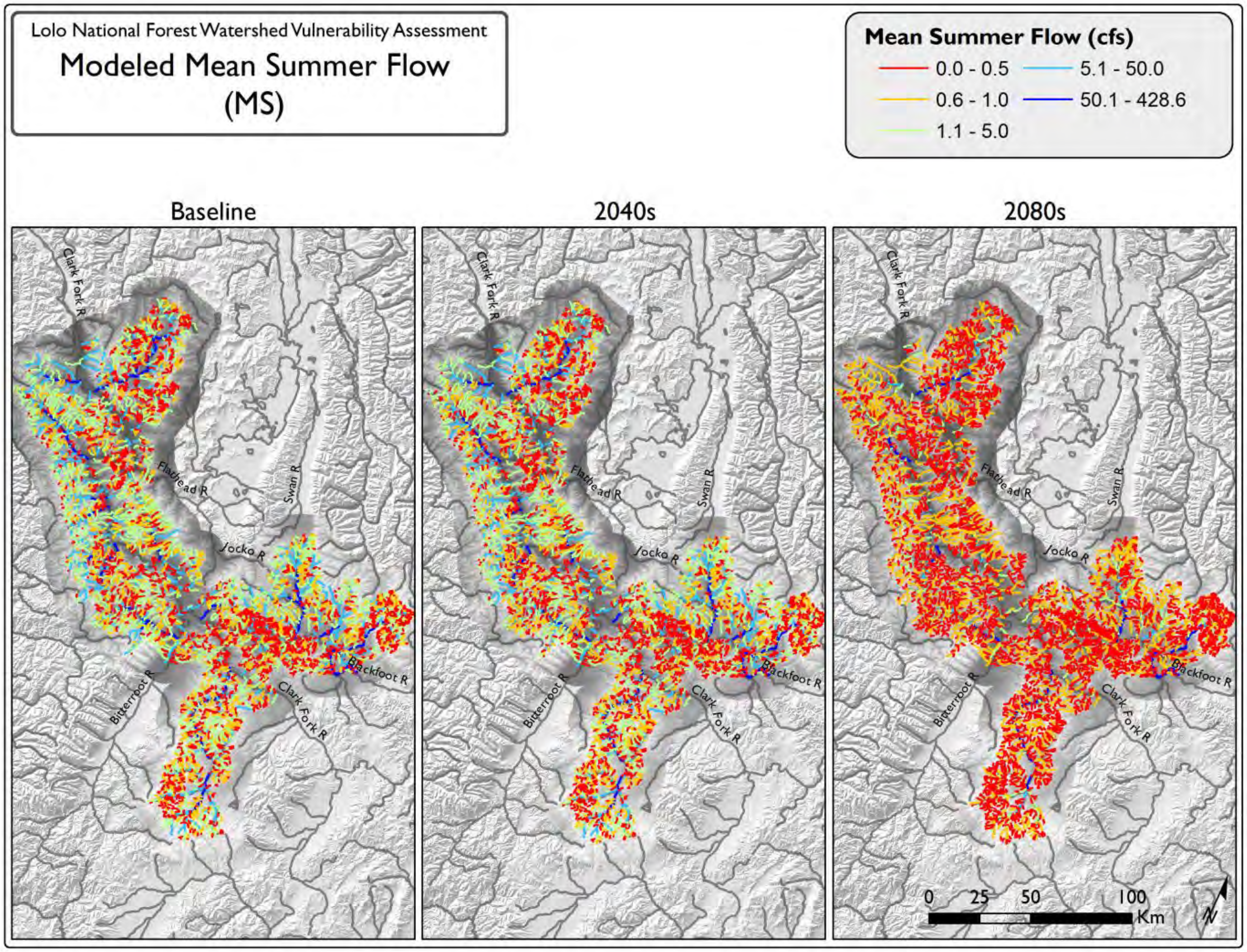

Figure ES.6. *Modeled mean summer flow (MS) for baseline and for the 2040s and 2080s.*

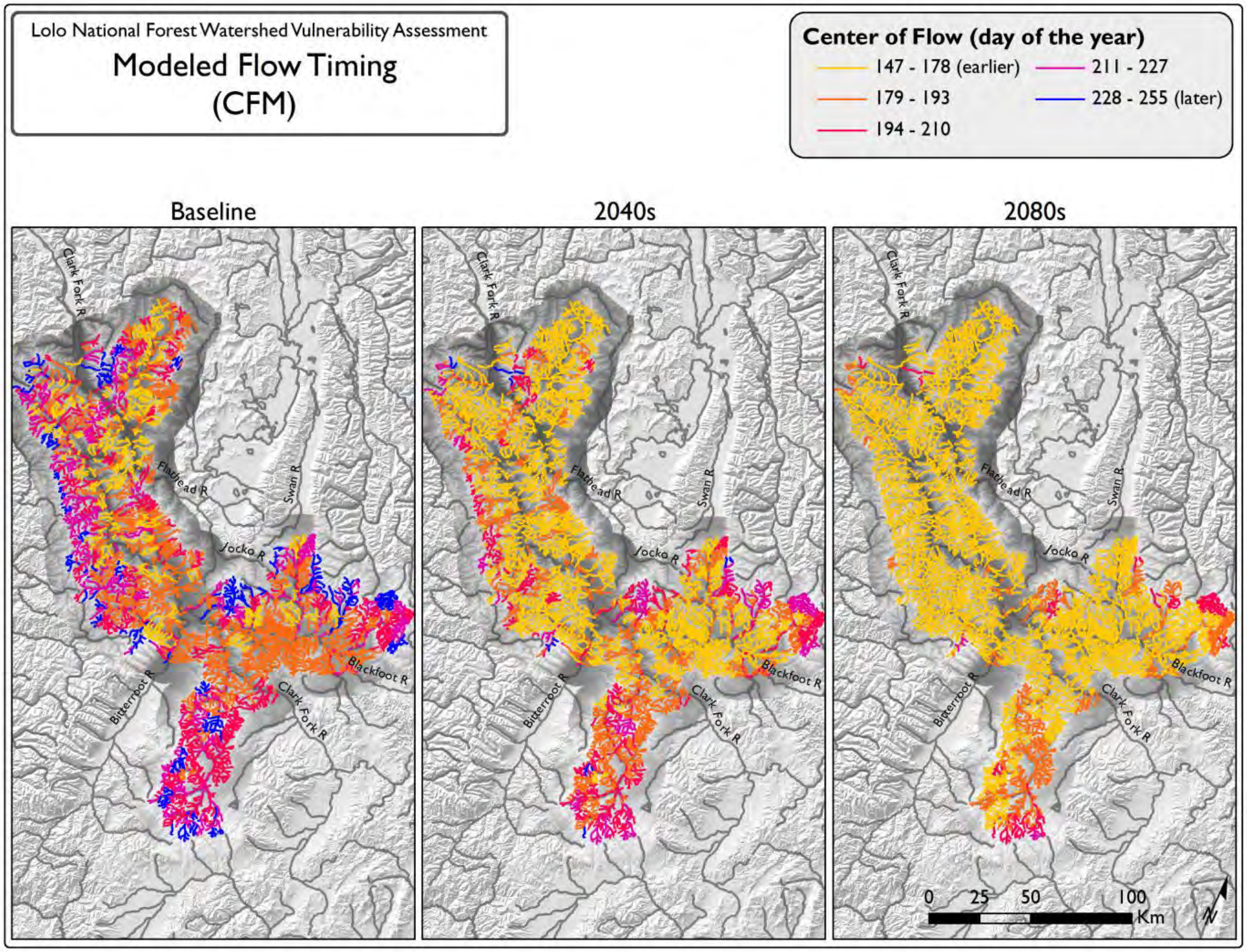

Figure ES.7. *Modeled flow timing (CFM) for baseline and for the 2040s and 2080s.*

Bull Trout Findings

For bull trout, we assessed vulnerability separately for temperature and flow because of the very different nature of temperature and flow exposure effects and because of the much higher uncertainty in flow indices as compared to temperature.

In general, Lolo Creek and the Thompson River areas stand out as areas that ranked most vulnerable to both flow and temperature stressors (having high exposure and sensitivity). In contrast, local bull trout populations in Rock Creek and the upper Blackfoot watersheds appeared to be least vulnerable. The least vulnerable watersheds were some of the highest elevation areas within the LNF.

Overall, bull trout local populations are projected to be more exposed to changes in flow than to increased temperatures. Because these rankings are relative across watersheds within the LNF, this does not necessarily indicate that bull trout are expected to be more impacted by flow than by temperature, only that *relative to other areas in the LNF*, temperature increases were not expected to be as great in bull trout local populations as in watersheds not inside a bull trout local population area (an area identified as having few to no bull trout). Bull trout generally occupy higher elevation streams which represent some of the best remaining thermally-suitable areas, and higher elevation streams are projected to warm less quickly than lower elevation streams. However, bull trout local populations are also situated in areas that are projected to have some of the greatest increases in winter flows, particularly in the western half of the study area. Further, the higher elevation headwater streams favored by bull trout currently have lower flow. These streams may be particularly susceptible to projected reductions in summer flows.

Table ES.1 (below) summarizes overall findings for exposure, sensitivity, and vulnerability for bull trout. Results for temperature-based vulnerability are illustrated in Figure ES.8 and flow-based vulnerability is shown in Figure ES.9.

Table ES.1. Summary of Bull Trout Findings

Analysis	General Result	Most Affected Areas	Least Affected Areas
Exposure			
Temperature	Greatest exposure is at lower elevations, generally not in areas with bull trout local populations	30% or more reduction in thermally suitable patch (<13˚C) in Lolo-Grave Creek, East Fork Clearwater, Upper and Middle Little Thompson Creeks, McGinnis Creek, Grant Creek, West Fork Petty and Eds Creeks, and Upper and Lower South Fork Fish Creeks.	0-16% reduction in patch <13 ˚C in local populations in Rock Creek, upper Blackfoot (North Fork, Monture, Cottonwood and Morrell), and lower Clark Fork areas (Trout, Cedar, St. Regis, Prospect and Graves)
Flow (Combined high winter flows and low summer flows)	For both high winter flows and low summer flows, the greatest exposure is in the western study area and extending south along the slopes of the Montana-Idaho border	Highest combined exposure to both high winter flows and reduced low flows in the 2040s was in the Prospect Creek local population, and in Albert Creek and parts of the St. Regis, Lolo, Graves, and Fish Creek local populations.	Lowest exposure was in the North Fork Blackfoot, Welcome and Hogback Creek bull trout populations.
Sensitivity			
Low population size/viability	Because both the calculation of the population viability metric and the delineation of bull trout local populations were on the basis of occupancy – few local populations had extremely low metric values. Higher elevation headwaters generally had the best population viability, lowland and river mainstems had the worst.	Graves Creek, Petty Creek, Hogback Creek, and Butte Cabin Creek had some of the highest metric values.	Four of the five local populations with the lowest population viability, on average, were in the Rock Creek drainage.
Low stream connectivity	Low stream connectivity, as measured here, comes substantially from culverts, as opposed to dams or natural impediments.	Connectivity was lowest in the Lolo Creek local population	Populations with no anthropogenic barriers included North Fork Blackfoot River, and Grant, Stony, Hogback, and Ranch Creeks.

Table ES.1, continued

Analysis	General Result	Most Affected Areas	Least Affected Areas
Sensitivity, continued			
Sediment (road proximity and crossings)	Areas in or immediately below wilderness have less stress from roads.	The Thompson, St. Regis River and Trout Creek local populations, on average, were expected to have the most sediment stress, followed by Lolo, Placid, and Grant Creek populations	Local populations in the Blackfoot and Rock Creek drainages, Prospect Creek, Graves Creek, Rattlesnake Creek and Fish Creek had lowest sediment stress.
Low physical complexity (riparian cover, roads near streams, grazing on shallow slopes)	Areas in or immediately below wilderness have less stress from riparian impacts.	Combining all these sub-metrics, only the lower St. Regis local population included a HUC-12 that had the highest level of stress from low physical complexity of channels and riparian areas.	On average, North Fork Blackfoot River, and Gold, Prospect, Hogback, and Welcome Creek local populations were least stressed.
Water diversions	Areas of high stress from water diversion were more heavily concentrated in the eastern half of the LNF. Diversion proportions ranged up to 40% of maximum mean summer flow.	Local populations with highest stress from water diversions included Rock Creek in the N. Fork Blackfoot population area, Placid Creek, McGinnis Creek in the Thompson River area, and Grant Creek.	The local populations with lowest stress, on average, were Welcome and Butte Cabin Creeks.
Low stream-floodplain connection	Bull trout populations in the LNF are mostly found in tributary reaches where terrain is steep and streams are relatively confined; thus most of the local populations were rated as high stress for this metric (confined mile per stream mile).	The northwestern portion of the study area was generally more confined. The local populations with nearly no unconfined streams included Graves, Hogback, and Welcome Creek.	No streams within HUC-12s ranked as low sensitivity to this metric.
Brook trout presence	No spatial trends identified in the study area.	Local populations that are expected to have highest stress from brook trout include Fish Creek, Lolo Creek, Grant Creek, Rattlesnake Creek, North Fork Clearwater, and Cottonwood Creek	Local populations that were *not* expected to have high stress from brook trout included North Fork of Blackfoot River, East Fork Clearwater, Morrell Creek, western portions of the Thompson River local population, Cedar Creek, West Fork Rock Creek, Stoney Creek, Hogback Creek, and Welcome Creek.

Table ES.1, continued

Analysis	General Result	Most Affected Areas	Least Affected Areas
Vulnerability			
Temperature exposure combined with sensitivity	Highest vulnerability areas were mostly outside of local population boundaries, generally at lower elevations. Of the areas considered to be Bull Trout Important Habitat (i.e., critical habitat or high abundance), most fell in the category of low exposure to increased temperature.	Bull trout patches most vulnerable to temperature, with both high exposure and high sensitivity were Lolo Creek, Thompson River, Grant Creek, Petty Creek and Fish Creek.	Bull trout patches least vulnerable to temperature included Prospect Creek, St. Regis River, Cedar Creek, Trout Creek, Gold Creek, Morrell Creek, Cottonwood Creek, Monture Creek, N. Fork Blackfoot River and all of the Rock Creek local populations
Flow exposure combined with sensitivity	Spatial variability of vulnerability to flow is high – there are no obvious patterns.	The bull trout patches most vulnerable to changes in flow, with both high exposure and high sensitivity included Lolo Creek, Thompson River, Prospect Creek, Graves Creek, Albert Creek, Lower Petty Creek, and portions of the St. Regis River	Local populations that were least vulnerable to changes in flow included Cedar Creek, Trout Creek, Grant Creek, Rattlesnake Creek, Gold Creek, Morrell Creek, Cottonwood Creek, Monture Creek, N. Fork Blackfoot River, and all of the local populations in Rock Creek.

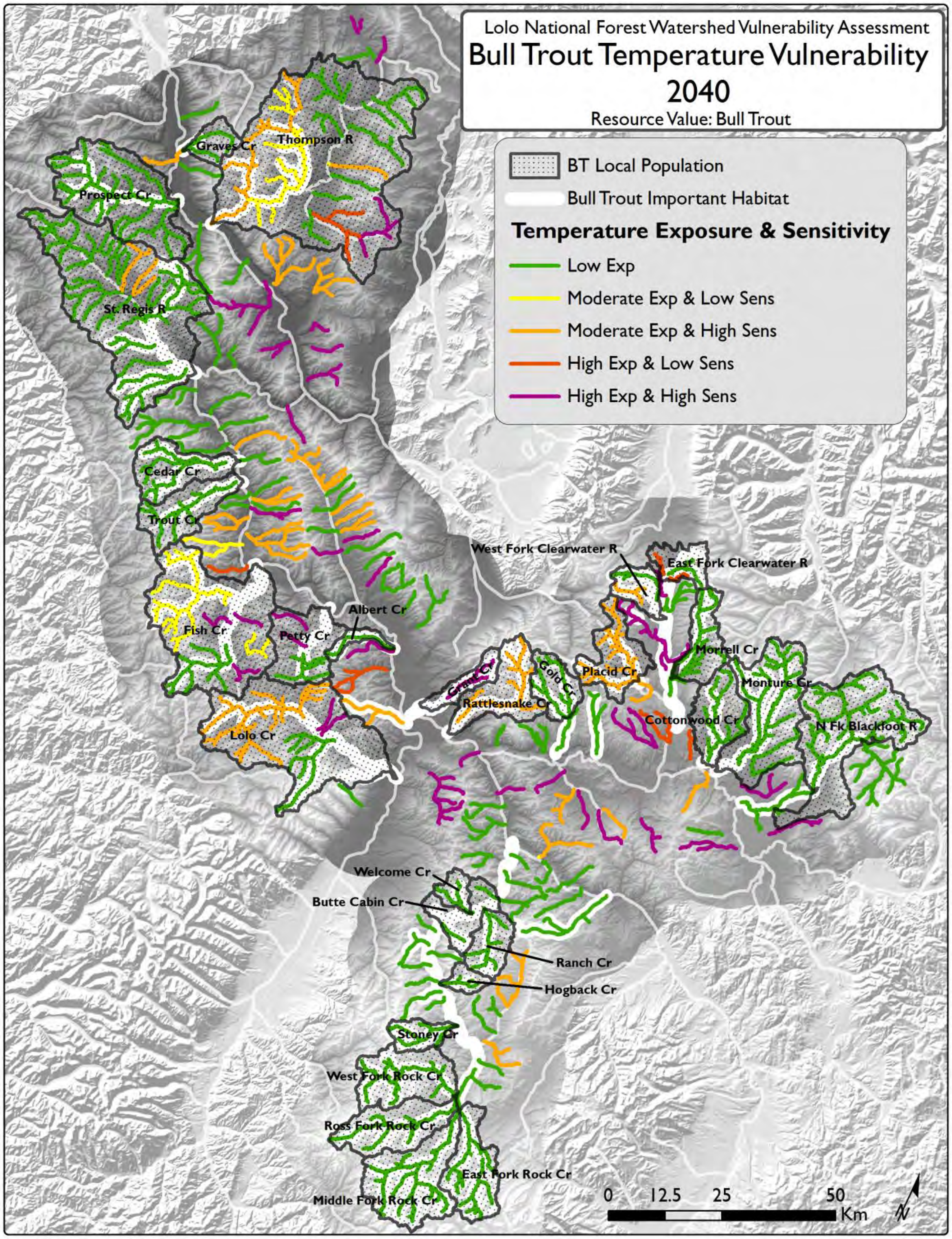

Figure ES.8. *Estimated vulnerability of bull trout to projected temperature changes, by patch, by the 2040s. Streams listed as having common or abundant bull trout by MFISH or as being critical habitat by FWS are shown in white ("Important Habitat") for reference.*

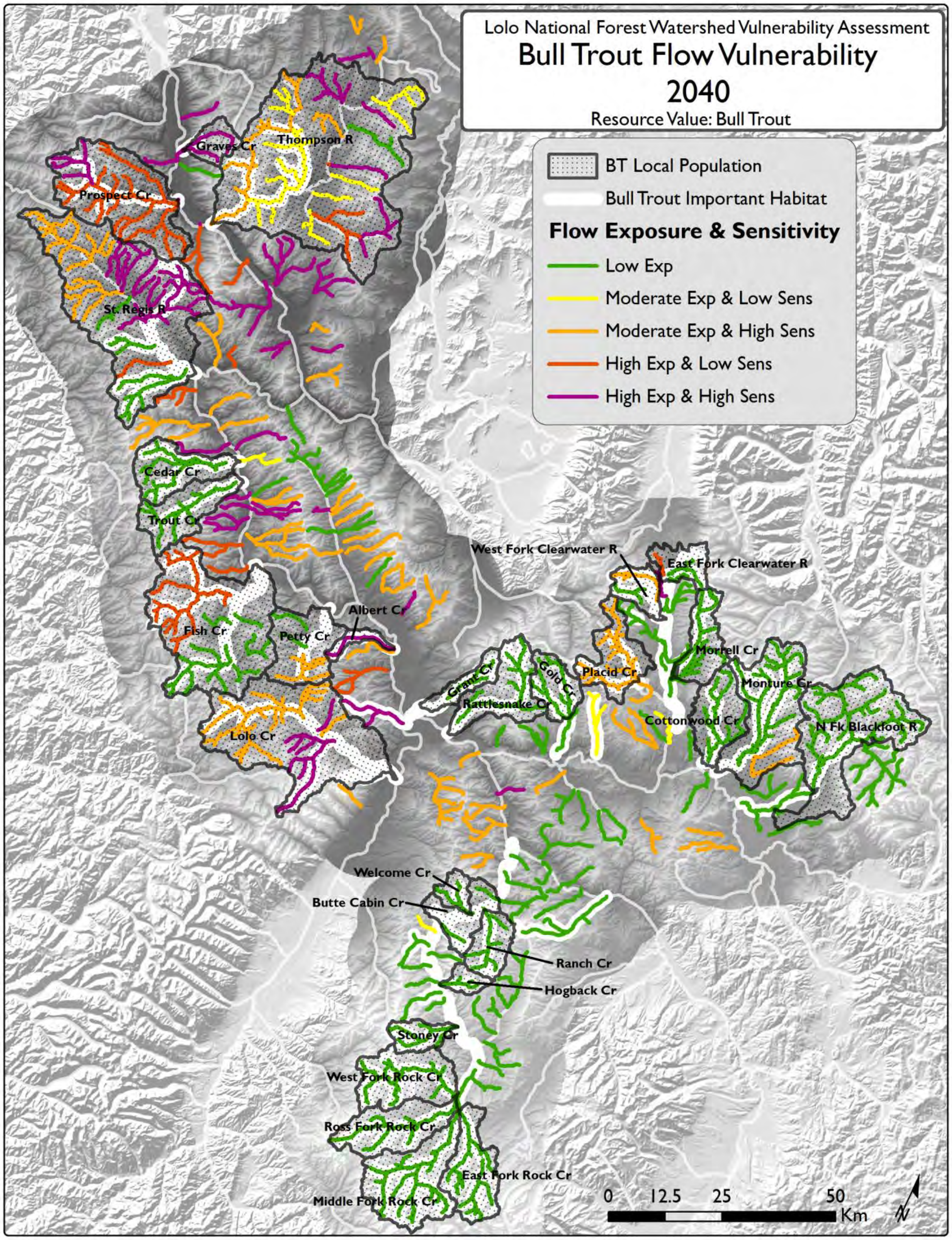

Figure ES.9. *Estimated vulnerability of bull trout to projected flow changes, by patch, by the 2040s.*

Water Supply Findings

The exposure index we used combined the low summer flow metric with the shift in timing of the center-of-flow-mass metric, and these two generally reinforced each other. The combined exposure distribution is not readily explained by elevation alone, although headwater streams generally have higher exposure, with the exception of Rock Creek. The only sensitivity metric we considered was water diversions. We note that there are watersheds where local knowledge suggests our methods have underestimated sensitivity (i.e., Lolo Creek is often dewatered). This issue arises because our data were incomplete – we lacked diversion flow quantities in some areas. Managers are reminded that results should be used to complement their knowledge of the area.

It was apparent that vulnerability closely tracked the exposure metrics. However, areas of high water diversion should be carefully considered when assessing vulnerability because actual diversions are unlikely to decrease over time. Table ES.2 summarizes overall findings for exposure, sensitivity, and vulnerability for water supply and Figure ES.10 illustrates estimated vulnerability of water supply on the LNF.

Table ES.2. Summary of Water Supply Findings

Analysis	General Result	Most Affected Areas	Least Affected Areas
Exposure			
Flow (combined low summer flow and shift in timing to earlier peak flow)	The patterns of lower summer flow and shift in flow timing reinforced each other. Combined exposure was greatest in the northwestern portions of the LNF and along the Montana-Idaho border, as well as in headwater streams of the Blackfoot River. Less exposure occurred generally in lower elevation valley streams and in Rock Creek.	High exposure occurred in Deep-Mosquito, Prospect, Lower Thompson-Fishtrap, Lolo, St. Regis, and Fish Creek drainages.	Lowest flow exposure occurred in E. Fk. Cooney, Lake-Rock, and Lost Prairie-Elk in the Blackfoot watershed, and in Deer-Cramer and Harvey-Bear along the Clark Fork drainage.
Sensitivity			
Water Diversion	Areas of high stress from water diversion were more heavily concentrated in the eastern half of the LNF. Diversion proportions ranged up to 40% of maximum mean summer flow.	Highest water diversion stress averaged by HUC-10 was expected in Deer, Cramer Creeks, Placid Creek, Rattlesnake, Grant Creeks, and Little Thompson Creek.	Most of the LNF was expected to have low to moderate stress from water diversion, although it is important to note that existing records available for this analysis may not be accurate.

Table ES.2, continued

Analysis	General Result	Most Affected Areas	Least Affected Areas
Vulnerability			
Exposure combined with sensitivity	Water supply vulnerability in the 2040s was estimated to be greatest in the higher elevation northwestern areas of the LNF, especially along the Montana-Idaho border and in higher elevation tributaries of the Blackfoot River.	Highest vulnerability (high exposure plus high sensitivity) watersheds include Dunham Creek, Morrell Creek, Upper Placid Creek, West Fork Fish Creek, Dry Creek, East Fork Lolo Creek, Upper Lolo Creek, West Fork Butte Creek, Chippy Creek, West Fork Fishtrap Creek, West Fork Lower Thompson River, Ashley Creek, and Upper Prospect Creek.	Lowest vulnerability (low exposure and/or moderate exposure plus low sensitivity) occurred in the Rock Creek drainage, in lower elevation tributaries on the LNF in general.

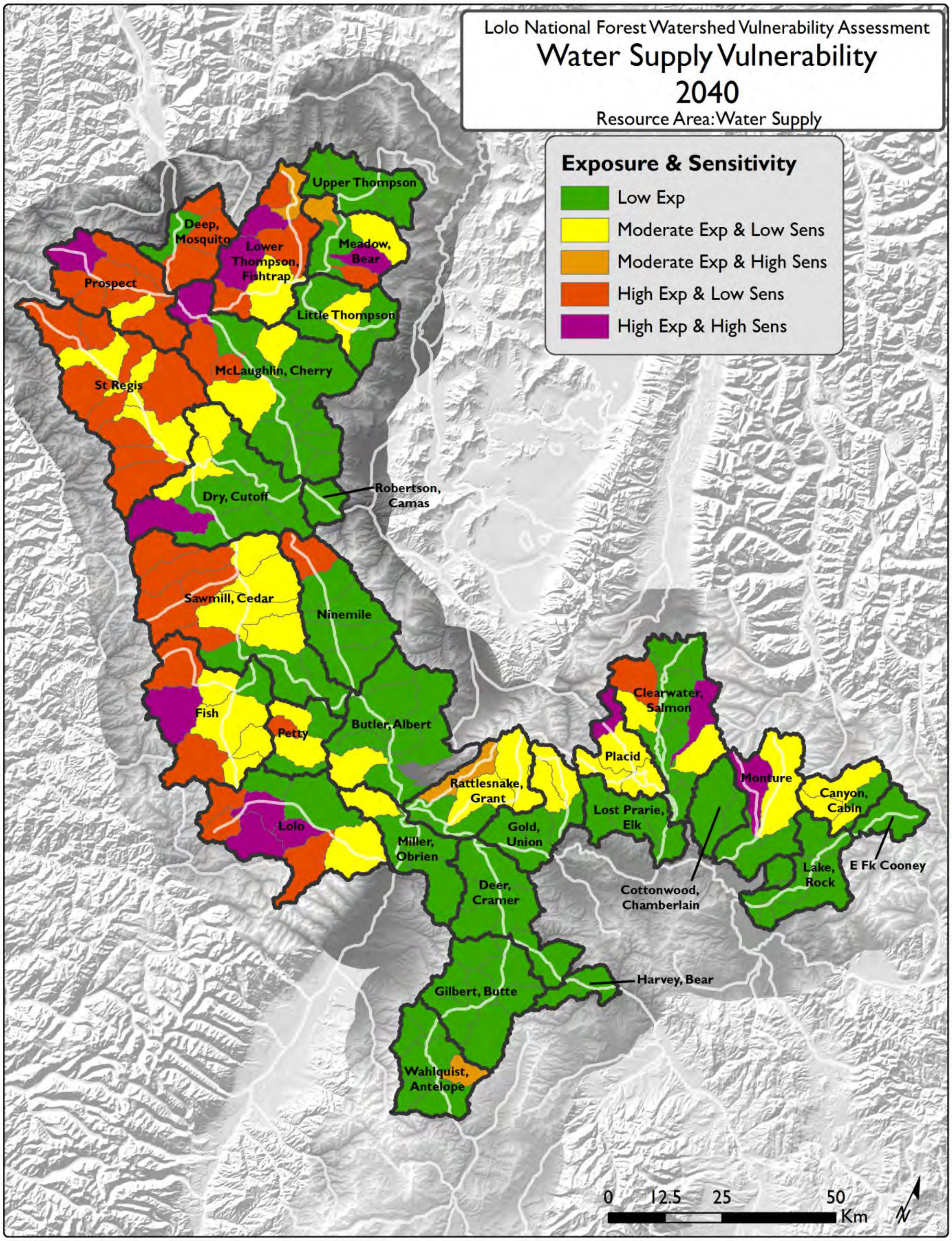

Figure ES.10. *Estimated water supply vulnerability, by HUC-12, by the 2040s.*

Infrastructure Findings

We characterized the exposure of recreation sites, trails, and jurisdictional roads to likelihood of winter flooding. Winter flooding was expected to increase across the area, with greatest exposure at lower elevations and relatively less exposure at higher elevations. High elevation areas that were currently expected to see 0 to 1 day of high winter flow would see 1 to 5 days by the 2040s.

Overall, recreation site and trail vulnerability fell generally into two vulnerability categories: high exposure plus low sensitivity (62% of HUC-12s for each) and moderate exposure plus low sensitivity (19 – 20% of HUC-12s). These watersheds have infrastructure that is more vulnerable because they are in floodplains or in areas of geologic hazard, or both. Clearly, as assessed here, exposure is a bigger issue with recreation site and trail infrastructure than is sensitivity, with a few targeted exceptions.

Forty-four percent of HUC-12s in the study area had roads in the highly vulnerable category of high combined exposure and sensitivity. The high vulnerability areas are scattered throughout the study area and are generally concentrated in lower elevation areas. Tables ES.3, ES.4, and ES.5 below summarize exposure, sensitivity and vulnerability results for recreation sites, trails, and roads, respectively, and Figures ES.11, ES.12, and ES.13 illustrate vulnerability for each infrastructure type.

Table ES.3. Summary of Recreation Site Infrastructure Findings

Analysis	General Result	Most Affected Areas	Least Affected Areas
Exposure			
Winter flooding	Winter flooding was expected to increase across the area, with greatest exposure at lower elevations and less exposure at higher elevations.	Most affected areas averaged by HUC-10 included Upper Thompson, Meadow-Bear, Little Thompson, McLaughlin-Cherry, Prospect, St. Regis, Dry-Cutoff, and Lost Prairie-Elk Creeks.	Least affected areas averaged by HUC-10 included Canyon-Cabin, East Fork Cooney and Rattlesnake-Grant Creeks.
Sensitivity			
Location in floodplain	Recreation sites were largely located out of floodplains	8 HUC-12s had 2-5 sites within the floodplain and one (in the Gilbert-Butte Creeks area) had 6-8 sites in the floodplain	Most of the LNF
Location in high geologic hazard area	There was no apparent spatial pattern for geologic hazard sensitivity across the LNF.	Averaged by HUC-10, most affected was Miller-O'Brien Creeks	Most of the LNF

Table ES.3, continued

Analysis	General Result	Most Affected Areas	Least Affected Areas
Vulnerability			
Exposure combined with sensitivity	As assessed here, exposure is a bigger issue with recreation site infrastructure than is sensitivity, with a few targeted exceptions.	HUC-12s with high exposure and high sensitivity included Rock Creek-Kitchen Gulch, Lower Clearwater River, Lower Fish Creek, Clark Fork River-Siegel Creek, Savenac Creek, Lower Lolo Creek, Bitterroot River-Hayes Creek, and Upper Fishtrap Creek.	Higher elevation areas were generally less vulnerable.

