Wildfire and River Restoration: Case Studies from the Methow River Watershed

For U. S. Bureau of Reclamation
July 2023

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ACKNOWLEDGEMENTS

The authors and contributors of this report gratefully acknowledge Yakama Nation Fisheries staff (Hans Smith, Brandon Rogers, Jarred Johnson, Chris Butler, and Maddie Eckmann) for collaborating on developing project objectives, coordinating site visits, and providing information from the case study project areas. Funding for this project was provided by the U. S. Bureau of Reclamation. We thank Jeff McLaughlin (USBR) and Sean Welch (Bonneville Power Administration) for providing overall project direction, and Christopher Cuhaciyan (USBR) and Steve Kolk (USBR) for their support of the project.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS

AGWA – Automated Geospatial Watershed Assessment

BAER – Burned Area Emergency Response

BiOp – Biological Opinion

BPA – Bonneville Power Administration

CIG – Climate Impacts Group

CIRC – Climate Impacts Research Consortium

CODNR – Colorado Department of Natural Resources

ELJ – engineered log jam

ESA – Endangered Species Act

FCRPS – Federal Columbia River Power System

GIS – Geographic Information System

GNSS – global navigation satellite system

GPS – global positioning system

LWD – large woody debris

MTBS – Monitoring Trends in Burn Severity

NFSC – Northwest Fire Science Consortium

OWEB – Oregon Watershed Enhancement Board

Rio ASE – Rio Applied Science & Engineering

RM – river mile

RTT – Regional Technical Team

THSC – Tributary Habitat Steering Committee

Tributary Assessment – Methow Sub-basin Geomorphic Assessment

UAV – uncrewed aerial vehicle

UCRTT – Upper Columbia Regional Technical Team

UCSRB – Upper Columbia Salmon Recovery Board

USBR – U.S. Bureau of Reclamation

USDA – U.S. Department of Agriculture

USFS – U.S. Forest Service

USGS – U.S. Geologic Survey

WADOE – Washington State Department of Ecology

YNF – Yakama Nation Fisheries

ABSTRACT

Under current climate change trends, wildfire frequency, extent, and severity are all projected to increase throughout western North America. As investments in salmonid habitat restoration in the Pacific Northwest continue, the compounding threat of wildfire creates an impetus for more rigorous consideration of wildfire impacts in the context of stream restoration design.

Rio Applied Science & Engineering (Rio ASE) and Inter-Fluve completed this report for the U. S. Bureau of Reclamation (USBR) and Bonneville Power Administration (BPA) in order to provide information on the emerging need to understand wildfire impacts on river restoration projects. The intent of this report is to inform future restoration designs by incorporating findings from recent scientific literature and lessons learned from restoration projects that have experienced direct and indirect effects from wildfires.

The report includes a brief background and introduction to recent literature highlighting observed and projected climate and wildfire trends in the Pacific Northwest. The relevance of those trends on rivers, floodplains, fish habitat, and stream restoration are briefly described. Lastly, this chapter includes mention of existing resources available to restoration practitioners for evaluating and planning for wildfire risks to river reaches under consideration for restoration.

The case studies from the Methow River Basin summarize observations of direct fire impacts to fish habitat restoration projects and potential indirect secondary post-fire impacts to restoration projects in the Chewuch River and Beaver Creek. Additionally, observations are summarized for fire impacts to a Wolf Creek reach, where no project work has been conducted, and additional observations in both Beaver Creek and the Chewuch outside of the limits of project work.

USBR and BPA can lead the efforts in adaptation of tributary habitat restoration to wildfire risks through:

- Coordination and support of ongoing and additional case studies of wildfire effects on stream restoration projects.
- Development of standardized guidelines for incorporating wildfire risks into restoration designs.

Through more rigorous consideration of observed and projected climate and wildfire trends, stream restoration actions can become more resilient to the effects of wildfire and habitat restoration projects can more effectively buffer some of the negative impacts of wildfire, thereby contributing to proactive management strategies aimed at climate change adaptation and mitigation.

1 INTRODUCTION

As part of the 2020 Federal Columbia River Power System (FCRPS) Biological Opinion (BiOp), the U. S. Bureau of Reclamation (USBR) and Bonneville Power Administration (BPA) participate on the Tributary Habitat Steering Committee (THSC) that is leading the strategy, planning, and implementation of tributary habitat restoration throughout the Columbia River Basin. Among their responsibilities, THSC is coordinating outreach and communication of technical information among subbasins included in the BiOp. This coordination includes the completion of case studies on emerging topics of interest to restoration practitioners throughout the BiOp subbasins.

Under current climate change trajectories, wildfire frequency, extent, and severity are all projected to increase throughout western North America (May et al., 2018; Ball et al., 2021). As investments in salmonid habitat restoration in the Pacific Northwest continue, the compounding threat of wildfire creates an impetus for more rigorous consideration of wildfire impacts in the context of stream restoration design.

This report provides information on the emerging need to understand wildfire impacts on river restoration projects. The overarching intent of this report is to inform future restoration designs by incorporating findings from recent scientific literature and lessons learned from restoration projects that have experienced direct and indirect effects from wildfires. The project was guided by the following goals and objectives:

Goals

1. Review available literature on wildfire impacts to watershed, hillslope, river, and floodplain processes/characteristics.
2. Describe observations of direct and indirect wildfire impacts to fish habitat restoration projects in the Methow River basin.
3. Evaluate commonalities between observations from the Methow River basin and findings from the literature review of typical post-fire watershed, hillslope, river, and floodplain processes/characteristics.
4. Identify lessons learned and risks to understand when designing river restoration projects in watersheds prone to wildfire.
5. Communicate the lessons learned and risk considerations to a non-technical and technical group of restoration practitioners to inform the design of future habitat restoration or enhancement projects in wildfire-prone watersheds.

Objectives

1. Compile available information, ground photos, and uncrewed aerial vehicle (UAV) imagery from three project reaches in the Methow River basin (Figure 1-1), two of which have had restoration treatments affected by wildfire and one of which is a reference reach (i.e., without prior restoration treatments) that has been affected by wildfire.
2. Complete a literature review of wildfire impacts on conditions and processes in river and floodplain settings similar to those of the focus project reaches.
3. Describe observations of direct fire impacts to fish habitat restoration projects and potential indirect secondary post-fire impacts to restoration projects in the Chewuch River and Beaver Creek. Describe observations of fire impacts to Wolf Creek reach where no project work has been conducted and additional observations in both Beaver Creek and the Chewuch outside of the limits of project work.
4. In the form of succinct case studies, summarize the information from each project reach (Chewuch projects, Beaver Creek projects, Wolf Creek reference reach). Describe what was learned in the post-fire response analysis case studies and summarize actions that can be applied to reduce and mitigate fire and post-fire impacts to future restoration projects constructed in wildfire-prone watersheds.
5. Summarize the literature review and case studies in a report written for a non-technical audience.

The following chapters of this report include a literature review organized by topics. Chapter 3 provides summary case studies for the Chewuch River, Beaver Creek, and Wolf Creek. The case studies are followed by a summary of lessons learned and recommendations for restoration designs.

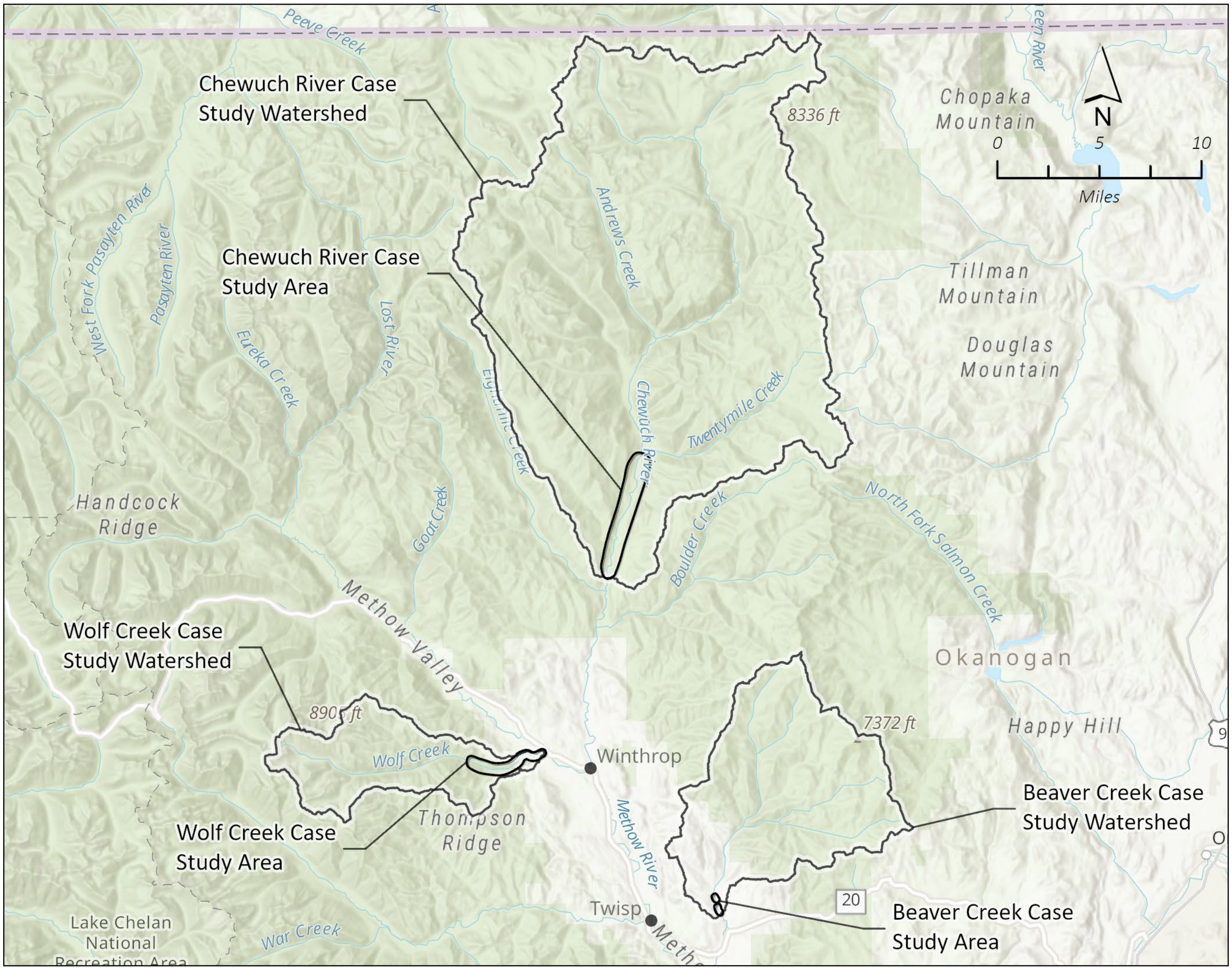

Figure 1-1. Case study project areas in the Methow River basin.

2 BACKGROUND AND LITERATURE REVIEW

This chapter provides a brief overview of wildfire impacts on the ecological processes considered in river restoration projects to enhance and inform future designs. Specific attention is focused on forested mountain systems with similar watershed characteristics to, and habitat treatment types (large wood structures, apex jams, side channels, and pools) used in, the Methow River watershed case study locations. This chapter begins with a brief introduction to recent literature highlighting observed and projected climate and wildfire trends in the Pacific Northwest. The relevance of those trends on rivers, floodplains, fish habitat, and stream restoration are briefly described. Lastly, this chapter includes mention of existing resources available to restoration practitioners for evaluating and planning for wildfire risks to river reaches under consideration for restoration.

Although there is a large body of knowledge related to the impacts of wildfire on hydrologic, geomorphic, and ecologic processes at a range of scales across watersheds, hillslopes, and valley bottoms (e.g., Swanson, 1981; Shakesby & Doerr, 2006), there is very little information specifically on the impacts of wildfire on habitat restoration projects, or conversely, on the impact of projects on wildfire dynamics. In general, the processes that habitat restoration designs aim to mimic may be either muted or enhanced by wildfire and post-fire disturbance cascades. In some cases, wildfire impacts and resulting disturbance cascades may work in the same direction of restoration objectives (e.g., addition of wood and spawning gravels). In other cases, wildfire has the potential to degrade or destroy the physical treatments designed to improve habitats (e.g., fill in pools with sediment, burn riparian forests, or directly burn instream wood structures). There may also be cases where the projects themselves affect the severity or pattern of fire, thereby influencing the magnitude or nature of the disturbance (e.g., increased wetted area may reduce burn severity). This literature review summarizes the available information related to these dynamics, and provides a technical foundation that, along with the Case Studies (Chapter 3), supports the lessons learned conclusions and recommendations.

2.1 Climate Change and Wildfire Trends

Throughout the western United States, climate change over the past several decades has resulted in increased forest disturbance from wildfire, drought, and disease; these climate impacts are likely to continue over the next several decades. Since 1895, average annual temperature has increased 1.3°F - 2.2°F throughout the Pacific Northwest, with most of this warming occurring in the past 50 years (Abatzoglou et al., 2021; Fleishman, 2023). In Idaho, 70% of the warmest years during 1895-2020 have occurred since 1990, while throughout the Pacific Northwest, 80% of the years from 1980 to 2011 were warmer than the 1901-1960 average (Abatzoglou et al., 2021; Fleishman, 2023). In June-July 2021, the Pacific Northwest experienced an extreme record-breaking heatwave that was one of the most anomalous heat events ever recorded globally, with average summer 2021 temperature approximately 6.5°F warmer than the 1951-1980 average (Heeter et al., 2023). Future climate projections based on intermediate levels of anthropogenic emissions suggest that 2021-like extreme summer temperatures have a 50% chance of annual occurrence by 2050 (Heeter et. al., 2023). Aside from predictions of extremely high summer temperatures, under existing greenhouse gas emission scenarios annual temperature in the Pacific Northwest is projected to increase by 5°F by the 2050s and 8.2°F by the 2080s, with the greatest seasonal increases in summer (Fleishman, 2023).

Warmer and drier climate conditions are likely to have detrimental effects on forest ecosystems and wildfire severity. Throughout the twentieth century in the Pacific Northwest, larger fires and greater burned area generally corresponded with years of relatively warm and dry conditions (Halofsky et al., 2020). Decreases in fuel moisture, coupled with increases in the periodicity and duration of warm, dry weather, results in large forest areas with dry fuels that are more likely to ignite and more prone to increased fire frequency, extent, and severity (Littell et al., 2016; Hagmann et al., 2021). Increases in the burned area of western forests are projected to be exacerbated by decreased summer precipitation (Holden et al., 2018). These detrimental effects of climate change on forests are compounded by more than 100 years of wildfire suppression, elimination of burning practices formerly used by indigenous peoples, logging of large, fire-resistant trees, and other forest management practices (Davis et al., 2023). Collectively, these changes have altered the structure, composition, and fire regime of western forests, whereby those that historically experienced low- and moderate-severity fire are now experiencing high-severity fire (Davis et al., 2023). Forests that experience high-severity fire are susceptible to ecological transformation through the loss of mature trees, alterations to microclimates and soil properties, and reductions in the seed sources needed for forest regeneration. Research by Davis et al. (2023) suggests that western forests in 40% to 42% of their study area are likely to exhibit post-fire conifer regeneration following low-severity but not high-severity fire under future climate scenarios from 2031 to 2050; however, by 2050 and beyond, projected climate conditions result in 26% to 31% of the study area exhibiting conditions whereby conifer regeneration is considered unlikely, regardless of fire severity. These interacting effects of climate change and forest ecosystem alterations have implications for post-fire hydrologic risks in the Pacific Northwest. Recent research suggests that more than 90% of extreme fire weather events in California, Colorado, and the Pacific Northwest will be followed by at least three spatially collocated extreme rainfall events within five years (Touma et al., 2022).

2.2 Fire Impacts on River Corridors and Habitats

Wildfires are important vegetation-altering hillslope disturbances in forested mountain regions and can instigate a cascade of hydrologic and geomorphic processes that enhance sediment and wood delivery to aquatic ecosystems and shape river environments (Ball et al., 2021). Removal of vegetation by fire, combined with changes to the physical and chemical properties of soil, can result in more precipitation reaching the ground, enhanced impacts of hydrophobic substances, and greater soil moisture, runoff, and streamflow. Although the prospect for increased streamflow may be seen as a positive outcome, increases in post-fire runoff, particularly after severe fire, are often accompanied by large sediment loads, reduced water quality, and enhanced flood, debris flow, and landslide hazards. Furthermore, post-fire hydrologic responses are not always straightforward because compensatory uptake by unburned downgradient vegetation can reduce measured wildfire effects on streamflow (Collar et al., 2022).

Post-wildfire precipitation can compound extreme events, including debris flows and flash floods, which will likely increase in frequency due to climate change across a broad portion of the western United States spanning a wide range of topographical and vegetation regimes (Luce et al., 2012; Littell et al., 2016; Hagmann et al., 2021; Touma et al., 2022; Heeter et. al., 2023). Recently burned areas have an elevated risk of debris flows, mudslides, and flash floods during rain events due to wildfire-induced changes in soil properties, vegetation loss, and ground cover (Staley et al., 2017). The hydrologic impacts and risk of debris flows can persist in burned areas for up to a decade following fire as soils and vegetation recover on hillslopes. While areas burned in a wildfire can start to recover some of their pre-fire conditions after one year, post-fire effects on vegetation, soil absorbency, and ground cover can remain up to eight years after a fire. During this time, a burned area will typically experience enhanced risks of flash floods and debris flows. Semiarid regions are especially prone to increased fire and therefore sediment yield, given their tendency toward greater drying under future climate and being neither fuel nor flammability limited (Goode et al., 2012; Littell et al., 2018; East & Sankey, 2020).

Wildfire shapes many aspects of forested ecosystems, and fire-related debris flows are a dynamic mechanism for delivering sediment, wood, and nutrients from tributaries to mainstem rivers (e.g., Marcus et al., 2011). The long-term role of climatic disturbances, such as drought, in regulating fuel supplies and fire regimes is well recognized (Pierce & Meyer, 2008), and the associated hillslope disturbances are important for replenishing gravel and wood to aquatic ecosystems (Reeves et al., 1995).

Timing, Biological Factors, and Recovery

While wildfire can initially be seen as a destructive process, several examples point to ecological benefits. In a semi-arid snowmelt-dominated basin in central Idaho, Jacobs et al. (2021) documented strong positive relationships between fire and the occurrence of Chinook spawning locations. In the Wenatchee River basin, which lies just to the south of the Methow River watershed (the focus of this study), modeling results of the impacts of wildfire on various life history stages of Endangered Species Act (ESA)-listed salmonid species suggest potential for increased habitat quality (Flitcroft et al., 2016).

The relative timing of wildfires and subsequent floods to salmonid life history and reproductive strategies (i.e., fall- versus spring-spawning species) may be an important determinant of how populations are affected by wildfire disturbance cascades (Reeder et al., 2021). An influx of sediment could be beneficial if sediment delivery occurs during runoff events that are competent enough to wash away fine sediments before spawning (Kondolf and Wilcock, 1996). Deposition of large wood and boulders may buffer downstream channels against sediment deposition by creating hydraulic roughness and structural complexity that increases sediment retention. Large woody debris (LWD) supplied by fire can also create pools and structural complexity that benefit salmonids (Flitcroft et al., 2016) in addition to controlling localized patches of scour and deposition. Similarly, reorganized channels along debris flow runout paths can be rapidly re-colonized by neighboring salmonid populations (Rosenberger et al., 2011). Climate-related increases in the frequency of post-fire debris flows could have a positive effect on aquatic populations by increasing the spatial heterogeneity of habitat patches within river networks and promoting greater diversity of species or life histories (Reeves et al., 1995; Bisson et al., 2009). However, an event that triggers a large pulse of fine sediment delivered during summer low flows can bury spawning gravels and fill pore spaces, reducing the survival of early salmonid life stages (Greig et al., 2005). At the population scale, climate-driven changes in the frequency, magnitude, and spatial extent of debris flow disturbances could negatively impact aquatic populations if these disturbances overwhelm the spatial distribution of a given metapopulation and its ability to absorb such disturbances (Dunham et al., 2003; Miller et al., 2003).

2.3 Wildfire and Stream Restoration

Projected climate change and wildfire trends present challenges and opportunities for stream restoration. Climate-driven increases in the size and severity of wildfires across the western U.S. (Westerling et al., 2006) are expected to impact terrestrial and aquatic ecosystems (Gresswell, 1999; Bisson et al., 2003; Davis et al., 2023). Management of these discrete but interconnected resources, however, is not always straightforward and requires integrative approaches (Rieman et al., 2010). For example, fire restoration aimed at reducing large-magnitude pulses of sediment, water, and wood to downstream ecosystems and communities may be at odds with habitat restoration that strives to restore dynamic sediment and wood processes. There are opportunities, however, to find overlaps and mutually beneficial approaches via collaboration among management entities.