Table ES.4. Summary of Trail Infrastructure Findings

Analysis	General Result	Most Affected Areas	Least Affected Areas
Exposure			
Winter flooding	Winter flooding was expected to increase across the area, with greatest exposure at lower elevations and less exposure at higher elevations.	Most affected areas averaged by HUC-10 included Upper Thompson, Meadow-Bear, Little Thompson, McLaughlin-Cherry, Prospect, St. Regis, Dry-Cutoff, and Lost Prairie-Elk Creeks.	Least affected areas averaged by HUC-10 included Canyon-Cabin, East Fork Cooney and Rattlesnake-Grant Creeks.
Sensitivity			
Location in floodplain	Trails were largely located out of floodplains	Averaged by HUC-10, most affected were East Fork Cooney, Canyon-Cabin, Ninemile, and Miller-O'Brien Creeks.	Most of the LNF
Location in high geologic hazard area	There was no apparent spatial pattern for geologic hazard sensitivity across the LNF.	Averaged by HUC-10, most affected were East Fork Cooney, Monture and Miller-O'Brien Creeks.	Most of the LNF
Vulnerability			
Exposure combined with sensitivity	As assessed here, exposure is a bigger issue with trail infrastructure than is sensitivity, with a few targeted exceptions.	HUC-12s with high exposure and high sensitivity included Rock Creek-Kitchen Gulch, Lake Creek, Lower Clearwater River, Ninemile-Butler, Stony Creek, Clark Fork River-Siegel Creek, Bitterroot River-Hayes Creek, Big Rock Creek, and Dry Creek	Higher elevation areas were generally less vulnerable.

Table ES.5. Summary of Road Infrastructure Findings

Analysis	General Result	Most Affected Areas	Least Affected Areas
Exposure			
Winter flooding	Winter flooding was expected to increase across the area, with greatest exposure at lower elevations and less exposure at higher elevations.	Most affected areas averaged by HUC-10 included Upper Thompson, Meadow-Bear, Little Thompson, McLaughlin-Cherry, Prospect, St. Regis, Dry-Cutoff, and Lost Prairie-Elk Creeks.	Least affected areas averaged by HUC-10 included Canyon-Cabin, East Fork Cooney and Rattlesnake-Grant Creeks.
Sensitivity			
Location in floodplain	Roads were largely located out of floodplains	Averaged by HUC-10, most affected were Monture, Clearwater-Salmon, Dry-Cutoff Creeks, and St. Regis River.	Most of the LNF
Location in high geologic hazard area	There was no apparent spatial pattern for geologic hazard sensitivity across the LNF.	Averaged by HUC-10, most affected were Ninemile, St. Regis River, Lolo and Little Thompson Creeks.	Most of the LNF
Number of culverts	Culverts throughout the LNF averaged mostly less than 1 per mile and distribution was relatively uniform with no discernable pattern.	Averaged by HUC-10, most affected were Clearwater-Salmon, Placid, Gold-Union, Ninemile, Dry-Cutoff, St. Regis River, Meadow-Bear, and Deep-Mosquito Creeks.	Most of the LNF had less than one culvert per mile.
Vulnerability			
Exposure combined with sensitivity	Seventy-two percent of HUC-12s had USFS roads with high exposure and low sensitivity, and these HUCs are concentrated in low-elevation areas. Roads in areas of moderate or lower exposure and either high or low sensitivity are generally located in HUC-12s within headwater areas at higher elevation.	Forty-four percent of HUC-12s in the study area had roads in the highly vulnerable category of high combined exposure and sensitivity. The high vulnerability areas are scattered throughout the study area and are generally concentrated in lower elevation areas.	Least affected areas are generally at higher elevations.

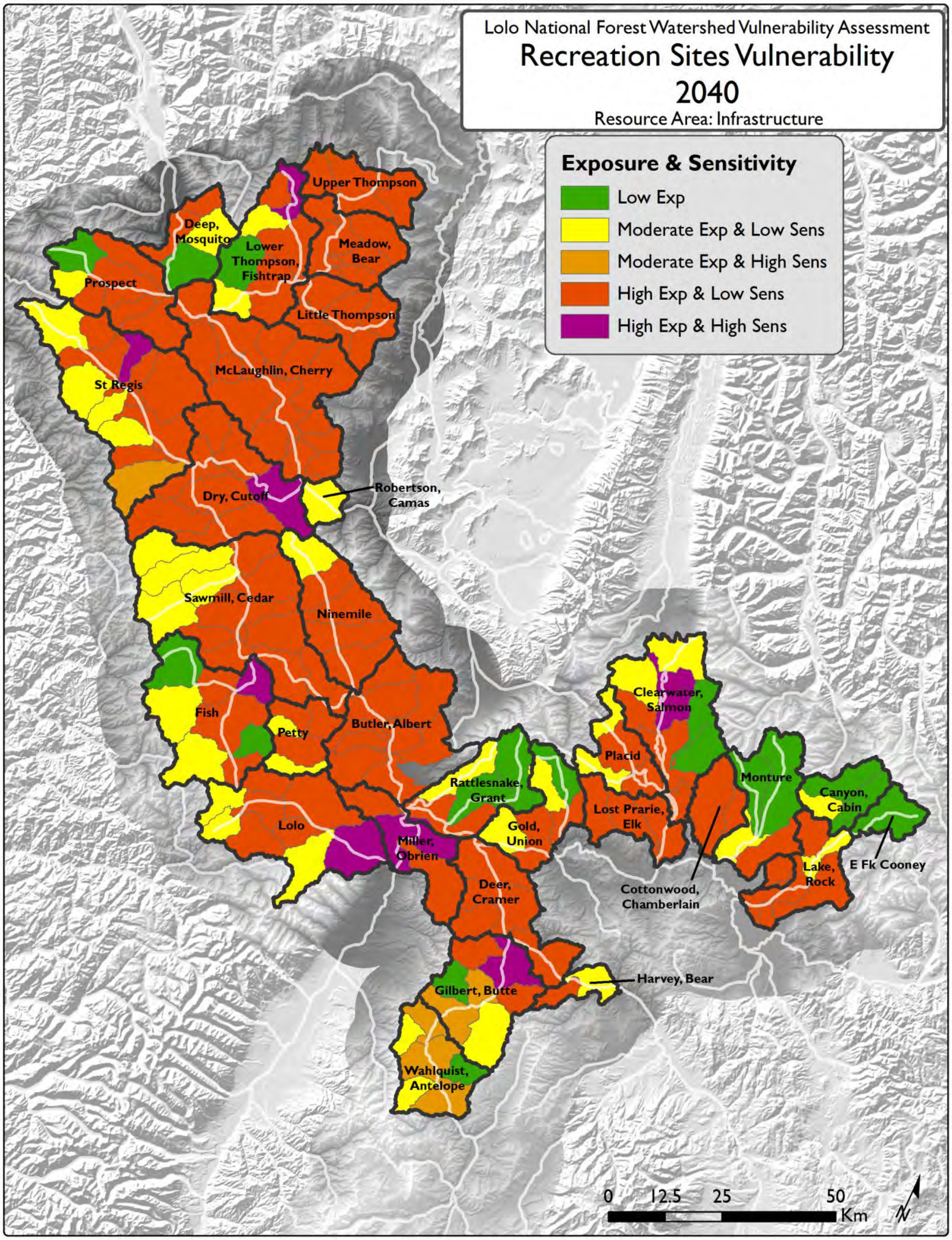

Figure ES.11. *Estimated vulnerability of recreation sites, by HUC-12, by the 2040s.*

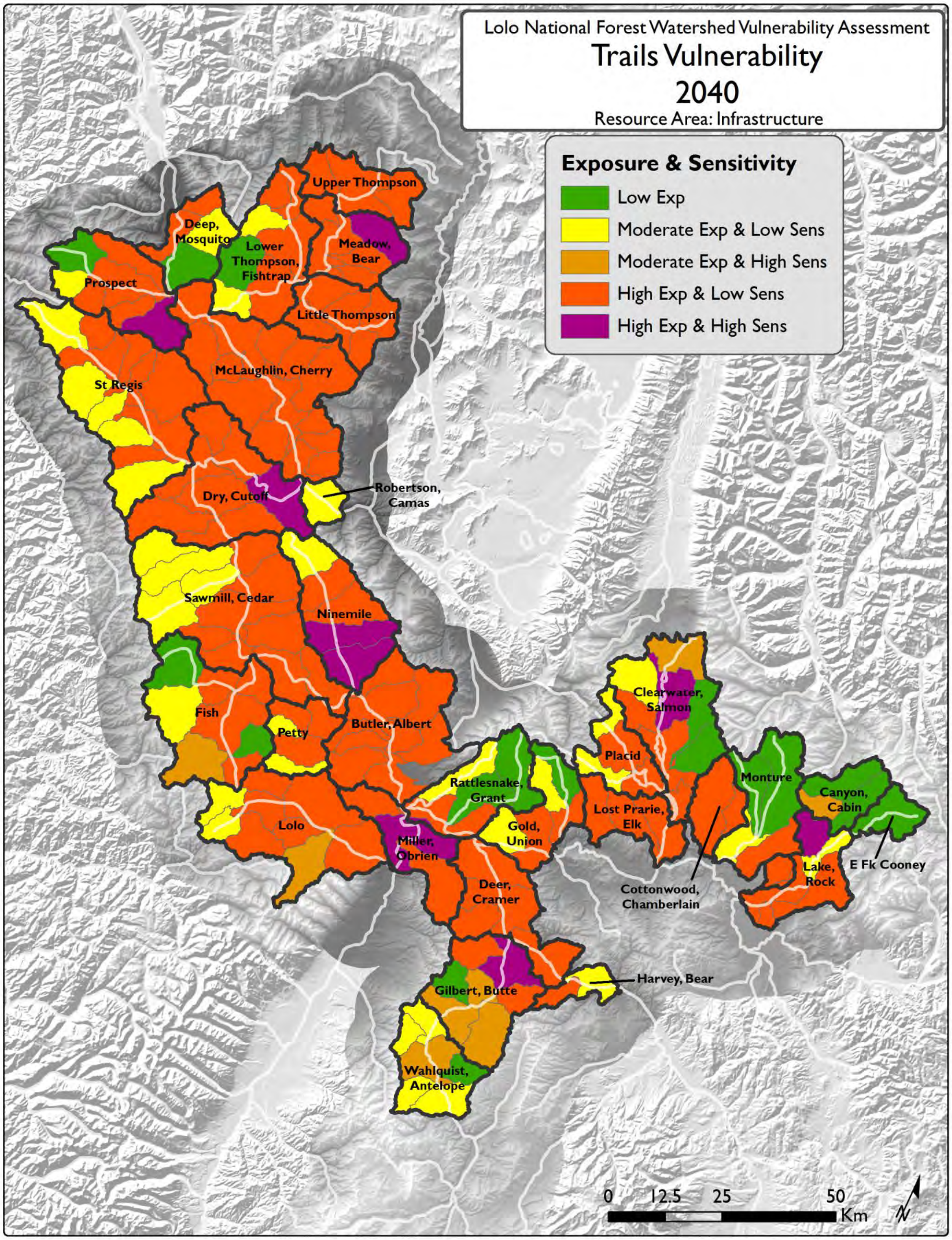

Figure ES.12. *Estimated vulnerability of trails, by HUC-12, by the 2040s.*

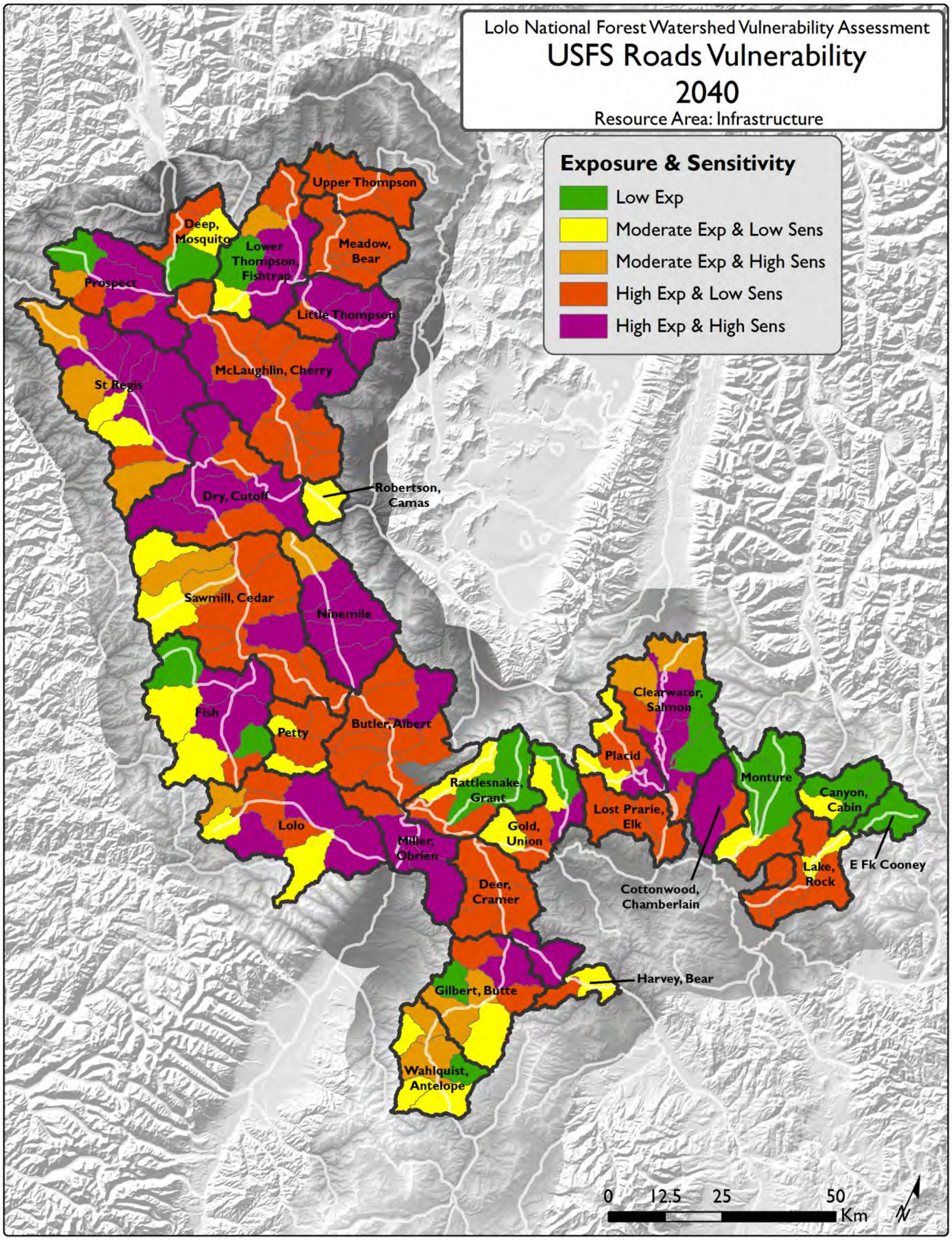

Figure ES.13. *Estimated vulnerability of LNF-jurisdiction roads, by HUC-12, by the 2040s.*

Management implications

The goal of this vulnerability assessment is to provide management guidance in meeting LNF conservation goals to maintain resilient ecosystems given the added uncertainties and complexities of climate change. This analysis provides insight into one potential quantification of vulnerability based on one scenario of climate exposure and key potential drivers of sensitivity, suggesting adaptation actions to reduce vulnerability (Figure ES.1, above). Assessing vulnerabilities and prioritizing management actions are but one step in a broader management framework (see Table I.1 in main report). Each watershed has unique attributes that will determine specific ecological dynamics and responses to climatic changes.

Managers can use the results of this assessment in numerous ways, including identification of data gaps, development of monitoring programs, integration with existing prioritization programs, development of short and long-term strategies to increase resilience of the resource where it is likely to have the most benefit, development of education and outreach materials, and collaboration with other agencies and local communities (Furniss et al. 2013).

We hope this analysis will further provide an opportunity for the LNF to educate the public about the potential climatic impacts to forest resources and LNF's adaptive management strategies to address potential impacts. In addition, this report can be used to identify where collaborative efforts with state, federal, and tribal agencies, community councils, and NGOs would be most productive in developing successful adaptation measures.

Bull Trout Management Implications

Bull trout require colder water than most other salmonids, and given documented increases in stream temperatures, a sizeable percent of their cold-water habitat may already have been lost (Isaak et al. 2010). Additionally, changes in hydrological regimes have measurably reduced summer flows (Luce & Holden 2009), and projections of increased frequency of higher flows are likely to result in increased scour during bull trout incubation (Goode et al. 2013). Although western Montana has been identified as likely providing some of the coldest waters across their range, recent projections of bull trout occurrence probability are low in many areas of the LNF under a scenario of high climatic changes (Isaak et al. 2015b).

Relative differences in vulnerability across the LNF are important, especially given the potential for bull trout to adapt to changing climatic conditions through evolutionary or plastic responses. As managers are faced with managing habitat for bull trout conservation, it is critical to understand where and which conservation and adaptation actions are likely to most contribute to increased resiliency of bull trout populations. A substantial amount of complementary research has been conducted for the species across multiple scales, and we urge managers to consider our results in conjunction with those efforts.

Improving bull trout habitat will be necessary, but not necessarily sufficient for bull trout recovery. For example, recent modeling suggests reducing impacts from nonnatives would provide relatively high improvement in bull trout population status, but restoration of natal habitat was found not likely to be highly effective (Peterson 2015). Beyond habitat, demographic and genetic trends are critical to long term species persistence (Moore et al. 2014; Nicotra et al. 2015; Kovach et al. 2015).

In summary, bull trout conservation is complex, and the findings here are aimed to provide LNF managers the context of vulnerability for optimizing forest operations with respect to both efficiency and effectiveness. Ideally, decisions should be considered within a broader context spatially and ecologically, which demands concurrent consideration and collaboration with other responsible stakeholders. The concepts of niche redundancy, resilience, and representation are critical to long-term conservation of bull trout. Management actions without expansive thought beyond the LNF boundaries will not be effective. Management that is too localized and singularly focused has plagued salmonid conservation throughout the Columbia Basin (Rieman et al. 2015). The findings provided here should be compared and complimented with other studies to adaptively manage bull trout, throughout their range and engaging with all stressors, to maximize the demographic, life-history, and genetic diversity of a comprehensive bull trout portfolio (Schindler et al. 2010).

Our analysis focused on these types of physical habitat drivers of bull trout sensitivity to climate change, where we believe managers can most successfully act to reduce vulnerability (Table ES.6).

Table ES.6. Example management actions for bull trout conservation.

Mode of Action	Example Management Actions
Assess	- Verify temperature and other climatic projections with monitoring - Continue active monitoring of bull trout presence, redd counts - Continue coordination with RMRS re: eDNA monitoring - Maintain and develop GIS layers of bull trout presence and abundance - Monitor for genetic and demographic trends
Engage	- Continue support for interpretive efforts, interacting with schools and other programs re: bull trout awareness - Continue coordination with FWP and MDT re: surveys, identification and eradication of non-natives, LWD replacement at bridges - Coordinate with FWP to increase monitoring - Engage ditch and water managers re: drought planning and reducing summer diversions
Manage	- Manage for resilience (reduce stressors in high sensitivity areas, protect refugia in low exposure areas, manage proactively in high exposure areas) ▪ Increase/maintain riparian shading and encourage species diversity in plantings ▪ Improve base flows via beaver reintroductions or beaver analogs ▪ Continue to remove unnatural barriers and improve habitat connectivity ▪ Interface with TMDL efforts to reduce sediment ▪ Restore/maintain channel complexity via rehabilitation pilots (e.g., LWD reintroduction), particularly at over-wintering habitat or areas of high summer thermal-stress ▪ Evaluate and manage road system in strategic locations such that modifications (relocation, removal, etc.) facilitate stream, floodplain and riparian processes (wood delivery, complexity, thermal buffering, etc.) ▪ Manage grazing allotments using stream and riparian-based methods (e.g., greenline-based approaches) ▪ Develop plan to manage/remove invasives ▪ Remove genetic and population bottlenecks

Water Supply Management Implications

Projected shifts in hydrological regimes may change availability of water for all uses, including instream flows for aquatic ecosystems, groundwater recharge supporting wetland ecosystems, municipal and public water supplies, agricultural irrigation diversions, and Forest Service potable water systems.

As summer water supply becomes scarcer in the future, managers will need to prioritize where enhancement of watershed storage would be beneficial as an adaptation strategy. Groundwater storage can increase watershed resiliency during drought cycles now and in the face of future climate-driven low flows. Enhancement could take the form of constructed impoundments at existing lakes, if feasible and ecologically benign, or could be achieved naturally, and with potentially greater ecological benefits, by beaver reintroduction.

This vulnerability analysis may also be useful for prioritizing where additional instream flow for aquatic life could be beneficial in the face of decreasing summer flows in the future. The Water Rights Compact between the State of Montana and the USDA Forest Service grants the USFS specific instream flow rights on a number of tributaries on the Lolo NF to protect base flows for fishery protection. Identifying especially vulnerable streams for both water supply and bull trout, combined with manager's knowledge of opportunities and limitations, may help guide prioritization decisions.

Table ES.7. provides examples of management actions to reduce the vulnerability of water supplies.

Table ES.7. Example management actions for maintaining sufficient water supply.

Mode of Action	Example Management Actions
Assess	- Verify diversion sites and quantify flow diversion - Continue existing monitoring and monitor flow withdrawals under SUPs to ensure adherence to water rights and appropriate habitat protections - Assess feasibility and potential influence of beaver or beaver analog projects; identify watersheds for pilot reintroductions - Perform stream reconnaissance during project assessments and inventory all human-related water withdrawals in accord with appropriate use
Engage	- Continue to educate community on outdoor watering restrictions and water-use guidelines - Coordinate with DNRC to provide verification of appropriate water use at key locations - Continue communications with state agency, NGO, and private partners on beaver management and enhancement - Coordinate with ditch managers and others to encourage drought planning and voluntary actions to reduce instream withdrawals, particularly in summer - Enhance partnerships for monitoring and actions that consider complete watershed dynamics headwaters to mouths - Continue Wyden authority towards necessary improvements on private lands
Manage	- Manage for resilience (reduce stressors in high sensitivity areas, protect refugia in low exposure areas, manage proactively in high exposure areas, implement water-saving efforts forestwide) ▪ Continue instream flow securement program; consider objections to new water rights where instream flow reservations are not established ▪ Implement water-saving initiatives forestwide: install water-saving facilities, meter water usage, and maintain LNF watering devices in good working order; use grey-water for irrigation as possible; xeriscape and use native, drought-resistant plants and water-smart landscaping; irrigate efficiently with timed sprinkler systems and allow for less vibrant summer lawns

Infrastructure Management Implications

Campgrounds, roads, and trails provide the foundation for recreational opportunities on public lands, and roads and trails are crucial for forest and fire management. The LNF is responsible for maintaining over 8,900 mi of roads, 1,698 mi of trails, and almost 300 recreation sites, including trailheads, loading ramps, campgrounds and picnic areas. Climate change is likely to make some of this infrastructure more exposed to flooding, especially early-season rain-on-snow events that may have greater magnitude than our present runoff regime. Along with the potential for winter flooding, infrastructure location in the floodplain or areas of high geologic hazard (landslides, avalanches, and alluvial fans) are inherent stressors considered in this analysis. For roads, another inherent stressor we considered was the number of culverts because they can increase the probability of road wash-outs.

Use of the vulnerability results in management decisions should be contingent on field verification of susceptibility to flooding and geologic hazards; this is true for both low and high vulnerability areas. Most floodplains on the LNF are not FEMA-mapped and our analysis of floodplain location is limited by modeling assumptions. Our analysis of geologic hazards is also limited by the scale at which data are available (for example, presence in an alluvial fan may not be hazardous in all instances). We strongly recommend that managers carefully analyze the figures and tables of the individual metrics that make up infrastructure vulnerability designations. Table ES.8. provides examples of management actions to reduce the vulnerability of infrastructure.

Table ES.8. Example management actions for maintaining infrastructure.

Mode of Action	Example Management Actions
Assess	- Verify infrastructure locations in flood prone or high geologic-risk locations - Continue monitoring to evaluate efficacy of AOP/Q100 stream simulation efforts and strategies for stream crossing structures - Create and maintain GIS layer of vulnerable roads, trail, and campground facilities
Engage	- Maintain and enhance partnerships for infrastructure improvements and monitoring
Manage	- Manage for resilience (reduce stressors in high sensitivity areas, protect refugia in low exposure areas, manage proactively in high exposure areas) ▪ Consider road and trail relocation and realignment to areas of lower risk ▪ Provide adequate drainage through road and trail prism and drainage reconstruction; if prisms cannot be relocated from flood prone areas, elevate surface above flood risk level and armor via rock or vegetation ▪ Relocate roads in transport dominated reaches where possible ▪ Provide adequate BMP and maintenance on road-stream crossings ▪ Replace outdated and undersized structures at road-stream crossings; ensure adequate flow given risks of rain-on-snow events and post-fire debris ▪ Ensure ditches do not connect to stream network and reduce diversion potential for stream flow down road ▪ Remove or modify vulnerable campgrounds ▪ Prevent new development in floodprone areas

Watershed Climate Change Vulnerability Assessment
Lolo National Forest

Wade, A.A., C. Brick, S. Spaulding, T. Sylte, and J. Louie. April 2016. **Watershed Climate Change Vulnerability Assessment: Lolo National Forest**. Publication Number R1-16-05. Missoula, MT: U.S. Department of Agriculture, Forest Service, Northern Region and Lolo National Forest. 132 p. Full report available on-line at: http://www.fs.usda.gov/main/lolo/workingtogether.

1. INTRODUCTION

Climate change is complicating the ability of the nation's forests to "sustain the health and productivity" of forestlands (USFS mission) and secure "favorable conditions of water flows" (Organic Act of 1897) in the nation's headwaters. A recent report by the U.S. Government Accountability Office (GAO) noted that federal lands are at risk from a wide range of potential climatic impacts, and that the agency will face multiple challenges in responding (USGAO 2007). Challenges include the need for the US Forest Service (USFS) to shift from focusing on historical conditions to anticipating and managing for an uncertain future and the need for more specific guidance on climate adaptation actions.

Subsequent to the GAO report, and despite limited resources, the USFS has engaged in many proactive efforts including providing a systematic guidebook for developing adaptation options (Peterson et al. 2011). Indeed, many, perhaps most, forest operations already work towards maintaining and restoring ecosystem resiliency, which is the singular most appropriate approach to managing for climatic change. Building on these efforts, the most critical work remains for individual forest managers to develop insight on specific resource vulnerabilities and devise management actions that most effectively respond to climatic variability. To this end, 11 National Forests have completed pilot watershed vulnerability assessments (Furniss et al. 2013). The climate change vulnerability assessment presented in this report is the Lolo National Forest's (LNF) initial effort to plan for proactive forest management under potential future climatic change, extending the conceptual approach of previous pilot assessments to develop a more detailed vulnerability assessment specific to the LNF.

With over 2 million acres of varied landscape providing diverse vegetation, wildlife habitat, water resources, and recreational opportunities, LNF seeks to proactively understand potential impacts from climate change to better manage its outstanding natural resources and maintain maximum ecosystem resiliency. The LNF is part of the Columbia River Basin (Figure 1, see Appendix 2), where minimum temperatures have increased by 1°C (~2°F) and maximum temperatures have increased by 1.3°C (~2.3°F) during the period 1970-2006 (Littell et al. 2010). During the same period, precipitation has shown indications of decline (Littell et al. 2010). Although the future is uncertain, reasonable scenarios of climate change suggest average annual air temperatures will increase by 1.8°C (3.2°F) by the decade of the 2040s and 3.0°C (5.3°F) by the 2080s (relative to a baseline of 1970-1999 average temperatures) (CIG 2008). These projections suggest average annual temperature will exceed the range of the 20th century variability. Average annual precipitation is not likely to exceed the range of variability of the previous century, though seasonal patterns in precipitation may shift (CIG 2008).

One of the clearest signals from climate and streamflow models is that seasonal shifts in precipitation and increased temperature will likely result in lower summer flows and earlier and (in lower elevation streams) potentially higher peak flows (Mantua et al. 2010; Wu et al. 2012). Earlier streamflow timing has been recorded across western North America (Stewart et al. 2005; Regonda et al. 2005). By the 2040s, spring snow water equivalent is projected to decline by 22-35%

in the Columbia Basin (Littell et al. 2010). Additional feedbacks in the climate system, such as dust on snow reducing albedo (reflectivity of land surface) (Painter et al. 2010; Skiles et al. 2012), will likely add to the complex and uncertain impacts of a changing climate.

This assessment considers climate vulnerability of three primary resource values likely to be strongly affected by climate change: aquatics (bull trout), water supply, and infrastructure (recreation areas, trails, and roads). This assessment seeks to understand the magnitude of potential climate change effects to these resource values and to proactively inform *where* resources are relatively more vulnerable and to investigate *why* they are likely to be vulnerable, thereby providing the basis for initial prioritization of watersheds for special management consideration.

Bull trout (*Salvelinus confluentus*) are a native salmonid on the LNF, currently listed as a threatened species under the US Endangered Species Act (ESA). Bull trout's requirements for cold, clean, complex and connected habitat make them an ideal keystone species for assessing changes in aquatic environments. The LNF also encompasses the headwaters for a number of streams and rivers where sufficient flow is critical for meeting water supply needs for municipal, industrial, agricultural, recreational, and wildlife interests. Forest infrastructure provides the foundation for recreational opportunities and roads and trails are important for forest and fire management.

We also include discussion of vulnerability of a second aquatic organism, the western pearlshell mussel (*Margaritifera falcate*) in Appendix 3. We had insufficient funding to complete an entire vulnerability analysis on this important benthic organism, currently listed by the Northern Region as a Sensitive Species, and thus, we provide preliminary vulnerability considerations in the appendix. Potential impacts to other resource areas, such as wildlife, biomass, etc., are not addressed herein.

This assessment extends upon initial National Forest vulnerability pilot assessments in several ways. First, we conduct the analysis at a finer, LNF-specific, scale. Second, we begin with a conceptual systems view of each resource area, identifying the predominant mechanisms that link climate change (i.e., stream temperature and flow variation) to potential resource impacts. Conceptual models for each resource area detail our hypotheses about the key stressors that influence a given resource's resiliency to climate change and help to identify potential gaps in data and understanding. Thus, our approach focuses on sensitivities to climate change in addition to climatic exposure. We then quantify the stressors in each conceptual model, allowing us to identify locations where stressors may compound to make a subwatershed relatively more vulnerable and to assess which stressors are most likely to drive climate vulnerability in a given location.

1.1. Managing for Resilience in an Uncertain Future

The results presented here must be considered within a broader framework of managing for resilient watersheds given the uncertainty of climatic variability. Essentially, managing for climatic change is managing for resilient ecosystems and infrastructure. Resiliency is the ability of a system to absorb perturbations effectively and return relatively quickly to its original state of being, maintaining existing relationships with other parts of the system (sensu Holling 1973).