After a long history of removing wood from rivers to improve flood conveyance, transportation, and navigation, the design and placement of wood structures is now a well-established tool for stream restoration practitioners. Indeed, manuals and guidelines exist to support habitat restoration projects in the Columbia River Basin of the Pacific Northwest (e.g., Oregon Water Enhancement Board [OWEB], 1999; Cramer, 2012; U.S. Bureau of Reclamation [USBR], 2014; Wheaton et al., 2019). Design guidance includes targets for wood metrics such as key piece size and density (e.g., Fox & Bolton, 2007). Because wood structure persistence is critical to habitat function over the project design life, modeling procedures are often applied to calculate wood stability using hydraulic stability analysis at design flows (Rafferty, 2016). However, guidelines to assess the risk of wildfire to structure function and persistence do not exist. This study demonstrates that habitat restoration projects in fire-prone landscapes would benefit from the development and application of fire risk assessment and design methods, similar to procedures that currently exist for estimating LWD structure hydraulic stability for design floods (e.g., Q_{100}).

In some stream restoration project settings, restoration treatments can be designed to accommodate and work synergistically with the effects of wildfire. Balancing risk management with expectations of dynamic and shifting conditions in river corridors is not a straightforward endeavor; the design and placement of wood in rivers is not only contingent on site-specific goals and constraints, but also requires an understanding of the reach-scale geomorphic context and natural wood regime (Wohl et al., 2019). For example, wood placed in populated setting is likely to have strict stability requirements, whereas wood placement in forested streams with limited infrastructure may be designed to accommodate some level of mobility and adjustment to geomorphic conditions and watershed processes, provided that overall structure integrity and function are maintained. Although large wood structures are typically designed to provide habitat, additional functions such as storage of post-wildfire sediment can be integrated into project objectives and plans.

There is a paucity of studies related to wildfire impacts on habitat restoration treatments—specifically, large wood structures aimed at scouring pools and providing cover and access to side channels. A brief review of the literature on the impacts of fire on instream wood persistence and function can serve as a baseline to compare post-fire impacts expected for engineered large wood structures designed for habitat restoration. In fire-prone watersheds, burned wood pieces tend not to survive. Their simple geometry, featuring fewer branches, means they are less securely anchored in the stream; once instream wood is burned, it has a higher decay rate than unburned instream wood. (Vaz et al., 2013; Vaz et al., 2015). Burned wood in streams also tends to decay, breakdown, and be transported through stream channels more readily (Merten et al., 2013), as well as have lower ecological functioning potential (Vaz at al., 2021). However, over slightly longer time scales (10^1 years) burned and downed wood can also become an integral part of the floodplain architecture and support the deposition of fine sediment and organic material that enhances soil development in floodplains (Wohl 2011; Collins et al., 2012). Standing dead trees can gradually fall into the channel after fire over longer lag times of a few decades (Wohl & Goode, 2008). Additionally, individual logjams remain relatively constant at time intervals of a decade or longer in the absence of major disturbance such as wildfire, insect outbreak, or large floods. Therefore, although individual pieces of wood are exchanged, some geomorphic and ecological effects of wood, including storage of sediment, organic matter, and solutes; boundary hydraulic roughness; localized scour of bed and banks; overhead cover for fish; and substrate diversity for macroinvertebrates, may be maintained at relatively constant levels over time spans of a decade or longer.

In some cases, restoration actions may have unintended positive outcomes for mitigating post-fire disturbance cascades. For example, although fire-related debris flow inputs of sediment may inundate channels, fill scour pools, and bury large wood habitat structures, it is important to consider the potential impacts without the placement of large wood structures. These may include important secondary impacts, such as capturing sediment and buffering the downstream impacts of fine sediment pollutants (Lo et al., 2021).

Habitat restoration projects also aim to enhance riparian communities to improve shade and access to side channel habitat, which also improves flood attenuation. These floodplain zones are important connections between hillslopes and channels, with ecological capacity and function dependent on valley confinement (Wohl et al., 2021). The extent to which a riparian area serves as a fire barrier depends on the size or extent of the stream and riparian area, topography, and characteristics of riparian fuels, including species adaptations that contribute to rapid recovery following fire (Dwire & Kauffman, 2003; Capon et al., 2013). Riparian zones can act as a natural barrier to limit the spread and spatial extent of upland wildfires (Pettit & Naiman, 2007). However, in drylands, especially in small order streams or under dry pre-fire conditions, riparian forests can turn into corridors for fire movement (Pettit & Naiman, 2007). By providing additional fuel in the stream corridor, engineered log structures and jams may enhance wildfire risks in the riparian zone if lower elevation fuels (slash) are not incorporated in a way that maintains submergence at low flows to keep structures from igniting.

Restoration projects that significantly increase the wetted area of the valley bottom during the fire season may provide increased resilience to wildfire. For example, this has been recently documented for projects that aim to restore unconfined depositional valley bottoms to a “Stage-Zero” condition (Powers et al., 2019). As defined by Cluer and Thorne (2014), Stage-Zero is a channel condition that may have been widespread prior to human disturbances related to early Euro-American settlement. It consists of a very well-connected channel-floodplain system often with multiple channel threads and abundant interconnected wetlands, even at base flows. One recent study from the McKenzie River in Oregon directly documents the value of "restoring to Stage-Zero" as a tool for improving fire resiliency by incorporating wetland complexes into the suite of restoration treatments (Pugh et al., 2022). Other recent investigations of restored wetland complexes make the case for using river valley bottoms as natural infrastructure to build in resilience to increased floods, fires, and droughts (Norman et al., 2022; Skidmore & Wheaton, 2022). Beaver-based restoration approaches are also commonly used as an effective "low-tech" method to connect streams to floodplains and create extensive valley bottom wetland complexes. Beaver-related restoration approaches range from construction of beaver dam analogs (BDA) that mimic the function of beaver dams (Corline et al., 2023) to relocation of animals back into areas where they would historically have been present. These approaches are rapidly becoming more accepted practices (Jordan & Fairfax, 2022; Skidmore & Wheaton, 2022) that have the potential to create greener/wetter stream corridors with saturated soils that are harder to ignite (firebreaks). These corridors can provide fire refugia for wildlife and their increased biodiversity can aid in quicker recovery post-fire (Fairfax & Whittle, 2020). The popularity of beavers in restoration and as a form of valley bottom resilience to fire is reflected beyond the scientific literature and into the mainstream media, as featured in a 2020 National Geographic magazine article (Goldfarb, 2020).

2.4 Planning for Resiliency

Recent trends in stream restoration science and practice offer opportunities to integrate emerging climate and wildfire science more holistically with the practice of habitat restoration. Through more rigorous consideration of observed and projected climate and wildfire trends, stream restoration actions can become more resilient to the effects of wildfire.

Over the past several decades, climate science in the Pacific Northwest has evolved into organizations and institutions that provide high-quality information to the region. These entities include the Climate Impacts Group (CIG) at the University of Washington, whose programs include the Northwest Climate Adaptation Science Center and the Northwest Climate Resilience Collaborative. In addition to these programs, the CIG is a resource for data, analytical tools, publications, training, and education (CIG, 2023). Complementary to the CIG is the Climate Impacts Research Consortium (CIRC) at Oregon State University. Through their science, analytical tools, and publications, the CIRC can support stream restoration practitioners in Oregon, Washington, Idaho, and western Montana in adapting to climate variability and change (CIRC, 2023). Notably, both the CIG and the CIRC provide resources for understanding the relationships between climate change and wildfire, and for applying that knowledge to adapting to the risks derived from both.

Knowledge of past wildfire occurrence and projected future wildfire risk is essential for the planning, design, and implementation of stream restoration projects. This knowledge can be developed through information provided by several resources, including the LANDFIRE program of the U.S. Department of Agriculture (USDA) Forest Service and the U.S. Department of the Interior (LANDFIRE, 2023). Among other functions, LANDFIRE is a source for decision support tools, data, and guidance for characterizing the existing fire regime conditions in a watershed that may affect a downstream restoration project reach. LANDFIRE integrates data from the Monitoring Trends in Burn Severity (MTBS) Program, which is a multiagency program designed to consistently map the burn severity and perimeters of fires across all lands of the United States from 1984 to present (Eidenshink et al., 2007). Complementary, emerging wildfire science is coordinated through the Northwest Fire Science Consortium (NFSC), whose efforts include collaboration with resource management practitioners to foster more informed decision making (NFSC, 2023).

Hydrologic effects from wildfire occurrence are important considerations for planning resilient stream restoration projects. Among the many hydrologic effects of wildfires are landslides, debris flows, and increases in the frequency, magnitude, and extent of flooding. Tools are rapidly evolving to improve the prediction of post-fire recovery, debris flow risks, and sediment volumes (Kean & Staley, 2021). The U.S. Geologic Survey (USGS) is a primary resource for post-fire landslide and debris flow hazards information, including data, analysis tools, and publications (USGS, 2023). This USGS effort includes a post-wildfire debris flow hazard assessment dashboard that uses geospatial data on basin morphometry, burn severity, soil properties, and rainfall characteristics to estimate the probability and volume of debris flows that may occur in response to a design storm. One important element of planning for potential debris flow and flooding impacts is evaluating a project reach for flood hazard and channel migration risks. While many resources are available for evaluating these risks, two of the more developed programs include the Colorado Wildfire Ready Watersheds program (Colorado Department of Natural Resources [CODNR], 2023), which includes tools for multiple hazards assessment, and the Washington State hazard assessment programs for flood, floodplain planning, and channel migration zones (Washington State Department of Ecology [WADOE], 2023). Each of these programs provides examples of analysis methods that can be applied to stream restoration project settings throughout the Pacific Northwest.

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3 CASE STUDIES

3.1 Chewuch River

The Chewuch River Basin is located in Okanogan County in northern Washington state on the east side of the Cascade Mountains. Hydrology is snowmelt dominant with peak flows occurring May/June. The total watershed area is 531 square miles and it sits within a valley of resistant crystalline bedrock upstream of river mile (RM) 9 and softer, more erodible sedimentary bedrock downstream of RM 9. Within the study area (upstream of RM 9), the valley bottom width and channel slopes are influenced by debris torrent fans formed by steep tributary channels. Upstream of the debris torrent fans the valley form is wider, alluvial channel morphology is common, and stream gradient is flatter. The opposite is true along stream reaches adjacent to alluvial fans. Within the previously established geologic and glacial setting, fire and post-fire geomorphic processes have in the past played an important role in determining and reinforcing where complex natural aquatic habitats are most likely to form and be maintained.

Table 3-1. Chewuch River Watershed Characteristics

Watershed Characteristic	Value
Watershed Area	531 sq. miles
Relief	6,880 feet
Average Annual Precipitation	27 inches
Hydrograph Character	Snowmelt Driven

Table 3-2. Chewuch River Hydrology at the Case Study Site (Inter-Fluve, 2015)

Flow Event	Discharge (cfs)
2-year	1,891
5-year	2,900
10-year	3,555
25-year	4,355
50-year	4,925
100-year	5,474

3.1.1 Reach Location

From 2009 to 2022, habitat work was designed and constructed in the Chewuch River by the Yakama Nation Fisheries (YNF) Program from RM 4 to RM 20 (Inter-Fluve, 2015a). The study area in this report is confined to the project reaches that burned during the Cub Creek 2 Fire in 2021. Project reaches directly impacted by fire and year of construction are shown in Figure 3-1 and described below.

- Chewuch RM 13 – 15.5 constructed in 2015
- Chewuch RM 15.5 – 17 constructed in 2017
- Chewuch RM 17 – 20 constructed in 2018

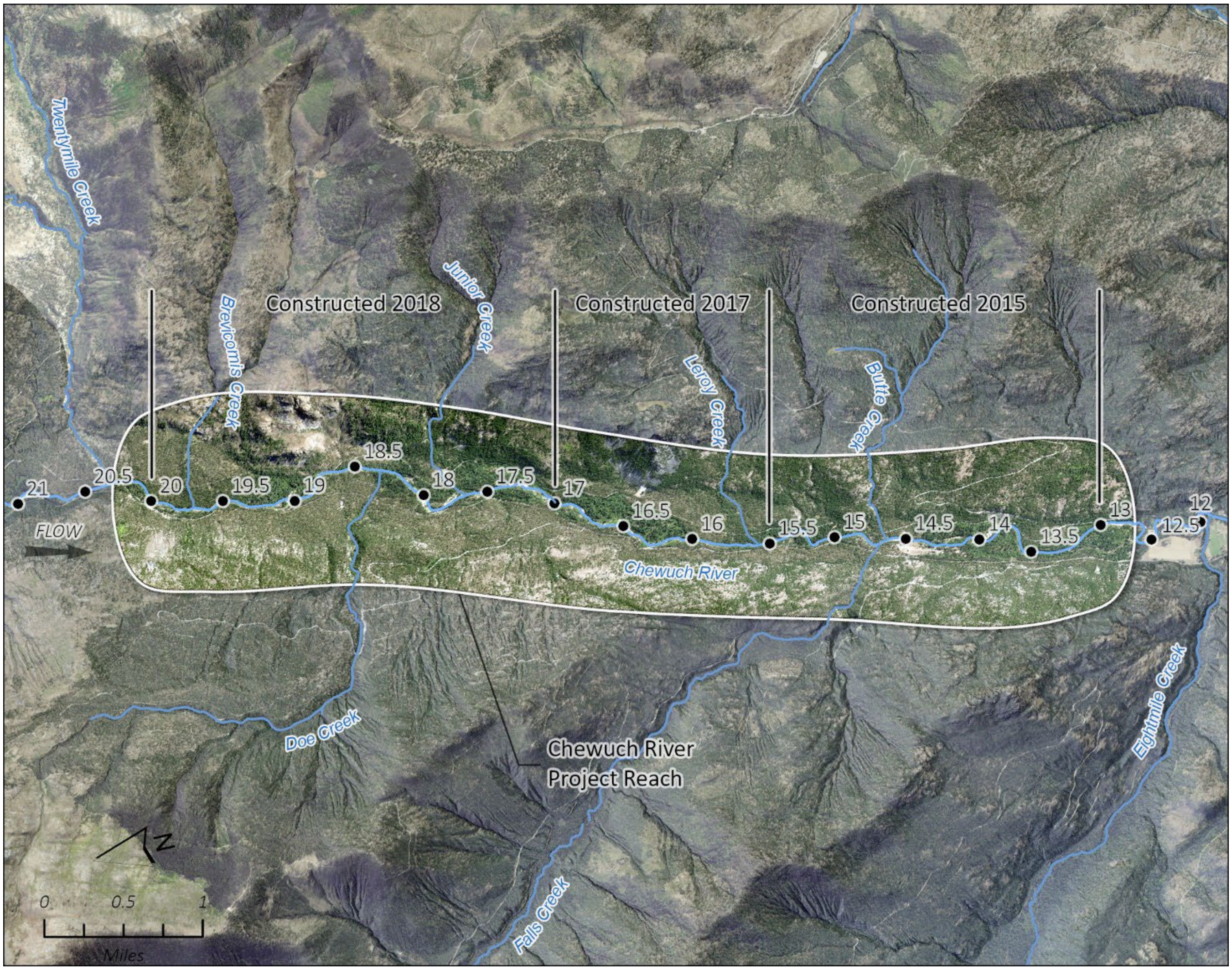

Figure 3-1. Overview map of the Chewuch case study area.

3.1.2 Fish Habitat Restoration Objectives

The goal of the habitat work conducted in the Chewuch River was to restore habitat conditions beneficial to Endangered Species Act (ESA)-listed salmon and steelhead in accordance with the Upper Columbia Spring Chinook Salmon and Steelhead Recovery Plan (Upper Columbia Salmon Recovery Board [UCSRB], 2007), and the associated Biological Strategy (Upper Columbia Regional Technical Team [UCRTT], 2017).

Fish species present include ESA-listed and endangered spring Chinook salmon and steelhead, and ESA-listed and threatened bull trout. The Chewuch River is a major spawning area for spring Chinook and steelhead. Bull trout use the area as a migration corridor, while westslope cutthroat trout are also present.

The RTT determined that the main factors that cumulatively impact river ecology and salmonid habitat in the Lower Chewuch River Assessment Unit include:

- Channel clearing and large woody debris (LWD) removal have reduced channel complexity in the Chewuch River
- Road placement and bank hardening have isolated some sections of the main channel from the floodplain and isolated side channels from the mouth to Eightmile Creek
- Skid roads in riparian areas and increases in dispersed recreation have impacted the river
- Low river flows that occur in late summer through winter reduce the quantity of rearing habitat

- Livestock grazing has impacted riparian areas in tributaries and the mainstem
- Some sub-watersheds have both high road densities and highly erosive soils, creating conditions that can elevate cumulative sediment loading and bank erosion
- A road constriction at RM 1.7 on Eightmile Creek creates a barrier for steelhead, bull trout, and spring Chinook salmon
- High densities of brook trout in Boulder, Eightmile, and Cub Creeks
- Much of the assessment watershed (about 85%) has burned since 2001
- A road that crosses the Twentymile Creek alluvial fan is a barrier for steelhead

The RTT has prioritized a list of restoration actions to address these key ecological concerns impeding salmon recovery goals for the Lower Chewuch River Assessment Unit. Actions and priorities are listed below.

1. Sediment
    a. Reduce and maintain roads to reduce sediment loading.
    b. Increase LWD recruitment rates within riparian and upland areas to retain sediment.
2. Peripheral and Transitional Habitats (side-channel and wetland habitats)
    a. Reconnect disconnected side channels and locations where low wood loading has changed the inundation frequency.
    b. Improve hydraulic connection of side channels and wood complexity within the side channels.
3. Channel Structure and Form (instream structural complexity)
    a. Install large wood and engineered log jams (ELJ) in geomorphically appropriate locations to provide short-term habitat benefit. The scale and location of these installations should be consistent with the biological objectives and geomorphic potential for the project reach and project site.
4. Riparian Condition
    a. Restore conditions in degraded areas associated with residential development or where there are legacy effects from past riparian logging practices.
    b. Improve LWD recruitment.
    c. Allow regeneration and stop removal practices so that wood can recruit naturally.
    d. Fence riparian areas and wetlands; maintain existing fences.
    e. Fix Twentymile Creek alluvial fan road so fish can migrate upstream of it.
5. Water Quantity
    a. Improve natural water storage by allowing off-channel connection, floodplain function, and beaver re-colonization.
    b. Increase stream flow through irrigation practice improvements and water lease purchases.
6. Food (altered primary productivity—no action identified)
7. Species Interactions (introduced competitors and predators)
    a. Reduce or eliminate brook trout in Eightmile Creek and other areas with high densities of brook trout.
8. Habitat Quantity (anthropogenic barriers diversion)
    a. Improve fish passage in Eightmile Creek at the U.S. Forest Service (USFS) road pinch point (Revised Biological Strategy Appendix E, 2014)

3.1.2.1 Tributary Assessments, Design, and Construction

In addition to the guidelines set forth by the RTT, the design and construction work were also founded on the Methow Sub-basin Geomorphic Assessment (U.S. Bureau of Reclamation [USBR], 2008), also known as the Tributary Assessment, as well as the Yakama Nation Fisheries (YNF) Reach Assessment of the Chewuch River from RM 2.2 to RM 20.0 (Inter-Fluve, 2010). The Tributary Assessment provided a watershed and valley-scale context for primary controls on bio-physical processes, and helped prioritize which reaches in the Methow

Subbasin to focus on for salmon habitat restoration actions. The Reach Assessment describes conditions operating at the scale of individual Chewuch River reaches and sub-reaches and identified general restoration opportunities at distinct geographical locations to address priority ecological concerns impeding salmon recovery goals.

Following assessment, more detailed reach-scale concepts were developed and presented to stakeholders. Once stakeholders agreed, several projects were taken to permitting, final design, and construction.

3.1.3 Chewuch River Restoration Treatments

Three primary components used to improve salmonid habitat within the Chewuch River have been large wood, pool habitat, and off-channel habitat. The USFS has identified existing and desired conditions for each component using regional research data, conditions of undisturbed channel segments similar to the project reach, and professional judgment.

Side channels were designed and constructed in locations that could support high quality side channel habitat during low summer flows. Opportunities for side channels found on the Chewuch are located upstream of valley-controlling alluvial fans where wider floodplain valleys, flatter slopes, and complex wetland habitats can either be re-watered or reconstructed. Apex large wood structures were constructed at side channel inlets to facilitate maintaining inlet conditions on all newly created side channel projects.

Bank-buried and/or pile-ballasted wood structures were constructed to enhance deep pool and cover habitat throughout each project reach. Pool habitats were constructed as part of apex, bank-buried, and side channel habitats.

3.1.4 Cub Creek 2 Fire

The Cub Creek 2 Fire started on July 16, 2021, and burned approximately 71,000 acres of state, private, and USFS land within the Chewuch River drainage. Approximately 19% of the watershed upstream of the case study area (RM 13) was burned. As Figure 3-2 shows, most of the high intensity burn areas were directly upslope from the case study area. Analysis of the USFS National Fire Boundary dataset showed that the Cub Creek 2 Fire was the third largest recorded fire in the watershed upstream of the case study area (Table 3-3). Additionally, this analysis shows that around 85% of the contributing watershed to the case study area has burned in the past 20 years. The recent widespread burns within the watershed are an interesting observation because their frequency does not correlate with the composition of fire regimes of the watershed as reported by LANDFIRE (2023), Table 3-3.

The USFS post-burn report estimated 41% of the burned area within the Cub Creek 2 Fire had high or moderate soil burn severity (Figure 3-2). Immediately after the fire, the USFS estimated water-repellent soils may have developed due to the burn. Vegetation mortality in the moderate and high soil burn severity areas ranged from 80 – 100% (USFS, 2021) and would be consistent with severe burn and development of water-repellent, easily eroded soils.

The USFS produced a post-fire hydrologic model to estimate runoff over much of the area burned in the Cub Creek 2 Fire. The model indicated flows in smaller drainages resulting from the 5-yr 1-hour rainstorm (20% probability of occurrence in the first year following the fire; about 50% probability in years 1-3) are predicted to increase flows 50 to 200 times greater than pre-fire flow levels.

Based on the post-fire survey of watershed soil conditions, hydrologic model results, steep tributary channels, and clear evidence of past debris torrents, the USFS also estimated post-fire debris torrent risk using United States Geological Survey (USGS) debris flow risk models. The models estimated a moderate to high level of debris flow hazard in large segments of the watershed area burned in the fire. Subwatersheds in the center of the burn area were found to have high (60-80%) to very high (>80%) probability of debris flow occurrence if the modelled hydrologic precipitation event occurred in those areas. Doe Creek, Falls Creek, Eight Mile Creek, and the Chewuch River were areas where debris flow risk was the highest (USFS, 2021).

Following the fire and USFS post-fire analysis, debris torrent formation began to be observed in the watershed, including three debris torrents from steep tributary streams that were observed in the summer of 2022. The timing and precipitation event that triggered them is unknown and their impacts to the Chewuch River were varied due to size and runout lengths. Two of the debris flows were relatively small. However, one debris torrent initiated in Leroy Creek was large enough to significantly impact the Chewuch River and deposited a large volume of fine sediment in the channel. Indeed, the USFS post-burn analysis and USGS debris flow modeling predicted that Leroy Creek was high risk for debris flows, so 2022 debris flows events appear to be consistent with both general research on post-fire debris flow timing and USGS debris flow risk modeling.

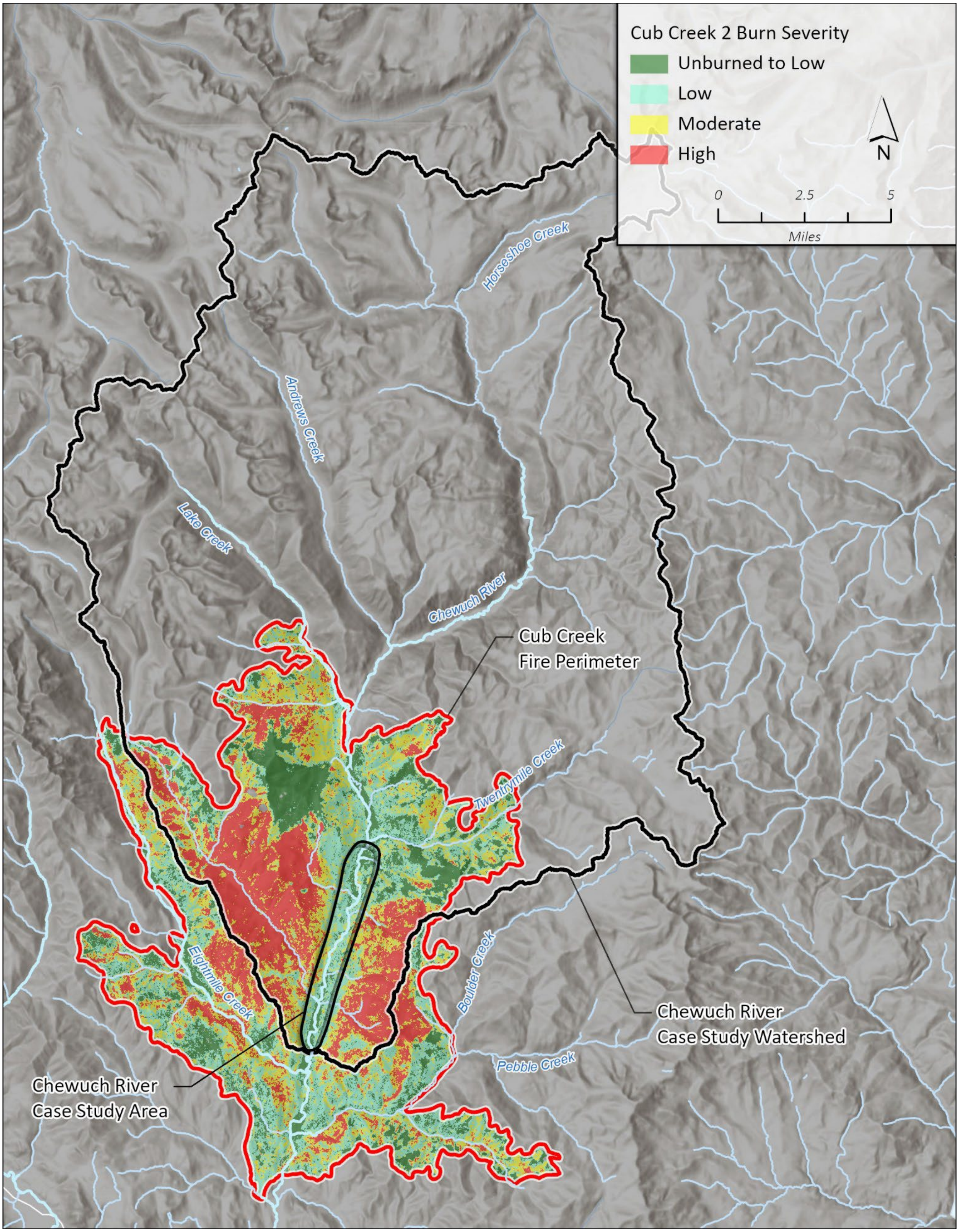

Figure 3-2. Overview of Cub Creek 2 Fire perimeter and burn severity.

Table 3-3. Chewuch Case Study Watershed Fire Regime Composition

Fire Regime	Fire Return Interval	Severity	Percent of Case Study Watershed
Regime I	≤ 35 years	Low and Mixed	38%
Regime II	≤ 35 years	Replacement	0%
Regime III	35 to 200 years	Low and Mixed	53%
Regime IV	35 to 200 years	Replacement	1%
Regime V	> 200 years	Any	8%

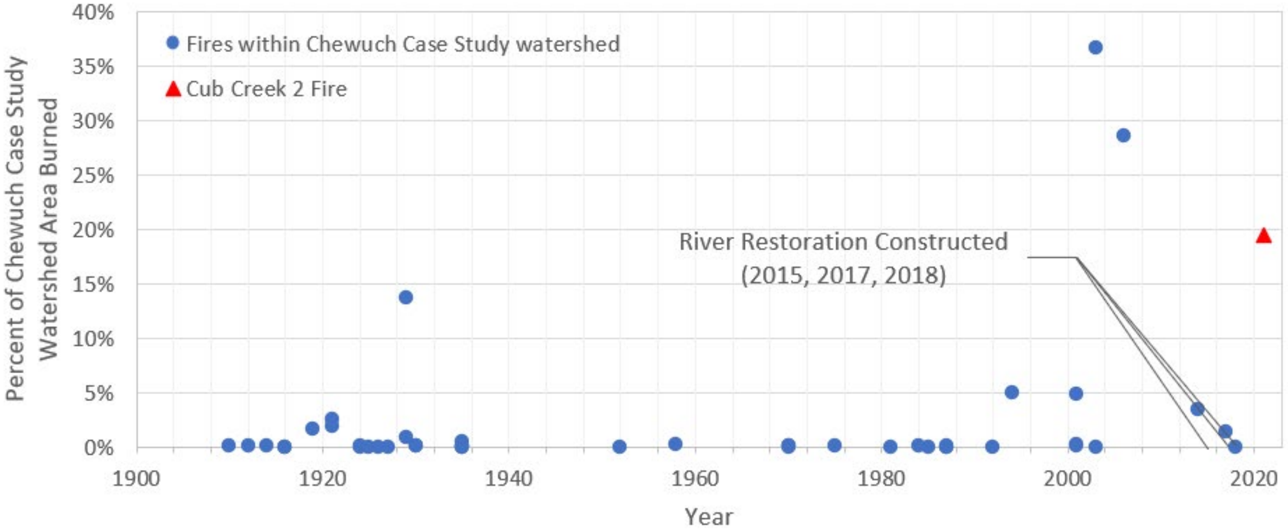

Figure 3-3. Plot of history of fire within the Chewuch Case Study watershed, according to USFS National Fire Perimeter shapefile. The y-axis shows the percent of the case study burned by each fire; the x-axis shows the year of the fire.

3.1.5 Wildfire Effects on Restoration

The Cub Creek 2 Fire burned segments of Chewuch River valley bottom and constructed restoration projects between RM 15.1 and 18.7 (Inter-Fluve, 2022a). Within this 3.6-mile burn reach, eight project sites (53%) out of a total of fifteen were fire impacted. The impacted sites are within three separate project reaches constructed from 2015-2018.

- Chewuch RM 13 – 15.5 was constructed in 2015 (Figure 3-4). Site Q of the project was fire impacted.
- Chewuch RM 15.5 – 17 was constructed in 2017 (Figure 3-5). Sites B, E, and J were fire impacted.
- Chewuch RM 17 – 20 was constructed in 2018 (Figure 3-6). Sites L, M, N, and P were fire impacted.

Figure 3-4. Chewuch River Fish Habitat Enhancement Project sites constructed in 2015. Red sites indicate sites impacted by fire.

Figure 3-5. Chewuch River Fish Habitat Enhancement Project sites constructed in 2017. Red sites indicate sites impacted by fire.

Figure 3-6. Chewuch River Fish Habitat Enhancement Project sites constructed in 2018. Red sites indicate sites impacted by fire.

Chewuch RM 13 – 15.5: Site Q (RM 15.2)

Site Q was a left-bank-buried large wood structure that extended 20 feet into the channel. It was constructed in 2015 and remained similar in shape and function until the Cub Creek 2 Fire, which burned most of the exposed wood in the structure. However, the burn was largely superficial and the wood in it remains structurally sound. Therefore, the post-fire structure has retained all of its post-project stability. One year after the fire, the alluvial fan and structure was partially buried by a mudflow deposit emanating from the LeRoy Creek watershed. The precipitation event and timing of the mudflow is unknown, but a significant volume of mud, boulders, and debris inundated the fan and Chewuch River. The mudflow was generated in a steep, severely burned side drainage previously mapped as high risk by the USGS following the Cub Creek 2 Fire. See Figure 3-7, Figure 3-8, and Figure 3-9 for images of Site Q after the debris flow.

Figure 3-7. Site Q post-fire and post-debris flow.

Figure 3-8. Leroy Creek debris flow runout within the channel of the Chewuch River. The Leroy Creek debris flow entered the Chewuch River on river left.

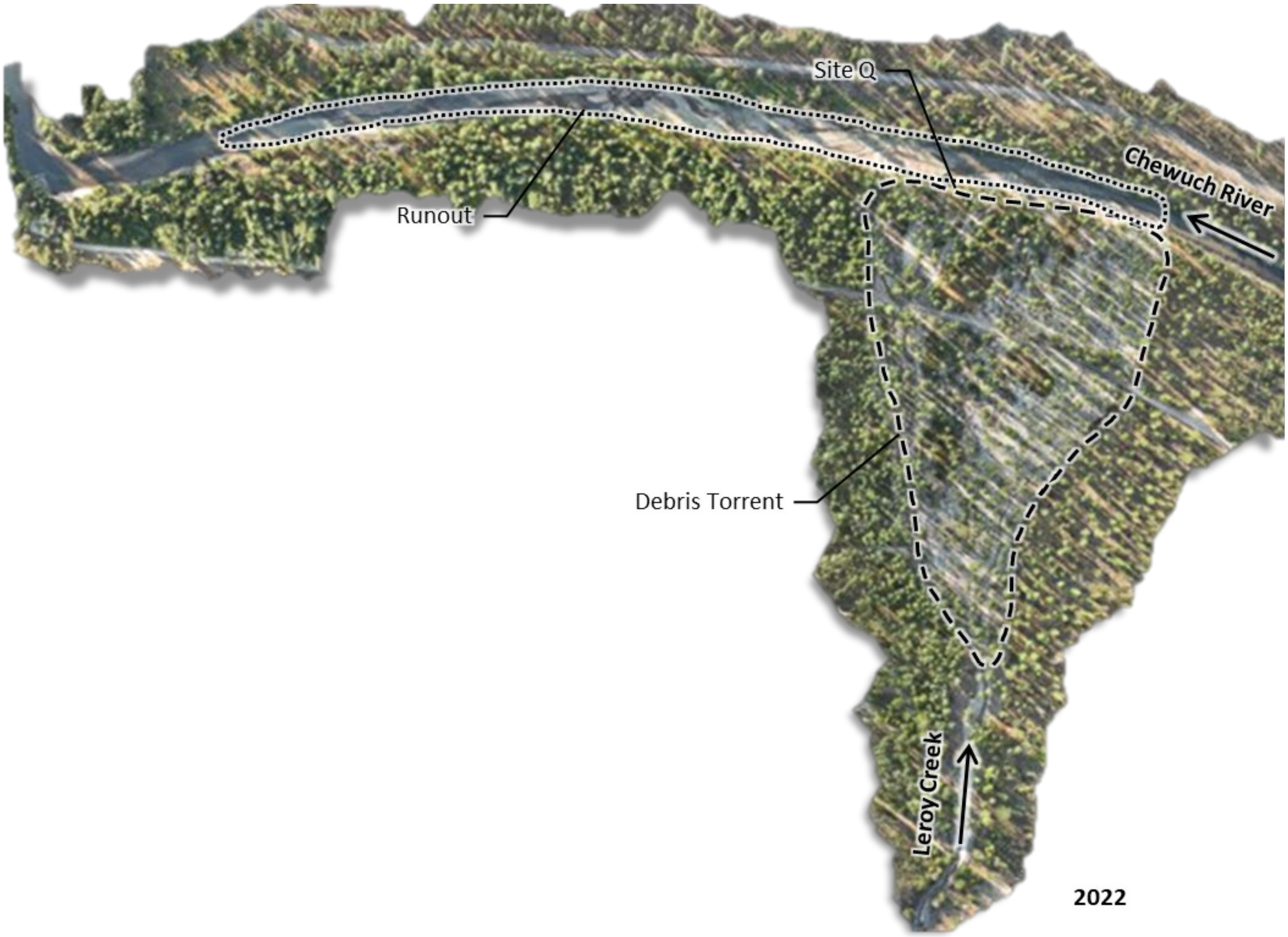

Figure 3-9. Drone photo of Leroy Creek debris flow.

Chewuch RM 15.5 – 17: Site B

Site B was constructed in 2017. The project is an apex wood structure that was designed to create the geomorphic and hydraulic conditions necessary to maintain a side channel inlet to an old wetland channel complex upstream of the Leroy Creek debris torrent fan. The upper elevation logs of the inlet apex structure burned while the base layer of the jam did not. However, fire consumed key structural pieces of the jam, which greatly reduced the structural strength and footprint required to maintain the original geomorphic and hydraulic design condition intent. In 2021 there was a concern that the log jam could be outflanked between the burned segment of the structure and the old bank line. The 2022 spring runoff eroded this area of concern and it is now behaving in a way consistent with future flanking along the former bank caused by the loss of wood mass and roughness. There is still buried wood in this segment of channel, but it is unlikely to prevent flanking over the long-term unless the structure becomes sealed with natural wood during subsequent high flows or wood is imported to replace that lost in the fire. Figure 3-10, Figure 3-11, and Figure 3-12 show Site B post-fire.

Figure 3-10. Overview of Site B after the Cub Creek 2 Fire. Flow is left to right.

Figure 3-11. Photos of Site B. Left is pre-fire, right is post-fire.

Figure 3-12. Photo of Site B post-fire looking downstream.

Chewuch RM 15.5 – 17: Site E

Site E is a right-bank and pile-ballasted large wood structure extending approximately 20 feet into the channel. It was constructed in 2017 and, until the fire, had not changed significantly since construction. Even after the fire, pool and cover habitat remain. However, the upstream 60% of the structure has been weakened from the fire. Logs and piles have smaller diameters and over time will fail to provide structural support during flood flows. Approximately 30% of the log jam structure is in good condition (Figure 3-13 and Figure 3-14). It is likely that some of the wood in the structure will leave the site and it is possible the front half of the structure will fail over time and collapse or accordion into the back half of the structure that remains unburned and relatively more stable.

Figure 3-13. Photo of Site E post-fire. Photo was taken looking downstream.

Figure 3-14. Overview of Site E post-fire. Flow is left to right.

Chewuch RM 15.5 – 17: Site J

Site J is a right-bank and pile-ballasted large wood structure extending approximately 15 feet into the channel. It was constructed in 2017 and incorporated a large spruce tree as part of the structure (Figure 3-16). There is still good habitat at this project site. However, many of the key pieces have burned down to 12-inches in diameter. Bank-buried pieces have burned to 12 inches in diameter or have been completely severed from buried segments of the wood used to ballast the jam in place. The structure no longer has the original design strength and it is possible a portion of this jam will mobilize during future flood flows. Most of the piles are sound but what remains have smaller diameters and are weaker than installed diameters. Post-fire conditions of Site J are shown in Figure 3-15 and Figure 3-16.

Figure 3-15. Photo of site J post-fire. Photo taken looking upstream.

Figure 3-16. Overview of Site J pre-fire (top) and post-fire (bottom). Flow is left to right.

Chewuch RM 17 – 20: Site L

Site L is a left-bank and pile-ballasted large wood structure extending approximately 15 feet into the channel. It was constructed in 2018 and there is still post-fire habitat at this project site. All of the slash (small wood material < 2” in diameter) components of the log jam structure were consumed in the fire and a significant amount of burn through occurred on structural key pieces (Figure 3-17). While the supporting piles that burned are still useful, they do not provide the structural support of the original designs and it is possible some of the imported and burned wood could leave the site during high flows. Revegetation plantings throughout the access trail also burned.

Figure 3-17. Site L post-fire. Flow is left to right.

Figure 3-18. Site L pre-fire (top) and post-fire (bottom). Flow is left to right.

Chewuch RM 17 – 20: Site M

Site M is a right-bank and pile-ballasted wood structure that extended 15 feet into the channel. It was constructed in 2018. Most of the Site M log jam was consumed by the Cub Creek 2 Fire (Figure 3-19 and Figure 3-20). Structural integrity has been significantly degraded and it is likely future flood flows will remove much of what is left of the jam over time. It is possible the lower or first layer of wood and remaining piles will collect wood that is transported from upstream sources and create wood habitat at the site.

Figure 3-19. Site M post-fire. Photo taken looking upstream.

Figure 3-20. Site M post-fire. Flow is right to left.

Chewuch RM 17 – 20: Site N

Site N is a left-bank and pile-ballasted wood structure extending 20 feet out into the channel. Cub Creek 2 Fire burned a significant volume of the Site N structure (Figure 3-21 and Figure 3-22). Design integrity has been lost and it is possible the top half of the structure will be removed by future flood flows. What remains of the piles is solid, but most threaded rod connections have been lost. The first layer of wood in the jam will likely remain, but without the top of the jam in place, the hydraulic forces necessary to maintain a scour pool will be less. It is possible the remaining piles of this structure will collect upstream-sourced wood and, if this occurs, it is possible a log jam will remain established at the site. If accumulations are large enough, a scour pool could be maintained. Natural vegetation is becoming re-established. Since the fire, a significant volume of slash has accumulated at the upstream face of the structure and remaining piles.

Figure 3-21. Site N post-fire. Flow is from right to left. Lighter-colored material on the upstream face of the jam is naturally rafted wood that accumulated post-fire.

Figure 3-22. Site N post-fire. Flow is from right to left.

Chewuch RM 17 – 20: Site P

Site P is a left-bank and pile-ballasted wood structure extending 15 feet out into the channel. Although damaged, the structure continues to function and can be expected to maintain its original design stability and habitat utility. Much of its resiliency can be attributed to the larger size class diameter of the wood used in the original construction (Figure 3-23 and Figure 3-24). Imported large wood with root wads that were delivered to the project had a specified minimum diameter range between 18-inches and 24-inches. By chance, wood delivered to Site P was in the upper range of the size specification (24-inches in diameter) and in some cases approached 28-inches in diameter. Although the burn intensity at Site P was similar to the burn intensity at other sites, larger diameter logs used at Site P resulted in logs with larger post-burn diameters and therefore greater post-fire resiliency and stability.

Figure 3-23. Site P post-fire. Flow is from left to right.

Figure 3-24. Site P post-fire. Flow is from right to left.

3.1.5.1 Summary of Wildfire Impacts on the Chewuch River Restoration Projects

Large wood structures, pool habitat, and side channel habitat were the three key components of habitat work completed in the Chewuch River. All three components were either directly or indirectly impacted by the Cub Creek 2 Fire and are evaluated below.