Within watersheds, resiliency refers to a "healthy" watershed that maintains natural processes and provides ecosystem services.

Vital signs of a healthy, resilient watershed

(adapted from Furniss et al. 2010)

- Provide diverse and connected habitat for native aquatic species
- Sustain favorable stream flows and natural hydrologic processes
- Store and recycle nutrients
- Support a diverse mosaic of riparian and floodplain areas and functions
- Capture and store rainfall
- Recharge groundwater, including soil-moisture in flood prone areas
- Minimize erosion losses and protect soil quality
- Resist and recover quickly from floods, fire, insect outbreaks, and other extreme events

Managing for climate change will be inherently uncertain and require shifts in thinking. For example, management will need to emphasize managing for inevitable ecological changes, not just for the persistence of existing conditions (Stein et al. 2013). Management will not be a linear process, but instead require adaptive management practices, whereby an iterative process of planning, acting, monitoring, and revised planning are continuously undertaken (see, for example Stankey et al. 2006).

The USFS *National Roadmap for Responding to Climate Change* lists three primary "modes of action" in managing for potential climatic shifts: assess, engage, and manage (USFS 2010). Table I.1, below, outlines these modes of action. In the Management Implications section, we provide examples of how adaptation actions addressing findings of this assessment could fit within this framework.

Table I.1. The USFS primary “modes of action” for climate change management. This climate change vulnerability assessment is one step within a broader management framework (Adapted from USFS *National Roadmap* 2010).

Mode of Action	Management Actions
Assess	- Review literature and best available information - Assess policy rules and regulations - **Assess climate vulnerability and prioritize locations** - Assess knowledge gaps and fill via data collection and models - Verify data, models, and results - Monitor systems and effectiveness of management actions - Iteratively reassess information, systems, policies, and plans
Engage	- Share knowledge, collaborate, and coordinate actions - Integrate climate change into planning efforts - Educate and engage community - Educate staff and partners
Manage	- Link research to adaptive management - Manage for resilient, diverse ecological and built systems - Link vulnerabilities to management for resiliency and prioritize management actions types ▪ Restore/maintain natural processes (all areas) ▪ Reduce stressors (high climate sensitivity) ▪ Protect refugia (low climate sensitivity/exposure) ▪ Proactively manage for climatic changes (high climate exposure)

2. Vulnerability: Conceptual Approach and Definitions

The Intergovernmental Panel on Climate Change (IPCC) defines vulnerability as "the degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change" (IPCC 2007). Thus, *vulnerability* is a function of *exposure* (the magnitude or probability of physical changes in climate conditions), *sensitivity* (the likelihood of adverse effects to an organism or system given climate changes and potential interacting non-climate stressors), and *adaptive capacity* (the intrinsic ability for an organism or system to reduce its sensitivity by successful response to changing climate [e.g., plastic or evolutionary responses, range shifts]) (IPCC 2007). Ultimately, the goal of a vulnerability assessment is to identify the potential future impacts from climatic change and to identify vulnerable areas to provide a solid foundation for climatic change *adaptation* management and planning (Glick et al. 2011).

Adaptation refers to conservation or management actions that reduce vulnerability (Figure V.1, below). Here, we focus on actions that can be effected by local managers to reduce exposure (e.g., riparian shading to buffer stream warming) or sensitivity (e.g., removing culvert barriers so bull trout have access to colder waters, improving and protecting critical aquatic habitat, or monitoring water diversions to ensure sufficient water supply). We do not discuss *mitigation* as a form of adaptation, which in climate circles refers to efforts to reduce carbon emissions. This form of *mitigation* is more difficult to address at the scale of the single forest. Note that adaptation management is different than *adaptive capacity*. Also, *adaptation management* is different than *adaptive management* (an iterative process of decision making, discussed further below). There may be significant opportunities for local adaptation management depending on the area, resource of concern, and existing human impacts.

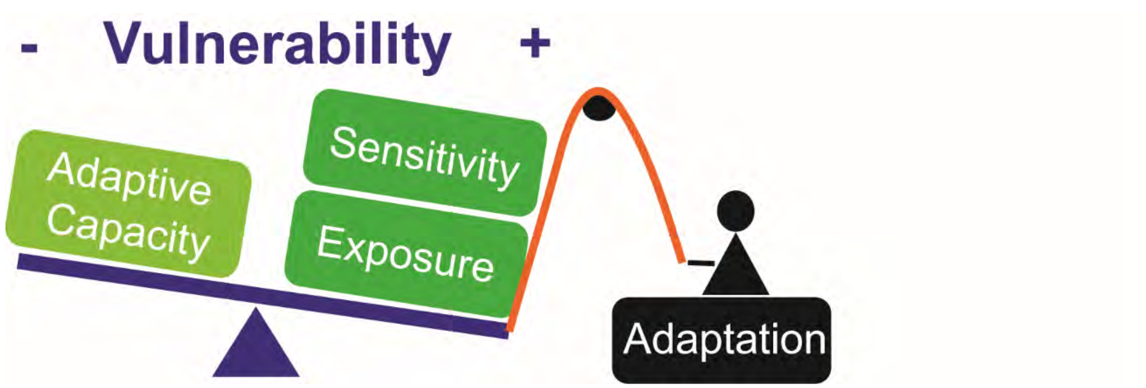

Figure V.1. *Vulnerability is a function of climate exposure and sensitivity. Adaptive capacity (a system's intrinsic ability to reduce its sensitivity) can reduce vulnerability. We do not address the adaptive capacity of each resource value in this report, but managers should consider this in planning. The goal of the vulnerability assessment is to plan for climate change adaptation management actions, which may reduce vulnerability, primarily through reducing climate sensitivity.*

We conducted a climate change vulnerability assessment for three key forest resources in the study area: aquatic species (resource values: bull trout and see preliminary discussion of pearlshell mussel vulnerability in Appendix 3), water supply, and forest infrastructure (resource values: roads, trails, and recreation sites). To address vulnerability, we calculated and combined measures of climate exposure and resource sensitivity believed to be reasonable proxies (i.e., surrogates) for assessing the magnitude of potential climatic changes and the sensitivity of these resources to those changes. We calculated climate exposure as the degree to which climate, specifically stream temperature and flow, is projected to change from baseline conditions (modeled average conditions for 1993-2011) under a "middle-of-the-road" scenario of carbon emissions. To represent climate exposure, we calculated change between modeled baseline climatic conditions and two future scenarios, one for the period of the 2040s (2030-2059) and the other for the 2080s (2070-2099) for comparison. The indices we used to quantify sensitivity are proxies for intrinsic and extrinsic stressors to the resources that may increase their sensitivity to climate change. Although some sensitivity measures are likely to change over time (e.g., riparian cover along streams), here, we assume they are temporally static. For the final vulnerability assessment, we combined the stressor indices into an inclusive sensitivity value and compared this against a combined exposure value for the 2040s. We did not assess 2080 vulnerability because of the significant uncertainty associated with that distant future. However, one can consider the 2080s maps as a "high" exposure scenario as compared to the 2040s, which can be considered a "moderate" mid-century exposure scenario.

The goal of this approach was to optimize trade-offs between practicality, transparency, comprehensiveness, and ecological relevance (for the aquatic species). Our primary focus is on exposure measures; however, sensitivity is a critical element of vulnerability, and the project team spent substantial time conceptualizing and quantifying key sensitivity stressors. Caution should be used when interpreting maps of sensitivity indices because of uncertainty in the exact relationship between our quantified stressors, natural variability, and resource responses. We offer these scenarios as a general and reasonable framework to help facilitate informed management decisions. Addressing specific indicators at local scales will likely require further investigation and perhaps more time to understand and witness true ecosystem response.

We did not incorporate adaptive capacity explicitly in this analysis, although it should be considered when using these results for adaptation planning, particularly when planning for biological resources (e.g., bull trout). Efforts to increase system resilience (e.g., by restoring natural processes) may broadly respond to increasing adaptive capacity. However, biotic systems may become more or less resilient independent of our actions and the natural world often presents surprises. Complete context, status of the value at risk, and a conservative approach are warranted. We have included what regional experts believe are key drivers of climate vulnerability for the resources considered. However, our efforts were limited by data availability and quality, and we discuss those limitations in the relevant sections below.

Finally, the findings of this report are not submitted as the final-say in climate change planning for the LNF's aquatic, water supply, and infrastructure resources. Managers are encouraged to use the exposure, sensitivity, and vulnerability results, either separately or combined, to guide site-specific studies, prioritize management actions, and inform strategic planning efforts that fulfill short-term needs while maintaining long-term efficacy in the face of climate change. Although areas with high vulnerability may appropriately receive focused attention and careful consideration, areas that have moderate (or even low) vulnerability should not be dismissed as "invulnerable" to climate change. Further, finer-scale assessments are necessary. **We urge a "risk-management" approach where focus is not a single value, but instead on the range of potential climate implications.**

A Note About Uncertainty

Before reading further, it is important to recognize the uncertainty inherent in this analysis. **First**, **climate projections are inherently uncertain**. All models are imperfect, and global circulation model (GCM) outputs, particularly in North America, cannot fully capture or accurately predict the complexity of the atmospheric system (Deser et al. 2012). Further, projections into the more distant future become more uncertain; thus, we focus on the period of the 2040s for the vulnerability assessment, although we provide maps of exposure indices out to the period of the 2080s. In general, one should consider the 2040s and 2080s scenarios "moderate" and "severe" projections of climate change, respectively, instead of projections of actual conditions in those decades. Additionally, the GCM outputs used are modeled on the basis of a single, middle-of-the-road scenario (A1B) of carbon emissions. The scenario follows a conceivable "story line" about what the future may look like including the global economy, technology advancements, and political will, but ultimately, these cannot be known. We note, however, that current carbon dioxide emissions are higher than those projected in the A1B scenario used here, and more recent climate scenarios (AR5; IPCC 2014) project greater climate variability and anomalies. Thus, our results may be conservative. **Second, translating GCM outputs into measures of in-stream temperature and flow requires additional models with additional assumptions leading to associated increases in uncertainty in the precision and accuracy of results**. Combined modeling approaches, and their concomitant uncertainty, make models of stream flow particularly tentative.

Third, this assessment relies on proxy measures we assume relate exposure and sensitivity to actual future impact from climatic change. We have chosen these measures with care, but we cannot be certain they directly impact resource values of concern; for example, reduced survival in bull trout, increased river dewatering from water diversions, or potential for flood damage to roads. **Fourth, all spatial data are imprecise**. Locations of rivers, roads, bull trout habitat, dams, floodplains, elevation changes, etc., as represented in a geographic information system (GIS), can never be perfect. **Finally, there are errors inherent to all data**. These can arise from collection error or merely incomplete datasets. For example, there is no flow rate data associated with water diversions for thousands of locations in the study area. The combination of these inaccuracies and biases affect the results. Results are presented as potential, relative, estimates of impacts under a single climate scenario and given our methods and current data availability. We cannot know what actual future impacts will be.

Despite the inherent modeling uncertainties, there is no doubt that the climate is changing. Average temperatures in the U.S. have risen by approximately 1.1°C (2°F) in the past 50 years. These changes have resulted in increased water temperatures (Kaushal et al. 2010), and additional changes in stream temperatures and hydrologic regimes are projected (Christensen et al. 2004; Adam et al. 2009; Mantua et al. 2010; Wu et al. 2012). Further, climate physics indicate that projected warming into 2040s is fairly certain as it results from current, known, carbon levels. Additionally, all models are relatively consistent in their projections of ongoing warming. Thus, uncertainty is not a cause for inaction; instead, the potential effects of climate change demand consideration. However, in the planning process, managers should operate within the context of associated uncertainty.

3. METHODS

3.1 METHODS OVERVIEW AND CLIMATE DATA USED IN THIS ASSESSMENT

3.1.1 STUDY AREA

For assessment of water resources and infrastructure, our study area incorporated all lands in the LNF (3,274 mi^2; 8,480 km^2) and intervening non-Forest Service lands, for a total study area of 5,135 mi^2 (13,300 km^2) (Figure 1, see Appendix 2). Because there are adjoining areas of critical importance to bull trout (bull trout populations do not stop at inter-forest boundaries), we used a larger study area boundary (6,429 mi^2; 16,650 km^2) for that analysis, incorporating a small portion of the Kootenai National Forest (~8 mi^2; ~20 km^2) to the north in the headwaters of the Thompson River watershed and the Rock Creek portion of the Beaverhead-Deerlodge National Forest (~455 mi^2; ~1,180 km^2) and intervening non-Forest Service lands to the south in the Rock Creek drainage. Study areas were defined following the boundaries of 6^{th} level hydrological unit codes (HUC). These are also known as "subwatersheds" or HUC-12 (12 digit HUC codes). There were 223 HUC-12s in the larger bull trout study area (area minimum = 6.9 mi^2, maximum = 65.6 mi^2, mean = 28.8 mi^2, SD = 11.6 mi^2) and 175 HUC-12s in the smaller study area used for other resource values (area minimum = 6.9 mi^2, maximum = 65.6 mi^2, mean = 29.3 mi^2, SD = 12.0 mi^2; two HUC-12s did not have NHD streams, and we therefore did not calculate indices for those HUC-12s). Table 1 (see Appendix 1) provides the names, ID number, size, and land ownership for each HUC-12 used in this analysis (sorted by HUC-12 name); Table 2 provides a list of the HUC-12 names sorted by ID number. To simplify result summaries, we report general findings for bull trout by bull trout local population (see bull trout Methods section for details; 29 local populations in the study area, mean = 110.2 mi^2) and by 5^{th} level HUC (HUC-10), into which the HUC-12s are nested, for the other resources (31 HUC-10s in the study area, mean = 155.3 mi^2).

3.1.2 CONCEPTUAL MODELS AND GENERAL METHODS

Conceptual models for each resource value are provided in the associated Methods section. For each resource value, we created a conceptual model linking resource needs to the quantification of vulnerability (see general schematic in Figure 3 in Appendix 2). For each *resource area* (Figure 3, row 1; here, aquatics, water supply, and infrastructure) and *resource value* (Figure 3, row 2), we listed the resource *needs* (Figure 3, row 3) that describe conditions necessary for maintaining the resource value. Resource needs in blue boxes are affected by climate (*exposure*) and those in green boxes represent other stressors that increase a resources' *sensitivity* to climate change. The *analytical unit* (Figure 3, row 4) for exposure and sensitivity was also shown in the conceptual model. We measured exposure using various types of habitat configurations (contiguous suitable habitat, or "patch") for aquatic species and HUC-12s for water supply and infrastructure. Although the unit of analysis was either a patch or a HUC-12, the unit of observation for exposure analyses was the stream reach, described further in the section below on climate data. We used HUC-12s as the unit of analysis for all measures of sensitivity.

The conceptual models listed the *stressors* (Figure 3, row 5) thought to most greatly affect each resource need in the study area and that could be quantified using metrics. For sensitivity, we considered both intrinsic (inherent to the system) and extrinsic (external to the system; primarily anthropogenic) stressors. More than one stressor may affect each resource need, and each of these was quantified (using the data and method described in rows 6 and 7, respectively) and summarized as a *metric* (Figure 3, row 8). In some instances, a sensitivity metric was calculated as the geometric mean of multiple *sub-metrics* (e.g., Figure 3, sensitivity metric 3). We used the geometric mean (the n^{th} root of the product of n values) for three reasons: it is the appropriate mean when data are proportions (which many metrics in this analysis were), it is the equivalent of the arithmetic mean of the log-transformed values (and many of metrics are highly skewed towards lower values with a few extreme values), and because it normalizes the various sub-metrics or metrics so that they are effectively on the same scale when combining. When there were multiple sub-metrics for a metric, we included a map of each sub-metric as well as a map of the sub-metrics combined into the single metric. This allows managers to gauge the influence of the contributing individual sub-metrics where appropriate.

For climate exposure stressors, we calculated all metrics using modeled future scenarios of climate change impacts on stream temperature and flow. All sensitivity metrics were assumed to be temporally static; a necessary assumption given the inability to project changes in those stressors.

We then calculated combined exposure and sensitivity *indices* by taking the geometric mean of all exposure and sensitivity metrics, respectively (Figure 3, row 9). We note that our approach gave an equal weighting to all metrics; lacking information that demonstrates otherwise, we assumed that each metric contributed equally to vulnerability. An alternative assumption could alter results.

For mapping of metrics and indices, we used the "natural breaks" clustering method, as implemented in ESRI ArcGIS 10.2. The algorithm chooses natural clusters in the data, minimizing within-group and maximizing between-group variations (based on the algorithm by Jenks 1977). We broke the data into five clusters. For each resource, we provided a tabular summary of all sub-metric, metric, and index values, as well as the result cluster for each index (with 1 being lowest stress and 5 having highest stress; see Appendix 1 for a list of tables available in supplementary materials, and Appendix 2 for figures, available on-line at http://www.fs.usda.gov/main/lolo/workingtogether).

Finally, we mapped relative vulnerability for each resource by comparing exposure and sensitivity index clusters (Figure 3, row 10). We assumed exposure index values in clusters 1 or 2 had low, cluster 3 had moderate, and clusters 4 and 5 had high exposure stress. For sensitivity, we assumed sensitivity index values in clusters 1 or 2 had low and in clusters 3, 4, or 5 had high sensitivity to exposure. Thus, we mapped vulnerability as follows:

- Low Exposure: exposure = 1 or 2 (regardless of sensitivity);
- Moderate Exposure and Low Sensitivity: exposure = 3 and sensitivity = 1 or 2;
- Moderate Exposure and High Sensitivity: exposure = 3 and sensitivity = 3, 4, or 5;
- High Exposure and Low Sensitivity: exposure = 4 or 5 and sensitivity = 1 or 2;
- High Exposure and High Sensitivity: exposure = 4 or 5 and sensitivity = 3, 4, or 5.

<table>
<tr><th></th><th></th><th colspan="5">Sensitivity</th></tr>
<tr><th></th><th>cluster</th><th>1</th><th>2</th><th>3</th><th>4</th><th>5</th></tr>
<tr><th rowspan="5">Exposure</th><td>1</td><td colspan="5" rowspan="2">Low Exposure</td></tr>
<tr><td>2</td></tr>
<tr><td>3</td><td colspan="2">Moderate Exposure, Low Sensitivity</td><td colspan="3">Moderate Exposure, High Sensitivity</td></tr>
<tr><td>4</td><td colspan="2" rowspan="2">High Exposure, Low Sensitivity</td><td colspan="3" rowspan="2">High Exposure, High Sensitivity</td></tr>
<tr><td>5</td></tr>
</table>

3.1.3 Climate Data

All exposure analyses relied on two climate datasets, the NorWeST temperature dataset (Isaak et al. 2015a) and the Western US Stream Flow Metric dataset (Wenger et al. 2010; Wenger & Luce 2011).

NorWeST Temperature Data

We calculated exposure to stream temperature changes using the NorWeST temperature dataset (Isaak et al. 2015a). The NorWeST dataset provides modeled stream temperatures representing the composite 19-year average August mean stream temperature (AMT) for a baseline time period (t_0, 1993-2011; NorWeST scenario number S1_93_11; Figure 4). The stream temperatures were estimated using a spatial statistical stream network model to interpolate temperatures between 1,163 observed stream temperature points in the study area, with statistical models calibrated with more than 4,000 additional observed points throughout the region. Variables used in the statistical model included watershed contributing area, drainage density, basin elevation, channel slope, incoming radiation, air temperature, and stream flow, among others.

Recently, the NorWeST dataset has been extended to include future scenarios. These scenarios were modeled from an ensemble of the 10 global climate models (GCM) with the best performance in simulating observed climate across the Northwest U.S. (Littell et al. 2010; Hamlet et al. 2013). The GCMs, using a middle-of-the-road A1B future greenhouse gas emissions scenario (IPCC 2007; Fourth Assessment Report [AR4]), were downscaled and outputs were used to parameterize the Variable Infiltration Capacity (VIC) model (Liang et al. 1994), which was used to generate projected future hydrographs (Hamlet et al., 2013). The downscaled GCM air temperature and VIC-derived stream flow projections were used in the statistical stream network model to project future stream temperatures. Additionally, the future projections accounted for differential river sensitivity by scaling the future changes to historical stream temperatures (cold streams were predicted to warm more slowly than warm streams; Isaak & Rieman 2013). Future stream temperatures were modeled for two averaged time periods, the 2040s (2030-2059; NorWeST scenario number S36_2040D; Figure 5) and the 2080s (2070-2099; NorWeST scenario number S38_2080D; Figure 6).

NorWeST stream temperatures were modeled at 0.62 mi (~1km) stream reach resolution (unit of observation), with streams following the National Hydrography Dataset (NHDPlus, Horizon Systems 2012) medium resolution segments. Table 1 provides information on the length of NHD reaches in each HUC-12 used in this assessment. The NorWeST data are in GNLCC projection

(Albers Conical Equal Area projection for the Great Northern Landscape Conservation Cooperative area) and all following analyses were conducted in this same resolution within ESRI ArcGIS 10.2.

USFS Stream Flow Metrics

We used the Western US Stream Flow Metric dataset (Wenger et al. 2010; Wenger & Luce 2011) to calculate all stream flow exposure indices. Baseline stream flow metrics were calculated using interpolated weather station data as meteorological inputs into the VIC model (Elsner et al. 2010) with outputs averaged over the period 1977-1997. Future climate scenario projections were modeled with GCM inputs as meteorological forcings into the VIC model. These scenarios were modeled from an ensemble of A1B greenhouse gas emissions scenario output for the 10 GCM with the best performance in simulating observed climate across the Northwest U.S. (Littell et al. 2010). Future scenarios were modeled for two averaged time periods, the 2040s (2030-2059) and the 2080s (2070-2099).

We used three of the flow metrics with relatively high performance statistics based on comparison of predicted vs. observed flow values for 55 gauging stations in the Pacific Northwest. However, GCM precipitation models are highly uncertain with greater discrepancy between GCM projections – significantly more so than temperature models (for a comparison, see Beechie et al. 2012; or, e.g., Luce et al. 2013). To provide high and low modeled flow change "sideboards", we included maps of the various flow metrics as modeled with the MIROC 3.2 GCM (more warming, drier) and PCM1 (less warming, wetter). Although we conducted this analysis using the ensemble GCM flow output, we urge managers to think in a risk management framework when considering future climate projection data and not focus on any single value.

The unit of observation for the flow metric dataset followed the NHDPlus (Horizon Systems 2012) stream segments (projected here into GNLCC spatial projection). Flow metrics were not calculated for main-stem rivers; therefore all flow analyses did not include high discharge rivers, like the Clark Fork, Bitterroot, and Blackfoot Rivers. For the stream reaches with data, the mean reach length was 1.2 mi (minimum 0.01, maximum 11.4, SD 0.9). Table 1 provides information on the length of NHD reaches in each HUC-12 used in this assessment.

To represent high flow effects, we used the winter 95 (W95) flow metric, in units of days (Figure 7; see Figure 8 for a larger map of baseline data; see Figure 9 for a comparison between the ensemble and lower and higher high flow projections from different GCM inputs). W95 is the number of days in winter in which flows are amongst the highest 5% for the year. Winter was defined as December 1 through February 28. We are concerned that these dates may miss some of the largest rain on snow events, which can occur in the study area in November and March; however for the purposes of this study, we are more concerned with relative changes than nominal values and these time frames are consistent with the references used. The W95 is strongly correlated with the highest projected annual flows (Wenger et al. 2010), and it is assumed that flows of this magnitude may scour redds or displace and kill newly emerged fry (Fausch et al. 2001).

We were concerned the W95 metric may be biased by HUC size. However, we found no relationship between the size of a HUC-12 and the mean weighted average (see Equation 1, below) W95 (3.12

days across all HUC-12s) nor the standard deviation (SD) of the weighted average W95 (1.7 days across all HUC-12s). We were also concerned that composite HUCs - the combination of multiple "pure" HUCs where all surface drainage converges to a single point - would not be represented as well by an averageW95 value. However, for a random sample of 51 (of 223 total, 24 composite and 27 pure) HUC-12s, we found relatively small difference in the SD of the weighted average W95 when comparing pure vs. composite HUC-12s (SD of 1.46 and 1.42, respectively). Pure HUC-12s, which tend to be located in headwater regions, had a lower weighted average W95 (2.37) compared to composite HUC-12s (3.44). In general, the largest uncertainty for this metric comes from the W95 data source itself, and we recommend reviewing the reach-level W95 maps and comparing across the different climate change scenarios (Figure 9).

To represent low flows, we used the mean summer (MS) flow metric, in units of cubic feet per second (cfs) (Figure 10; see Figure 11 for a larger map of baseline data; see Figure 12 for a comparison between the ensemble and lower and higher low flow projections from different GCM inputs). Summer was defined, for each stream segment, as starting on the first day after June 1 when flows fell below the mean annual value. For all segments, summer was assumed to end on September 30. This period often sees lowest flows, highest water temperatures, and may be most limiting to fish (Isaak et al. 2010).

To represent shifts in timing of flow regimes, we used the center of flow mass (CFM) metric, with units of day of the water year (Figure 13; see Figure 14 for a larger map of baseline data; see Figure 15 for a comparison between the ensemble and smaller and greater timing shift projections from different GCM inputs). CFM represents the day of the water year at which 50% of the year's flow has passed; also known as the center of the mass of flow or the center of timing.

3.2. Methods for Calculating Exposure and Sensitivity Metrics and Indices

3.2.1 Aquatic Resources: Bull Trout Methods

Native to mountain streams throughout the Pacific Northwest, bull trout require cold, clean water and connected, complex habitat (Goetz 1989; Rieman & McIntyre 1993; Watson & Hillman 1997; Selong et al. 2001). As the salmonid with the most demanding habitat requirements, bull trout serve as excellent indicators of stream health. Unfortunately, in a 1992 review of bull trout status, the Montana Department of Fish, Wildlife, and Parks found the fish had been extirpated from over 50% of their historical range. As a result, bull trout have been listed throughout their range as "threatened" under the Endangered Species Act since 1999.

Our conceptual model of bull trout vulnerability (Figure 16, Appendix 2) included stress from exposure to increased stream temperatures and winter scour and reduced summer flows. We used modeled potential thermally suitable natal bull trout habitat patches as our unit of analysis for calculating exposure indices (Figure 17). Patch data for the baseline time period were modeled by Dunham et al. (2001) and represented contiguous segments of 0.6 mi stream reaches (from the NorWeST temperature dataset, described above) that were below a threshold temperature. The general pejus temperature threshold used was 13°C (increases in temperature beyond this threshold result in decreased growth; Selong et al. 2001), although short lengths of slightly warmer temperature reaches would not break the contiguity of the patch. Potential natal patches were also limited to areas with a minimum mean summer flow (from the USFS flow metric data, described above) of 1.2 CFS, and we further refined patches by removing any upstream headwater patch end that had a reach slope of 15 percent or greater (Isaak et al. 2009; Peterson et al. 2013). We also removed any patch less than 3.1 mi (5 km) in total length as extremely small patches have a low probability of bull trout occupancy (Isaak *et al.* 2010). Modeled patches do not necessarily represent actual bull trout presence or absence; model validation has not yet been completed.

Primary stressors hypothesized to increase sensitivity to climate change included low population viability, low stream connectivity, sediment, low channel complexity, water diversions, low floodplain connectivity, and the presence of non-natives. Sensitivity metrics were summarized by HUC-12 (6th level hydrological unit codes; Figure 17).

We did not consider the adaptive capacity of bull trout because we had insufficient data for such an analysis. However, the ability for bull trout to adapt likely depends on their genetic variation as a foundation for evolutionary and phenotypic responses to climatic change in combination with metapopulation dynamics. It is estimated that to maintain adaptive genetic variation, effective bull trout population size should include a minimum of 50-500 fish (Rieman & Allendorf 2001). Abundance estimates are currently unavailable for the bull trout populations in the study area, but future monitoring could provide the necessary data to estimate the number of spawners. Perhaps more near-term, genetic studies can eventually be used to directly estimate the genetic variation, and particularly the presence of adaptive alleles, in bull trout populations. Until then, we recommend managers seek to maintain sufficient population sizes with the knowledge that larger populations may have greater capacity to adapt to climate changes (Hoffmann & Sgrò 2011). The question of whether those adaptations can be expressed quickly enough to allow for resilient fish populations is left to other studies.

3.2.1.1 Bull Trout Methods: Exposure

Exposure to Increased Temperature. We calculated the percent decrease in the proportion of a patch with AMT < 13°C between baseline time period and the 2040s and between baseline and the 2080s. Bull trout are highly sensitive to warming waters, and population occurrence declines as the size of a patch shrinks (Rieman & McIntyre 1993; Isaak et al. 2010), with presence declining sharply over 13°C (Rieman & Chandler 1999; Jones et al. 2014).

Confidence in metric: moderate-high. Baseline temperature data are well-calibrated to the study area; however, there are several watersheds where few empirical temperature readings were taken (Figure 4). In these areas, historical temperature estimates (and accordingly, future projections) are less reliable. Future temperature data represent only one plausible scenario of warming temperatures. For the scenario considered here, results reflect potential future habitat patch reductions given the threshold temperature documented in the literature.

Exposure to Winter High Flows. Flows are also a controlling factor in bull trout presence and abundance (Peterson et al. 2013). High flows may scour spawning sites, and bull trout may be particularly at risk from increased scour under a changing climate when compared to other salmonids (Goode et al. 2013). For the metric, we took the patch weighted average of the number of days in the winter in which flows are among the highest 5% for the year (W95) for the future time period (either 2040s or 2080s). The patch weighted average (by reach mile) accounts for varied NHD reach lengths (within all patches, mean reach length was 1.2 mi, minimum 0.01, maximum 11.4, SD 1.2); specifically, it is calculated as:

$$weighted\ average_{UA} = \sum_i^I Value_i * le_i \Big/ \sum_i^I le_i \quad , \qquad \text{Equation 1}$$

where, *UA* is the unit of analysis (here, patch), $Value_i$ and le_i are the metric value and length, respectively, for the i^{th} NHD reach, ranging from *i…I* in the *UA*.

In their Bayesian belief network, Peterson *et al.* 2013 chose threshold categories of <1, 1-4, and >4 days of high winter flows based on the observed range of values (0 – 8. 4 days, mean = 0.884 day) in Wenger *et al*. 2011(a). Peterson *et al.* 2013 also states, "A threshold value of two events per winter delineated hydrologic regimes as either predominantly snowmelt (less than two) or mixed rain-on-snow and snowmelt (more than two). The threshold value was based on ad hoc interpretation of the geographic distribution of modeled winter high flow frequencies across the Pacific Northwest and Intermountain West United States. Similar approaches have been used to approximate transition points between so-called hydrologic regimes (e.g., Mantua et al. 2010)."

Confidence in metric: low-moderate. Precipitation projections and flow models have high uncertainty. Combining carbon emission scenario and modeling uncertainties with natural variations in precipitation patterns, estimates of precipitation changes in the pacific northwest range from -6% to +14% (Beechie et al. 2012). Our analysis does not account for this range in future precipitation projections, and the modeled historical W95 used here, when compared to observed data, is only moderately accurate (Mean Absolute Percent Error 22%, Bias -3%; Wenger et al. 2010). We avoided the use of a high flow threshold in measuring exposure, instead using only future projected high flows. However, this does not reduce the amount of uncertainty. Further, whether W95 flows actually lead to scour depend on channel geomorphology and substrate conditions, which we were unable to consider here.