Large Wood Structures and Pools

No structure was entirely consumed by fire and several structures retain the original habitat functions. However, all burned structures now have reduced stability due to compromised vertical piles and reduction in wood diameters. Most structures, though damaged, will continue to collect wood and provide habitat, but individual or groups of logs may become loose or broken during large flooding.

Secondary impacts to structures caused by debris torrents and elevated sediment loads have occurred. These impacts are likely to continue in the short term (1-2 years). Increased sediment loads have and may bury more pools and portions of structures both within and outside the burn zone.

Although mainstem wood structures have been and could be further buried, it is likely that over time they will be naturally re-scoured as the burned areas recover and sediment loads return to pre-fire levels. Therefore, habitat loss due to mainstem channel filling and pool volume loss near large wood habitat may be temporary. To date, there has been only one example of a buried large wood structure near the Leroy debris torrent runout (Figure 3-7). However, other downstream project sites might experience similar impacts as sediment from existing and future debris torrents moves through the system.

Side Channels

Observations within side channel projects downstream of the fire indicate there is a greater risk of long-term loss in habitat function over time. Risk of side channel filling is elevated by several potential factors that include:

- Debris accumulations at side channel inlets can reduce flows that enter the side channel to scour, mobilize, and clear sediments.
- Reduced flow energy can encourage beaver activity.
- Debris that moves into a side channel can cause blockages that induce deposition.
- Vegetation can become established on deposited sediment.

Elevated silt and sand volumes during years of post-fire conditions may deposit in constructed side channels, reducing wetted areas and even causing loss of flow during summer low flow periods. As continued sediment inputs become stored by debris and beaver dam blockages and sediment becomes stabilized by colonizing vegetation, the ability of the side channel to flush these retained sediments during high flows weakens.

There has already been documented post-fire debris plugging a newly constructed side channel near RM 4.2, which is far downstream of the burn area. In the future it is possible that debris and sediment deposition will remain problematic until fine sediment load and debris returns to pre-fire levels.

3.1.6 Chewuch River Projects Lessons Learned

The lessons learned from the monitoring of the Chewuch River restoration sites before, during, and after the Cub Creek 2 Fire are listed below.

- Bank-buried and pile-ballasted structures with limited projection (15 feet to 20 feet) into the active channel were particularly susceptible to burning. Increasing the submergence of the structure, through either greater projection into the channel and/or more structure members placed at lower elevations, would have increased the resiliency of the structure to burning. However, this may have required a tradeoff for reduced hydraulic pool scour that higher profile structures provide.

- While the apex structure at Site B experienced significant burning and loss of wood mass, the base layer did not burn and logs ballasted with alluvium remained as part of the structure. This suggests the need to build lower elevation structures in greater contact with the wetted channel and to couple this with fewer vertically oriented piles or other log members projecting well above the core of the structure.
- At Site B, a large wood structure built in a way that observations suggest would reduce burn risk (i.e., lower elevation) may not meet hydraulic objectives to emulate a natural apex log jam of the size required to maintain a side channel inlet. Therefore, Site B is an example of a restoration treatment that may present a tradeoff between fire resiliency and design objectives.
- At Site B, alluvium ballast was effective at retaining log members (even burned logs) that continue to function in collecting mobile wood. Large diameter whole trees were also fundamental in providing the mass required to maintain the apex structure following the fire.
- An increased use of alluvium ballast for all wood structures would have increased the long-term availability of large wood pieces remaining within the structure footprint. The quantity and location of alluvial ballast should consider the geomorphic context of the site and the goals of void space within the large wood structures that provide complex fish habitat across a range of flows.
- The log structure at Site Q was built at the terminus of an alluvial fan and in close proximity to a contributing watershed previously mapped with high risk of debris flows. This log structure may have been buried less by the post-fire Leroy Creek debris flow if the structure had been located elsewhere along the fan terminus or along the riverbank opposite the fan terminus. The stable channel boundary adjacent to Site Q suggests that the large wood structure may re-scour when post-fire sediment loads return to pre-fire conditions. Site Q is a good example of risk/benefit/cost analysis that could be made in future projects.
- Structures that were constructed with larger diameter wood material had a greater capacity to withstand the burn period than those structures or segments of structures with smaller diameter wood material. The ability of a structure to remain viable and positively impact post-fire habitat was greater where larger diameter wood was used because more was left unburned after the fire. This is also true for piles used to ballast wood structures.
- Elevated structure members were more vulnerable to damage from the fire than submerged or partially submerged members. Lower profile structures should be considered in fire-prone projects.
- Structures with larger volumes of slash within them burned easier, longer, and ignited more of the larger diameter structural pieces than wood structures that did not have as much slash.
    - The natural depositional location of slash (upstream face) associated with wood structures increases the likelihood of ignition and burn near the upstream face.
    - In many cases the downstream section of the structure did not burn as badly because there was less slash (fuel) there. This may allow the wood structures to retain structural integrity long-term and rebuild naturally with post-fire wood rafting into the structures.
- Not all of the structures that burned had direct fire front impingement upon them. In several cases it appears the wood structures were ignited by fire brands or spotting. Slash within the wood structures likely played a key role in spot fire vulnerability and burn.
- Distribution of slash within structures should be considered in fire-prone projects. Slash that is not submerged increases the risk of damage to a structure in the event of a fire.
- It should be noted that natural wood deposits are developed during flood flows and are therefore vertically higher during low flows, which cause them to be natural fuel sources during wildfires. Vertically integrated wood provides the hydraulics necessary for pool scour and habitat at low and high flood stage. Placing wood only at low flow to reduce wildfire damage at a given site may not emulate natural wood processes at all flows and should be considered during analysis of opportunity, fire risk, and benefits.

- Natural repair caused by wood rafting into the upstream face of fire-damaged structures has been observed at some burned project sites such as at Site N (Figure 3-21).

3.2 Beaver Creek

Beaver Creek is a tributary to the Methow River joining the Methow about 5 miles downstream of the town of Twisp in northern Washington state. Watershed characteristics of Beaver Creek are summarized in Table 3-4 and hydrology is summarized in Table 3-5. Development and resource extraction in the watershed have resulted in degraded conditions for ESA-listed salmonids. Fish species of concern present in Beaver Creek include ESA-listed and endangered Upper Columbia spring Chinook salmon and steelhead, and ESA-listed and threatened Columbia River bull trout. YNF, in coordination with the Methow Watershed Action Team, has identified Beaver Creek as a high value area for intensive habitat restoration and enhancement actions to benefit these species (Tetra Tech, 2017). In 2012, Inter-Fluve was contracted by YNF Program to design fish habitat enhancements on Beaver Creek within what is known as the Schoolhouse Reach.

Table 3-4. Beaver Creek Watershed Characteristics (Inter-Fluve, 2012)

Watershed Characteristic	Value
Watershed Area	80 sq. miles
Relief	5,200 feet
Average Annual Precipitation	24 inches
Hydrograph Character	Snowmelt Driven

Table 3-5. Beaver Creek Hydrology at the Case Study Site (Inter-Fluve, 2012)

Flow Event	Discharge (cfs)
2-year	178
5-year	350
10-year	481
25-year	663
50-year	806
100-year	953

3.2.1 Reach Location

The Case Study is located at the Schoolhouse Fish Enhancement Project, which spans from about RM 4.3 to 5.3. There are two distinct reaches delineated within the Schoolhouse Project, the Upper Project Area and the Lower Project Area (Figure 3-25, Figure 3-26, Figure 3-27). Both the Upper and Lower Project Areas have long segments of immobile channel boundaries that control local channel gradient and lateral stability. At these locations, the channel is armored by large boulders that form steep riffles with about 4% slopes. The boulders are a remnant component of glacial till deposits left behind during the Cordilleran ice sheet outwash and are immobile during Beaver Creek floods. Between the steep riffle segments there are lower gradient channel segments with about 2% slopes where alluvial deposition has occurred. The Upper Project Area has complex wetlands supported by active wall-base springs along the west side of the valley bottom (Inter-Fluve, 2014).

Pre-project salmon habitat generally occurred in the lower gradient channel segments and was largely a function of large wood material and small wood material racking onto large wood or existing trees. The riparian tree-lined banks were not easily eroded, so encroachments formed by large wood create complex hydraulics that scour pools and sort gravel to create spawning and rearing habitat (Inter-Fluve, 2014).

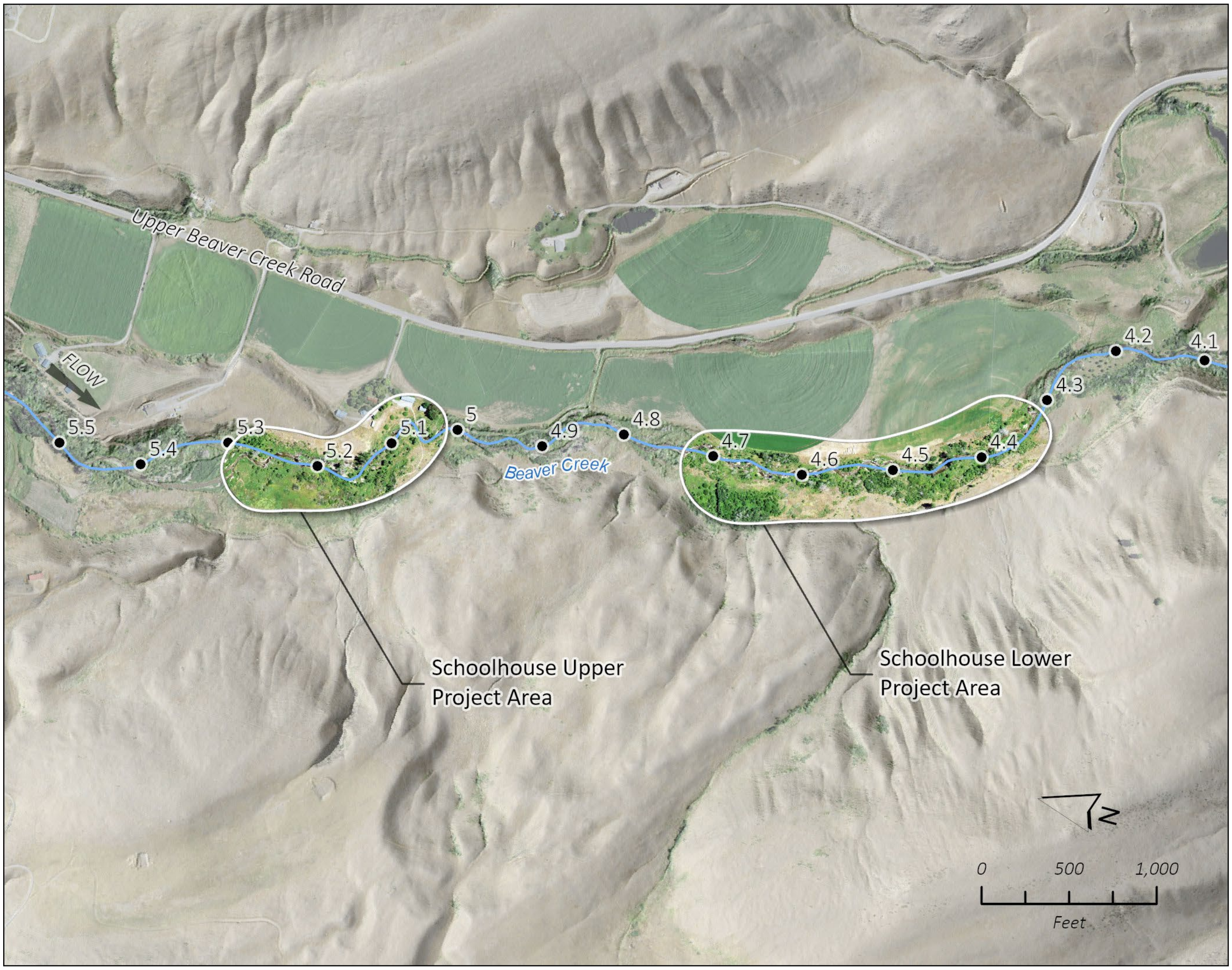

Figure 3-25. Overview map of the Beaver Creek case study area.

3.2.2 Fish Habitat Restoration Objectives

The Schoolhouse Fish Habitat Enhancement Design Report and Monitoring Plan determined that the following factors affect habitat conditions for salmonids in Beaver Creek:

- Residential development and agriculture adversely affect riparian and floodplain condition.
- High road density in upper watersheds contributes to fine sediment loading.
- Low flows in later summer (and winter) affect juvenile survival and passage.
- It is thought the long-term effectiveness of existing diversion structures will likely degrade over time or in response to high flow events, causing a potential ongoing maintenance problem.

The following restoration objectives were identified to guide design:

- Restore or mimic historical channel structure and complexity to promote juvenile rearing habitat
- Create off-channel habitat
- Improve large wood recruitment and retention
- Increase floodplain inundation
- Increase channel complexity to provide:
  - Cover
  - Velocity refuge

    - Increased food sources
- Design a resilient project that:
    - Achieves desired levels of lateral and vertical channel stability (imported wood and structures are stable during flood flows)
    - Addresses potential beaver impacts, where possible

3.2.3 Beaver Creek – Schoolhouse Fish Habitat Enhancement Treatments

The primary habitat enhancement strategy of the Schoolhouse Fish Habitat Enhancement was to use imported large wood material to create large wood structures and hydraulic conditions to scour new pools and deepen existing pools while providing cover (Inter-Fluve, 2014). Construction of The Schoolhouse Fish Habitat Enhancement Project was completed in the summer of 2013.

Lower Project Area

The Lower Project Area primary design approach created large wood structures to scour new pools, maintain existing pools, and provide cover habitat at all flows. Figure 3-26 shows the spatial distribution of project treatments in the Lower Project Area.

Figure 3-26. Overview of lower project area treatments.

Upper Project Area

The Upper Project Area had more potential for varied design elements. There are springs present in this reach that were utilized to improve fish rearing opportunities. Some habitat through this reach was lost due to a prior channel avulsion. The restoration treatments included filling the avulsion channel and plugging the inlet with a log structure, which was intended to restore flow to the more complex abandoned channel. Similar to the Lower Project Area, log jams were created to scour new pools and maintain existing pools while also providing cover habitat during all flows. Figure 3-27 shows a map of the project treatment areas within the Upper Project Area.

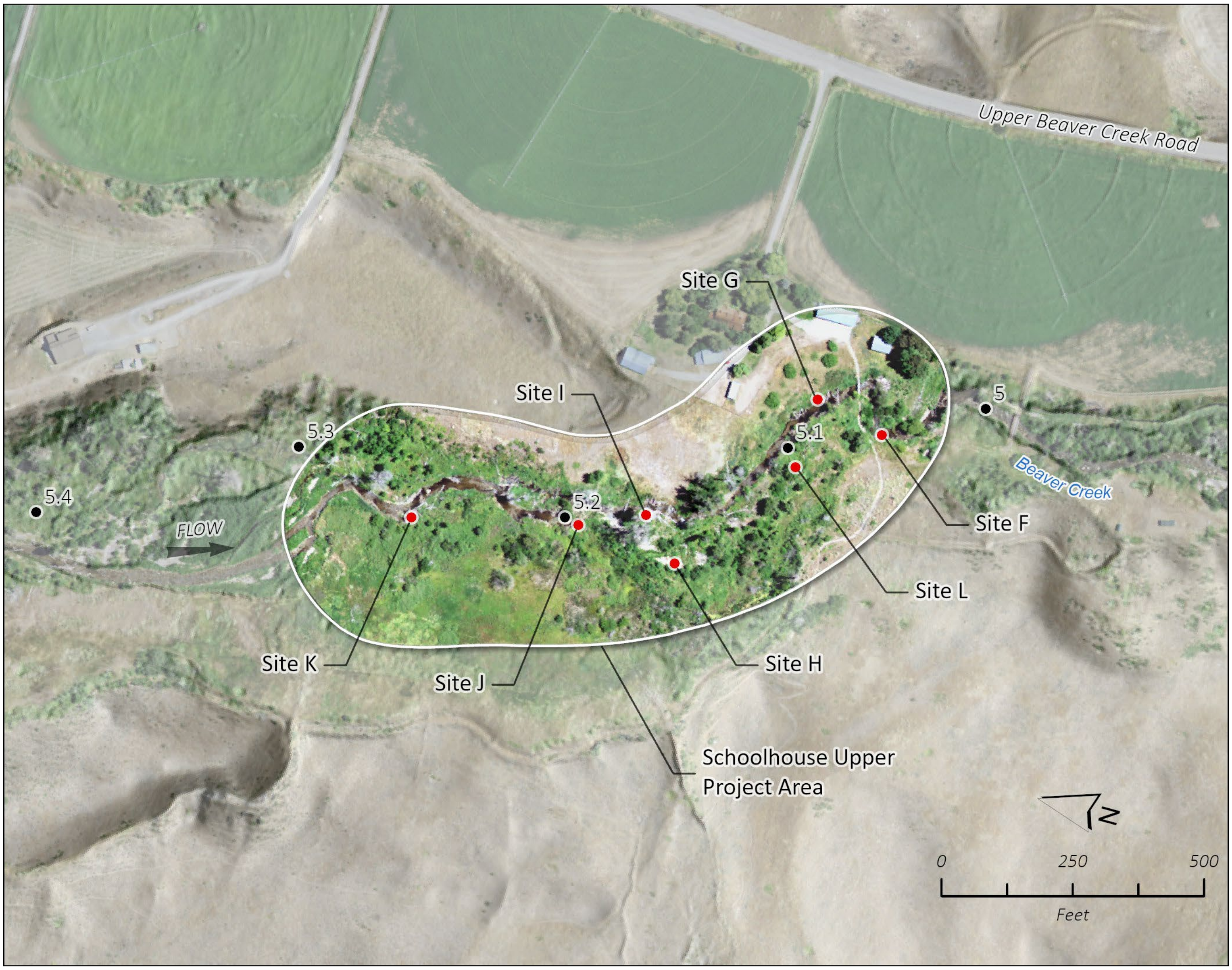

Figure 3-27. Overview of upper project area treatments.

3.2.4 Carlton Complex Fire

The Carlton Complex Fire started on July 14, 2014, from lightning strikes and eventually burned 255,181 acres of a combination of federal, tribal, state, and private lands. The fire was declared 100% contained on August 25, 2014 (USFS, 2014). The Carlton Complex Fire is the largest single wildfire in recorded history in Washington state. The fire burned segments of the recently constructed (summer of 2013) Schoolhouse Project area and 36% of the contributing watershed upstream of this site. Figure 3-28 shows the extent of the Carlton Complex Fire and the contributing watershed to the Schoolhouse Project area. Analysis of the USFS National Fire Boundary dataset showed that the Carlton Complex burned about the same percentage of the watershed as the Tripod Fire, which burned in 2006 (Figure 3-29). Combined, these two fires burned 75% of the watershed within eight years. The frequency and magnitude of these burns in the watershed roughly correlate with the predicted fire regimes within the watershed provided by LANDFIRE. LANDFIRE estimates 72% of the watershed as Fire Regime I, which has a recurrence interval of less than 35 years and a low to mixed intensity (Table 3-6).

The following statistics were estimated for the entire Beaver Creek Watershed from the Burned Area Emergency Response (BAER) report (USFS, 2014).

- 42% of the Beaver Creek Watershed burned (36% upstream of the case study)
- 12% of the burn in the Beaver Creek Watershed was moderate to high severity
- 40% of riparian areas in Beaver Creek burned
- 16% of the riparian burn was moderate to high severity
- 18-fold increase in sediment yield potential
- Predicted 1.5-fold (Automated Geospatial Watershed Assessment [AGWA] model) to 13-fold (Wildcat 5 model) increase in flow in Beaver Creek based on a 25-year 1-hour storm

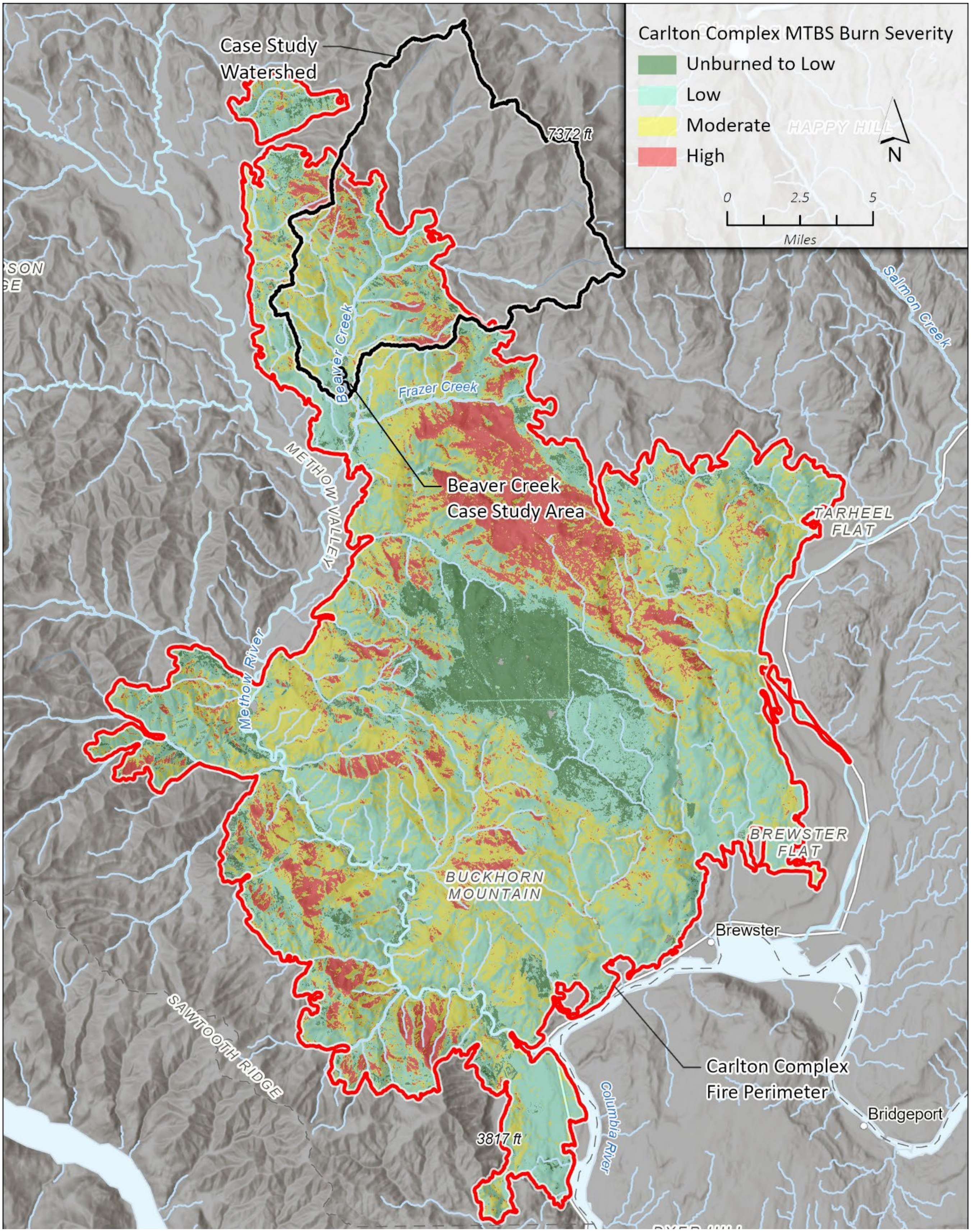

Figure 3-28. Overview of Carlton Complex Fire perimeter and burn severity.

Table 3-6. Beaver Creek Case Study Watershed Fire Regime Composition

Fire Regime	Fire Return Interval	Severity	Percent of Case Study Watershed
Regime I	≤ 35 years	Low and Mixed	72%
Regime II	≤ 35 years	Replacement	0%
Regime III	35 to 200 years	Low and Mixed	21%
Regime IV	35 to 200 years	Replacement	6%
Regime V	> 200 years	Any	1%

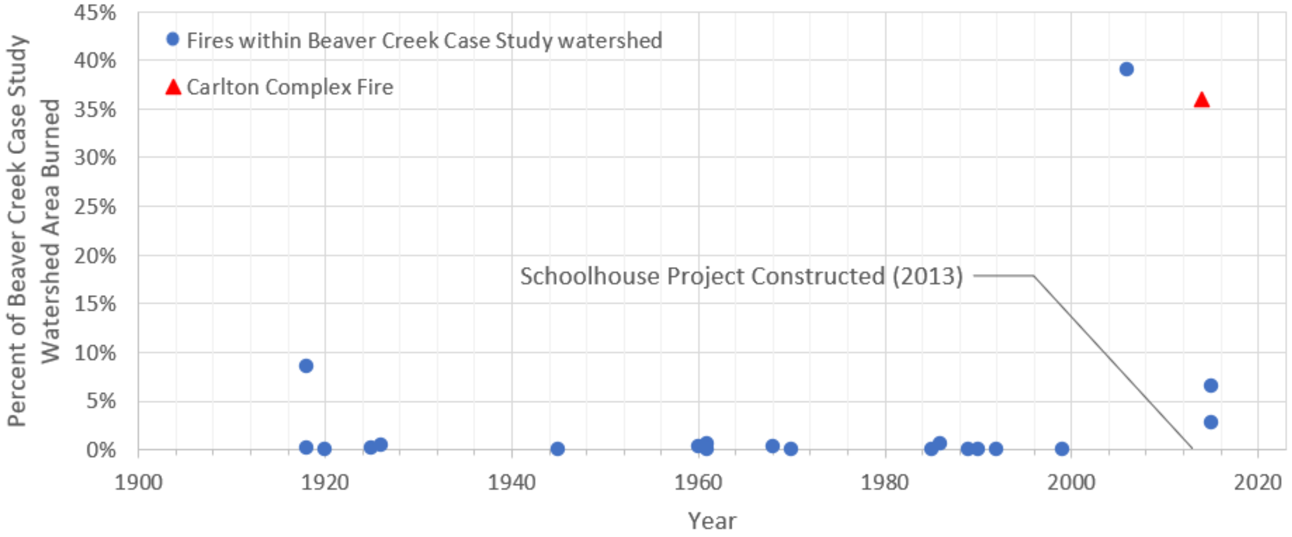

Figure 3-29. Plot of history of fire within the Beaver Creek Case Study watershed according to USFS National Fire Perimeter shapefile. The y-axis shows the percent of the case study burned by each fire; the x-axis shows the year of the fire.

3.2.5 Wildfire Effects on Restoration

The Carlton Complex fire (July through August 2014) burned through the recently constructed (2013) Schoolhouse Fish Enhancement Project, directly burning some of the constructed log jams and 36% of the contributing watershed. All habitat structures associated with the project survived the fire. On August 13, 2014, while the fire was still technically active, there was a large rainstorm that caused what was estimated to be a 5-year flow event on Beaver Creek at the Schoolhouse site. This storm also triggered numerous debris flows into ephemeral drainages that feed into Beaver Creek and resulted in exceptionally high sediment loading to the Schoolhouse Project site. This storm also mobilized a large volume of slash-sized wood, which rafted up against the habitat structures. In 2017, there was a storm that resulted in what was estimated to be at least a 7.5-year event, but no gages exist on Beaver Creek, so the nearby Twisp River gage was used as a representative gage. Flows from this storm are believed to have been amplified in their magnitude due to the recently burned condition of the watershed. This event caused substantial channel migration in areas as well as channel avulsion. Figure 3-30 illustrates a timeline of significant geomorphic events at the Schoolhouse Project Reach on Beaver Creek.

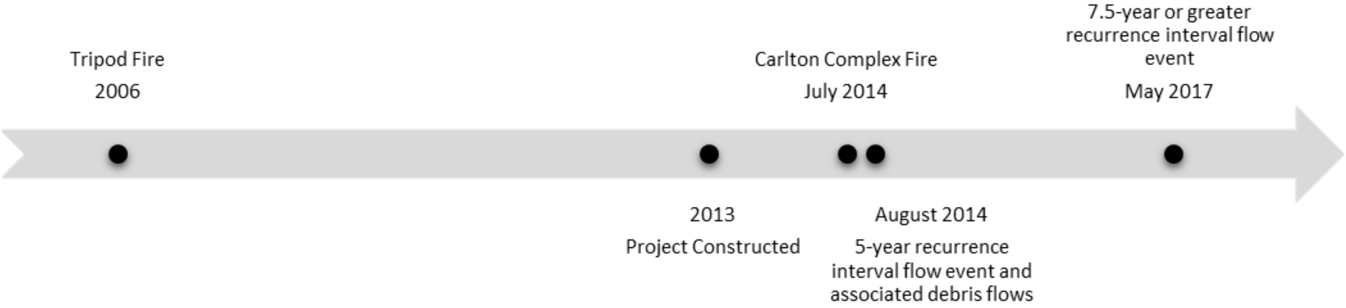

Figure 3-30. Timeline of events on Beaver Creek at the Schoolhouse Project reach.

Direct and indirect impacts at each project site are summarized below (Inter-Fluve, 2015b, 2016, 2017, 2018). Sites F, G, L and J were not significantly impacted by the fire or post-fire sediment loading and are not included in the summary. Photographs of the examples of the direct and indirect impacts on constructed habitat structures within the Schoolhouse Project are provided with the summaries (Figure 3-31 to Figure 3-42).

Site A

Site A was designed to provide cover habitat and enhance an existing pool bedform. Figure 3-31 and Figure 3-32 show the immediate impacts from the debris flows associated with the 5-year flow event that occurred on August 13, 2014. The adjacent riparian area and wood structure were not burned during the fire. However, the elevated sediment load during the 2014 post-fire debris torrent event buried the old channel alignment, former pool habitat, and wood structure. A new avulsion channel was established during the event when cobble and gravel substrate deposited upstream of Site A and the channel migrated laterally through adjacent fully burned riparian area. Site A is located in a relatively wider valley bottom segment of Beaver Creek and naturally more susceptible to a loss in sediment transport, lateral migration, and avulsion response to high bedload transport events. The source material that buried Site A appeared to have been from the upstream riparian bank failure caused by debris jam development and channel migration into fire burned and weakened banks.

Figure 3-31. Site A looking downstream. Left: immediately post-construction (2013). Right: post-fire, post-5-year flow event (2014).

Figure 3-32. Site A showing new avulsion channel following fire and 5-year flow event (2014).

Site B

Site B was constructed to create habitat at the bottom of a steeper, more entrenched boulder bed channel segment at the beginning of a flatter, wider valley segment. The intent of the log jam was to force lateral migration and enhance gravel deposition, pool formation, and rearing habitat at all flows. To meet those objectives, the structure occluded approximately 80 percent of the channel capacity. Although the wood structure was not burned, adjacent native and post-project riparian plantings were completely consumed by the fire. Post-fire flooding caused the right bank lateral migration as intended and the structure collected a significant volume of burned slash and spawning-sized gravel downstream of the site. Figure 3-33 shows the changes to Site B after the fire and estimated 5-year flow event of 2014. The constructed log jam racked slash-size material and has caused bank erosion and channel migration to the right.

Figure 3-33. Site B looking downstream. Left: immediately post-construction (2013). Right: post-fire, post-5-year flow event (2014).

Site C

Site C was constructed to enhance a natural slope break and pool bedform in a relatively wider flood-prone segment of the valley downstream of a steeper channel segment composed of cobble, gravel, and boulder lag deposits. The structure was intended to improve complexity and rearing habitat during low and high flows. The riparian area and post-fire plantings were burned but the structure was largely unburned by the fire. Flood flows and sediment loads did not significantly impact the project site and habitat.

Figure 3-34. Site C looking downstream. Left: immediately post-construction (2013). Right: post-fire, post-5-year flow event (2014).

Site D

Site D was designed to enhance an existing pool bedform adjacent to a valley terrace. A large wood structure was constructed to provide rearing habitat during all stream flows. The fire burned the entire riparian area and a significant portion of the imported wood used to construct the habitat. The 2014 post-fire flood and elevated sediment load partially filled the pool. However, the footprint and hydraulic influence of the structure continued to provide enhanced pool scour and ability to re-scour a pool during subsequent annual runoffs. The structure collected post-fire and flood-generated wood after the 2014 flood event and recovered much of the cover habitat that was burned in the fire. Revegetation, pool maintenance, and overhead cover were found to be in good condition when monitored in 2017 after the 7.5-year flow event.

Figure 3-35. Site D looking upstream. Upper left: immediately post-construction (2013). Upper right: post-fire, post-5-year flow event (2014). Bottom: post-7.5-year flow event (2017).

Site E

Site E was designed to enhance scour and provide cover habitat within an existing pool bedform. The site was severely burned and although the wood composing the structure was burned and degraded, it was resilient enough to accumulate fire-sourced slash during the 2014 post-fire flood. Site E was stable as of 2017 after the 7.5-year flow event. The structure is providing low flow pool cover, habitat, and maintaining a scour pool.

Figure 3-36. Site E looking upstream. Upper left: immediately post-construction (2013). Upper right: post-fire, post-5-year flow event (2014). Bottom: post-7.5-year flow event (2017).

Site H

Site H restored a historic channel alignment with greater channel length. Two right-bank-buried wood structures were constructed in the re-watered channel to enhance rearing habitat, spawning gravel, and adult holding. The previous straighter, down-valley channel was filled with large wood and substrate at the upstream end and allowed to function as a backwater habitat at the downstream end where the old and re-watered channels met. Site H did not significantly change after the fire and 2014 flood. However, beavers were actively felling cottonwood trees and adding material to the channel in the years following the fire. Small avulsion channels were developing from 2014 flood flow slash deposits at the upstream bank-buried wood structure but remained static from 2014 post-flood conditions up until 2017. An estimated 7.5-year flow event occurred in 2017. During this flow, significant slash accumulation and sediment deposition occurred upstream of two bank-buried wood structures. The wood and sediment backwatered flows and caused the development of an avulsion channel against the left (east) valley terrace, resulting in a channel with significantly less length and steeper slope.

Figure 3-37. Downstream jam of Site H looking upstream. Upper left: immediately post-construction (2013). Upper right: post-fire, post-5-year flow event (2014). Bottom: post-7.5-year flow event (2017).

Figure 3-38. Looking upstream at Site H avulsions that developed during the 7.5-year flow event (2017).

Site I

Site I filled a straighter, down-valley channel to enable Site H—a historic, longer channel—to exist. After the fire and 2014 flow event, Site I was functioning as designed. The channel fill was excluding flow from the pre-project channel. In 2015, a beaver dammed the main channel with a 3ft high dam, as shown in Figure 3-39. This dam reduced flow on the main channel down to about 50% of the total flow and forced about 50% of the flow across the former floodplain and channel that Site I was designed to seal off. In 2016 the beaver dam washed away, which resulted in the majority of flow returning to the main channel as designed. The 2017 flood resulted in the development of an avulsion channel upstream of the Site I channel. This new channel ran adjacent to the valley terrace and re-entered Site I (old channel) halfway to the Site H channel confluence. During low flow the channel limited upstream salmonid passage and was modified to allow upstream passage more easily in 2018.

Figure 3-39. Site I looking downstream at the face. Upper left: immediately post-construction (2013). Upper right: beaver dam activity on the main channel (2015). Lower left: beaver dam washed away (2016). Lower right: post-7.5-year flow event (2017).

Figure 3-40. Downstream of Site I looking upstream at avulsion pathways that developed from the 7.5-year flow event (2017).

Following the 2017 flood and effects to Sites H and I, a reconnaissance of the project reach was conducted. Approximately 250 feet upstream of the project reach and 800 feet upstream of site H, it was found that a channel avulsion and lateral right-bank migration had occurred during the 2017 flood discharge. Field observations of the upstream avulsion, right-bank migration, and sediment volume delivered downstream were consistent with the flood effects observed at Sites H and I (below).

At the time of the reconnaissance visit there was no upstream property access. Therefore, observations of the flood processes that initiated the migration were limited. Later, aerial photographs were used to supplement initial field observations. The photos suggest the development of a debris jam that, in combination with elevated post-fire sediment loads, created a down-valley avulsion channel at or near the riparian vegetation and pasture vegetation boundary. The avulsion channel consolidated into a single down-valley channel that rapidly down cut into floodplain sediment and then migrated through less resilient banks and bank sediments (Figure 3-41). The processes that were observed near Sites H and I following the 2017 flood are similar to those observed at Site A following the 2014 post-fire flood.

Figure 3-41. Aerial view of 2017 post-flood Beaver Creek channel conditions near Sites H and I.

Site K

Site K was designed to enhance scour and cover habitat within an existing pool bedform. Site K was badly burned and much of the complexity and small wood component of the structure was consumed by the fire. However, key large pieces of the structure still remained and continued to function. Over time this structure collected native slash-sized wood and habitat continued to improve following the fire. As of 2017, Site K was still stable, providing low-flow habitat, maintaining a pool, and accumulating slash.

Figure 3-42. Site K Looking at the face of the structure. Upper left: immediately post-construction (2013). Upper right: post-fire, post-5-year flow event (2014). Bottom: post-7.5-year flow event (2017).

3.2.5.1 Summary of Wildfire Impacts on the Beaver Creek Schoolhouse Restoration Project

The direct and indirect effects of the Carlton Complex Fire that were observed at the Schoolhouse Project are as follows:

- Burned riparian area, including native and planted vegetation (Sites B, C, D, E, K, and H).
- Post-fire sediment loading and channel avulsion (Sites A, H, and I).
- Burned log jam structures (Sites C, D, E, and K).
- Post-fire slash accumulation at all project sites.

Post-fire processes, such as those observed at Site A in 2014, were also observed at Sites B, H, and I in 2017, where local sub reach bed and banks are similarly flatter, less efficient at sediment transport, and composed of alluvial deposits. Observations indicate these channel segments appeared to be more vulnerable to channel expansion and/or avulsion activity due to post-fire elevated bed loads and riparian vegetation burn. In contrast, Sites C, D, E, F, and K have channel boundaries partially composed of boulder lag deposits, locally steeper channel slopes, and excess sediment transport capacity. Observations indicate these channel segments were more stable and more resilient to post-fire sediment loads and adjacent riparian burn.

3.2.6 Lessons Learned

Lessons learned from post-construction, post-fire evaluations at the Beaver Creek Schoolhouse Project include:

- Large wood structures using larger diameter wood were not as affected during the fire as those with smaller diameter wood. While large diameter wood burned, enough remained after the fire to maintain structural integrity, hydraulic influence (bed scour), and ability to collect post-fire slash that restored previously burned cover habitat.
- Large wood structures and key members of the structures that projected well into the active channel and were built at low elevation relative to the floodplain were resistant to fire. Some of these structures experienced minimal fire damage while others experienced burning of upper elevation logs and racking material with minimal fire damage to lower elevation key members.
- Large wood structures in steeper reaches with boulder lag deposits designed to enhance pool scour and provide cover habitat were more resilient to elevated post-fire sediment loads. In general, these structures recovered their habitat function by collecting native slash to replace wood that was lost during the fire. The structure hydraulic influence remained and re-scoured post-flood sediment and pool habitat.
- Habitat created in alluvial valley bottom reaches were vulnerable to elevated post-fire sediment load, channel burial, avulsions, and lateral migration into burned riparian vegetation or into pasture areas outside of burned riparian vegetation.
- The project areas with broad valley bottoms and low elevation floodplains provided the space available for channel migration and avulsion processes in response to upstream bedload deposition. The resulting channel-floodplain morphology is viewed as a resilient response to the effects from fire and corresponding debris flows and increases in bedload deposition.
- Channel avulsion and migration into floodplain areas was expedited by lack of floodplain forest and corresponding resistance to flow. Increasing the roughness along the floodplain (e.g., pasture areas) upstream of the project reach would have reduced the rate of channel migration and incision and resulted in more geomorphic complexity within the newly occupied floodplain channels.
- Recovery from post-fire impacts due to elevated peak flood flow, sediment load, debris torrent activity, and burned riparian area continued through 2017, or three years after the fire.
- Dynamic channel responses can be expected in the first few years post-fire especially in depositional reaches. Structures constructed in depositional reaches of fire-prone projects will have a higher risk of becoming buried or abandoned. This is especially true downstream of tributary channels capable of developing debris torrents.
- The project areas include broad valley bottoms with low elevation floodplains. These areas have robust riparian plant communities that were resilient to fire by reducing the fire severity on vegetation and/or fostering relatively rapid post-fire riparian regeneration. It took about three years for the vegetation to fully re-establish on the project sites. Mature cottonwood mortality will require several more decades to recover.
- Beaver activity was observed before and after construction, as well as before and after the fire and subsequent flooding events. The effects of beaver activity (e.g., ponds, small channels, and floodplain soil moisture) likely improved the resiliency of the projects sites to fire as well as fostered the rapid post-fire recovery of riparian vegetation and geomorphic complexity.

3.3 Wolf Creek

Wolf Creek is a tributary of the Methow River set in the eastern foothills of the Cascade Mountains in central Washington. Wolf Creek joins the Methow River 2.5 miles upstream of the town of Winthrop, Washington. Watershed characteristics of Wolf Creek are summarized in Table 3-7 and hydrology is summarized Table 3-8.

The hydrology data for Wolf Creek lacks accuracy because there are only three years of stream gaging data available for analysis. Wolf Creek was identified by YNF as a priority tributary in the Methow River Basin to enhance habitat for ESA-listed salmonids which include Upper-Columbia Summer Steelhead, Upper-Columbia Spring Chinook, and Columbia River bull trout. YNF contracted Inter-Fluve to complete an assessment and restoration strategy plan for Wolf Creek RM 0 to 4.5 in 2020 (Inter-Fluve, 2020).