Exposure to Reduced Summer Low Flows. The low flow exposure metric represented the potential for lost habitat from reduced flows with the potential to cause dewatering, reduced floodplain connectivity, or insufficient flow to create pool refugia for juveniles. We calculated the metric as the percent decrease in low flows. Specifically:

$$low\ flow_{reach} = \left(MS_{t0} - MS_{t1} \Big/ MS_{t0} \right) * 100 \quad , \qquad \text{Equation 2}$$

where MS was the mean summer flow in cfs, t_0 was the baseline time period, and t_1 was the future time period (either 2040s or 2080s). We then took the weighted average (by reach mile, Equation 1) of the low flow metric within each patch.

Confidence in metric: low. Modeled MS values are only moderately accurate when compared to observed data (Mean Absolute Percent Error 32%, Bias -10%; Wenger et al. 2010), and issues with uncertainty in precipitation projections persist. Further, the true magnitude of stress from low flows depends on channel morphology, which we were unable to consider here. Again, to partially account for high uncertainty, we avoided the use of a threshold in measuring exposure, instead seeking to calculate the relative reduction in low flows.

Combined Bull Trout Temperature Exposure Index. We used only one metric (percent reduction in thermally-suitable patch) to represent this index, so no combining was necessary and the metric and index were the same.

Combined Bull Trout Flow Exposure Index. We combined the high flow (winter scour) and low flow (summer habitat) metrics by calculating their geometric mean. We did not combine flow with temperature because of the very different nature of temperature and flow effects and because of the much higher uncertainty in flow indices as compared to temperature.

3.2.1.2 Bull Trout Methods: Sensitivity

Stress from Low Population Viability. It is a first principle of population ecology that larger, stronger populations are less susceptible to extinction. We did not have sufficient data to directly map larger, stronger bull trout populations, but we assumed that HUCs with more potential natal patch area (described previously) and HUCs known to be important bull trout habitat were likely bull trout "strongholds". Conversely, we assumed locations with little patch or little sufficient suitable habitat were more sensitive to climate change. We calculated stress from low population viability by combining two measures: 1) the amount of patch in each HUC-12 and 2) the known presence of bull trout or bull trout habitat in a HUC-12.

Greater habitat area has long been associated with reduced risk of extinction (Fahrig 1997). Specifically for bull trout, larger patches are associated with greater likelihood of fish presence (Dunham & Rieman 1999; Rieman & McIntyre 2011). Thus, to represent the amount of patch in each HUC-12, we took the geometric mean of 3 patch length measures (Figure 18 maps the mean of the patch measures and shows a schematic of our approach): 1) the total length (mi) of all patch contained within a given HUC-12 boundary, 2) the longest (mi) patch segment contained within the HUC-12 boundary, and 3) the longest patch (mi) that intersected the HUC-12 boundary (but may have extended beyond the given HUC-12 boundary). We used the geometric mean (the mean of the log-transformed values) because it normalizes the range of the values being averaged.

We then multiplied the calculated patch measure by an "occupancy weight" (Figure 19). We compared three datasets to develop this weight: 1) *Conservation Strategy for Bull Trout* (USFS & USFWS 2013) local populations, 2) Montana Fisheries Information System (MFISH) data estimating abundance of bull trout, and 3) FWS designated bull trout critical habitat. The occupancy weight represented either the known presence of bull trout (MFISH and BTCS) or the assessment of high quality habitat (FWS). BTCS local populations, mapped as aggregations of HUC-12s, represent populations known to be present with both spawning and rearing habitat as determined by the US Fish and Wildlife Service (FWS) and are presumed to be the smallest group of fish likely to reproductively interact on a consistent basis. Local populations are nested within bull trout core areas, which are assumed to provide habitat elements to sustain a group of populations, although core areas can be "simple", containing only one local population. "Complex" core areas, containing more than one local population, are assumed to incorporate genetic and phenotypic diversity amongst connected, interacting local populations (USFS & USFWS 2013). MFISH data are updated annually and report estimated fish abundance for all surveyed streams in Montana (Montana Fish, Wildlife, and Parks 2013). The FWS data identify critical habitat areas considered essential for the conservation of a species listed under the Endangered Species Act; bull trout critical habitat data were from October 19, 2010 (USFWS (US Fish and Wildlife Service) 2010). Both the MFISH and FWS data are mapped at the stream reach scale. We only considered a HUC-12 to have bull trout presence or critical habitat if there were a minimum of 3.1mi (5km) of MFISH stream designated as having common or abundant bull trout or FWS stream designated as critical habitat. We used this length threshold to match our definition of bull trout patch with potential occupancy. We did not include mainstem data in this weighting (Clark Fork River, Bitterroot River, and Blackfoot River) as these are important seasonal overwintering or migratory habitats for sub-adults and adults, but often not year round habitats that support spawning and rearing. We calculated the occupancy weight (*OW*) as 2 + number of datasets showing bull trout or bull trout habitat in the HUC-12; otherwise 1 if no datasets showed presence of bull trout or habitat. Thus *OW* could be assigned the value of 1, 3, 4, or 5.

The final low population viability metric was calculated as:

$$Low\ population_{\mathrm{HUC}} = \max\,(GMP * OW) + 1 - (GMP_{\mathrm{HUC}} * OW_{\mathrm{HUC}}), \qquad \text{Equation 3}$$

where GMP was the geometric mean of the three patch measures (described above) and OW was the occupancy weight (described above).

Confidence in metric: moderate-high. We used combined data from four significant efforts to represent likely high quality bull trout habitat. We overlaid the low population viability metric with all available bull trout redd count data (MFWP fisheries data files, Helena) and there was an excellent match between our metric and the average number of redds surveyed over the past 10 years. We did not account for adfluvial/fluvial vs. resident fish, which may have different habitat "stronghold" needs. These are important demographic characteristics of bull trout and should be considered at a finer scale. However, the majority of known existing populations in the study area are resident mix of resident and fluvial populations with few remaining migratory populations that are considered stable or increasing (USFS & USFWS 2013).

Stress from Barriers (low stream connectivity). Habitat connectivity is recognized as a critical element for population viability (Hanski 1999), and is likely even more critical for metapopulation dynamics in fish species (Fagan 2002). Studies suggest patch-scale persistence of bull trout is influenced by stream connectivity (Dunham & Rieman 1999) and fluvial bull trout particularly rely on connected tributary habitats (Swanberg 1997). Restoring longitudinal connectivity may be one of the best bang-for-buck options for fish conservation (Roni et al. 2002), particularly under a changing climate (Beechie et al. 2012) and especially if coordinated in space and time (Neeson et al. 2015). To date, the Lolo has made good progress on opening up aquatic habitats from partial and complete road-stream crossing barriers (USFS & USFWS 2013). More work is needed, particularly in those watersheds where culvert barriers exist near the confluences of cold-water tributaries and larger, warmer mainstems. In these situations, the culvert can preclude fish movement to cooler tributaries offering refugia from undesirable or lethal mainstem temperature conditions (e.g., Chelgren & Dunham 2015). Ultimately, a more advanced analysis of barriers and culverts would be necessary to identify those that had the greatest impact given passability, downstream barriers, and potential to open new habitat versus restoration costs.

We calculated the low stream connectivity metric as the number of fish barriers per stream length (mi) in each HUC-12. We developed the fish barriers dataset from data provided by three sources: the Forest Service culvert data, Montana Department of Natural Resources and Conservation (DNRC) points of water diversion data, and the Montana Dams dataset.

The Forest Service Region 1 Fish Passage Database provided an inventory of many culverts on fish bearing streams on the Lolo and Beaverhead-Deerlodge National Forests thought to pose the greatest threat to connectivity including stream segments of known or probable bull trout presence and where there was potential habitat upstream (Hendrickson et al. 2008). We queried the database for any culvert rated as a barrier to fish during either the adult or juvenile life stage (TOTAL=Barrier at all flows; RED=Barrier at some flows; ORANGE=Partial barrier). There were a total of 611 culverts identified as fish barriers.

We retrieved the water rights points of diversion (POD) dataset from the DNRC. We assumed only diversions that were either listed as a dam (210) or diversion dam (58) would be potential barriers to fish, for a total of 268 potential barriers. To reduce over-counting or bias where there were multiple POD points under the same water right, we removed all upstream and self-overlapping points. We maintained the site farthest downstream, assuming the farthest downstream barrier would restrict any further fish movement upstream, leaving a total of 144 unique POD fish barrier locations.

We retrieved the Montana Dams dataset from the Montana GIS Portal (gisportal.msl.mt.gov/), which provides a statewide spatial coverage of Montana dams. In 2003, Montana Fish, Wildlife and Parks compiled this dataset from two prior datasets, the National Inventory of Dams, (U.S. Army Corps of Engineers 2001) and the dams feature class from the Geographic Names Information System, (U.S. Geological Survey 2000). There were 43 unique points identified in the dams dataset for our study site. We overlaid this dataset with the previously modified POD dataset and buffered each dam point by 0.6mi (1 km). Where the information was available, the dam ownership and water body names were compared to the POD points falling within the 0.6mi buffer. Any dam points matching the POD points were removed, with the assumption that the POD points are more spatially accurate. Of the original 43 dam points, 16 remained after this process.

We merged all three modified datasets (FS fish passage, POD, Montana Dams) into one layer to create the fish barriers dataset, for a total of 771 fish barrier points (Figure 20).

Confidence in metric: moderate-high. LNF has been one of the more aggressive forests in Western Montana to systematically quantitatively assess numerous road crossings, prioritize them for restoration, and track accomplishments (Hendrickson et al. 2008). However, refinements are necessary to move beyond potential miles of stream blocked to fish access to better quantification of biological risk. National pilots are underway to better quantify these risks. Further, many, but not all, dams present significant barriers to fish. Dam impacts to fish passage are less well known within the study area.

Stress from Sediment. Sediment may have lethal consequences for bull trout and other salmonids through direct mortality, reduced fry survival, and loss of habitat. Other sub-lethal impacts include reduced growth rates, increases disease, and physiological stress from biophysical impacts as well as behavioral changes to avoid areas with high fine sediment loads (see review of literature provided in Muck 2010). We had insufficient data to consider fire effects on increased sediment delivery, something likely to increase under a changing climate (Goode et al. 2012). Wildfire may also relate to stream warming, although recent studies suggest that wildfire may contribute relatively little to water temperatures compared to direct effects from increased air temperatures (Holsinger et al. 2014). Wildfire is also noted as a fundamental agent of disturbance that potentially influences heterogeneity, diversity, and productivity in aquatic ecosystems (Rieman et al. 2012). Landslides and mass wasting are also potential contributors to in-stream sediment, but slope failure is not a predominant source of disturbance in the study area (pers. comm. Traci Sylte, November 2013). Thus, given insufficient data, we did not pursue development of a metric for this sediment source.

Here, we focused on available road data given that roads, particularly unpaved, may increase sediment delivery by an order of magnitude, with the majority of sediment load occurring at road-stream crossings (MacDonald & Coe 2008). Culvert failure poses an additional significant risk for increased in-stream sediment. Roads parallel to streams may also contribute sediment, but only if they are proximate or hydrologically connected to the stream through gullying (MacDonald & Coe 2008). Recent forest road survey projects, including one in the study area, found the greatest sediment effects were at crossings or from parallel roads within the near-stream environment (generally, within 30 feet)(Montana DEQ 2008; Cissel et al. 2013).

We selected roads within 100 feet of streams as the metric of sediment delivery risk. The amount of fine sediment from road systems that reach stream channels is typically exponentially reduced as the distance between the road segments and the streams increases (Akay et al. 2008; Elliot et al. 2010). We chose 100 feet as the distance from roads to be conservative and because it is an intermediate distance given other management direction and can refer to sediment issues arising as far as 300 feet from roads (USFWS 1998).

This metric is not a precise measurement of the quantity of fine sediment that is delivered to waterways, nor is the 100-foot distance a known threshold between effect and no effect. Certainly, hillslope, geology, road design, location, condition, use, and maintenance status can all interact to influence fine sediment delivery to streams. In the field, road slope, underlying geology, and distance to the stream are most correlated with sediment delivery (Luce & Black 1999; Fu et al. 2010). However, the accuracy of the road data used is +/- 150 feet; therefore, overlaying them on relatively confined areas of geologic risk could add bias to our analysis. Further, data for landslide potential were not available across the entire study area (but see Figure 28). Lastly, we did not have information as to whether parallel roads further than 100 feet from a stream were hydrologically connected (e.g., whether gullying occurred). Therefore, we opted to use a simple measure of length (mi) of roads within 100 feet of streams per the total length (mi) of streams within each HUC-12 to avoid unnecessary complications and potential biases from road location inaccuracies. We also counted the number of road stream crossings per the total length (mi) of streams within each HUC-12. We included all roads, regardless of surface type, because although paved roads may have less surface erosion, they can contribute to in-stream sediment increases through sanding and accelerated erosion problems.

We combined the two road sub-metrics into the sediment metric by calculating the geometric mean. Because the sub-metrics could have zero values and the geometric mean is a multiplicative function, we added 0.01 to the sub-metrics before taking the geometric mean.

For road data, we compiled a dataset representing all roads in the study area (Figure 21) by combining three road data sources: 1) LNF roads, obtained from the INFRA database on November 18, 2013; 2) Region 1 road dataset, updated July 2011, and obtained from the R1 website; and 3) roads from the U.S. Census Bureau 2000 TIGER files. We used the Lolo NF roads as the primary dataset as they were most finely resolved and recently updated. We used only roads coded as "Existing" (we did not include decommissioned, converted, planned, or roads with no status listing). However, these data did not cover all roads on private lands nor did they cover all areas of the study area. Therefore, we selected out all R1 roads (also coded as "Existing") that were <20 meters from the Lolo roads but not connected to another R1 dataset road >20 m from a Lolo road. We used 20m because this was the approximate maximum spatial error between the two datasets. We assumed R1 roads <20 m from the Lolo dataset roads, but connected to a R1 road that was >20m from a Lolo dataset road, were likely intersections where the R1 data displayed a spur road not included in the Lolo NF dataset. We assumed those <20m but not connected to a more distant R1 road were duplicates, running parallel to the Lolo NF roads, and we removed these from the dataset. We merged the remaining R1 roads with the Lolo roads. We then did a similar spatial comparison between the Tiger 2000 roads and the merged Lolo and R1 roads, but we instead used a distance of 30m because the Tiger data were more spatially off-set from the Lolo NF road data. We merged the remaining Tiger road data with the forest service road data to create a final estimate of all roads in the study area. We note that our approach did not remove all duplicate road segments; however, remaining duplicate roads are mostly in areas of high paved road density (cities and towns) and do not tend to occur in areas of high forest road density (because the R1 dataset was mostly spatially coincident with the Lolo NF data and the less spatially-accurate Tiger data did not cover many forested areas). Our approach also tended to remove some road segments at intersections leaving a gap in road data. Stream data were from the NHD.

Confidence in metric: moderate. There are other controlling factors that determine sediment delivery, including fire, slope and slope instability, road type, and gullying. A detailed assessment of roads and other sediment sources was not possible. This metric captures what are known primary sources of sediment in the study area. Road data are moderately inaccurate, but metric of combined road crossings and parallel road mi should reflect relative stress from road-caused sediment.

Stress from Low Channel Complexity (low physical complexity). This metric represents increased bull trout sensitivity to climate change arising from anthropogenic and natural stressors that reduce channel complexity and riparian structure, thereby reducing habitat quality. The metric incorporated four metrics: riparian cover, two separate metrics concerning roads near streams, and grazing near streams. Fire can also have significant implications for riparian vegetation and stream cooling (Isaak et al. 2010). However, to avoid introducing greater uncertainty into our methods, we avoided sensitivity metrics which required projection models, as would fire, instead relying on metrics that reflect current conditions. Further, recent studies suggest bull trout have recovered relatively easily from past fire effects (Sestrich 2005; Holsinger et al. 2014; Eby et al. 2014).

Riparian vegetation provides large woody debris (LWD) input into channels, increasing habitat complexity and quality for bull trout and potentially providing pools that provide thermal refugia (Watson & Hillman 1997; Hauer et al. 1999). Further, riparian shading has the potential to mitigate increases in water temperatures. For the riparian vegetation metric, we calculated the percent of area in each HUC-12 that did not have riparian cover within a 150 ft. buffer on either side of the stream. To determine riparian vegetation, we retrieved two vegetation cover datasets from the Forest Service Northern Region GIS Library on January 17, 2014. We combined the R1-VMap (Versions 11 and 12, 15m resolution) and Landfire (Version 1.1.0, 90m resolution) datasets to cover the entire study area. VMap is a vegetation layer for all Region 1 forests and grasslands, with intended uses at broad, mid- and project levels of analysis. Landfire data are the best available vegetation data for non-Forest Service lands. We merged these datasets to develop a generalized riparian dataset which identifies potential "shade" and "non-shade" vegetation cover along riparian areas in our full study site at a 15m resolution within LNF boundaries and 90m resolution outside of LNF boundaries. The mid-level VMap data comprises the majority of the dataset. Using the ArcGIS Spatial Analyst Reclassify tool, we reclassified the Landfire raster into Shade [1] – TREE (4000), SHRUB (3300); and Non-Shade [2] – HERB (3100), SPVEG (7000), WATER (5000). This was converted to a vector dataset to merge with the VMap vector dataset (reorganized in the same shade/non-shade groupings). We then identified shade and non-shade vegetation within a 150 ft. riparian buffer on either side of the NHD streams. The buffer size was determined based on positional accuracies of the NHD and R1 VMap datasets and literature reviews for recommended buffer size in adequate stream shading at mid-latitudes (DeWalle 2010).

We included two separate metrics of roads near streams because of the various mechanisms through which roads can reduce channel complexity, thereby reducing bull trout habitat quality (Dunham & Rieman 1999). First, we quantified the amount of road that was either within stand potential tree height (SPTH; we assumed 100 ft.) or within the 100-year flood plain, whichever was greater. We calculated the metric of the length of road (mi) in these areas per the total stream length (mi) in each HUC-12. Roads within the SPTH from a river may reduce the amount of large wood contributed to neighboring stream, thereby reducing habitat complexity (Fausch & Northcote 1992; Czarnomski et al. 2008; Meredith et al. 2014). Roads can also result in channel confinement, reducing sinuosity in low gradient streams. Salmonids have demonstrated a habitat preference for highly sinuous, low gradient areas, which provide high quality, complex habitat, important for spawning and rearing (Fukushima 2001; Quinn 2005). We included a second metric to account for this, quantifying the amount of road in low-gradient reaches within SPTH. We considered anything with a slope of <=4% to be low-gradient (Rosgen 1994; Montgomery & Buffington 1997). The metric was calculated as the length of road (mi) in these areas per the total low-gradient stream length (mi) in each HUC-12.

To calculate these metrics we used the road data described above (see Stress from Sediment section). To estimate the 100-year floodplain, we applied the landscape scale valley confinement algorithm of Nagel et al. (2014) (Figure 22). The algorithm estimates unconfined valley bottoms (UVB) from elevation and stream data in a GIS. We used the NHD streams and 30m National Elevation Dataset (NED) data packaged with the NHD dataset. The UVB algorithm calculates a first-pass estimate of UVB using a GIS cost-distance approach (distance from stream times ground slope), and results are then refined using a valley-filling procedure where a valley is "flooded" to a set flood height above the stream channel elevation. The flood height is set as a user-defined "flood factor" multiplied by bankfull depth. We used a flood factor of 5 in this analysis. The flood height is spread outward from the stream until it intersects a valley wall, and is further confined by a user-defined maximum ground slope, which we set to 5%. We used an annual mean precipitation value of 136 cm for the study area, and all other variables in the algorithm were set to defaults. Further details on the algorithm can be found in Nagel et al. (2014). We used the percent slope calculated as part of the UVB algorithm (using the 30m NED data).

Grazing reduces riparian vegetation and LWD input, increases flooding, contributes to sedimentation, and may widen and shallow the stream (see list of references in Beechie et al. 2012), thereby reducing fish production and growth (Keller & Burnham 1982). Grazing on low-gradient streams may pose particular risk to aquatic habitat because low-gradient reaches are generally depositional with finer textured soils that can be more easily mobilized from livestock trampling; further these areas depend more on riparian vegetation for channel stability (Rosgen 1994). Finally, livestock may preferentially choose these areas for ease of river crossing and desirable forage. To calculate the grazing metric, we calculated the area (mi^2) of grazing allotments that were within SPTH (30m from a stream) and on less than a 4% slope as a proportion of total stream length (mi) on less than 4% slope within each HUC-12. Grazing allotment data were obtained from the LNF, updated January 4, 2008 and the Beaverhead-Deerlodge National Forest from 2003. Because not all grazing allotments have substantial streamside impacts, we used expert opinion review to determine where there were no impacts despite grazing within the riparian area of a HUC-12. These HUC-12s were given a grazing metric value of 0.00 (Figure 23).

We combined the riparian vegetation, roads within SPTH or the floodplain, roads within the SPTH and on low gradients, and grazing on low gradient sub-metrics into the physical complexity metric by calculating the geometric mean. Because the sub-metrics could have zero values and the geometric mean is a multiplicative function, we added 0.01 to the sub-metrics before taking the geometric mean.

Confidence in metric: low-moderate. There are many controls on channel complexity; the metrics here only capture a few potential effects. The relatively coarse riparian vegetation data averaged over a watershed, however likely represent a reasonable proxy for riparian shade and LWD input. A detailed assessment of roads was not possible, but the road data are moderately accurate. Grazing data are also coarse, but again the metric likely captures relative impacts across HUCs.

Stress from Water Diversions. Substantial reduction of summer flows can reduce juvenile salmonid survival (May & Lee 2004) and reduce spawning and migration habitat. Areas with existing low summer flows are particularly sensitive to further reductions. Further, climate induced changes to flow may compound increasing water temperatures. We considered water diversions as the primary non-climatic cause of low baseflows. The rate of diversion for granted water rights may outstrip water availability, and in some instances, more water may be diverted than is allowed by right. Although, streams with high groundwater inputs may be buffered from reduced summer flows, we did not have sufficient data to consider groundwater contributions.

To calculate the water diversion metric, for each HUC-12, we summed the flow rate (CFS) for all unique water right diversion locations and calculated the maximum of the MS flow (CFS) from the US flow metric dataset for the baseline time period (Figure 24). We then calculated the water diversion metric as the proportion of diversionary flow rate to MS flow for each HUC-12:

$$\text{Water diversion}_{\text{HUC}} = \sum_{HUC} POD\ flow\ rate \Big/ \max_{HUC}(\ reach\ MS\ flow), \qquad \text{Equation 4}$$

We obtained water rights data from the Montana DNRC (2013). From the points of diversion (POD) data, we selected out 10,689 POD that were within our study area, were active or pending surface water rights and that were diversionary (not inlake or instream). We obtained allowable maximum flow rate or volume data for each unique water right from the point of use (POU) dataset. Because each unique water right can have multiple PODs, we assigned the entire allowed diversionary amount to the farthest downstream diversion location, resulting in 6,022 unique water right PODs. Of these, 3,817 had associated maximum allowable flow rate data (we converted data in Gallons per Minute [GPM] to cubic feet per second [CFS] as necessary; 1 CFS = 448.8 GPM). An additional 82 points had associated maximum allowable diversionary volume but no flow rate data. Given the near perfect linear relationship between allowable flow rate and volume within the data (N = 2,716; flow rate cfs = 438.3+ 0.62*volume; R^2 = 0.99, P-value = 3.8E-41), we were able to transform volume to flow rate where necessary, giving us a total of 3,899 POD with flow rate data (Figure 24). There were 22 (out of 223 HUC-12s) with insufficient data to calculate the diversion metric. For these HUCS, we used the average metric value (2.08).

There are several caveats associated with our diversion metric. First, the USFS flow metric dataset does not include metrics for mainstem rivers. However, the majority of streams in this assessment are tributaries, which are more likely to be on lands under USFS ownership and therefore the focus of this analysis. Second, we do not have data on the percentage of water associated with a given water right that is diverted across multiple PODs. Assigning the entire allowable diversion to the furthest downstream point may bias our measure against non-headwater HUCs. Most PODs for a unique water right do lie within the same HUC, however, thereby minimizing this bias. Finally, we have maximum flow rate data for only 65% of the known unique water right PODs in our study area. In particular, there are a large number of PODs without flow rate data in the vicinity of the Blackfoot River. While this affects mapping of the metric, the majority of the missing data represented diversion types that generally have low flow rates or maximum diversionary volumes, such as wildlife or stock water use direct from the stream (67%; Table 3). The diversion metric is likely conservative: we do not account for instream flow reservations and “paper water rights” do not necessarily translate to actual water withdrawals. Nonetheless, the metric is useful for relative comparisons between watersheds.

Confidence in metric: moderate-low. Water right data are often disordered, and we did not have volumetric diversion rates for many POD - there are over 2,000 POD in the study area without flow data, thus there may be locations with substantial diversion that are not reflected in our dataset. Further, because a water right could be divided amongst multiple PODs and we assigned the diversion to the furthest downstream point, there are likely to be locations where greater impacts are likely to occur beyond those mapped here.

Stress from Low Floodplain Connectivity. Because of their water temperature sensitivity, bull trout presence may be associated with alluvial valleys that provide for cold upwelling water (Watson & Hillman 1997; Baxter & Hauer 2000). Floodplains also provide necessary off-channel habitat for spawning and rearing. Floodplain connectivity can be affected by management actions (e.g., mining, grazing or harvest that increases channel incision), but here we focus on current floodplain connectivity as modeled using digital elevation models. We calculated the floodplain connectivity metric as the proportion of stream length in each HUC-12 without a 100-year floodplain adjacent to the channel area. We estimated the 100-year floodplain as described above (see Stress from Low Channel Complexity section).

Confidence in Metric: moderate. Experts reviewed our estimated floodplain locations, and we compared outputs with FEMA maps and geologic maps of stream bottoms. We do not submit that the estimated floodplain locations are completely accurate, but believe the metric captures the relative relationship between streams and floodplains well. However, we are less certain that floodplain connectivity directly effects sensitivity of bull trout to climatic changes.

Stress from Non-Natives (brook trout). Non-native brook trout (*Salvenius fontinalis*) are the primary invasive threatening bull trout in the study area. There is evidence that brook displace bull trout (Wenger et al. 2011), particularly to higher elevations (Rieman et al. 2006), and may hybridize with bull trout (Kanda et al. 2002).

We calculated a binary metric of brook trout presence or absence using MFISH data. We considered any HUC-12 with a minimum of 3.1mi (5km) of reach designated as having abundant or common brook trout to be occupied by brook trout.

Confidence in metric: low-moderate. MFISH data do not provide a comprehensive assessment of brook trout occupancy or abundance, and our binary metrics provides only a very-limited estimate of brook trout effects on bull trout sensitivity to climatic changes.

Combined Bull Trout Sensitivity Index. We calculated the combined sensitivity index by calculating the geometric mean of the low population viability, low stream connectivity, sediment, low physical complexity, low baseflow, low floodplain connectivity, and brook trout sensitivity metrics. We added 0.01 to metrics before taking the geometric mean.

Our assessment of bull trout sensitivity did not include a number of factors important to bull trout habitat and resilience. These include the impacts to habitat from fires or mass wasting (which are interrelated). We did not have sufficient data on fire potential for the study area. However, the study area is not particularly fire or slide prone. Disease may be another major factor affecting bull trout as waters warm, but data are lacking.

3.2.1.3 Bull Trout Methods: Vulnerability

For bull trout (and all resource values), we mapped vulnerability by comparing exposure and sensitivity indices on the basis of a clustering algorithm. See the Conceptual Models and General Methods section, above, for details on how we chose “low” and “high” index clusters. We then mapped five categories of vulnerability: 1) areas with low exposure, assuming they would have low vulnerability to climate change, 2) moderate exposure and low sensitivity, 3) moderate exposure and high sensitivity, 4) high exposure and low sensitivity, and 5) areas with highest vulnerability – those with high exposure and high sensitivity. For bull trout, we assessed vulnerability separately for temperature and flow because of the very different nature of temperature and flow exposure effects and because of the much higher uncertainty in flow indices as compared to temperature. We mapped vulnerability by patch (patch exposure ranking vs. HUC-12 sensitivity ranking).

3.2.2 Water Supply Methods

Projected shifts in hydrological regimes may reduce availability of water for all uses, including instream flows for aquatic ecosystems, groundwater recharge supporting wetland ecosystems, municipal and public water supplies – in addition to Forest Service potable water systems, and irrigation diversions. Although we are not able to quantify ecosystem water supply requirements, there are 6,813 total active, diversionary, surface water right points of diversion (POD) in the study area. These are summarized by type of diversion and purpose of diversion in Table 4 and Table 5, respectively.

For water supply, we conceptualized three primary potential stressors (Figure 25 in Appendix 2). Climate-driven stressors include exposure to reduced mean summer flows and reduced length of water availability throughout the water year as a result of shifting hydrological regime. We considered water diversions (that may outstrip water supply) as the single sensitivity stressor.

3.2.2.1 Water Supply Methods: Exposure

Exposure to Reduced Summer Flows. Reduced summer flows may impact water supplies when both instream and diversionary water needs are greatest. We calculated the metric as the percent decrease in summer low flows, as described in Equation 2, above. We then took the weighted average (by reach mile, Equation 1) low flow metric for each HUC-12.

Confidence in metric: low. Modeled MS values are only moderately accurate when compared to observed data (Mean Absolute Percent Error 32%, Bias -10%; Wenger et al. 2010), and issues with uncertainty in precipitation projections persist. Further, channel morphology can also affect stress from low flows, , which we were unable to consider here (i.e. wide, uniform, shallow-flow-depth channels pose higher risks than more narrow, complex, deeper-flow-depth channels). To partially account for high uncertainty, we avoided the use of a threshold in measuring exposure, instead seeking to calculate the relative reduction in low flows.

Exposure to Reduced Length of Water Availability. Changes in temperature and precipitation are expected to result in hydrological shifts, particularly to hydrographs with earlier peaks and reduced summer flows (Mantua et al. 2010; Wu et al. 2012). This may impact water supply sufficiency during summer, again when demands are greatest. We calculated the flow timing metric as the projected earlier shift in the center of flow mass of the hydrograph, specifically:

$$flow\ timing_{reach} = (CFM_{t1} - CFM_{t0}), \quad \text{Equation 5}$$

where CFM is the day of the water year when 50% of the flow had passed, t_0 was the baseline time period, and t_1 was the future time period (either 2040s or 2080s). We then took the weighted average (by reach mile, Equation 1) of the flow timing metric for each HUC-12.

Confidence in metric: low-moderate. This measure had a median error of 12 days when compared to observed data, with a negative bias for snowmelt (i.e., the model predicts melt to occur too early) (Wenger et al. 2010). Although nominally uncertain, there are many lines of evidence suggesting an earlier shift in the hydrograph and almost all studies project the same hydrologic signature relative to shifts in flow timing (Hamlet & Lettenmaier 2007; Wu et al. 2012). This metric likely captures the approximate spatial pattern of potential future shifts.

Combined Water Supply Exposure Index. We combined the low flow and flow timing metrics by calculating the geometric mean of the flow exposure (low flow and flow timing) metrics.