Table 3-7. Wolf Creek Watershed Characteristics

Watershed Characteristics	Value
Watershed Area	40 sq. miles
Relief	7,050 feet
Average Annual Precipitation	57 inches (headwaters) 15 inches (mouth)
Hydrograph Character	Snowmelt Driven

Table 3-8. Wolf Creek Hydrology at the Mouth

Flow Event	Discharge (cfs)
2-year	263
5-year	467
10-year	638
25-year	886
50-year	1110
100-year	1340

3.3.1 Reach Location

The Wolf Creek Case Study Reach was selected as a reference condition to be compared with the Beaver Creek and Chewuch case studies. Unlike the Beaver Creek and Chewuch case study reaches, the Wolf Creek Study Reach has not seen any river restoration work. Not only has there not been any restoration within the study reach, but much of the contributing watershed is in a state that is relatively undisturbed from anthropogenic impacts in the way of roads, logging, or development. Eighty percent of the Wolf Creek watershed lies within the Chelan-Sawtooth Wilderness and the remainder of the contributing hillslopes within the National Forest are relatively inaccessible for timber harvest or development due to steep topography (USFS, 2005). Anthropogenic disturbance is limited to the lower 1.5 miles of channel and floodplain on the Wolf Creek alluvial fan, within the Little Wolf Creek subbasin, and at the Wolf Creek ditch/aqueduct outtake at RM 4.5 (Inter-Fluve, 2020). This reach was also selected because there is pre-fire data available from an assessment completed in 2020 by Inter-Fluve for YNF, a year before the Cedar Creek Fire that started in July of 2021. The Wolf Creek Case Study focuses on this assessment reach, which is the lower 4.5 miles of Wolf Creek (Figure 3-43).

Figure 3-43. Overview map of the Wolf Creek case study area.

3.3.2 Fish Habitat Restoration Objectives

No restoration work has been implemented on Wolf Creek; however, according to the revised Biological Strategy for the Upper Columbia Region (Upper Columbia Regional Technical Team [UCRTT], 2017) the primary concerns in the Wolf Creek watershed for salmonids are:

- Injury or mortality (mechanical injury)
- Riparian condition (riparian condition and large wood recruitment)
- Peripheral and transitional habitat (side channel and wetland connection)
- Channel structure and form (instream structural complexity)
- Water quantity (decreased water wuantity)

The Wolf Creek Reach Assessment & Restoration Strategy identified the following actions for restoration on Wolf Creek (Inter-Fluve, 2020):

- Planting of native riparian vegetation in areas disturbed by human infrastructure
- Fencing out grazing animals along riparian areas
- Upgrading bridge crossings
- Removal/decommissioning of outdated irrigation withdrawals
- Installation of large wood jams to increase habitat complexity

- Installation of boulders to increase habitat complexity
- Excavation of inset floodplain along entrenched channels

3.3.3 Cedar Creek Fire

The Cedar Creek Fire started on July 8, 2021, from a lightning strike. The Cedar Creek Fire went on to burn 55,000 acres before it was considered contained on August 15, 2021. The fire directly burned about half of the assessment area that is being considered in this case study and burned 80% of the contributing watershed. Figure 3-44 shows the extent of the Cedar Creek Fire, the fire intensity distribution, and the Wolf Creek watershed. According to the USFS National Fire Boundary dataset, the Cedar Creek Fire is the largest fire within the Wolf Creek watershed that has been recorded (Figure 3-45). The results in Figure 3-45 don't correlate well with the fire regime composition of the watershed according to LANDFIRE (Table 3-9), which estimates 59% of the watershed to have a fire return interval of less than 35 years. The fire history of the watershed shows relatively minimal fire activity in the past 100 years.

According to the BAER report, 48% of the burned area within the Cedar Creek Fire exhibited high or moderate soil burn severity with vegetation mortality in these zones ranging from 80 to 100%. Preliminary hydrologic models estimated flow increases in headwater channels to be greater than 100 times the pre-fire flow rates for a given recurrence interval storm (USFS, 2021).

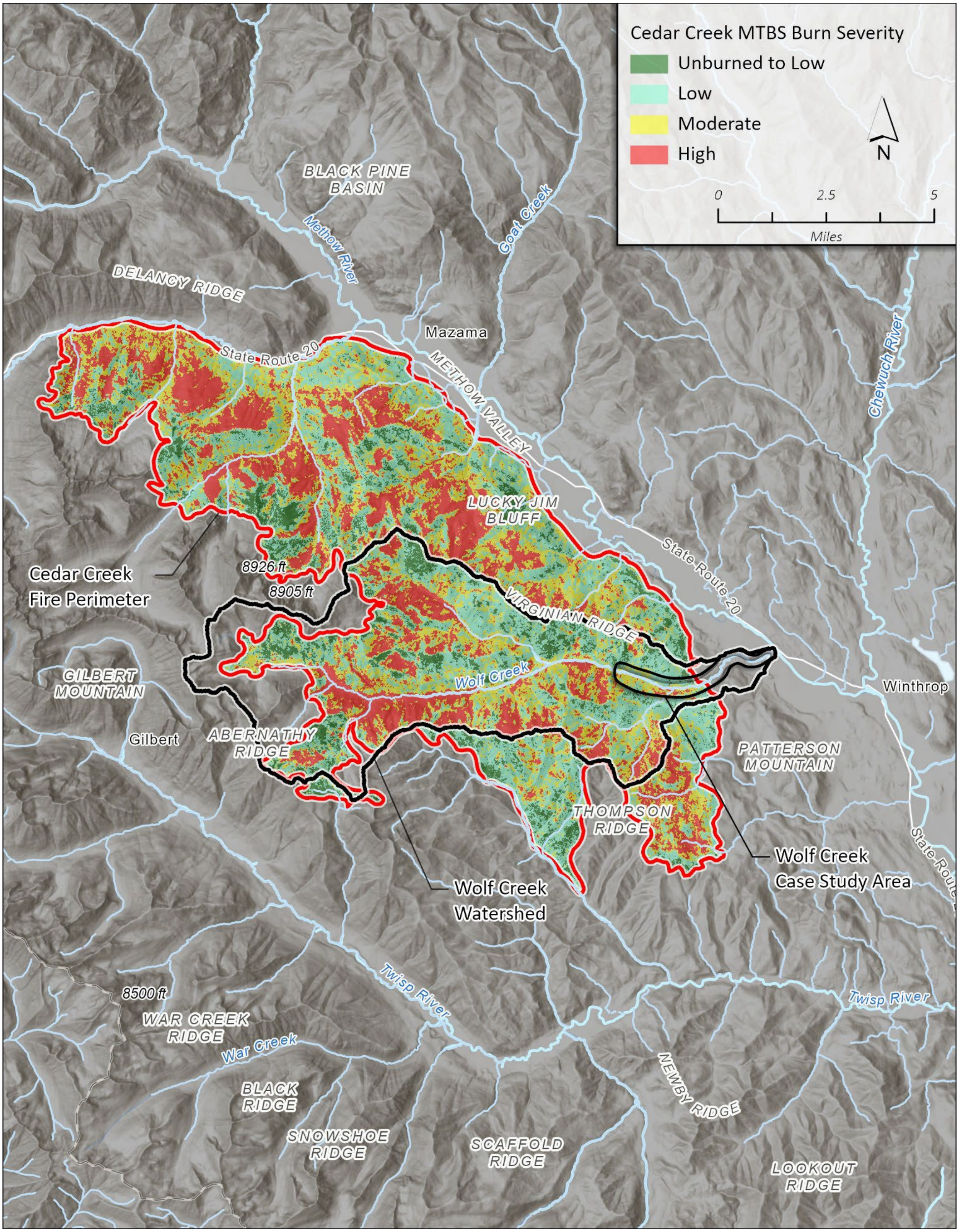

Figure 3-44. Overview of Cedar Creek Fire perimeter and burn severity.

Table 3-9. Wolf Creek Watershed Fire Regime Composition

Fire Regime	Fire Return Interval	Severity	Percent of Case Study Watershed
Regime I	≤ 35 years	Low and Mixed	59%
Regime II	≤ 35 years	Replacement	0%
Regime III	35 to 200 years	Low and Mixed	23%
Regime IV	35 to 200 years	Replacement	1%
Regime V	> 200 years	Any	17%

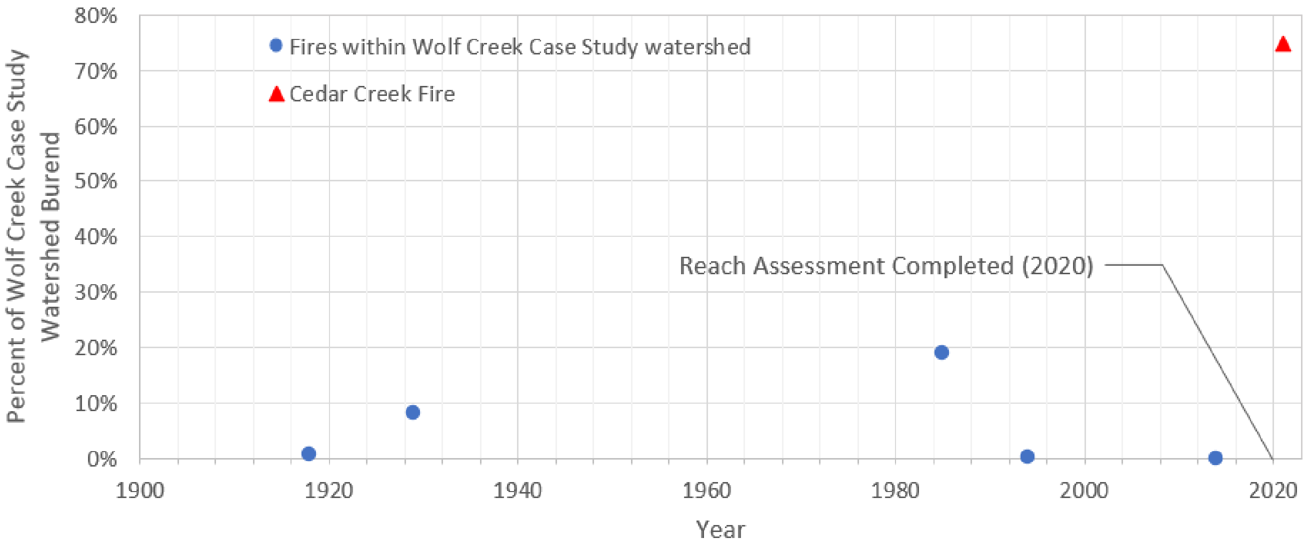

Figure 3-45. Plot of history of fire within the Wolf Creek Case Study watershed according to USFS National Fire Perimeter shapefile. The y-axis shows the percent of the case study burned by each fire; the x-axis shows the year of the fire.

3.3.4 Wildfire Effects on Project Reach

The wildfire effects on the Wolf Creek Case Study area pertinent to the condition of the Wolf Creek can be summarized as impacts to vegetation and soil, channel, hillslopes, and large wood. The following sub-sections discuss and provide examples of the impacts to each of these categories. The majority of this section is sourced from the technical memorandum titled *1-year Post Cedar Creek Fire Site Walk Through and Restoration Strategy Recommendations* (Inter-Fluve, 2022b).

Vegetation and Soil

Vegetation loss and altered soil composition, including hydrophobic conditions, were noted during the post-fire field observations of the project area in 2021. The degree of vegetation loss and soil alterations noted in 2021 correlated spatially, depending on burn severity. For reference on burn severity, please see the Soil Burn Severity Map from the Cedar Creek BAER report (USFS, 2021) with the Wolf Creek project area (RM 2.2-4.53) (Figure 3-44). In high and moderate severity sections, vegetation and organic matter including large wood jams in the channel, tree root mass, and organics in the soil were burned. In these areas, a layer of ash debris coated the soil surface. In some high-severity areas, the fire was hot enough to induce spalling (flaking) of boulders. In the least-severe burn areas, only the underbrush and portions of the top organic layer of the soil were impacted while large trees and riparian vegetation survived or partially survived.

Vegetation regrowth observed in August of 2022 was primarily groundcover recovery (forbs, shrubs, ferns, etc.) on the floodplain, banks, and hillslopes. The density of groundcover reestablishment throughout the project area was patchy and appeared to be related to soil burn severity and surface stability (Figure 3-46). As expected, post-fire soil composition and varied persistence of hydrophobic conditions in the severely to moderately burned floodplain areas appeared slower at reestablishing ground cover one year post-fire compared to less severely burned areas. Riparian shrub and tree (dogwood, alder, maple, etc.) regeneration was most successful in the low- and moderate-severity burn areas where root survival hosted the sprouting of fresh shoots or in proximity to riparian vegetation that survived the 2021 burn. Hillslope groundcover recovery was similarly patchy to that observed on the floodplain and banks. Where hillslope steepness and instability were noted, less established groundcover was observed in areas that were burned baren in 2021. Conifer tree regeneration was not observed the first year after the fire but will be an important component of hillslope and floodplain stability as fire-killed tree roots decay and soil strength decreases (DeGraff et al., 2015).

Figure 3-46. Examples of patchy groundcover regeneration that were baren in 2021 at A) low soil burn severity area on floodplain at RM 3.8; B) moderate soil burn severity on floodplain with surface collapse at burned root ground piping at RM 4.5; and C) high soil burn severity on floodplain with surface collapse and soil erosion at burned root ground piping and high ash content at RM 3.41. Photos collected August 11, 2022.

Soil condition and stability were noted in the 2022 field survey. Soil burn severity imposed a varied response to soil recovery in the project area that appears to be related to a range of persistent hydrophobic conditions that repel water and interrupt infiltration (UCRTT, 2019) and presence, or lack thereof, of root strength. One year of seasonal precipitation (snow and rain) initiated soil infiltration processes and hydrologic function after the 2021 wildfire. As expected, soil erosion was observed as processes of overland flow transport, piping, surface collapse associated with piping, rill development, bank failure, and hillslope contributions (Figure 3-47). The observed relationship of vegetation recovery and processes of erosion illustrates the interdependence of hydrologic, geomorphic, and ecologic recovery post-wildfire in the Wolf Creek watershed. Over time, soil infiltration, root strength stabilization, and the accumulation/integration of organic material from reestablished vegetation is expected to improve soil composition and stability.

Figure 3-47. Example photos of post-fire soil erosion processes at A) burned root void collapse and piping instigating upslope rill-development on a floodplain terrace at RM 4.08; and B) destabilized bank collapse at RM 4.47. Photos collected August 11, 2022.

Channel

Channel form and post-fire processes were evaluated and noted during the 2022 field survey. Minimal changes to channel form occurred within the project area compared to 2021 and 2020 conditions. Bank erosion associated with subtle channel widening was observed in localized areas where bank/hillslope failure occurred, usually associated with areas of burn-related riparian vegetation loss and where burned-out log structures decreased in-channel complexity. As predicted, increased erosion processes in the first year produced and transported fines and ash from the adjacent unvegetated surfaces into the channel. Alluvial accumulations of fines (silt and fine sand) rich in ash (clay content) were observed in low flow-velocity areas coating the channel bed, creating new bars, topping existing bars and channel margins, and behind wood and debris accumulations as shown in Figure 3-48 and Figure 3-49. It was observed that salmonid and general aquatic habitat conditions (i.e., gravels coating and embedding) were negatively impacted in the study area by the first year of erosion response (Figure 3-50). The presence of new fines was related to proximity to source and low-flow hydraulic opportunities in the channel. The presence of fines in the channel decreased downstream of the burn boundary.

Figure 3-48. Fines accumulated behind large wood and debris at the margin of the channel at RM 3.02. Photo collected August 11, 2022.

Figure 3-49. Fine sediment accumulation and bar deposition within the channel.

Figure 3-50. Photo of redd at RM 4.34 in 2021 (left) with clean gravels and channel bed and 2022 photo (right) of the same redd coated with silts and fines.

Hillslopes

The steep soil-mantled hillslopes on the north (river left) side of the valley have been identified as high-to-moderate risk of debris flow generation. The Cedar Creek BAER report provides a map of the USFS's analysis for potential combined hazard of debris flows (see Figure 8 in USFS 2021), including within Wolf Creek. Although runoff potential and burn severity is high on the south (river right) side of the channel, the report predicts lower debris flow risk here as a result of the terraced topography. No new debris flow was identified in the project area in 2022. Unstable hillslopes currently contributing sediment and/or wood to the channel are the same as those identified in 2020 and 2021. Those hillslopes are at RM 2.56, 2.67, 2.75, 3.37, and 4.10—all on the river left (north) side of the channel (Figure 3-51).

The hillslopes on the north side (river left) of the valley floor between RM 3.6 – 4.5 show evidence of historical instability and active mass wasting. Large unstable areas are expected to have an increased risk of hillslope failure in the next decade as fire-damaged trees on the hillside decay and the root strength they currently provide to hillslope stability decreases faster than natural forest regeneration will be able to compensate for. Hillslope and bank sediment sources of gravel continue to be important localized contributions for rejuvenating channel bed substrate for aquatic habitat.

Figure 3-51. Unstable hillslope at R 3.37 on river left – contribution sediment and large wood. Photo taken August 11, 2022.

Large Wood

Prior to the 2021 Cedar Creek Fire, the quantity of large wood in Wolf Creek between RM 1.3-2.31 (Reach 2) was below minimum requirements and upstream of RM 2.31 (Reaches 3-5) met the minimum requirements for number of effective pieces of large wood (32/mile) (Fox & Bolton, 2007) to provide basic habitat complexity for salmonids (Inter-Fluve, 2020). In areas of Reaches 2-5, limited or no large wood accumulation occurred but adequate geomorphic and hydraulic conditions existed to support habitat enhancement. Thus, in 2020 it was recommended that large wood loading be done via helicopter placement. These locations have characteristics that support jam formation and maintenance, such as suitable channel form, large boulders in the channel or adjacent floodplain for bracing, adequate gradient and flow hydraulics, and some amount of available adjacent floodplain to dissipate flood flow and stream energy. It is probable that the locations where large wood jams existed prior to the fire will become large wood accumulation areas at times in the future.

The 2021 wildfire burned most of the existing large wood jams located in the channel upstream of RM 2.3. As a result, the channel today (2022) is lacking in adequately sized large wood pieces and jams throughout the project area (Reaches 1-5). During the October 2021 site walk, probable large wood accumulation areas were recorded using a high-accuracy global navigation satellite system (GNSS) hand-held global positioning system (GPS) unit and then compared to the proposed 2020 large wood installation zones (Inter-Fluve, 2021). During the August 2022 site walk, areas of large wood inputs and initiation of accumulations as well as confirmation of zones/sites appropriate for large wood installations were recorded, again using GPS. When compared, the large wood accumulation zones mapped in 2022 remain the same as those observed and mapped in 2021.

Figure 3-52. Left: channel-spanning large wood jam at RM 3.36 prior to the Cedar Creek Fire (July 2020), the same jam post-fire partially burned (October 2021), and accumulations of small wood 1-year post-fire (August 2022). Right: channel-spanning large wood jam at RM 4.43 prior to the Cedar Creek Fire (July 2020), the same jam post-fire partially burned (October 2021), and accumulations of small wood 1-year post-fire (August 2022).

The accumulations observed at the few partially burned jams in 2022 were mostly small pieces that, without key pieces of large wood in place for maintenance, would likely be temporary and redistributed downstream (Zelt & Wohl, 2004). An example of two jams that partially burned and their capacity to aid in accumulation of wood, mostly debris and small pieces, is shown in Figure 3-52.

Recovery of the geomorphic and habitat complexity that large wood has the potential to provide in Wolf Creek varies temporally and spatially and appears to be dependent on proximity to recruitment source and quantity of wood contributed. For example, the largest channel-spanning wood jam recorded in the project area in 2020 at RM 3.43 was severely burned in the 2021 wildfire. Before the fire, the jam maintained split flow complexity upstream and a high-quality covered pool at the downstream end. Although the site has all of the characteristics to be an excellent accumulation zone for a large wood jam, by August of 2022 no new wood accumulation had occurred at the site and habitat complexity remained diminished.

3.3.5 Lessons Learned

In Wolf Creek, a watershed relatively free of anthropogenic disturbance, the following lessons were learned about post-fire stream response following the Cedar Creek Fire:

- The degree of vegetation loss and soil alterations observed several months post-fire correlated spatially with burn severity. In high- and moderate-severity sections, vegetation and organic matter including large wood jams in the channel, tree root mass, and organics in the soil were burned. In the least-severe burn areas, only the underbrush and portions of the top organic layer of the soil were impacted while the large trees and riparian vegetation survived or partially survived.
- Vegetation regrowth observed one-year post-fire was primarily groundcover recovery (forbs, shrubs, ferns, etc.) on the floodplain, banks, and hillslopes. The density of groundcover re-establishment throughout the study area was patchy and appeared to be related to soil burn severity and surface stability. Riparian shrub and tree (dogwood, alder, maple, etc.) regeneration was most successful in the low- and moderate-severity burn areas where root survival hosted the sprouting of fresh shoots or in proximity to riparian vegetation that survived the 2021 burn. Conifer tree regeneration was not observed the first year after the fire.
- Soil burn severity imposed a varied response to soil recovery in the project area that appears to be related to a range of persistent hydrophobic conditions that repel water and interrupt infiltration and presence/absence of root strength. Soil erosion was observed as processes of overland flow transport, piping, surface collapse associated with piping, rill development, bank failure, and hillslope contributions.
- Post-fire processes have resulted in minimal changes to channel morphology. Localized bank erosion associated with subtle channel widening was observed where bank and hillslope failure occurred, usually associated with areas of burn-related riparian vegetation loss. The muted channel response is largely due to immobile streambed and streambank boundaries comprised of bedrock, boulders, and old debris-flow runout deposits.
- Increased erosion processes one-year post-fire produced and transported fines and ash from the adjacent unvegetated surfaces into the channel. Alluvial accumulations of fines (silt and fine sand) rich in ash (clay content) were observed in low flow-velocity areas. The presence of fines in the channel decreased downstream of the burn boundary.
- The steep soil-mantled hillslopes on the north (river left) side of the valley have been identified as high-to-moderate risk of debris flow generation. These unstable hillslopes are currently contributing sediment and/or wood to the channel. No new debris flows have been identified in the project area. Hillslope and bank sediment sources of gravel continue to be important localized contributions for rejuvenating channel bed substrate for aquatic habitat.
- Natural log jams that were partially burned were located within the active channel, had key members that were partially submerged and/or in contact with the low-flow channel, and were ballasted by alluvium or braced by vertically oriented large boulders that impede downstream movement. These characteristics likely contribute to the partial persistence of these natural log jams, which are still functioning to accumulate mobile wood and sediment supplied from upstream.