3.2.2.2 Water Supply Methods: Sensitivity

Stress from Water Diversions. We assessed water supply in part to ensure adequate water supply for diversionary uses; however, excessive diversions have a direct impact on sufficient supply for both consumptive and in stream water needs. Methods for calculating the water diversion metric are described above under the water diversion metric for bull trout (Equation 4). However, the study area for water supply was smaller than that for bull trout, so the number of diversions was lower. Briefly, we summed the flow rate (CFS) for all unique water right diversion locations and calculated the maximum of the MS flow (CFS) from the US flow metric dataset for the baseline time period (Figure 24). We then calculated the water diversion metric as the proportion of diversionary flow rate to MS flow for each HUC-12. For the water supply analysis study area, there were a total of 6,813 POD (Table 4, Table 5) locations representing 4,219 unique water rights. Of the 4,219 downstream unique water right POD locations, we were able to obtain or calculate flow rate data for 2,967 POD. The caveats for this metric are the same as described for the water diversion metric under the bull trout analysis. Although, for the smaller study area, we had flow rate data for a higher percentage (70% vs. 65%) of the POD. In the water supply study area, 17 HUCs did not have sufficient data for calculating the diversion metric. For those 17, we used the average metric value in the study area (1.87).

Confidence in metric: low-moderate. Water right data are often disordered, and we did not have volumetric diversion rates for many POD - there are over 1,00 POD in the study area without flow data, thus there may be locations with substantial diversion that are not reflected in our dataset. Further, because a water right could be divided amongst multiple PODs and we assigned the diversion to the furthest downstream point, there are likely to be locations where greater impacts are likely to occur beyond those mapped here. We did not consider effects of impoundments on water supply, but we provide a table of HUCs containing impoundments (Table 6).

Combined Water Supply Sensitivity Index. We used only one metric (water diversions) to represent this index, so no combining was necessary and the metric and index were the same.

3.2.2.3 Water Supply Methods: Vulnerability

We mapped vulnerability by comparing exposure and sensitivity indices on the basis of a clustering algorithm. See the Conceptual Models and General Methods section, above, for details on how we chose "low" and "high" index clusters. We then mapped five categories of vulnerability: 1) areas with low exposure, assuming they would have low vulnerability to climate change, 2) moderate exposure and low sensitivity, 3) moderate exposure and high sensitivity, 4) high exposure and low sensitivity, and 5) relatively high vulnerability – areas with high exposure and high sensitivity.

3.2.3 Infrastructure Methods

We conducted the analysis for three infrastructure types: recreation sites, trails, and forest jurisdiction roads. The LNF is responsible for maintaining over 8,900 mi of roads, 1,698 mi of trails, and almost 300 recreation sites, including trailheads, loading ramps, campgrounds and picnic areas. Changes in hydrologic regime as a result of climate change will make some of this infrastructure more vulnerable to flooding. Our analysis aims to identify the areas within the forest that are relatively more vulnerable in order to better prioritize those areas for future planning and management.

We obtained infrastructure data from the LNF GIS data manager in January 2014. We selected out the 297 recreation sites managed by the LNF that fell within our study area (Figure 26 and Table 7, Appendices 2 and 1, respectively). We also assessed vulnerability of 1,698 mi of trails (Figure 26, Table 8) and 8,997 mi of roads. For the roads, we only assessed those with route status = "existing", jurisdiction = "Forest Service", and system = "National Forest System Roads" (NFSR; 'System') or "undetermined" or "not needed" ('Non-System') (Figure 26, Table 9).

For infrastructure, we conceptualized three primary potential stressors to recreation sites and trails, with an additional fourth stressor for roads (Figure 27). We presumed a single climate-driven stressor related to potential of flooding from high winter flows (including increased rain on snow events). The primary stressors we identified as contributing to infrastructure sensitivity to flooding include infrastructure being located in the floodplain or in an area considered to have high geologic hazard, and for roads, the number of culverts that may contribute to wash-outs.

3.2.3.1 *Infrastructure Methods: Exposure*

Exposure to Winter Flooding. Flooding is the most imminent threat to infrastructure under a changing climate. We calculated the flooding exposure metric following the methods detailed for bull trout, above. We used the number of days in winter in which flows are among the highest 5% for the year (the W95 stream flow metric) as a proxy for increased likelihood of rain-on-snow events. However, instead of taking a weighted average of the flooding metric (by reach mile, Equation 1) over a patch, we took the weighted average over each HUC-12. We used the HUC-12 as the unit of analysis because exposure to flooding can affect infrastructure throughout the watershed, not just near streams. Because the flooding exposure metric was calculated across each HUC-12, it was the same for all three infrastructure types. We used only one metric (flooding) to represent the exposure index, so the metric and index were the same.

Confidence in metric: low. Precipitation projections and flow models have high uncertainty. Combining carbon emission scenario and modeling uncertainties with natural variations in precipitation patterns, estimates of precipitation changes in the pacific northwest range from -6% to +14% (Beechie et al. 2012). Our analysis does not account for this range in future precipitation projections, and the modeled historical W95 used here, when compared to observed data, is only moderately accurate (Mean Absolute Percent Error 22%, Bias -3%; Wenger et al. 2010). We avoided the use of a high flow threshold in measuring exposure, instead using only future projected high flows. However, this does not reduce the amount of uncertainty. Further, whether W95 flows actually lead to scour depend on channel geomorphology and substrate conditions, which we were unable to consider here.

3.2.3.2 *Infrastructure Methods: Sensitivity*

Stress from Proximity to Floodplain. Recreation sites, trails, and roads that are in flood prone areas are more more likely to suffer damage. We counted the number of recreation sites or the length (mi) of trails and roads that fell within the 100-year floodplain in each HUC-12.

To estimate the 100-year floodplain, we applied the landscape scale valley confinement algorithm of Nagel et al. (2014). The algorithm estimates unconfined valley bottoms (UVB) from elevation and stream data in a GIS (Figure 22). We used the NHD streams and 30m NED data packaged with the NHD dataset. The UVB algorithm calculates a first-pass estimate of UVB using a GIS cost-distance approach (distance from stream times ground slope), and results are then refined using a valley-filling procedure where a valley is “flooded” to a set flood height above the stream channel elevation. The flood height is set as a user-defined “flood factor” multiplied by bankfull depth. We used a flood factor of 5 in this analysis. The flood height is spread outward from the stream until it intersects a valley wall, and is further confined by a user-defined maximum ground slope, which we set to 5%. We used an annual mean precipitation value of 53.5 in (136 cm) for the study area, and all other variables in the algorithm were set to defaults. Further details on the algorithm can be found in Nagel et al. (2014). We used the percent slope calculated as part of the UVB algorithm (using the 30m NED data).

Confidence in Metric: moderate-high. Experts reviewed our estimated floodplain locations, and we compared outputs with FEMA maps and geologic maps of stream bottoms.

Stress from Geologic Hazards. Recreation sites, trails, and roads that overlay areas of unstable geology, soils, and slopes are more sensitive to flood impacts. We counted the number of recreation sites or the length (mi) of trails and roads that were on areas rates as high geologic hazard or on alluvial fans. Areas of high geologic hazard were determined from the LNF's Land System Inventory (LSI; Sasich & Lamotte-Hagen 1989) (Figure 28). The LSI is a comprehensive inventory of soil and vegetation resources for managers on the LNF. It was designed as a tool for identification of areas that require special management treatment and on-site evaluation. We used a recent spreadsheet that refines and categorizes the LSI descriptions for areas identified as high, moderate and low geologic hazard based on propensity for landslides and avalanches. In addition, we identified the areas classified as alluvial fans as high hazard because streams on fans have a higher likelihood of avulsion (i.e., stream flow may abandon the current channel).

Confidence in Metric: moderate. The LSI has been used and field- verified over the years since it was developed. The LSI is generally accurate at coarser scales; however, hazards may differ at finer scales.

Stress from Culvert Failure. Undersized culverts are a primary cause of road damage during floods. We calculated the number of culverts per road mi in each HUC-12 (Table 9). Location data for 6,681 existing culverts were obtained from the USFS INFRA (infrastructure) database on December 31, 2013. We selected only those culverts within 10m of roads used in the infrastructure analysis (as described above), for a total of 6,358 culverts.

Confidence in Metric: moderate-high. The most direct hydrologic connection between roads and stream channels occurs at road-stream crossings (Furniss et al. 2000). Road impacts are especially prevalent where crossings are undersized and prone to failure. Data collected in USFS Region 1 suggest that approximately 90% of culverts constrict the active channel width (Hendrickson et al. 2008). Constriction of the active channel width is a primary indicator of culvert failure risk (USFS (US Department of Agriculture, Forest Service) 2008). The LNF has been one of the more aggressive forests in Western Montana in systematically assessing road crossings, prioritizing them for mitigation, and replacing nearly 90 undersized culverts. Because of the assessment extent, individual culvert condition and risk are not addressed within this assessment; however, the numbers of crossings that occur on each road remain an appropriate and strong indicator of infrastructure risk.

Combined Infrastructure Sensitivity Index. We calculated the combined sensitivity index by calculating the geometric mean of the flashiness, floodplain, and geologic hazard sensitivity metrics. For road infrastructure, the geometric mean also included the culvert metric. We added 0.01 to metrics before taking the geometric mean.

3.2.3.3 *Infrastructure Methods: Vulnerability*

We mapped vulnerability by comparing exposure and sensitivity indices on the basis of a clustering algorithm. See the Conceptual Models and General Methods section, above, for details on how we chose “low” and “high” index clusters. We then mapped five categories of vulnerability: 1) areas with low exposure, assuming they would have low vulnerability to climate change, 2) moderate exposure and low sensitivity, 3) moderate exposure and high sensitivity, 4) high exposure and low sensitivity, and 5) relatively high vulnerability – areas with high exposure and high sensitivity.

4. FINDINGS

Results of the vulnerability assessment should be interpreted as hypotheses about relative impacts from potential climatic exposure and the potential sensitivity to that exposure. As with all initial hypotheses, they should be reassessed as additional information becomes available. The vulnerability assessment results are relative, not nominal, and results are dependent on the assumptions made herein. Both the exposure and sensitivity metrics have associated uncertainty, as detailed in the Methods sections above and as indicated in figure captions. Vulnerability maps should be viewed alongside the exposure and sensitivity maps on which they are based. Management decisions potentially require tradeoffs and prioritization between resources and locations. Managers are encouraged to exercise judgment when using these findings, recognizing their uncertainty and using an adaptive management approach that includes monitoring, feedback, and continued reevaluation as climatic conditions shift.

Detailed results are presented in tables and figures listed in Appendix 1 and 2, respectively, and can be found in the supplementary materials on the accompanying CD or on-line at: http://www.fs.usda.gov/main/lolo/workingtogether. Results for the unit of analysis for water supply and infrastructure exposure and all sensitivity metrics – 6th level HUCs (HUC-12) – are provided in the supplementary tables and maps. Results for bull trout exposure unit of analysis – patches – are provided only in supplementary material figures. See Appendix 1, Table 10 for bull trout, Table 11 for water supply, and Table 12 for infrastructure results. See Appendix 2 figures 29-75 for results maps. Exposure results are provided in the supplementary materials for both the 2040s and the 2080s time periods in tables and maps.

In the tables within the body of this report, below, we summarize exposure results only for the 2040s. To summarize results, we averaged metric and index results by local populations for bull trout and by 5th level HUC (HUC-10) for water supply and infrastructure. We binned these results into low, medium, and high exposure or sensitivity based on index value "cluster" as identified in the mapped results (Appendix 2; mapped results were binned into 5 categories using the "natural breaks" algorithm, explained in the Methods section; for tables, below, we assumed lowest two bins were "low" and highest two bins were "high" exposure or sensitivity). For the following summary tables, we assumed metric or index values in clusters 1 or 2 had low, cluster 3 had moderate, and clusters 4 or 5 had high exposure or sensitivity. We only determined overall vulnerability for the 2040s time period.

4.1 AQUATIC RESOURCES: BULL TROUT FINDINGS

4.1.1 BULL TROUT FINDINGS: EXPOSURE

We characterized the exposure of bull trout to climate change for the 2040s and 2080s by considering three metrics as described in the Methods section: increased stream temperature, increased winter high flows, and reduced summer low flows.

Exposure to Increased Temperature. Many of the patches with the greatest exposure to high temperatures in 2040 were located in areas of lower elevation within the watershed and did not fall in a local population (Figure 29 and Table 10 in Appendices 2 and 1, respectively). However, a number of 6th level HUCs (HUC-12) that hold local populations had 30% or more reduction in thermally suitable habitat (patch <13˚C) including: Lolo-Grave Creek, East Fork Clearwater, Upper and Middle Little Thompson Creeks, McGinnis Creek, Grant Creek, West Fork Petty and Eds Creeks, and Upper and Lower South Fork Fish Creeks. Table F.1 (below) shows results averaged by local population (but in the case of East Fork Clearwater and Grant Creek, these are results from the single stream in that area rather than averages). Local populations in Rock Creek, upper Blackfoot (North Fork, Monture, Cottonwood and Morrell), and lower Clark Fork areas (Trout, Cedar, St. Regis, Prospect and Graves) had lower exposure (0-16% reduction in patch <13 ˚C). However extensive exposure throughout the entire study area, including Rock Creek, was expected under a more severe climate scenario (2080s; Figure 30, Table 10).

Table F.1. Estimated exposure of bull trout local populations to increased temperatures by the 2040s (percent reduction in patch area with temperature > 13°C). Bull trout exposure indices were calculated at the patch level. To summarize, we averaged index values across all patches within each HUC-12 and then took the average of all HUC-12 index values within each local population. Low, moderate, and high bins are based on "natural breaks" algorithm used in mapping results (bin values provided in parentheses). Local populations are not ranked within bins. See Table 10 in supplementary materials for rankings by HUC-12.

Average % reduction in patch<13˚C		
Low Exposure (0 - 16%)	**Moderate** (17 - 28%)	**High Exposure** (29 - 100%)
- North Fork Blackfoot River - Monture Creek - Cottonwood Creek - Gold Creek - West Fork Clearwater - Morrell Creek - Thompson River - Prospect Creek - Graves Creek - Albert Creek - Trout Creek - Cedar Creek - St. Regis River - East Fork Rock Creek - Middle Fork Rock Creek - Ross Fork Rock Creek - West Fork Rock Creek - Stoney Creek - Hogback Creek - Ranch Creek - Welcome Creek - Butte Cabin Creek	- Lolo Creek - Placid Creek - Rattlesnake Creek - Fish Creek	- East Fork Clearwater - Grant Creek - Petty Creek

Exposure to Winter High Flows. Exposure to increased winter high flows by the 2040s was highest in the Albert, Prospect, Thompson, and Cottonwood Creek local populations (Table F.2), and in general was greatest in the western study area extending south along the slopes of the Montana-Idaho border (Figure 31, and Figure 7 for comparison to baseline). By the 2040s, all of the local populations had, on average, more than 1 day of scouring winter flow, and only Gold, Morrell, Grant, Rattlesnake, and East Fork Rock Creek local populations had 2 or fewer days of winter high flows, on average. By the 2080's the number of W95 days increased to 3 or more in these local populations, and 5-9 days, on average, everywhere else (Figure 32).

Table F.2. Estimated exposure of bull trout local populations to high winter flow exposure in the 2040s (winter days of flow in highest 5% for year)

Average days flow highest 5% of year		
Low Exposure (<1 – 2.9)	**Moderate** (3 – 4.9)	**High Exposure** (5 -1 0.7)
- North Fork Blackfoot River	- Lolo Creek	- Cottonwood Creek
- Monture Creek	- East Fork Clearwater	- Thompson River
- Gold Creek	- Placid Creek	- Prospect Creek
- West Fork Clearwater	- Graves Creek	- Albert Creek
- Morrell Creek	- Petty Creek	
- Rattlesnake Creek	- Fish Creek	
- Grant Creek	- Trout Creek	
- East Fork Rock Creek	- Cedar Creek	
- Middle Fork Rock Creek	- St. Regis River	
- Ross Fork Rock Creek	- Stoney Creek	
- West Fork Rock Creek	- Butte Cabin Creek	
- Hogback Creek		
- Ranch Creek		
- Welcome Creek		

Exposure to Reduced Summer Low Flows. For low summer flows, moderate to high reductions of 14-66% in flow in the 2040s were expected for patches in the western study area extending south along the slopes of the Montana-Idaho border (Figure 33). Local populations in Rock Creek and the upper Blackfoot fared better (Table F.3). The pattern remained similar but more intensified by the 2080s (Figure 34).

Table F.3. Estimated exposure of bull trout local populations to low summer flow exposure in the 2040s (percent reduction in mean summer flow)

Average % reduction in low flow		
Low Exposure (4 – 13.9%)	**Moderate** (14 – 19.1%)	**High Exposure** (19.2 – 67%)
- North Fork Blackfoot River - Monture Creek - Cottonwood Creek - Gold Creek - East Fork Clearwater - Grant Creek - Petty Creek - East Fork Rock Creek - Middle Fork Rock Creek - Ross Fork Rock Creek - West Fork Rock Creek - Stoney Creek - Hogback Creek - Ranch Creek - Welcome Creek - Butte Cabin Creek	- West Fork Clearwater - Placid Creek - Thompson River - Rattlesnake Creek - Albert Creek - Trout Creek - Cedar Creek - St. Regis River	- Lolo Creek - Morrell Creek - Prospect Creek - Graves Creek - Fish Creek

Combined Bull Trout Flow Exposure Index. We calculated the combined flow exposure index by taking the geometric mean for the high and low flow metrics for both the 2040s and 2080s (Figure 35 and Figure 36). On average, the highest combined exposure to both high winter flows and reduced low flows in the 2040s was in the Prospect Creek local population, and was also relatively high in Albert Creek and parts of the St. Regis, Lolo, Graves, and Fish Creek local populations. Lowest exposure was in the North Fork Blackfoot, Welcome and Hogback Creek bull trout populations. As exposure increased overall by the 2080s, local populations in Welcome and Hogback Creek and the upper Blackfoot River and Rock Creek were the only areas on the Lolo NF with considerably lower relative exposure.

4.1.2 Bull Trout Findings: Sensitivity

We used seven stressor metrics to evaluate the sensitivity of bull trout to climatic change (see Methods section, above; results summarized in Table F. 1). These included:

1. low population viability metric;
2. low stream connectivity metric;
3. sediment metric that combined sub-metrics for road-stream crossings and roads parallel to streams;
4. low physical complexity metric that combined sub-metrics for riparian cover, roads in the 100-year floodplain or near streams, and roads and grazing near streams on shallow slopes;
5. water diversion metric;
6. low floodplain connectivity metric; and

7. brook trout presence or absence metric.

Stress from Low Population Viability. Because both the calculation of the population viability metric and the delineation of bull trout local populations were on the basis of occupancy – few local populations had extreme low metric values. However, because local populations had differing amounts of thermally suitable habitat patch (and differing FWS critical habitat amounts and MFISH abundance counts; see methods), there were some differences (Figure 37 and Table F.4, below). Graves Creek, Petty Creek, Hogback Creek, and Butte Cabin had some of the highest metric values. In general, higher elevation headwaters were expected to have the best population viability, lowland and river mainstems were expected to have the worst. Four of the five local populations with the lowest stress from population viability, on average, were in the Rock Creek drainage.

Table F.4. Estimated sensitivity of bull trout local populations to low population viability (based on patch size and occupancy). Low, moderate, and high bins are based on "natural breaks" algorithm used in mapping results (bin values provided in parentheses). See Table 10 in supplementary materials for rankings by HUC-12.

Average low population viability metric value		
Low Sensitivity (1 – 155)	**Moderate** (155.1 – 200)	**High Sensitivity** (200.1 – 250.9)
- Monture Creek	- Lolo Creek	- Graves Creek
- Cottonwood Creek	- North Fork Blackfoot River	- Petty Creek
- Morrell Creek	- Gold Creek	- Hogback Creek
- Placid Creek	- East Fork Clearwater	- Butte Cabin Creek
- Prospect Creek	- West Fork Clearwater	
- Rattlesnake Creek	- Thompson River	
- Cedar Creek	- Grant Creek	
- East Fork Rock Creek	- Albert Creek	
- Middle Fork Rock Creek	- Fish Creek	
- Ross Fork Rock Creek	- Trout Creek	
- West Fork Rock Creek	- St. Regis River	
- Stoney Creek	- Welcome Creek	
- Ranch Creek		

Stress from Barriers (low stream connectivity). Stress from low stream connectivity was greatest in the Lolo Creek local population (Figure 38 and Table F.5, below). The stress, as measured here, comes substantially from culverts, as opposed to dams, and discrete locations of these potential fish passage barriers are shown in Figure 38. Local populations that had no anthropogenic barriers included North Fork Blackfoot River, and Grant, Stony, Hogback, and Ranch Creeks.

Table F.5. Estimated sensitivity of bull trout local populations to low stream connectivity (barriers per stream mile)

Average barriers/ stream mile		
Low Sensitivity (0 – 0.1)	**Moderate** (0.2)	**High Sensitivity** (0.3 – 0.8)
- North Fork Blackfoot River - Monture Creek - East Fork Clearwater - West Fork Clearwater - Morrell Creek - Thompson River - Prospect Creek - Graves Creek - Grant Creek - Albert Creek - Petty Creek - Trout Creek - Cedar Creek - East Fork Rock Creek - Middle Fork Rock Creek - Ross Fork Rock Creek - West Fork Rock Creek - Stoney Creek - Hogback Creek - Ranch Creek - Welcome Creek - Butte Cabin Creek	- Cottonwood Creek - Gold Creek - Placid Creek - Rattlesnake Creek - Fish Creek - St. Regis River	- Lolo Creek

Stress from Sediment. Stress from sediment was expected to come from road-stream crossings and roads that run within 100 feet of streams. Portions of the Thompson, St. Regis, Trout, Fish, Petty, Lolo and Morrell Creek local populations had the highest number of road crossings per stream mile (Figure 39). Portions of the Thompson and St. Regis local populations had the greatest likelihood of sediment contribution from parallel roads, and Cedar, Petty and Lolo Creek local populations were also impacted (Figure 40). Combining these two metrics into the sediment metric, the Thompson and St. Regis River and Trout Creek local populations, on average, were expected to have the most sediment stress, followed by Lolo, Placid, and Grant Creek populations (Figure 41 and Table F.6, below).

Table F.6. Estimated sensitivity of bull trout local populations to sediment (based on roads near streams)

Average sediment metric value		
Low Sensitivity (0 – 0.3)	**Moderate** (0.4)	**High Sensitivity** (0.5 – 1.3)
- North Fork Blackfoot River - Monture Creek - Cottonwood Creek - Gold Creek - East Fork Clearwater - West Fork Clearwater - Prospect Creek - Graves Creek - Rattlesnake Creek - Fish Creek - East Fork Rock Creek - Middle Fork Rock Creek - Ross Fork Rock Creek - West Fork Rock Creek - Stoney Creek - Hogback Creek - Ranch Creek - Welcome Creek - Butte Cabin Creek	- Morrell Creek - Placid Creek - Grant Creek - Albert Creek - Petty Creek - Cedar Creek	- Lolo Creek - Thompson River - Trout Creek - St. Regis River

Stress from Low Channel Complexity (low physical complexity). Stress from low physical complexity was defined as a combination of riparian area without shade cover, roads within floodplains or 100 feet of streams, roads within 100 feet of streams and on shallow slopes, and grazing areas within 100 feet of streams and on shallow slopes. Stress due to poor riparian shade cover was generally low in most of the local populations except in portions of Ross Fork and East Fork Rock Creek and North Fork Blackfoot River local populations (Figure 42). Roads within flood plains or 100 feet of streams can reduce channel complexity, and portions of the Thompson, St. Regis, and Lolo populations were likely to be most sensitive to this (Figure 43). With respect to roads within 100 feet of streams and on shallow slopes, the portions of the St. Regis River population was the most sensitive, followed by the Thompson, Prospect and Petty Creek populations (Figure 44). Stress from grazing on shallow slopes near streams was expected to be highest in portions of Albert Creek, Thompson and Lolo populations, and all of the upper Rock Creek populations (Figure 45). Combining all these sub-metrics, only the lower St. Regis local population included a HUC-12 that had the highest level of stress from low physical complexity of channels and riparian areas (Figure 46). Lolo Creek, Grant Creek, Trout Creek, upper St. Regis River and its tributaries, East and West Fork Rock Creek, Stoney Creek and Butte Cabin Creek were moderately stressed, on average, relative to other local populations (Table F.7). On average, North Fork Blackfoot River, and Gold, Prospect, Hogback, and Welcome Creek local populations were least stressed.

Table F.7. Estimated sensitivity of bull trout local populations to low physical (channel) complexity (based on riparian vegetation, roads, slope, and grazing)

Average physical complexity metric value		
Low Sensitivity (0 – 0.4)	**Moderate** (0.5 – 0.7)	**High Sensitivity** (0.8 – 1.8)
- North Fork Blackfoot River - Monture Creek - Cottonwood Creek - Gold Creek - East Fork Clearwater - West Fork Clearwater - Morrell Creek - Placid Creek - Thompson River - Prospect Creek - Graves Creek - Rattlesnake Creek - Albert Creek - Petty Creek - Fish Creek - Cedar Creek - Middle Fork Rock Creek - Ross Fork Rock Creek - Hogback Creek - Ranch Creek - Welcome Creek	- Lolo Creek - Grant Creek - Trout Creek - St. Regis River - East Fork Rock Creek - West Fork Rock Creek - Stoney Creek - Butte Cabin Creek	

Stress from Water Diversions. We hypothesized that water diversions would contribute to reduced base flows, although this impact was not uniformly distributed within local bull trout populations (Figure 47 and Table F.8). Local populations with highest stress from water diversions included Rock Creek in the N. Fork Blackfoot population area, Placid Creek, McGinnis Creek in the Thompson River area, and Grant Creek. The local populations with lowest stress, on average, were Welcome and Butte Cabin Creeks. We note that there are watersheds where local knowledge suggests our methods have underestimated sensitivity (i.e., Lolo Creek is often dewatered). This issue arises because our data were incomplete – we lacked adequate diversion flow quantities in many areas. Managers are reminded that results should be used to complement their knowledge of the area.

Table F.8. Estimated sensitivity of bull trout local populations to water diversions (water diversion flow/mean summer flow)

Average water diversion flow / mean summer flow		
Low Sensitivity (0 – 1.7)	**Moderate** (1.8 – 6)	**High Sensitivity** (6.1 – 40)
- Lolo Creek - North Fork Blackfoot River - Monture Creek - Gold Creek - East Fork Clearwater - West Fork Clearwater - Thompson River - Prospect Creek - Graves Creek - Rattlesnake Creek - Petty Creek - Fish Creek - Trout Creek - Cedar Creek - St. Regis River - Middle Fork Rock Creek - Ross Fork Rock Creek - Stoney Creek - Ranch Creek - Welcome Creek - Butte Cabin Creek	- Cottonwood Creek - Morrell Creek - Thompson River - Albert Creek - East Fork Rock Creek - West Fork Rock Creek - Hogback Creek	- Placid Creek - Grant Creek

Stress from Low Floodplain Connectivity. Stress from low floodplain connectivity is calculated as a percentage of confined stream miles to total stream miles. Therefore, stream systems dominated by a large number of confined tributaries trend as more sensitive, although some tributaries and the main stems may be relatively unconfined. As with all metrics, watershed context dominates this metric, and specific considerations should be accounted with appropriate scale. Bull trout populations in the LNF are generally found in headwater reaches where terrain is steep and streams are relatively confined, thus most of the local populations were rated as high stress for this metric (defined as confined mile per stream mile), especially in the northwestern portion of the study area (Figure 48, Table F.9 below). The local populations with nearly no unconfined streams included Graves, Hogback, and Welcome Creek

Table F.9. Estimated sensitivity of bull trout local populations to low floodplain connectivity (proportion confined stream miles)

Average confined stream miles/stream miles		
Low Sensitivity (0 – 0.6)	**Moderate** (0.7 – 0.8)	**High Sensitivity** (0.9 – 1.0)
	- Monture Creek	- Lolo Creek
	- Cottonwood Creek	- North Fork Blackfoot River
	- Morrell Creek	- Gold Creek
	- Placid Creek	- East Fork Clearwater
	- Grant Creek	- West Fork Clearwater
	- East Fork Rock Creek	- Thompson River
	- Middle Fork Rock Creek	- Prospect Creek
	- Ross Fork Rock Creek	- Graves Creek
	- West Fork Rock Creek	- Rattlesnake Creek
		- Albert Creek
		- Petty Creek
		- Fish Creek
		- Trout Creek
		- Cedar Creek
		- St. Regis River
		- Stoney Creek
		- Hogback Creek
		- Ranch Creek
		- Welcome Creek
		- Butte Cabin Creek

Stress from Non-Natives (brook trout). Stress from brook trout presence was expected to occur throughout many of the local populations (Figure 49). Because this metric is defined as presence/absence of brook trout, we did not average across the local populations, so a separate table is not presented for this metric. See Table 10 in supplementary materials for rankings by HUC-12. Local populations that were *not* expected to have high stress from brook trout included North Fork of Blackfoot River, East Fork Clearwater, Morrell Creek, western portions of the Thompson River local population, Cedar Creek, West Fork Rock Creek, Stoney Creek, Hogback Creek, and Welcome Creek.

Combined Bull Trout Sensitivity Index. We calculated the combined sensitivity index by taking the geometric mean of all sensitivity metrics (Figure 50; see individual metrics in Table 10 in supplementary materials). Results were highly variable across HUC-12s in local bull trout populations, but combined sensitivity was highest overall, on average, in Cottonwood Creek, Albert Creek, Grant Creek and Lolo Creek. The lowest relative sensitivity, on average, occurred in Welcome and Prospect Creek and North Fork Blackfoot River local populations. All other local populations had a mix of HUC-12s in high, moderate and low sensitivity bins. There is no apparent correlation with elevation.

4.1.3 Bull Trout Findings: Vulnerability

We assessed vulnerability by combining exposure and sensitivity indices within each HUC-12. We mapped vulnerability by patch, assessing vulnerability separately for temperature (Figure 51 or Figure ES.5 in the Executive Summary) and flow (Figure 52 or Figure ES.6), for the time period of the 2040s. The results for individual HUC-12s within local populations are also tabulated in Table 10. The vulnerability maps represent aggregations of the individual exposure and sensitivity indices; therefore, it is important to interpret them alongside the individual metrics and indices and to verify with on-the-ground knowledge before using for management purposes. Furthermore, the results are relative differences in vulnerability between watersheds, not absolute measures. We reiterate that vulnerability maps represent hypotheses about climate effects given one potential climate scenario and the assumptions made within. As with all hypotheses, they should be reassessed as additional information becomes available.

The bull trout patches **most vulnerable to temperature**, with both high exposure and high sensitivity (Figure 51 or Figure ES.5), were mostly outside of local population boundaries, although several local populations contained **bull trout patches ranked as having the highest vulnerability to temperature changes**, including:

- Lolo Creek
- Thompson River
- Grant Creek
- Petty Creek
- Fish Creek

The areas that were **least vulnerable to temperature** include:

- Prospect Creek
- St. Regis River
- Cedar Creek
- Trout Creek
- Gold Creek
- Morrell Creek
- Cottonwood Creek
- Monture Creek,
- N. Fork Blackfoot River
- and all of the Rock Creek local populations

Very few local populations had **high exposure and low sensitivity**, including:

- Thompson River
- East Fork Clearwater

Of the areas considered to be Bull Trout Important Habitat (i.e.., critical habitat or high abundance; see Figure 51), most fell in the category of low exposure to increased temperature, but drainages in Fish Creek and Thompson River were ranked as having moderate exposure and low sensitivity, drainages in Thompson River, Lolo Creek, Rattlesnake Creek, Placid Creek and West Fork

Clearwater were ranked as having moderate exposure and high sensitivity, and Grant Creek was ranked as having high exposure and high sensitivity.

The **bull trout patches most vulnerable to changes in flow, with both high exposure and high sensitivity** (Figure 52 or Figure ES.6), include:

- Lolo Creek
- Thompson River
- Prospect Creek
- Graves Creek
- Albert Creek
- Lower Petty Creek
- and portions of the St. Regis River

Local populations that were **least vulnerable to changes in flow** include:

- Cedar Creek
- Trout Creek
- Grant Creek
- Rattlesnake Creek
- Gold Creek
- Morrell Creek
- Cottonwood Creek
- Monture Creek
- N. Fork Blackfoot River
- and all of the local populations in Rock Creek

Several local populations had streams with **high exposure to flow and low sensitivity** and these included:

- Prospect Creek
- Thompson River
- northern Fish Creek
- East Fork Clearwater

Of the areas considered to be Bull Trout Important Habitat (as delineated in Figure 52), those in the Rock Creek, Blackfoot, Cedar Creek, Trout Creek, southern Fish Creek, Grant Creek, Rattlesnake Creek and Gold Creek drainages fell in the category of low exposure, while parts of the Thompson River were ranked as having moderate exposure and low sensitivity, drainages in Thompson River, Lolo Creek, Petty Creek, Placid Creek and West Fork Clearwater were ranked as having moderate exposure and high sensitivity, and Albert Creek and parts of Lolo Creek, Prospect Creek, and St. Regis River ranked as having high exposure and high sensitivity.

Lolo Creek and the Thompson River areas stand out as areas that ranked relatively most vulnerable to both flow and temperature stressors (and have high sensitivity). In contrast, local populations in Rock Creek and the upper Blackfoot watersheds appeared to be

relatively least vulnerable. The least vulnerable watersheds are some of the highest elevation areas within the LNF.

Overall, bull trout local populations are projected to be more exposed to changes in flow than to increased temperatures. Because these rankings are relative across watersheds within the LNF, this does not necessarily indicate that bull trout are expected to be more impacted by flow than by temperature, only that *relative to other areas in the LNF*, temperature increases were not expected to be as great in bull trout local populations as in watersheds not inside a bull trout local population area (an area identified as having few to no bull trout). Bull trout occupy higher elevation headwater streams which represent some of the best remaining thermally-suitable patches, and higher elevation streams are projected to warm less quickly than lower elevation streams (Luce et al. 2014, Lisi *et al.* 2015). However, bull trout local populations are also situated in areas that are projected to have some of the greatest increases in winter flows, particularly in the western half of the study area. Further, the higher elevation headwater streams favored by bull trout currently have relatively lower flow. These streams may be particularly susceptible to projected reductions in summer flows.

4.2 Water Supply: Sufficient Water Supply Findings

4.2.1 Water Supply Findings: Exposure

We characterized the exposure of water quantity in streams to climate change in 2040 by considering two metrics as described in Methods section: lower mean summer flows and a shift in the timing of the center of flow mass of the annual hydrograph. All results for water supply exposure and sensitivity are tabulated by HUC-12s in Table 11 (see Appendix 1).

Exposure to Reduced Summer Flows. Reductions in mean summer flow in the 2040s were generally low across much of the study area (“low” is relative and defined here as 5-17% reduction using the natural breaks clustering algorithm; Figure 53 in Appendix 2, Table F.10 below). Areas of moderate to moderately high flow reduction (17-36%) among HUC-12s were mostly located in higher elevation streams along the northwestern portion of the study area and the Montana-Idaho border area, including western Lower Thompson-Fishtrap, Deep-Mosquito, Prospect, upper St. Regis, upper Sawmill-Cedar, upper Fish, and upper Lolo. However when averaged across HUC-10s, only Deep-Mosquito and Prospect Creeks ranked as moderately exposed to low flows. Drainages in the upper Blackfoot (E. Fk. Cooney, Lake-Rock, Cottonwood Chamberlain, and Lost Prairie-Elk) had lowest exposure, on average. By the 2080s, flow reductions intensified in the same areas, decreasing by an additional 5-10% (Figure 54 and Table 11).

Table F.10. Estimated exposure of HUC-10s to lower mean summer flow by 2040s (percent reduction in mean summer flow). Low, moderate, and high bins are based on "natural breaks" algorithm used in mapping results (bin values provided in parentheses). HUC-10s are not ranked within bins. See Table 11 in supplementary materials for rankings by HUC-12.

Average % reduction in low flow		
Low Exposure (4.8 – 17%)	**Moderate** (17.1% – 23.4%)	**High Exposure** (23.5% – 66.2%)
- Harvey, Bear - Wahlquist, Antelope - Gilbert, Butte - Deer, Cramer - Canyon, Cabin - East Fork Cooney - Lake, Rock - Monture - Cottonwood, Chamberlain - Clearwater, Salmon - Lost Prairie, Elk - Placid - Gold, Union - Rattlesnake, Grant - Butler, Albert - Ninemile - Petty - Fish - Sawmill, Cedar - Dry, Cutoff - St. Regis River - Lolo - Miller, OBrien - Robertson, Camas - Upper Thompson - Meadow, Bear - Little Thompson - Lower Thompson, Fishtrap - McLaughlin, Cherry	- Prospect - Deep, Mosquito	

Exposure to Reduced Length of Water Availability. Spatial patterns in the timing shift of flow center-of-mass were very similar to those for decreased low flows in that the greatest changes were expected to occur in the northwestern areas of the LNF, and especially along the Montana-Idaho border (Figure 55 and Table F.11, below). Flow was expected to be 22 to 40 days earlier in the 2040s in these areas and 28 to 68 days earlier by the 2080s (Figure 56). Mountain streams in the Grant, Rattlesnake, Gold, Placid, Clearwater, Cottonwood, Monture and Canyon-Cabin were also expected to see moderate shifts in flow timing of 17-28 days earlier by the 2040s.

Table F.11. Estimated exposure of HUC-10s to shift in flow timing by 2040s (days center of flow mass has shifted earlier in the year)

Average shift in days earlier of center of flow mass		
Low Exposure (5.7 – 16.8)	**Moderate** (16.9 – 21.5)	**High Exposure** (21.6 – 40.1)
- Harvey, Bear - Wahlquist, Antelope - Gilbert, Butte - Deer, Cramer - East Fork Cooney - Lake, Rock - Lost Prairie, Elk - Butler, Albert - Ninemile - Miller, OBrien - Robertson, Camas - Upper Thompson - Little Thompson - McLaughlin, Cherry	- Canyon, Cabin - Monture - Cottonwood, Chamberlain - Clearwater, Salmon - Gold, Union - Rattlesnake, Grant - Petty - Sawmill, Cedar - Dry, Cutoff - Meadow, Bear	- Placid - Fish - St. Regis River - Lolo - Lower Thompson, Fishtrap - Prospect - Deep, Mosquito

Combined Flow Exposure Index. Combining the two flow exposure metrics, the patterns of lower summer flow and shift in flow timing reinforced each other. Combined exposure was greatest in the north-western portions of the LNF and along the Montana-Idaho border, as well as in headwater streams of the Blackfoot River (Figure 57). Based on HUC-10 averages, high exposure occurred in Deep-Mosquito, Prospect, Lower Thompson-Fishtrap, Lolo, St. Regis, and Fish Creek drainages. Less exposure occurred generally in lower elevation valley streams and in Rock Creek. Based on HUC-10 averages, lowest flow exposure occurred in E. Fk. Cooney, Lake-Rock, and Lost Prairie-Elk in the Blackfoot watershed, and in Deer-Cramer and Harvey-Bear along the Clark Fork drainage. The distribution is not readily explained by elevation alone, although headwater streams generally have higher exposure, with the exception of Rock Creek. Patterns were similar, although intensified, in the 2080s (Figure 58). See Table 11 in supplementary materials for rankings by HUC-12.

4.2.2 Water Supply Findings: Sensitivity

One metric, water diversion, was used to evaluate the sensitivity of watersheds to reduced streamflows for water supply considerations.

Stress from Water Diversion. Areas of high stress from water diversion were more heavily concentrated in the eastern half of the LNF (Figure 59 and Table F.12, below), which corresponds to the area with the highest concentration of diversions (Figure 24; also see a list of diversions by type and purpose for the LNF in Table 4 and Table 5, respectively). Diversion proportions ranged up to 40% of maximum mean summer flow. There are watersheds where local knowledge suggests our methods have underestimated sensitivity (i.e., Lolo Creek is often dewatered). This issue arises because our data were incomplete – we lacked diversion flow quantities in many areas. Managers are reminded that results should be used to complement their knowledge of the area.

Table F.12. Estimated sensitivity of HUC-10s to water diversions (diversion flow/mean summer flow). HUC-10s are not ranked within bins. Low, moderate, and high bins are based on "natural breaks" algorithm used in mapping results (bin values provided in parentheses). See Table 11 in supplementary materials for rankings by HUC-12.

Average water diversion flow / mean summer flow		
Low Sensitivity (0 – 1.5)	**Moderate** (1.6 – 3.8)	**High Sensitivity** (3.9 - 40)
- Wahlquist, Antelope - Gilbert, Butte - Canyon, Cabin - East Fork Cooney - Clearwater, Salmon - Lost Prairie, Elk - Gold, Union - Ninemile - Fish - Petty - Sawmill, Cedar - Dry, Cutoff - St. Regis River - Lolo - Miller, OBrien - Robertson, Camas - Upper Thompson - Meadow, Bear - Lower Thompson, Fishtrap - Prospect - Deep, Mosquito	- Harvey, Bear - Lake, Rock - Monture - Cottonwood, Chamberlain - Butler, Albert - McLaughlin, Cherry	- Deer, Cramer - Placid - Rattlesnake, Grant - Little Thompson

4.2.3 Water Supply Findings: Vulnerability

We assessed vulnerability by combining exposure and sensitivity indices within each HUC-12. The vulnerability maps represent aggregations of the individual exposure and sensitivity metrics; therefore, it is important to consider vulnerability alongside all of the individual metrics and to verify with on-the-ground knowledge for management purposes. We reiterate that vulnerability maps represent hypotheses about climate effects given one potential climate scenario and the assumptions made within. As with all hypotheses, they should be reassessed as additional information becomes available.

Generally, water supply vulnerability in the 2040s was estimated to be greatest in the higher elevation northwestern areas of the LNF, especially along the Montana-Idaho border and in higher elevation tributaries of the Blackfoot River. (Figure 60 or Figure ES.7 in Executive Summary). Highest vulnerability (high exposure plus high sensitivity) watersheds include:

- Dunham Creek
- Morrell Creek
- Upper Placid Creek
- West Fork Fish Creek
- Dry Creek
- East Fork Lolo Creek
- Upper Lolo Creek
- West Fork Butte Creek
- Chippy Creek
- West Fork Fishtrap Creek
- West Fork Lower Thompson River
- Ashley Creek
- Upper Prospect Creek

It was apparent that vulnerability closely tracked the exposure metrics. However, areas of high water diversion should be carefully considered when assessing vulnerability because actual diversions are unlikely to decrease over time. Vulnerability findings are tabulated for all HUC-12s in Table 11 in supplementary materials.

4.3. INFRASTRUCTURE: RECREATION SITES, TRAILS, AND ROADS FINDINGS

4.3.1 INFRASTRUCTURE FINDINGS: EXPOSURE

Exposure to Winter Flooding. We characterized the exposure of recreation sites, trails, and jurisdictional roads to climate change in the 2040s and 2080s by considering the likelihood of winter rain-on-snow flooding as described in Methods section. Winter flooding was expected to increase across the area, with greatest exposure at lower elevations and relatively less exposure at higher elevations (Figure 61 in Appendix 2 and Table F.13, below, see baseline conditions in Figure 8). High elevation areas that were currently expected to see 0 to 1 day of high winter flow would see 1 to 5 days by the 2040s. By the 2080s, most of the study area was expected to experience 7-12 days of winter high flows (Figure 62).

Table F.13. Estimated exposure of HUC-10s to high winter flow exposure in the 2040s (winter days of flow in highest 5% for year). Low, moderate, and high bins are based on "natural breaks" algorithm used in mapping results (bin values provided in parentheses). HUC-10s are not ranked within bins. See Table 12 in supplementary materials for rankings by HUC-12.

Average number of days when flow is highest 5% of year in winter		
Low Exposure (<1 – 2.9)	**Moderate** (3 – 4.9)	**High Exposure** (5 -10.1)
- Canyon, Cabin	- Wahlquist, Antelope	- Harvey, Bear
- East Fork Cooney	- Gilbert, Butte	- Deer, Cramer
- Rattlesnake, Grant	- Monture	- Lake, Rock
	- Clearwater, Salmon	- Cottonwood, Chamberlain
	- Placid	- Lost Prairie, Elk
	- Gold, Union	- Butler, Albert
	- Fish	- Ninemile
	- Robertson, Camas	- Petty
		- Sawmill, Cedar
		- Dry, Cutoff
		- St. Regis River
		- Lolo
		- Miller, OBrien
		- Upper Thompson
		- Meadow, Bear
		- Little Thompson
		- Lower Thompson, Fishtrap
		- McLaughlin, Cherry
		- Prospect
		- Deep, Mosquito

4.3.2 Infrastructure Findings: Sensitivity

Intrinsic and anthropogenic sensitivity metrics that increase infrastructure vulnerability include (1) location of the recreation site, trail or road within the estimated 100-year floodplain, (2) location of the recreation site, trail or road near a potential geologic hazard (landslide, avalanche, or alluvial fan), and (3) for forest roads, the number of culverts per mile. Information on types of recreation sites, location of recreation sites in floodplain or geologic hazard areas, and miles of trails and roads in hazard areas are listed by HUC-10 and HUC-12 in Tables 7, 8, and 9 respectively. All indices for exposure and sensitivity are listed in Table 12.

Stress from Location in Floodplain. Infrastructure located in the floodplain is inherently more vulnerable to surface and/or groundwater flooding, channel avulsions, and debris flow events. Recreation sites, trail miles and road miles in the modeled floodplain were counted for each HUC-12. In general, most forest roads, recreation sites, and trails were clear of floodplains, and there was no apparent geographic pattern for floodplain sensitivity across the forest (Figures 63, 64 and 65). Since these results are based on modeled floodplain delineation, they should be verified in the field. Averages for HUC-10s are presented in the tables below.

Table F.14. Estimated sensitivity of recreation sites in floodplains averaged over HUC-10s. Low, moderate, and high bins are based on "natural breaks" algorithm used in mapping results (bin values provided in parentheses). HUC-10s are not ranked within bins. See Tables 7 and 12 in supplementary materials for numbers of sites and rankings by HUC-12.

Average number of recreation sites in the floodplain		
Low Sensitivity (0-1)	**Moderate** (2-3)	**High Sensitivity** (4-8)
- Harvey, Bear - Wahlquist, Antelope - Gilbert, Butte - Deer, Cramer - Canyon, Cabin - East Fork Cooney - Lake, Rock - Monture - Cottonwood, Chamberlain - Clearwater, Salmon - Lost Prairie, Elk - Placid - Gold, Union - Rattlesnake, Grant - Butler, Albert - Ninemile - Petty - Fish - Sawmill, Cedar - Dry, Cutoff - St. Regis River - Lolo - Miller, OBrien - Robertson, Camas - Upper Thompson - Meadow, Bear - Little Thompson - Lower Thompson, Fishtrap - McLaughlin, Cherry - Prospect - Deep, Mosquito		

Table F.15. Estimated sensitivity of trails in floodplains averaged over HUC-10s. Low, moderate, and high bins are based on "natural breaks" algorithm used in mapping results (bin values provided in parentheses). HUC-10s are not ranked within bins. See Tables 8 and 12 in supplementary materials for total miles and rankings by HUC-12.

Average trail miles in the floodplain		
Low Sensitivity (0 - 0.3)	**Moderate** (0.4 - 0.5)	**High Sensitivity** (0.6 - 1.8)
- Harvey, Bear	- Canyon, Cabin	- East Fork Cooney
- Wahlquist, Antelope	- Ninemile	
- Gilbert, Butte	- Miller, OBrien	
- Deer, Cramer		
- Rattlesnake, Grant		
- Monture		
- Clearwater, Salmon		
- Placid		
- Gold, Union		
- Fish		
- Robertson, Camas		
- Lake, Rock		
- Cottonwood, Chamberlain		
- Lost Prairie, Elk		
- Butler, Albert		
- Petty		
- Sawmill, Cedar		
- Dry, Cutoff		
- St. Regis River		
- Lolo		
- Upper Thompson		
- Meadow, Bear		
- Little Thompson		
- Lower Thompson, Fishtrap		
- McLaughlin, Cherry		
- Prospect		
- Deep, Mosquito		

Table F.16. Estimated sensitivity of roads in floodplains averaged over HUC-10s. Low, moderate, and high bins are based on "natural breaks" algorithm used in mapping results (bin values provided in parentheses). HUC-10s are not ranked within bins. See Tables 9 and 12 in supplementary materials for total miles and rankings by HUC-12.

Average road miles in the floodplain		
Low Sensitivity (0 - 0.6)	**Moderate** (0.7 - 1.3)	**High Sensitivity** (1.4 - 4.5)
- Harvey, Bear - Wahlquist, Antelope - Gilbert, Butte - Deer, Cramer - Canyon, Cabin - East Fork Cooney - Rattlesnake, Grant - Placid - Gold, Union - Fish - Robertson, Camas - Lake, Rock - Cottonwood, Chamberlain - Lost Prairie, Elk - Butler, Albert - Ninemile - Petty - Sawmill, Cedar - Lolo - Miller, OBrien - Upper Thompson - Meadow, Bear - Little Thompson - Lower Thompson, Fishtrap - McLaughlin, Cherry - Prospect - Deep, Mosquito	- Monture - Clearwater, Salmon - Dry, Cutoff - St. Regis River	

Stress from Geologic Hazards. To evaluate geologic hazards, we counted the number of recreation sites or the length (mi) of trails and roads in each HUC-12 that were in areas described as high geologic hazard or on alluvial fans in the LNF's Land System Inventory (Figure 28). There was no apparent geographic pattern for geologic hazard sensitivity across the LNF although more trails were located in areas of higher geologic hazard than recreation sites or roads (Figures 66, 67, and 68). Areas of "moderate to high" sensitivity warrant field verification based on site specific geology, soils, and topography. Averages for HUC-10s are presented in the tables below.

Table F.17. Estimated sensitivity of recreation sites to geologic hazards averaged over HUC-10s. Low, moderate, and high bins are based on "natural breaks" algorithm used in mapping results (bin values provided in parentheses). HUC-10s are not ranked within bins. See Tables 7 and 12 in supplementary materials for numbers of sites and rankings by HUC-12.

Average number of recreation sites in areas of geologic hazard		
Low Sensitivity (0 - 3)	**Moderate** (4 - 5)	**High Sensitivity** (6 - 17)
- Harvey, Bear - Wahlquist, Antelope - Gilbert, Butte - Deer, Cramer - Canyon, Cabin - East Fork Cooney - Lake, Rock - Monture - Cottonwood, Chamberlain - Clearwater, Salmon - Lost Prairie, Elk - Placid - Gold, Union - Rattlesnake, Grant - Butler, Albert - Ninemile - Petty - Fish - Sawmill, Cedar - Dry, Cutoff - St. Regis River - Lolo - Robertson, Camas - Upper Thompson - Meadow, Bear - Little Thompson - Lower Thompson, Fishtrap - McLaughlin, Cherry - Prospect - Deep, Mosquito		- Miller, OBrien

Table F.18. Estimated sensitivity of trails to geologic hazards averaged over HUC-10s. Low, moderate, and high bins are based on "natural breaks" algorithm used in mapping results (bin values provided in parentheses). HUC-10s are not ranked within bins. See Tables 8 and 12 in supplementary materials for total miles and rankings by HUC-12.

Average trail miles in areas of geologic hazard		
Low Sensitivity (0 – 4.2)	**Moderate** (4.3 – 8.5)	**High Sensitivity** (8.6 – 30.7)
- Harvey, Bear	- Canyon, Cabin	- East Fork Cooney
- Wahlquist, Antelope	- Rattlesnake, Grant	- Monture
- Gilbert, Butte	- Ninemile	- Miller, OBrien
- Deer, Cramer	- Fish	
- Lake, Rock		
- Cottonwood, Chamberlain		
- Clearwater, Salmon		
- Lost Prairie, Elk		
- Placid		
- Gold, Union		
- Butler, Albert		
- Petty		
- Sawmill, Cedar		
- Dry, Cutoff		
- St. Regis River		
- Lolo		
- Robertson, Camas		
- Upper Thompson		
- Meadow, Bear		
- Little Thompson		
- Lower Thompson, Fishtrap		
- McLaughlin, Cherry		
- Prospect		
- Deep, Mosquito		

Table F.19. Estimated sensitivity of roads to geologic hazards averaged over HUC-10s. Low, moderate, and high bins are based on "natural breaks" algorithm used in mapping results (bin values provided in parentheses). HUC-10s are not ranked within bins. See Tables 9 and 12 in supplementary materials for total miles and rankings by HUC-12.

Average road miles in areas of geologic hazard		
Low Sensitivity (0 – 8.1)	**Moderate** (8.2 - 14)	**High Sensitivity** (14.1 – 47.9)
- Harvey, Bear - Wahlquist, Antelope - Gilbert, Butte - Deer, Cramer - Canyon, Cabin - East Fork Cooney - Lake, Rock - Monture - Cottonwood, Chamberlain - Clearwater, Salmon - Lost Prairie, Elk - Placid - Gold, Union - Rattlesnake, Grant - Butler, Albert - Petty - Fish - Sawmill, Cedar - Dry, Cutoff - Robertson, Camas - Upper Thompson - Meadow, Bear - McLaughlin, Cherry - Prospect - Deep, Mosquito	- Miller, OBrien - Lower Thompson, Fishtrap	- Ninemile - St. Regis River - Lolo - Little Thompson

Stress from Culvert Failure. For forest roads, we also included the number of culverts per mile as an additional sensitivity metric since culvert failure is the primary cause of road damage during flooding. Higher numbers of stream crossings through a road inherently equate to higher flooding risks. Ground verification, including as-built records, can refine this listing further from which the projected risk level can be lowered if upgrades to "stream simulation standards" have occurred. The distribution of culverts throughout the LNF was relatively uniform with no discernable pattern (Figure 69). Averages for HUC-10s are presented in the table below.

Table F.20. Estimated sensitivity of roads to culverts averaged over HUC-10s. Low, moderate, and high bins are based on "natural breaks" algorithm used in mapping results (bin values provided in parentheses). HUC-10s are not ranked within bins. See Tables 9 and 12 in supplementary materials for culvert numbers and rankings by HUC-12.

Average number of culverts per road mile		
Low Sensitivity (0 – 0.7)	**Moderate** (0.8 – 1.3)	**High Sensitivity** (1.4 – 4.1)
- Harvey, Bear - Wahlquist, Antelope - Gilbert, Butte - Deer, Cramer - Canyon, Cabin - East Fork Cooney - Lake, Rock - Monture - Cottonwood, Chamberlain - Lost Prairie, Elk - Rattlesnake, Grant - Butler, Albert - Petty - Fish - Sawmill, Cedar - Lolo - Miller, OBrien - Robertson, Camas - Upper Thompson - Little Thompson - Lower Thompson, Fishtrap - McLaughlin, Cherry - Prospect	- Clearwater, Salmon - Placid - Gold, Union - Ninemile - Dry, Cutoff - St. Regis River - Meadow, Bear Deep, Mosquito	

Combined Infrastructure Sensitivity Index. The combined sensitivity ranking was determined by taking the geometric mean of the floodplain and geologic hazard metrics for recreation sites, trails and roads. For road infrastructure, the combined sensitivity index also includes the culvert metric. We emphasize that combined sensitivity indices are relative to other HUCs in the study area, and are best interpreted alongside the individual metrics upon which they are based.

Combined Sensitivity of Recreation Sites. The combined sensitivity was relatively low throughout most of the study area with a few exceptions in the Rock Creek watershed, the lower Lolo Creek – Miller-O'Brien area on the Bitterroot, and single HUC-12 drainages within Dry-Cutoff and St. Regis watersheds (Figure 70 and Table 12).

Combined Sensitivity of Trails. The combined sensitivity was slightly higher than for recreation sites, but was still generally low throughout most of the study area. Areas of high sensitivity occurred in the northern Blackfoot tributaries, the Miller-O'Brien area on the Bitterroot, southern Ninemile, and N. Fk. Fish Creek (Figure 71 and Table 12).

Combined Sensitivity of Roads. Relative sensitivity to floodplains, geologic hazards, and number of culverts was generally higher for roads in the study area than it was for recreation sites or trails, likely because there are more miles of roads than trails or numbers of recreation sites. HUC 12s of highest sensitivity were located within the St. Regis, Dry-Cutoff, Clearwater-Salmon and Wahlquist-Antelope watersheds (Figure 72 and Table 12). Areas of moderately high sensitivity included the Ninemile and Monture watersheds and areas of lowest sensitivity were in the North Fork Blackfoot and Lost Prairie-Elk drainage of the Blackfoot, Rattlesnake-Grant Creek drainages and Harvey-Bear Creeks along the Clark Fork, and northwestern portions of the LNF including Upper Thompson, Meadow-Bear, and Robertson-Camas.

4.3.3 Infrastructure Findings: Vulnerability

We assessed vulnerability by comparing exposure and sensitivity indices within each HUC-12. The vulnerability maps represent aggregations of the individual exposure and sensitivity indices; therefore, it is important to consider them alongside all of the individual metrics and indices and to verify with on-the-ground knowledge before using for management purposes. We reiterate that vulnerability maps represent hypotheses about climate effects given one potential climate scenario and the assumptions made within. As with all hypotheses, they should be reassessed as additional information becomes available. Results are mapped in Figure 73 (or Figure ES.8, recreation sites), Figure 74 (or Figure ES.9, trails), and Figure 75 (or Figure ES.10, roads), and listed in Table 12.

Overall, recreation site and trail vulnerability fell generally into two vulnerability categories: high exposure plus low sensitivity (62% of HUC-12s for each) and moderate exposure plus low sensitivity (19 – 20% of HUC-12s). These watersheds have infrastructure that is more vulnerable because they are in floodplains or in areas of geologic hazard, or both. Clearly, as assessed here, exposure is a bigger issue with recreation site and trail infrastructure than is sensitivity, with a few targeted exceptions.

For recreation sites, **the following HUC-12 had high exposure and high sensitivity**:

- Rock Creek-Kitchen Gulch
- Lower Clearwater River
- Lower Fish Creek
- Clark Fork River-Siegel Creek
- Savenac Creek
- Lower Lolo Creek
- Bitterroot River-Hayes Creek
- Upper Fishtrap Creek

For trails, **the following HUC-12 had high exposure and high sensitivity**:

- Rock Creek-Kitchen Gulch
- Lake Creek
- Lower Clearwater River
- Ninemile-Butler
- Stony Creek
- Clark Fork River-Siegel Creek

- Bitterroot River-Hayes Creek
- Big Rock Creek
- Dry Creek

Forest roads have overall higher vulnerability and are influenced by both exposure and sensitivity. Forty-four percent of HUC-12s in the study area had roads in the highly vulnerable category of high combined exposure and sensitivity. The high vulnerability areas are scattered throughout the study area and are generally concentrated in lower elevation areas (see Figure 75).

For roads, **the following HUC-12 had high exposure and high sensitivity**:

- Rock Creek – Kitchen Gulch
- Clark Fork River – Ryan Creek
- Cottonwood Creek
- Lower Clearwater River
- Seeley Lake
- Placid Lake
- Lower Gold Creek
- Mill Creek
- Ninemile – Little Bear Creek
- Ninemile – McCormick Creek
- Ninemile – Butler Creek
- Ninemile – Stony Creek
- Upper Fish Creek
- Lower South Fork Fish Creek
- Lower Fish Creek
- Nemote Creek
- Dry Creek
- Clark Fork – Showey Gulch
- Tamarack Creek
- Clark Fork – Cold Creek
- Clark Fork – Siegel Creek
- Packer Creek
- Big Creek
- Savenac Creek
- Middle St Regis River
- Twelvemile Creek
- Lower St Regis River
- East Fork Lolo Creek
- Lolo - Grave Creek
- Lower Lolo Creek
- Miller Creek
- Bitterroot – Hayes Creek
- Upper Little Thompson River

- McGinnis Creek
- Middle Little Thompson River
- Lower Little Thompson River
- Lower Fishtrap Creek
- Thompson River – Deerhorn Creek
- Lynch Creek
- Swamp Creek
- Cherry Creek
- Clear Creek
- Dry Creek
- Lower Prospect Creek

Seventy-two percent of HUC-12s had USFS roads with high exposure and low sensitivity, and these HUCs are similarly concentrated in low-elevation areas. Roads in areas of moderate or lower exposure and either high or low sensitivity are generally located in HUC-12s within headwater areas at higher elevation.

5. Management Implications

The goal of this vulnerability assessment is to provide management guidance in meeting LNF conservation goals to maintain resilient ecosystems given the added uncertainties and complexities of climate change. This analysis provides insight into one scenario of vulnerability and the potential drivers of that vulnerability, suggesting adaptation actions to reduce vulnerability (Figure I.2 in Introduction, above). Assessing vulnerabilities and prioritizing management actions are but one step in a broader management framework (Table I.1 in Introduction, above). Each watershed has unique attributes that will determine specific ecological dynamics and responses to climatic changes. Management and adaptation actions should be considered in conjunction with other finer-scale assessments, data and evidence, and within an adaptive management framework. Most importantly, flexibility will be essential and managers must be willing to follow evidence, not just interest or intuition (Sutherland et al. 2004).

Managers should develop management options that consider a range of possible future conditions, but most important are efforts that promote ecosystem resilience for desired functions and services. Further, adaptation management strategies that address impacts common to a range of possible future conditions are more robust than the traditional prescriptive management of a single outcome (see Daniels et al. 2012).

A Reminder About Uncertainty

We reiterate that this analysis should not be considered as the single source of guidance for prioritization of conservation action. There are multiple uncertainties associated with this analysis (see above in Vulnerability: Conceptual Approach and Definitions section):

1. climate projections are inherently uncertain;
2. translating climate projections into models of stream temperature and flow requires additional assumptions and uncertainties;
3. this assessment relies on proxy measures which we assume relate to actual risk of impacts
4. all spatial data are imprecise;
5. there are additional errors inherent to all data.

Results provided here must be considered within the broader context of additional data and analyses. Further, the choice of whether to focus conservation efforts on the most vulnerable or most viable areas must also account for social, economic, and legal values (Glick et al. 2011). Most importantly, managing for resiliency under a changing climate will not follow a linear management plan. Management and optimal adaptation strategies will need to respond to changing conditions and scientific understanding. Although it is difficult to develop and enact adaptation strategies for forest resources given an uncertain climate, ecosystem management is always rife with uncertainty, and inaction in the face of climate change is not an option.

Managers can use the results of this assessment in numerous ways, including identification of data gaps, development of monitoring programs, integration with existing prioritization programs, development of short and long-term strategies to increase resilience of the resource where it is likely to have the most benefit, development of education and outreach materials, and collaboration with other agencies and local communities (Furniss et al. 2013). Specifically, there are a number of current USFS planning efforts into which this assessment can be incorporated (Table MI.1, below).

It is also important for managers to note that human actions have had a far greater effect than climate variation in the past (Arrigoni et al. 2010) and may continue to have greater effects in the future. Thus, in managing for greater resiliency, managers should consider specific metrics and vulnerability findings in conjunction with the degree of legacy effects from human influences. For example, in a watershed that has been highly altered by water withdrawals and designated as highly vulnerable for bull trout persistence, management should carefully consider permitting new activities and fully investigate options for adaptation actions in permit renewals. In contrast, if a particular watershed is functioning within historical reference conditions and climate change vulnerability of a particular metric is projected as low to moderate, management has greater discretion to authorize additional uses with some assurance of low risk to aquatic resources or infrastructure. Similarly, managers can focus efforts in watersheds vulnerable to low flows by obtaining Montana State water rights for instream resource benefits under the MT Water Compact (see MT Water Compact 85-2-234, MCA) and if done with a strategic eye towards water development, knowledge of climate change vulnerabilities can help reduce future water development risks in key aquatic ecosystems.