- Wood accumulation in the channel post-fire remains small material (approximately less than four inches in diameter) for at least the first year.
- Subreaches and sites that were previously identified as potential locations for large wood accumulations (natural and placed) remained post-fire as locations that were functioning to accumulate mobile wood and sediment. These locations have characteristics that can be used to guide future restoration actions involving large wood placement, including the availability of large boulders and channel form roughness that foster wood and sediment retention and are resilient to burning.

3.4 References

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4 SUMMARY

Wildfire frequency, extent, and severity are all projected to increase throughout western North America (May et al., 2018; Ball et al., 2021). Habitat restoration projects may have the capacity to buffer some of the negative impacts of wildfire and thereby contribute to proactive management strategies aimed at climate change adaptation and mitigation. As a warming climate drives more intense and frequent wildfires in drylands around the world (Westerling et al., 2006), it becomes increasingly important to understand the characteristics that foster river corridor resilience to wildfire disturbance cascades (Wohl et al., 2022), such that opportunities for climate and fire resiliency can be built into the scope of habitat restoration projects.

4.1 Recommendations

This section provides a synthesis of the information gleaned from the literature review and lessons learned from the case studies. The following is intended to serve as a primer for river restoration practitioners and stakeholders to understand and consider the risks wildfires pose to restoration projects, and suggestions for mitigating those risks.

4.1.1 Project Wildfire Risk Assessment

As evidenced by the case studies covered in this report, it is becoming increasingly important for project designers and stakeholders to consider river restoration projects within the context of wildfire on the landscape. There are publicly available GIS data that can be used as assessment tools to determine wildfire history, fire regime composition (predicted burn intensity and recurrence interval), and debris flow hazards for a project site and the contributing watershed. By interpreting and comparing these data one can develop an understanding of what areas of the watershed have burned in the recent past, what areas of the watershed are overdue for a wildfire, and what areas hold the potential to be large sources of sediment in the form of debris flows. The following bulleted list outlines suggested analyses for practitioners and stakeholders to develop a qualitative understanding of the risk of wildfire impacts to a project, followed by incorporation of risk analysis into the environmental assessment of the project reach and the basis of design.

- Analysis to understand risk of wildfire at a project site and within the contributing watershed.
    - Download the U.S. Forest Service (USFS) National Fire Perimeters shapefile and clip it to your watershed.
    - Interpret the spatial and temporal distribution of the available record of fire within your watershed within a Geographic Information System (GIS) platform.
    - Plot percent of watershed burned vs. time for fires occurring within your watershed.
    - Download the LANDFIRE Fire Regimes shapefile and clip it to your watershed.
    - Interpret the spatial distribution of fire regime composition of your project site and watershed.
    - Compare historical fires within the watershed to the fire regime composition of the watershed and identify which areas of the watershed are predicted to be overdue for a wildfire.
    - Map the results from assessments of debris flow and landslide hazards in watersheds upstream of your project reach.
    - Map the occurrence and timing of historical debris flows and landslides in watersheds upstream of your project reach.
    - Map the results of flood hazard assessments upstream, within, and downstream of the project reach.
- Incorporate evaluation of wildfire impact risk within your basis of design.
    - Describe the current and potential future climate and hydrology at the project reach.
    - Map the contemporary valley bottom and potential channel migration zone to evaluate the potential process space available for channel-floodplain dynamics.

  - Map the existing riparian and floodplain plant communities to evaluate potential resiliency to fire and channel migration and avulsion.
  - Map the water table elevation within the riparian zone and floodplain to evaluate the potential post-fire recovery of riparian plant communities.
  - Describe the existing and potential use of the project reach by beaver to evaluate the potential resiliency to and recovery from fire.

4.1.2 Design for Fire Risk Mitigation and Resiliency

The analysis approach outlined in the previous section serves to develop a qualitative understanding of the risk of wildfire related impacts to a project. If it is determined that there is reasonable risk and the project stakeholders agree that the risks are worth mitigating, then the design should consider mitigation measures for the mechanisms in which fire can influence restoration projects. These mechanisms as identified in the literature review and case studies are summarized as follows:

- Increased sediment loading
- Burning of project elements (e.g., large wood structures)
- Burning of riparian vegetation
- Increased peak flows and sediment supply

The following section outlines design considerations to mitigate wildfire impacts that were distilled from the case studies of this report. The project goals and objectives define which wildfire-related impacts are considered detrimental to the success of a given project. It is worth noting that negative wildfire impacts may vary from project to project, and wildfire impacts are not necessarily detrimental (e.g., supply of large wood and coarse-gravel bed material; creation of complex secondary channels). The Chewuch and Beaver Creek case studies were primarily focused on improving salmonid habitat with the use of engineered log jams (ELJs) (large wood structures) and creation of side channels. The detrimental impacts observed in these projects can be summarized as:

- Filling of pools with sediment
- Burial of large wood structures with sediment
- Burning and destruction of large wood structures
- Burning of planted vegetation used for post-construction native vegetation restoration
- Channel avulsion around structures
- Abandonment and/or filling of side channels

These impacts are assumed to be widely applicable to the majority of restoration projects focused on the improvement of salmonid habitat. However, it is important to consider how wildfire impacts may influence the success of each project on an individual basis. The design considerations below are broken up into the initial scoping of the project, followed by design suggestions and considerations to mitigate major processes by which wildfire influences river restoration projects. There are tradeoffs to mitigating fire risk that may reduce the effectiveness of restoration and enhancement treatments. One challenge is to acknowledge and consider alternative methods for reducing wildfire risk within the context of individual watersheds, project reach processes, and aquatic habitat needs.

Project Scoping and Conceptual Development

- Use wildfire disturbance and fire history in initial project scoping and locating within a watershed. This evaluation should incorporate an analysis of the road conditions for potential increased contributions of sediment to stream channels.
- Consider the design life of the project. Project stakeholders should consider the minimum amount of time in which the project is expected to function as intended.

    - Considerations when determining design life include:
        - Large wood structure longevity
        - Rate of local geomorphic change
        - Geomorphic trajectory and process domains (i.e., steep, well-connected hillslopes vs. unconfined floodplain systems)
        - Vegetation establishment rates
        - Wildfire risk
        - Project cost/benefit analysis

Sediment

- Avoid building structures on or immediately downstream of debris flow fans and/or alluvial fans.
- Design structures such that the bottom members encourage scour even if the scour pool is occasionally filled in with high sediment loads from upstream.
- Design structures for sediment retention, and/or to accommodate sediment accumulation, as a tool for fire resiliency. Factor in the road network conditions in contributing watersheds and the associated potential sediment supply.
- Based on the physical characteristics of a project site, design restoration treatments to accommodate channel migration and avulsion, as applicable.

Wood Structures

- Build low-profile structures where all key members are submerged or at least partially submerged under low-flow conditions (key members can be described as wood pieces critical to the structural integrity of the structure).
- Limit slash (small diameter wood < 2” in diameter) to locations within structures where it will stay wetted.
- Use key members and piles with as large of a diameter as possible.
- Incorporate boulders into structures; even if the structure burns, the boulders will be left behind to accumulate wood and debris post-fire.
- Use coarse alluvium ballast for securing large wood instead of log piles.
- Consider sourcing wood from adjacent forests and hillslopes within the watershed for additional benefit of fuel reduction, especially if fire history suggests higher risk of severe wildfire in the early stages of project life expectancy (0 - 10 years).
- Where appropriately located, significantly increasing the large wood abundance within a project reach may increase the magnitude and duration of channel-floodplain connectivity and improve sediment retention, thereby reducing local fire intensity and downstream sedimentation impacts.
- In fire-prone project areas, building structures on or immediately downstream of debris flow fans should be avoided, if possible, as these structures are vulnerable to being buried. Alternatively, log structures may be more resilient to the effects from debris flows (and may provide sediment capturing benefits) if the structures are located further downstream along the fan terminus or along the riverbank opposite of the fan terminus. Additionally, the log structures may be more resilient to burning if the structures are designed to emulate debris flow log accumulations, including the use of more alluvium ballast in addition to log pile ballast.

Vegetation

- Increase groundwater levels to increase moisture available to riparian vegetation:
    - Create ponds
    - Promote floodplain and wetland connections
    - Create side channels, alcoves, and groundwater-fed channels

    - Encourage beaver activity
- Vegetation management at project reach scale will help reduce fuel availability.

Hydrology

- Hydrologic modeling of potential burn scenarios or recent burns in the watershed can inform increases to design peak flows.
- Changes in hydrology should be incorporated into design elements. Design for the hydrology within the system under existing conditions and for future projected climate and fire conditions. In watersheds that have recently burned, incorporate post-fire effects on changes in hydrology within the watershed:
    - Design of wood structures and ELJs
    - Substrate and bank mobility
    - Infrastructure elevations

4.1.3 Foster Design Adaptation

As investments in salmonid habitat restoration in the Pacific Northwest continue, the compounding threat of wildfire creates an impetus for more rigorous consideration of wildfire impacts in the context of stream restoration design. The Tributary Habitat Steering Committee (THSC) can lead the efforts in adaptation of tributary habitat restoration to wildfire risks through:

- **Coordination and support of ongoing and additional case studies of wildfire effects on stream restoration projects.** There remains the need for additional understanding of wildfire impacts on restoration projects and the resiliency of restoration projects to wildfire effects. Data and information should continue to be gathered from the case studies described in this report and additional data and information should be gathered from restoration projects representing diverse biological and physical settings with a wide range of restoration treatment types. Collectively, this information would provide the guidance necessary to adaptively design wildfire resilient river-floodplain restoration projects.
- **Development of standardized guidelines for incorporating wildfire risks into restoration designs.** Given the projected trends in climate change and wildfire regimes throughout the Pacific Northwest, there is an urgent need to evaluate wildfire risks during the planning, assessment, and design phases of restoration projects. As summarized in this report, over the past several decades climate change and wildfire science in the Pacific Northwest has evolved into organizations and institutions that provide high-quality data, information, and analytical tools to the region. Standardized design guidelines should be developed for incorporating these resources into a design process that results in wildfire resilient river-floodplain restoration projects.

Just as climate change and wildfire science have advanced in recent decades, so too has the practice of stream habitat restoration advanced by applying emerging science and engineering principles to restoration designs. These advances offer opportunities to holistically integrate emerging climate and wildfire science with the practice of habitat restoration. Through more rigorous consideration of observed and projected climate and wildfire trends, stream restoration actions can become more resilient to the effects of wildfire and habitat restoration projects can more effectively buffer some of the negative impacts of wildfire and thereby contribute to proactive management strategies aimed at climate change adaptation and mitigation.

4.2 References

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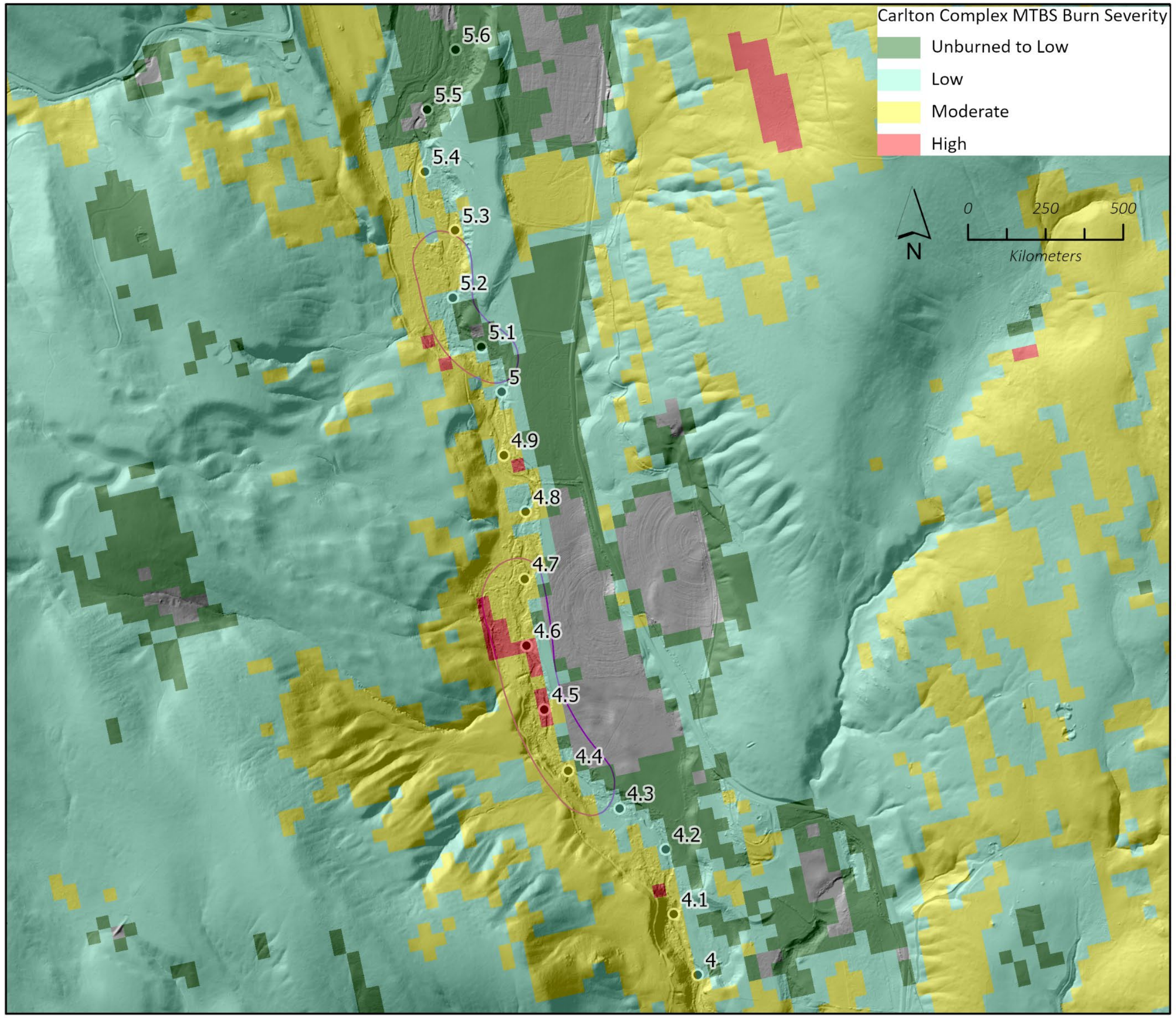
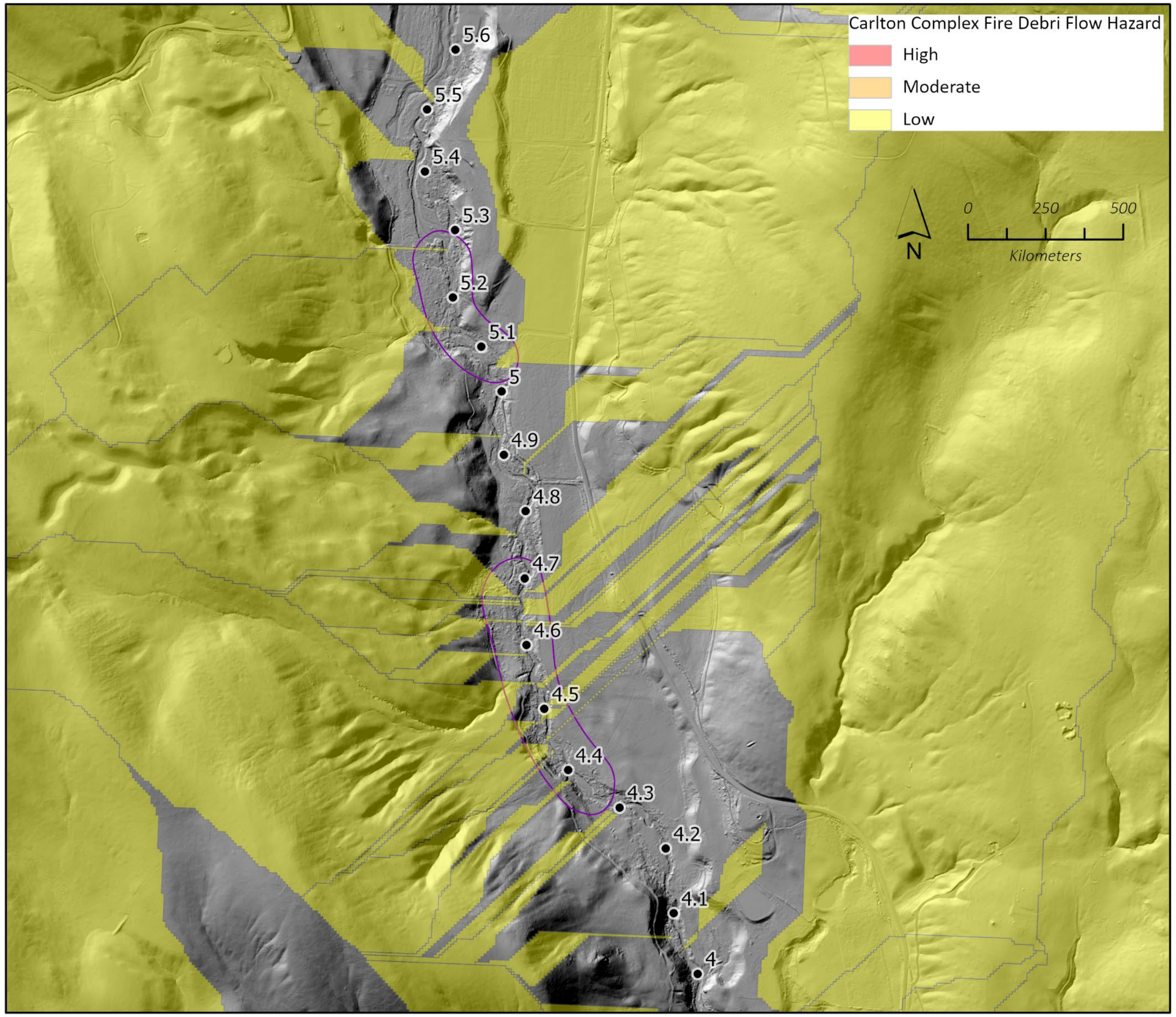
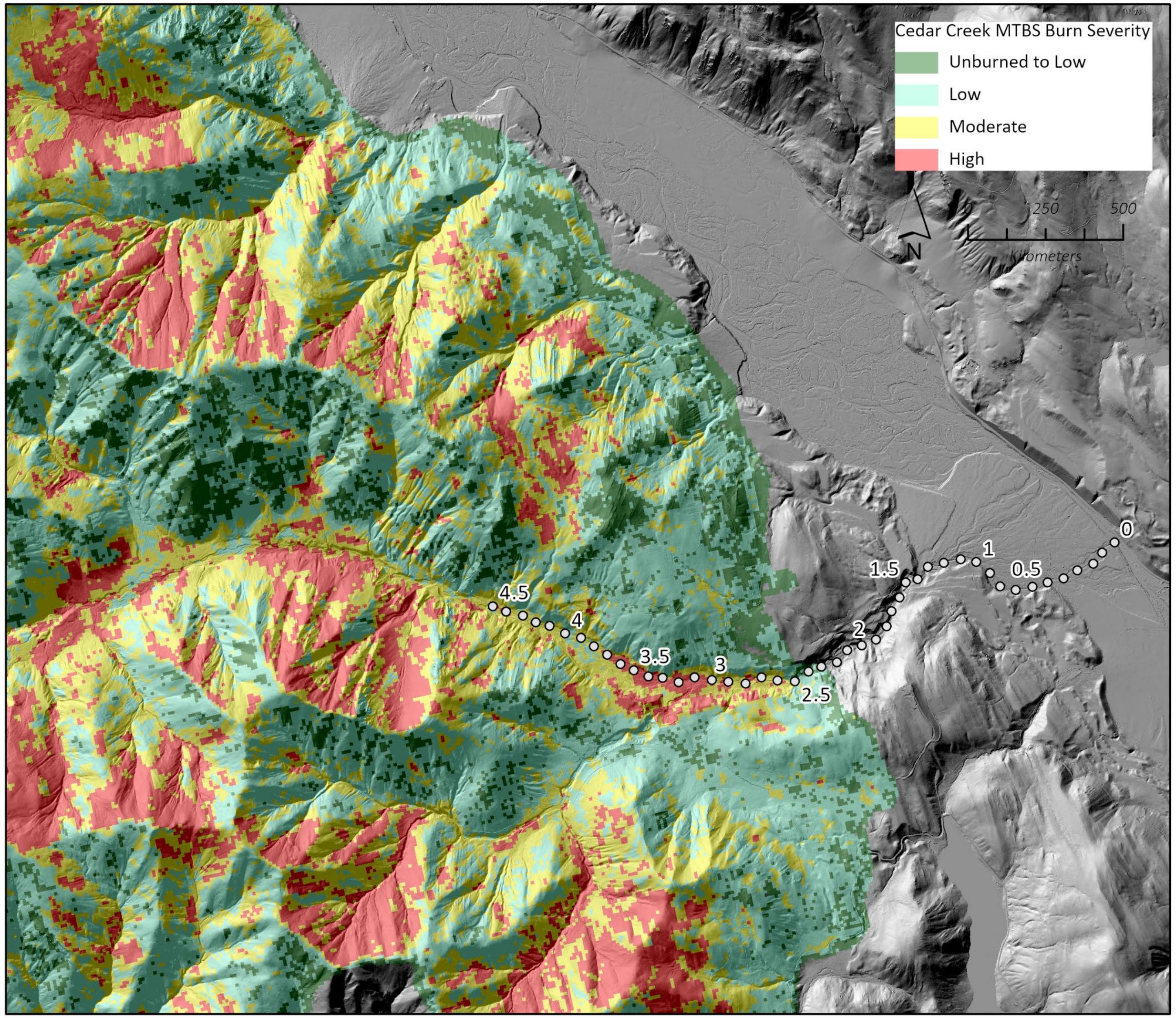
APPENDIX A CASE STUDIES SUPPORTING MATERIAL