We hope this analysis will further provide an opportunity for the LNF to educate the public on the potential climatic impacts to forest resources and LNF's adaptive management strategies to address potential impacts. In addition, this report can be used to identify where collaborative efforts with state, federal, and tribal agencies, community councils, and NGOs would be most productive in developing successful adaptation measures.

Table MI.1. There are numerous planning efforts that can be informed by this climate change vulnerability assessment either for revision or application.

Planning Effort	Resource Area
Forest Plan Revision	All
Rapid Assessment – Forest 5-yr Planning	All
Transportation Planning	Aquatic Resources Infrastructure
Watershed Condition Framework	All
Individual/NEPA Projects	All
Climate Score Card	All
Collaboration: grant solicitation	All
Public Education	All
Conservation Strategy for Bull Trout on USFS Lands in Western Montana	Aquatic Resources
Best Management Practices (BMP)	All
Forest Flood Emergency Response Plan	Infrastructure
Watershed Aquatic Recover Strategy (WARS)	Aquatic Resources
Water Rights Compact between the State of Montana and the USDA	Water Supply

5.1 BULL TROUT: MANAGEMENT IMPLICATIONS

Conservation and management of bull trout is a complex endeavor. Many factors influence bull trout persistence including dams, non-native competition, and overall fisheries management, as well as population genetics and demographics. However, recent studies suggest poor habitat conditions are one of the main limits to salmonid population recovery despite ongoing conservation efforts (ISAB 2015). Our analysis focused on these types of physical habitat drivers of bull trout sensitivity to climate change, where we believe managers can most successfully act to reduce vulnerability (Table MI.2, below).

Bull trout require colder water than most other salmonids, and climate change related stream temperature warming rates of 0.1-0.2°C per decade (Isaak et al. 2012) are gradually reducing the size of their cold-water habitats. Additionally, changes in hydrological regimes have measurably reduced summer flows (Luce & Holden 2009), and projections of increased higher flows are likely to increase scour during bull trout incubation (Goode et al. 2013). A pragmatic view of our results suggests that maintaining bull trout across their entire current range may not be viable. Although western Montana has been identified as likely providing some of the coldest waters across their range, projections of bull trout occurrence probability are low in many areas of the LNF under a scenario of high climatic changes (Isaak et al. 2015b). We identified relatively high vulnerability (high exposure and sensitivity) throughout much the Graves, Lolo, Albert, Grant, and Petty Creeks and St. Regis River local populations. However, we found that relative to other locations in the LNF, watersheds identified as being important local bull trout populations are relatively less exposed to warming temperatures and, in the eastern portion of the LNF, relatively less exposed to changes in flow as well. In general, cold-water habitat patches appear to drive bull trout occurrence, and thus, restoration actions that cool streams (e.g., improved riparian conditions, decreased water withdrawals) and maintain connectivity within and amongst patches (e.g., removing impediments to fish movement) should be beneficial (Rieman & McIntyre 1993; Dunham & Rieman 1999). Deciding where to invest in these types of actions needs to be strategically targeted at those watersheds where bull trout have the best chance of long-term persistence (Peterson et al. 2013; Isaak et al. 2015b).

Relative differences in vulnerability are important, especially given the potential for bull trout to adapt to changing climatic conditions through evolutionary or plastic responses. Currently, the adaptive capacity of bull trout is not well known, and we did not consider it in our analysis. However, bull trout and other salmonids have evolved and adapted to climatic variability for thousands of years, and may well do so into the future, if provided the river habitat quality and quantity needed to support demographically and genetically rich populations. Therefore, as managers are faced with managing habitat for bull trout conservation, it is critical to understand where and which conservation and adaptation actions are likely to most contribute to increased resiliency of bull trout populations.

We reiterate that there is no "right answer", only that multiple lines of evidence should be considered complimentarily. The "best answer" will only come through coordination of restoration both spatially (and across scales) and temporally to ensure that conditions are optimized across bull trout's range, as opposed to solely within the LNF (Neeson et al. 2015). A substantial amount of complementary research has been conducted for the species across multiple scales, and we urge managers to consider our results in conjunction with those efforts. For example, the report *Climate Change, Aquatic Ecosystems, and Fishes in the Rocky Mountain West* (Rieman & Isaak 2010) provides a broad overview of potential climatic changes throughout the Rocky Mountains and lists general management suggestions. These include: enhancing resistance and resilience of bull trout, prioritizing conservation actions, developing local information, coordinating efforts, and facilitating transition of bull trout to new locations (or alternatively, allow colonization by new species). Examples of management options are provided for each action. This report responds directly to several of these management suggestions, specifically, developing local information that guides conservation action prioritization in the effort to enhance resistance of bull trout to climatic changes. Importantly, as stated in the above cited report, locally-developed information must be considered within a broader context.

The *Conservation Strategy for Bull Trout on USFS Lands in Western Montana* report, completed jointly by the LNF and Fish and Wildlife Service (USFS & USFWS 2013), provides additional context and comparison for the findings presented in this report. For example, of the local populations that we identified as having the highest climate exposure (temperature: Petty and Grant Creeks and East Fork Clearwater; combined flow: Albert, Graves, Prospect, and Lolo Creeks and Thompson River), only Petty, Grant, Albert, and Graves Creeks are listed as being at high risk to climate change in the *Conservation Strategy* report (Rattlesnake and Prospect Creeks and Thompson River are listed as being moderately vulnerable to climatic changes). These differing results are due to very different approaches; the *Conservation Strategy* used a qualitative and descriptive assessment of climatic influences only when calculating "vulnerability to climate change"; the analysis did not include sensitivity elements. The variance in results highlights the need to carefully consider evidence from multiple sources.

Our analysis incorporated numerous sensitivity elements into the ranking of vulnerability, and we found Cottonwood, Albert, Lolo, and Grant Creek population areas had the highest, and Welcome and Prospect Creeks and North Fork Blackfoot River the lowest combined sensitivity index values. In general, habitat stressors are spread throughout the LNF, potentially increasing bull trout sensitivity to climate change. Thus, the guidance provided in this report for the prioritization of management actions to improve habitat is critical.

Improving bull trout habitat will be necessary, but not necessarily sufficient for bull trout recovery. For example, recent modeling suggests habitat restoration was less effective than reducing impacts from nonnative species (Peterson 2015). In spawning and rearing habitats where it is feasible, brook trout suppression or eradication could improve the resilience and abundance of bull trout populations (Buktenica et al. 2013; Isaak et al. 2015b). Beyond habitat, demographic and genetic trends are critical to long term species persistence (Moore et al. 2014; Nicotra et al. 2015; Kovach et al. 2015). Our study did not detail demographic trends that are of critical importance to bull trout persistence. We incorporated a measure of patch size and connectedness, but as or more important will be demographic connectedness across populations and core areas and the ability for recolonization (Rieman et al. 2007). For Example, Chelgren and Dunham (2015) found that only through consideration of meta-population dynamics could restoration of fish passage at road-stream crossing culverts be prioritized effectively. Reintroduction of bull trout into likely high-quality habitats from which they have been extirpated is another possible issue not explicitly considered herein. We leave that to local consideration, guided by our maps of habitat-related stressors.

Life history characteristics (such as fluvial versus adfluvial) are also key, but not considered here. Life history variation provides a buffer against perturbations (Araki et al. 2007; Greene et al. 2009; Schindler et al. 2010), and may play a significant role in species' response to climate change (Moore et al. 2014). The loss of life history forms, particularly migratory forms, increases the risk of extirpation and loss of genetic diversity (Nelson et al. 2002). The need to maintain a "portfolio" of life history diversity is important for salmonids, particularly under a changing climate (Schindler et al. 2010; Haak & Williams 2012). We also did not consider lake trout, which are a major competitor with bull trout in addition to brook trout. Additionally, we did not consider plastic and evolutionary factors that may ultimately determine bull trout response to changing climatic conditions (Harrisson et al. 2014; Nicotra et al. 2015). For example, previous research has indicated that bull trout in low-elevation, warming waters may be in double-jeopardy from climatic change as thermal stress may lead to reduced genetic diversity, and thus reduced resilience in populations with the greatest need (Kovach et al. 2015).

In summary, bull trout conservation is complex, and the findings here are aimed to provide LNF managers context of vulnerability for optimizing forest operations with respect to both efficiency and effectiveness. Ideally, decisions should be considered within a broader context spatially and ecologically, which demands concurrent consideration and collaboration with other responsible stakeholders. The concepts of niche redundancy, resilience, and representation are critical to long-term conservation of bull trout. Management actions without expansive thought beyond the LNF boundaries will not be effective. Management that is too localized and singularly focused has plagued salmonid conservation throughout the Columbia Basin (Rieman et al. 2015). The findings provided here should be compared and complimented with other studies to adaptively manage bull trout, throughout their range and engaging with all stressors, to maximize the demographic, life-history, and genetic diversity of a comprehensive bull trout portfolio (Schindler et al. 2010).

Table MI .2. Example management actions for bull trout conservation.

Mode of Action	Example Management Actions
Assess	- Verify temperature and other climatic projections with monitoring - Continue active monitoring of bull trout presence, redd counts - Continue coordination with RMRS re: eDNA monitoring - Maintain and develop GIS layers of bull trout presence and abundance - Monitor for genetic and demographic trends
Engage	- Continue support for interpretive efforts, interacting with schools and other programs re: bull trout awareness - Continue coordination with FWP and MDT re: surveys, identification and eradication of non-natives, LWD replacement at bridges - Coordinate with FWP to increase monitoring - Engage ditch and water managers re: drought planning and reducing summer diversions
Manage	- Manage for resilience (reduce stressors in high sensitivity areas, protect refugia in low exposure areas, manage proactively in high exposure areas) ▪ Increase/maintain riparian shading and encourage species diversity in plantings ▪ Improve base flows via beaver reintroductions or beaver analogs ▪ Manage to reduce peak flows that increase bull trout mortality, including consideration of timber harvest impacts (Tonina et al. 2008) ▪ Continue to remove unnatural barriers and improve habitat connectivity ▪ Interface with TMDL efforts to reduce sediment ▪ Restore/maintain channel complexity via rehabilitation pilots (e.g., LWD reintroduction), particularly at over-wintering habitat or areas of high summer thermal-stress ▪ Evaluate and manage road system in strategic locations such that modifications (relocation, removal, etc.) facilitate stream, floodplain and riparian processes (wood delivery, complexity, thermal buffering, etc.) ▪ Manage grazing allotments using stream and riparian-based methods (e.g., greenline-based approaches) ▪ Develop plan to manage/remove invasives ▪ Remove genetic and population bottlenecks

5.2 Water Supply: Management Implications

The LNF encompasses the headwaters of many streams and rivers that supply flow for diverse needs throughout western Montana and beyond. Projected shifts in hydrological regimes may change availability of water for all uses, including instream flows for aquatic ecosystems, groundwater recharge supporting wetland ecosystems, municipal and public water supplies, agricultural irrigation diversions, and Forest Service potable water systems.

The two primary climate stressors considered in this analysis were projected change in timing of peak flows to earlier in the year and consequently lower summer mean flows. A climate shift that results in warmer temperatures and earlier peak flows could also create issues with regards to the timing of diversions if irrigators need water earlier in the year. Earlier diversion would compound seasonal dewatering effects and may also influence water right and other regulatory provisions and issues. The degree to which these climate-driven changes affect a given stream will depend on the proportion of diverted flow to mean summer flow, and on the extent to which a watershed is buffered by natural or constructed water storage in the watershed, especially groundwater storage. Unfortunately, there is little to no field-verified information on groundwater storage and its contribution to streamflows on most USFS lands. This is something the USFS is working to change, recognizing that groundwater and surface water are a connected, integral resource (see http://www.fs.fed.us/geology/groundwater.html). An understanding of how climate may affect water supply for all uses in the future will greatly benefit from better documentation of flashy vs. non-flashy watersheds, groundwater storage, beaver presence and influence, and groundwater-dependent ecosystems.

We considered several metrics to estimate watershed storage, including impoundments, base-flow index (http://ks.water.usgs.gov/pubs/abstracts/of.03-263.htm), and valley confinement (Nagel et al. 2014), but concluded that these measures lacked enough specificity or accuracy to provide a meaningful measure of watershed storage for this analysis. Thus, the only sensitivity measure we used was the proportion of diversionary flow rates to mean summer flow for the 70% of 4,219 unique surface right points of diversion (POD) in the study area where flow data was available. In light of the above, the results of this analysis should be considered in the context of local knowledge of diversions. We do not account for instream flow reservations, and "paper water rights" do not necessarily translate to actual water withdrawals. Nonetheless, the metric is useful for relative comparisons between watersheds.

As summer water supply becomes scarcer in the future, managers will need to prioritize where enhancement of watershed storage would be beneficial as an adaptation strategy (Table MI.3, below). Groundwater storage can increase watershed resiliency during drought cycles now and in the face of future climate-driven low flows. Enhancement could take the form of constructed impoundments at existing lakes, if feasible and ecologically benign, or could be achieved naturally, and with potentially greater ecological benefits, by beaver reintroduction. Beaver dams slow streamflow, capture runoff, and can potentially maintain or increase late season stream flows by inducing more groundwater recharge as they impound water and cause flood prone areas to be more saturated than without beaver presence. In addition, beaver activity helps diversify habitat for other species, especially in groundwater-dependent ecosystems. A good discussion of beaver reintroduction considerations is found in Pollock *et al.* (2015).

This vulnerability analysis may also be useful for prioritizing where additional instream flow for aquatic life could be beneficial in the face of decreasing summer flows in the future. The Water Rights Compact between the State of Montana and the USDA, Forest Service grants the USFS specific instream flow rights on a number of tributaries on the Lolo NF to protect baseflows for fishery protection. Identifying especially vulnerable streams for both water supply and bull trout, combined with manager's knowledge of opportunities and limitations, may help guide prioritization decisions.

Table MI .3. Example management actions for maintaining sufficient water supply.

Mode of Action	Example Management Actions
Assess	- Verify diversion sites and improve models of potential dewatering - Assess feasibility and potential influence of beaver or beaver analog projects; identify watersheds for pilot reintroductions - Continue existing monitoring and monitor flow withdrawals under SUPs to ensure adherence to water rights and appropriate habitat protections - Perform stream reconnaissance during project assessments and inventory all human-related water withdrawals in accord with appropriate use
Engage	- Continue to educate community on outdoor watering restrictions and water-use guidelines - Coordinate with DNRC to provide verification of appropriate water use at key locations - Continue communications with state agency, NGO, and private partners on beaver management and enhancement - Coordinate with ditch managers and others to encourage drought planning and voluntary actions to reduce instream withdrawals, particularly in summer - Enhance partnerships for monitoring and actions that consider complete watershed dynamics headwaters to mouths - Continue Wyden authority towards necessary improvements on private lands
Manage	- Manage for resilience (reduce stressors in high sensitivity areas, protect refugia in low exposure areas, manage proactively in high exposure areas, water-saving efforts forestwide) ▪ Continue instream flow securement program; consider objections to new water rights where instream flow reservations are not established ▪ Implement water-saving initiatives forestwide: install water-saving facilities, meter water usage, and maintain LNF watering devices in good working order; use grey-water for irrigation as possible; xeriscape and use native, drought-resistant plants and water-smart landscaping; irrigate efficiently with timed sprinkler systems and allow for less vibrant summer lawns

5.3 Infrastructure: Management Implications

Campgrounds, roads, and trails provide the foundation for recreational opportunities on public lands, and roads and trails are crucial for forest and fire management. The LNF is responsible for maintaining over 8,900 mi of roads, 1,698 mi of trails, and almost 300 recreation sites, including trailheads, loading ramps, campgrounds and picnic areas. Climate change is likely to make some of this infrastructure more exposed to flooding, especially early-season rain-on-snow events that may have greater magnitude than our present runoff regime. Along with the potential for winter flooding, infrastructure location in the floodplain or areas of high geologic hazard (landslides, avalanches, alluvial fans) are inherent stressors considered in this analysis. For roads, another inherent stressor we considered was the number of culverts because they can increase the probability of road washouts.

Use of the vulnerability results in management decisions (Table MI.4, below) should be contingent on field verification of susceptibility to flooding and geologic hazards; this is true for both low and high vulnerability areas. Most floodplains on the LNF are not FEMA-mapped and our analysis of floodplain location is limited by modeling assumptions. Our analysis of geologic hazards is also limited by the scale at which data are available (for example, presence in an alluvial fan may not be hazardous in all instances). We strongly recommend that managers carefully analyze the figures and tables of the individual metrics that make up infrastructure vulnerability designations.

Table MI.4. Example management actions for maintaining infrastructure.

Mode of Action	Example Management Actions
Assess	- Verify infrastructure locations in flood prone or high geologic-risk locations - Continue monitoring to evaluate efficacy of AOP/Q100 stream simulation efforts and strategies for stream crossing structures - Create and maintain GIS layer of vulnerable roads, trail, and campground facilities
Engage	- Maintain and enhance partnerships for infrastructure improvements and monitoring
Manage	- Manage for resilience (reduce stressors in high sensitivity areas, protect refugia in low exposure areas, manage proactively in high exposure areas) ▪ Consider road and trail relocation and realignment to areas of lower risk ▪ Provide adequate drainage through road and trail prism and drainage reconstruction; if prisms cannot be relocated from flood prone areas, elevate surface above flood risk level and armor via rock or vegetation ▪ Relocate roads in transport dominated reaches where possible ▪ Provide adequate BMP and maintenance on road-stream crossings ▪ Replace outdated and undersized structures at road-stream crossings; ensure adequate flow given risks of rain-on-snow events and post-fire debris ▪ Ensure ditches do not connect to stream network and reduce diversion potential for stream flow down road ▪ Remove or modify vulnerable campgrounds ▪ Prevent new development in flood prone areas

Appendix 1. List of Tables in Supplementary Materials

All tables with alphanumeric designations (e.g., Table F.1) can be found within the body of this report. **Tables listed here (with only a number; e.g., Table 1) can be found in Excel format (WCCVA_LNF_Appendix_1_TABLES.xlsx) in the supplementary materials on the accompanying CD or on-line at: http://www.fs.usda.gov/main/lolo/workingtogether**.

Table 1. Summary information for each of the 223 6^{th} level hydrologic unit codes (HUC) used in this assessment, including HUC ID number, percent type of land ownership, total length of national hydrography dataset (NHD) stream reaches, and whether the HUC is only in the larger area used for the bull trout vulnerability analysis. Several HUCs share the same name; Table 2 provides a list of HUC names sorted by HUC number.

Table 2. List of 6^{th} level HUCs used in this analysis sorted by HUC ID number.

Table 3. Details on 2,123 water right points of diversion (POD) in the bull trout study area without flow rate data, and therefore, not used in calculating the water diversion metric. The majority of POD were for stock water (87%) and were used by animals direct from the stream (67%).

Table 4. POD for active, surface, diversionary water rights in the water supply study area, summarized by means of diversion and a total count of POD on Lolo National Forest (LNF) lands by HUC. HUCs not included in the list have no POD. See Table 2 for a list of HUC names associated with each HUC ID number.

Table 5. POD water rights in the water supply study area, summarized by purpose of diversion by HUC. HUCs not included in the list have not POD. See Table 2 for a list of HUC names associated with each HUC ID number.

Table 6. List of HUCs containing 103 total known impoundments in the water supply vulnerability assessment study area. Impoundments were POD data with type listed as “dam” or “diversion dam”, and non-redundant dams from the National Inventory of Dams dataset.

Table 7. Recreation sites by HUC and recreation type used in the infrastructure vulnerability assessment. Each site is labeled as being either in the floodplain or in an area of potentially high geologic hazard.

Table 8. Trails used in infrastructure vulnerability assessment, by HUC.

Table 9. Summary of road length and count of LNF-managed culverts, by HUC, for roads used in the infrastructure vulnerability assessment. Only existing roads under LNF jurisdiction were considered in the analysis. National Forest System Roads (NFSR) are listed as “system” roads versus other “non-system” roads.

Table 10. Summary of bull trout vulnerability assessment by HUC; values for all sub-metrics, metrics, and indices (see conceptual model, Figure 16). HUC names that are in bold italics represent the HUCs that we found to be relatively most vulnerable, with both high exposure (2040, either temperature or combined flow) and sensitivity indices. Index "cluster" represents the result rankings from the "natural breaks" clustering method (as realized in ESRI ArcGIS 10.2; 1 = lowest exposure or sensitivity, 5= highest).

Table 11. Summary of water supply vulnerability assessment by HUC; values for all metrics and indices (see conceptual model, Figure 25). HUC names that are in bold italics represent the HUCs that we found to be relatively most vulnerable, with both high combined exposure (2040) and sensitivity indices. Index "cluster" represents the result rankings from the "natural breaks" clustering method (as realized in ESRI ArcGIS 10.2; 1 = lowest exposure or sensitivity, 5= highest).

Table 12. Summary of infrastructure vulnerability assessment by HUC; values for all metrics and indices (see conceptual model, Figure 27). HUC names that are in bold italics represent the HUCs that we found to be relatively most vulnerable, with both high combined exposure (2040) and sensitivity rankings for at least one of the three infrastructure types (recreation sites, trails, or roads). Index "cluster" represents the result rankings from the "natural breaks" clustering method (as realized in ESRI ArcGIS 10.2; 1 = lowest exposure or sensitivity, 5= highest).

APPENDIX 2. LIST OF FIGURES IN SUPPLEMENTARY MATERIALS

All figures with alphanumeric designations (e.g., Figure ES.1) can be found within the body of this report. **Figures listed here (with only a number; e.g., Figure 1) can be found in the supplementary materials on the accompanying CD or on-line at: http://www.fs.usda.gov/main/lolo/workingtogether.**

Metric and index result map legend colors are generally displayed using the Jenks natural breaks clustering method (as realized in ESRI ArcGIS 10.2), which seeks to minimize within class, but maximize between class, variation (green = lowest stress, red = highest stress). In some instances, other binning was applied (but red remains highest stress). We provide an estimate of confidence in each metric; justifications are given in the Methods section.

Figure 9. Comparison of modeled high winter flows (W95) using different GCM input for the 2040s. MIROC 3.2 GCM tends to project higher warming and less summer precipitation; PCM1 tends to project the opposite. In the middle panel is the output using an ensemble of GCMs; the data used for the analyses in this report.

Figure 10. Modeled mean summer flow (MS) for baseline and for the 2040s and 2080s using an ensemble of GCMs. See Figure 11 for a larger map of the baseline modeled MS and see Figure 12 for a comparison of model outputs for the 2040s using different GCMs.

Figure 11. Modeled mean summer flow (MS) for baseline time period.

Figure 12. Comparison of modeled mean summer flow (MS) using different GCM input for the 2040s. MIROC 3.2 GCM tends to project higher warming and less summer precipitation; PCM1 tends to project the opposite. In the middle panel is the output using an ensemble of GCMs; the data used for the analyses in this report.

Figure 13. Modeled flow timing (CFM) for baseline and for the 2040s and 2080s using an ensemble of GCMs. See Figure 14 for a larger map of the baseline modeled MS and see Figure 15 for a comparison of model outputs for the 2040s using different GCMs.

Figure 14. Modeled shift in timing of flows (CFM) for baseline time period.

Figure 15. Comparison of modeled shift in timing of flows (CFM) using different GCM input for the 2040s. MIROC 3.2 GCM tends to project higher warming and less summer precipitation; PCM1 tends to project the opposite. In the middle panel is the output using an ensemble of GCMs; the data used for the analyses in this report.

Figure 16. Conceptual model for bull trout resource needs and resource stressors used in determining exposure and sensitivity indices.

Figure 17. For the bull trout analysis, we used potential natal habitat patches as the unit of analysis for exposure metrics. Each unique color represents a unique patch. Exposure metrics were summarized by 6th level hydrological unit code (HUC-12). We summarize results by local populations. We show bull trout core areas (USFS & USFWS 2013), into which local populations are nested, for reference. Overall, in western Montana, there are 13 complex core areas containing 108 local populations and 6 simple core areas (with one local population each). Our study area includes portions of 6 core areas

Figure 18. To calculate the low population viability metric (Figure 37), we first calculated the amount of patch in each HUC-12 (see insert of schematic of our methods: the patch area shown as green) We calculated the geometric mean of 3 patch length measures: 1) the total length (mi) of all patch contained within a given HUC-12 boundary (schematic panel B) (, 2) the longest (mi) patch contained within the HUC-12 boundary (schematic panel C), and 3) the longest patch (mi) that intersected the HUC-12 boundary (but may have extended beyond the given HUC-12 boundary; schematic panel D).

Figure 19. We weighted the amount of patch in a HUC-12 (Figure 18) by an "occupancy weight" to create the final population viability metric (Figure 37). The occupancy weight compared three datasets that depicted known presence of bull trout or exceptional bull trout habitat. The occupancy weight was 1 (lowest occupancy) if the HUC-12 had no datasets depicting presence, otherwise it was the number of datasets depicting presence + 2.

Figure 20. Fish barriers, colored by type (culvert vs. dam or diversion) used in calculating low stream connectivity metric (Figure 38).

Figure 21. Roads used in bull trout analysis.

Figure 22. Modeled unconfined valley bottom (UVB) using algorithm from Nagel et al. (2014), used in calculating floodplain related metrics (Figure 43, Figure 48, Figure 63, Figure 64, and Figure 65).

Figure 23. HUC-12s with grazing allotments within 100 feet of streams and on <=4% slopes and those HUC-12s identified as having no grazing related impacts by expert opinion (blue cross hatching).

Figure 24. The water diversion metric (Figure 47, Figure 59) required data on the maximum mean summer (MS) flow in each HUC-12 and the flow rate associated with all water right points of diversion (POD) in each HUC-12. There were no flow rate data for 35% of the POD; the majority of which were located in the vicinity of the Blackfoot River.

Figure 25. Conceptual model for water supply resource needs and resource stressors used in determining exposure and sensitivity indices.

Figure 26. Map of infrastructure assessed for vulnerability: trails, roads, and recreation sites.

Figure 27. Conceptual model for infrastructure resource needs and resource stressors used in determining exposure and sensitivity indices.

Figure 28. Areas with high geologic hazard or alluvial fan used in calculating the geologic hazard metrics (Figure 66 through Figure 68).

Figure 29. Temperature exposure index (here, only one metric used for this index) for bull trout by the 2040s. We calculated the percent decrease in the proportion of the patch length with AMT <=13°C between baseline modeled conditions and the 2040s. Local bull trout populations, designated in the *Conservation Strategy for Bull Trout* are shown overlain in stippling (here and in all following bull trout maps). Confidence in metric: **moderate-high**

Figure 30. Temperature exposure index (and metric) for bull trout by the 2080s. Confidence in metric: **moderate**

Figure 31. High flow exposure metric for bull trout by the 2040s. We used the number of projected future days with high (95%) winter flows. Confidence in metric: **low-moderate**

Figure 32. High flow exposure metric for bull trout by the 2080s.
Confidence in metric: **low-moderate**

Figure 33. Low flow exposure metric for bull trout by the 2040s. We calculated the percent decrease in mean summer flows between baseline modeled conditions and the 2040s.
Confidence in metric: **low**

Figure 34. Low flow exposure metric for bull trout by the 2080s. Confidence in metric: **low**

Figure 35. Combined flow exposure index for bull trout by the 2040s. We calculated the geometric mean of the high (Figure 31) and low (Figure 33) flow exposure metrics.

Figure 36. Combined flow exposure index for bull trout by the 2080s.

Figure 37. Low population viability metric (sensitivity), calculated from combining two measures, representing the amount of patch in a HUC-12 (Figure 18) and the presence of bull trout or exceptional bull trout habitat (Figure 19). We subtracted the product of these two measures from the maximum resulting product (so that high values represented high stress, as is the case in all sensitivity metrics). Local bull trout populations, designated in the bull trout conservation strategy (BTCS), are shown overlain in stippling (here and in all following bull trout maps).
Confidence in metric: **moderate-high**

Figure 38. Low stream connectivity metric (sensitivity), calculated as the number of fish barriers (Figure 20). Confidence in metric: **moderate-high**

Figure 39. Total number of road-stream crossings by HUC-12. . This sub-metric is used in calculating the sediment metric (Figure 41).

Figure 40. Length of roads within 100 feet of streams as a proportion of stream length in each HUC-12. This sub-metric is used in calculating the sediment metric (Figure 41).

Figure 41. Sediment metric (sensitivity), calculated as the geometric mean of the two road sub-metrics (Figure 39 and Figure 40). Confidence in metric: **moderate**

Figure 42. Percent of riparian area without shade cover. This sub-metric is used in calculating the physical complexity metric (Figure 46).

Figure 43. Road length within the 100-year flood plain or stand potential tree height (SPTH, assumed to be 100 feet) of streams as a proportion of stream length in each HUC This sub-metric is used in calculating the physical complexity metric (Figure 46).

Figure 44. Road length within SPTH of streams and on low-gradient slopes (<=4%) as a proportion of low-gradient stream length. This sub-metric is used in calculating the physical complexity metric (Figure 46).

Figure 45. Grazing within SPTH of streams and on >=4% slope as a proportion of total area on >=4% slope and within 30m of streams in each HUC. This sub-metric is used in calculating the physical complexity metric (Figure 46).

Figure 46. Low physical complexity metric (sensitivity), calculated as the geometric mean of the riparian, road length within SPTH or floodplains, road length within SPTH on low gradient areas, and grazing sub-metrics (Figure 42, Figure 43, Figure 44, Figure 45).
Confidence in metric: **low-moderate**

Figure 47. Water diversion metric (sensitivity). For each HUC, we calculated the ratio of (1) the sum of the maximum flow rate allowed for all water right points of diversion that fell in the HUC to (2) the maximum of the mean summer (MS) flow across all non-mainstem reaches within the HUC. Figure 24 maps the data inputs for this metric. Confidence in metric: **low-moderate**

Figure 48. Low floodplain connectivity metric (sensitivity), calculated as the percent of stream length outside of the 100-year flood plain. Confidence in metric: **moderate**

Figure 49. Brook trout metric (sensitivity), calculated as a binary measure of brook trout presence (value of 2) or absence (value of 1). Confidence in metric: **low-moderate**

Figure 50. Combined sensitivity index for bull trout. We calculated the geometric mean of the low population viability (Figure 37), low stream connectivity (Figure 38), sediment (Figure 41), low physical complexity (Figure 46), water diversion (Figure 47), low floodplain connectivity (Figure 48), and brook trout (Figure 49) metrics.

Figure 51. Estimated vulnerability of bull trout to projected temperature changes, by patch, by the 2040s, based on comparing the temperature exposure (Figure 29) and combined sensitivity (Figure 50) indices. Streams listed as having common or abundant bull trout by MFISH or as being critical habitat by FWS are shown in white ("Important Habitat") for reference (see methods for details).

Figure 52. Estimated vulnerability of bull trout to projected flow changes, by patch, by the 2040s, based on comparing the flow exposure (Figure 35) and combined sensitivity (Figure 50) indices. Streams listed as having common or abundant bull trout by MFISH or as being critical habitat by FWS are shown in white ("Important Habitat") for reference (see methods for details).

Figure 53. Low flow exposure metric for water supply by the 2040s. We calculated the percent decrease in mean summer flows between baseline modeled conditions and the 2040s.
Confidence in metric: **low**

Figure 54. Low flow exposure metric for water supply by the 2080s. Confidence in metric: **low**

Figure 55. Flow timing exposure metric for water supply by the 2040s. We calculated the shift in the day of the water year when 50% of the annual flow has passed.
Confidence in metric: **low-moderate**

Figure 56. Flow timing exposure metric for water supply by the 2080s.
Confidence in metric: **low-moderate**

Figure 57. Combined flow exposure index for water supply by the 2040s. We calculated the geometric mean of the low flow (Figure 53) and flow timing (Figure 55) stressor metrics.

Figure 58. Combined flow exposure index for water supply by the 2080s.

Figure 59. Water diversion index (sensitivity; here, only one metric used for this index). For each HUC-12, we calculated the ratio of (1) the sum of the maximum flow rate allowed for all water right points of diversion that fell in the HUC-12 to (2) the maximum of the mean summer (MS) flow across all non-mainstem reaches within the HUC-12. Figure 47 maps the data inputs for this index.
Confidence in metric: **low-moderate**

Figure 60. Estimated vulnerability of water supplies, by HUC-12, by the 2040s, based on comparing the flow exposure (Figure 57) and sensitivity (Figure 59) indices.

Figure 61. Flooding exposure index (here, only one metric used for this index) for infrastructure by the 2040s, using the number of projected future days with high (95%) winter flows.

Figure 62. Flooding exposure index for infrastructure by the 2080s. Confidence in metric: **low**

Figure 63. Floodplain metric for recreation sites (sensitivity), calculated as the number of sites located within the 100-year floodplain. Confidence in metric: **moderate-high**

Figure 64. Floodplain metric for trails (sensitivity), calculated as the length of trails (mi) located within the 100-year floodplain. Confidence in metric: **moderate-high**

Figure 65. Floodplain metric for LNF-jurisdiction roads (sensitivity), calculated as the length of roads (mi) located within the 100-year floodplain. Confidence in metric: **moderate-high**

Figure 66. Geologic hazard metric for recreation sites (sensitivity), calculated as the number of sites located on an alluvial fan or within an area rated as having high geologic hazard.
Confidence in metric: **moderate**

Figure 67. Geologic hazard metric for trails (sensitivity), calculated as the length of trails (mi) located on an alluvial fan or within an area rated as having high geologic hazard.
Confidence in metric: **moderate**

Figure 68. Geologic hazard metric for LNF-jurisdiction roads (sensitivity), calculated as the length of roads (mi) located on an alluvial fan or within an area rated as having high geologic hazard.
Confidence in metric: **moderate**

Figure 69. Culvert metric for LNF-jurisdiction roads (sensitivity), calculated as the count of LNF-maintained culverts per LNF-jurisdiction road length (mi). Confidence in metric: **moderate-high**

Figure 70. Combined sensitivity index for recreation sites. We calculated the geometric mean of the floodplain (Figure 63) and geologic hazard (Figure 66) metrics.

Figure 71. Combined sensitivity index for trails. We calculated the geometric mean of the floodplain (Figure 64) and geologic hazard (Figure 67) metrics.

Figure 72. Combined sensitivity index for LNF-jurisdiction roads. We calculated the geometric mean of the floodplain (Figure 65) and geologic hazard (Figure 68), and culvert (Figure 69) metrics.

Figure 73. Estimated vulnerability of recreation sites, by HUC-12, by the 2040s, based on comparing the flooding exposure (Figure 61) and combined sensitivity (Figure 70) indices.

Figure 74. Estimated vulnerability of trails, by HUC-12, by the 2040s, based on comparing the flooding exposure (Figure 61) and combined sensitivity (Figure 71) indices.

Figure 75. Estimated vulnerability of LNF-jurisdiction roads, by HUC-12, by the 2040s, based on comparing the flooding exposure (Figure 61) and combined sensitivity (Figure 72) indices.

APPENDIX 3. WESTERN PEARLSHELL MUSSEL

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Morrison-Maierle Consulting and Montana Natural Heritage Program

BACKGROUND

The western pearlshell mussel (WEPE), *Margaritifera falcata,* is the only mussel inhabiting cold water streams of USFS Region 1 (Montana, Idaho). In Montana, it has experienced significant statewide range reductions in the last 100 years and is now known from ~85 populations, of which, only ~20 are expected to be viable 100 years from now (Stagliano 2010). In the short-term, many of these remaining populations are at risk of extirpation due to stochastic events able to wipe out these small isolated populations, and in the long-term, they are at risk from the lack of reproduction with non-native salmonid host species or climate change (Hastie et al. 2003). Because of the WEPE's intricate reproductive host fish relationship with westslope cutthroat trout, declines in westslope cutthroat trout populations due to stream degradation and competition with non-native salmonids have led to extirpations of WEPE populations. Recent attempts to locate new WEPE populations in 25 previously un-surveyed stream reaches of the Madison and other upper Missouri River basins have yielded negative results (Stagliano 2013). Three small WEPE populations that we have resurveyed since 2007 are now documented to be extirpated, and two others are on the verge of disappearing. More discouraging were our findings in 2012 that two WEPE populations in the Clearwater River, previously thought to be the most abundant in the state, were not able to provide the requisite number of individuals (n = 500) for a relocation project (Stagliano 2013).

The declining status of the WEPE has led to its designation as a Tier 1 invertebrate species in the State Wildlife Action Plan (MFWP 2014), a Species of Concern by the State of Montana (MTNHP 2008), and a Sensitive Species by the U.S. Forest Service Region 1 (USFS 2011). Further declines may upgrade the WEPE's Nature Serve conservation status in Montana from imperiled (S2) to critically imperiled (S1).

Due to budget and time constraints, we were unable to complete a full vulnerability assessment for WEPE. However, we have outlined methods for a future vulnerability assessment of this vital species.

PROPOSED METHODS

UNIT OF ANALYSIS

We will use modeled potential suitable mussel bed habitat as our unit of analysis for calculating exposure metrics (Figure A3.1).

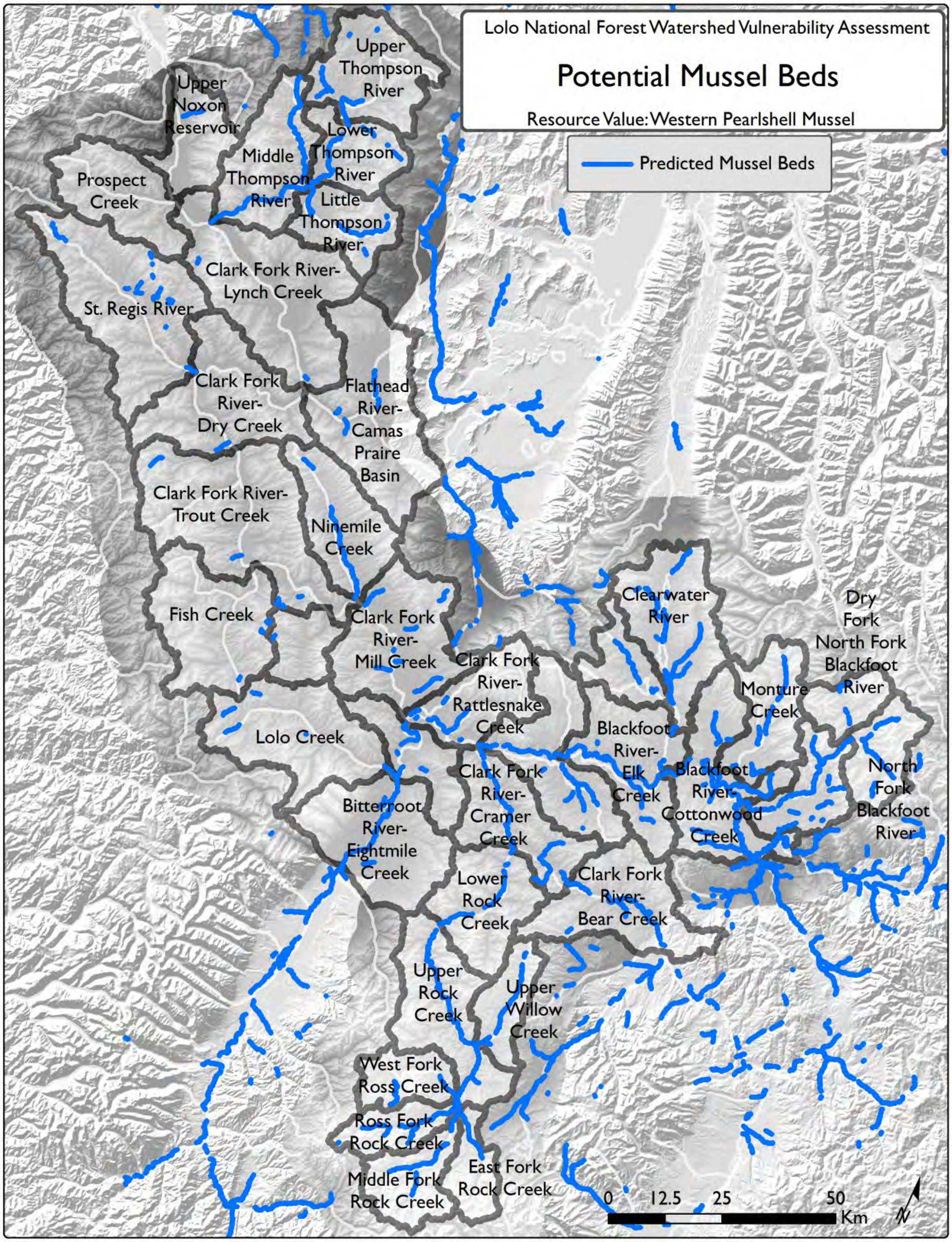
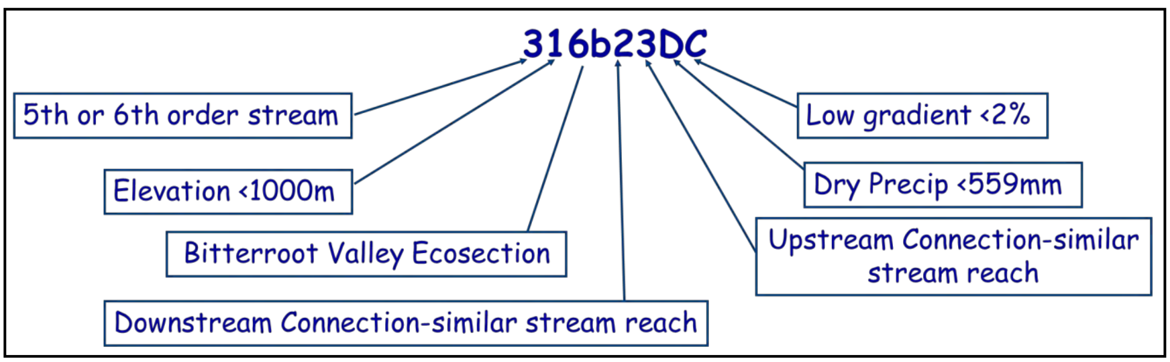


Figure A3.1. *Predicted suitable habitat for Western Pearlshell (WEPE) mussel beds*.

Mussel bed occurrence and potential was modeled by Dave Stagliano of the Montana Natural Heritage Program (MNHP). To produce this model of potential mussel bed locations, we compiled all available mussel surveys, occurrence records and field habitat variables from databases, field studies or reports that have been performed since 2009 for watersheds within the Lolo Forest boundary and appended them to existing data files (maintained by Stagliano for MNHP) to produce updated full WEPE occurrence coverage for the Lolo National Forest.

Stream reaches for this model were classified from the USGS National Hydrography Database (NHD) Plus by seven landscape variables: stream order, elevation, downstream and upstream connectivity, gradient, lithology, and precipitation. All stream classification variables except precipitation and lithology were calculated using the attribute tables from the NHD Plus dataset. Lithology and precipitation were derived from the USFS 1:500,000 Ecological Subsections and PRISM Average Annual Precipitation 1971-2000, respectively. Montana's Columbia Basin contains 26,052 NHD reaches and 1044 unique reach codes (316b23DC, 316b22DC, 316b12DC) which we've derived into 34 Aquatic Ecological System codes (B009, B010) (Stagliano2009).The resulting AES code from this compilation (see Text Box) translates to the Medium Intermountain River AES which includes sections of the Bitterroot, Clark Fork, and Clearwater Rivers).



From the compiled survey data, the western pearlshell occurred predominately in 3rd-4th Strahler order streams (80%), 15% in 5-6th order and ~5% in 2nd order streams. From presence data, 90% of western pearlshell occurrences were located in field estimated Rosgen C (C3-C4) stream reaches, 10% in B or E (B3 or E4) reaches. Eighteen records of pearlshell occurrence were within the AES code 217b23DC. For predictive capabilities we used the gradient variable in the NHD reach code to highlight expected pearlshell habitat (C or E = <2%, B = 2-4%).

From field data, the average wetted stream width where pearlshells were located at the time of the survey was 5.5m (1.2-45m) and riparian canopy cover averaged 50%, but there are no variables within the AES code representing these conditions.

Oftentimes pearlshells can occur in unpredicted stream reaches, "they are where you find them", because of the randomness in which juvenile mussels can be delivered to different streams by their host fish. In the minds of many pearlshell researchers, stable channels and host fish densities are probably more important than stream size.

The NHDPlus was downloaded for region 17b of the Pacific Northwest and region 10U of the Mississippi: http://www.horizon-systems.com/nhdplus/index.php. Flowlines with FLOWDIR = Uninitialized did not have attributes calculated in the NH Plus and were therefore not used in analysis. All water bodies whose FTYPE was not Lake/Pond or Reservoir were deleted. The NHDPlus doesn't seem to accurately designate reservoirs/dammed water bodies. To get at these features, the NHDPlus water bodies were compared with the high-resolution NHD water bodies and the dam's layer from NRIS. All features that contained the word "reservoir" in their name, intersected high-resolution NHD reservoirs, or contained a dam within a 200 meter buffer were designated as reservoirs.

Data sources:

*Stream Order***.** Stream order was downloaded from the Data Extensions section of the NHDPlus website (http://www.horizon-systems.com/nhdplus/download.php). The hydrologic main path was isolated by deleting data where SC (Strahler Calculator) equaled zero. (ftp://ftp.horizon-systems.com/NHDPlusExtensions/SOSC/SOSCmetadata.pdf). Streams were categorized according to class definitions for Aquatic Ecological Systems (AES).

Elevation. Elevation values for the NHDPlus are taken from the 30m National Elevation Dataset (NED). The data are found in flowlineattributesflow.dbf and include minimum and maximum reach elevations (in meters) and a reach slope calculation. The minimum and maximum elevations for each reach were averaged, and this value was used to separate reaches into AES classes.

Lithology/Ecosection. USFS 1:500,000 Ecological Subsections were downloaded as EcoSect.shp from the NRIS website. Reaches were classified by first selecting the subsection and then selecting and designating all reaches whose centroids were found in that subsection.

Downstream Connectivity. Class 2 (stream of similar or next order) was given as the default downstream connectivity class. Class 1 was given to reaches whose centroids were within waterbodies. The FromNodes of these waterbody reaches were related to flowline ToNodes. Related flowlines were given class 1. Class 3 is given to reaches flowing into larger rivers at least 2 orders larger. Beginning with third order streams, streams were selected and their LEVELPATHI was related to flowline DNLEVELPAT. The related flowline selection was queried for SO = 1 and for reaches that intersected third order streams. Reaches whose connectivity was 2 were given a connectivity of 3. The same process was completed for higher-level streams; querying the related flowlines for streams at least 2 orders lower. Reaches flowing into larger order streams can be short at times. To extend the classification, first order, class 3 reaches were related to flowlines by LEVELPATHI. The flowline selection was reduced to first order streams that intersected the related reaches and were originally class 2. The process was repeated for all stream orders. Reaches whose terminal flag = 1 were given class 0. Exceptions were reaches flowing across the Canadian border.

*Upstream Connectivity***.** Class 3 (stream or river) was given as the default class for all stream reaches. To isolate stream reaches with upstream connectivity to lakes, reaches with their centroids in natural water bodies were selected and given a class 1. The ToNodes of the lake reaches were related to flowline FromNodes, and the related reaches were given a connectivity of 1. The procedure was applied to man-made reservoirs as well. All first order streams were given a connectivity of 0, except for those reaches that intersected reaches already classified as 1 or 2

Stream Length. The LEVELPATHI field in the flowline attribute table was summarized and the sum of LENGTHKM was included as a summary statistic.

Conceptual Model

Our conceptual model of WEPE vulnerability (Figure A3.2) included stress from exposure to increased stream temperatures and winter scour and reduced summer flows. These will be summarized by modeled potential mussel beds.

Primary stressors hypothesized to increase sensitivity to climate change include low population viability (some percentage due to human take), low stream habitat quality due to sediment, low baseflow and the loss of native host fish. Sensitivity metrics will be summarized by HUC-12 (6th level hydrological unit codes).

We do not consider the adaptive capacity of western pearlshell in this section. However, the ability for WEPE to adapt to warming conditions likely depends on having enough individuals and genetic variation across numerous meta-populations across the Lolo Forest. It is presumed that warming water temperatures may open up suitable stream habitat currently considered thermally unsuitable (<50°F; 10°C) (Stagliano, unpublished data). It has been estimated that WEPE in Montana are losing reproductive diversity to reproductive self-fertilization of females in low populations (Mock and Brim Box 2008) (See Low Population Viability). Thus, supplementation or management actions to try and increase non-viable populations may have to be investigated to maintain adaptive genetic variation. It is commonly believed that genetic conservation can be maintained at 500 individuals in a population (Rieman & Allendorf 2001). Another positive adaptive aspect of the WEPE is the host fish use of the non-native brook trout (Oswald 2008, Stagliano 2010). The presence of non-native salmonids (i.e. Brook Trout), that are considered a detriment to bull trout survival, may actually improve the adaptability of the western pearlshell in the face of climate stresses because they can use this species as a surrogate host fish. The question of whether those adaptations can be expressed quickly enough to allow for resilient, viable WEPE populations is left unanswered in this study.

Exposure

Exposure to Increased Temperature. We will calculate the percent decrease in the proportion of a predicted mussel bed with AMT > 77°F (25°C) between current time period and the 2040s and between current and the 2080s. Stagliano (2010) found no WEPE presence in streams surveyed having summer daytime water temperatures <50°F (10°C) or > 77°F (25° C; avg. 62.4°F or 16.9°C, n=98). WEPE populations documented in streams with maximum daily temperatures ~77°F (25°C) appeared stressed and had poor viability (D, Smith River and East Fork Gallatin). Rodland et al. (2008) found frequency of adduction and valve closure in *M. falcata* peak at 77°F (25°C), and continuous gaping is observed above 85.1°F (29.5°C ; thermally stressed above 77°F or 25°C in the lab was likely due to low dissolved oxygen uptake). Stone et al. 2004 found WEPE positively correlated to dissolved oxygen (DO) concentrations in stream channel positioning.

Warming water temperatures in streams currently with daily temperatures <50°F (10°C) that have suitable habitat at higher elevations may hold adaptive benefits to WEPE by opening up stream miles upstream.

Exposure to Winter High Flows. WEPE prefer channels with low velocities, low shear stress and stable substrates (Stock 1996, Howard & Cuffey 2003, Vannote & Minshall 1982, Stone et al. 2004, Davis 2008). Stream velocities have been found to affect intra-stream habitat selection (Oswald 2008), and this species can frequently be found in eddies or pools (Howard & Cuffey 2003) or areas with boulders that shelter mussel beds from scour during flood events (Vannote & Minshall 1982). Therefore, higher winter flows may increase potential for scour events that can dislodge mussels from the substrate and, at these temperatures, there is little chance of a pearlshell reestablishing itself. If populations are able to withstand increased flows, periodic flushing flows of floods can have some beneficial effects. For example, a mussel bed may be 'improved' as potentially harmful materials (i.e. ammonia, feces, etc.), built up during low flow conditions, are flushed out of the sediments (Hastie et al 2003).

We will take the number of days with highest 5% flows (W95); see bull trout methods). We will then take the weighted average (by reach mi, Equation 1) of the high flow metric within each bed.

Exposure to Reduced Summer Low Flows. In Montana 55% of WEPE occupied stream sites are 3rd-4th Strahler stream order and 27% of total were 1st-2nd order streams (Stagliano 2010). WEPE were not found in streams less than 8 km long with watersheds less than 30km^2 or with flows < 1.0cfs. Therefore, as stream baseflows are reduced by future climate predictions, some streams may be considered inadequate for WEPE and removed from original predicted or documented habitat (Stagliano 2010). Future changes in stream size (reduced summer wetted width) will be considered as a measure of exposure. The low flow exposure metric represents the potential for lost habitat from reduced flows with the potential to cause dewatering, reduced stable channel flows, or insufficient flow to create side channel or pool refugia for juvenile mussels.

We will calculate the metric percent reduction in mean summer flows, as given by Equation 2 under bull trout methods. We will then take the weighted average (by reach mile, Equation 1) of the low flow metric within each bed.

Combined Flow Exposure Index. We will combine the winter scour (high flow) and summer habitat (low flow) metrics by calculating their geometric mean. We did not combine flow with temperature because of the very different nature of temperature and flow effects and because of the much higher uncertainty in flow as compared to temperature.

Sensitivity

Stress from Low Population Viability. Larger, stronger populations are less susceptible to extinction than those with reduced population viability. We will use two sub-metrics to account for population viability. First, we will calculate population size sub-metric following the methods outlined under the bull trout analysis. We will take the geometric mean of 3 patch length measures: 1) the total length (mi) of all beds contained within a given HUC-12 boundary, 2) the longest (mi) contiguous bed contained within the HUC-12 boundary, and 3) the longest contiguous bed (mi) that intersects the HUC-12 boundary (but may have extended beyond the given HUC-12 boundary). We used the geometric mean (the mean of the log-transformed values) because it normalizes the range of the values being averaged.

We will then multiply the calculated bed measure by an "occupancy weight using WEPE population viability measures derived by Stagliano (2010, A-E) to define known WEPE "strongholds" (A and B viability). Thus, populations with low viability and little reproductive capacity or lacking suitable habitat are determined to be more sensitive to climate change. The occupancy weight (OW) will be as follows: high viability populations (rank = A or B), OW = 5; moderate viability (rank = C or D), OW = 3; low viability (rank = E), OW =1. If there are multiple viability rankings in a bed, we will use the highest OW in the bed.

The final low population viability metric will then be calculated as:

$$Low\ population\ viability_{\mathrm{HUC}} = \max(GMP * OW) + 1 - (GMP_{\mathrm{HUC}} * OW_{\mathrm{HUC}}),$$

where GMP is the geometric mean of the three bed measures (described above) and OW is the occupancy weight (described above).

A further negative stress factor to population viability is the mussel bed's proximity to publically available Fishing Access Sites (FAS) or campgrounds. We (Stagliano, Podner and Pierce, unpublished data) have documented significant decreases in the numbers of mussels in the vicinity of easily accessed FAS from direct take, presumably for consumption, but sometimes out of curiosity. Therefore, we included a sub-metric for determining threats for populations within 0.6 mi (1km) of a public accessible FAS or campground. We will calculate the average inverse distance of all beds within a HUC-12 to a FAS or campground site, within a 0.6 mi (1 km) radius.

Note: We are currently working with Fisheries Managers at MTFWP to designate "no take or possession" regulations for the Western Pearlshell Mussel in Montana

We will combine the two population size sub-metrics into the population viability metric by calculating their geometric mean.

Confidence in metric (for confidence in all other metrics, refer to Bull Trout methods): high. We have quality data from numerous surveys and modeling efforts to represent most of the WEPE populations and high quality western pearlshell habitat in the study region. Low habitat suitability and low population viability correlate quite well. We do detect significant absences in suitable habitat where know diversions or dewatering events have occurred.

Stress from Sediment. Sediment may have lethal consequences for WEPE. Mussels smothered by sediments as little as 5 cm deep during dredging operations experienced 10-30% mortality (Vaughn and Taylor 1999, Marking and Bills 1979). Mussels within an in situ experiment with sediment experienced significantly more adverse physical affects as temperatures were increased (Archambault et al. 2014). Mussel populations in Midwestern US, elevated-sediment, agricultural watersheds had lower viability and abundance than less agriculturally dominated watersheds (Cao et al 2013). Less research has been done on western mussels population, but WEPE appear to be intolerant of sedimentation; in the Salmon River of Idaho, WEPE covered with shifting sand and gravel were unable to uncover themselves and perished (Vannote & Minshall 1982). Although, Stagliano (personal observation) has documented WEPE inhabiting deep-silted, low-flow, side channel areas where the channel had migrated away from the mussel bed. Sublethal impacts of sediments include reduced growth rates, physiological stress, as well as behavioral effects to avoid areas with high fine sediment loads (Gascho Landis et al. 2013).

To measure sediment effects on mussel beds, we will use sub-metrics and metric already calculated for the bull trout analysis. We will include both the number of road stream crossings and the number of parallel roads within 100 feet per total stream mi within a HUC-12. We combined the two road sub-metrics into the sediment metric by calculating their geometric mean (see Figure 39, Figure 40, and Figure 41 in Appendix 2).

Stress from Low Channel Complexity

The metric will incorporate three sub-metrics: riparian cover, valley confinement, and grazing near streams. All sub-metrics have already been calculated as part of the bull trout analysis.

For the riparian vegetation metric, we calculated the percent of area in each HUC-12 that, within a 150 ft. buffer on either side of the stream, did not have shade cover (see Figure 42 in Appendix 2).

Unconfined valley bottoms (floodplain areas) provide for cold water upwelling and mitigate high flow effects. We used the valley bottom algorithm of Nagel et al. (2014) as described above under the bull trout low floodplain connectivity metric (see Figure 48 in Appendix 2).

To calculate the grazing metric, we calculated the area (mi^2) of grazing allotments that were within SPTH (100 feet from a stream) and on less than a 4% slope as a proportion of total stream length (mi) on less than 4% slope within each HUC-12 (see Figure 45 in Appendix 2).

We will combine the three complexity sub-metrics into the physical complexity metric by calculating their geometric mean.

Stress from Low Baseflow. Western pearlshells require perennial stable baseflows, but prefer to be out of the thalweg of the stream (Stock 1996, Oswald 2008), and juveniles are often found in the margins of depositional areas (Stagliano, pers. obs.). A substantial reduction of summer flows can reduce juvenile habitat at the margins and constrict the overall channel habitat. Areas with existing low baseflows from diversions are particularly sensitive to reduced summer flows. Further, climate induced changes to flow may compound increasing water temperatures. The rate of diversion for granted water rights may outstrip water availability, and in some instances, more water may be diverted than is allowed by right. Methods were the same as used for the bull trout analysis. To calculate the water diversion metric, for each HUC-12, we summed the flow rate (CFS) for all unique water right diversion locations and calculated the maximum of the MS flow (CFS) from the US flow metric dataset for the historical time period (see Figure 47 in Appendix 2).

Stress from non-natives. Non-native brook trout (*Salvenius fontinalis*) are the primary invasive species threatening bull trout in the study area. However, the presence of non-native salmonids (i.e. Brook Trout) that are considered a detriment to Bull Trout survival, may actually improve the adaptability of the western pearlshell in the face of climate stresses because they can use this species as a surrogate host fish (Murphy 1941, Stagliano and Oswald, pers. obs. Selway Creek, BVDL). The question of whether those host fish swapping adaptations can be expressed quickly enough to allow for resilient, viable WEPE populations is left unanswered in this study.

We will calculate a binary metric of brook trout presence or absence using MFISH data. We considered any HUC-12 with a minimum of 3.1 mi (5 km) of reach designated as having abundant or common brook trout to be occupied by brook trout.

Resource Area: Aquatics
Value: Western Pearlshell Mussel

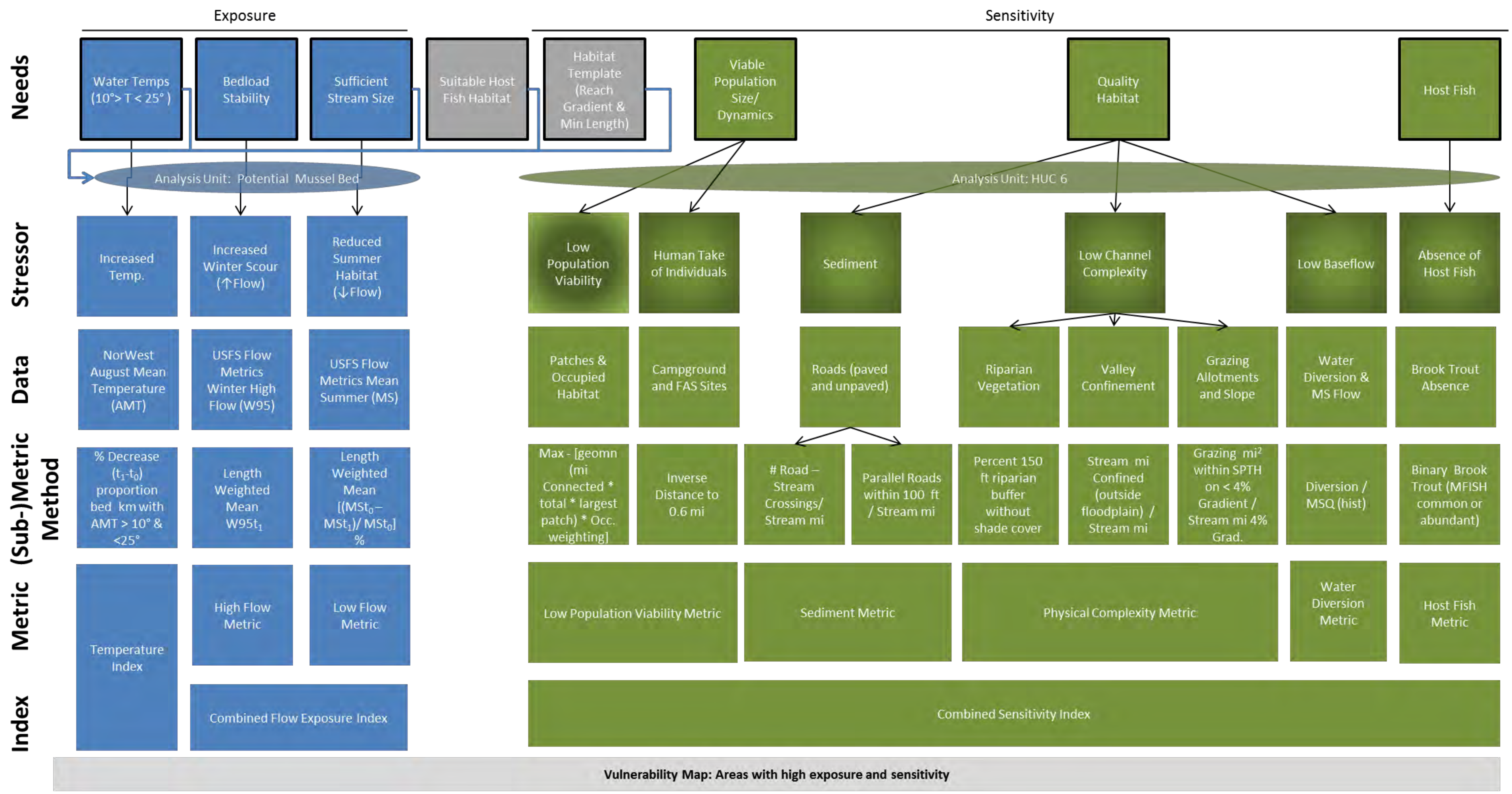


Figure A3.2. *Conceptual model for WEPE.*

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