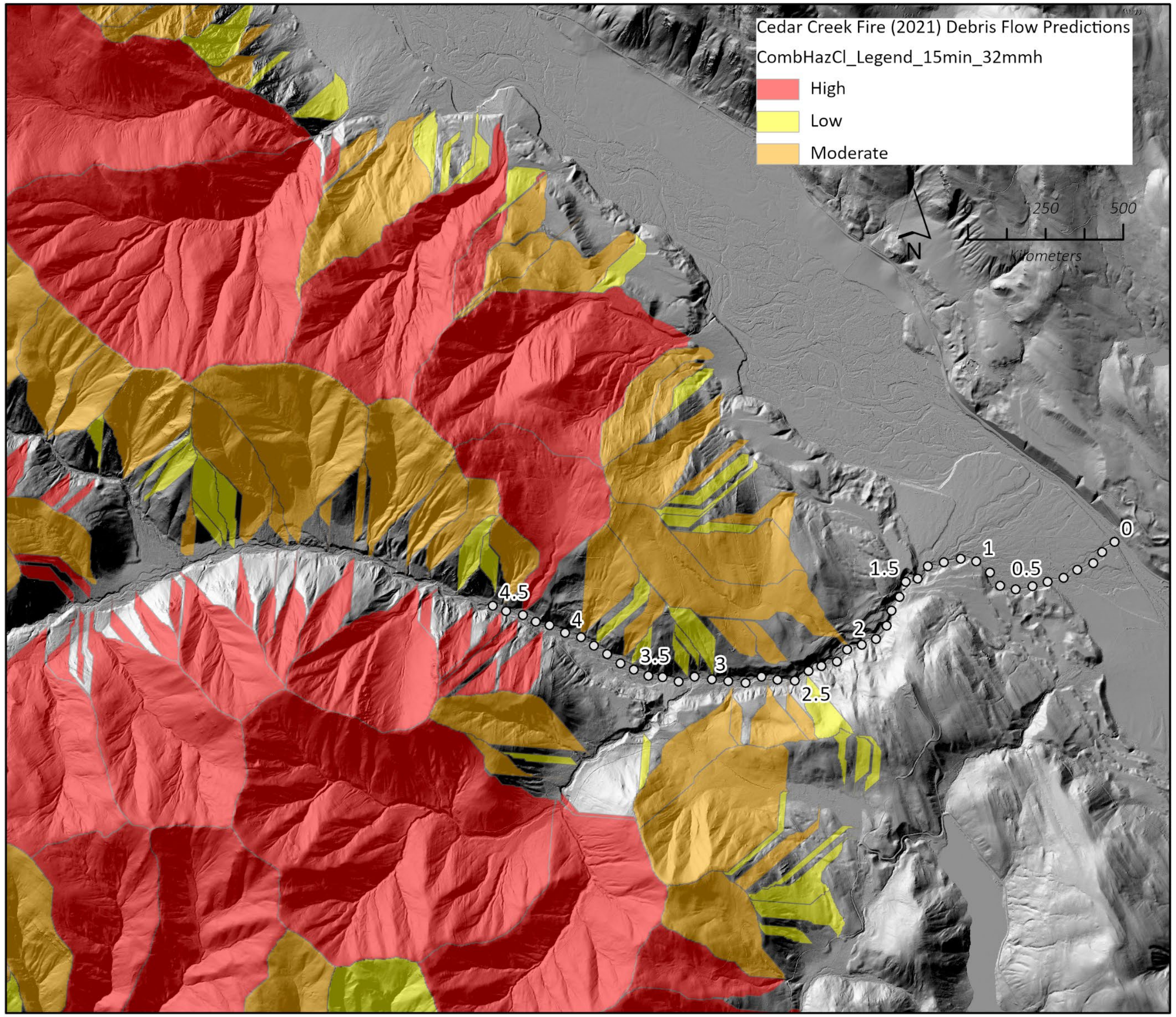
Beaver Creek – Burn Severity and Debris Flow hazards (Carlton Complex Fire 2014)



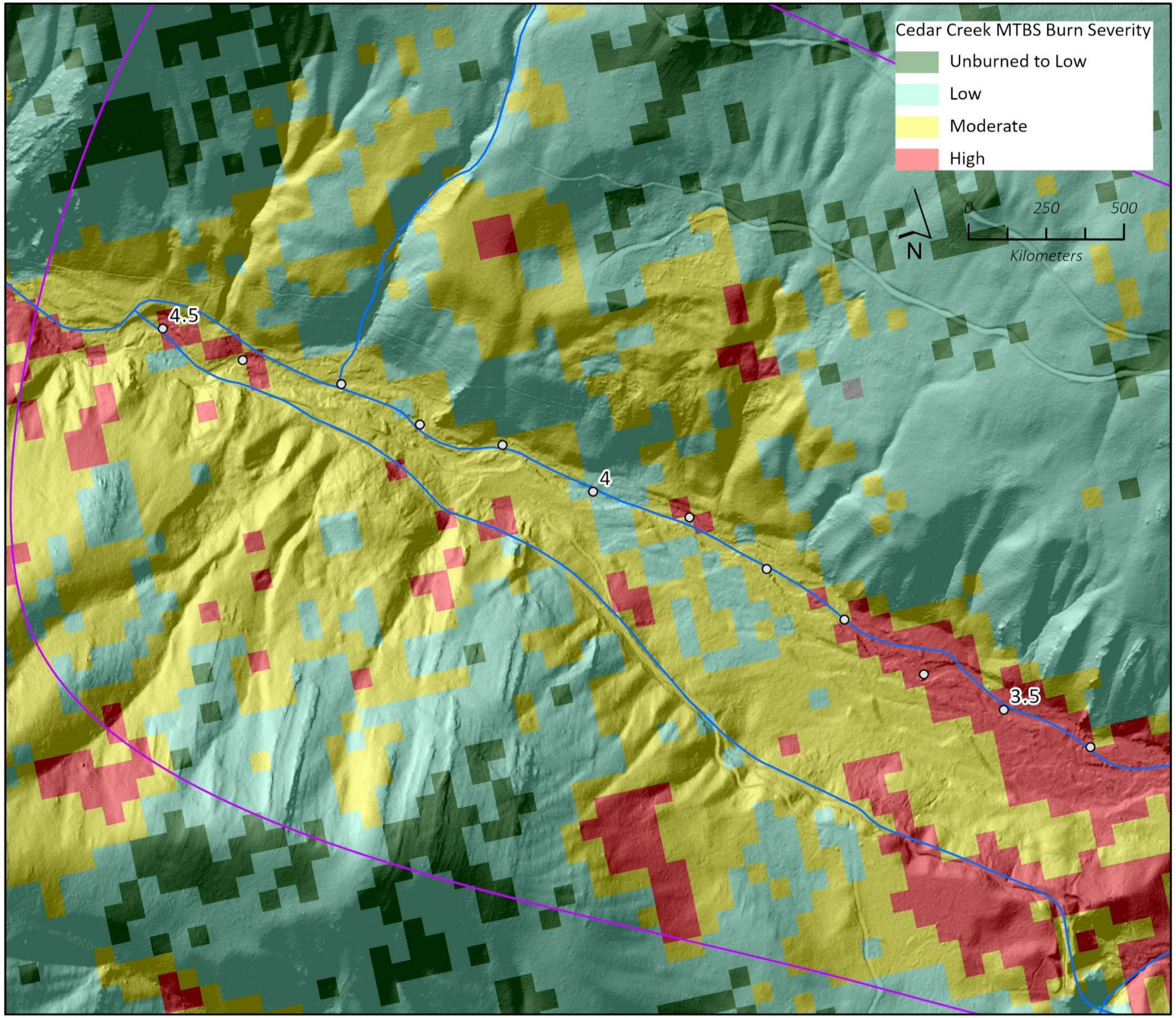


Wolf Creek – Reference control site – Burn Severity and Debris Flow hazards

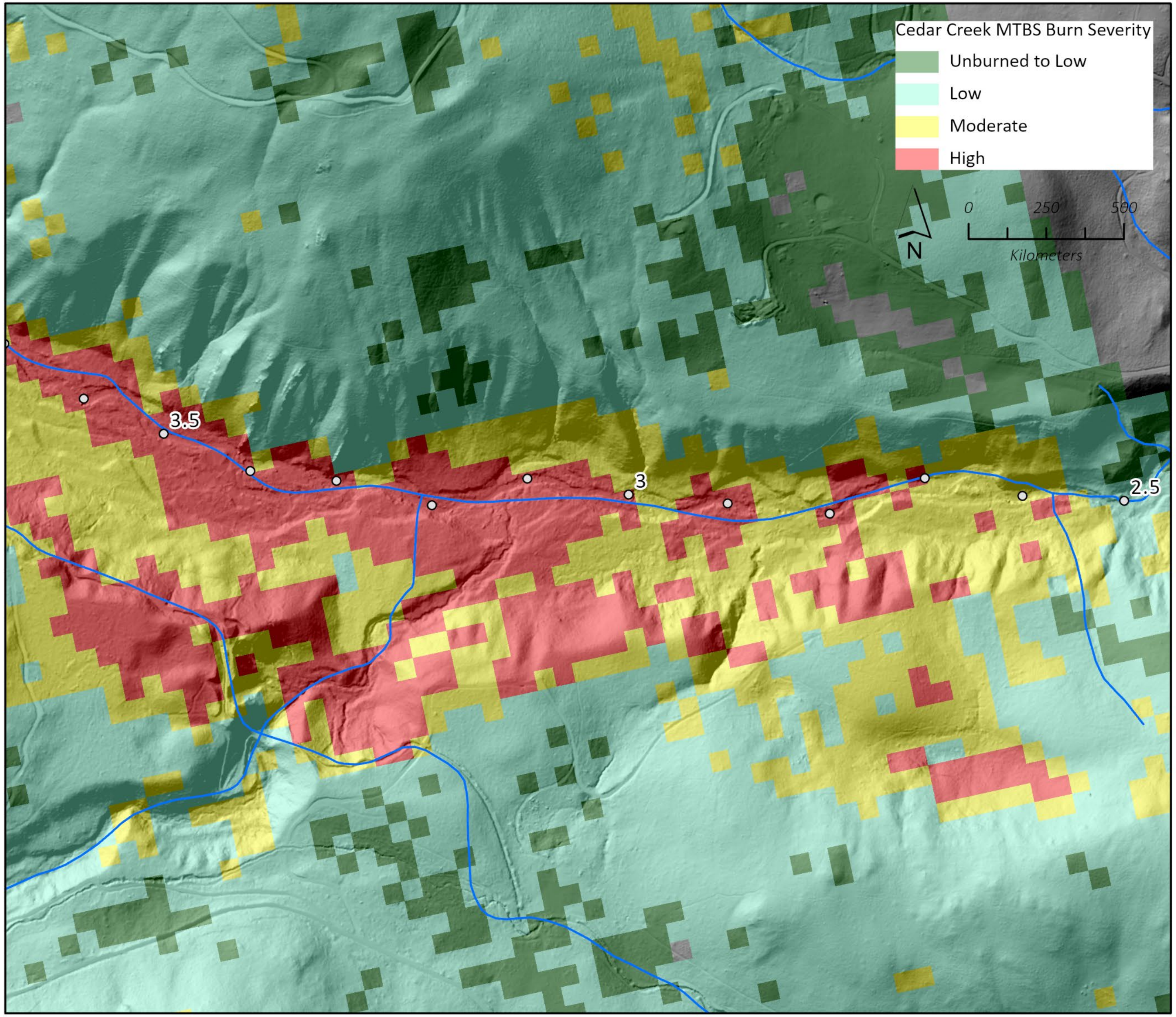




Wolf Creek – Reference control site – Burn Severity

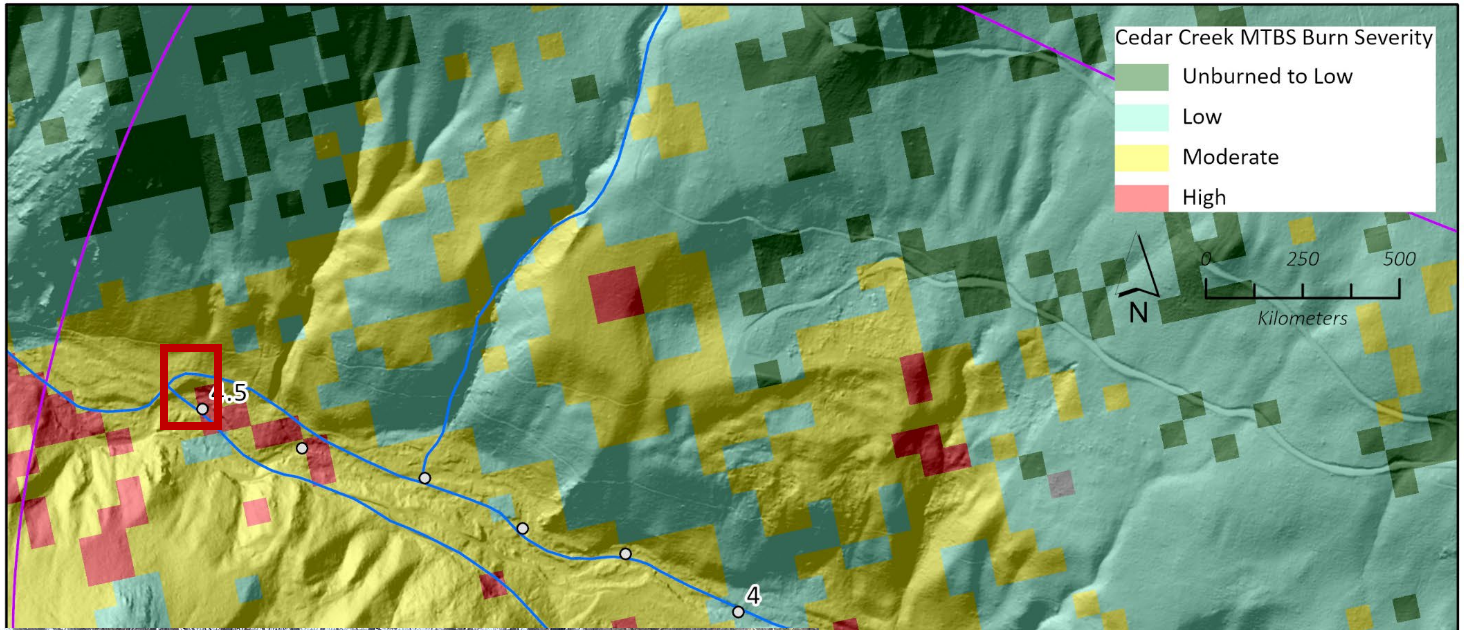


Wolf Creek – Reference control site – Burn Severity



Wolf Creek – Reference control site – Burn Severity


July 2020


Cedar Creek MTBS Burn Severity

- 🟩 Unburned to Low
- 🟩 Low
- 🟨 Moderate
- 🟥 High

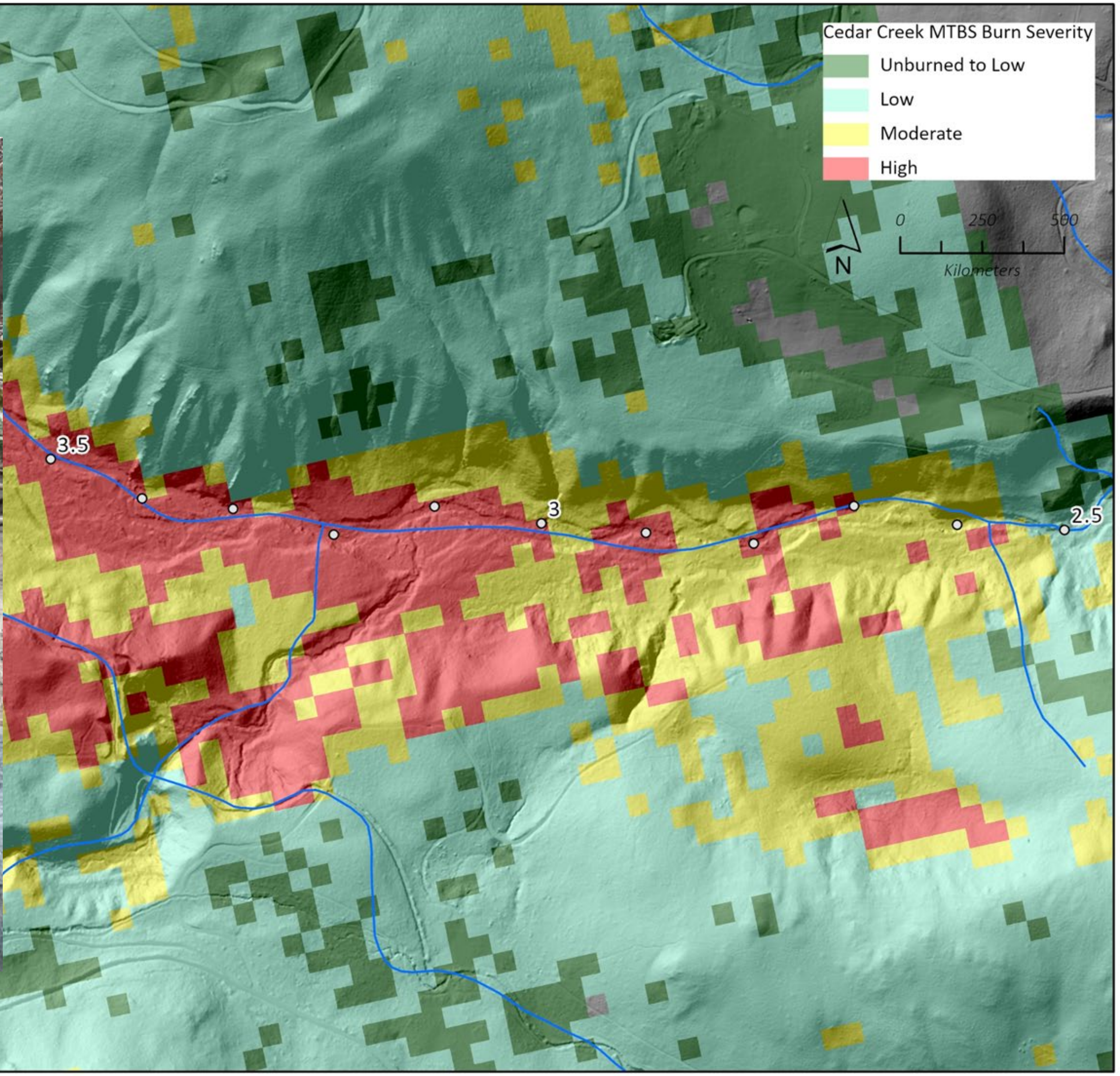
Large Wood jam at RM 4.43


Oct 2021


Aug 2022

Wolf Creek – Reference control site – Burn Severity

Figure 5. Fines accumulation behind large wood and debris and at the margin of the channel at RM 3.02. (8/11/2022)



Wolf Creek – Reference control site – Burn Severity

Figure 10. LEFT: looking downstream at channel-spanning large wood channel-spanning jam at RM 3.43 – July 2020. RIGHT looking downstream at RM 3.43 – August 2022.